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by

Robert Charbonneau

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Dedication

Je tiens à dédier cette thèse à ma famille, à mes amis et à mes collègues, qui par leur appui, leurs encouragements, leur aide et amitié ont contribué de mille et une façons à ce travail.

Abstract

The theory surrounding plasmon-polariton wave propagation on infinitely wide thin metal film structures was rederived, understood and is presented. Mode dispersion curves as a function of metal thickness were obtained for various metals and wavelengths. Field distributions for various structures of interest were computed and are presented. The results, along with a discussion of the significance of these simulations are presented.

Fresnel coefficients have been derived for an n -layer structure to simulate the expected reflectance measurements of attenuated total reflectance (ATR)¹ experiments. ATR experiments have been performed to excite surface plasmon-polaritons on a 20 nm thick titanium (Ti)-gold (Au)-Ti film embedded in SiO₂. These measurements were seen to be in good agreement with theory. Measurements of the sensitivity of the thin metal film infinite in width to incident polarisation were performed experimentally confirming the transverse magnetic (TM) nature of surface plasmon-polaritons.

A first mask was designed to experimentally verify the optical mode confinement of a thin metal film finite in width. Single mode operation of a straight metal optical wave guide² was observed for the first time on an 8 μm wide, 20 nm thick and 3.5 mm long gold (Au) film embedded in SiO₂. The wave guide was excited in an end-fire experiment using a polarisation maintaining fiber connected to a 1550 nm semiconductor laser. A guide as long as 6 mm was excited, demonstrating the long-range propagation of plasmon-polaritons. *S*-bend shaped guides of various width were excited and demonstrated that the confinement was sufficiently strong to allow light to be guided along curves.

The sensitivity of a straight 8 μm guide to the angle of incident polarisation of the input light was verified for the first time. Qualitative and quantitative measurements were performed and confirmed the importance of the input polarisation on the light

¹ Attenuated total reflectance (ATR) is a useful method for exciting plasmon-polaritons at a metal-dielectric interface, and can be used to characterise the optical properties of thin metal films. The technique, along with experimental and theoretical results, will be presented in Chp. 4.

² In this thesis, the term *wave guide* refers to thin metal films finite in width, and although thin films infinite in width constitute wave guiding structures, they are referred to as slabs or thin films infinite in width.

confinement abilities of the guide. A minimum in transmitted light along the wave guide was observed for a TE incident polarisation whereas the maximum was observed for a TM incident polarisation. Finally, unit length loss measurements were performed on the $8\text{ }\mu\text{m}$ wide straight wave guides.

A second mask was designed with the knowledge acquired from the the first one. Straight wave guides of various widths were excited and unit length loss measurements were performed. *S*-bends of various widths and of different radii of curvature have been characterised. The effect of sharp bends as a function of angle was also verified to determine the confinement strength of these devices. *Y*-junctions formed by the juxtaposition of two back-to-back *S*-bends were also characterised for different radii of curvature. As the radius of curvature of the bends was reduced, more power was radiated by the bends and less light was observed at the output. Nevertheless, the light was found to be well confined and two circularly symmetric spots were observed at the output of the *Y*-junctions. Couplers designed with $8\text{ }\mu\text{m}$ wide wave guides were tested for different coupling separations. Experiments confirmed that synchronous couplers can be designed using metal optical wave guides and that the separation distance in the coupling region allows different power splits. It is thus possible to optimise the design such as to obtain a specific power split, or even a full power transfer from the input port to the coupled port. The experimental results in this thesis demonstrate for the first time that a new integrated optics technology based on optical propagation along thin metal films of finite width is feasible.

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Introduction

Motivation : Importance of optical communications

In recent years, we have seen an explosion in the growth of the telecommunications industry resulting in large part from the unparalleled popularity of the internet and the need for high speed and high bandwidth data transfer. Conventional co-axial and microwave communication links are no longer sufficient to satisfy the demand and optical networks are now the norm. Companies are striving to develop components that provide faster transmission rates, high reliability and low system losses while they also attempt to reduce manufacturing costs. Many innovations, such as erbium-doped fiber amplifiers (EDFA) [1, 2], optical cross-connects (OXC) [3, 4] and wavelength-division multiplexing (WDM) [5] have surfaced in recent years and have forever changed the way networks operate. Still, new components may provide cheaper alternatives and help further reduce system costs.

Passive optical components are an integral part of optical networks. Examples of passive optical components are couplers, power splitters, power taps and star couplers. Simpler structures such as straight wave guides, bends and Y -junctions form the basis of both passive and active optical components. For this reason, it is important to characterise passive components of new and emerging technologies. Such work serves as a starting point for future research, design and development.

Thesis objectives

The main purpose of this thesis is to design and test thin gold (Au) wave guides and characterise their ability to guide light at communications wavelengths. Recently, optical modal analysis has revealed that a thin metal film finite in width is capable of supporting a bound plasmon-polariton propagating mode [6–9]. Following this discovery, it was important to verify experimentally the existence of these bound modes.

The first objective of this thesis is to acquire the theoretical background necessary to

better understand the mechanisms by which plasmon-polariton modes are supported and investigate numerically the effect of the various structure design parameters. In order to do so, it will be necessary to derive relations using Maxwell's equations that enable accurate modelling of the structures of interest.

A second objective of this thesis is to repeat attenuated total reflectance (ATR) measurements presented in the literature such as to excite plasmon-polariton modes on unpatterned thin metal films, or slab guides. Prior to performing the experiments, it will be necessary to model the expected reflectance curves using Fresnel's coefficients, such that adequate samples are designed and fabricated.

The third and main objective of this thesis is to excite plasmon-polariton modes on thin Au films of finite width and experimentally characterise their properties. The design of lithographic masks will be required such that various passive optical structures may be fabricated and tested. The results of these experiments will be analysed and discussed.

Thesis contributions

The body of literature on the subject of plasmon-polaritons includes some books and many papers, however, most of the literature on the subject is not relevant to today's optical communications needs. In this thesis, a considerable effort was devoted to analysing plasmon-polariton modes in practical structures at communications wavelengths.

ATR measurements performed on a Ti-Au-Ti metal film have verified the existence of plasmon-polariton modes on thin metal films infinite in width. The TM-nature of the mode supported has also been verified in a polarisation sensitivity measurement.

The optical mode confinement of a thin Au film finite in width has been experimentally verified for what is believed to be the first time. The polarisation sensitivity of the propagation supported by a thin metal film finite in width was investigated and the results are presented. In addition, the design of two lithographic masks was undertaken and important passive structures such as straight wave guides, *S*-bends, sharp bends, *Y*-junctions, couplers and a Mach-Zehnder-like device were tested and characterised for various design parameters.

This thesis, it is hoped, presents a good literature review of published work on the subject, develops the theoretical background for a deep understanding of plasmon-polariton waves and provides a basis for important parameters that may be used to design optical devices for today's communications needs using thin metal film wave guides.

Thesis organisation

Many papers on surface plasmon-polaritons waves have been published, however, very few people are familiar with these waves. Therefore, a definition and description of plasmon-polaritons is in order. In Chapter 1, a description of the modes supported by thin metal film structures will be given, along with a historical review of the past research conducted in this field.

Part I of the thesis, consisting of Chapters 2 to 4, presents the results of an investigation on thin metal films that are infinite in width. In Chapter 2, we present the equations describing the propagating bound modes as well as the computer model used to find the modes. In Chapter 3, theoretical results are presented and analysed for various structures of interest. This chapter, it is hoped, furthers our understanding of plasmon-polaritons, the mechanism that guides them and the ones that affect them. In Chapter 4, Fresnel reflection coefficients are derived and presented. In addition, results of attenuated total reflectance (ATR) measurements, performed to characterise devices fabricated during the course of this thesis, are presented and discussed. The simulated results are compared and reconciled with experiments performed on thin films infinite in width. This chapter also presents the polarisation sensitivity of surface plasmon-polaritons.

Part II presents the main contributions of this research. In Chapter 5, the experimental results of the excitation of thin metal films of finite width are presented. A description of two mask designs is presented, along with details of the device fabrication and experimental measurements. Included are the qualitative results of the first experimental evidence of optical mode confinement of a straight wave guide, with evidence of light confinement along important passive structures, such as *S*-bends, *Y*-junctions, couplers and more. Also included are measurements presenting the polarisation sensitivity of a 8 μm wide, 20 nm thick and 3.5 mm long straight Au wave guide. Preliminary unit length loss measurements for metal optical wave guides are also presented. A few words on fabrication issues relevant to this technology are presented in §5.5 and §5.6.

The Conclusion contains remarks and potential directions for future work. Appendix A contains a list of acronyms and their respective meaning. Appendix B presents a list of the variables used in this thesis and a brief description for each. Appendix C presents tables of measurement data used to plot the various graphs displayed in this thesis. Finally, a list of bibliographic references is presented at the very end of this thesis.

1. Literary review

1.1. Historical review

In the late seventies and early eighties, significant interest and energy was devoted to the investigation of surface polaritons. This interest follows the discoveries, in 1968, of Otto [10], Kretschmann and Raether [11, 12] presenting methods for exciting surface polaritons using an attenuated total reflectance (ATR) setup. These discoveries paved the way for the career of many researchers.

Interest on the subject stems from the fact that surface plasmon-polaritons are very localised at a metal-dielectric interface and their sensitivity to the quality of this interface offers researchers a powerful investigative tool. For instance, they have been used to examine the properties of thin overlayers [13–17], to investigate electrochemical interfaces [18–20], to study the thermodynamics of condensation [21, 22] and they have also been used in chemical and biological sensing applications [23–26]. In the next sections, we will describe the physical nature of plasmon-polaritons in the hope of giving to the reader a clearer understanding of these electromagnetic waves.

1.2. Definition of plasmon-polaritons

An electromagnetic wave propagating through a polarisable medium is modified by the polarisation it induces and becomes coupled to this medium [27, Chp. 1]. Such coupled modes are termed bulk polaritons when propagation occurs in an unbounded medium, and surface polaritons when propagation occurs at the interface between two media as a result of coupling of the EM radiation to surface dipole excitations [27, Chp. 4].

At optical wavelengths, some metals are characterised by a permittivity having a negative real part and may be modeled as a free-electron gas or plasma. Their relative permittivity is determined according to the Drude free-electron theory as follows [27, 28]:

$$\tilde{\epsilon}_r(\omega) = \epsilon' - j\epsilon'' \quad (1.1)$$

$$\epsilon' = 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2} \quad (1.2)$$

$$\epsilon'' = \frac{\omega_p^2 \tau}{\omega (1 + \omega^2 \tau^2)} \quad (1.3)$$

$$\omega_p^2 = \frac{4\pi N e^2}{m_0} \quad (1.4)$$

$$\tau = \frac{1}{\nu} \quad (1.5)$$

where ω_p is the plasma frequency, N is the density of conduction electrons, m_0 is their effective optical mass, e is the electronic charge, τ is the relaxation time (or dc conductivity) of the electrons and ν is the effective electron collision frequency. Some metals at near-infrared frequencies are characterised by $1 + \omega^2 \tau^2 < \omega_p^2$, such that $\epsilon' < 0$.

From Maxwell's equations, it is possible to show that the interface between two media having real part of permittivities of opposite sign will support a mode [27, p. 17]. This mode is referred to as a plasmon-polariton. As such, plasmon-polaritons are simply transverse magnetic, surface electromagnetic waves propagating at the interface between two media and characterised by exponentially decaying amplitude with increasing distance from the interface such that the field's amplitude tends towards zero as the distance from the interface tends towards infinity [29]. These propagating waves essentially disrupts surface charge densities and becomes coupled to these surface charges.

1.3. Description of supported modes

In the simplest case, we have an interface between two non absorbing media characterised by purely real permittivities of opposite signs. The surface mode which may exist at this interface were described by Fano [30]. In general, however, all dielectrics have losses and thus are more adequately described by a complex permittivity. When one medium at a two media interface is absorbing, such that its permittivity is complex, the surface waves that may be supported are termed Zenneck modes [31].

It is almost always stated in the literature that surface polaritons are only supported at the interface of two media, the first medium characterised by a negative real part of its dielectric constant ($\epsilon'_1 < 0$) and the second medium with a positive dielectric constant ($\epsilon'_2 > 0$), provided that the inequality $|\epsilon'_1| > \epsilon'_2$ is satisfied. Reference [29], however, points out that this is only true in the case of Fano modes. In fact, they show

that a surface mode may be supported at the interface of two media, one of which having a real permittivity ϵ'_2 and the other a complex relative permittivity $\tilde{\epsilon}_{r1} = \epsilon'_1 - j\epsilon''_1$ with the real part (ϵ'_1) of the latter being negative, zero or even positive. In the case where $\epsilon'_1 \gg \epsilon''_1$, a Zenneck mode is no longer supported. Instead, a purely radiative Brewster wave propagates.

Although a single metal–dielectric interface supports plasmon–polaritons, it is much more interesting, for reasons that will become clear, to consider the propagation of plasmon–polaritons along thin metal films supported above and below by dielectrics, as shown in Figure 1.1. For a sufficiently thin metal film embedded in a dielectric, the plasmon–polaritons supported at the two metal–dielectric interfaces will be coupled to each other through the effect of tunneling. Two bound modes have been identified for such a structure: the symmetric bound mode (s_b) and the asymmetric bound mode (a_b) [32]. These modes are labeled for their respective field distributions. The s_b is considered symmetric because the parallel component of its magnetic field, labeled H_y , does not exhibit a phase reversal within the metal. Likewise, the a_b mode is termed asymmetric because its H_y component exhibits a 180° –phase reversal within the metal.

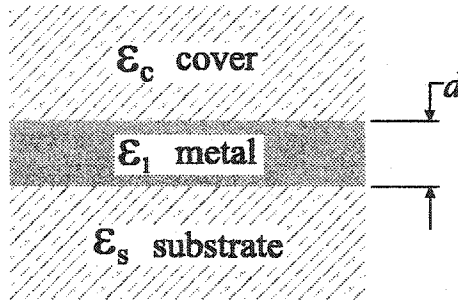


Figure 1.1.: A thin metal film infinite in width, characterised by a permittivity $\tilde{\epsilon}_1$ and a thickness d , supported by an infinite substrate of permittivity $\tilde{\epsilon}_s$ and covered by an infinite dielectric of permittivity $\tilde{\epsilon}_c$.

The modes supported by a infinitely wide thin metal film are strictly TM in nature for non-magnetic metals (i.e. $\tilde{\mu}_r = 1$, $\tilde{\epsilon}_r \neq 1$). In the case of a purely magnetic material (i.e. $\tilde{\epsilon}_r = 1$, $\tilde{\mu}_r \neq 1$), the modes supported would be entirely TE in nature and are then referred to as surface magnons [33, 34].

The surface plasmon–polariton symmetric bound mode is of most interest since it exhibits dispersion with metal thickness such that a significant decrease in attenuation is observed for decreasing metal thickness. Indeed, this was verified experimentally [35, 36]. As the thickness of the metal film tends towards zero, the mode supported by the structure evolves into the plane wave supported by the surrounding medium. The

symmetric bound mode is also of interest since its field pattern lends itself to good mode overlap using an ATR setup. End-fire excitation was proposed in Ref. [37], but to our knowledge, was never demonstrated.

The asymmetric mode also exhibits dispersion with metal thickness, however, its attenuation increases for decreasing metal thickness. In addition, unlike the symmetric mode, the field distribution of the asymmetric mode does not lend itself to easy optical excitation.

Recently [6, 7], optical modal analysis has revealed that thin metal films finite in width also support plasmon-polariton modes similar to those described above with the additional benefit of providing lateral as well as vertical field confinement. Such a structure is illustrated in Figure 1.2. Four fundamental modes were discovered and a suitable nomenclature for them was presented in Ref. [6]. The modes are labeled aa_b^0 , as_b^0 , sa_b^0 and ss_b^0 , where the letters a and s identify asymmetry or symmetry of the main electric field component along the z and y confinement directions, respectively, and the b and l^1 indicate a bound or leaky mode, respectively. These modes are not purely TM in nature; rather, they must be described by all six electromagnetic field components. For a metal optical wave guide having an aspect ratio *width* : *thickness* $\gg 1$, the electric field normal to the horizontal metal surface dominates.

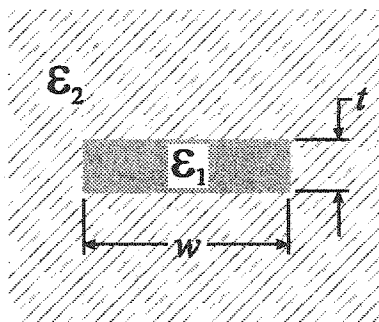


Figure 1.2.: A metal film finite in width, characterised by a permittivity $\tilde{\epsilon}_1$, a thickness t and a width w embedded in a dielectric of permittivity $\tilde{\epsilon}_2$.

As in the case of the infinitely wide metal film, the ss_b^0 is of most interest since its attenuation decreases significantly with decreasing metal thickness. In addition, attenuation is further reduced for decreasing metal width [7]. As the thickness and the width of the metal film are decreased, the mode is less tightly bound to the structure and it evolves into a quasi-TEM mode.

¹ The nomenclature of the modes presented in Ref. [6] is sufficiently broad to allow for bound and leaky modes, however, at this time, leaky modes that may be supported by this structure have not been investigated.

The end-fire operation of a 8 μm wide, 20 nm thick and 3.5 mm long Au wave guide embedded in SiO_2 has been experimentally verified [39] along with the polarisation sensitivity of the device. In this thesis, a theoretical investigation of infinitely wide metal films and experimental observations of plasmon-polaritons propagating along thin metal films infinite and finite in width will be presented and the results analysed.

Part I.

Thin metal films infinite in width

2. Unpatterned thin metal films

2.1. Derivation of the dispersion equation of a thin metal film infinite in width

In the previous section, we have seen that researchers have investigated surface plasmon-polariton modes on thin metal films infinite in width for many years. Although our end goal is to characterise metal films finite in width, it is appropriate to present results for thin metal films infinite in width.

In the case of finite width metal film, all six electromagnetic field components are present and a powerful, modal analysis tool is required. For thin metal films infinite in width, also referred to in this thesis as unpatterned thin metal films, surface plasmon-polaritons are characterised by only three electromagnetic field components and thus the modelling of such structures is greatly simplified. The analysis of metal slab guides should provide valuable insight on the expected properties of finite width metal optical wave guides.

The derivation presented in this thesis will first be for a 1-layer film supported above and below by an infinite dielectric, as illustrated in Figure 2.1. This derivation is presented to help the reader follow more easily the procedure used to derive the dispersion relation and to help him visualise the field distributions of the modes supported by a thin metal film embedded in dielectrics. Then, in the subsequent section, a more general derivation will be presented for an n -layer structure, such that we may more accurately model the specimens fabricated for these experiments.

2.1.1. Derivation of the dispersion equation for a thin metal film supported above and below by a semi-infinite isotropic dielectrics

In order to derive the dispersion equations of the plasmon-polariton modes¹, we begin by using Maxwell's equations to determine the modes propagating along the structure illustrated in Figure 2.1, in which a thin metal film of thickness d is surrounded above and below by two dielectrics. This structure is characterised by three relative permittivities, $\tilde{\epsilon}_s$, the permittivity of the substrate, $\tilde{\epsilon}_1$, the permittivity of the metal film and $\tilde{\epsilon}_c$, the permittivity of the cover. All relative permittivities may be complex and are given in the form $\tilde{\epsilon}_r = \epsilon' - j\epsilon''$. The reader should realise that, although electronic transitions in solids are more directly related by the permittivity [28], it is sometimes more convenient to describe layers by their complex index of refraction. The relative permittivity and the index of refraction are simply related by the relation $\tilde{\epsilon}_r = \epsilon' - j\epsilon'' = \tilde{n}^2 = (n - jk)^2 = n^2 - k^2 - j2nk$. The complex index of refraction, $\tilde{n}$, is thus seen to be comprised of the index of refraction, n , and the extinction coefficient k . In this thesis, unless otherwise indicated, it will be understood that the term index of refraction refers to the complex index of refraction, $\tilde{n}$.

The structure under investigation cannot support a TE mode in the case of a non-magnetic metal (i.e. where the relative permeability of the metal is $\tilde{\mu}_r = 1$) [27, p. 17]. Thus, for the non-magnetic metal that we wish to investigate at present, only a transverse magnetic (TM) mode will propagate along the metal-dielectric interfaces and so we will be concerned only with the E_x , E_z and H_y field components. We use a right hand cartesian coordinate system in which propagation occurs in the $+x$ direction, and follow the derivation presented in Ref. [32].

Since we are analysing a structure supporting TM-modes, we begin by proposing suitable H_y , E_x and E_z fields for the structure of interest. The propagation occurs in the $+x$ direction and the fields may be expressed as follows:

$$\overline{H} = \hat{y}H_{y_i}(z)e^{j(\omega t - k_x x)} \quad (2.1)$$

$$\overline{E} = [\hat{x}E_{x_i}(z) + \hat{z}E_{z_i}(z)]e^{j(\omega t - k_x x)} \quad (2.2)$$

where $H_{y_i}(z)$, $E_{x_i}(z)$ and $E_{z_i}(z)$ are functions which describe the dependence of the H and E fields on z in the substrate, metal and cover layers, $i = s, 1, c$, respectively, and $k_x = \beta - j\alpha$ is the propagation constant parallel to the surface that must be the same in

¹ The derivations presented in §2.1.1 and §2.1.2 are used in this thesis to investigate plasmon-polariton modes, however, these derivations could also be used to find slab modes in dielectric layered structures.

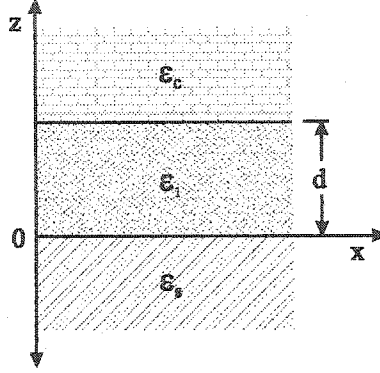


Figure 2.1.: Thin metal film infinite in width supported above and below by semi-infinite dielectrics.

all media.

It is possible to find the dependence of the $E_x(z)$ and $E_z(z)$ fields from the well-known Maxwell curl equations presented below in phasor form.

$$\nabla \times \bar{H}_i = j\omega\epsilon_0\tilde{\epsilon}_{r_i}\bar{E}_i \quad (2.3)$$

$$\nabla \times \bar{E}_i = -j\omega\mu_0\bar{H}_i \quad (2.4)$$

From equation 2.3, we may find $E_z(z)$ and $E_x(z)$:

$$E_{x_i}(z) = \frac{j}{\omega\epsilon_0\tilde{\epsilon}_{r_i}} \frac{dH_{y_i}(z)}{dz} \quad (2.5)$$

$$E_{z_i}(z) = \frac{-k_x}{\omega\epsilon_0\tilde{\epsilon}_{r_i}} H_{y_i}(z) \quad (2.6)$$

We now wish to find an expression to describe the dependence of $\bar{H}$ in the z -direction, in the various media. In the substrate ($\tilde{\epsilon}_{r_s}$), where $z \leq 0$, we have:

$$H_{y_s}(z) = Ae^{jk_{zs}z} \quad (2.7)$$

$$k_{zs} = \pm\sqrt{\tilde{\epsilon}_{r_s}k_0^2 - k_x^2} \quad (2.8)$$

where A is a normalisation constant and $H_{y_s}(z)$ is chosen such that it decays exponentially with increasing distance from the metal-dielectric interface positioned at $z = 0$, such that $H_{y_s}(z) \rightarrow 0$ as $z \rightarrow -\infty$. In the metal ($\tilde{\epsilon}_1$), where $0 \leq z \leq h$, we propose the following general solution to Maxwell's wave equations:

$$H_{y_1}(z) = B \cosh(jk_{z_1}z) + C \sinh(jk_{z_1}z) \quad (2.9)$$

$$k_{z_1} = \pm \sqrt{\tilde{\epsilon}_{r_1} k_0^2 - k_x^2} \quad (2.10)$$

And in the cover ($\tilde{\epsilon}_{r_c}$), where $z \geq h$, we have:

$$H_{y_c}(z) = D e^{-j k_{z_c}(z-d)} \quad (2.11)$$

$$k_{z_c} = \pm \sqrt{\tilde{\epsilon}_{r_c} k_0^2 - k_x^2} \quad (2.12)$$

where $H_{y_c}(z)$ is chosen such that it decays exponentially with increasing distance from the metal–dielectric interface positioned at $z = d$, such that $H_{y_c}(z) \rightarrow 0$ as $z \rightarrow \infty$. In the above equations, $k_0 = \frac{2\pi}{\lambda_0}$, and $\tilde{\epsilon}_{r_i}$ is the relative permittivity of medium i on which the tilde indicates that the permittivity may be complex. In order for the notation and the signs used in this derivation to be valid, the k_{z_i} 's are chosen such that $\Im\{k_{z_i}\} < 0$. In choosing the $\pm$ accordingly, we will ensure that the mode selected is non-radiative. The effective index of refraction is defined as $N_{eff} = \frac{k_x}{k_0}$. The effective index of refraction may be used to easily model a structure of interest.

We may now solve for the constants B , C and D by applying boundary conditions at the interfaces $z = 0$ and $z = d$. Thus, we force the tangential E and H fields to be continuous across both interfaces. At the substrate–metal interface, where $z = 0$, we may write:

$$H_{y_s}(z) = H_{y_1}(z)|_{z=0} \Rightarrow A = B \quad (2.13)$$

$$E_{x_s}(z) = E_{x_1}(z)|_{z=0} \Rightarrow C = \frac{k_{z_s} \tilde{\epsilon}_{r_1}}{k_{z_1} \tilde{\epsilon}_{r_s}} A \quad (2.14)$$

At the metal–cover interface, where $z = d$, we find by imposing $H_{y_1}(z) = H_{y_c}(z)|_{z=d}$:

$$D = A \left[\cosh(j k_{z_1} d) + \frac{k_{z_s} \tilde{\epsilon}_{r_1}}{k_{z_1} \tilde{\epsilon}_{r_c}} \sinh(j k_{z_1} d) \right] \quad (2.15)$$

Finally, by setting $E_{x_1}(z) = E_{x_c}(z)|_{z=d}$ at $z = d$, we may obtain the transcendental equation that allows us to solve numerically for the propagation constant of the modes supported by this structure. After some algebraic manipulation, we find the following dispersion relation:

$$\tanh(j k_{z_1} d) \left[\tilde{\epsilon}_{r_s} \tilde{\epsilon}_{r_c} k_{z_1}^2 + \tilde{\epsilon}_1^2 k_{z_s} k_{z_c} \right] + [\tilde{\epsilon}_{r_1} (\tilde{\epsilon}_{r_s} k_{z_c} + \tilde{\epsilon}_{r_c} k_{z_s}) k_{z_1}] = 0 \quad (2.16)$$

By simultaneously solving for equations 2.8, 2.10, 2.12 and 2.16, it is possible to find k_x , the propagation constant of the modes supported by this structure.

The equations for the electromagnetic fields in all three layers are as follows: in the substrate, where $z \leq 0$, we have:

$$H_{y_s}(z) = Ae^{jk_{z_s}z} \quad (2.17)$$

$$\omega\epsilon_0 E_{x_s}(z) = \frac{-k_{z_s}}{\tilde{\epsilon}_{r_s}} Ae^{jk_{z_s}z} \quad (2.18)$$

$$\omega\epsilon_0 E_{z_s}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_s}} Ae^{jk_{z_s}z} \quad (2.19)$$

In the metal, where $0 \leq z \leq d$, we have:

$$H_{y_1}(z) = [B \cosh(jk_{z_1}z) + C \sinh(jk_{z_1}z)] \quad (2.20)$$

$$\omega\epsilon_0 E_{x_1}(z) = \frac{-k_{z_1}}{\tilde{\epsilon}_{r_1}} [B \sinh(jk_{z_1}z) + C \cosh(jk_{z_1}z)] \quad (2.21)$$

$$\omega\epsilon_0 E_{z_1}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_1}} [B \cosh(jk_{z_1}z) + C \sinh(jk_{z_1}z)] \quad (2.22)$$

And finally, in the cover, where $z \geq d$, we have:

$$H_{y_c}(z) = De^{-jk_{z_c}(z-d)} \quad (2.23)$$

$$\omega\epsilon_0 E_{x_c}(z) = \frac{k_{z_c}}{\tilde{\epsilon}_{r_c}} De^{-jk_{z_c}(z-d)} \quad (2.24)$$

$$\omega\epsilon_0 E_{z_c}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_c}} De^{-jk_{z_c}(z-d)} \quad (2.25)$$

From the above equations, along with the dispersion equation 2.16, it is possible to fully characterise a TM mode supported by a thin metal film of infinite width embedded in two dielectrics. In the next section, a more general derivation will be presented for a thin metal film embedded in a dielectric composed of n -layers.

2.1.2. Derivation of the dispersion equation for a thin metal film embedded in an n -layer isotropic stratified media

The previous derivation is a good approximation to an actual device so long as the thickness of the dielectric in which the metal is embedded is many wavelengths thick. In practice, however, it is not always easy, feasible or even desirable to fabricate a sample with a very thick dielectric. The added thickness of dielectric requires a longer deposition time for the dielectric and thus is more expensive to fabricate. In addition, it is sometimes difficult for various reasons to obtain a thick and uniform dielectric layer. Typically, the thicker the dielectric, the greater the strain that accumulates to the point where it may

break under its own stress. Care must be taken when depositing dielectric layers many microns thick. Finally, in an ATR experiment, it is actually undesirable to have a thick cover because the thicker it is, the smaller the amount of power that will be coupled to the metal slab wave guide. Therefore, it is of great interest to be able to model adequately the plasmon–polariton mode propagation along a thin metal slab embedded in a multiply layered media.

Also of interest, although not modeled in this thesis, are thin metal slab structures in which two metal slabs are embedded in a dielectric and are separated from each other by this dielectric [41, 42]. The resulting super–modes have characteristics very similar to the plasmon–polariton mode investigated in this thesis, on which electro–optics effects may be exploited. This being said, we now turn our attention to deriving the field equations and dispersion relation for the n –layer structure illustrated in Figure 2.2. The derivation that will be presented follows Refs. [43–46].

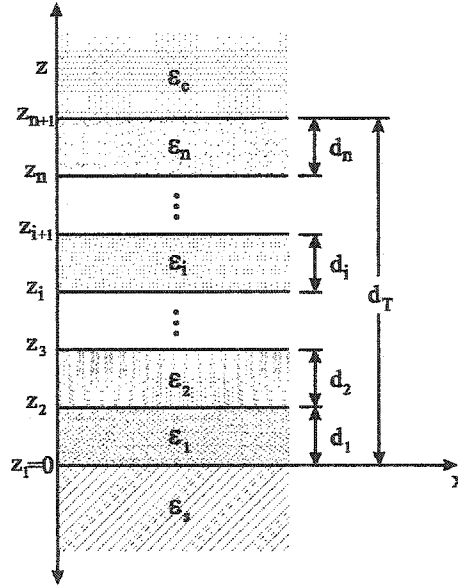


Figure 2.2.: Illustration of the n –layer structure for which the plasmon–polariton modes are derived.

We begin deriving the dispersion equation in a manner similar to the 1–layer case, that is, by describing the E and H field distributions for the TM–modes supported by the structure. Once again, we use the same right hand cartesian coordinate system and we try as much as possible to use the notation presented in §2.1.1. Because the mode supported by the structure is TM in nature, we again only have the H_y , E_x and E_z field

components. We may write the E and H field distributions in the i -th layer as follows:

$$\overline{H}_i = \hat{y}H_{y_i}(z)e^{j(\omega t - k_x x)} \quad (2.26)$$

$$\overline{E}_i = [\hat{x}E_{x_i}(z) + \hat{z}E_{z_i}(z)]e^{j(\omega t - k_x x)} \quad (2.27)$$

In the above equations, $H_{y_i}(z)$, $E_{x_i}(z)$ and $E_{z_i}(z)$ represent the dependence on z of the electromagnetic field components. We now proceed to find the distributions of these field components using the well-known Maxwell equations in phasor form for each layer:

$$\nabla \times \overline{H}_i = j\omega\epsilon_0\tilde{\epsilon}_{r_i}\overline{E}_i \quad (2.28)$$

$$\nabla \times \overline{E}_i = -j\omega\mu_0\overline{H}_i \quad (2.29)$$

We use $\tilde{\epsilon}_{r_i}$ to denote the complex relative permittivity of layer i . From the above curl equations, we may find the interdependence of the tangential field components and write them as follows.

$$\frac{dH_{y_i}(z)}{dz} = -j\omega\epsilon_0\epsilon_{r_i}E_{x_i}(z) \quad (2.30)$$

$$\omega\epsilon_0\frac{dE_{x_i}(z)}{dz} = -\frac{jk_{z_i}^2}{\epsilon_{r_i}}H_{y_i}(z) \quad (2.31)$$

where:

$$k_{z_i} = \pm\sqrt{\tilde{\epsilon}_{r_i}k_0^2 - k_x^2} \quad (2.32)$$

Once again, in order for the notation and the signs used in this derivation to be valid, the value of k_{z_i} is chosen such that $\Im m\{k_{z_i}\} < 0$. In choosing the $\pm$ accordingly, we will ensure that the mode selected is non-radiative.

Equivalently, we may write equations 2.30 and 2.31 in matrix-form as follows:

$$\frac{d}{dz} \begin{pmatrix} H_{y_i}(z) \\ \omega\epsilon_0 E_{x_i}(z) \end{pmatrix} = \begin{pmatrix} 0 & -j\epsilon_{r_i} \\ -\frac{jk_{z_i}^2}{\epsilon_{r_i}} & 0 \end{pmatrix} \begin{pmatrix} H_{y_i}(z) \\ \omega\epsilon_0 E_{x_i}(z) \end{pmatrix} \quad (2.33)$$

Equation 2.33 contains a set of two first order coupled differential equations which we uncouple by increasing the order of these differential equations to two. In doing so, we find:

$$\frac{d^2 H_{y_i}(z)}{dz^2} + k_{z_i}^2 H_{y_i}(z) = 0 \quad (2.34)$$

$$\frac{d^2 E_{x_i}(z)}{dz^2} + k_{z_i}^2 E_{x_i}(z) = 0 \quad (2.35)$$

to which the general solution is of the form:

$$H_{y_i}(z) = B_i \cosh(jk_{z_i}(z - z_i)) + C_i \sinh(jk_{z_i}(z - z_i)) \quad (2.36)$$

$$\omega \epsilon_0 E_{x_i}(z) = \frac{-k_{z_i}}{\epsilon_{r_i}} [B_i \sinh(jk_{z_i}(z - z_i)) + C_i \cosh(jk_{z_i}(z - z_i))] \quad (2.37)$$

where B_i and C_i are constants. The fields within a layer may be written in terms of the fields at the bottom of this layer, where $z = z_i$. At $z = z_i$, we find from equation 2.36 that $H_{y_i}(z)|_{z=z_i} = B_i$ and from equation 2.37 we find that $\omega \epsilon_0 E_{x_i}(z)|_{z=z_i} = \frac{-k_{z_i}}{\epsilon_i} C_i$. Hence B_i and C_i for a specific layer may be determined as follows:

$$B_i = H_{y_i}(z_i) \quad (2.38)$$

$$C_i = \frac{-\omega \epsilon_0 \tilde{\epsilon}_{r_i}}{k_{z_i}} E_{x_i}(z_i) \quad (2.39)$$

The values for B_i and C_i will later be determined by forcing the E and H tangential fields to be continuous across all interfaces (cf. equations 2.52–2.55). From the above results, it is possible to express the E and H field distributions within a layer as follows:

$$\begin{pmatrix} H_{y_i}(z) \\ \omega \epsilon_0 E_{x_i}(z) \end{pmatrix} = \begin{pmatrix} a_{11,i} & a_{12,i} \\ a_{21,i} & a_{22,i} \end{pmatrix} \begin{pmatrix} B_i \\ \frac{-k_{z_i}}{\epsilon_{r_i}} C_i \end{pmatrix} \quad (2.40)$$

The coefficients $a_{11,i}$, $a_{12,i}$, $a_{21,i}$ and $a_{22,i}$ may be found by comparing equations 2.40, 2.36 and 2.37. In doing so, we obtain the following result:

$$\begin{pmatrix} H_{y_i}(z) \\ \omega \epsilon_0 E_{x_i}(z) \end{pmatrix} = \begin{pmatrix} \cosh(jk_{z_i}(z - z_i)) & \frac{-\epsilon_{r_i}}{k_{z_i}} \sinh(jk_{z_i}(z - z_i)) \\ \frac{-k_{z_i}}{\epsilon_{r_i}} \sinh(jk_{z_i}(z - z_i)) & \cosh(jk_{z_i}(z - z_i)) \end{pmatrix} \begin{pmatrix} B_i \\ \frac{-k_{z_i}}{\epsilon_{r_i}} C_i \end{pmatrix} \quad (2.41)$$

If it is not singular, we may invert this square matrix and write the field distribution at the bottom of a layer with respect to the field within that layer. In fact, for the case of an n -layer structure, the fields at the interface between the substrate and the first dielectric may be related to the fields at the interface between the last layer of dielectric and the cover in the following manner.

$$\begin{pmatrix} H_{y_s}(z) \\ \omega \epsilon_0 E_{x_s}(z) \end{pmatrix} \Big|_{z=0} = \prod_{i=1}^n M_i \begin{pmatrix} H_{y_c}(z) \\ \omega \epsilon_0 E_{x_c}(z) \end{pmatrix} \Big|_{z=d_T} \quad (2.42)$$

$$\begin{pmatrix} H_{y_s}(z) \\ \omega\epsilon_0 E_{x_s}(z) \end{pmatrix} \Big|_{z=0} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} H_{y_c}(z) \\ \omega\epsilon_0 E_{x_c}(z) \end{pmatrix} \Big|_{z=d_T} \quad (2.43)$$

where the matrix with coefficients m_{11} , m_{12} , m_{21} and m_{22} is termed the transfer matrix and M_i is defined as:

$$M_i = \begin{pmatrix} \cosh(jk_{z_i}d_i) & \frac{\epsilon_{r_i}}{k_{z_i}} \sinh(jk_{z_i}d_i) \\ \frac{k_{z_i}}{\epsilon_{r_i}} \sinh(jk_{z_i}d_i) & \cosh(jk_{z_i}d_i) \end{pmatrix} \quad (2.44)$$

It is of great interest to write these equations in matrix form since it enables us to obtain the dispersion equation and the E and H field distributions for an n -layer structure simply by multiplying the M_i matrices.

