

MINIATURIZED WAVELENGTH INTERROGATION FOR THE AIRCRAFT STRUCTURAL HEALTH MONITORING AND OPTOFLUIDIC ANALYSIS

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LIST OF ACRONYMS

AWG	Arrayed Waveguide Grating
BBS	Board Band Source
DAQ	Data Acquisition
EDG	Echelle Diffractive Grating
DSB	Double Sideband
DSB-SC	Double Sideband with Suppressed Carrier
EDFA	Erbium-doped Fiber Amplifier
EOM	Electro-Optic Modulator
FBG	Fiber Bragg Grating
FP	Fabry-Perot
FSR	Free Spectral Range
FWHM	Full Width at Half Maximum
IM	Intensity Modulation/Modulator
InP	Indium Phosphide
LD	Laser Diode
LPG	Long Period Grating
MZI	Mach-Zehnder Interferometer
MZM	Mach-Zehnder Modulator
NDE	Non Destructive Evaluation
NI	National Instrument
OPAMP	Operational Amplifier

OSA	Optical Spectrum Analyzer
OSC	Oscilloscope
PC	Polarization Controller
PD	Photodetector
PLCs	Planar Lightwave Circuits
PM	Phase Modulation/Modulator
RF	Radio Frequency
RTD	Resistance Temperature Detector
SCFBG	Sampled Chirped Fiber Bragg Grating
SHM	Structural Health Monitoring
SMF	Single-Mode Fiber
SSB	Single Sideband
TEC	Thermal Electric Cooler
WDM	Wavelength Division Multiplexing

ABSTRACT

In this thesis, miniaturized wavelength interrogators based on planar lightwave circuits (PLCs) are investigated and developed for the optical fiber sensing applications in the aircraft structural health monitoring (SHM) and optofluidic analysis. Two interrogation systems based on an arrayed waveguide grating (AWG) and an Echelle diffractive grating (EDG) are developed and used to convert the optical sensing signals into strain, temperature, vibration, damage, and humidity information for the aircraft SHM. A fiber Bragg grating (FBG) sensing system using developed interrogators is then demonstrated in a field test for aircraft SHM applications. For optofluidic analysis, a PLCs based optofluidic device consisting of two on-chip lens sets is built to enhance the optical manipulation capability of particles. Then, a solution to a multi-functional Lab-on-a-Chip platform for optofluidic analysis is proposed, which integrates the developed particle maneuvering device, grating-structured sensors, and miniaturized interrogators.

CHAPTER 1

INTRODUCTION

1.1. Background review

Optical fiber sensors have great potential in the aircraft structural health monitoring (SHM) applications and optofluidic analysis. A common requirement is the need of a compact and robust wavelength interrogation unit for these sensors. In this thesis, planar lightwave circuits (PLCs) based interrogation units are developed to fulfill this requirement. The optical fiber sensors in these two fields have similar structures. The wavelength interrogation for these optical fiber sensors is also having the same fundamental operation mechanism. Thus, the developed wavelength interrogation units can be shared in the two fields. The background review is divided into two parts. The first part is to describe the requirements for the PLCs based interrogation units in the aircraft SHM applications. The second part is to introduce the use of the developed wavelength interrogation units in the optofluidic analysis incorporation with optical sensors and the proposed Lab-on-a-Chip platform.

First, in the aircraft SHM applications, commercial aircraft operators are faced with the requirements of reducing the operating and maintenance cost, while at the same time increasing the safety and reliability of aerospace vehicles [1-7]. For military aircrafts, the need to serve beyond their designed life cycle further imposes the economic pressure resulted from the heavy maintenance and inspection burdens [8-9]. Although conventional periodic on-ground inspection has successfully ensured the safety and reliability of these aerospace vehicles, it fails to avoid the high cost [10]. In addition, the conventional methods might require disassembling and reassembling components, which increases the potential of introducing unexpected damage

and degradation to structures and auxiliary systems [11-14]. The concept of the aircraft SHM is proposed and developed to reduce the complexity and the costs associated with these conventional methods by the implementation of on-board and real-time monitoring sensors [1].

Aircraft structures are mostly built by metallic and composite materials [14]. The types of damage in the aircraft structures for the two materials are different. For the metallic material, the fatigue cracking is the most common damage form, followed by the corrosion. The impact damage is major for the composite material, followed by bonding/debonding. Therefore, aircraft SHM generally consists of two critical aspects, i.e. operational load monitoring and impact damage detection [12-15]. Operational load monitoring is used to support the fatigue life management, such as estimating the pattern of the structural fatigue life and providing information about the possible structural damage. More specifically, the fatigue life assessment is evaluated by measuring the local stresses, which can be either directly obtained using sensors or derived from various global flight parameters and structural usage data, such as flight speed, altitude, mass, and acceleration [16-17]. The latter approach is regarded as an unreliable method since loads need to be converted from other parameters and fatigue life calculations are based on the imprecise damage accumulation rules. Nevertheless, it is the only option until the emerging of effective and reliable strain sensors. Currently, load monitoring is performed by the combination of the two methods, i.e. limited number of strain sensors mounted in some critical points for the direct measurement and monitoring of flying parameters for the estimation of loads in other locations. Obviously, the number of those selected critical points will have a significant impact on the final definition of the load monitoring. As the only proven aircraft SHM method, operational load monitoring has already been applied to different types of military and civilian aircrafts for the estimation of the accumulated fatigue damages and the

remaining aircraft operation life. However, load monitoring alone is not able to directly detect and monitor the structural damages (another critical aspect of the aircraft SHM). For example, operational load monitoring cannot directly provide the information of the source of cracks and damages resulted from cracks and corrosion in the metallic materials [18], and delamination in the composite materials [19]. Therefore, another method capable of directly detecting/monitoring the cracks and damages is required. This can be potentially achieved by integrating a sensing system onto or into the structural components, thus allowing the direct measurement of the occurrence, size, and location of cracks and damages. Currently, the only proven method for the crack and damage detection is the ultrasonic/acoustic non-destructive technology.

For the operational load monitoring, strain gauges, accelerometers, and fiber optic sensors are the main choices [20]. Both strain gauges and accelerometers are relatively mature, but their wirings pose significant challenges in the sensor deployment. On the other hand, one optical fiber can be used to multiplex tens or hundreds of fiber optic load sensors, thus greatly lessening the wiring issue. For the crack and damage detection, ultrasonic/acoustic sensors based on piezoelectric materials are currently the standard pick even though they are still in the development stage [21]. Similar to the strain gauges and accelerometer, the multiplexing capability of these piezoelectric sensors is limited and their wiring is also a big challenge for the deployment. Again, using fiber optic acoustic sensors can effectively address this wiring issue. Furthermore, fiber optic sensors have the potential of using the same sensor for both the operational load and impact damage measurement.

Over several decades, a wide range of fiber optic sensor approaches have intensively been studied and widely implemented [22-51]. Among these candidates for the development in the

aircraft SHM applications, fiber Bragg grating (FBG) sensors have received the wider visibility and acceptance [52-58].

Fiber Bragg grating (FBG) sensors are regarded as the most mature grating-based sensors and have already been widely used [59-81]. An FBG sensor reflects a portion of the incoming light of a particular wavelength, called the Bragg wavelength or center wavelength, and leaves the rest of the incoming light pass without altering its property [61]. The Bragg wavelength is defined by the fiber refractive index and grating pitch, which are affected by the external environment changes, such as temperature, strain, vibration, and other parameters. All these changes are reflected on the Bragg wavelength shift. Therefore, by monitoring the Bragg wavelength shift, environmental changes, such as temperature, strain, pH, humidity, acceleration, and *et al.*, can be monitored using FBG sensors [55]. FBG sensor technology also has a high multiplexing capability. In the past 20 years, wavelength multiplexing technology has become mature, tens or hundreds of FBG sensors with different wavelengths can be cascaded in one single optical fiber [56]. Besides the wavelength multiplexing capability, FBG sensors have the main advantages of low cost, compact size, and good linearity. In addition to the wide applications in temperature and strain sensing, FBG sensors have found applications in the measurement of acoustic/ultrasonic signals [82-102]. In other words, they can be used for the crack and damage detection. In this type of applications, FBG sensors substitute the conventional PZT sensors to pick up the ultrasonic/acoustic waves to reduce the complicated wiring issue. FBG sensors have the potential to be deployed in a large quantity by utilizing their multiplexing capability, therefore, to achieve a full-scale monitoring. This feature is one of the most competitive advantages of FBG sensors over traditional PZT sensors and other types of fiber optic sensors. Therefore, all these features make FBG sensors receive a considerable

attention and become one of the leading candidates in the aircraft SHM applications [103-105]. With the rapid development in the past few years, FBG sensing technology has been targeted as the major leading technology in contrast to other competing fiber optic sensing technologies. A growing number of global enterprises, including National Instrument [106], Luna Innovations [107], Micron Optics [108], SmartTec [109], SmartFibre [110], and Bayspec [111] are now developing and commercializing FBG sensor systems.

To fully exploit the benefits of FBG sensors in the aircraft SHM applications, several challenges should be addressed. As one of the challenges, the lack of a suitable wavelength interrogation unit hinders the field deployment of FBG sensors. FBG interrogation methods can be classified by the measurement frequency as shown in Fig. 1.1.