In this more general case where we have an n -layer structure, we find the dispersion equation by expanding equation 2.43 as follows:

$$H_{y_s}(z=0) = m_{11}H_{y_c}(z=d_T) + m_{12}\omega\epsilon_0 E_{x_c}(z=d_T) \quad (2.45)$$

$$E_{x_s}(z=0) = m_{21}H_{y_c}(z=d_T) + m_{22}\omega\epsilon_0 E_{x_c}(z=d_T) \quad (2.46)$$

We may find $H_{y_s}(z=0)$, $E_{x_s}(z=0)$, $H_{y_c}(z=d_T)$ and $E_{x_c}(z=d_T)$ using equations 2.17, 2.18, 2.23 and equation 2.24, respectively. By doing so, we find the following dispersion relation for an n -layer structure:

$$\frac{k_{z_s}}{\epsilon_{r_s}}m_{11} + \frac{k_{z_s}}{\epsilon_{r_s}}\frac{k_{z_c}}{\epsilon_{r_c}}m_{12} + m_{21} + \frac{k_{z_c}}{\epsilon_{r_c}}m_{22} = 0 \quad (2.47)$$

It is straight forward to verify that equation 2.47 reduces to the dispersion relation presented as equation 2.16 in the case where there is only one layer present between the substrate and the cover. By solving equation 2.47 and equation 2.32 numerically for all layers, it is possible to find the propagation constant k_x of the modes supported by this structure.

The expansion of these equations from a 1-layer structure to an n -layer device is important since it enables us to accurately model devices of practical interest. In practice, the effect of having a finite thickness of the substrate and of the cover is not negligible and must be incorporated in the model if one wishes to obtain representative results. In the next chapter, dispersion curves for structures having many layers will be presented. In addition, we will analyse the field distributions for various structures in order to better understand plasmon-polariton modes.

In the substrate, where $z < 0$, we have assumed an exponentially decreasing field

distribution. Hence we may write the TM fields in that region as:

$$H_{y_s}(z) = Ae^{jk_{z_s}z} \quad (2.48)$$

$$\omega\epsilon_0 E_{x_s}(z) = \frac{-k_{z_s}}{\tilde{\epsilon}_{r_s}} Ae^{jk_{z_s}z} \quad (2.49)$$

$$\omega\epsilon_0 E_{z_s}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_s}} Ae^{jk_{z_s}z} \quad (2.50)$$

$$k_{z_s} = \pm\sqrt{\tilde{\epsilon}_{r_s}k_0^2 - k_x^2} \quad (2.51)$$

In order to solve for the various constants in this model, we use Maxwell's boundary conditions at the interfaces. At the substrate-layer 1 interface, the tangential fields must be continuous. This implies that:

$$H_{y_s}(z_1) = H_{y_1}(z_1) \Rightarrow B_1 = A \quad (2.52)$$

$$E_{x_s}(z_1) = E_{x_1}(z_1) \Rightarrow C_1 = \frac{k_{z_s}\tilde{\epsilon}_{r_1}}{k_{z_1}\tilde{\epsilon}_{r_s}} A \quad (2.53)$$

We may also apply Maxwell's boundary conditions at the interface between layer i and layer $i+1$ to obtain the following:

$$H_{y_{i+1}}(z_{i+1}) = H_{y_i}(z_{i+1}) \Rightarrow B_{i+1} = B_i \cosh(jk_{z_i}d_i) + C_i \sinh(jk_{z_i}d_i) \quad (2.54)$$

$$E_{x_{i+1}}(z_{i+1}) = E_{x_i}(z_{i+1}) \Rightarrow C_{i+1} = \frac{k_{z_i}\tilde{\epsilon}_{r_{i+1}}}{k_{z_{i+1}}\tilde{\epsilon}_{r_i}} [B_i \sinh(jk_{z_i}d_i) + C_i \cosh(jk_{z_i}d_i)] \quad (2.55)$$

Hence, in layer i , the TM fields may be written as:

$$H_{y_i}(z) = [B_i \cosh(jk_{z_i}(z - z_i)) + C_i \sinh(jk_{z_i}(z - z_i))] \quad (2.56)$$

$$\omega\epsilon_0 E_{x_i}(z) = \frac{-k_{z_i}}{\tilde{\epsilon}_{r_i}} [B_i \sinh(jk_{z_i}(z - z_i)) + C_i \cosh(jk_{z_i}(z - z_i))] \quad (2.57)$$

$$\omega\epsilon_0 E_{z_i}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_i}} [B_i \cosh(jk_{z_i}(z - z_i)) + C_i \sinh(jk_{z_i}(z - z_i))] \quad (2.58)$$

$$k_{z_i} = \pm\sqrt{\tilde{\epsilon}_{r_i}k_0^2 - k_x^2} \quad (2.59)$$

We now consider the E and H fields in the cover region. Once again we will describe the E and H field distributions as exponentially decaying fields as follows:

$$H_{y_c}(z) = De^{-jk_{z_c}(z-d_T)} \quad (2.60)$$

$$\omega\epsilon_0 E_{x_c}(z) = \frac{k_{z_s}}{\tilde{\epsilon}_{r_c}} D e^{-jk_{z_c}(z-d_T)} \quad (2.61)$$

$$\omega\epsilon_0 E_{z_c}(z) = \frac{-k_x}{\tilde{\epsilon}_{r_c}} D e^{-jk_{z_c}(z-d_T)} \quad (2.62)$$

$$k_{z_c} = \pm \sqrt{\tilde{\epsilon}_{r_c} k_0^2 - k_x^2} \quad (2.63)$$

$$d_T = \sum_{i=1}^n d_i \quad (2.64)$$

The constant D may be determined by applying Maxwell's boundary conditions at $z = z_{n+1}$. In doing so, we find:

$$H_{y_c}(z_{n+1}) = H_{y_i}(z_{n+1}) \Rightarrow D = B_n \cosh(jk_{z_n} d_n) + C_n \sinh(jk_{z_n} d_n) \quad (2.65)$$

Using the above equations, we may plot the field distributions in the various layers of the structure.

2.2. Modelling of a slab structure using Matlab / Octave

A code to find the TM modes supported by an n -layer stratified media structure using the equations derived in §2.1.2 was written in Matlab and was then converted to Octave². The code was divided into functions in order to make it as modular as possible. One function, called *nlayers.m*, was simply the implementation of the dispersion equation 2.47, rewritten as:

$$F = \frac{k_{z_s}}{\tilde{\epsilon}_{r_s}} m_{11} + \frac{k_{z_s}}{\tilde{\epsilon}_{r_s}} \frac{k_{z_c}}{\tilde{\epsilon}_{r_c}} m_{12} + m_{21} + \frac{k_{z_c}}{\tilde{\epsilon}_{r_c}} m_{22} \quad (2.66)$$

where the value F is zero when a mode is found. Parameters such as the index of refraction of the various layers, their respective thickness, the wavelength of interest and a guess for the propagation constant k_x are passed as arguments to the function. A second function is used to find the zero of the dispersion relation. Although many algorithms may be used to find the zero of a function, Muller's method [47] was selected since it is quite robust in solving problems having complex numbers. The implementation of the Muller algorithm was coded in the function called *muller.m*.

Finally, a function was created to control the whole process. At first, it is necessary to find adequate initial guesses to the propagation constant of the two bound modes. Once these values are found for the two modes for a given structure and operating wavelength, it is necessary to track the mode as the thickness of the metal film is varied. This ensures

² Octave is simply a Matlab-like mathematical software used in Linux.

that the guess supplied to the Muller algorithm is always close to the answer and prevents the code from finding either the other plasmon-polariton mode or a dielectric slab mode supported by the structure.

2.3. Validation of the numerical implementation of the dispersion relations

We have seen in the previous sections a derivation of the dispersion relations that govern the general TM mode propagation in multi-layer slab structure. Before we proceed to present the simulation results obtained from the numerical implementation of these equations, we will, in this section, compare simulation results obtained from this code with results presented in the literature. This will enable us to validate the code used for subsequent simulations.

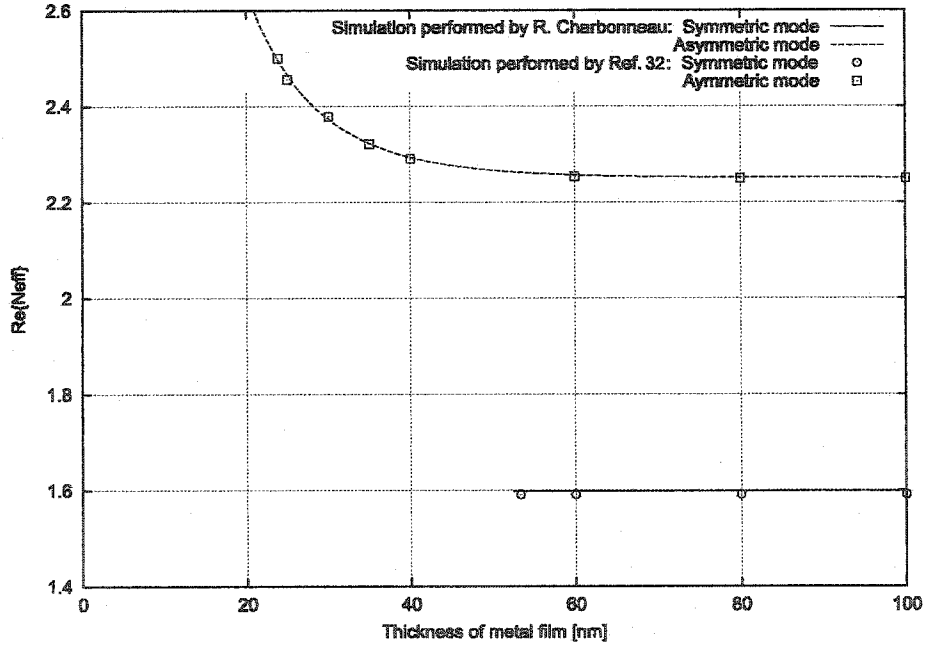


Figure 2.3.: Comparison between simulated real part of the effective index of refraction of the mode that we obtained with simulated results presented in Ref. [32]. The results are for a thin Ag film supported above and below by semi-infinite dielectrics. The permittivities of the substrate, Ag and cover are $\tilde{\epsilon}_{r_s} = \sqrt{2.0}$, $\tilde{\epsilon}_{r_1} = -19 - j0.53$ and $\tilde{\epsilon}_{r_c} = \sqrt{1.5}$, respectively, and the simulation is for a free space wavelength of 632.8 nm.

In Figures 2.3 and 2.4, we compare simulated results performed with the code described in §2.2 with simulation results presented in Ref. [32]. These results are for a

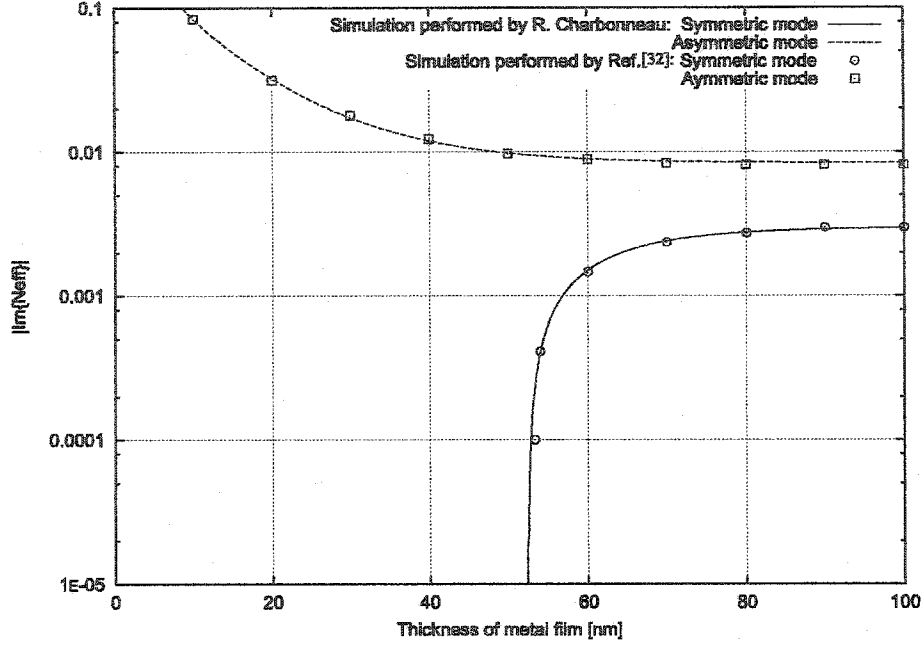


Figure 2.4.: Comparison between simulated imaginary part of the effective index of refraction of the mode that we obtained with simulated results presented in Ref. [32]. These results are for a thin Ag film supported above and below by semi-infinite dielectrics. The permittivities of the substrate, Ag and cover are $\tilde{\epsilon}_{r_s} = \sqrt{2.0}$, $\tilde{\epsilon}_{r_1} = -19 - j0.53$ and $\tilde{\epsilon}_{r_c} = \sqrt{1.5}$, respectively, and the simulation is for a free space wavelength of 632.8 nm.

simulation of a thin metal Ag film, with permittivity $\tilde{\epsilon}_{r_1} = -19 - j0.53$, supported by a substrate characterised by a refractive index of $n_s = 2.0$ and covered with a cover of refractive index $n_c = 1.5$. The simulation is conducted at a free space wavelength of 632.8 nm.

We see in these figures that for both the symmetric and the asymmetric modes, the real and the imaginary parts of the effective index of refraction of our model is in good agreement with the one presented in Ref. [32]. A more indepth analysis of the simulation results will be presented in Chapter 3.

In order to validate our model in the case of an n -layer structure, we compare our results with some presented in Ref. [45]. For this example, the results are presented in tabular form in Table 2.1. The results obtained by the present method are identical to the ones presented in Ref. [45] to nine decimal places for this 4-layer structure. From these results, it is clear that the present method is an accurate representation of the equations derived in §2.1.2 for an n -layer stratified media.

For this particular example, one plasmon-polariton mode has been found propagating

along the metal film. In addition, the TM_0 slab mode has been found propagating within the layered media structure. As stated previously, this code is capable of finding non plasmon-polariton slab modes. Simulation results and their analysis for various metal structures excited at different wavelengths will be presented in Chapter 3.

Mode	Effective index			
	Present method		Ref. [45]	
	$\frac{\beta}{k_0}$	$\frac{\alpha}{k_0}$	$\frac{\beta}{k_0}$	$\frac{\alpha}{k_0}$
TM plasmon mode	3.334498481	7.518872326e-3	3.334498481	7.518872326e-3
TM_0	3.248098484	5.4630701344e-4	3.248098484	-5.4630701343e-4

Table 2.1.: Comparison between the present method and results tabulated in Ref. [45] for a 4-layer active wave guide characterised as follows: $\tilde{n}_s = 3.16$, $\tilde{n}_1 = 3.16 - j0.0001$, $\tilde{n}_2 = 3.6 - j0.002$, $\tilde{n}_3 = 3.16 - j0.0001$, $\tilde{n}_4 = 0.18 - j10.2$, $\tilde{n}_c = 1.0$, $d_1 = 3.0\mu\text{m}$, $d_2 = 0.15\mu\text{m}$, $d_3 = 1.0\mu\text{m}$, $d_4 = 0.04\mu\text{m}$ and $\lambda_0 = 1.30\mu\text{m}$.

3. Simulation results for various metal structures excited at different wavelengths

The ability to model the propagation of plasmon-polaritons along thin metal films of infinite width embedded in dielectrics is of great interest for many reasons. Although ultimately the goal of this research is to characterise thin metal films finite in width, the characteristics of an infinite width metal film are similar in many ways to its finite width counterpart. In particular, both the finite width and infinite width structures are characterised by vanishing attenuation for decreasing metal thickness. Thus, in this regard, it is possible to compare the unit length losses of various metals, and in doing so, we may obtain these results more rapidly than by doing an analysis of a finite width structure. Such an analysis allows us to select the appropriate metal for fabrication of the specimens. Knowing that the attenuation of a metal optical wave guide decreases as the guide width is reduced [7], the analysis of an infinitely wide metal film gives us what could be considered a worst case unit length loss estimation.

It is also interesting to study the effect of wavelength on these structures. Thin metal films may support plasmon-polaritons over a large area of the optical spectrum but clearly, we want these structure to be low loss in the communication band. Hence, we can study the sensitivity of these devices on the operating wavelength. In addition, various dispersion curves were obtained for noble metals at various wavelengths of interest, and these results are presented in this chapter.

3.1. Selection of the metal for operation at a free space wavelength of 1550 nm

In this section, we consider the effect of selecting different metals for operation at a free space wavelength of 1550 nm. From our perspective, it is clear from an attenuation stand

point that only noble metals are of interest since other metals will be characterised by high intrinsic losses. Metals that have been considered are Au, Ag, Cu and Al. All these metals suffer from certain drawbacks. Since Au does not oxidise, it adheres poorly to the SiO₂ so there are always adhesion issues when depositing Au on SiO₂. Ag, in contrast, oxidises very quickly and it was easier for the CRC, our fabrication partner, to deposit Au. Cu and Al should adhere well to the SiO₂, however, as we will see, they are characterised by a higher attenuation. In addition, Al has a low melting point of 660°C, a definite problem if we wish to anneal the SiO₂ supporting the metal.

We will also consider Ti since it may be used in practice to improve the adhesion of Au to a dielectric. The personnel at the CRC has recommended that a thin layer of Ti be evaporated or sputtered as an intermediate layer between the SiO₂ and the Au. Results of simulations will present a structure fabricated using a thin film of Ti embedded in SiO₂ as well as a structure comprised of SiO₂-Ti-Au-Ti-SiO₂, in which the thicknesses of the Ti-Au-Ti metal films layers are 5-10-5 nm, respectively.

In Table 3.1, we compare the index of refraction of the metals of interest at a free space wavelength of 1550 nm. It is not possible to estimate the attenuation of a plasmon-polariton mode propagating along a metal-dielectric interface directly from the index of refraction of the metal. The list simply presents the values used to perform the simulation. In the case of Au and Al, two different n and k values are presented in the reference for the wavelength of interest. For this reason, the average of the two values is used in the simulation. In Table 3.1, the extinction coefficient of the SiO₂ is stated to be 0, which implies that the material is lossless at the wavelength of interest. In practice, no material is lossless, however, the extinction coefficient of the SiO₂ characterised in [48] was too small to be measurable. For this reason and for the purpose of our simulations, we have assumed lossless SiO₂ layers in our structures.

Although we have stated that very little in terms of expected unit length attenuation may be deduced from the index of refraction, we can still get a feel for the quality of these metals as light propagating media. We know that we may use the permittivity to characterise these metals. From the index of refraction, it is easy to obtain the relative permittivity using:

$$\tilde{\epsilon}_r = n^2 - k^2 - j2nk \quad (3.1)$$

The ideal metal for use in optical wave guiding is one that most closely resembles an ideal cold plasma. Thus, we desire a permittivity having a high negative real part and a low imaginary component. Hence, it is desirable to have a metal characterised by an index of refraction having $k > n$ and a small nk product. From this, one would expect

Metal	Complex index of refraction ($\tilde{n} = n - jk$)	
	Index of refraction n	Extinction coefficient k
Au [48]	0.559	9.81
	0.550	11.5
Au _{avg}	0.555	10.66
Ag [48]	0.514	10.8
Al [48]	1.44	16
	1.50	15.5
Al _{avg}	1.47	15.75
Cu [48]	0.606	8.26
Ti [49]	2.94	3.59
SiO ₂ [48]	1.444020	0

Table 3.1.: Index of refraction of various metals and of SiO₂ at a free space wavelength of 1550 nm.

that the best metals would be Ag and Au, followed closely by Cu and the Al. We note that these are all noble metals. Ti, in contrast, is not a noble metal and we see from table 3.1 that it is a rather poor substitute for an ideal plasma. Nevertheless, we will perform simulations for all these metals and compare the results.

Figure 3.1 presents the real part of N_{eff} for a Au film ($N_{Au} = 0.555 - j10.66$) supported above and below by amorphous SiO₂ ($N_{SiO_2} = 1.444020$) and excited at a free space wavelength of 1550 nm. We note that for the symmetric bound mode (s_b), the effective index of refraction tends towards the background index as the thickness of the metal film decreases. Thus, for a metal film having a thickness $t \rightarrow 0$, the mode supported tends towards the plane wave propagating in the background medium. For a thin metal film, most of the power of the s_b mode is in the surrounding dielectric and thus the value of N_{eff} is mainly governed by the value of the supporting medium. In the case of the asymmetric bound mode (a_b), the value of N_{eff} is seen to tend asymptotically towards infinity, indicating that the velocity of the propagating mode decreases as $t \rightarrow 0$. This results from the higher penetration of the electromagnetic fields inside the metal film for the asymmetric mode.

We may also note from Figure 3.1 that the symmetric and asymmetric bound modes are distinct for ultra thin metal films. As the film thickness increases, the modes converge to the mode supported by a single metal–dielectric interface. As the film thickness is decreased, the plasmon–polaritons modes supported at each metal–dielectric interface become coupled by tunneling through the metal film and we observe the creation of two bound modes identified as symmetric and asymmetric. The reason for this nomencla-

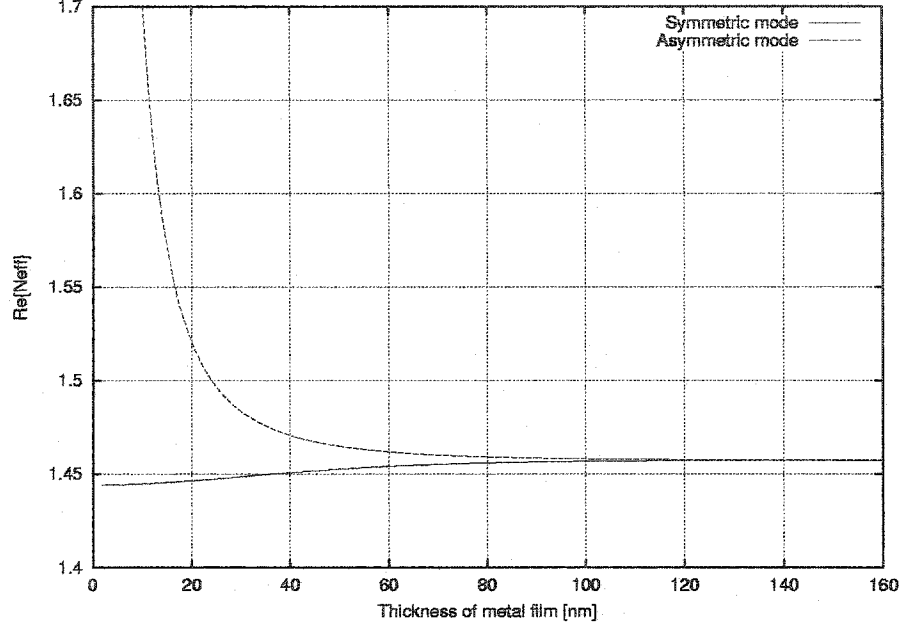


Figure 3.1.: Simulated dispersion curves $\Re\{N_{eff}\}$ of the two bound modes s_b and a_b supported by a thin Au film embedded in infinite SiO_2 . The indices of refraction are $N_{Au} = 0.555 - j10.66$ and $N_{\text{SiO}_2} = 1.44402$, for the Au and SiO_2 regions, respectively. The analysis was conducted at a free space wavelength of 1550 nm.

ture will become apparent in §3.4, when the distributions of the propagating fields are presented.

Perhaps of greater interest to us are the results of Figure 3.2, presenting the imaginary part of N_{eff} . From this graph, it is possible to deduce the unit length attenuation of a thin metal film. We note that in the case of the symmetric mode, the attenuation decreases with metal thickness. Once again, this result stems from the fact that the mode tends towards a plane wave propagating in the supporting dielectric and as the film thickness decreases, the attenuation of the mode is dominated by the losses in the dielectric and in this case they are neglected.

In a real structure, there are three loss mechanisms that may be identified: metal losses, dielectric losses and scattering losses. At this wavelength, the extinction coefficient of SiO_2 as taken from Ref. [48] is zero and so there are no losses associated with the dielectric in our model. In addition, we assume a perfect metal dielectric interface such that scattering losses are neglected. Hence, in our model, we only consider losses occurring in the metal.

For the s_b mode, we observe vanishing losses with decreasing metal thickness. As the

thickness of the metal film decreases, the mode evolves into the plane wave supported by the dielectric. Since in our model, we neglect the losses in the surrounding dielectric, the attenuation tends towards zero. If the dielectric is characterised by a non-zero extinction coefficient, then $\Im m \{N_{eff}\}$ tends towards that value as the thickness of the metal film decreases.

In the case of the a_b mode, the attenuation is seen to increase for a decreasing metal thickness. This results from more penetration of the electromagnetic fields inside the metal film as the thickness of the metal decreases. In our model, the only loss mechanism is through the metal and so a higher field concentration within the metal translates into higher propagation losses.

From the results presented in Figure 3.2, it is possible to calculate the expected power attenuation per unit length for an Au metal film embedded in amorphous SiO_2 and excited at a free space wavelength of 1550 nm. The mode power at a distance x from a reference point is given by:

$$P(x) = P(0)e^{-2\alpha x} \quad (3.2)$$

If we wish to convert the losses to decibels, we may write:

$$\text{Attenuation per unit length} = \frac{10}{x} \log \left[\frac{P(0)}{P(x)} \right] = 8.686\alpha \text{ [dB/cm]} \quad (3.3)$$

where:

$$\alpha = \Im m \{k_x\} = \Im m \{N_{eff}\} \cdot k_0 \quad (3.4)$$

Hence, from equation 3.3, and using our simulated results, it is possible to determine the attenuation per unit length of a thin metal film infinite in width. Using the values computed from the simulation, we find that the attenuation per unit length for the symmetric bound mode supported by a 20 nm thick Au film embedded in SiO_2 and excited at a free space wavelength of 1550 nm is 12.5 dB/cm. In contrast, the unit length loss for the asymmetric bound mode in the same structure is 5200 dB/cm. From these results, it is clear that it is in our interest to focus on the symmetric bound mode. An attenuation of 12.5 dB/cm is high in comparison to competing technologies. For instance, researchers reported an insertion loss of 0.66 dB for a 20 mm long wave guide fabricated using germanium (Ge)-doped silica on silica [50]. Simulations for finite width metal optical wave guides, however, indicate that the unit length losses may be reduced substantially for wave guides one to two microns in width [38].

The simulated curve of $\Re e \{N_{eff}\}$ at a free space wavelength of 1550 nm is plotted in

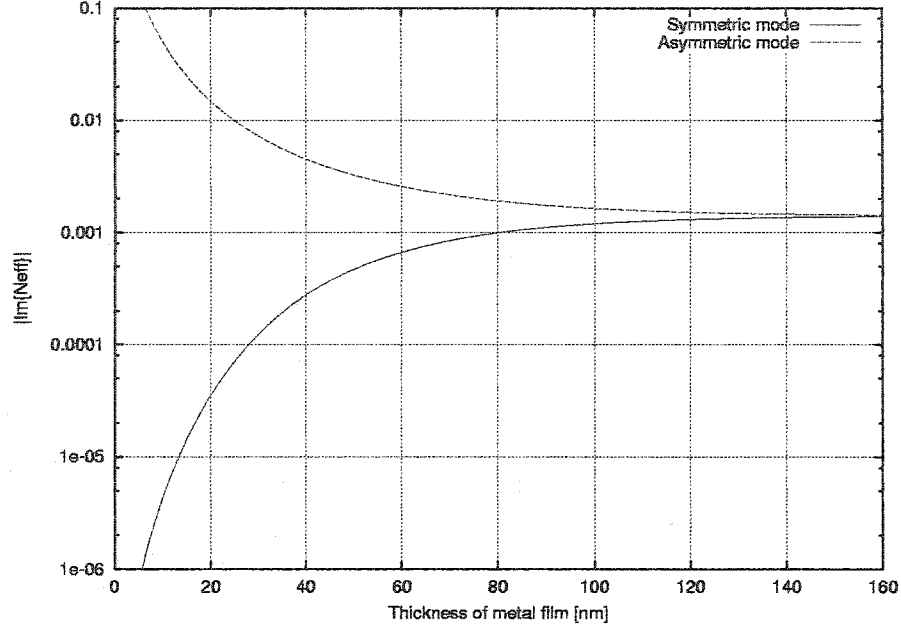


Figure 3.2.: Simulated dispersion curves $\Im m\{N_{eff}\}$ of the two bound modes s_b and a_b supported by a thin Au film embedded in infinite SiO_2 . The indices of refraction are $N_{Au} = 0.555 - j10.66$ and $N_{\text{SiO}_2} = 1.44402$, for the Au and SiO_2 regions, respectively. The analysis was conducted at a free space wavelength of 1550 nm.

Figure 3.3 for the various slab wave guides constituted of the metals listed in Table 3.1 and embedded in SiO_2 . We note that the overall shape of the curves remains unchanged, for the most part, regardless of the metal used in the simulation. The effect of varying the metal is simply to shift the curve upwards or downwards, relative to the curve for Au. We note from Figure 3.3 that for this wavelength, the curves for Au and Ag almost overlap, an indication that both these metals are essentially equivalent in terms of their guiding characteristics.

Simply looking at the $\Re\{N_{eff}\}$, however, is not that meaningful in our case. It tells us that the phase velocity of the s_b and a_b modes are different for the various metals. Of course, our interest lies mainly in estimating the losses per unit length for these metals. In order to do so, we must consider the curves of $\Im m\{N_{eff}\}$ for various metals. Such curves are plotted in Figure 3.4.

Comparing only the curves for the symmetric mode supported by the different metals, we note that the one having the lowest losses for a metal thickness of 20 nm is Ag, followed closely by Au. As was the case in the $\Re\{N_{eff}\}$ plot, the curves for Au and Ag essentially overlap, and there appears to be very little advantage in using either one or the other for

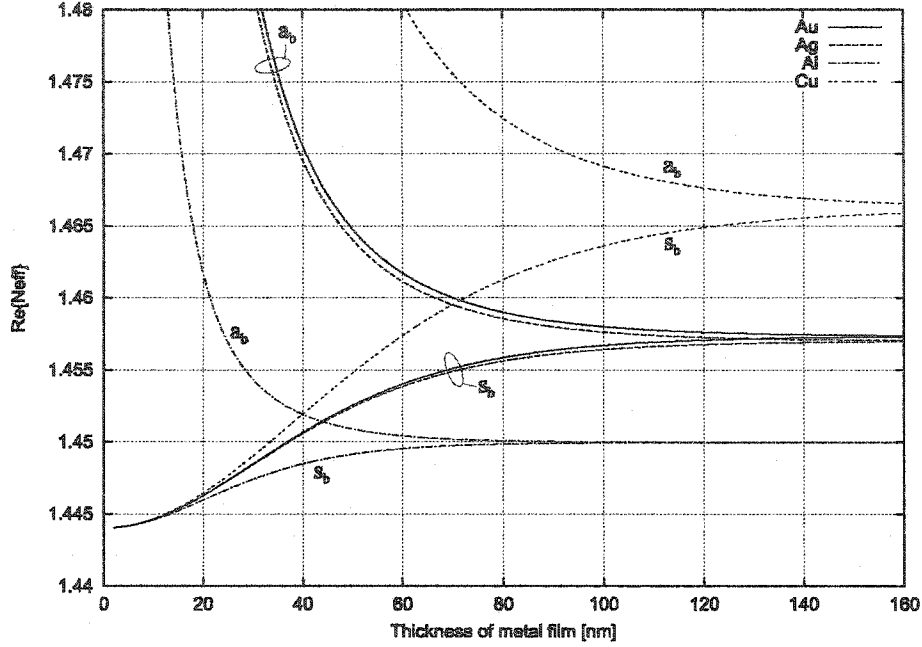


Figure 3.3.: Simulated dispersion curves $\text{Re}\{N_{eff}\}$ of the two bound modes s_b and a_b supported by a thin metal film embedded in infinite SiO_2 . The indices of refraction used to produce these curves are presented in Table 3.1 and are for a free space wavelength of 1550 nm.

the purpose of guiding plasmon-polaritons. The next metals of choice for low attenuation are Cu and Al, respectively. Although the losses for Au are somewhat higher than those of Ag, it was easier for the CRC to fabricate wave guides in Au and for this reason, all experiments on wave guides performed and presented in this thesis are for Au wave guides fabricated by the CRC.

A quantitative comparison of the losses for these metals is presented in Table 3.2. This table shows that the calculated unit length losses for Au and Ag are very similar. In addition, we observe that the losses for Cu are comparable to those of Au and Ag. In the case of Al, we note a significant increase in the attenuation per unit length. Our experience has been that when non-noble metals are considered, the attenuation is even greater and often becomes impractical from an experimental stand point.

We have seen in this section the effect of the choice of metal on the calculated unit length losses. In the next few sections, we will further our understanding of plasmon-polaritons by studying further the characteristics of these electromagnetic waves.

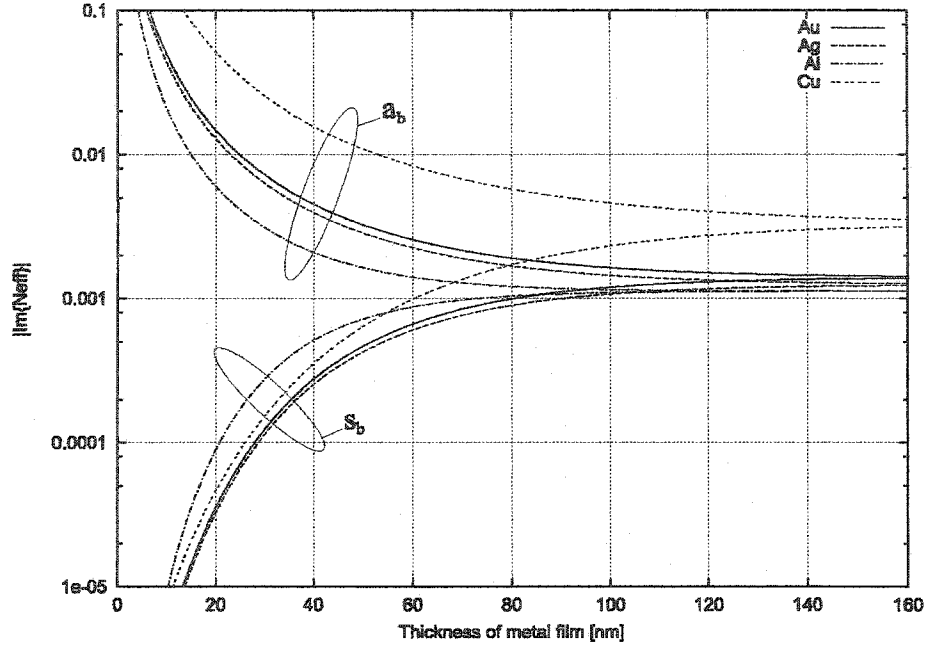


Figure 3.4.: Simulated dispersion curves $\text{Re}\{N_{eff}\}$ of the two bound modes s_b and a_b supported by a thin metal film embedded in infinite SiO_2 . The indices of refraction used to produce these curves are presented in Table 3.1 and are for a free space wavelength of 1550 nm.