A review of the wavelength interrogation techniques is reported in [112]. Optical spectrum analyzers (OSA) are the most standard instrument for the wavelength interrogation. Though it provides large measurement range and high accuracy, it has limitations of bulky size, heavy weight, and is not suitable for the field applications. So far, several types of compact size interrogation units have been reported. Among them, tunable Fabry-Perot (FP) filter is the most mature and widely used for the wavelength interrogation [62, 113-115]. It employs the principle of a tunable optic filter of a very narrow wavelength bandwidth and is fabricated with either bulk optics [116] or fiber optics [62]. Other major wavelength interrogation techniques include arrayed waveguide grating (AWG) [117-122], diffractive grating with a charge coupled device (CCD) array [123-126], Mach-Zehnder interferometer [127-130], Michelson interferometer [131], all fiber based optical filter [132], matched FBG pair [133-134], chirped FBG [135], long period grating (LPG) [136], and Fourier transform spectroscopy [137]. In the aircraft SHM applications, requirements for the interrogation units in the operational load monitoring and

impact damage detection are different. For the operational load monitoring, it is required to measure large changes (thousands of $\mu\epsilon$) at a low speed (static). While for the impact damage detection, the capability of measuring acoustic waves, i.e. small changes (tens or hundreds of $\mu\epsilon$) at an ultrafast speed (50 kHz - 500 kHz), is usually required for a standard FBG sensor with a 10-mm grating length [87]. Based on the review of the interrogation techniques listed in Fig. 1.1, tunable FP filter is used when the speed required is under 1 kHz, and the combination of a diffractive grating and CCD array is suitable for the speed from 1 kHz to 20 kHz [54]. For the speed from 20 kHz up to 500 kHz, three methods have been reported, i.e. the use of a laser diode with its output wavelength fixed at the middle of one FBG sensor spectrum slope [90], an FP filter with a broadened and fixed spectrum [138], and an AWG with a fixed spectrum [103]. Additionally, the recent development of FBG sensors has offered them dual measurement capabilities of doing both operational load monitoring and impact damage detection, which is also preferred in the aircraft SHM applications [84]. Thus, in order to deploy FBG sensors in the aircraft SHM applications, a single interrogation unit should have the basic features of compact size, light weight, robustness, multichannel measurement capability, and low power consumption. Furthermore, it should have the capability to work for the two aspects of the SHM applications [14].

It is seen that only the AWG based interrogation unit has this capability. Furthermore, an AWG is one type of PLCs. PLCs devices are fabricated with the standard silicon foundry tools, materials, and processes, having the features of small size, light weight, low cost, and strong reliability required by the stringent telecommunication standards [139-144]. The use of PLCs in an interrogation unit inherits these features [145], making it ideal for the aircraft SHM applications [105, 146].

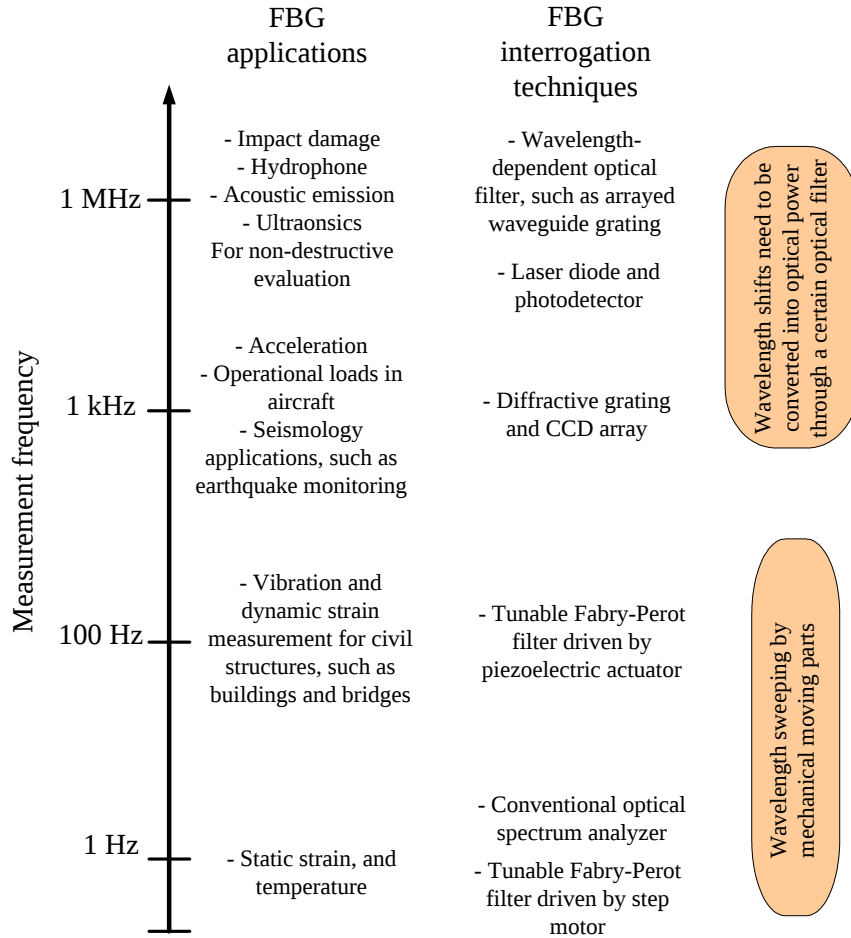


Fig. 1.1. FBG interrogation methods classified by measurement frequency.

Second, in the optofluidic analysis, biomedical analysis of cells without altering their properties is vital to biologists, medics, and colloidal physicians in hospitals and laboratories around the world. The emerging demands posed by the rapid pathogen detection, clinical diagnosis, and forensic science necessitate the development of Lab-on-a-Chip devices, which could integrate and scale down laboratory functions and processes to a miniaturized chip format. Although the conventional diagnostic instrument is very efficient in dealing with large amount of cells and are sought-after by the large hospitals and research institutions, they are bulky and expensive. In addition, these sophisticated instruments are not capable of handling small numbers of cells, a

situation frequently met with the cases that large populations of primary cells or any otherwise precious cells cannot be obtained. Therefore, an advanced technique is required to meet this requirement, where photonic technology is one of the strongest candidates. Photonic technology can provide advanced optical sensors for obtaining the biomedical information of the cells without changing their properties. Furthermore, photonic technology can combine the optics and microfluidics together to form a commonly known optofluidic device to achieve a Lab-on-a-Chip platform. The studies of optical sensors in the optofluidic analysis are well described in [49, 50, 52]. To achieve a Lab-on-a-Chip device for the optofluidic analysis, we propose a PLCs based platform with the details described in Chapter 6.1. In general, the device has three functions, sorting cells, sensing cells, and identifying cells. A detailed review of using the photonic technology in this device is present in Chapter 6.2, where PLCs based on-chip lens sets are introduced to enhance the particle manipulation capability.

1.2. Major contribution of this thesis

The major contributions of this thesis are

- (1) Develop miniaturized wavelength interrogation units based on the PLCs for FBG sensors in the aircraft SHM applications and optofluidic analysis.
- (2) Introduce the PLCs based on-chip lens sets to build an optofluidic device for an enhanced optical manipulation of particles.
- (3) Propose a PLCs based Lab-on-a-Chip platform for the optofluidic analysis.

(Note that most of the presented work consists of materials re-written from various published articles)

In the aircraft SHM applications, the aging aircrafts are mostly built using metallic materials. Thus, our developed wavelength interrogation units are designed for the metallic materials. These interrogation units are made based on two major PLCs, AWG and EDG, which are fabricated with the standard silicon foundry tools. Different from the conventional interrogation units using these PLCs, we introduce spectrum tuning methods to achieve better measurement resolution, range, and accuracy. Especially, the mechanical tuning method is the first time proposed and demonstrated. In addition, we propose the design of a dual-function wavelength interrogation unit, which is able to measure both the loading and acoustics signals used for the two major aspects in the aircraft SHM applications. At last, the performance of the developed units is verified in a real structure mimic to the aircraft wing.

An AWG based wavelength interrogation unit with a thermal tuning spectrum is built. The AWG spectrum has a linear dependency on its temperature. Thus, by adjusting the AWG temperature, its spectrum shifts, which can be used to detect the sensor signal. By using the peak matching method, it is known that when the two spectra overlap together, the received light will reach the maximum value and the center wavelength the AWG channel is the same as the center wavelength of the sensor. Thus, by knowing the temperature corresponding to the peak value of the received light power, the center wavelength of the AWG channel can be obtained as well as the center wavelength of the sensor. This wavelength interrogation technique is used for multiple FBG sensors. To minimize the channel cross talk, the center wavelength of FBG sensors are designed that each FBG sensor corresponds to one AWG channel. A total of 6 FBG sensors have been successfully interrogated.

The above demonstration has a condition that one AWG channel can only cover one FBG sensor. To explore the use of multiple AWG channels, we perform the wavelength interrogation of a long period grating (LPG) sensor with three AWG channels. As the LPG sensor has a much wider bandwidth, only one AWG channel is not enough to cover the LPG spectrum. Thus, three AWG channels are used. It is obvious that the LPG dip only falls into one AWG channel and the other two AWG channels are used to show the rising and falling edge of the LPG spectrum. Similar to the peak matching method, the temperature corresponding to the minimum light power is observed and used to convert to the center wavelength of the AWG channel, which is equal to the center wavelength of the LPG sensor. This work has been published in the Photonic Technology Letters [147].