Metal	Attenuation per unit length [dB/cm]
Ag	11.5
Au	12.5
Cu	16.3
Al	31.4

Table 3.2.: Comparison of the calculated unit length attenuation of the symmetric mode for noble metals. The simulation was conducted at a free space wavelength of 1550 nm and is for a metal thickness of 20 nm.

3.2. Comparison between an Au, a Ti-Au-Ti and a Ti slab guide embedded in SiO_2 and excited at a free space wavelength of 1550 nm

Thus far we have only touched lightly the subject of fabrication, however, we have already mentioned that there are adhesion issues when depositing a layer of Au directly on SiO_2 . These issues have not been dealt with in the fabrication industry for the simple

reason that it is not customary to fabricate such structures. Typically, CMOS and other processes use Al or sometimes Cu.

When a layer of Au needs to be deposited on SiO₂, a thin film of Ti may be deposited as an intermediate layer between the Au and the SiO₂. In electronic circuits, the layer of Ti is much thinner than the layer of Au and so the properties of the Au filament are unaffected by the intermediate Ti layer. In our case, however, the guiding characteristics of the plasmon-polariton modes supported may be affected since the thicknesses of the Ti and Au considered are similar.

Simulations have been performed to compare the attenuation per unit length of a structure fabricated with a Ti film instead of Au. In addition, a second layer geometry has been considered, in which thin layers of Ti are deposited above and below an Au film. The results are presented in Table 3.3.

Description of layers	Thickness of layers [nm]	Attenuation [dB/cm]
SiO ₂	semi-infinite	12.5
Au	20	
SiO ₂	semi-infinite	
SiO ₂	semi-infinite	188
Ti	20	
SiO ₂	semi-infinite	
SiO ₂	semi-infinite	104
Ti	5	
Au	10	
Ti	5	
SiO ₂	semi-infinite	

Table 3.3.: Comparison of attenuation per unit length of various layer configurations using Au and Ti films.

As can be seen from Table 3.3, the attenuation for a single 20 nm thick Ti film embedded in SiO₂ is very high. This is not unexpected since we have already stated that only noble metals exhibit low attenuation. Although a significant improvement is achieved by having a Ti-Au-Ti layered film, the attenuation is too high for practical applications. The reason why the attenuation is still very high in the case of a Ti-Au-Ti stratified film as opposed to a single Ti film, is quite clear. Plasmon-polaritons propagate mainly at a metal-dielectric interface. In this case, the metal-dielectric interface consists of Ti and SiO₂; the Au layer does not have the desired impact in reducing the losses. Although reducing the thickness of the Ti layer could further reduce the attenuation, in practice, the CRC could not deposit a uniform, high quality layer of Ti thinner than

5 nm.

3.3. Effect of wavelength on a Au slab guide embedded in SiO₂

As demand for bandwidth increases, system manufacturers are attempting to increase capacity by transmitting data at bit rates as high as 40 Gb/s and in closely spaced channels (WDM/DWDM), separated by a fraction of a nanometer and capable of carrying more than 100 independent optical channels [5]. To satisfy this demand for high bandwidth, component manufacturers are designing ever faster devices. It is of great importance for emerging integrated optics technologies to support a wide bandwidth around a wavelength of 1550 nm. In addition, a significant portion of existing fiber infrastructure currently operates at a wavelength of 1300 nm and so it is also important for this technology to be capable of supporting this wavelength band.

To accurately model the effect of wavelength on the plasmon-polariton modes, we turn once more to simulations to estimate the performance of thin metal films as optical components. In Figure 3.5, we present the real part of the index of refraction of SiO₂ [48], the real part of the index of refraction of Au [48] and the effective index of refraction for the symmetric mode propagating along a 20 nm thick Au film embedded in SiO₂ as a function of wavelength. We note that the curve for the symmetric mode follows closely the curve of the index of refraction of SiO₂. The sudden variation of the $\text{Re}\{N_{eff}\}$ curve around a free-space wavelength of 500 nm is a result of a sudden increase in the real part of the index of refraction of Au in that region of the spectrum.

Of greater interest perhaps is the imaginary part of the index of refraction of N_{eff} as a function of wavelength, as presented in Figure 3.6. Two mechanisms are associated with the observed changes of the s_b as a function of wavelength: the material dispersion of the metal film and the geometrical dispersion which changes the apparent thickness of the film [7, p. 10500]. The material dispersion is modelled using the index of refraction of the material or equivalently, its permittivity. For the 250–1700 nm wavelength range, the extinction coefficient of SiO₂ is assumed zero thus all attenuation is the result of losses within the metal film only. We have already stated that for a metal to be characterised by low attenuation, we desire $k > n$ and a small nk product. From these criteria, losses in the metal should increase with increasing wavelength. In fact, if we model the metal film using equation 1.2 and equation 1.3, we note that the magnitude of $|\epsilon'|$ varies approximately as $\frac{1}{\omega^2}$ or in a λ^2 fashion whereas the magnitude of $|\epsilon''|$ varies approximately as $\frac{1}{\omega^3}$ or in a λ^3 fashion. At a longer wavelength, however, the apparent

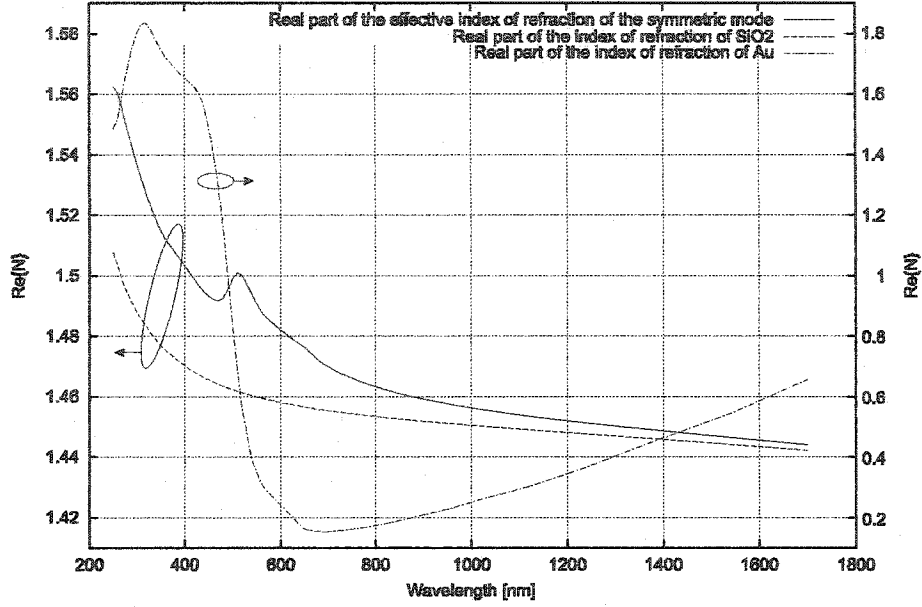


Figure 3.5.: Effect of wavelength on $\Re\{N_{eff}\}$ for the symmetric mode of a 20 nm thick Au film supported above and below by SiO_2 .

optical thickness of the film is reduced. In addition, the increase of $|\epsilon'|$ with increasing wavelength reduces the penetration of the mode field in the metal. As a result, we observe from our simulations a decrease in the attenuation of the s_b for increasing wavelengths.

From Figure 3.6, it is possible to determine the attenuation per unit length at various wavelengths of interest. These results are tabulated in Table 3.4. We see from this table that the attenuation at 1550 nm and at 1300 nm are high, however, the losses per unit length decrease rapidly when the width of the metal film is reduced [38]. The attenuation for shorter wavelengths, however, is very high. From these simulation results, we see that plasmon-polaritons are still supported at these wavelengths but the high attenuation makes metal optical wave guides impractical in that region of the spectrum.

Wavelength [nm]	Attenuation [dB/cm]
632.8	1003
850	89
1300	20.8
1550	12.5

Table 3.4.: Attenuation per unit length at various wavelength for a 20 nm thick Au film embedded in SiO_2 .

As it turns out, this technology is characterised by lower attenuation for increasing

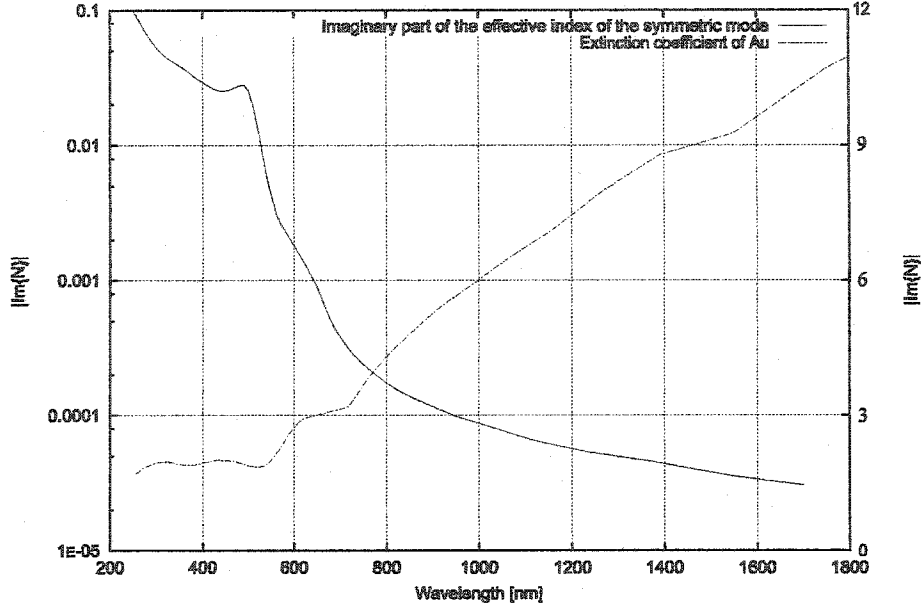


Figure 3.6.: Effect of wavelength on $\text{Im}\{N_{eff}\}$ for the symmetric mode of a 20 nm thick Au film supported above and below by SiO_2 .

wavelengths for a given film thickness, and thus is more favorable to the 1300 nm and 1550 nm wavelength ranges. This is most encouraging considering that the current and foreseeable future of optical communication needs will be in and near these spectral windows.

3.4. H_y , E_x and E_z field distributions for a Au slab guide embedded in SiO_2 and excited at a free space wavelength of 1550 nm

In this thesis, we have often stated that a slab wave guide supports two plasmon-polariton modes: the symmetric mode and the asymmetric mode. In this section, we will present the field distributions of these modes such that the nomenclature becomes clear. Having already described the method for finding modes as well as the field distributions in the various layers of a specimen, it becomes straightforward to plot the field distributions of the H_y , E_x and E_z components. In addition, we will also present the distribution of the Poynting vector, given by:

$$\vec{S} = \vec{E} \times \vec{H}^* \quad (3.5)$$

For TM modes, the above yields the following time averaged components of the Poynting vector:

$$S_x = -\frac{1}{2}\Re\{E_z \times H_y^*\} \quad (3.6)$$

$$S_z = \frac{1}{2}\Re\{E_x \times H_y^*\} \quad (3.7)$$

The Poynting vector is of special interest since it gives us an idea of the power flow and of the power distribution near the wave guide. For simplicity, we will begin by presenting the field distribution of a 1-layer structure, as illustrated in Figure 2.1.

3.4.1. Electromagnetic field distributions of a Au slab guide supported above and below by semi-infinite SiO₂

In an attempt to better understand the field distributions of plasmon-polaritons, we will investigate the case of a simple 20 nm thick Au slab guide surrounded by SiO₂. This investigation will be performed at a free space wavelength of 1550 nm and so the index of refraction of Au is taken from Table 3.1 as $N_{Au} = 0.555 - j10.66$ and the index of refraction of SiO₂ is $N_{SiO_2} = 1.444020$. The field distributions for the symmetric bound mode supported by this structure are presented in Figure 3.7.

The nomenclature for the field distributions of bound plasmon-polariton modes was first discussed in Ref. [32] and will be followed throughout this thesis for consistency. Using this nomenclature, a plasmon-polariton mode is termed symmetric when its H_y and E_z fields are symmetric about the metal slab. Likewise, a mode is referred to as asymmetric when its H_y and E_z fields are asymmetric about the metal.

For Figures 3.7, 3.8, 3.9 and 3.10, $z < 0$ corresponds to the field distributions within the substrate, $0 < z < 0.02 \mu\text{m}$ corresponds to the field distributions within the metal and the region $z > 0.02 \mu\text{m}$ presents the fields in the cover.

In Figure 3.7, we note that the H_y and E_z field components are symmetric. The symmetric nature of the E_z field is of particular interest to us since it enables us to state that the symmetric plasmon-polariton mode is more easily excited than the asymmetric mode. The symmetric nature of the field profile, we believe, lends itself to better mode overlap with the field distribution of the input optical fiber or a similar source used to excite the mode.

Although arbitrary units are used (i.e. $A = 1$ in equation 2.7), the relative magnitude of the field components is conserved and comparisons can be made. The amplitude of the

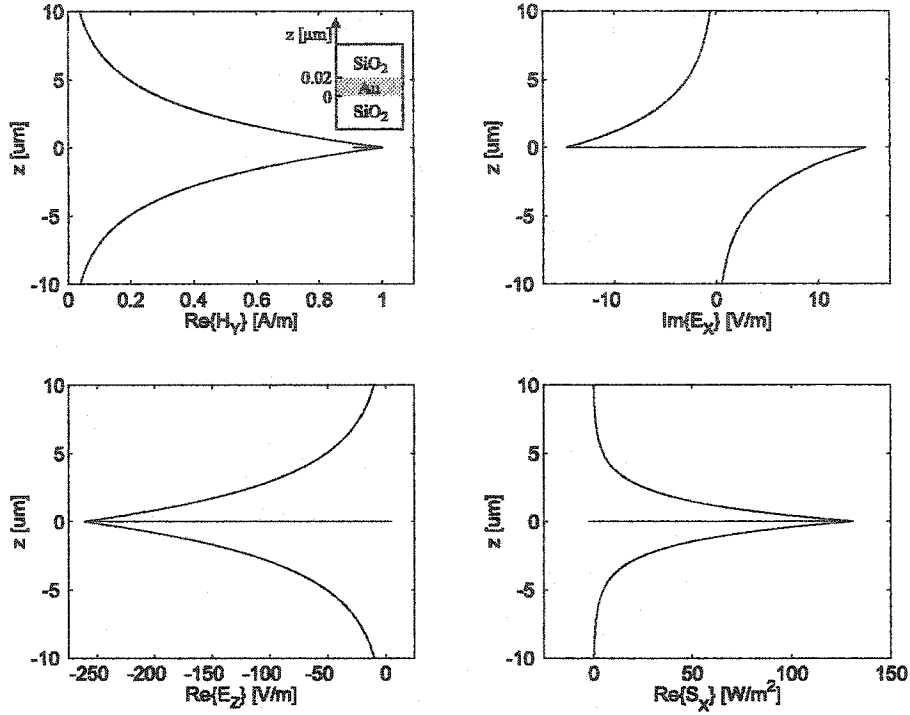


Figure 3.7.: Field distributions and Poynting vector of the symmetric bound mode of an Au slab guide embedded in SiO₂ and excited at the free space wavelength of 1550 nm.

E_z field is the most important and is more than an order of magnitude greater than the magnitude of the E_x field. The H_y field is also relatively weak in amplitude, relative to the E_z field. This suggests that it is possible to excite plasmon-polaritons along a thin metal film embedded in a dielectric simply by launching a highly polarised TM beam at the input of the guide.

Finally, from Figure 3.7, we note that even though the thickness of the metal is only 0.02 μm , the E and H fields extend vertically to 15 μm . From the Poynting vector, we gather that the power is confined vertically within $\pm 5 \mu\text{m}$ of the metal. This model, which assumes a semi-infinite dielectric above and below the metal, will be valid in a physically realisable structure if we deposit a thick dielectric.

In Figure 3.8, we see in detail the field distributions in the immediate vicinity of the metal. We again note the symmetric nature of the H_y and E_z field components with respect to the center of the metal film. It is interesting as well to take a closer look at the Poynting vector, in Figure 3.8 (d). In this Figure, we note that the majority of the optical power is in the dielectric and very little optical power is actually inside the metal

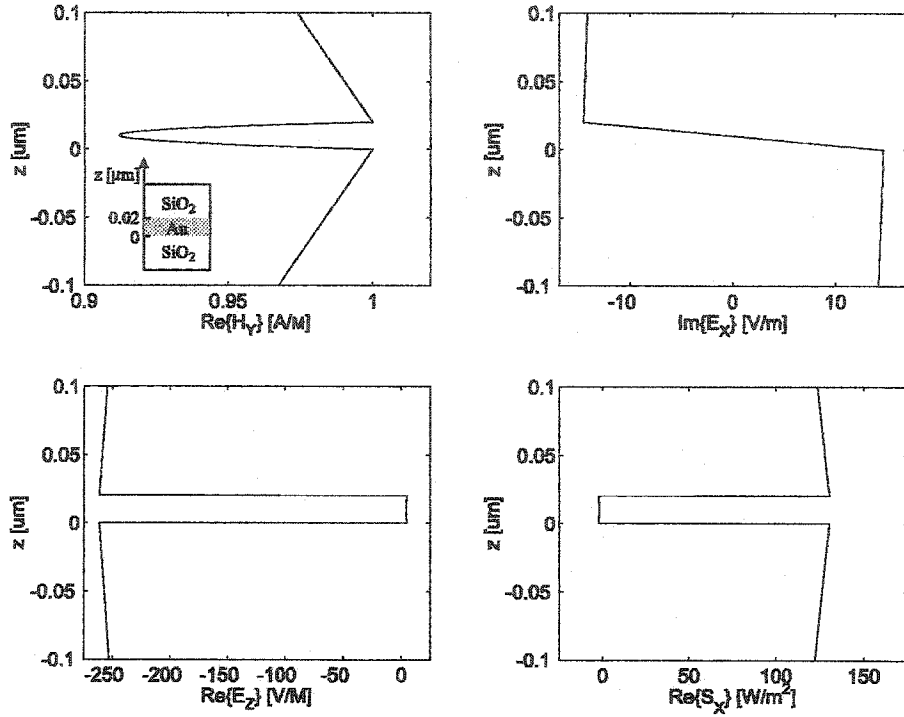


Figure 3.8.: Close-up view of the field distributions and Poynting vector of the symmetric bound mode of a Au slab guide embedded in SiO₂ and excited at the free space wavelength of 1550 nm.

film. This explains why we observe relatively low attenuation values.

We now consider the asymmetric bound mode supported by this structure. The field distributions of the different TM-components are presented in Figure 3.9 and, as expected, we note that the field distributions of the H_y and E_z are asymmetric.

It is interesting to note that the optical field of the asymmetric bound mode is more strongly confined than it is for the symmetric bound mode. This is obvious from the smaller vertical spread of the field. By comparing Figure 3.9 with Figure 3.7, we note that the E and H fields extend to about $2 \mu\text{m}$ for the asymmetric mode whereas they extend to $15 \mu\text{m}$ in the case of the symmetric mode. In the metal, the optical field of the a_b mode is stronger than the s_b in the metal, where losses occur. This is the reason why we observe significantly higher attenuation for this mode.

A close-up of the field components of the asymmetric mode is presented in Figure 3.10 in order to better compare the field distributions of the asymmetric and the symmetric modes. The scales are the same for both cases.

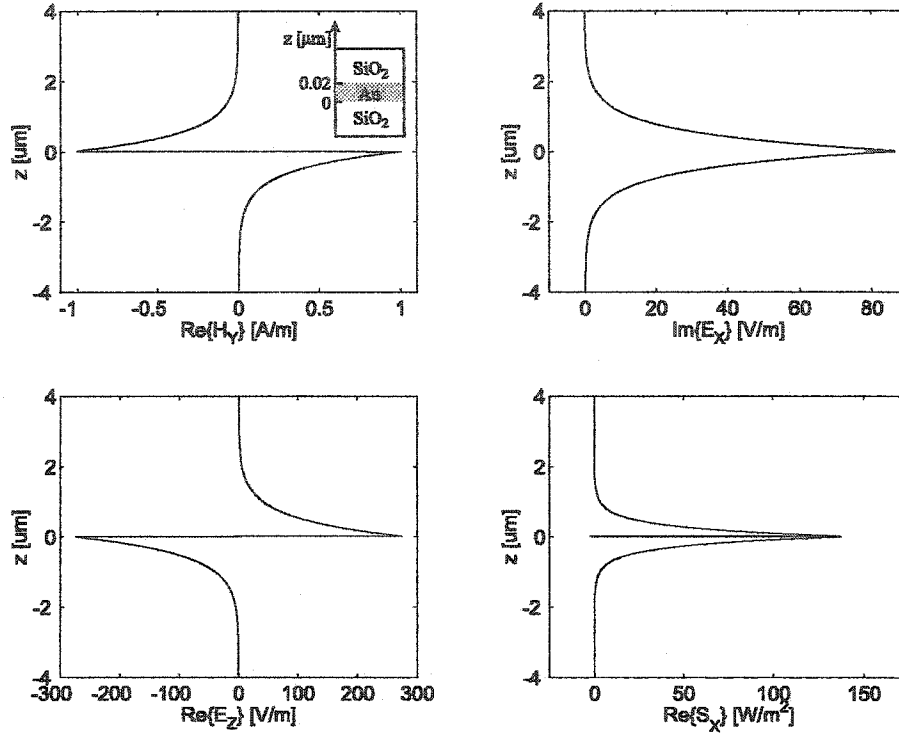


Figure 3.9.: Field distributions and Poynting vector of the asymmetric bound mode of an Au slab guide embedded in SiO₂ and excited at the free space wavelength of 1550 nm.

By closely examining Figure 3.10, we again note the asymmetry present in the H_y and E_z field components. We also note, by comparing it with the close-up of the field distributions in the symmetric case (cf. Figure 3.8), that the magnitude of the E_x component is greater for the asymmetric mode than it is for the symmetric mode. This stronger field inside the metal translates into higher losses.

The analysis of the field distributions has allowed us to better visualise plasmon-polaritons and understand the distinction between the symmetric and the asymmetric bound modes. In the next few sections, we will further investigate properties of these modes through modelling work.

3.4.2. Effect of field confinement of a Au slab guide upon variations in the permittivity of the surrounding dielectric

We will now investigate the effects seen on the plasmon-polariton modes when the index of refraction of the supporting media is varied. We begin our analysis by investigating the

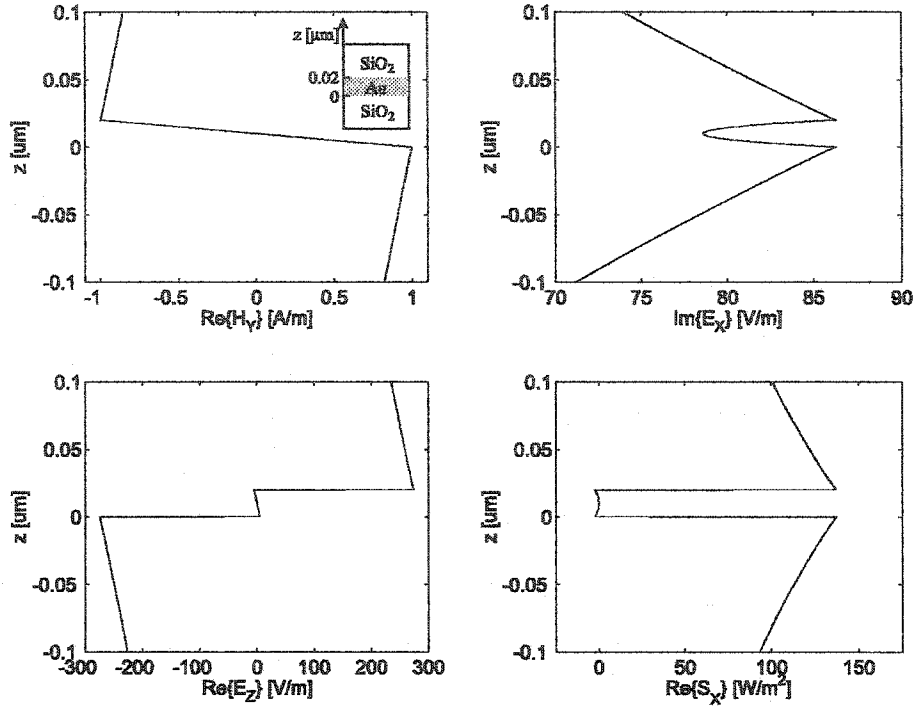


Figure 3.10.: Close-up view of the field distributions and Poynting vector of the asymmetric bound mode of an Au slab guide embedded in SiO₂ and excited at the free space wavelength of 1550 nm.

effects of varying the refractive index of the supporting media for a structure consisting of a 20 nm Au film ($N_{Au} = 0.555 - j10.66$) supported above and below by semi-infinite dielectrics of equal permittivity, and excited at a free space wavelength of 1550 nm. In Figure 3.11, we present simulation results of the real part of the effective index of refraction of the plasmon-polariton modes supported by this structure. For a thin metal film, we note in the case of the symmetric bound mode that the effective index of refraction is very similar to the index of refraction of the supporting media. The effective index of both modes increases more rapidly than the index of refraction of the surrounding dielectrics, indicating a stronger confinement of the electromagnetic fields.

If the fields are more tightly confined, it would not be surprising to observe an increase in the attenuation of the plasmon-polariton modes. In Figure 3.12, we note that, for a 20 nm thick Au film, increasing the index of refraction of its supporting media from $n_s = n_c = 1$ to $n_s = n_c = 2$ results in a 10-fold increase in the imaginary part of the effective index of refraction. This translates into an increase in attenuation per unit length from 3.6 dB/cm for $n_s = n_c = 1$ to an attenuation of 41.5 dB/cm for $n_s = n_c = 2$.

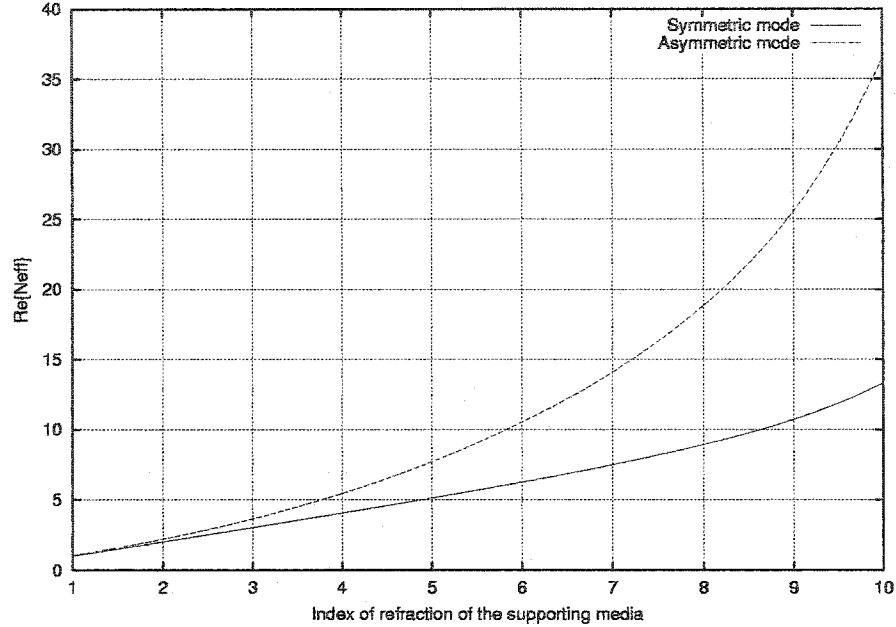


Figure 3.11.: Effect on the effective index of refraction of varying the index of refraction of the dielectric supporting a 20 nm Au film ($N_{Au} = 0.555 - j10.66$). The investigation is conducted at a free space wavelength of 1550 nm.

We now consider the field distributions in order to better visualise the changes that occur for the plasmon-polariton modes as the index of refraction of the surrounding dielectric varies. In this case, it will be most insightful to present a plot of the Poynting vector, as illustrated in Figure 3.13. Although only the case for the symmetric bound mode is presented, the same conclusions could be drawn from looking at the plot of the asymmetric mode.

We observe a significant increase in vertical confinement of the fields as the index of refraction of the supporting media is increased. In Figure 3.12, however, we had seen that the attenuation of the modes increased when the index of refraction of the supporting dielectric was increased. Hence, from these figures, it becomes apparent that in order to propagate a plasmon-polariton mode characterised by low attenuation, it is desirable to support the metal film in a dielectric having an index of refraction close to that of air. If, however, we desire a device characterised by a strong vertical confinement, then we choose to use a higher refractive index dielectric. Clearly, there is a trade-off between confinement and attenuation.

Of course, in the design of devices, there are other considerations of practical nature. For instance, the choice of dielectric may be made such as to match the dielectric constant

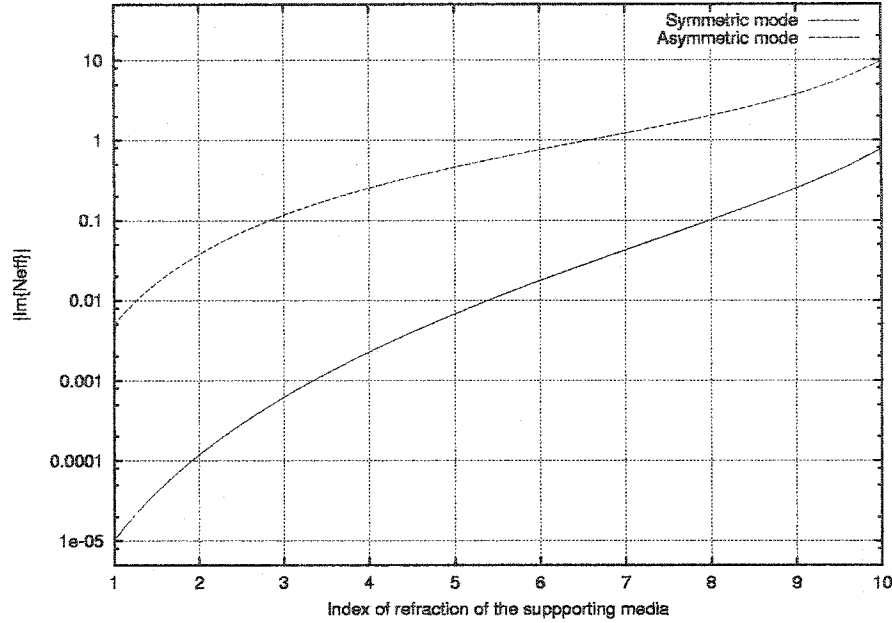


Figure 3.12.: Effect on the attenuation of varying the index of refraction of the dielectric supporting a 20 nm Au film ($N_{Au} = 0.555 - j10.66$). The investigation is conducted at a free space wavelength of 1550 nm.

of the media propagating the incident beam. This reduces reflections at the input and thus reduces the coupling loss. The same can be done at the output of the device. In our experiments, we have always chosen SiO_2 as the supporting dielectric since its index of refraction is matched to the refractive index of the input and output fibers, and because it provides a balance between attenuation and confinement.

3.4.3. Electromagnetic field distributions of a Au slab guide embedded in a dielectric of finite thickness

So far, we have considered only the case of a thin metal film supported above and below in semi-infinite dielectrics, however, in practice, we may only deposit a certain thickness of dielectric. Simulations presented above indicated that for a Au film embedded in SiO_2 , a minimum of 10 μm of dielectric should be used such that the fabricated structure adequately represents the simulated model.

For the work performed in this thesis, all of the fabrication was performed at the CRC, and although it is possible to deposit SiO_2 layers tens of microns in thickness [50], the CRC's PECVD deposition machine can only deposit 2 μm of SiO_2 . The CRC can sputter SiO_2 to a thickness of 4 μm . In this section, we will investigate the effect of this

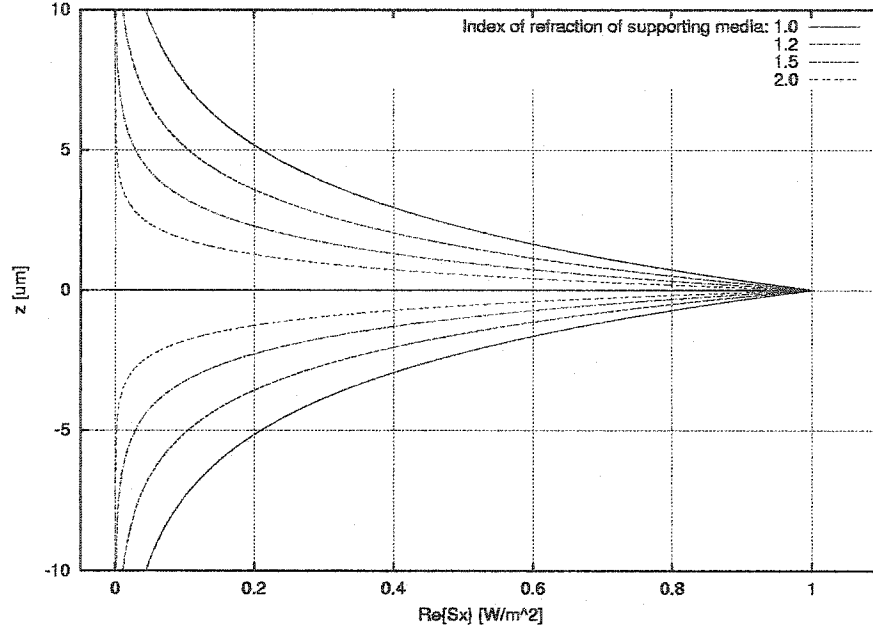


Figure 3.13.: Real part of the Poynting vector of the symmetric mode supported by a 20 nm thick Au film ($N_{Au} = 0.555 - j10.66$) supported above and below by a dielectric having the index of refraction indicated. The investigation is conducted at a free space wavelength of 1550 nm.

finite thickness of dielectric on the propagation of plasmon-polaritons. In our attempt to do so, we will model the structures fabricated using the formulas derived for a n -layer stratified structure (cf. §2.1.2).

The actual devices fabricated consist of wave guides of various widths, ranging from 1 μm to 8 μm in width. Clearly, modelling these wave guides as a slab is only a first approximation that will, it is hoped, provide useful insight into the properties of plasmon-polariton modes. The properties of the various layers used in this simulation are presented in Table 3.5.

Layer	Thickness [μm]	Index of refraction
air (cover)	semi- ∞	1.0
SiO ₂	2	1.444020
Au	variable	0.555 - j 10.66
SiO ₂	7	1.444020
Si (substrate) [48]	semi- ∞	3.4764

Table 3.5.: Properties of the various layers used for simulating a fabricated structure. The layers are presented in the order in which they would be fabricated in an actual device.

Once again, for this structure, the symmetric and the asymmetric bound modes are found. The dispersion curves for the real part of the effective index of refraction is presented in Figure 3.14.

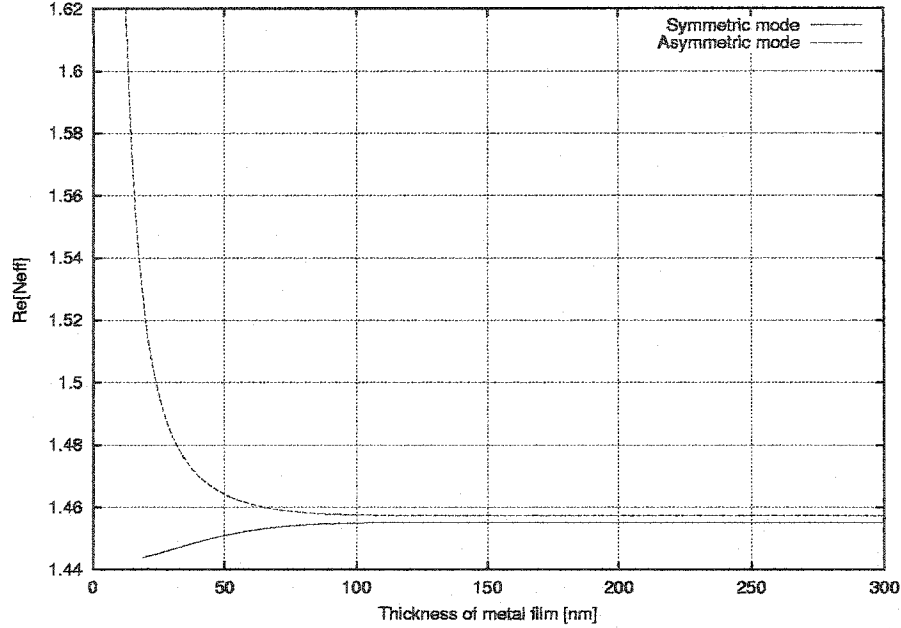


Figure 3.14.: Real part of the effective index of refraction of the bound modes supported by a structure consisting of a Au film deposited over $7\text{ }\mu\text{m}$ of SiO_2 . The Au film is covered with $2\text{ }\mu\text{m}$ of SiO_2 . It is assumed that the structure rests on Si and the top is covered with air. This simulation is performed at a free space wavelength of 1550 nm .