Besides the thermal tuning spectrum method, we also propose another novel technique, which can tune the spectrum in a much larger range at a higher speed. The new technique is named as the mechanical tuning, which is based on the theory that the center wavelength of one AWG channel is dependent on the input light position along the AWG input coupler. The design of the AWG input coupler has a Rowland Circle profile at the fiber input port. To simplify the fiber coupling process, we cut part of the Rowland Circle into a slab waveguide. Experiential results show that (1) the linear relationship between the center wavelength of an AWG channel and the input light position exists, and is named as the space-to-wavelength mapping in this thesis, and (2) the slight cut of the Rowland Circle does not affect the AWG spectrum profile. To our best acknowledgement, it is the first time to propose and demonstrate the space-to-wavelength mapping and apply it in the wavelength interrogation of FBG sensors.

Space-to-wavelength mapping requires the position change of the input light along the AWG input coupler. This is achieved by mounting the fiber on a V-groove and glued on top of a piezo

motor. Classified by the manner of the motion control, the space-to-wavelength mapping is subcategorized into open-loop and closed-loop. In the open-loop motion control, only the start and end position are known, there is no real time feedback of the input light position during the position scan. To overcome this drawback, we introduce a wavelength reference component. In our design, a sampled chirped FBG (SCFBG) is used. The SCFBG has multiple peaks with the distance controllable during its fabrication. In the setup, the sensor under test and the SCFBG are located at two paralleled path separated by a 3dB coupler. The light power from the two paths is recorded with the same trigger signal. Thus, the sensor wavelength and the SCFBG wavelengths can be correlated and converted via the space-to-wavelength mapping. This work has been published in the Optics Letters [148].

Though the open-loop motion control works, it is always of great interest if the input light position can be achieved directly by a position sensor. In this case, the wavelength reference can be removed from the setup and the measurement accuracy will be improved. Thus, a position sensor is installed into the piezo motor to build a closed-loop motion controller, which provides the position feedback while the fiber is scanning along the AWG input coupler. With the closed-loop motion control, four FBG sensors have been successfully interrogated. This work has been published in the Journal of Lightwave Technology [149].

Previous closed-loop wavelength interrogation unit has a small measurement range which is limited by the travel range of the piezo motor. To show the capability of the space-to-wavelength of an AWG, a new piezo motor is used with an improved travel range. In the new design, a larger measurement range is achieved. To validate its performance, a tilted FBG is successfully interrogated for its application in measuring refractive index using the Bragg mode

and a higher-order mode. This work has been published in the IEEE Sensor 2010 Conference [150].

An EDG, which has a similar performance to an AWG, is also used to build the wavelength interrogation unit. Due to the intrinsic operational principle that an EDG uses the reflection light to separate lights while an AWG uses the transmission light, an EDG has a chip size at least half smaller than an AWG. This feature makes it more strong for the aircraft SHM applications.

The EDG used in this thesis is a commercially packaged device with a monolithically integrated photodetector array and temperature control module. As the input fiber tail has already been attached to the device, we only apply the thermal tuning technique to the EDG based interrogation unit. The EDG device has 32 channels. In our first design, we connect the odd number channels, which is limited to the number of data acquisition channels. We build the prototype and use it for a field application. In this test, an FBG sensor is glued on metallic coupon and the metallic coupon is then loaded on a load frame. The prototype has successfully obtained the loads that are applied on the FBG sensor and the result accords well with the readings from a commercial wavemeter [151].

In our first prototype, the temperature tuning technique is to increase or decrease the temperature in steps. This method provides a good resolution and accuracy, but extends the measurement time. To shorten the measurement time while keeping the measurement accuracy and resolution, the temperature control is changed. By using temperature scan from the start value to the end value without introducing steps, the measurement time is significantly reduced. By increasing the sampling rate of the data acquisition during the temperature sweep, the measurement resolution and accuracy can be maintained. The prototype is modified to use this

temperature control plan and used to interrogate an FBG/LPG sensor pair. This work has been published in the Journal of Lightwave Technology [152].

As discussed in Chapter 1.1, two major aspects of the aircraft SHM are the operational load monitoring and impact damage detection. The current EDG based interrogation unit is proved to be able to perform the operational load, but has limitations to reach a high interrogation speed for the damage detection. To achieve this, we modify the EDG interrogation unit and release an advanced model. The new design allows the EDG to work in two operation modes, the sweeping mode and the parked mode. The sweeping mode uses the thermal tuning technique, while the parked mode uses the power ratio from the two adjacent EDG channels to determine the sensor wavelength. The modified prototype has successfully obtained the static and dynamic strain changes that are applied on an FBG sensor.

Besides the use of the developed wavelength interrogation units in the aircraft SHM applications, it is found that the use of FBG sensors and EDG based wavelength interrogation unit is able to achieve a multichannel RF signal receiver. In this design, the microwave signal is converted to an optical signal of two sidebands using an optical carrier and a Mach-Zehnder modulator (MZM). One of the sidebands is then filtered out by a fiber Bragg grating (FBG), while the other sideband is characterized by an EDG based wavelength interrogation unit. Due to the high interrogation resolution of in pm magnitude of this interrogation unit, the center wavelength of the left sideband is accurately measured. Combining this data with the wavelength of the optical carrier, the frequency of the microwave signal can be calculated. This work has been published in the Photonics Technology Letters [153].