It is interesting to compare this plot with the one obtained in the case of a simple Au film embedded in infinite SiO_2 , as presented in Figure 3.1. In the case of a Au film embedded in infinite SiO_2 , we note that the two modes become increasingly similar as the thickness of the film increases. This is not what we observe in Figure 3.14. Instead, we note that the two modes remain clearly distinct even for thick metallisations. As the thickness of the metallisation increases, the plasmon-polariton modes propagating at both metal-dielectric interfaces are no longer coupled, and tend towards a plasmon-polariton mode supported by a single metal-dielectric interface. In this case, because the structure is asymmetric in z , the mode supported at the metal-substrate interface will differ from the mode supported at the metal-cover interface, hence the reason why the symmetric and asymmetric modes remain distinct as the thickness of the metallisation increases.

Even more interesting is the plot of the imaginary part of the effective index of

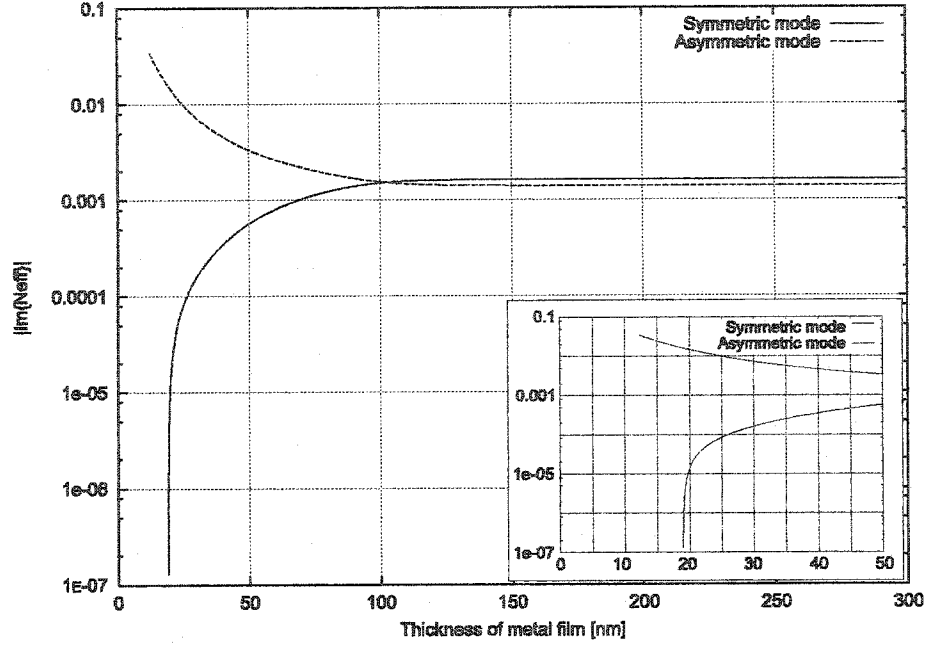


Figure 3.15.: Imaginary part of the effective index of refraction of the bound modes supported by a structure consisting of a Au film deposited over $7\text{ }\mu\text{m}$ of SiO_2 . The Au film is covered with $2\text{ }\mu\text{m}$ of SiO_2 on Si. It is assumed that the structure is covered with air. This simulation is performed at a free space wavelength of 1550 nm .

refraction, presented in Figure 3.15. We note once more that the two modes remain very distinct for thick metallisation. We also observe a cut-off thickness for the symmetric mode in the vicinity of 19 nm , at which point a symmetric bound mode is no longer supported for a structure consisting of a thinner metal film. It is possible that below the cut-off thickness, the symmetric mode evolves into a leaky mode. In contrast, the asymmetric mode does not have a cut-off thickness.

In addition, we note that for metal thicknesses in excess of 110 nm , the asymmetric mode becomes less lossy than the symmetric mode. This was not observed in the case of a simple structure geometry. In order to better understand these phenomena, we will once again study the field distributions of the modes supported by this structure.

In Figure 3.16, we see the field distributions of the symmetric mode. As it can be seen, the field is far from being perfectly symmetrical. The field is still referred to as symmetrical since the H_y and E_z distributions at both metal-dielectric interfaces have the same sign and display characteristics usually associated with the symmetric mode.

In this simulation, the layers are as presented in Table 3.6. We note a large transition in the the field distributions where the metal film is positioned. Above the metal, the

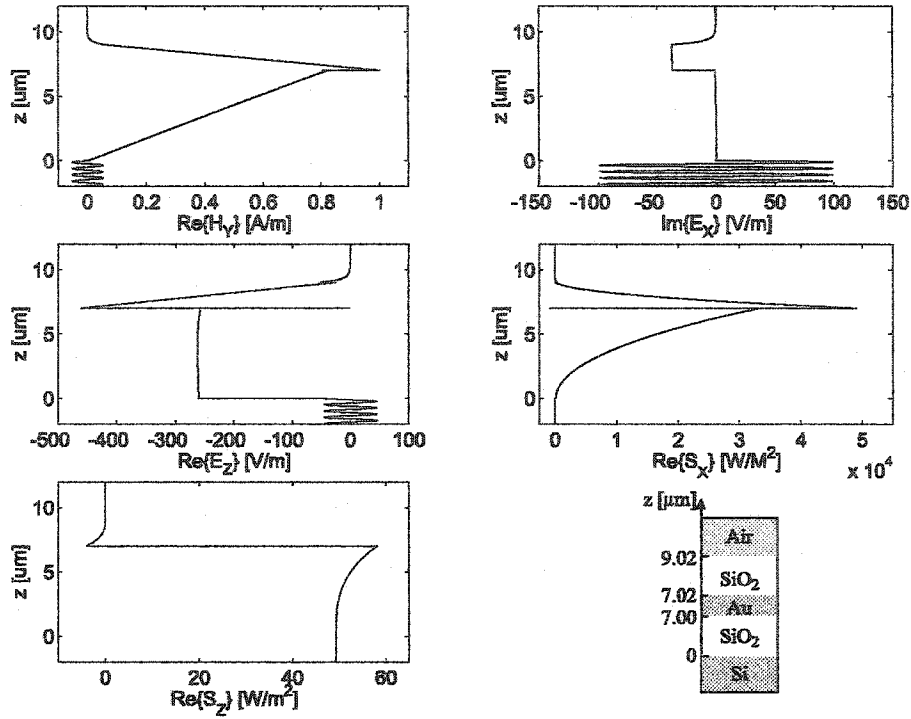


Figure 3.16.: Simulated TM field distributions and Poynting vector of the symmetric mode supported by a structure consisting of a $7\text{ }\mu\text{m}$ SiO_2 on Si substrate, covered by a 20 nm thick Au film. The cover is assumed to be made of $2\text{ }\mu\text{m}$ of SiO_2 and is covered by air. The analysis is performed at a free space wavelength of 1550 nm . The indices of refraction used in this model may be found in Table 3.5 and the layer positions are described in Table 3.6.

fields are confined within the $2\text{ }\mu\text{m}$ SiO_2 cover. As we know from general electromagnetic theory, fields are confined to regions of higher index of refraction. In this case, the SiO_2 above the metal film has an index of refraction much greater than the air that covers it. Below, the metal, there is a $7\text{ }\mu\text{m}$ thick layer of SiO_2 that allows the mode to spread. In addition, the high index of refraction Si region below the SiO_2 attracts the fields. In fact, we observe oscillations in the E and H field components in the Si region. The plot of $\Re\{S_z\}$ shows significant radiation of the mode in that region, suggesting that a thicker substrate is required.

The attenuation per unit length of the symmetric bound mode in this structure is, in theory, less than it is for the semi-infinite dielectric case. The field distribution, however, is such that it does not lend itself to easy excitation. For example, there will be less mode overlap from a fiber to the metal guiding structure, and thus higher coupling losses should

Layer	Position [μm]
Air	$9.02 < z$
SiO ₂	$7.02 < z < 9.02$
Au	$7 < z < 7.02$
SiO ₂	$0 < z < 7$
Si	$z < 0$

Table 3.6.: Position of the various layers in simulated structure.

be observed.

The asymmetric mode simulated field distributions are presented in Figure 3.17 and are seen to be less affected by the finite thickness of the dielectric layers. When presenting simulation results for the asymmetric mode supported by a thin Au film embedded above and below in semi-infinite SiO₂, it was noted that the fields were more strongly confined vertically to the metal layer than for the symmetric mode. As a result, the fields did not extend much beyond 1 μm inside the dielectrics and no radiation to the Si region is observed.

In Figure 3.17, even though the thickness of the SiO₂ cover is only 2 μm , this is more than sufficient to adequately support the plasmon-polariton asymmetric mode. In the case of the symmetric mode, it is obvious that a significantly thicker dielectric region is required in order to support the mode in such a way that its field distribution appears unhindered by the finite thickness of the dielectrics.

We now wish to verify our claim that a sufficiently thick dielectric can indeed support a symmetric mode with field distributions closely resembling those observed in the case of the semi-infinite dielectrics. In order to do so, we present in Figure 3.18 simulation results for a structure consisting of layers of Si, SiO₂, Au, SiO₂ and air with layer thicknesses being semi-infinite, 10 μm , 20 nm, 10 μm and semi-infinite, respectively.

As can be seen from Figure 3.18, the the field distributions are very close in shape to the ones displayed in Figure 3.7, for the semi-infinite dielectric case. Oscillations of the E and H fiels are significantly reduced and as a result, less of the mode power is radiated to the Si region. As the thickness of the supporting SiO₂ is further increased, the mode distribution tends towards the one for a structure having infinitely thick dielectric.

3.4.4. Effect of the metallisation thickness on the field distribution of a Au slab guide embedded in SiO₂

We now have a better understanding of the field distributions of the plasmon-polariton mode propagating along a thin metal film infinite in width. In this last section, we will

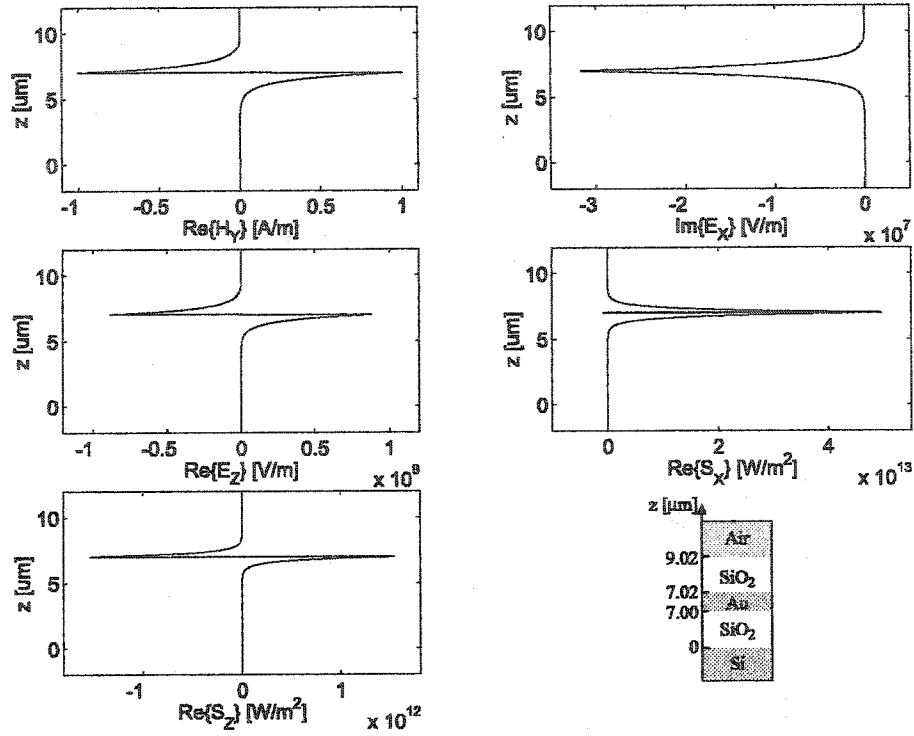


Figure 3.17.: Simulated TM field distributions of the asymmetric mode supported by a structure consisting of a $7\text{ }\mu\text{m}$ SiO_2 on Si substrate, covered by a 20 nm thick Au film. The cover is assumed to be made of $2\text{ }\mu\text{m}$ of SiO_2 and is covered by air. The analysis is performed at a free space wavelength of 1550 nm . The indices of refraction used in this model may be found in Table 3.5.

investigate the effect on the Poynting vector when the metal thickness is increased. We already know that increasing the thickness of the metal film results in higher attenuation for the symmetric mode, thus, we may suspect that the higher losses are a result of a Poynting vector more closely confined to the metal. Figure 3.19 presents the real part of the Poynting vector of the symmetric mode supported by a structure consisting of a Au metal film supported above and below by SiO_2 . The thickness of the metal film is indicated on the graph.

From Figure 3.19, it is clear that the vertical field confinement provided by a thick metal film is much stronger than the one provided by a thin film. For a thick metal film, the mode supported tends towards the one that we would observe at a semi-infinite single metal-dielectric interface, in that the larger thickness of the metal film prevents

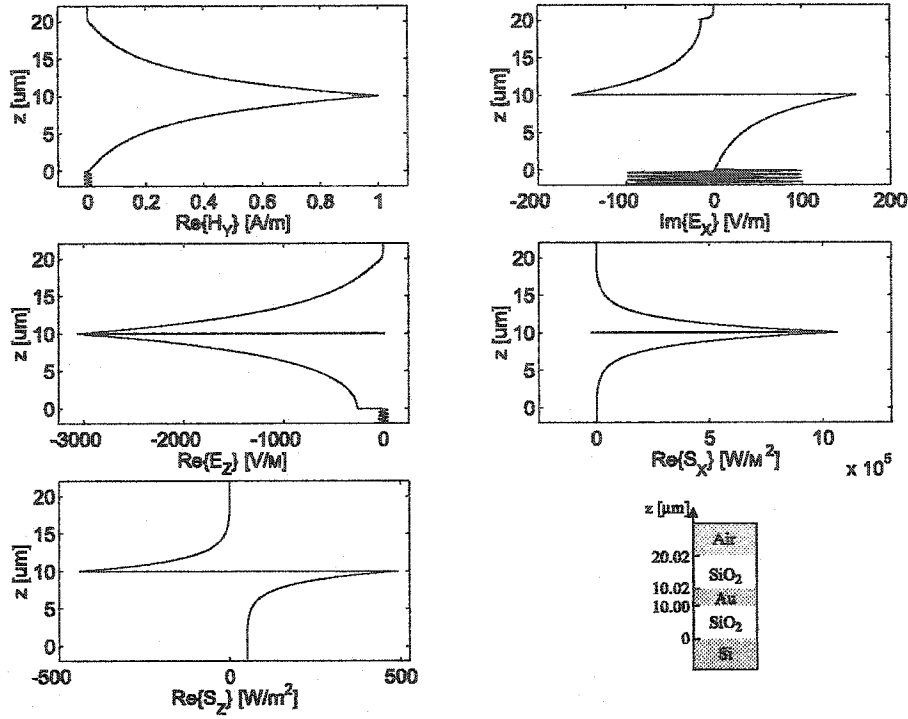


Figure 3.18.: Simulated TM field distributions of the symmetric mode supported by a structure consisting of a 10 μm SiO₂ on Si substrate, covered by a 20 nm thick Au film. The cover consists of 10 μm of SiO₂ and is covered by air. The analysis is performed at a free space wavelength of 1550 nm. The indices of refraction used in this model may be found in Table 3.5.

plasmon-polaritons from one metal-dielectric interface to tunnel and thus couple to the plasmon-polaritons at the other metal-dielectric interface.

The same result would be observed if we investigated the field distributions for a fixed metal thickness but varied the wavelength. A smaller wavelength for a given metallisation thickness will result in greater field confinement with higher attenuation. For this technology and for a given metal film thickness, it is advantageous, in terms of attenuation, to operate at longer wavelengths.

In this chapter, we have acquired a better understanding of plasmon-polariton modes propagating along a thin metal film infinite in width. Our analysis of the field distribution has given, it is hoped, a clearer understanding of plasmon-polaritons. In the next chapter, we will continue building on this knowledge while studying the excitation of plasmon-polaritons using an attenuated total reflectance experimental setup.

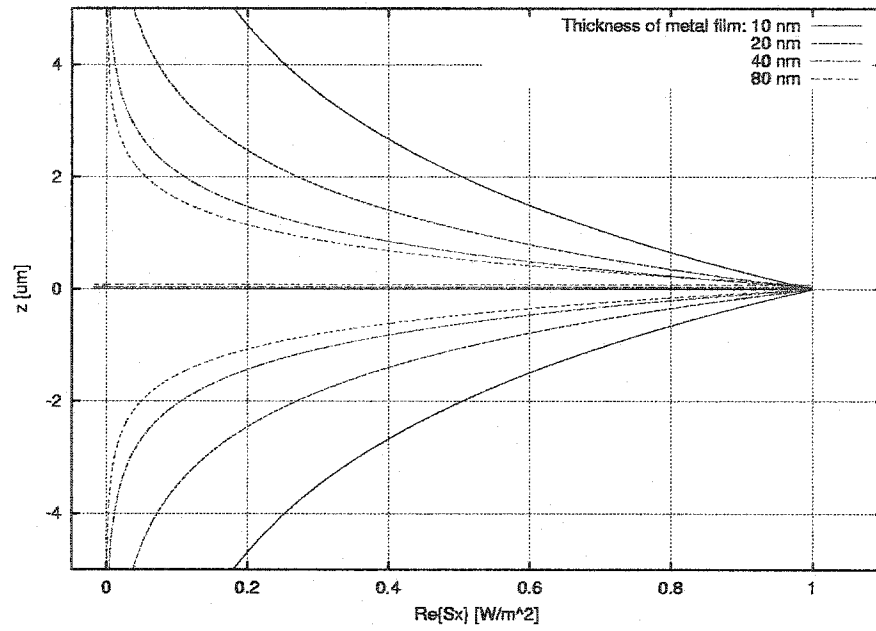


Figure 3.19.: Simulated $\text{Re}\{S_x\}$ TM field distribution of the symmetric mode supported by a structure consisting of a Au metal film embedded in SiO_2 . The thickness of the metal film is indicated on the graph. The analysis is conducted at a free space wavelength of 1550 nm.

4. Analysis of plasmon–polaritons using an attenuated total reflectance (ATR) setup

4.1. Derivation of Fresnel reflection coefficients for TM incident light

During the course of this thesis, the use of ATR as a characterisation tool for determining the properties of a thin metal film was undertaken. The method was studied and a modelling tool was developed. In addition, an experimental study was initiated, however, it was abandoned due to encouraging results obtained for propagation of plasmon–polaritons along a thin metal film finite in width (cf. Chp. 5). Consequently, the experimental results presented in this chapter are incomplete. Still, we have chosen to include the work performed on ATR in this thesis because it gives an overview of the topic to the reader unfamiliar with the method and because it may be helpful to the reader interested in performing such experiments.

ATR measurements are often used since they are a powerful characterisation tool. The technique can be used to determine the refractive index of a material or to determine the surface roughness at an interface. In the past, experimentalists have also made use of ATR to excite surface plasmon–polaritons [35, 57]. A simple setup to excite plasmon–polaritons is illustrated in Figure 4.1.

In the literature, one will find two ATR configurations pertaining to plasmon–polaritons: the Otto [10] and the Kretschmann–Raether [11, 12] configurations. In the Otto configuration, the metal is placed in close proximity to the base of the prism and is separated by a thin layer of air. Very thin spacers are placed to ensure that the sample is parallel to the base of the prism and to maintain the desired distance. In the Kretschmann–Raether configuration, the metal is deposited directly on the base of the prism. Sometimes, another dielectric is then deposited on the metal, such that the metal is captured between

the prism and a dielectric. Figure 4.1 presents the Kretschmann–Raether and Otto configurations, sometimes referred to as prism–metal–air (PMA) and prism–air–metal (PAM) configurations, respectively [27].

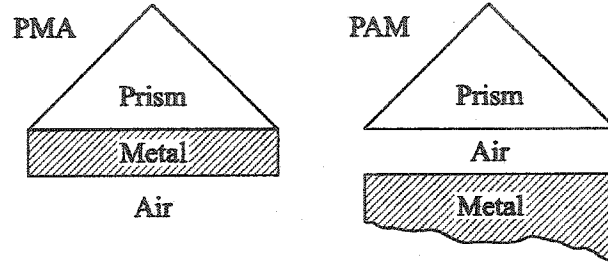


Figure 4.1.: Illustration of the Kretschmann–Raether [11, 12] (PMA) and of the Otto [10] (PAM) ATR configurations used to excite surface plasmon–polaritons.

For the experiment to work, a prism with a refractive index higher than that of the underlying medium is necessary such that the polarised collimated coherent light beam entering the prism will be totally internally reflected at the base of the prism. Ray–theory would have us believe that the power is totally reflected at the interface, however, we know that the power penetrates the underlying medium. It is possible to excite the surface plasmon–polaritons by varying the angle of incidence of the laser beam. At a certain angle, the $k_{||}$ –vector in the prism will exactly match the $k_{||}$ –vector of the plasmon–polariton mode supported by the metal. For this angle, the light is not totally reflected at the base of the metal, rather, a percentage of the power is converted to surface electromagnetic waves that constitute plasmon–polaritons.

Plasmon–polaritons are surface electromagnetic waves, that is, they propagate mostly at the metal–dielectric interface. Hence, plasmon–polaritons are sensitive to surface roughness and thus are an ideal tool to characterise the quality of the interface. By fitting experimental and theoretical curves of a metal–dielectric layered structure, it is possible to determine the optical and physical properties of the device under investigation. This is the reason why we have done ATR measurements on our samples.

We use Fresnel’s reflection coefficients to model the effect of varying the angle of incidence of a TM incident beam. This has been done in the literature for three layer media [27, pp. 32–33], allowing one to model a simple system in the Otto or the Kretschmann–Raether configurations. Obviously, such a set of equations may be expanded to allow modelling of an n –layered structure. Below is a simple derivation for an n –layered structure, which follows Ref. [27, pp. 143–150] and Ref. [46]. The notation is defined in Figure 4.2.

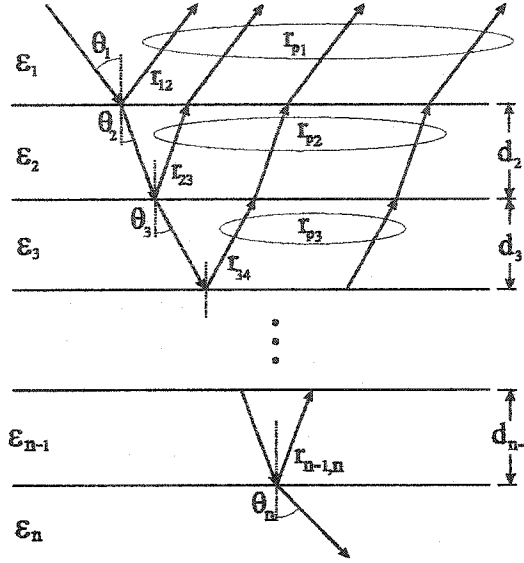


Figure 4.2.: Fresnel reflection coefficients of a TM wave incident on an n -layer isotropic stratified media.

For a TM polarisation, the reflection at the layer 1-layer 2 interface is given by:

$$r_{TM} = \frac{\tilde{n}_2 \cos(\theta_1) - \tilde{n}_1 \cos(\theta_2)}{\tilde{n}_2 \cos(\theta_1) + \tilde{n}_1 \cos(\theta_2)} a_{TM} \quad (4.1)$$

and the Fresnel reflection coefficient at the interface between medium 1 and 2 is simply:

$$r_{12} = \frac{r_{TM}}{a_{TM}} = \frac{\tilde{n}_2 \cos(\theta_1) - \tilde{n}_1 \cos(\theta_2)}{\tilde{n}_2 \cos(\theta_1) + \tilde{n}_1 \cos(\theta_2)} \quad (4.2)$$

where:

- $\tilde{n}_i$: refractive index of medium i
- a_{TM} : amplitude of the electric field incident wave
- r_{TM} : amplitude of the reflected electric field from the interface between two media
- θ_1 : angle of incidence
- θ_2 : angle of transmission

For the stratified structure presented in Figure 4.2, we may define the following Fresnel coefficients at each interface:

$$r_{12} = \frac{\tilde{n}_2 \cos(\theta_1) - \tilde{n}_1 \cos(\theta_2)}{\tilde{n}_2 \cos(\theta_1) + \tilde{n}_1 \cos(\theta_2)} \quad (4.3)$$

$$r_{23} = \frac{\tilde{n}_3 \cos(\theta_2) - \tilde{n}_2 \cos(\theta_3)}{\tilde{n}_3 \cos(\theta_2) + \tilde{n}_2 \cos(\theta_3)} \quad (4.4)$$

$$\vdots$$

$$r_{n,n+1} = \frac{\tilde{n}_{n+1} \cos(\theta_n) - \tilde{n}_n \cos(\theta_{n+1})}{\tilde{n}_{n+1} \cos(\theta_n) + \tilde{n}_n \cos(\theta_{n+1})} \quad (4.5)$$

and the angles are determined using Snell's law as follow:

$$\theta_2 = \arccos \left(\left[1 - \frac{\tilde{\epsilon}_{r1}}{\tilde{\epsilon}_{r2}} \sin^2 \theta_1 \right]^{1/2} \right) \quad (4.6)$$

$$\theta_3 = \arccos \left(\left[1 - \frac{\tilde{\epsilon}_{r1}}{\tilde{\epsilon}_{r3}} \sin^2 \theta_1 \right]^{1/2} \right) \quad (4.7)$$

$$\vdots$$

$$\theta_{n+1} = \arccos \left(\left[1 - \frac{\tilde{\epsilon}_{r1}}{\tilde{\epsilon}_{r_{n+1}}} \sin^2 \theta_1 \right]^{1/2} \right) \quad (4.8)$$

where ϵ_{r_i} is the relative permittivity in layer i . It should be noted that in this chapter, in order to be consistent with the formulation presented in the literature, the permittivity is given as $\tilde{\epsilon}_r = \epsilon' + j\epsilon''$, where a plus sign is used in front of the imaginary part of the relative permittivity. This change in notation results from a temporal dependence of the EM fields given by $e^{j\omega t}$ whereas in §2.1.1 we have defined it as $e^{-j\omega t}$. The index of refraction of layer i is still defined as $\tilde{n}_i = \sqrt{\tilde{\epsilon}_{r_i}}$.

At first glance, it may appear that equations 4.6 to 4.8 are erroneous since the term in the $\arccos$ function is, for all angles, given in terms of $\tilde{\epsilon}_{r1}$ and θ_1 . However, one may readily verify that this is a simple substitution making use of Snell's law. For instance,

$$\theta_{n+1} = \arccos \left(\left[1 - \frac{\tilde{\epsilon}_{r_n}}{\tilde{\epsilon}_{r_{n+1}}} \sin^2 \theta_n \right]^{1/2} \right) \quad (4.9)$$

$$= \arccos \left(\left[1 - \frac{\tilde{\epsilon}_{r1}}{\tilde{\epsilon}_{r_{n+1}}} \sin^2 \theta_1 \right]^{1/2} \right) \quad (4.10)$$

since Snell's law tells us that:

$$\tilde{\epsilon}_{r_n} \sin^2 \theta_n = \tilde{\epsilon}_{r_{n-1}} \sin^2 \theta_{n-1} = \dots = \tilde{\epsilon}_{r1} \sin^2 \theta_1 \quad (4.11)$$

The Fresnel coefficients written recursively for the various layers are:

$$r_{p_n} = \frac{r_{n,n+1} + r_{n+1,n+2} \exp(j2\alpha_{n+1}d_{n+1} \cos \theta_{n+1})}{1 + r_{n,n+1}r_{n+1,n+2} \exp(j2\alpha_{n+1}d_{n+1} \cos \theta_{n+1})} \quad (4.12)$$

$$r_{p_{n-1}} = \frac{r_{n-1,n} + r_{p_n} \exp(j2\alpha_n d_n \cos \theta_n)}{1 + r_{n-1,n}r_{p_n} \exp(j2\alpha_n d_n \cos \theta_n)} \quad (4.13)$$

$$\vdots$$

$$r_{p_1} = \frac{r_{12} + r_{p_2} \exp(j2\alpha_2 d_2 \cos \theta_2)}{1 + r_{12}r_{p_2} \exp(j2\alpha_2 d_2 \cos \theta_2)} \quad (4.14)$$

and in which:

$$\alpha_{n+1} = \sqrt{\tilde{\epsilon}_{r_{n+1}}} \frac{\omega}{c} \quad (4.15)$$

$$\alpha_n = \sqrt{\tilde{\epsilon}_{r_n}} \frac{\omega}{c} \quad (4.16)$$

$$\vdots$$

$$\alpha_1 = \sqrt{\tilde{\epsilon}_{r_1}} \frac{\omega}{c} \quad (4.17)$$

Hence, with the above equation, it is possible to model an n -layered structure. The TM reflectance of this structure is given by $R_p = |r_{p_1}|^2$.

In an ATR experiment, the frequency of the incident beam typically remains constant while the angle of incidence is varied. At the angle $\theta_1 = \theta_p > \theta_c$ (θ_c is the critical angle at the metal/air interface) for which plasmon-polaritons are excited, a minimum in the reflected intensity will be observed. Experimental and theoretical results of the excitation of surface plasmon-polaritons via the ATR technique will be presented in §4.5.

4.2. Validation of ATR model

The equations for the Fresnel reflection coefficients of an n -layer stratified media presented in the previous section were coded. The code is written such that the theoretical reflectance curve of an n -layered structure may be modeled given the incidence angle, the thickness and the permittivity of the various layers, and the free space wavelength of operation. In order to validate this code, we compare theoretical results obtained from our simulations with those presented in the literature.

In Figure 4.3, we compare theoretical results obtained from our simulations with the ones presented in Ref. [57] for the structure shown in inset. The permittivities of the prism, Ag and MgF₂ layers are 3.781162, $-9.564 + j0.309$ and 1.9044, respectively, and

the analysis is conducted at a free space wavelength of 495 nm. We see that our model is in good agreement with the one presented in Ref. [57].

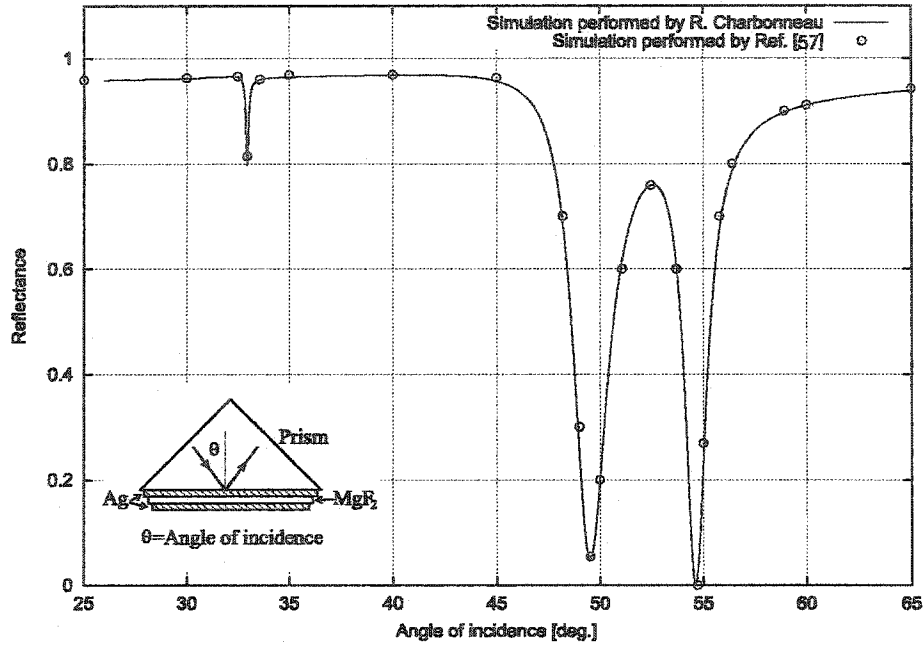


Figure 4.3.: Comparison between simulated reflectance that we obtained with simulated results presented in Ref. [57]. The structure analysed is shown in inset. The analysis was conducted at a free space wavelength of 495 nm and the relative permittivities of the prism, Ag and MgF_2 layers are 3.781162, $-9.564 + j0.309$ and 1.9044, respectively.

4.3. Modelling of reflectance in an ATR setup

Modelling of the expected results of an ATR experiment was undertaken before the fabrication of samples in order to ensure that the samples received would enable us to properly excite plasmon-polariton modes. Using the equations derived in §4.1, a Matlab code was written. This code was later converted to Octave for practical reasons.

Results of ATR measurements of plasmon-polariton modes presented in the literature are most often for samples fabricated using the Kretschmann configuration or a slight variant, in which the metal film is evaporated or deposited by other means directly on the base of the prism. The metal may be covered by a dielectric. In some instances, a thin layer of dielectric is deposited directly on the base of the prism before the deposition of the metal. A second layer of dielectric usually covers the metal.

In our case, it was more practical to fabricate a separate sample and place it at the

base of the prism for the ATR experiment. Figure 4.4 illustrates the various layers present in the sample. Of course, if we are to model the reflectance accurately, it is necessary to account for all layers present in our structure.

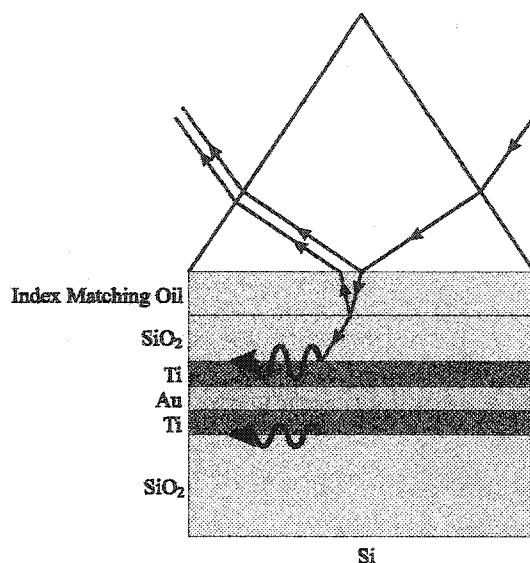


Figure 4.4.: Illustration of the layered structure used for the attenuation total reflectance measurement experiment.

For the curve fitting to be accurate, the number of parameters must be minimal. In a PMA structure, for instance, the only two parameters unknown to the experimentalist are the index of refraction of the metal and the thickness of the metal film. Typically, the index of refraction of the prism is known very accurately. When additional layers are added, more parameters are available to fit the simulated curve to the experimental one, such that when a good fit is obtained, one may not be sure of its validity.

In order to limit the uncertainties brought upon by the additional layers, their properties must be known with a fair degree of accuracy. For the structure illustrated in Figure 4.4, we note that there are two different types of metals, Au and Ti, where the Ti layers help resolve adhesion issues between Au and SiO_2 . Table 4.1 presents the properties of the different layers for the sample measured at a free space wavelength of 632.8 nm. This wavelength was selected in order to be consistent with published ATR measurement results [51–56], and because HeNe lasers are inexpensive, easily available and of good quality.

In Table 4.1, the index of refraction of the various layers are taken directly from the literature, except for the prism and the index matching oil, which we obtained from the manufacturer. The index of refraction of the various layers in our samples are in fact

Layer	Thickness [nm]	Index of refraction	Fabrication technique
Prism	-	1.83957 / 1.61656 [†]	
Index matching oil	2500 est.	1.63	
SiO ₂	750	1.457 [48]	PECVD
Ti	5	2.94 + j3.59 [49]	Evaporation
Au	10	0.162 + j3.21 [48]	Evaporation
Ti	5	2.94-j3.59	Evaporation
SiO ₂	2000	1.457	PECVD
SiO ₂	5000	1.457	Thermal oxydisation
Si	-	3.882 + j0.019 [48]	

Table 4.1.: Properties of the various layers of the sample fabricated and measured in an ATR experiment. The index of refraction are given for a free space wavelength of 632.8 nm. The sample is approximately 10 mm in width and 20 mm in length.