TABEL 1.1. TARGET SPECIFICATIONS OF DESIGNED FBG SENSING SYSTEM AND ITS COMPARISON WITH THE AVAILABLE COMMERCIAL SYSTEMS IN MARKET

	Micron Optics	Smartec	Yokogawa	Bayspec	Insensys	Smart Fibres	Luna	OURS
Model	Sm125-500	MUST Unit-500	FB200	FBGA Analyzer	Oem-1000	SmartScan	DSS 4300	
Picture								
Optical Channel	4	4	1	1		1-4		1-4
Frequency (Hz)	2	500	100	5-5k	2k-4k	2.5k	0.3	100-500k
Wavelength Range (nm)	1510-1590	1510-1590	1527-1567 1568-1607	1525-1565 1510-1590	9 nm per sensor for up to 100 sensors	1528-1568	1525-1605	1525-1565 1510-1590
Wavelength Accuracy (pm)	1	2	<50	10	1.7	5	1.5	<10
Wavelength Resolution (pm)	1	1	1	1	0.8	1	0.02	<1
Dimension (mm)	117x234x125	135x268x120	170x28x220	96x68x15.8	EuroCard PCB Size 100x160x40	140x110x70	Bench Type	Target: 120x100x50
Weight (kg)	2	2	1.2		0.5	0.9		Target: 0.25
Operating Temperature (°C)	0 to 50	0 to 50	0 to 60	-5 to +70		-15 to +55		Not specified
Input Voltage	7-36 VDC	7-36 VDC	5 VDC		24 VDC	9-36 VDC		7-24 VDC
Power Consumption (w)	20	35	10		3	7.5		<5
Cost	>\$15k CAD			\$5500 CAD				<\$3k CAD

Field tests of evaluating fiber optic sensor technology in the aircraft SHM applications are also performed. A platform is especially built to simulate the aircraft wing structures, and to assess different SHM technologies, of which fiber optic sensor technology is the most promising one. We design and make an FBG sensing system with the optimal specifications in Table 1.1, as well as its comparison with the available FBG sensing systems in the market.

In the field tests, FBG sensors are selected for various measurements, including static strain ramp test, dynamic strain test, acoustic signal receiving test, and relative humidity test. Results show that our developed fiber sensing system meets the designed requirement and can be used for the operational load monitoring and early stage of the impact damage detection.

In the optofluidic analysis, we integrate the PLCs into the microfluidic devices. With the advantages of the PLC technology, we can trim the shape of the PLCs into the desired ones, such as lens sets. These lens sets can then be used to change the light beam wave front, which can enhance photon-solid interaction efficiency, thus increase the manipulation capability of the small particles in μm level. An optofluidic chip with such on-chip lens sets is made using SU-8 as the PLC material. Results show that the proposed scheme of using the PLCs to build the on-chip lens structures is able to enhance the performance of particle transport, separation, and concentration. This work has been published in the Journal of Selected Topics Quantum Electronics [154].

1.3. Organization of this thesis

This thesis consists of two parts. In the first part, Chapter 1 to Chapter 5, we investigate the miniaturized wavelength interrogation units based on the PLCs, including the AWG and EDG,

and demonstrate the applications in the aircraft SHM with the use of apodized FBG sensors. In the second part, Chapter 6, we propose to integrate PLCs into microfluidic devices to build a multi-functional platform for the optofluidic analysis.

Specifically, in Chapter 1, the background of the aircraft SHM is first introduced followed with the development of the wavelength interrogation techniques for the FBG sensors. The major contributions of the work in this thesis are then summarized. In Chapter 2, the theoretical basis of an AWG is presented. The two spectrum tuning techniques, thermal tuning and mechanical tuning, are described and the spectrum tuning coefficients are calculated. The peak matching method to find the FBG wavelength from spectrum tuning is also discussed. AWG and EDG based interrogation units and their applications are present in Chapter 3 and Chapter 4 respectively. Field tests of using our developed FBG sensing system in the aircraft SHM applications are demonstrated in Chapter 5, which includes the operational load monitoring, acoustic signal test, and relative humidity measurement. In Chapter 6, the use of the developed interrogation unit is introduced into the optofluidic analysis with a proposed Lab-on-a-Chip platform based on the PLCs. In Chapter 6.1, the PLCs based platform is proposed with three functions: (1) sorting and concentrating cells with PLCs, (2) sensing biomedical changes with PLCs based grating-structured optical sensors, and (3) analyzing optical sensing signal and identifying cells with interrogation unit. In Chapter 6.2, we demonstrate the manipulation of small particles using the developed PLCs based device, which is a key component of the proposed platform.

Finally, a conclusion is drawn in Chapter 7 with the recommendations for the future work.

CHAPTER 2 THEORETICAL OVERVIEWS

PLC technology, originally developed for the low-cost optical access communication network [141], has already achieved the sophisticated fabrication level of small and rugged package. These PLCs have a similar fabrication process in many ways to the electronic counterparts, such as using wafer-level processing techniques [144], which makes it possible to use the state-of-the-art semiconductor foundry to produce PLCs. This leads to the tremendous deployment of PLCs in the optical communication network, lowers down the price, and consolidates the performance. As described in the introduction, PLCs, such as AWG and EDG, have also been widely used in the wavelength interrogation of FBG sensors [117, 119, 149, 152-153]. In these applications, their spectra are fixed. Though the measurement resolution can be increased by decreasing AWG channel spacing, it also reduces the measurement range as the trade-off, since the measurement range in a spectrum fixed AWG is the product of the channel spacing and the total channel number. In order to increase the measurement resolution while keeping the measurement range not reduced, we introduce spectrum tuning techniques in the AWG and EDG based wavelength interrogation units. In this session, the operation principle of an AWG is first described. Then, two spectrum tuning techniques, thermal tuning and mechanical tuning, are presented as well as the linear wavelength dependence to temperature and input light position respectively. Third, peak matching method, which is used to explore the FBG center wavelength, is introduced.

2.1. Principle of planar lightwave circuits

To fully describe the operating principle, the fundamental principle of an AWG is first introduced [141]. An AWG is a passive PLCs chip and consists of input/output waveguides and has been widely applied in the optical communication systems [155-162]. It consists of two focusing slab regions (input/output coupler), and an array of multiple channel waveguides located between the two slab regions with a constant path difference of ΔL between adjacent waveguides as shown in Fig. 2.1(a). Light introduced into the input coupler from the input channel transmits through the input coupler and is coupled into the arrayed waveguide. The arrayed waveguides are designed that the optical path length difference between adjacent waveguides is equal to an integer multiple of the center wavelength of the AWG. The phase retardations of two light beams passing through the i th and $(i+1)$ th channel waveguide are analyzed within the region of the second focusing slab (output coupler) as shown in Fig. 2.1(b).

Fig. 2.1(a) shows the schematic configuration of the whole AWG, and Fig. 2.1(b) shows the enlarged output coupler region. The channel waveguides separation is d , the radius of curvature is f . After the light beams, Beam a and b, travel through the i th and $(i+1)$ th channel waveguide respectively, they constructively interfere at the focal point x . The geometrical distance of the two beams could be expressed by

$$f + \frac{d}{2} \sin \theta \approx f + \frac{dx}{2f} \quad (2-1)$$

$$f - \frac{d}{2} \sin \theta \approx f - \frac{dx}{2f} \quad (2-2)$$

where (2-1) and (2-2) are for Beam a and b respectively. In order to satisfy the condition of constructive interference, the difference between the total phase retardations of the two beams passing through the i th and $(i+1)$ th channel should be an integer multiple of 2π . Considering that the input coupler has the same configuration, the interference condition can be written as [141]