[†]Two experiments were conducted, one using a prism with a refractive index of 1.83957 and the other with a prism having an index of refraction of 1.61656.

different than the ones obtained from the literature due to impurities. For instance, the Si wafer on which the layers were deposited is P-doped. In addition, we assume that the index of refraction of the SiO₂ deposited by PECVD is equal to the SiO₂ layer obtained by thermal oxidation from the wafer manufacturer. We may perform the simulation using the equations derived in §4.1 and compare the results with experiment.

The thickness of the layer of index matching oil is not known precisely and has been estimated. By comparing simulations for this structure in which the thickness of the index matching oil is varied, we find that for thicknesses less than 5 μm , the index matching oil has little impact on the overall shape of the reflectance curve. In our simulations, we have observed a layer of index matching oil thicker than 5 μm , ripples were added to the reflectance curve. Since such ripples have not been observed in our experiment, we conclude that there is only a thin layer of index matching oil.

4.4. Description of ATR measurement setup

Before we present simulation results, it would be important describe the setup that is used to measure the reflectance such that the reader unfamiliar with ATR measurements will better understand the arrangement. The setup available at the CRC and used for the ATR measurements presented in this thesis is illustrated in Figure 4.5.

In our case, we use a 20 mW polarised helium–neon (HeNe) laser with a wavelength of 632.8 nm to excite the plasmon–polariton mode at the metal–dielectric interfaces. An

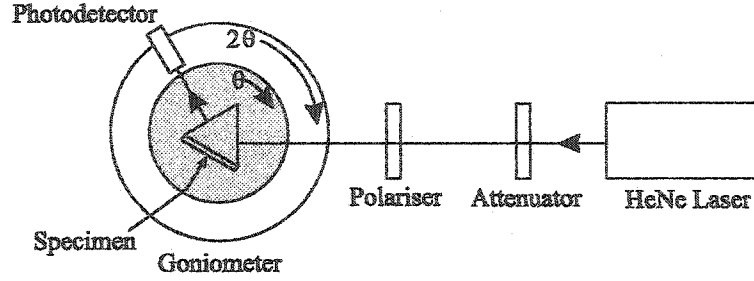


Figure 4.5.: Attenuated total reflectance (ATR) measurement setup used to excite plasmon-polaritons.

attenuator is placed between the laser and the prism ensures that the photodetector operates in its linear region. A polariser is used to ensure that the light incident on the sample is TM-polarised since plasmon-polariton modes on a metal film are purely TM in nature.

The specimen or sample is placed at the base of the prism, which rests at the center of the goniometer. In this case, we are working with a $\theta/2\theta$ goniometer. This means that when the shaded-grey circle on which rests the prism rotates by an angle of θ , the outer circle on which is attached the photodetector rotates by an angle of 2θ . This ensures that the light reflected from the sample is aligned with the photodetector as the prism is rotated. The setup is fully automated such that once all the necessary alignments are performed, the system rapidly records the reflected power for various angles of incidence. The data generated is then compared with theory.

4.5. Comparison of simulated and experimental results

We now compare our simulation results with our experimental ones. The values for the thickness of the various layers and the indices of refraction of these layers are taken directly from Table 4.1.

Two ATR experiments were performed, both at a wavelength of 632.8 nm and using the same sample. The experiments were performed in exactly the same manner, except that in one case the prism used had an index of refraction of 1.61656 and in the other case, its index of refraction was 1.83957. We used two prisms such as to enable us to compare simulation with theory for two cases. The results of the experiment performed using the prism with a refractive index of 1.61656 are presented in Figure 4.6. In Figure 4.7, we compare the experimental results with theory obtained while using the 1.83957 index prism.

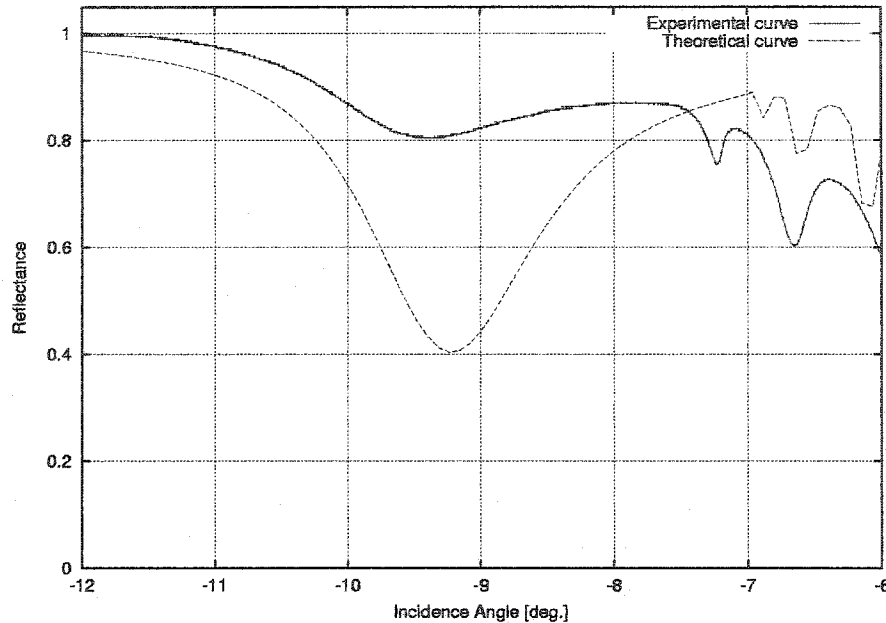


Figure 4.6.: Comparison between experimental and theoretical reflectance curve for the structure described by Table 4.1 using the prism with an index of refraction of 1.61656. The experiment is conducted at a free space wavelength of 632.8 nm.

As can be seen from Figures 4.6 and 4.7, the experimental and theoretical curves are similar in shape for both the lower index and higher index prisms. In Figure 4.6, we see that the plasmon-polaritons were excited for an angle of incidence of -9.4° when the 1.61656 refractive index prism is used whereas they were excited for an angle of incidence of 3.0° when using the 1.83957 refractive index prism, as can be seen in Figure 4.7. In both cases, the theoretical dip is deeper than the experimental one. This suggests that power was not maximally coupled to the plasmon-polaritons. This could be due to the thickness of the SiO_2 cover being thicker than the 750 nm expected, although this was not verified.

Of greater importance than the deepness of the dip is its angular position. We note that for both Figure 4.6 and for Figure 4.7, the angular position of the experimental dip is very close to the theoretical one. The angle at which the dip occurs is very much dependant on the thickness of the metal films and on their refractive indices. The fact that the angular positions of the experimental and theoretical dips match is convincing proof that plasmon-polaritons have been excited.

In order to determine precisely the index of refraction of the various layers, it would be necessary to perform many experiments in which a simple layered structure is used

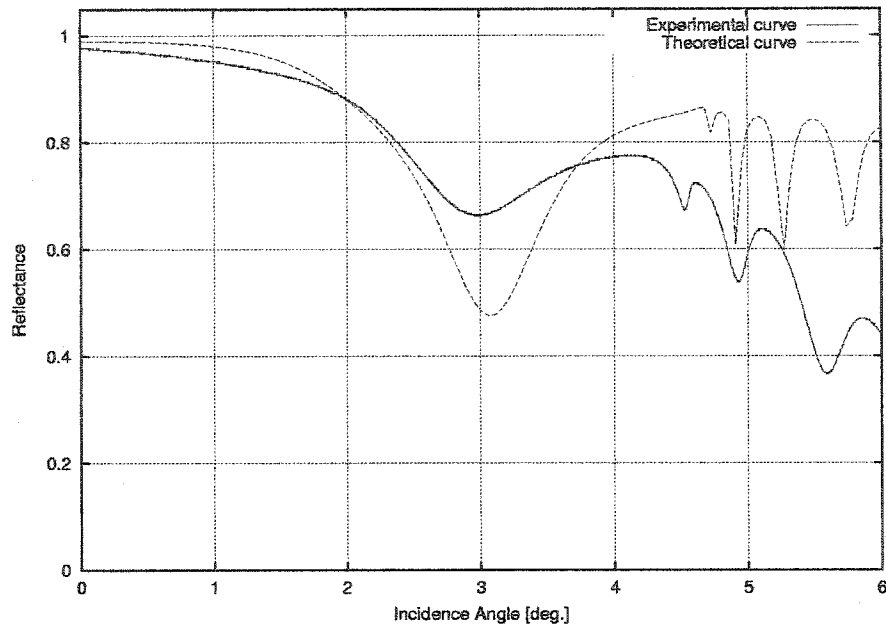


Figure 4.7.: Comparison between experimental and theoretical reflectance curve for the structure described by Table 4.1 using the prism with an index of refraction of 1.83957. The experiment is conducted at a free space wavelength of 632.8 nm.

and designed such as to isolate one parameter. By performing curve fitting and matching the simulated results to the experimental ones, we could characterise the quality of the samples fabricated.

4.6. Other ATR measurements

4.6.1. Investigation of an Al film evaporated on BK7 glass

A second sample was measured using the attenuation total reflectance method. The sample consisted of a 20.4 nm Al film evaporated on a piece of 1 mm thick optically flat BK7 Schott glass. The sample was covered with index matching oil and the higher refractive index prism was used for this measurement. Table 4.2 presents the properties of the various layers of the investigated structure.

In Table 4.2, the index of refraction of the prism, the index matching oil and of the BK7 glass were obtained from the manufacturer. The thickness of the Al film was measured during its evaporation using a crystal oscillator. The thickness of the index matching oil was determined from the comparison between experimental and theoretical results presented in Figure 4.8.

Layer	Thickness [nm]	Index of refraction	Fabrication technique
Prism	-	1.83957	
Index matching oil	2150	1.63	
Al	20.4	$1.45 + j7.51$ [48]	evaporation
BK7 Schott glass	1 000 000	1.51590	

Table 4.2.: Properties of the various layers of a sample consisting of an Al film evaporated on BK7 Schott glass. The values given are at a free space wavelength of 632.8 nm. The sample is square, with sides 20 mm in length.

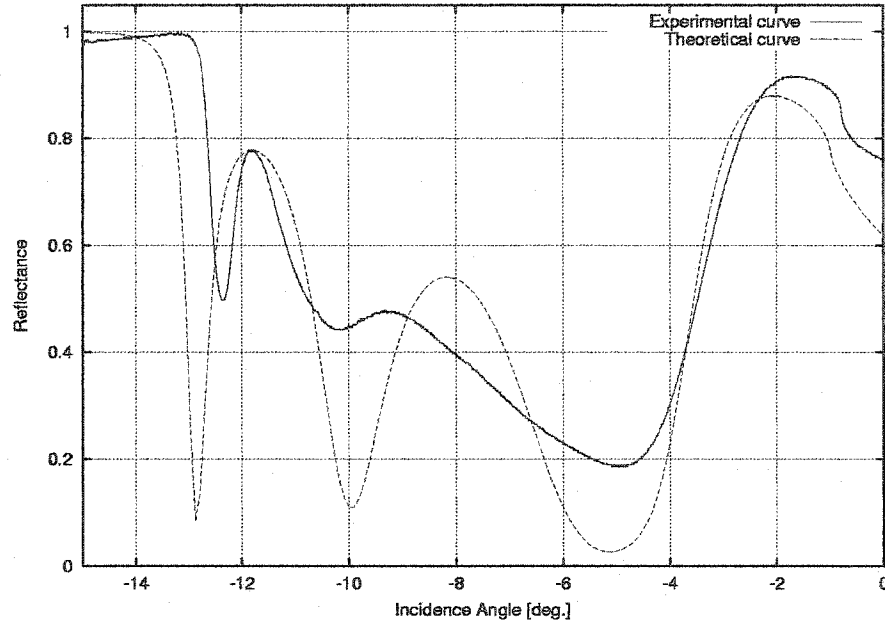


Figure 4.8.: Comparison between experimental and theoretical reflectance curves for the structure described in Table 4.2. The experiment was conducted at a free space wavelength of 632.8 nm.

We see from Figure 4.8 that the theoretical and experimental curves are similar in shape, however, the fit is not optimal. In §4.3, for the structure consisting of layers of Ti-Au-Ti embedded in SiO_2 , we had stated that simulation results showed that the thickness of the index matching oil had little effect on the overall shape of the reflectance curve so long as it was maintained below $5 \mu\text{m}$. Simulation results for the structure considered in this section, however, tell us that the thickness of the index matching oil has a significant effect on the shape of the curve.

ATR experiments typically presented in the literature [11, 57], are conceived such that the metal film is evaporated directly on the base of the prism. By doing so, it is

possible to eliminate the uncertainties related to the thickness of the index matching oil and its refractive index. Such an implementation would more accurately yield the properties of the metal film under investigation. For this experiment, it was not possible to determine accurately the properties of the Al film.

4.6.2. Investigation of a Au film evaporated on BK7 glass

A third sample was measured using the attenuation total reflectance method. The sample consisted of a 21.2 nm Au film evaporated on a piece of 1 mm thick optically flat BK7 Schott glass. The sample was covered with index matching oil and the higher refractive index prism was used for this measurement. Table 4.3 presents the properties of the various layers for the structure of interest.

Layer	Thickness [nm]	Index of refraction	Fabrication technique
Prism	-	1.83957	
Index matching oil	1700	1.63	
Au	20.4	$0.162 + j3.21$ [48]	evaporation
BK7 Schott glass	1 000 000	1.51590	

Table 4.3.: Properties of the various layers of a sample consisting of a Au film evaporated on BK7 Schott glass. The values given are at a free space wavelength of 632.8 nm. The sample is square, with sides 20 mm in length.

In Table 4.3, the index of refraction of the prism, the index matching oil and of the BK7 glass were obtained from the manufacturers. The thickness of the Au film was measured during its evaporation using a crystal oscillator. The thickness of the index matching oil was determined from the comparison between experimental and theoretical results presented in Figure 4.9.

As it was the case for Figure 4.8, we see in Figure 4.9 that the theoretical and experimental curves are similar in shape. The difficulties related to the uncertainty of the thickness of the index matching oil described in §4.6.1 were also present for this experiment, and for this reason, the properties of the Au film could not be determined accurately.

4.7. Polarisation sensitivity measurements on a thin Ti-Au-Ti metal film embedded in SiO₂

We have often stated that a thin metal film infinite in width only supports transverse magnetic (TM) modes, and if this is the case, we should observe a polarisation sensitivity.

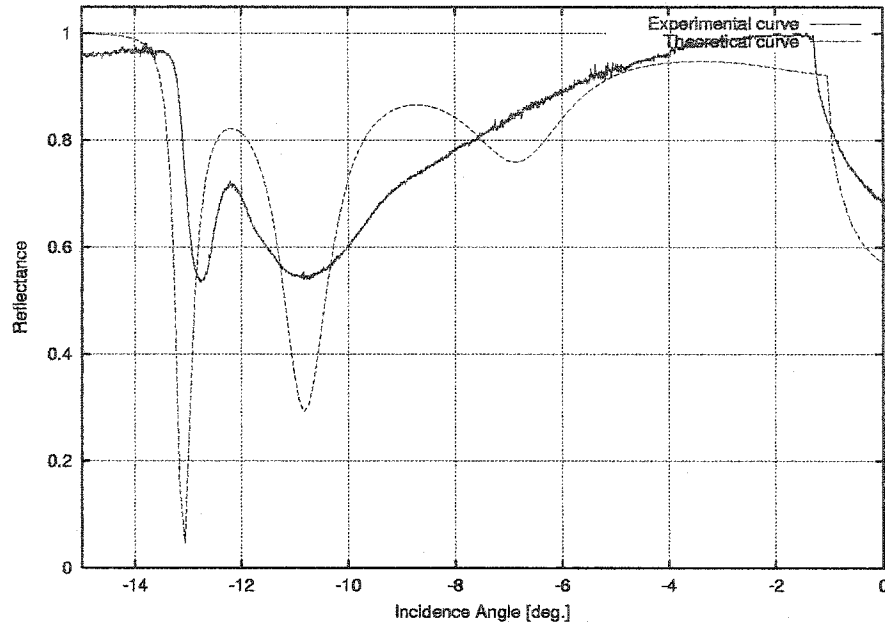


Figure 4.9.: Comparison between experimental and theoretical reflectance curves for the structure described in Table 4.3. The experiment was conducted at a free space wavelength of 632.8 nm.

In this section, we present the results of the sensitivity to the incident polarisation of the sample described in Table 4.1 excited using the higher index prism.

Using a TM incident polarisation, the angle at which the plasmon-polariton resonant dip occurs (-9.5°) was determined and the goniometer was set to this angle. The helium-neon laser was then physically rotated and the reflected power was recorded for the various angles of incident polarisation. For this experiment, the polariser shown in the setup presented in Figure 4.5 was not used. The HeNe laser is linearly polarised with an extinction ratio greater than 500:1. The results of the experiment are presented in Figure 4.10.

The results show that a maximum in reflectance is observed for a 0° -TE incident polarisation, indicating that the plasmon-polariton mode is not excited by this polarisation state. The measured reflected power is seen to decrease for increasing angles of polarisation, reaching a minimum for a 90° -TM polarisation. For a TM polarisation, the reflectance power is not 0 but actually in the vicinity of 0.63. In fact, from Figure 4.6 (b), we note that the plasmon-polariton reflectance dip observed at an angle of 3° does not go down to 0 but actually goes down to approximately 0.65, or essentially the same value as that observed in the polarisation sensitivity measurement.

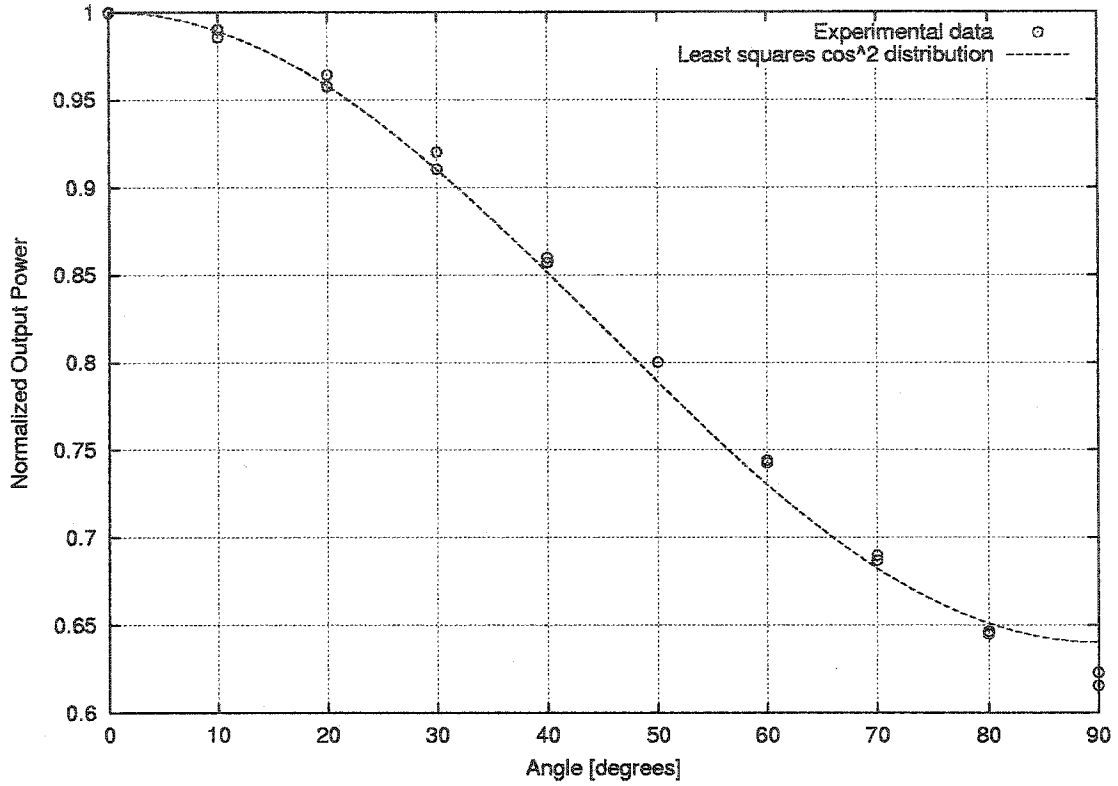


Figure 4.10.: Measured reflectance as a function of the incident angle of polarisation. A 0° angle corresponds to a TE incident polarisation whereas a 90° angle represents a TM polarisation. The experiment is conducted at a free space wavelength of 632.8 nm for the sample described in Table 4.1 using the 1.83957 index of refraction prism. The $\cos^2(\theta)$ curve corresponds to the least squares distribution for this data set and follows the equation $a \cdot \cos^2(\text{angle}) + b$, where $a = 1 - b$, and $b = 0.64032$.

We also see that the data presented in Figure 4.10 follows a $\cos^2(\theta)$ -type distribution in agreement with Malus' law [58]. This is in fact the type of curve that we would expect from our theoretical understanding of plasmon-polaritons. If only the TM component contributes to the excitation of the modes, then for any polarisation angle, the magnitude of the TM component of the E-field would be proportional to $\cos(\theta)$, and the resulting power would be that magnitude squared. Hence, we see that plasmon-polaritons propagating along a thin metal film infinite in width indeed support only transverse magnetic fields.

Part II.

Thin metal films finite in width

5. Passive optical metal wave guide structures

5.1. Summary of LIT9 and LIT11 mask designs

Following optical modal analysis suggesting the existence of lateral and vertical confinement of light by metallic wave guides [6, 7], various passive optical experimental structures such as straight wave guides, *S*-bends, *Y*-junctions, sharp bends and others were designed such as to enable us to first confirm and then characterise the plasmon-polariton mode supported by this structure. The structure of interest in this chapter is illustrated in Figure 5.1 and consists of a thin metal film characterised by a permittivity ϵ_1 , a width $w \sim 1 - 8 \mu\text{m}$ and a thickness $t \sim 20 \text{ nm}$, supported in a dielectric of permittivity ϵ_2 .

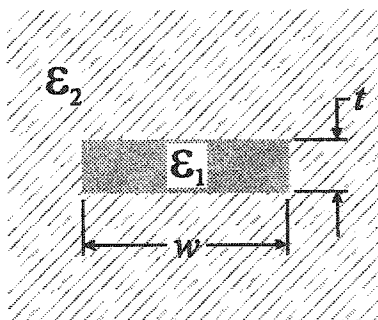


Figure 5.1.: Illustration of a thin metal film wave guide finite in width. The illustration is not to scale.

Two mask designs were completed and numerous structures were fabricated and tested. The first mask, identified from hereon as LIT9, was designed such as to verify experimentally the existence of plasmon-polariton modes propagating along a thin metal film finite in width.

A significant amount of time was devoted to attempting to optically couple the light

to the metal optical wave guide. For many weeks, futile attempts were made using a 632.8 nm wavelength, highly polarised collimated HeNe laser beam and focussing it on-axis of the wave guide using a microscope objective. The HeNe laser was selected since it emits in the visible spectrum, thus greatly facilitating the alignment of the setup. As it turns out, however, optical losses of a Au wave guide at a 632.8 nm wavelength are very large. We have seen from the simulation results presented in Table 3.4 that the attenuation of an infinitely wide Au metal film at a free space wavelength of 632.8 nm is 1003 dB/cm whereas the same structure will display an attenuation of 12.5 dB/cm at a free space wavelength of 1550 nm. No evidence suggesting the existence of a plasmon-polariton mode was observed at the HeNe wavelength.

Using the same metal wave guide, an attempt was made to excite the plasmon-polariton mode at 1550 nm via a polarisation maintaining (PM) fiber. Very shortly, evidence of optical mode confinement was observed using an infrared (IR) sensitive camera. After many weeks of fruitless work at the HeNe wavelength, we were very excited. Still, considerable effort was devoted to ensure that the metal optical wave guide structure indeed supported an optical mode. The results of the numerous measurements performed to verify the existence of plasmon-polariton waves supported by a thin metal film finite in width are compiled in this chapter.

The LIT9 mask was designed in order to experimentally verify the modal simulations indicating that waveguiding along a thin metal film finite in width was supported, and it served its purpose very well. Although there were many structures (straight wave guides, Y-junctions, S-bends) on the mask, they were found to be difficult to excite and to characterise. From the experiments performed of the LIT9 devices, it was found that the measured output power increased with an increase in the metal film width. This is contrary to simulations. In theory, as the width of the metal film decreases, an important reduction in attenuation should be observed and thus greater output power should be measured. The reason for this discrepancy was not fully understood, however, it was believed that the light exiting the input PM fiber did not couple as well to narrow wave guides than it did for wider ones due to less field overlap between the modes. In addition, the structures do not have enough SiO₂ and this impacts the narrow wave guides more than the wide ones due to confinement issues.

After having observed wave guiding in the structures designed with the LIT9 mask, much enthusiasm was generated and the design of a second mask was undertaken. The intent behind the design of the LIT11 was to fully characterise these passive structures using our better understanding of the propagation of the plasmon-polariton mode acquired from the first mask. In the design of the LIT11 mask, almost all structures were

designed such as to have an $8\text{ }\mu\text{m}$ wide metal film at the input and at the output such that the width of the metal film approximately matches the core diameter of the input and output fibers and thus reducing coupling losses. A taper is then used to reduce the width of the wave guide. The only structures that do not have the $8\text{ }\mu\text{m}$ input tapers are the ones made in a set of experiments to verify the optimum input and output widths.

The experiments performed on the LIT9 mask also indicated large insertion losses, and although some structures were designed to be 10 mm in length, the longest straight wave guide for which light was observed at the output was 6 mm in length. From the power measurements obtained using these structures, it was deemed risky to have any structure much longer than that. For this reason, the structures on mask LIT11 are all 7 mm, except a few which are 14 mm in length. Some reasons explaining the high insertion losses of these metal optical wave guides will be given subsequently, however, we now expect to be capable of measuring the output of structures in excess of 20 mm in length.

Finally, the LIT9 mask contained some *S*-bends of various widths and having a radius of curvature of 16.95 mm that were successfully excited. Thus, on the LIT11 mask, all curved structures had at least this radius or greater. This ensured that at least some of the structures would work. Today, from our measurements, we know that it is possible to design structures with smaller radii of curvatures without significant radiation losses.

The knowledge obtained from the LIT9 mask allowed us to design the LIT11 mask such as to enable us to characterise many passive structures. Successfully excited structures on the LIT11 layout include straight wave guides of various widths, *S*-bends, sharp bends, Y-junctions, couplers and mach-zenhders. The results of these characterisations are presented in this chapter.

5.2. Experimental setup

The very first metal optical wave guide structures excited were straight wave guides from the LIT9 mask. This mask contained a set of parallel wave guides of varying widths. The wave guides were 1 cm in length and had widths of 2, 3, 4, 5, 6, 7 and $8\text{ }\mu\text{m}$. At the begining, a considerable effort was devoted to excite these guides using a helium-neon (HeNe) laser having a wavelength of 632.8 nm. The setup used at the time is illustrated below in Figure 5.2.

The incident polarisation of the laser beam is TM due to the polarisation sensitivity of our guides. The laser used provided a beam already strongly polarised and collimated. A lens focusses the incident beam at the input of the wave guide. Another lens is focussed

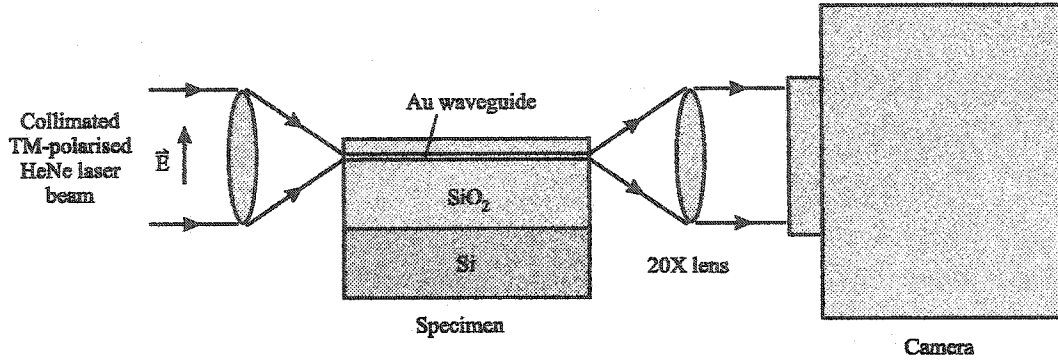


Figure 5.2.: First experimental setup used to excite thin metal film wave guides.

at the output of the wave guide and collimates the beam for the camera.

In principle, it should be possible to excite plasmon-polaritons on metal optical wave guides using this technique, however, no light was ever observed at the output. Calculations performed in parallel with these experiments estimate that the attenuation of a Au film 20 nm thick and infinitely wide are of the order of 1000 dB/cm (cf. Table 3.4) at the HeNe wavelength of 632.8 nm. Clearly, it is not surprising that no light output was ever seen.

Following the calculations presented in §3.3, a new setup using end-fire excitation and a longer operating wavelength was devised since simulations indicate that for a 20 nm thick Au film, the attenuation decreases at longer wavelengths. The setup illustrated in Figure 5.2 is more difficult to work with at infra-red wavelengths since the beam cannot be seen directly with the human eye, and a special IR sensitive card must constantly be used to determine the position and focus point of the beam. It is much more convenient if light from a fiber can be coupled into the wave guide using an end-fire technique.

A more practical approach is to use a fiber to excite these metal optical wave guides. Theory predicts low attenuation losses for Au wave guides in the 1550 μm communication wavelength band, and consequently, a new setup was devised to excite them. The idea of end-fire excitation from a fiber to a metal optical wave guide was promising for many reasons. First, by using a polarisation maintaining (PM) fiber, it is possible to provide a TM incident beam as required for these wave guides. Secondly, the mode field diameter of fibers in the communication wavelength band is approximately 8-9 μm , which is of the same order or equal to the width of the metal guides. Finally, the power distribution of a fiber is approximately Gaussian and closely resembles the power distribution around the metal guide. Thus, a fiber inherently provides strong mode overlap with the metal optical wave guides. A schematic of the setup used to observe the infra-red output of

our metal optical wave guides is illustrated in Figure 5.3.

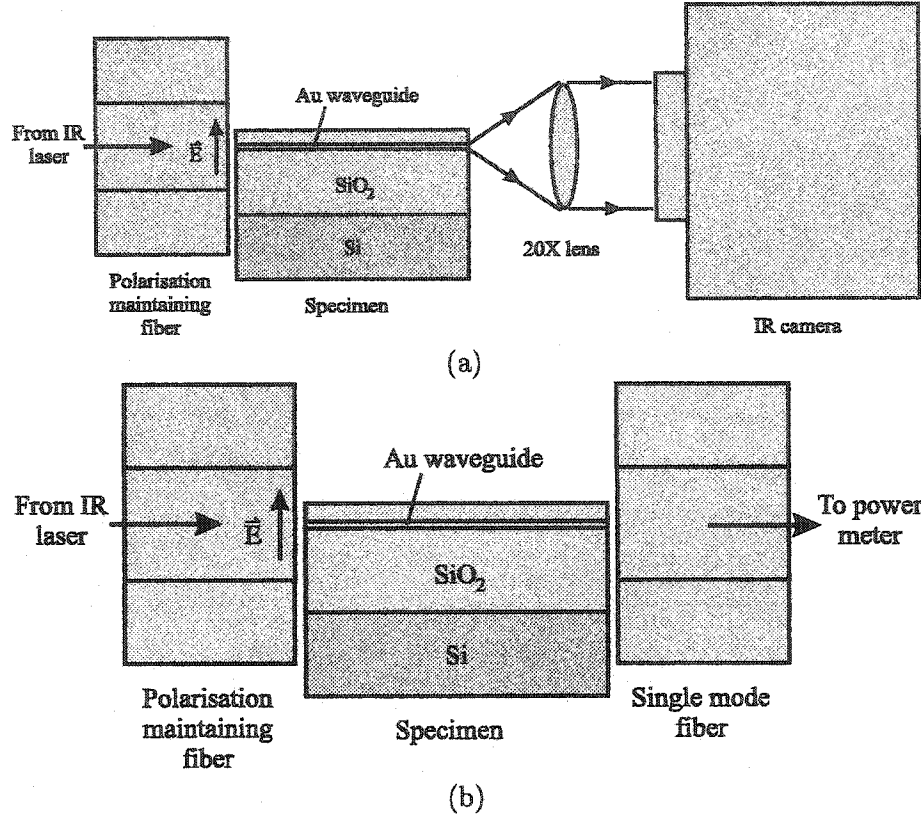


Figure 5.3.: (a) Experimental setup used to observe the IR output of optical wave guides.
(b) Experimental setup used for optical output power measurements.

The two setups illustrated in Figure 5.3 were used for all experimental results presented in this thesis. Newport 561-xyz positioners were used for the precise positioning of the input and output fibers. A Newport 561-yz positioner was used to support the sample. The input fiber is a PM fiber, always aligned such as to provide a TM incident polarisation, is connected directly to a highly-polarised semiconductor laser source emitting at a wavelength of 1550 nm. The output power is measured through a SM fiber connected directly to an Anritsu ML910B optical power meter with a Anritsu MA9305B optical power sensor. The setup was found to be very stable and the high quality actuators allowed for precise and repeatable measurements.

5.3. Device fabrication

From the masks LIT9 and LIT11, it was seen that the design of simple passive structures is relatively easy, although a simulation tool would be a great asset in this pursuit. Currently, a modelling tool for 3-D structures is unavailable, however, a modal modelling tool exists. Because we are unable to simulate propagation along 3-D structures, experiments were designed on the LIT9 and LIT11 masks in which one parameter is varied and as such enables the experimenter to characterise the metal optical wave guides. Perhaps the hardest part of the design is limiting the number of experiments to perform as one can easily get carried away. The fabrication of all the devices was done at the CRC.

The devices tested and for which the results are presented in this thesis were fabricated at the CRC during three fabrication runs. The samples were fabricated differently in each of these runs, however, in the text, it will always be clear which devices are used in any experiment. Presented below is a description of the fabrication process followed for each fabrication run.

Run A

A 7.62 cm diameter Si wafer with 5 μm of native thermal oxide SiO_2 is used. The layout is patterned for lift-off using mask LIT9. A thin 20 nm of layer of Au is evaporated on the patterned wafer. The photoresist is removed in a solution of HF. An additional 2 μm of SiO_2 is PECVD deposited to cover the Au.

Run B

A 7.62 cm diameter Si wafer with 5 μm of native thermal oxide SiO_2 is used, on which 2 μm of PECVD SiO_2 is deposited. The layout is patterned for lift-off using mask LIT11. A thin 20 nm of layer of Au is evaporated on the patterned wafer. The photoresist is removed in a solution of HF. An additional 2 μm of SiO_2 is PECVD deposited to cover the Au.

Run C

A 7.62 cm diameter Si wafer with 5 μm of native thermal oxide SiO_2 is used, on which 2 μm of PECVD SiO_2 is deposited. The layout is patterned for lift-off using mask LIT11. A thin 20 nm of layer of Au is evaporated on the patterned wafer. The photoresist is removed in a solution of HF. An additional 4 μm of SiO_2 is sputtered to cover the Au. The cover layer consists of two successive sputtering runs during which 2 μm of SiO_2 were

deposited in each run. The vacuum of the sputtering chamber was not broken during the two runs to ensure a greater homogeneity of the SiO_2 .

Simulations performed after the fabrication of the devices designed on the LIT11 mask indicate that the $2\text{ }\mu\text{m}$ cover of SiO_2 on top of the metal optical wave guide is insufficient (cf. §3.4.3). Ideally, the wave guide would be embedded in an infinite dielectric, however, in practice, it is difficult and expensive to deposit more than a few microns of dielectric. Simulations indicate that the finite dimensions of the surrounding dielectric result in a cut-off metal thickness and width for the propagation of the mode. Thus, the mode propagated in the samples available differs from the mode simulated in the ideal structure. The mode propagated by our samples is somewhat deformed and so the properties measured will differ from the results predicted by the theoretical model.

In order for the experiment to better approximate the infinite dielectric model, for most measurements, index matching oil was deposited on top of the samples¹. Depositing index matching oil was seen to have a profound effect in reducing the transmission losses. The measured power at the output of a 7 mm long metal optical wave guide having a cover of $2\text{ }\mu\text{m}$ of SiO_2 increases by approximately 15 dB when index matching oil is deposited on top of the sample. Devices having $4\text{ }\mu\text{m}$ of SiO_2 on top of the wave guide still had a 10 dB improvement in transmitted power when index matching oil was applied. In order to ensure that the addition of index matching oil on top of the sample did not lead to the propagation of slab modes within the oil layer, the output of the metal optical wave guides was always verified before and after each optical power measurement using an IR sensitive camera.

5.4. Characterisation of devices

5.4.1. Excitation of straight wave guide

The very first metal optical wave guide successfully excited was a 20 nm thick, $8\text{ }\mu\text{m}$ wide and 3.5 mm long Au wave guide excited at a free space wavelength of 1550 nm using a polarisation maintaining (PM) fiber with TM incident polarisation in an end-fire experiment. The sample (Run A) was fabricated by evaporating a 20 nm Au film on a 7.62 cm diameter $5\text{ }\mu\text{m}$ SiO_2 on Si wafer. The $5\text{ }\mu\text{m}$ native oxide layer was formed by standard thermal oxidation techniques. The Au was patterned using standard lift-off techniques along with mask LIT9 to form wave guides. The wave guides were covered

¹ In order to fully characterise the properties of metal optical waveguides, it would be necessary to obtain samples fabricated with a thick ($\sim 20\text{ }\mu\text{m}$) SiO_2 substrate and cover. The use of optical index matching oil is far from being optimal and representative of the true abilities of this technology.

with 2 μm of PECVD SiO_2 . The infrared output of this wave guide is presented in Figure 5.4.

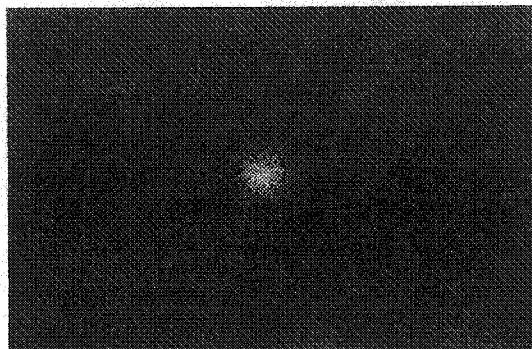


Figure 5.4.: Infrared output of a 20 nm thick, 8 μm wide and 3.5 mm long Au wave guide excited at a free space wavelength of 1550 nm using a polarisation maintaining fiber with TM incident polarisation in an end-fire experiment.

Figure 5.4, obtained using the setup presented in Figure 5.3(a), shows a circularly-symmetric spot indicating lateral and vertical confinement of the light. When observing the IR output of an optical wave guide in such a manner, the experimentalist must make sure that the wave guide is properly excited and that the lens is focussed at the output of the wave guide and not on the input fiber. A simple procedure to verify that this is indeed the case is to move the position of the input fiber laterally and vertically by a small distance such that light from the input fiber no longer couples to the wave guide. If the lens is focussed at the output of the wave guide, the circularly-symmetric spot should disappear. If, however, the lens is focussed on the input fiber, the intensity and the shape of the spot will not be affected. We indeed observed that small vertical and lateral displacements resulted in the disappearance of the spot, indicating proper excitation of the metal optical wave guides.

The analysis of the image presented in Figure 5.4 can reveal the power distribution of the mode supported by a 20 nm thick, 8 μm wide Au film. This analysis was performed using imaging software from Scion Corporation and is presented in Figure 5.5. We see that the mode power distribution appears gaussian in shape.

We may compare the beam profile presented in Figure 5.5 to one expected from the output of a single mode fiber. In Figure 5.6, we present the intensity distribution at the output of a Corning SMF-28 fiber. Comparing Figure 5.5 and Figure 5.6, we note that both intensity distributions are very similar in shape, suggesting that a good mode overlap is achievable by end-fire excitation of the finite width metal waveguides using an optical fiber.

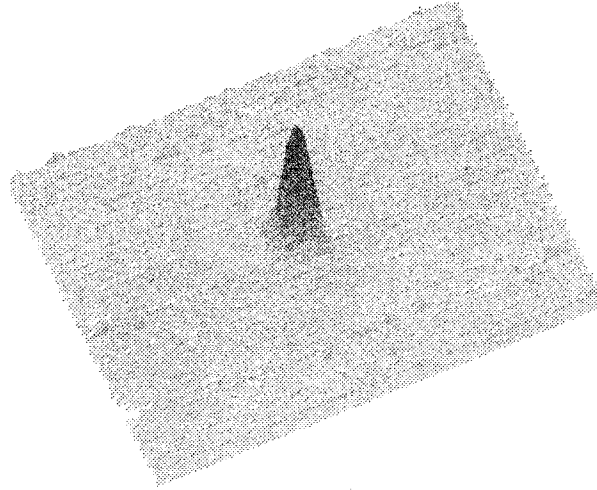


Figure 5.5.: Intensity distribution obtained from the analysis of the infrared image presented in Figure 5.4. The analysis was performed using imaging software from Scion Corporation (www.scioncorp.com).

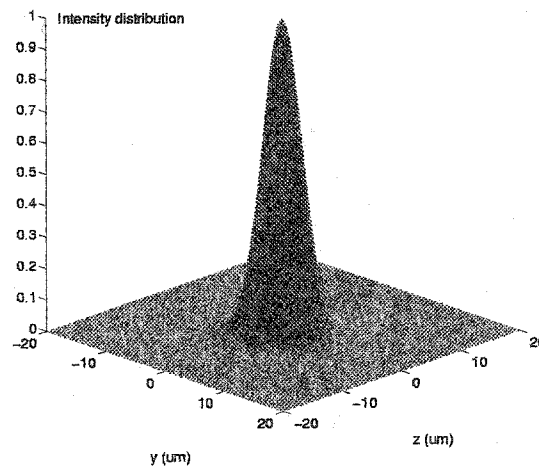


Figure 5.6.: Simulated intensity distribution of a Corning SMF-28 fiber. The simulation was performed using Matlab code obtained from P. Berini.

Qualitative and quantitative investigation of wave guides of various widths on samples fabricated using mask LIT9 were performed. The experimental results showed higher measured optical output power for the wider metal optical wave guides. This is in contradiction with results of optical modal analysis presented in Ref. [7]. We believed that the lower optical output power of narrow metal optical wave guide was the result of

smaller mode overlap between the input PM fiber and the narrow guides. Since the core of the fiber is approximately $8\text{ }\mu\text{m}$ in diameter, tapers were devised and implemented on all structures designed for mask LIT11 such as to improve coupling between the input and output fibers and the metal optical wave guide. An illustration of the taper implemented on mask LIT11 is presented in Figure 5.7. The tapers are designed to be $200\text{ }\mu\text{m}$ in length such that the change in width of the metal optical wave guide occurs over an electrically long propagation distance.

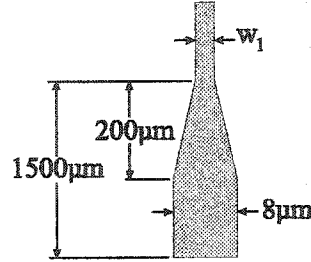


Figure 5.7.: Illustration of the taper implemented in the design of all structures on mask LIT11.

Experiments on straight wave guides designed with tapers and fabricated using the LIT11 mask were performed, however, the results showed once again a higher optical output power for the wider metal optical wave guides. We suspected that a thicker supporting layer of SiO_2 was required above and below the metal wave guides. Since we were not capable of fabricating samples with thicker SiO_2 , drops of index matching oil were deposited on top of the samples, thus increasing the effective thickness of the SiO_2 cover layer. Significantly lower attenuation was experimentally observed for samples covered with index matching oil, and straight, narrow wave guides did indeed demonstrate lower attenuation as predicted by optical modal analysis [7] for samples covered with index matching oil. In the next sections, results will be presented for measurements performed on samples with and without index matching oil.

5.4.2. Effect of polarisation on a straight wave guide

In §2.1, we have seen that only the TM component of the surface plasmon-polaritons are supported along a thin, infinitely wide metal film. For a guide finite in width, all six electromagnetic field components are present, however, the E_z component is the strongest for a guide characterised by an aspect ratio $\frac{w}{t} > 1$ (w is the width of the metal film and t is its thickness). This is the case for all of the wave guides fabricated thus far since the width ranges from $2\text{ }\mu\text{m}$ up to $8\text{ }\mu\text{m}$ and the thickness is always 20 nm .

In theory, a metal optical wave guide having a square cross-section (aspect ratio of $\frac{w}{t} = 1$) or a circular cross-section would have no polarisation dependence. In practice, however, it is not clear how one would go about fabricating a circular cross-section guide having a diameter of 20 nm, or even a square guide having an equal width and thickness of 20 nm. In our case, since $\frac{w}{t} \gg 1$, we expect the polarisation dependence of finite width guides to be similar to a slab guide.

A qualitative and quantitative investigation of the polarisation dependence was performed using a straight Au wave guide 8 μm wide, 20 nm thick and 3.5 mm long, supported by a native 5 μm thermal oxide SiO_2 on Si substrate and covered by a 2 μm thick SiO_2 cover. No index matching oil was used during this experiment. The end-fire excitation technique was used with a PM fiber to excite the wave guide. The fiber was physically rotated in a gimbal mount in order to vary the angle of incident polarisation. For the qualitative investigation, a lens was focussed at the output of the wave guide and the IR image was captured for various incident polarisation angles. For the quantitative experiment, the same fiber was used to excite the plasmon-polaritons, and the power was measured by capturing the light output using a SM fiber in close proximity to the output of the wave guide, and recording the light intensity using an optical power meter. Both experiments confirmed the polarisation sensitivity of the finite width wave guides. In Figure 5.8, we see a sequence of images presenting the IR output of this straight Au metal optical wave guide, in which the polarisation sensitivity of the metal guides is clearly demonstrated.

In Figure 5.8, we observe a well defined circularly-symmetric spot for an incidence angle of 0° representing a TM polarisation. As the angle of incident polarisation is varied from TM to TE, the plasmon-polariton mode profile is not well matched by the incident beam and as a result, the wave guide is not properly excited. Light, in this case, propagates in the dielectric in what appears to be slab modes. The slab guiding along the sides of the wave guide is asymmetric for the simple reason that there are other metal optical wave guides to one side and parallel to the wave guide under investigation.

When the polarisation angle of incidence is 90° , corresponding to a TE polarisation, the plasmon-polariton mode is not supported. It was mentioned previously that in order to excite a wave guiding structure, it is necessary to have a strong mode overlap between the incident beam and the mode supported by the structure. When the angle of polarisation is 90° (TE), for this width of metal guide, there is very little mode overlap and the plasmon-polariton mode is not excited. When a 0° -TM polarisation is launched along the wave guide, a stronger mode overlap is present and the plasmon-polariton mode supported by the wave guide is excited.

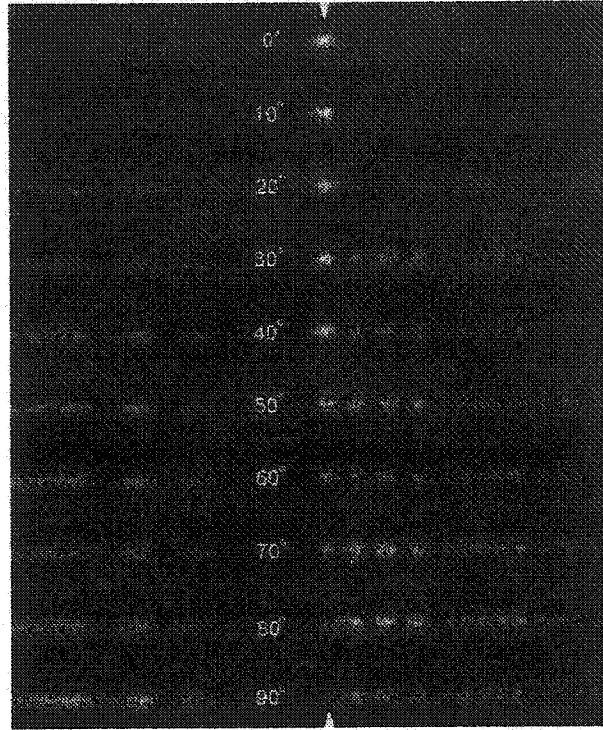


Figure 5.8.: Sequence of images illustrating the polarisation sensitivity of an $8\text{ }\mu\text{m}$ wide, 20 nm thick and 3.5 mm long Au wave guide embedded in SiO_2 . A 0° angle corresponds to a TM incident polarisation whereas a 90° angle corresponds to a TE incident polarisation.

A quantitative investigation of the effect of polarisation on the measured output power was undertaken and the results are presented in Figure 5.9. These results are once again for the 3.5 mm long Au metal guide described previously. The experiment was performed by initially setting the incident polarisation to 0° or TM. A SM fiber was used to capture the light at the output of the wave guide. Its position was set at the beginning of the experiment such that the optical output power was maximised, and its position was never varied afterwards. The two sets of results presented in Figure 5.9 are for measurements performed in incremental steps of 10° and ranging from 0° to 90° , and then back to 0° .

The graph is seen to corroborate the qualitative results presented in Figure 5.8. For a 0° -TM incident polarisation, we observe a maximum in the transmitted power indicating that for this polarisation angle, the best mode overlap and beam coupling are achieved. As the polarisation is changed from TM to TE, we note a significant decrease in the normalised transmitted power. For this metal optical wave guide geometry, the

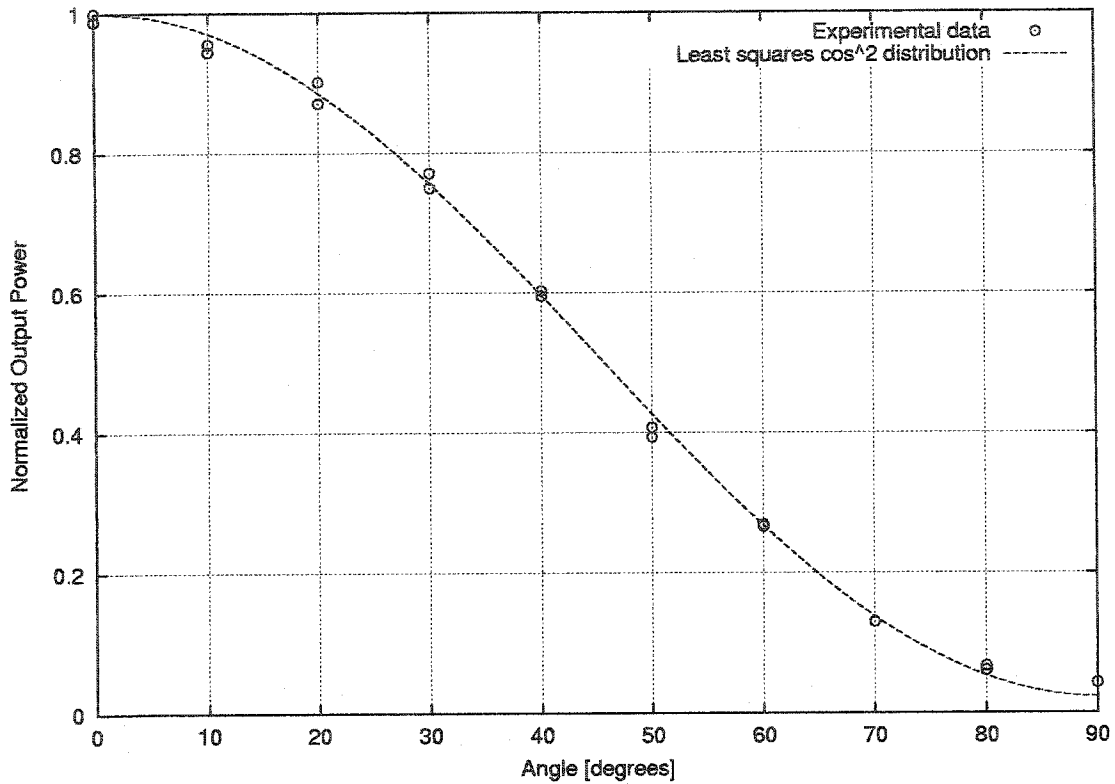


Figure 5.9.: Effect of a variation in the incident polarisation on the normalised measured output power for an 8 μm wide, 20 nm thick and 3.5 mm long Au wave guide embedded in SiO_2 . A 0° angle corresponds to a TM incident polarisation whereas a 90° angle corresponds to a TE incident polarisation. The $\cos^2(\theta)$ curve corresponds to the least squares distribution for this data set and follows the equation $a \cdot \cos^2(\text{angle}) + b$, where $a = 1 - b$, and $b = 0.02348$.

excitation of the plasmon-polaritons is a result mainly of the E_z field component and the E_y field component is seen to contribute very little. Once again, we note that the curve follows a $\cos^2(\theta)$ in agreement with Malus' law [58]. This structure is experimentally seen to favour the propagation of a TM mode.

5.4.3. Unit length loss measurements for wave guides of various widths

Description of common measurement methods for the determination of attenuation per unit length

One of the most important parameters of any wave guiding medium is the attenuation per unit length. A wave guide, to be of interest, must be characterised by low losses. This

is particularly true today as many different material and fabrication processes are used to produce optical wave guides with low values of measured attenuation.

Measurements of unit length attenuation in integrated optics wave guides is not a trivial task and much care and attention is required to ensure that the results obtained are truly representative of the losses. Many techniques are commonly employed to determine with a fair degree of precision the attenuation of the optical wave guide. The cut-back method is perhaps the simplest to use. It consists of taking a series of optical output power measurements of the wave guide, for various lengths of the structure. The wave guide is successively cut to ever shorter lengths and the optical output power is measured for each length. By plotting the measured output power for various lengths of the wave guide, it is possible to obtain the unit length loss simply by calculating the slope of the curve, and the coupling loss is obtained by determining the y -axis intercept. This technique is commonly employed to determine the attenuation of fibers, however, it is more difficult to apply to integrated optics. First, wave guides used in integrated optics are very short, of the order of a few centimetres, and as such are difficult to cleave to precise lengths. This is not a problem for fibers since the lengths of fibers used for these measurements are typically long and fibers are easily cleaved using commercially available cleavers. Secondly, the precision of the measurement is affected to a fair degree by the fact that the output cleave of the sample is different for each measurement and the alignment of the input and output coupling fibers must be redone for each measurement. Finally, the cut-back method is destructive such that in order to complete a set of measurements, the sample must be destroyed.

Another method makes use of two prisms in order to measure the propagation losses of a wave guide. This method is commonly used for planar wave guides fabricated close to the surface of dielectric. The first prism is used to excite the wave guide. A laser is aligned at an angle such that the parallel propagation constant in the prism equals the propagation constant of the wave guide as in an ATR setup. When this occurs, power couples to the wave guide. The second prism collects the light at a certain distance from the input. By recording the output power as the second prism is displaced along the length of the wave guide, it is possible to determine the unit length attenuation of the optical guide. This method is very practical and allows one to take loss measurements very rapidly. Some commercial systems are specifically designed to make such measurements in a few minutes. Unfortunately, the two-prism approach to attenuation measurement does not lend itself to all wave guides. First, it is necessary that the wave guide be relatively close to the upper surface of the dielectric, which is not the case for metal optical wave guide technology. In fact, for metal optical wave guides to operate properly,

a thick layer of cover is required. Secondly, the refractive index of the prisms required in the experiment must be higher than that of the dielectric. Although this is not a problem in our case since we use a low refractive index dielectric, in some circumstances such as for Si wave guides, this prevents one from using this approach.

A third technique that is commonly used and considered to be more accurate than the single-pass approaches presented previously is the Fabry-Pérot resonance method. This technique makes use of resonant and antiresonant transmission coefficients to determine the single-pass loss [59]. A wave guide with nice cleaves at the input and at the output is required. By varying the temperature of the sample over a small range, typically by about 10°C, many resonant and antiresonant cycles will be observed, from which the resonant and antiresonant transmission coefficients may be extracted. Although this method is considered one of the most accurate, it requires very good cleaves. Any angle in the cleave with respect to the wave guide must be accounted for in the calculations. In addition, this method relies on the fact that light will propagate many times along the wave guide and so this method is usually used for low-loss wave guides.

The approach devised in our case is two-fold. First, we determine the unit length loss for a given width of metalisation through cut-back measurements and then use this information to determine the unit length attenuation for other wave guide widths using specially designed experiments. These experiments were designed assuming that the attenuation of an 8 μm wide metal optical wave guide is known.

Although only the attenuation of the 8 μm is necessary, the LIT9 and LIT11 masks have many sets of parallel wave guides of various widths designed such as to allow cut-back measurements for widths of 1², 2, 3, 4, 5, 6, 7 and 8 μm . Wave guides of these widths were placed along side each other and allow rapid measurements to be performed. The cut-back method was not actually used in these experiments. Instead, the optical output power of wave guides on different samples of various lengths was recorded. This is simpler than actually cleaving the same sample repeatedly, however, it assumes that the input and output coupling conditions are constant. As in all experiments, the input and output cleaves for all sample lengths measured were verified under a powerful optical microscope to ensure that they were of good and consistent quality.

²The 1 μm wide waveguide is only present on the LIT11 mask

Attenuation measurements on Au wave guides of various widths from samples patterned using mask LIT9

Measurements for various widths were taken for the first samples fabricated using the LIT9 mask in the manner described below. A sample of a certain length is selected and the end facets are inspected under a powerful optical microscope. The sample is then placed on a yz positionner and the input and output fibers are visually aligned such as to be parallel to the wave guide. Although there is a risk of observing a periodic fluctuation in power due to the Fabry-Pérot effect when the input and output fibers are parallel to the wave guide and when the fiber and device cleaves are not angled, such an effect was not observed. A drop of index matching oil is deposited on top of the sample. For this experiment, index matching oil was present between the input PM-fiber and the sample and between the output SM-fiber and the sample. The PM input fiber is then positionned such as to excite the plasmon-polariton mode supported by the wave guide, and a 20X microscope objective is placed such as to focus the output of the wave guide onto an infra-red sensitive CCD camera. The position of the input fiber is then adjusted such as to maximise the brightness of the spot at the output of the wave guide. Then, the objective is replaced with a SM-fiber and the position of the input and output fibers is adjusted to maximise the optical output power. This power is recorded. The output SM-fiber is replaced by the 20X microscope objective and the output of the wave guide is observed once more to ensure that the wave guide is still properly excited after having adjusted the position of the input fiber. The position of the input fiber is changed such that a different guide is excited and the measurement procedure is repeated. Once the measurements are complete, the sample is removed, cleaned and replaced by a sample of different length.

The results of optical output power measurements for wave guides of various widths and lengths are presented in Figure 5.10. These samples (Run A) were fabricated by evaporating 20 nm of Au directly on the 5 μm native thermal oxide SiO_2 on Si layer. The Au was patterned using standard lift-off techniques and the wave guides were covered by 2 μm of PECVD SiO_2 .

From Figure 5.10, we may obtain a lot of information regarding these structures; the slope provides the attenuation per unit length and the intercept is equal to the combined input and output coupling losses. These results are tabulated in Table 5.1. From this table, we note an appreciable reduction on the measured attenuation as the width of the wave guide is reduced, as predicted by optical modal analysis, however, the measured attenuation values are higher than predicted [38]. There are many reasons that may explain this discrepancy.

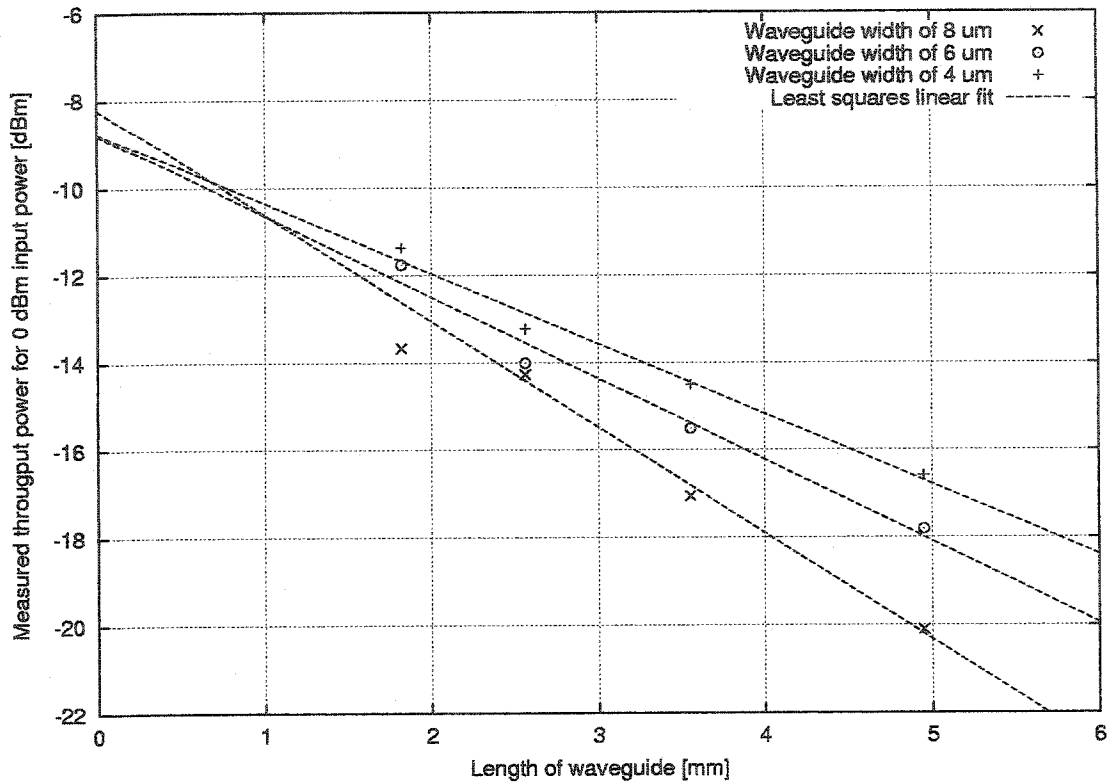


Figure 5.10.: Measured optical output power of wave guides of various widths for LIT9 samples of different lengths†. Drops of index matching oil were deposited on top of the samples, and index matching oil was placed between the input and output fibers and the sample to reduce coupling losses.

†The least squares linear fit was determined from all experimental data points in the case of the 4 μm and 6 μm wide metal optical wave guides, and in the case of the 8 μm wide metal optical wave guide, only the data points corresponding to structure lengths of 2.56, 3.55 and 4.95 mm were used.

First, the thickness of the SiO_2 substrate is only 5 μm , much less than we desire. In addition, the cover consists of only 2 μm of PECVD SiO_2 and a few drops of index matching oil. The optical modal analysis assumes that the Au wave guide is surrounded by an infinite medium of SiO_2 [38]. Because of the thin substrate and cover, and due to the large refractive index of Si on which the devices are constructed and the low index of refraction of air above the sample, the mode field is not symmetrically distributed above and below the metal (cf. Figure 3.16).

Secondly, the losses are very dependant on the thickness of the metal film, however, in practice it is difficult to obtain a uniform film 20 nm in thickness. It is possible that the thickness of the film varies over the length of the wave guide. It is also difficult to control accurately the thickness of such a thin film during the evaporation process and

the average thickness of the film may actually vary by ± 10 % or more [60].

Thirdly, the theoretical model assumes a perfect metal–dielectric interface, however, it is possible that there is a roughness associated with the surface of the metal. This would result in the scattering of the electromagnetic wave propagating along the interface and would increase the losses.

Finally, the simulation assumes a lossless dielectric. Due to the fabrication process, SiO_2 is known to have an OH absorption peak close to the $1.548 \mu\text{m}$ wavelength used in these experiments. In order to ensure that the OH-bond is not present, an annealing step would be required.

Wave guide width [μm]	Measured attenuation per unit length [dB/cm]	Theoretical attenuation per unit length [dB/cm]	Total coupling loss [dB]†
4	14	4 [38]	8.8
6	16	N/A	8.8
8	24	10 [38]	8.2

Table 5.1.: LIT9 attenuation and coupling loss measurements of wave guides of various widths. Theoretical values are for a 20 nm thick Au film supported in an SiO_2 medium.

†The least squares linear fit and total coupling loss were determined from all experimental data points in the case of the $4 \mu\text{m}$ and $6 \mu\text{m}$ wide metal optical wave guides, and in the case of the $8 \mu\text{m}$ wide metal optical wave guide, only the data points corresponding to structure lengths of 2.56, 3.55 and 4.95 mm were used.

Attenuation measurements of an $8 \mu\text{m}$ wide Au wave guide embedded in thicker dielectric and patterned using mask LIT11

A second cut-back measurement experiment was later undertaken using different samples. The new samples were fabricated with thicker layers of dielectric and using a variation of the process (Run C). First, $2 \mu\text{m}$ of SiO_2 were PECVD deposited on the native $5 \mu\text{m}$ thermal oxide SiO_2 on silicon. A 20 nm layer of Au was evaporated and patterned using a standard lift-off technique. Finally, the Au was covered with a total of $4 \mu\text{m}$ of sputtered SiO_2 to form the cover. The cover layer consists of two successive sputtering runs during which $2 \mu\text{m}$ of SiO_2 were deposited in each run. The vacuum of the sputtering chamber was not broken during the two runs to ensure a greater homogeneity of the SiO_2 .

Attenuation measurements were performed only on $8 \mu\text{m}$ wide straight wave guides in the manner described below. A sample of a certain length is selected and the end facets are inspected under a powerful optical microscope. The sample is then placed on a yz positioner and the input and output fibers are aligned such as to be parallel to the

wave guide. The TM polarised PM input fiber is then positionned such as to excite the plasmon-polaritons mode supported by the wave guide, and a 20X microscope objective is placed such as to focus the output of the wave guide onto an infra-red sensitive CCD camera. The position of the input fiber is then adjusted to maximise the brightness of the spot at the output of the wave guide. The objective is then replaced with a SM-fiber and the position of the input and output fibers is adjusted to maximise the optical output power. This power is recorded. A drop of index matching oil is deposited on top of the sample, the input and output fibers are adjusted again to maximise the optical output power and the power is recorded once more. The output SM-fiber is replaced by the 20X microscope objective and the output of the wave guide is observed once more to ensure that the wave guide is still properly excited after having adjusted the position of the input fiber. The sample is removed, cleaned and replaced with a sample of different length.

Although one might first think that it should not be necessary to readjust the position of the fibers after the deposition of the drop of index matching oil, a minor readjustment proved to increase the throughput optical power by 0.5–0.7 dB. For this experiment, the index matching oil was not in contact with the input and output fibers; the oil was simply spread on top of the sample. The reason, we suspect, for the requirement to adjust the position of the input and output fibers is that the once the index matching oil is deposited on the sample, the mode power is allowed to spread further inside the cover layer and the oil. Thus, if we wish to maximise the mode overlap of our samples once they are covered by a layer of index matching oil, it is necessary to heighten the position of the input and output fibers.

Optical output power measurements were performed on three samples of different lengths in order to obtain the graph presented in Figure 5.11. This graph presents two sets of data: one set recorded without index matching oil on top of the sample and the other set recorded once the index matching oil was deposited. Unfortunately, only three samples of different lengths were available for the measurements. Clearly, a greater number of samples would have been desirable and would result in more conclusive measurements. We immediately note a significant increase in transmitted power, or equivalently, a decrease in the attenuation when the index matching oil covers the sample. Clearly, the thicker the top dielectric, the lower the transmission losses.

A discrete least-squares approximation was applied on the data gathered in order to determine the slope and intercept of the curves and thus determine the attenuation per unit length and the input and output coupling losses, respectively. These results are presented Table 5.2. We note once more the significant reduction in attenuation per unit

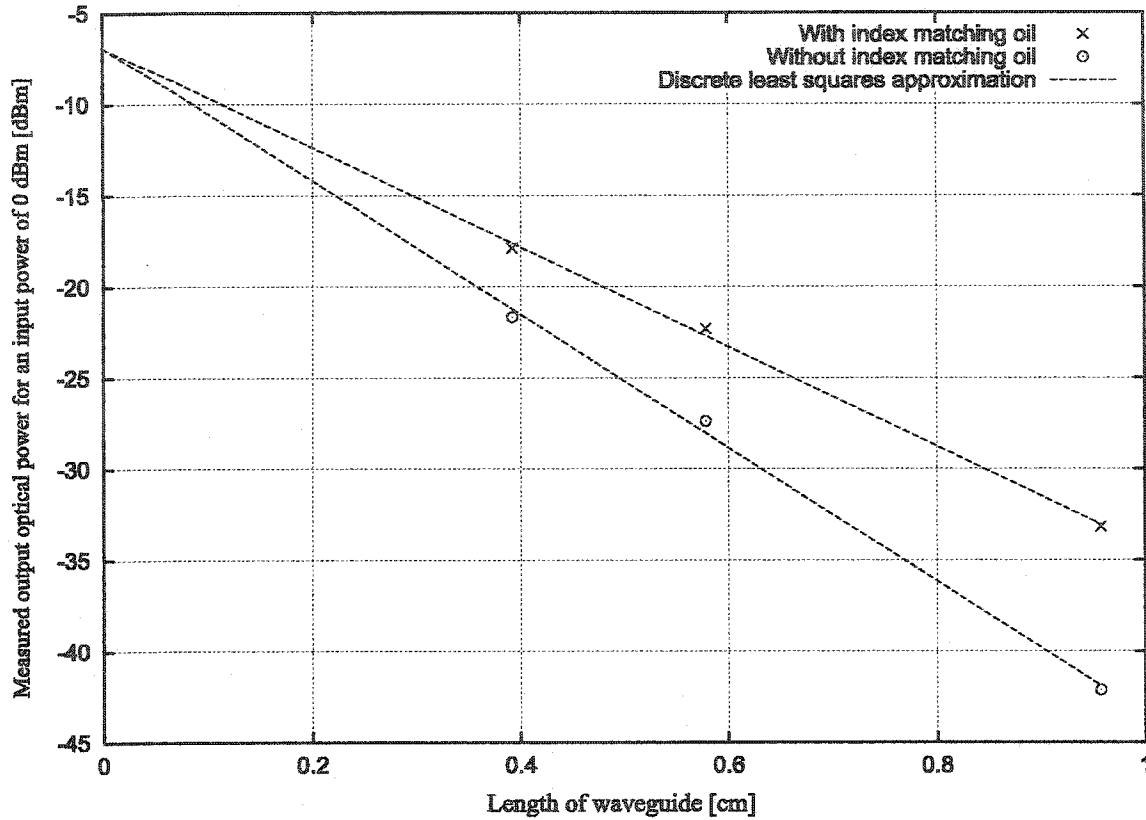


Figure 5.11.: Transmission measurements on three different samples of various lengths for an 8 μm wide, 20 nm thick Au wave guide.

length for a sample covered with index matching oil. The measured attenuation value of 27.3 dB/cm for the sample covered with index matching oil and is greater than the one of 24 dB/cm presented in Table 5.1.

Description of the experiment (with or without index matching oil)	Measured attenuation [dB/cm]	Input and output coupling losses [dB]
No index matching oil	36.6	6.9
Sample covered with index matching oil	27.3	6.9

Table 5.2.: Attenuation loss measurements and coupling measurements of an 8 μm wide, 20 nm thick Au wave guide with and without index matching oil.

It was expected that having a thicker substrate and a thicker cover would reduce the attenuation per unit length, however, this was not observed. Although the exact reasons for this discrepancy are not fully understood, certain hypotheses may be put forward. First, the quality of the metal optical wave guides does not appear to be of the same

as the ones obtained in previous fabrication runs. Small pin-holes were present along the length of the wave guides, and one wave guide was partially damaged. Since the Au has been consistently and successfully evaporated for many samples, we suspect that the damage to the wave guides occurred during the SiO₂ sputtering process, where SiO₂ molecules bombard the specimen. Since plasmon-polaritons propagate at the metal-dielectric interface, a poorer quality of metalisation would result in higher unit length attenuation.

A second point that is noteworthy and which may explain the higher than expected attenuation stems from the fact that the cover consists of sputtered SiO₂ whereas the substrate is fabricated from PECVD and thermal oxide SiO₂. The sputtered SiO₂ may not be as homogeneous as the PECVD deposited SiO₂, and may potentially be grainy. This would not only change the index of refraction of the cover, but might also allow the index matching oil covering the sample to diffuse through the cover and change their optical properties via chemical reaction. Clearly, in order to better compare the effect of the cover thickness on the attenuation of straight metal optical wave guides, it would have been preferable to compare samples fabricated using the same techniques. When this project was initiated, however, the CRC could PECVD deposit at most 2 μm of SiO₂. Through process development, the CRC later devised a method to sputter up to 4 μm of SiO₂ to form the cover of our samples.

In an unrelated experiment, a different sample from this fabrication run was positioned in preparation for a demonstration and covered with index matching oil. The output of the wave guide was observed using an IR-sensitive camera and presented a nice, circularly-symmetric spot. The setup was left overnight and the next morning, significant slab guiding was noted when the output of the wave guide was once more viewed using the IR camera. A full investigation of the causes of this slab guiding was not undertaken, however, the process was seen to be reversible by cleaning the sample using isopropanol alcohol, suggesting that a soaking process was responsible for the effect observed.

Finally, for the sample fabricated using the LIT9 mask, the Au was evaporated directly on the thermal oxide SiO₂ whereas in the case of the LIT11 mask, it was always deposited on the 2 μm PECVD deposited SiO₂. As a result, it is possible that the surface of the thermal oxide SiO₂ is smoother than the PECVD deposited SiO₂, thus reducing scattering losses at the metal-dielectric interface.

In order to fully characterise the attenuation per unit length of metallic wave guides, it would be necessary to obtain samples fabricated with a thick (~ 20 μm) SiO₂ substrate and cover. The use of optical index matching oil is far from being optimal and

representative of the true abilities of this technology.

It is worthwhile to point out that the input and output coupling loss presented in Table 5.2 are lower than the ones presented in Table 5.1. The lower coupling losses, we suspect, results from better mode overlap between the input and output fibers and the metal optical wave guides due to the thicker dielectric. We have seen, in Figure 3.16, that the mode profile of the plasmon-polariton wave propagating along a thin metal film infinite in width is significantly altered by the finite thickness of the dielectric (cf. Figure 3.7). As the thickness of the dielectric supporting the metal film increases (cf. Figure 3.18), the mode profile evolves into the one supported by infinitely thick dielectric.

Determination of the attenuation per unit length of a 4 μm wide, 20 nm thick Au wave guide

In order to rapidly determine the attenuation per unit length of various widths of wave guides, we used our understanding of these metal optical wave guides obtained through simulation to design a series of experiments. Optical modal analysis indicate that the attenuation of plasmon-polariton wave guides varies significantly as a function of the width of the metal strip [38]. The experiment consists of a series of measurements in which the total length of a set of wave guides is constant but on which the length of sections of different widths of the wave guides is changed. The experiment is illustrated in Figure 5.12.

The unknown parameters in this experiment are the input and output coupling losses and the unit length losses of section of metal guides of widths w_1 and w_2 . These parameters will affect the slope and the intercept of the curve. The results of one such set of measurements is illustrated in Figure 5.13. In this particular experiment, the input and output width is 8 μm whereas the width of the middle section is 4 μm .

We may do simple calculations in order to better understand how the various physical parameters of these wave guides are reflected in the graph. Assuming equal input and output coupling and a lossless, reflectionless taper region, we may write the following equation to describe the power transmission in [dB]:

$$P_{out} = P_{inc} - 2P_{cpt} - P_{att1} - P_{att2} \quad (5.1)$$

where:

- P_{out} : measured optical output power
- P_{inc} : incident optical power

- P_{cpl} : coupling loss at one facet
 P_{att1} : total attenuation for the section of wave guide of width w_1
 P_{att2} : total attenuation for the section of wave guide of width w_2

Let l_t be the total length of the wave guide, l_1 the length of the wave guide of width w_1 , and α_{P1} and α_{P2} the unit length power attenuation coefficient in [dB/cm]³ of wave guides of width w_1 and w_2 , respectively. Then we may rewrite the equation as:

$$P_{out} = P_{inc} - 2P_{cpl} - \alpha_{P1}l_1 - \alpha_{P2}(l_t - l_1) \quad (5.2)$$

or equivalently:

$$P_{out} = \underbrace{(\alpha_{P2} - \alpha_{P1})l_1}_{\text{slope}} + \underbrace{P_{inc} - 2P_{cpl} - \alpha_{P2}l_t}_{\text{intercept}} \quad (5.3)$$

We see from equation 5.3 that the slope obtained from a series of measurements as presented in Figure 5.13 represents the difference between the unit length attenuation of wave guides of width w_2 and of width w_1 . If we can determine α_2 using a series of cut-back measurements of a wave guide of width w_2 , say, then in principle it is possible to determine the unit length attenuation of wave guides of other widths. The series of experiments designed on the LIT11 mask are such that if we know the unit length attenuation of an 8 μm wide wave guide, then it is possible to determine the unit-length attenuation for wave guide widths of 1, 2, 3, 4, 5, 6 and 7 μm . From the intercept it is possible to determine the coupling losses.

For the graph presented in Figure 5.13, we used the least-squares algorithm to determine the best line fit. From this fit, it is possible to extract the slope and the intercept. We find a slope of 13.1 dB/cm, representing the difference in the unit length attenuation α_2 of an 8 μm wide guide and the unit length attenuation α_1 of a 4 μm wide wave guide. The intercept is found to be -23.3 dBm. From theoretical calculations presented in Table 5.1, we would expect the difference in attenuation to be of the order of 6 dB, however, the observed value is more than twice that amount. One possible explanation is that the losses per unit length are higher in practice than predicted by theory. If this is the case, then a reduction in the metal guide width would result in a greater variation in the unit length losses, as we have observed. We must remember that the guides fabricated

³ Do not confuse the unit length power attenuation coefficients α_{P1} and α_{P2} , given in [dB/cm], with α , the electromagnetic field unit length attenuation given in [Np/m] and defined in §2.1.1 as part of the propagation constant $k_z = \beta - j\alpha$.

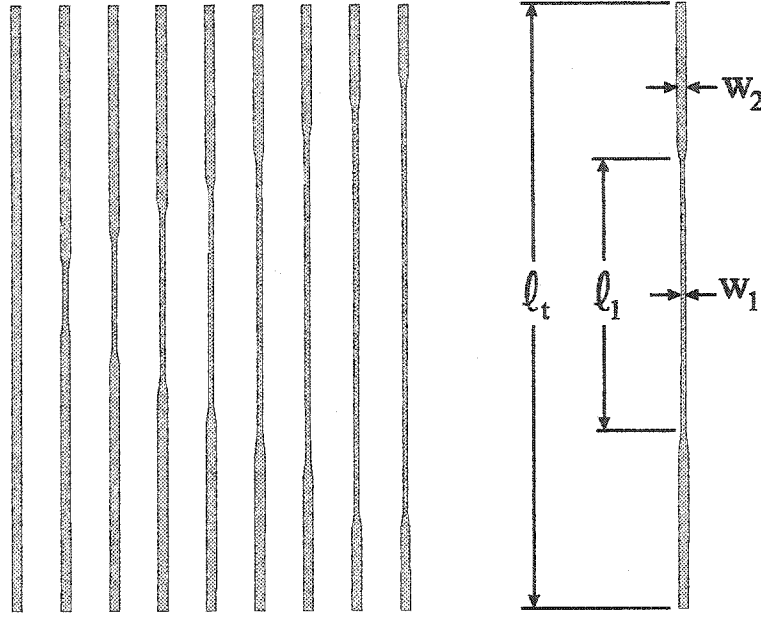


Figure 5.12.: Illustration of an experiment to determine the attenuation per unit length of a metal optical wave guide of width w_1 .

differ substantially from the ones used in the simulation in terms of the thickness of the dielectric layers. The index matching oil added on top of the sample definitely helps reduce the losses, however, a sample with an SiO_2 substrate and cover many wavelengths thick would be required to more accurately determine the model's ability to predict unit length losses.

Another reason that may explain the higher than expected difference between the unit length losses of an $8\text{ }\mu\text{m}$ wide guide and a $4\text{ }\mu\text{m}$ wide guide is if the metal wave guides are thicker than expected. All the guides fabricated are supposed to be 20 nm thick, however, it is relatively difficult to evaporate such a thin layer of Au to an accurate thickness. If the guides are 25 nm thick, then a 9 dB/cm slope would be observed.

5.4.4. Excitation of *S*-bends

S-bends are important optical structures to characterise for many reasons. First, in integrated optics, they are often the building blocks of more complex components such as *Y*-junctions and couplers. Secondly, they provide insight into the confinement offered by the wave guiding structures. As the light follows the *S*-bend, a certain portion of the optical power will be radiated depending on the confinement provided by the wave guide. In order to design components, it is imperative to be able to determine the amount

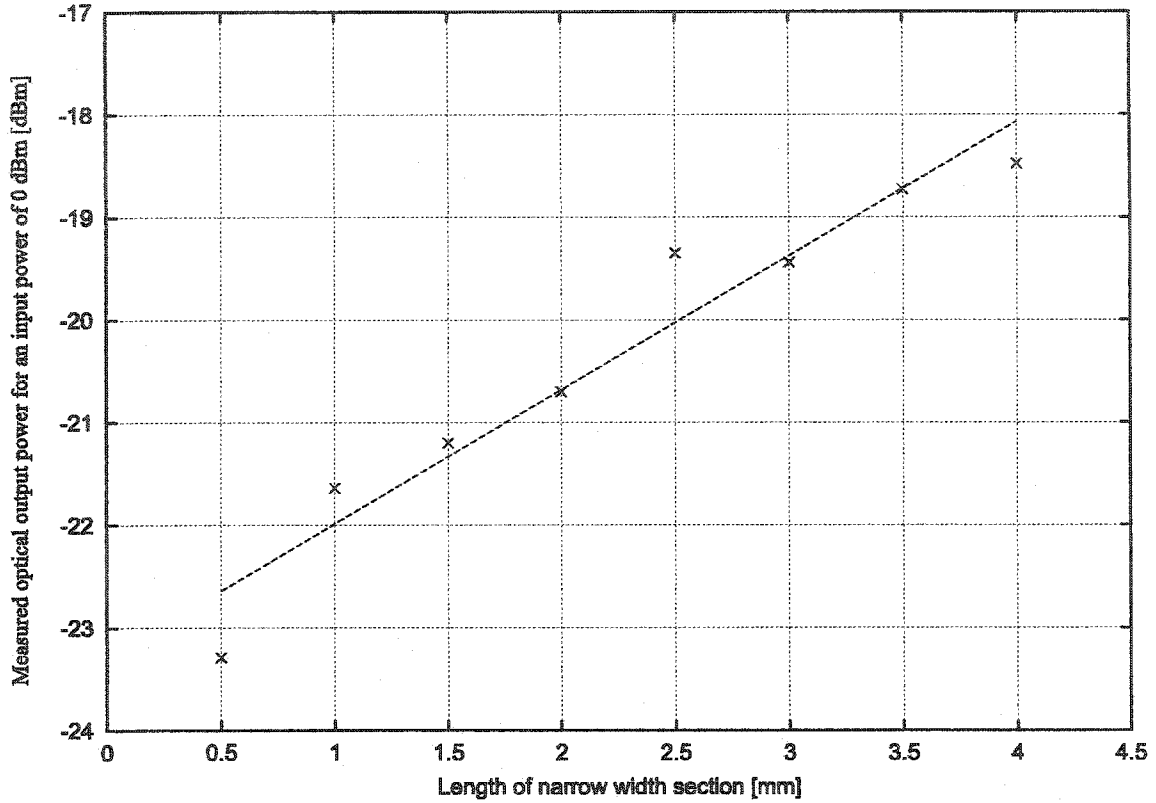


Figure 5.13.: Transmission measurements of $4\ \mu\text{m}$ wide wave guides of varying lengths with $8\ \mu\text{m}$ input and output tapers, and of total length of 7 mm. The experiment was performed on a sample having a $5+2\ \mu\text{m}$ SiO_2 substrate and a $2\ \mu\text{m}$ SiO_2 cover, covered with index matching oil.

of radiated power for a given bend radius such that the bend radius selected results in tolerable losses. Experiments were designed such as to provide this valuable information for metal optical wave guides of different widths. A series of *S*-bends of various radii and for wave guide widths of $2\ \mu\text{m}$, $4\ \mu\text{m}$ and $8\ \mu\text{m}$ were placed next to each other. Measurements of the optical output power were performed only on $8\ \mu\text{m}$ *S*-bends since it was found that narrower wave guides require thicker supporting dielectrics.

An illustration similar to the *S*-bend experiment is presented in Figure 5.14. On this illustration, we see *S*-bends of various radii placed close to each other. In the experiment, *S*-bends were in groups of three. For a given group, the radius of curvature of the *S*-bends was the same, however, the width of the wave guide was varied to include widths of $2\ \mu\text{m}$, $4\ \mu\text{m}$ and $8\ \mu\text{m}$. The bent section of waveguide is 4 mm in length, and the radius of curvature is controlled by lateral offset between the input and output. In the case of the $2\ \mu\text{m}$ and $4\ \mu\text{m}$ wide *S*-bends, tapers $200\ \mu\text{m}$ in length, as shown in Figure 5.7, were

added to $8\text{ }\mu\text{m}$ wide, 1.3 mm long, straight sections at the input and output of the metal optical wave guide to ensure adequate coupling with the optical fibers.

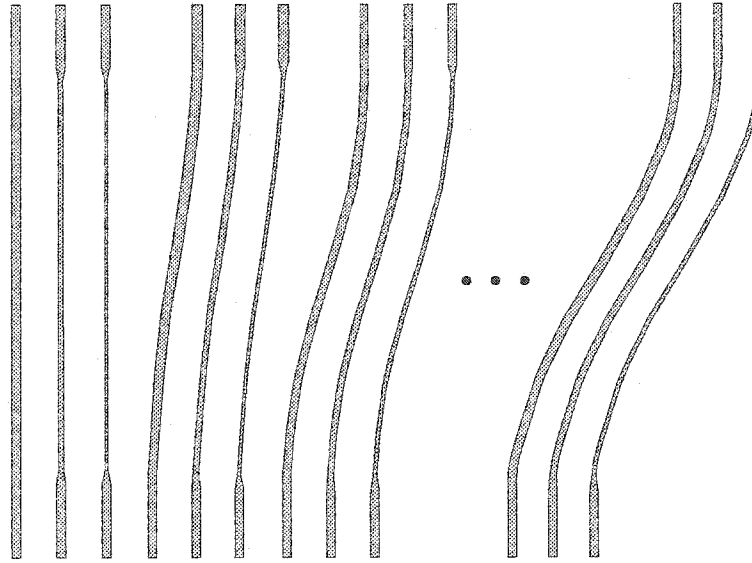


Figure 5.14.: Illustration presenting an *S*-bend experiment.

The results of the experiment for the series of $8\text{ }\mu\text{m}$ wide *S*-bend wave guides are shown in Figure 5.15. The graph presents the transmitted power for a given bend radius. The setup used for the experiment is pictured in Figure 5.3. A highly polarised 1550 nm semiconductor laser is used to excite the wave guide. The laser is connected to a polarisation maintaining (PM) fiber for which the the output is vertically polarised. The vertical polarisation ensures that the incident mode field overlaps as much as possible the field distribution supported by the metal optical wave guide. The input PM fiber is aligned as close as possible to the metal optical wave guide in order to couple as much light as possible to the wave guide. Once the light exits the wave guide, it is collected using a standard single-mode (SM) fiber. Adjustments are performed on the input and output fibers to maximise the optical output power. The power is recorded using an Anritsu power meter.

In Figure 5.15, we see two sets of data obtained for two different samples. Both samples have been fabricated by PECVD depositing $2\text{ }\mu\text{m}$ of SiO_2 on top of the $5\text{ }\mu\text{m}$ native oxide. Then, 20 nm thick Au wave guides are evaporated and patterned using a standard lift-off technique. On one sample (Run B), the Au was covered by depositing $2\text{ }\mu\text{m}$ of PECVD SiO_2 , and on the other sample (Run C), the Au was covered by sputtering twice $2\text{ }\mu\text{m}$ of SiO_2 , without breaking the vacuum, for a total cover thickness of $4\text{ }\mu\text{m}$. For

these experiments, no index matching oil was used.

We see in both cases that the transmitted power is approximately constant for radii in excess of 10 mm, and we note that the 3 dB point occurs for a radius of approximately 8 mm, for these *S*-bends. As the bend radius becomes smaller, the amount of radiated power was observed to increase significantly. In the case of the thicker cover, the measured optical output power was approximately and consistently 5 dB higher than in the case of the thinner cover, indicating lower transmission losses.

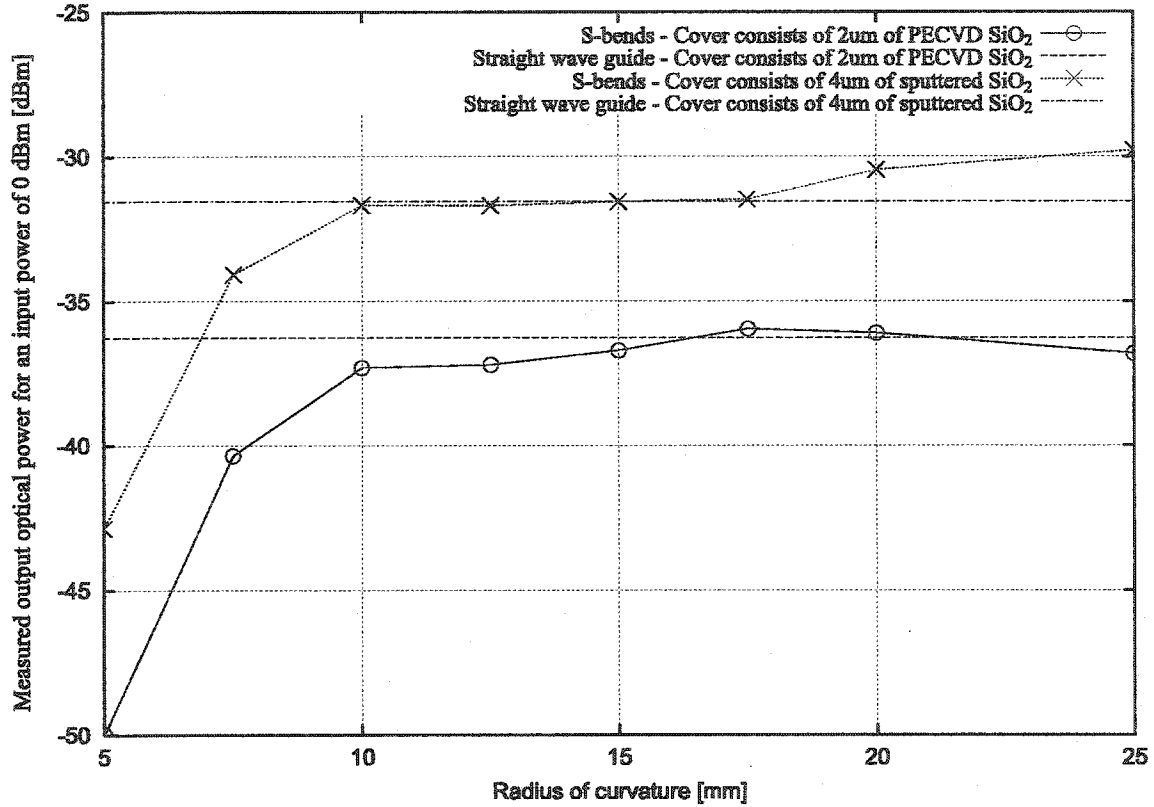


Figure 5.15.: Measured transmittance of 8 μm wide *S*-bend wave guides

The experiment described above using the sample having a 2 μm thick SiO₂ cover was repeated for the same sample on which we placed a piece of 7 μm thick SiO₂ on Si was placed, forming what we coined a flip-chip. A thin layer of index matching oil was spread between the cover of the sample and the additional piece of SiO₂ in order to eliminate air between the samples. The results of this experiment are presented below in Figure 5.16. The other curve presents the optical output power measurement for the same sample, when index matching oil only is deposited on top of the sample. The results from Figure 5.15 for the case of the 2 μm thick SiO₂ PECVD cover are added to the

graph for comparison.

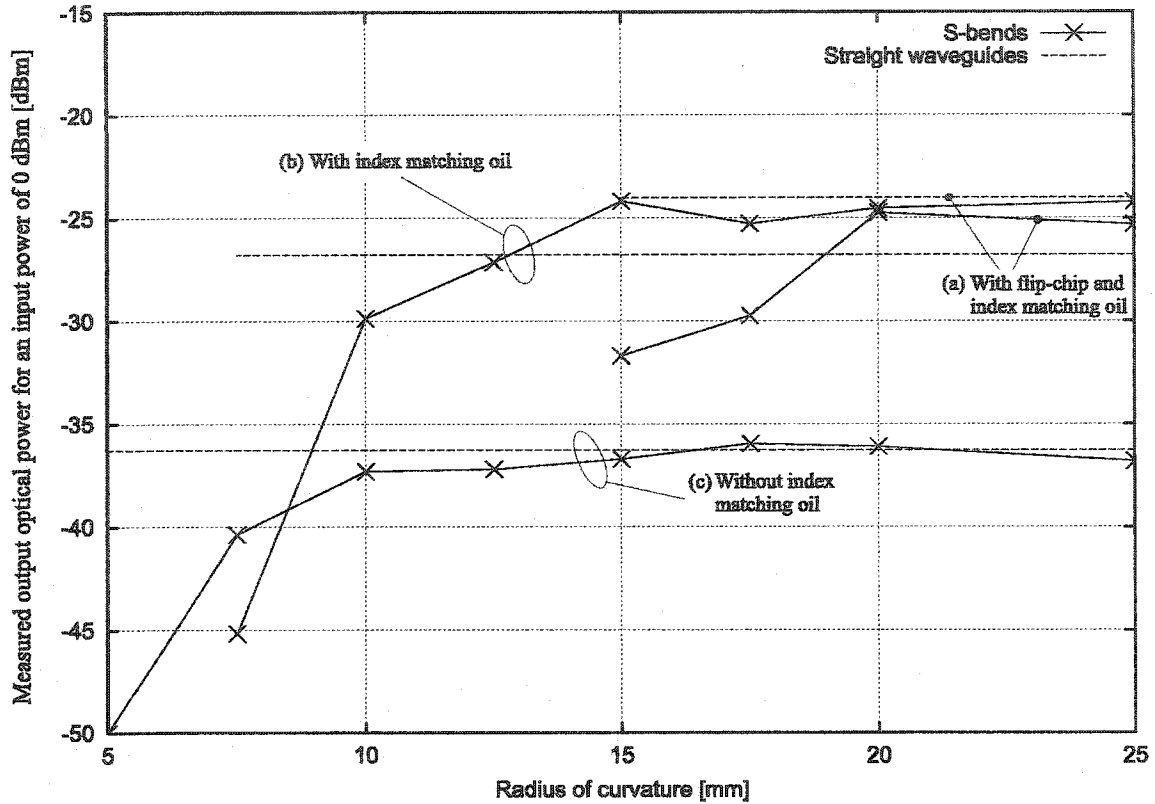


Figure 5.16.: Comparison between measured transmittance power of $8\ \mu\text{m}$ wide *S*-bend wave guides for samples with and without a flip-chip.

We note that the transmitted power has increased significantly by the increase of the thickness of the cover, in both the case where the flip-chip is used and in the case where simple index matching oil is used. This indicates a reduction in the attenuation of the mode propagating along the $8\ \mu\text{m}$ wide Au wave guide. We also note that the mode appears to be less strongly confined since the 3 dB point appears to be in the vicinity of 12.5 mm in the case of the flip-chip and 17 mm in the case of index matching oil only. It is possible that the thicker dielectric allows the mode to expand into the cover resulting in a less strongly confined mode.

5.4.5. Field confinement of sharp bends

While *S*-bends provide a means of redirecting power by gradually curving the wave guide, sharp bends change the direction of the propagation of the optical power by abruptly redirecting the wave guide. An example of the sharp bend experiment devised for these

devices is presented in Figure 5.17. In this experiment, the length of the structures is 7 mm, however, along the length are four sharp bends of equal angle that modify the direction of power flow. The angles chosen are wide ranging, varying from 0.5° to 15° . A straight wave guide is adjacent to these structures for comparison.

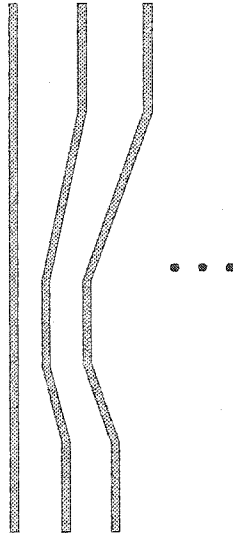


Figure 5.17.: Illustration of the sharp bend metal optical wave guide experiment on mask LIT11. The angles of the structures illustrated have been exaggerated for clarity, and are much larger than they are on the actual structures tested.

The sharp bends tested were fabricated by first PECVD depositing $2\text{ }\mu\text{m}$ of SiO_2 on the native $5\text{ }\mu\text{m}$ of thermal oxide SiO_2 on Si layer (Run B). Then, 20 nm of Au was evaporated and patterned using the LIT11 mask and standard lift-off technique. An additional $2\text{ }\mu\text{m}$ of SiO_2 was PECVD deposited to form the cover. In this experiment, no index matching oil was used.

In Figure 5.18, we present the measured radiative losses per degree for sharp bends for an $8\text{ }\mu\text{m}$ wide metal film. We were able to determine these losses by using the straight wave guide adjacent to these structures as a reference. This is reasonable since the path length difference between all structures is very small. The difference in transmitted optical power between the straight wave guide and one designed with sharp bend is entirely due, we assume, to radiative losses of the bends. Since these sharp bend wave guides have four bends, we divide the difference by four to obtain the radiative loss, per bend, for a given angle.

From Figure 5.18, we may get a better appreciation of the strength of lateral field confinement provided by an $8\text{ }\mu\text{m}$ wide metal optical wave guide. For instance, we note

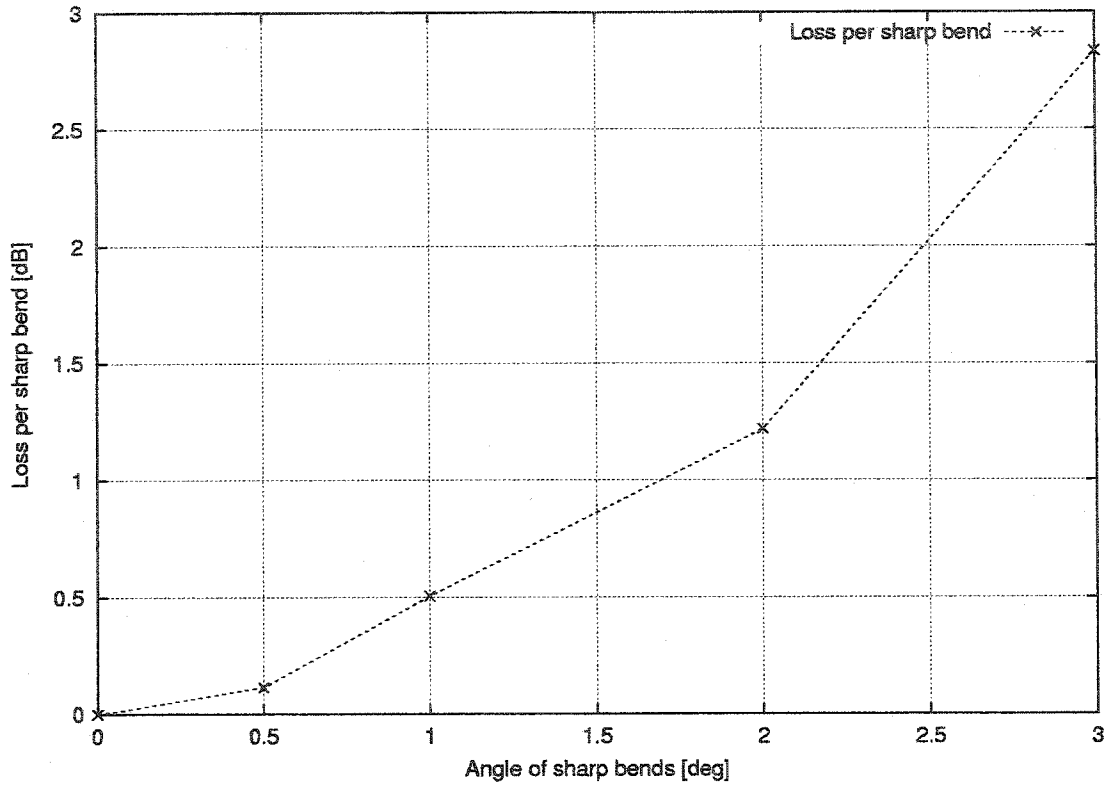


Figure 5.18.: Measured radiative losses per degree for sharp bends for an $8\text{ }\mu\text{m}$ wide metal film. The experiment was conducted at a free space wavelength of 1550 nm .

that for angles less than 1° , very little optical power is radiated per bend. When the angle of the bend becomes larger than 1° , however, the radiative losses per bend rapidly becomes significant.

It is possible to design Y -junctions by splitting the branches using sharp bends as the ones presented in this section. These results may be used as design guidelines for future design work.

5.4.6. Excitation of Y -junctions

A very interesting passive structure to investigate and characterise is the Y -junction. Although it is possible to design these structures in many ways, we have chosen to design ours by placing two mirror image S -bends as illustrated in Figure 5.19. The separation of the output branches is always $250\text{ }\mu\text{m}$, such that two fibers could be connected side by side to capture the output light.

In our design, no attempt was made to optimise the Y -junction, instead, we concerned

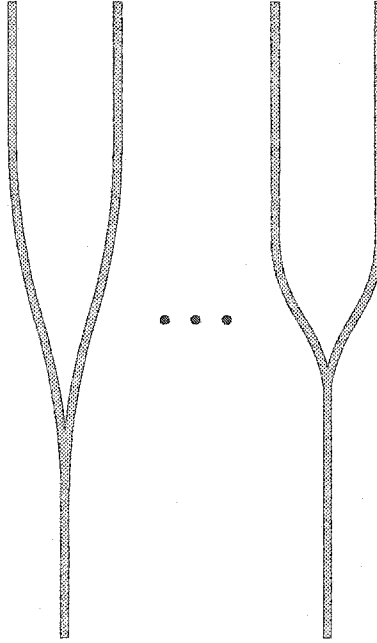


Figure 5.19.: Illustration presenting a Y-junction experiment.

ourselves with finding a radius of curvature that would provide little excess loss for this structure. In the literature, it is easy to find various implementations of Y-junctions, sometimes designed in a simple V-shape [61–63], sometimes having a wider input line resulting in multimode propagation over a short distance prior to the branch split, or other variants.

The Y-junctions tested were fabricated by first PECVD depositing $2\text{ }\mu\text{m}$ of SiO_2 on the native $5\text{ }\mu\text{m}$ of thermal oxide SiO_2 on Si layer (Run B). Then, 20 nm of Au was evaporated and patterned using the LIT11 mask and standard lift-off technique. An additional $2\text{ }\mu\text{m}$ of SiO_2 was PECVD deposited to form the cover. In this experiment, no index matching oil was used.

The experiment consists of optically exciting the plasmon-polaritons using a vertically polarised PM fiber in an end-fire experiment at a free space wavelength of 1550 nm . Various Y-junctions, $8\text{ }\mu\text{m}$ in width, were tested sequentially and the optical output power captured by a SM fiber was recorded. All the Y-junctions designed on mask LIT11 have a separation between the output branches of $250\text{ }\mu\text{m}$, such that it would be possible to pigtail two fibers side-by-side to capture the output power from the two branches. This separation also ensures that a fiber collecting the light from one output branch will not be picking up light from the output branch.

The division of power from the two output branches was found to vary somewhat

as a function of the lateral position of the input fiber. For this reason, the throughput power was maximised by adjusting the input fiber and output fiber positions, where the output fiber is placed such as to capture the light from the left branch (looking from the top) of the Y-junction. Once this measurement was taken, the input fiber was no longer displaced. The output fiber was then moved such as to record the optical power output of the right branch, and the optical output power was maximised by adjusting the position of only the output fiber. The experimental results, for the various radii of curvature tested, are presented graphically in Figure 5.20.

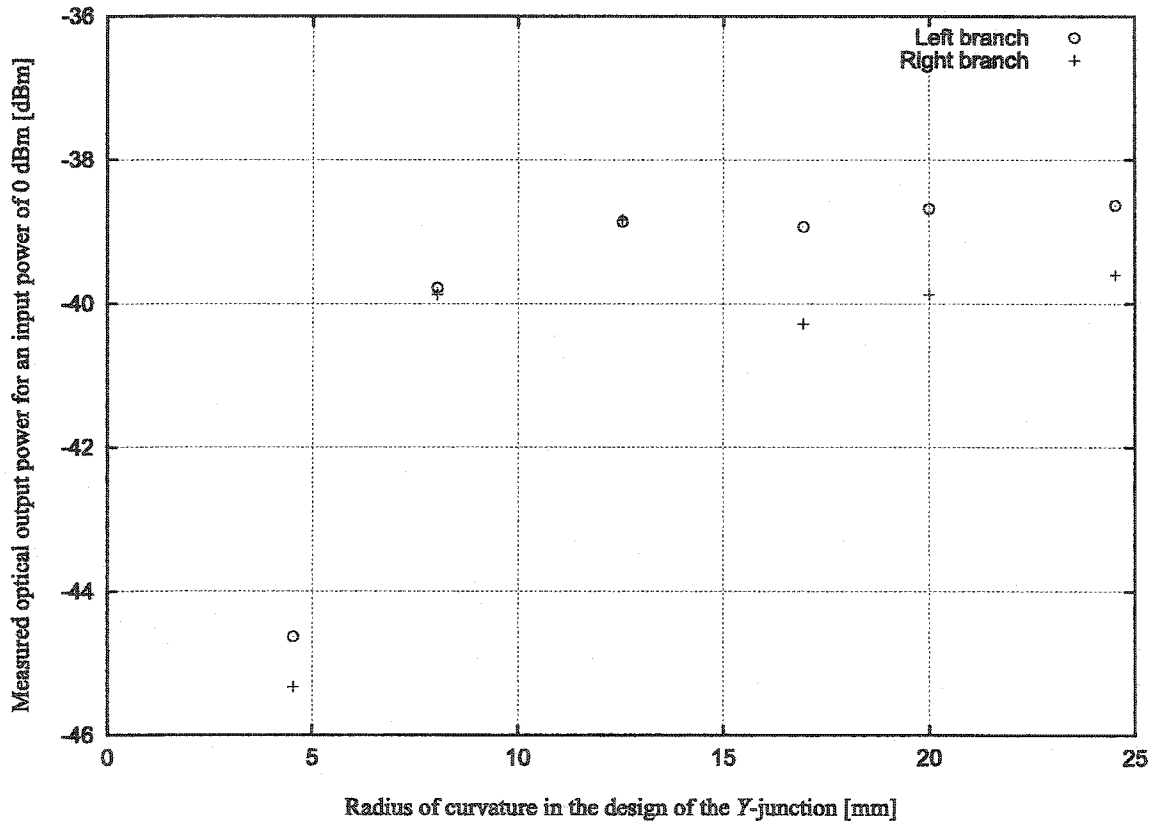


Figure 5.20.: Measured throughput power of Y-junctions for various radii of curvature of the branches. The Y-junction are fabricated of $8\ \mu\text{m}$, 20 nm thick Au lines. The experiment was conducted at a free space wavelength of 1550 nm.

From the results presented in Figure 5.20, we see that the measured output optical power is essentially the same for radii of curvature above 8 mm. The power drops for a radius of 8 mm, and a significant radiative loss is observed when the radius of curvature is 4.5 mm. The power at the output of the two branches is seen to be almost the same for small radii of curvatures whereas it differs by more than 1 dB in the case of the larger

radii. When the radius of curvature used in the design of these Y-junctions is larger, the two output branches slowly drift apart, resulting in an optically long section of wave guide for which the width of the metallisation increases from $8\text{ }\mu\text{m}$ to $16\text{ }\mu\text{m}$ before the branches split. In this section, it is possible that the wave guide supports multimode operation resulting in a greater sensitivity to the position of the input fiber. In the case of the smaller radii of curvature, the branches split rapidly such that the mode profile of the propagating plasmon-polariton may not evolve in a multimode field distribution, thus explaining the insensitivity of these structures to the position of the input fiber. It should be noted, however, that optical modal analysis has not been performed yet on thin Au films $16\text{ }\mu\text{m}$ wide and 20 nm thick to verify the existence of higher order modes and to confirm this hypothesis.

In order to be sure that the Y-junctions were properly excited, the output of the structures was observed before and after every measurement. A sequence of IR output images presenting the output of the Y-junctions for the various radii of curvature is shown in Figure 5.21. The images were recorded after the measurements, such that the optical output power was maximised. The sequence of images illustrates in a qualitatively manner the results presented in Figure 5.20.

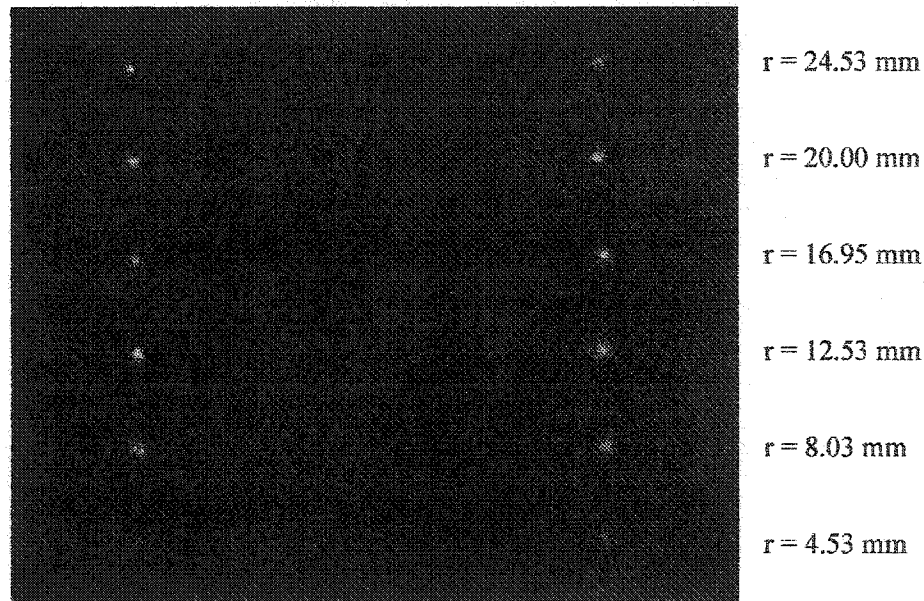


Figure 5.21.: Sequence of images showing the IR output of Y-junctions for decreasing radius of curvature.

We see from Figure 5.21 that the IR output are very similar in intensity for radii of curvature equal or greater than 8.03 mm . We observe an important decrease in the

optical output power for the radius of curvature of 4.53 mm. For all instances, however, we note that the power is relatively well divided between the two branches.

5.4.7. Excitation of couplers

Our analysis of various passive structures would not be complete without a characterisation of couplers. Couplers are important structures since they can divide the input power unequally between the through and coupled output ports. This allows one, for instance, to tap a small percentage of the power for monitoring or feedback purposes. An illustration showing metal couplers is presented in Figure 5.22.

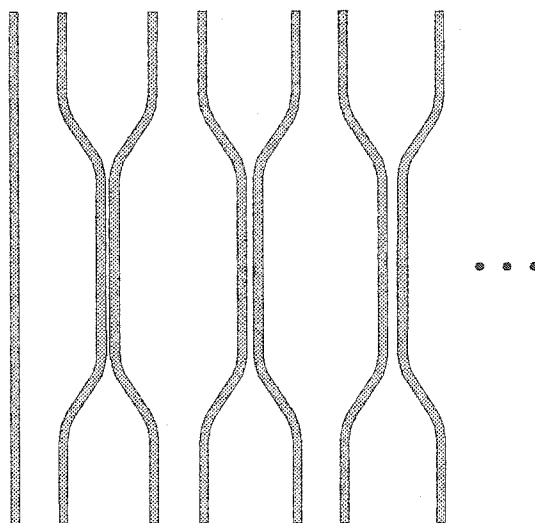


Figure 5.22.: Illustration of the coupler experiment on mask LIT11.

The design of the coupled section is defined by four parameters for a given wavelength: the coupling length, the separation between the parallel wave guides, the thickness of the wave guides and their widths. In the experiment designed on the LIT11 mask, the coupling length remained fixed while the separation was varied from $2\text{ }\mu\text{m}$ to $8\text{ }\mu\text{m}$ in increments of $1\text{ }\mu\text{m}$. In addition, four sets of such couplers were designed in which the width of the guides were 2 , 4 , 6 and $8\text{ }\mu\text{m}$ wide. For all couplers, the radius of curvature selected for the bends was 16.95 mm because this bend radius had been demonstrated to work on mask LIT9. Table 5.4 below summarizes the design parameters of the couplers. Unfortunately, it was found that the structures fabricated did not have a sufficiently thick cover and as a result, only the $8\text{ }\mu\text{m}$ wide wave guides were characterised. Qualitative measurements are compiled in Figure 5.23.

When experiments on couplers were undertaken, the importance of a thick SiO_2 cover

wave guide width [μm]	Coupling length [mm]	separation between wave guides [μm]
2	0.50	2, 3, 4, 5, 6, 7 and 8
4	1.15	
6	1.25	
8	1.50	

Table 5.4.: Design parameters of couplers on mask LIT11.

had not been fully appreciated and for this reason, only the $8\ \mu\text{m}$ wide coupling structures were studied. For this reason, more data exists for these structures than for the others. In fact, it was interesting to be able to compare qualitatively the power ratio of the various couplers designed with $8\ \mu\text{m}$ wide wave guides and fabricated with a $2\ \mu\text{m}$ SiO_2 PECVD cover (left of Figure 5.23) with the ones fabricated with $4\ \mu\text{m}$ of sputtered SiO_2 cover with a layer of index matching oil (right of Figure 5.23).

We note that for the $2\ \mu\text{m}$ PECVD cover that total coupling occurs for this structure when the separation between the parallel wave guide is about $3\ \mu\text{m}$ and an equal power split is observed for a separation of about $6\ \mu\text{m}$. In contrast, in the case of the $4\ \mu\text{m}$ cover thickness, we observe total coupling for a separation of $4\ \mu\text{m}$ and 3-dB coupling for guide separations of $7\ \mu\text{m}$ and approximately $2\ \mu\text{m}$. When the cover is thin, the air on top of the sample forces the propagating wave deeper inside the higher refractive index medium and the wave is more strongly confined. When a thick cover is present, the wave spreads further from the metal and thus it couples more easily to an adjacent wave guide. In our case, we note that in order to achieve total coupling, it is possible to use a larger guide separation when the cover is thick.

From the sequence of images presented in Figure 5.23, it is also possible to conclude that couplers fabricated using thin metal films are synchronous in nature. An asynchronous coupler can at most transfer 50% of the incident power to the coupled port whereas from the images it is clear that it is possible to obtain total coupling. Total power transfer from the input port to the coupled port is only possible in synchronous couplers.

A quantitative investigation of the couplers designed with $8\ \mu\text{m}$ wide wave guides and covered with $4\ \mu\text{m}$ of sputtered SiO_2 was undertaken. The couplers were excited through a PM fiber using a polarised semiconductor laser having a wavelength of $1550\ \text{nm}$. The transmitted power was collected using a SM fiber positioned at either the through or the coupled port. Index matching oil was used between the input and output fibers and the sample in order to reduce the coupling losses. For every measurement, the output of the excited coupler was observed using the IR camera and the position of the input fiber

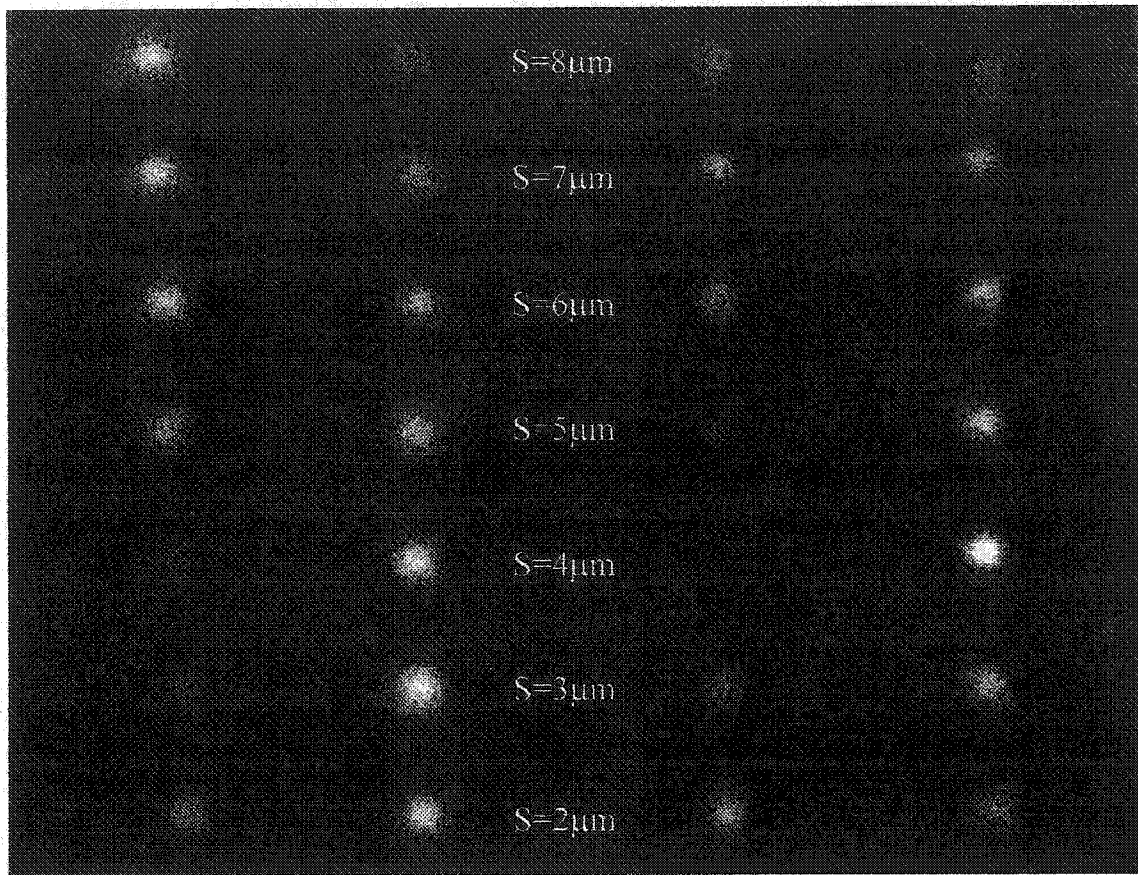


Figure 5.23.: IR output of couplers fabricated with $8\text{ }\mu\text{m}$ wide metal wave guides. The sequence of images on the left is for the couplers with no index matching oil and $2\text{ }\mu\text{m}$ of PECVD SiO_2 cover whereas on the right, index matching oil was deposited on top of the sample and $4\text{ }\mu\text{m}$ of sputtered SiO_2 covered the wave guides.

was optimised. Then, the output fiber was aligned with the output of the coupler having the highest optical output power. The measured power was maximised by adjusting the position of the output and input fibers. Once optimised, the measured power was recorded. The output fiber was then displaced and aligned with the other output of the coupler. Its position was adjusted in order to maximise the measured power and the power was recorded. The input fiber was not moved during this optimisation. The output of the coupler was then observed once again using the IR camera and a picture of the IR output was taken. These are the pictures forming the sequence of images presented in Figure 5.23. The measured transmitted power for the various wave guide separations are presented in Figure 5.24 below.

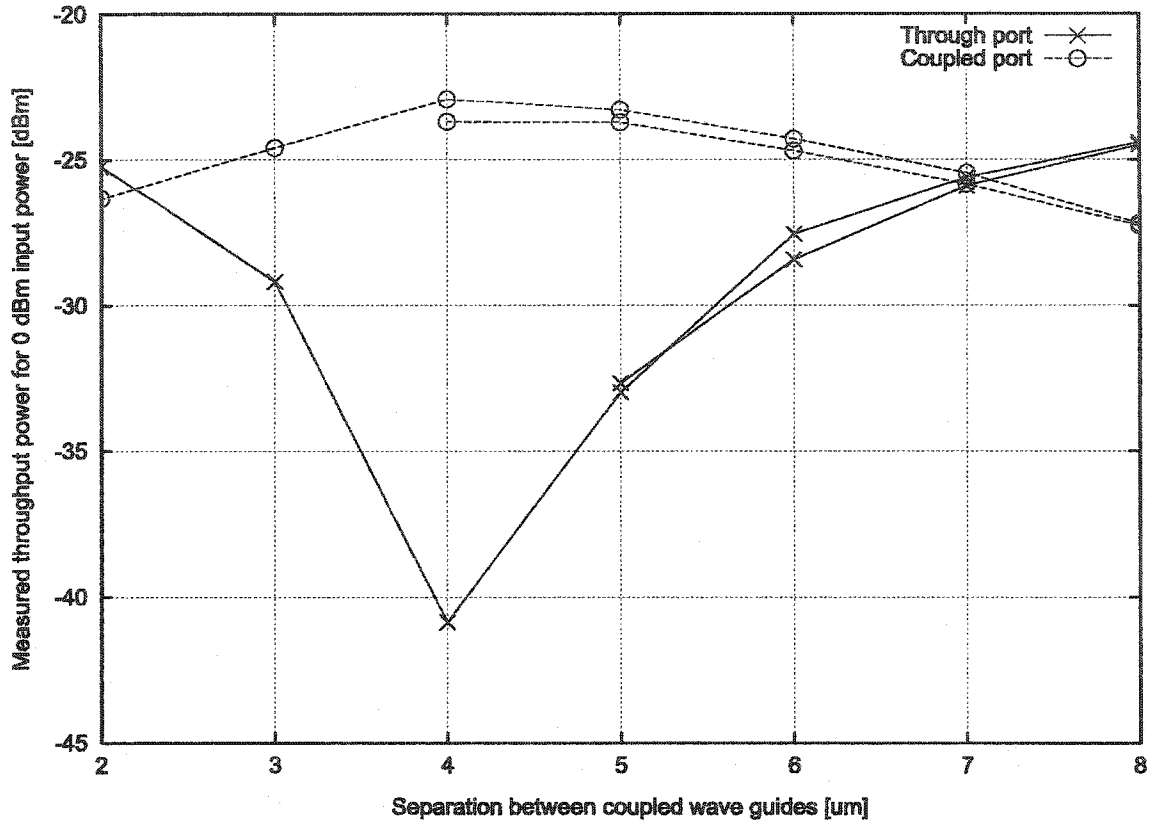


Figure 5.24.: Measured optical output power for a 0 dBm-1550 nm polarised incident beam as a function of wave guide separation for 8 μm wide thin metal film couplers having a coupling length of 1.5 mm.

The two sets of data in Figure 5.24 correspond to measurements taken on two different days between which the sample was cleaned. The good agreement between these sets of data indicates good repeatability of the measurements even when index matching oil is used on top of the sample. We see that, as was presented in the sequence of images, total coupling occurs for a guide separation of 4 μm whereas an equal power split is observed for separations of 2.2 μm and 7 μm .

5.4.8. Excitation of a Mach-Zenhder

The mach-zenhder (MZ) interferometer is a key structure in today's optics industry as it is commonly used in the design of high speed electro-optic modulators. Modulation is obtained by varying slightly the optical properties of one arm of the MZ in order to obtain a phase difference where the two arms recombine. By doing so, total constructive or destructive interference can be made to occur thus modulating the intensity of the

light. The intent of the LIT11 mask is not to design a modulator, however, before such a design is undertaken, it is important to verify that the basic building block operates properly.

Two MZs were designed on the mask: one with both arms of equal lengths thus providing constructive interference, the other with arms unequal in length such that the signals from both arms recombine destructively. For the MZ with arms unequal in length, the effective index of refraction of the mode supported by an $8\text{ }\mu\text{m}$ wide, 20 nm thick Au wave guide embedded in SiO_2 was used to determine the required path length difference between the two arms such that total destructive interference occurs.

The output power of the two MZ were not measured; the output were simply observed and recorded with the IR camera. This still enables us to conclude that the light from the two arms of the MZ recombine properly. Figure 5.25 presents the IR output of a MZ structure designed with arms of equal length. From Figure 5.25, we conclude that the power from the two branches recombine constructively to produce the circularly-symmetric spot observed at the output.

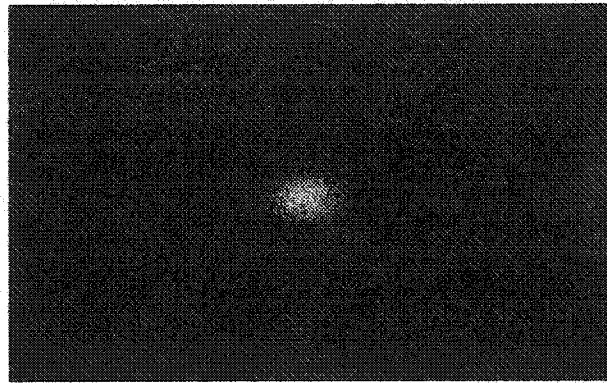


Figure 5.25.: IR output of a MZ structure designed with arms of equal length.

The MZ with unequal arm was also tested and no output was observed, however, since no light output is expected, it is difficult to determine if the MZ is properly excited. An experiment in which MZs placed in a row and on which the length of one arm is increased gradually would enable the experimentalist to better characterise Mach-Zehnder structures. Varying the wavelength of the incident light on a MZ structure with arms unequal in length would have the same effect.

5.5. Adhesion of metal to SiO_2

Fabrication of the metal optical wave guides is relatively easy in comparison to other technologies such as germanium doped silica on silica wave guides, however, there are some fabrication issues that must be dealt with when fabricating these wave guides. We have already mentioned that Au does not adhere very strongly to SiO_2 . In some electronics applications, a thin layer of Ti is deposited prior to the Au deposition. Depositing a layer of Ti increases the losses for plasmon-polaritons significantly (cf. Table 3.3) and is thus undesirable.

There are various types of interfacial reactions that occur at metal-dielectric interfaces and which may explain the adhesion mechanism [64]:

1. Ion exchange: For this bonding mechanism, metal ions replace sodium ions in the glass surface
2. Metal oxide cementing layers: A thin layer of oxide forms at the metal-dielectric interface and improves adhesion. Evaporated oxide films evaporated generally have a high interfacial adhesion to glass.

Item two is of most interest to us. Metals which form an oxide layer tend to adhere strongly to glass. The adhesion of glass to Pt, Ag or Cu has been attributed to the diffusion of oxygen into the metal lattice forming a transition zone of bridging ions. The adhesion of nobler metals is generally not as good when they are deposited on glass *in vacuo*. Base metals, on the other hand, generally adhere strongly to glass. It is believed that an interfacial cementing oxide layer forms at the start of the evaporation process, arising either as a result of a reaction with oxidising gases in the vacuum or from the water absorbed by the glass. It is possible, in the case of Ag, to improve its adhesion by deliberately contaminating it with oxygen during its initial growth.

In the case of Au, a bismuth oxide or Ti cementing layer is sometimes deposited prior to the deposition of the Au. Al, or its oxide, adheres strongly to glass and may be used to join glass to metals.

For this thesis, wave guides in Au were used for all guiding experiments. Although Au does not adhere strongly to glass, very thin and narrow metal films are required to form the wave guides, which are then covered by SiO_2 . From experience, we have seen that the Au adheres sufficiently strongly to the SiO_2 substrate to survive the lift-off process and the deposition of the cover, after which the Au wave guides are trapped.

Poor adhesion resulting from the deposition of Au to a glass surface was observed, in our case, when attempting to cover a wide surface of unpatterned Au with SiO_2 ; no

yield was obtained in this case. The yield for patterned Au covered with SiO₂ was 75%.

5.6. Annealing of metal optical wave guide devices

Thus far, we have fabricated our devices by embedding a thin metal film within SiO₂. It is well known, however, that during the fabrication process, the water vapor within the chamber results in the formation of OH-bonds within the SiO₂ and cause a large absorption peak around 1400 nm. This absorption peak results in higher losses for devices operating at 1300 nm and 1550 nm.

It is possible to reduce the attenuation due to the water content of the SiO₂ by annealing the samples at high temperatures (700°C to 1100°C) in a dry atmosphere for a few hours. Obviously, the lower the temperature, the longer the samples must be maintained at the elevated temperature. More research must be done to determine the feasibility of annealing of metal wave guides.

Conclusion and future work

In this thesis, we have attempted to present clearly and in a logical manner, it is hoped, our understanding and findings on the subject of plasmon-polaritons. We have started by presenting a literary review of the previous work conducted on this subject matter and we have described the modes supported by thin metal films. We then derived dispersion equations that enabled us to find the modes supported by thin metal films infinite in width for a metal embedded in semi-infinite dielectrics and in the more general case where the metal is part of a n -layer stratified structure. The field equations for the various electromagnetic components were also derived.

Once the modes were found, the dispersion equations were validated and simulation results presented. The simulation results although being for thin metal films infinite in width and not for the metal optical wave guides which interest us the most. Nevertheless, the results are still relevant and help us better understand the characteristics of plasmon-polariton modes. A number of simulation results were presented and discussed, showing the importance of the selection of our metal, the effect of wavelength on a structure consisting of a Au slab embedded in SiO_2 , and presenting the field distributions for various layered structures.

Following these simulations, we derived Fresnel's reflection coefficients for a n -layer stratified structure, and validated the model. We then proceeded to compare experimental and theoretical reflectance curves obtained for a Ti-Au-Ti metal film supported by a SiO_2/Si substrate and covered by SiO_2 and index matching oil. The experimental results were seen to be in good agreement with theory. The sensitivity on the incident polarisation for plasmon-polariton modes was also demonstrated for a sample and was seen to be what one would expect from our understanding of plasmon-polaritons.

We then turned our attention to experiments on thin metal films finite in width. Optical propagation was observed for what is believed to be the first time on a 20 nm thick, 3.5 mm long and 8 μm wide straight Au wave guide embedded in SiO_2 . The wave guide was excited in an end-fire experiment using a TM incident polarisation from a PM fiber operating at a free space wavelength of 1550 nm. The polarisation sensitivity of

this wave guide was also measured and confirmed the TM-nature of the mode supported. Numerous experiments for straight wave guides, *S*-bends, sharp bends, *Y*-junctions, couplers and Mach-Zehnders were performed and the results presented. Through a series of experiments, the structures were characterised and the results provide guidelines for future design work on metal optical wave guides the operation of basic integrated optics building blocks has been demonstrated for the first time.

When this thesis was undertaken, optical mode confinement of a finite width thin metal film had been predicted by theory [6, 7]. Today, we have experimental confirmation of the existence of such modes, and we have acquired a better understanding of the characteristics of these structures. Because of their simple design, novelty and their electrical and optical characteristics, metal optical wave guides open the door to a world of possibilities. It is quite easy to think of interesting experiments to try with these structures since every experiment is new and much remains to be learned.

Future work on this technology should be directed towards modelling wave propagation along these structures, research and development of the fabrication process and further characterisation of passive structures. Although a powerful modelling tool has been developed using the method of lines (MoL) [6], from a design point of view, it would be practical to be capable of modelling structures such as bends, *Y*-junctions, etc. in order to optimise their design. Commercial CAD tools are currently incapable of handling metal optical wave guides.

During the course of this thesis, the importance of having metal optical wave guides supported by thick SiO_2 became apparent and a considerable effort was devoted in attempting to find means of compensating for it. One of the key advantage of metal optical wave guides is that they can be printed in much the same way that current electrical integrated circuits are fabricated. The technology required for the fabrication of these wave guides already exists, and it is only a matter of finding the right combination of process steps and technologies for their fabrication. In this respect, energy should be devoted to improving the fabrication of these devices.

Finally, because of the novelty of these structures, there is much work that remains to be done to help further our understanding of metal optical wave guides. Various branches could be investigated in an attempt to improve on the performance of present optical wave guiding structures and exploit the optical and electrical properties of these structure. Perhaps the biggest difficulty in this avenue is to restrict ourselves in the number of experiments to try.

Metal optical wave guide technology is a fascinating topic since it offers a multitude of potential research directions. This combined with the current growth of the optical device

market and the need for ever-increasing bandwidth promise to make this technology a most interesting one.

Part III.

Appendix

Appendix A : List of acronyms

ATR:	Attenuated total reflection.
Ag:	Silver.
Al:	Aluminium.
Au:	Gold.
CRC:	Communications Research Centre Canada.
CVD:	Chemical vapour deposition.
DWDM:	Dense wavelength division multiplexing.
EM:	Electromagnetic.
Ge:	Germanium
HF:	Hydrofluoric (acid).
IR:	Infrared.
LIT9:	Name of first lithographic mask produced for this thesis.
LIT11:	Name of second lithographic mask produced for this thesis.
MoL:	Method of lines.
MZ:	Mach-Zenhder.
NSERC:	National sciences and engineering research council of Canada.
OGS:	Ontario graduate scholarship.
PAM:	Prism-air-metal ATR configuration [10].
PECVD:	Plasma enhanced chemical vapour deposition.
PM:	Polarisation maintaining (fiber).
PMA:	Prism-metal-air ATR configuration [11, 12].
SM:	Single-mode (fiber).
TE:	Transverse electric.
TEM:	Transverse electromagnetic.
TM:	Transverse magnetic.
Ti	Titanium.

Appendix B : List of constants

- a_b : Asymmetric bound mode supported by a thin metal film infinite in width.
- aa_b^0 : Asymmetric-asymmetric bound mode supported by a thin metal film finite in width.
- as_b^0 : Asymmetric-symmetric bound mode supported by a thin metal film finite in width.
- e : Electronic charge, $e = 1.602 \times 10^{-19}$.
- α : Imaginary part of the propagation constant, k_x .
- β : Real part of the propagation constant, k_x .
- $\vec{E}$: Electric field vector.
- $E_{x_i}(z)$: Electric field's x component dependence on z position, in medium i .
- $E_{z_i}(z)$: Electric field's z component dependence on z position, in medium i .
- ϵ_0 : Permittivity of vacuum.
- ϵ' : Real part of the relative permittivity of a material.
- ϵ'' : Imaginary part of the relative permittivity of a material.
- $\tilde{\epsilon}_r$: Relative permittivity of a material, $\tilde{\epsilon}_r = \epsilon' - j\epsilon''$.
- $\vec{H}$: Magnetic field vector.
- $H_{y_i}(z)$: Magnetic field's y component dependence on z position, in medium i .
- k : Imaginary part of the index of refraction of a material.
- k_0 : Propagation constant in the vacuum, $k_0 = \frac{2\pi}{\lambda}$.
- k_x : Propagation constant in the x direction, $k_x = \beta - j\alpha$, equal in all media.
- k_{z_i} : Propagation constant in the z direction, in layer i .
- n : Real part of the index of refraction of a material.
- $\tilde{n}$: Complex index of refraction, $\tilde{n} = n - jk$.
- N : Density of conduction electrons.
- N_{eff} : Effective index of refraction of a mode, $N_{eff} = \frac{k_x}{k_0}$.
- ν : Effective electron collision frequency.
- m_0 : Effective optical mass of conduction electrons.
- $\tilde{\mu}_r$: Relative permeability of a material.
- $P(x)$: Mode power, $P(x) = P(0)e^{-2\alpha x}$, function of propagation distance x .

- s_b : Symmetric bound mode supported by a thin metal film infinite in width.
- sa_b^0 : symmetric-asymmetric bound mode supported by a thin metal film finite in width.
- ss_b^0 : Symmetric-symmetric bound mode supported by a thin metal film finite in width.
- $\vec{S}$: Poynting vector, $\vec{S} = \vec{E} \times \vec{H}^*$.
- S_x : x component of the Poynting vector.
- τ : Relaxation time (or dc conductivity) of electrons.
- ω : Frequency of electromagnetic wave.
- ω_p : Plasma frequency.
- $\hat{x}$: Unit length vector in the x direction.
- $\hat{y}$: Unit length vector in the y direction.
- $\hat{z}$: Unit length vector in the z direction.

Appendix C: Measured data for figures presented in this thesis

Included in this thesis are many figures that facilitate the visualisation of the measurements recorded. Because it is often difficult and imprecise to obtain values directly from these graphs, the actual measured data points are presented below for most of the plots, along with additional notes not mentioned in the body of the thesis. Note that in some tables, the measured power is given along with a variation ($\pm$). This variation should not be considered the absolute error of the measurement, rather, it corresponds to the fluctuation of the measured optical power.

Figure 4.10: Slab polarisation sensitivity

Description:

Table 5.6 presents the measured reflectance power for a 632.8 nm polarised incident beam as a function of the polarisation angle for a Ti–Au–Ti film as described in Table 4.1.

Table 5.6.: Recorded data used for Figure 4.10.

Angle of incident polarisation [°]	Measured reflectance power [μ A]	
0	21.40	21.41
10	21.10	21.20
20	20.50	20.64
30	19.49	19.70
40	18.35	18.41
50	17.13	17.13
60	15.90	15.93
70	14.77	14.71
80	13.84	13.81
90	13.34	13.18

Notes:

- The data was measured from a 0° -TE polarisation in 10° increments, up to a 90° -TM polarisation and back to a 0° polarisation.

Figure 5.9: Wave guide polarisation sensitivity

Description:

Table 5.7 presents the measured optical output power for a 1550 nm polarised incident beam as a function of the polarisation angle for a 8 μm wide thin Au films.

Table 5.7.: Recorded data used for Figure 5.9.

Angle [°]	Measured optical output power [dBm]	
0	-24.50 ± 0.10	-24.45 ± 0.15
10	-24.70 ± 0.10	-24.65 ± 0.15
20	-25.05 ± 0.15	-24.90 ± 0.10
30	-25.58 ± 0.10	-25.70 ± 0.05
40	-26.65 ± 0.15	-26.70 ± 0.15
50	-28.50 ± 0.30	-28.35 ± 0.15
60	-30.20 ± 0.25	-30.15 ± 0.15
70	-33.30 ± 0.30	-33.30 ± 0.20
80	-36.20 ± 0.25	-36.60 ± 0.20
90	-38.10 ± 0.20	

Notes:

- The data was measured from a 0°–TM polarisation in 10° increments, up to a 90°–TE polarisation

Figure 5.11: Losses per unit length

Description:

Table 5.8 presents the measured optical output power for a 1550 nm polarised incident beam for different sample lengths. The measurements were performed with and without optical index matching oil.

Table 5.8.: Recorded data used for Figure 5.11.

Length of samples [cm]	Measured transmitted power without index matching oil [dB]	Measured transmitted power with index matching oil [dB]
0.392	-24.40 ± 0.15	-20.60 ± 0.13
0.578	-30.10 ± 0.10	-25.04 ± 0.10
0.957	-44.85 ± 0.10	-35.90 ± 0.10

Notes:

- The input power was $-2.72 \pm 0.01\text{dBm}$.
- The IR output of the wave guides was viewed in all cases and proved to be a very nice, circularly symmetric spot in all cases, except in the case of the 0.957 cm long sample, with index matching oil. For that case, the output was not as nicely defined.

Figure 5.12: Losses per unit length

Description:

Table 5.9 presents the measured optical output power for a 1550 nm polarised incident beam for the experiment illustrated in Figure 5.12.

Table 5.9.: Recorded data used for Figure 5.12.

Length of narrow width section [mm]	Measured transmitted power [dB]
0.5	-29.81 ± 0.04
1.0	-28.16 ± 0.02
1.5	-27.72 ± 0.03
2.0	-27.22 ± 0.01
2.5	-25.87 ± 0.04
3.0	-25.96 ± 0.03
3.5	-25.25 ± 0.02
4.0	-25.00 ± 0.01

Notes:

- The input power was -6.59 ± 0.01 dBm.
- The IR output of the wave guides was viewed in all cases and proved to be a very nice, circularly symmetric spot in all cases.

Figure 5.15: *S*-bends

Description:

Table 5.10 presents the measured optical output power for a 1550 nm polarised incident beam as a function of *S*-bend radii for 8 μm wide thin Au films.

Table 5.10.: Recorded data used for Figure 5.15

<i>S</i> -bend radius	Measured optical output for data set 1 [dBm]	Measured optical output for data set 2 [dBm]
∞	-42.65 ± 0.1	-38.11 ± 0.11
25	-43.20 ± 0.1	-36.35 ± 0.08
20	-42.50 ± 0.1	-37.03 ± 0.15
17.5	-42.35 ± 0.1	-38.05 ± 0.05
15	-43.10 ± 0.1	-38.13 ± 0.07
12.5	-43.60 ± 0.2	-38.27 ± 0.10
10	-43.70 ± 0.1	-38.25 ± 0.08
7.5	-46.75 ± 0.1	-40.65 ± 0.10
5	-56.40 ± 0.1	-49.45 ± 0.15
3	N/A	N/A

Notes:

- Data set 1 corresponds to the sample having a cover of 2 μm of deposited PECVD SiO_2 , whereas data set 2 corresponds to the sample having 4 μm of sputtered SiO_2 .
- The input power for data set 1 is -6.39 dBm and the input power for data set 2 is -6.57 dBm.
- For a straight wave guide, the radius is indicated as ∞ .
- In the case of the radius of 3 mm, no light was observed at the output.

Figure 5.16: *S*-bends

Description:

Table presents the measured optical output power for a 1550 nm polarised incident beam as a function of *S*-bend radii for 8 μm wide thin Au films.

Table 5.11.: Recorded data used for Figure 5.16

<i>S</i> -bend radius	Measured optical output for data set 1 [dBm]	Measured optical output for data set 2 [dBm]
∞	-33.21 ± 0.05	-30.46 ± 0.01
25	-30.65 ± 0.1	-31.77 ± 0.03
20	-30.95 ± 0.1	-31.20 ± 0.03
17.5	-31.70 ± 0.1	-36.20 ± 0.05
15	-30.60 ± 0.1	-38.15 ± 0.05
12.5	-33.60 ± 0.1	N/A
10	-36.31 ± 0.1	N/A
7.5	-51.60 ± 0.1	N/A
5	N/A	N/A
3	N/A	N/A

Notes:

- Data set 1 corresponds to the sample having a flip-chip, whereas data set 2 corresponds to the sample having only index matching oil. The data for the curve for the sample having no flip-chip and no index matching oil is presented in Table 5.10 as data set 1.
- The experiment with the sample covered with the flip-chip was performed using an input optical power of -6.42 ± 0.01 dBm, whereas the experiment with only the index matching oil was performed using an input optical power of -6.45 ± 0.01 dBm
- For a straight wave guide, the radius is indicated as ∞ .

Figure 5.18: Sharp bends

Description:

Table 5.12 presents the measured optical output power for a 1550 nm polarised incident beam as a function of bend angle for 8 μm wide thin Au films.

Table 5.12.: Recorded data used for Figure 5.18

Bend angle [$^{\circ}$]	Measured optical output power [dBm]	Loss per bend [dBm]
0.0	-41.2 ± 0.10	N/A
0.5	-41.7 ± 0.15	0.13
1.0	-43.3 ± 0.10	0.53
2.0	-46.2 ± 0.10	1.25
3.0	-52.7 ± 0.15	2.88

Notes:

- The input optical power for this experiment was -5.15 dBm.

Figure 5.20: Y-junctions

Description:

Table 5.13 presents the measured optical output power for a free space 1550 nm polarised incident beam as a function of the radius of curvature for 8 μm wide, 20 nm thick Au Y-junctions.

Table 5.13.: Recorded data used for Figure 5.20.

Radius of curvature [mm]	Measured output power [dBm]	
	Left branch	Right branch
4.531	-43.20 ± 0.20	-44.17 ± 0.10
8.031	-43.25 ± 0.10	-44.45 ± 0.15
12.531	-43.50 ± 0.15	-44.85 ± 0.15
16.950	-43.43 ± 0.18	-43.40 ± 0.10
20.000	-44.35 ± 0.10	-44.45 ± 0.01
24.531	-49.20 ± 0.10	-49.90 ± 0.10

Notes:

- The input optical power for this experiment was $-4.57 \text{ dB} \pm 0.01$.

Figure 5.24: Couplers

Description:

Table 5.14 presents the measured optical output power for a 1550 nm polarised incident beam as a function of wave guide separation for 8 μm wide thin metal film couplers having a coupling length of 1.5 mm.

Table 5.14.: Recorded data used for Figure 5.24.

Input power [dBm]	wave guide separation [μm]	Measured output power [dBm]	
		Through port	Coupled port
-6.63 ± 0.01	4	N/A	-30.32 ± 0.01
	5	-39.30 ± 0.02	-30.34 ± 0.01
	6	-35.05 ± 0.02	-31.32 ± 0.01
	7	-32.52 ± 0.01	-32.47 ± 0.01
	8	-31.12 ± 0.01	-33.89 ± 0.01
-6.66 ± 0.01	2	-31.89 ± 0.01	-33.00 ± 0.01
	3	-35.85 ± 0.01	-31.24 ± 0.01
	4	-47.53 ± 0.01	-29.58 ± 0.01
	5	-39.65 ± 0.01	-29.94 ± 0.01
	6	-34.20 ± 0.01	-30.94 ± 0.01
	7	-32.27 ± 0.01	-32.12 ± 0.01
	8	-31.06 ± 0.01	-33.85 ± 0.01

Notes:

- The value indicated for the through port of the couplers having a 4 μm separation are in the noise region of the powermeter. In the first case, it was not possible to obtain a valid measurement, and in the second case, the value indicated should only be considered an indication of the actual power.

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