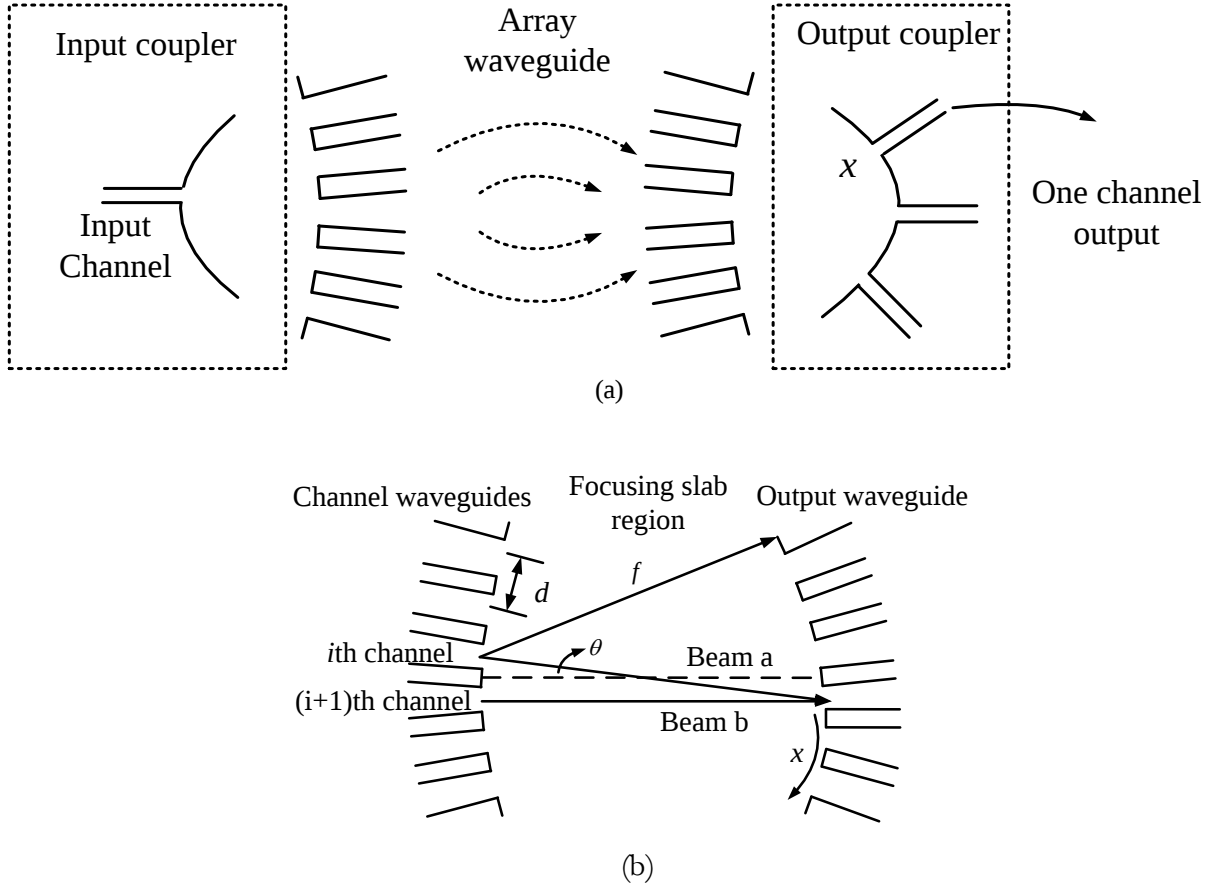


Fig. 2.1. Schematic representation of the AWG. (a) Overview of the AWG and (b) Enlarged view of the second focusing slab region.

$$\begin{aligned} & \{\beta_s(\lambda_c)(f_1 - \frac{d_1 x_1}{2f_1}) + \beta_a(\lambda_c)[L_0 + (i+1)\Delta L] + \beta_s(\lambda_c)(f + \frac{dx}{2f})\} \\ & - \{\beta_s(\lambda_c)(f_1 + \frac{d_1 x_1}{2f_1}) + \beta_a(\lambda_c)[L_0 + i\Delta L] + \beta_s(\lambda_c)(f - \frac{dx}{2f})\} = 2m\pi \end{aligned} \quad (2-3)$$

The terms in the first and second $\{\cdot\}$ represent the phase retardations in Beam a and b respectively. d_1 and f_1 are the channel waveguide separation and radius of curvature in the first focusing slab region, x_1 is the input light position, β_s and β_a denote the propagation constants in the slab region and channel waveguide, L_0 is the minimum channel waveguide length, λ_c is the center wavelength of the AWG, and m is an integer.

As the phase difference of Beam a and b is an integer multiple of 2π , the field distribution at the output channel is a mirror image of the field distribution at the input channel resulted from a constructive interference at this particular wavelength, λ_c , in this case. Therefore, the light with the wavelength λ_c will be focused in the center of the image plane, which is the designed AWG output channel. While light transmits through the arrayed waveguides, if the input wavelength is detuned from this center wavelength λ_c , phase changes correspondingly in the arrayed waveguides. Due to the constant path difference between adjacent waveguides, phase is changing linearly from the inner to outer waveguides, resulting in a tilting wave front. As a result, the focused point in the image plane will be physically shifted away from the center focal point, similar to a focal lens with a tilted input light beam. Therefore, different wavelengths have different focal points along the output coupler exit. On the other hand, lights with different wavelengths will be spatially separated at the output channels.

2.2. Spectrum tuning technique

In (2-3), if the layout, structure, and material of an AWG are fixed, we can simply rewrite (2-3) into a simple format

$$\lambda_c = g(\beta_s, \beta_a, x) \quad (2-4)$$

By the definition of β_s and β_a as of the propagation constant, they are dependent on the effective refractive index n_s and n_a in the term of

$$\beta_s = \frac{2\pi}{\lambda_c} n_s \quad (2-5a)$$

$$\beta_a = \frac{2\pi}{\lambda_c} n_a \quad (2-5b)$$

Thus, the wavelength of this particular AWG channel can also be expressed as

$$\lambda_c = h(n_s, n_a, x) \quad (2-6)$$

Then, it is seen that the AWG spectrum will shift if the refractive index of input/output coupler changes or the input light position along the input coupler changes.

In this thesis, thermal tuning refers to the refractive index changes, while mechanical turning stands for the input light position changes.

2.2.1. Thermal tuning

The simplest way to achieve the thermal tuning is to use a heater and a closed-loop temperature control [163]. It is reported that the center wavelength of an AWG channel has a linear relationship with respect to its temperature [156]. In the optical communication network, when using AWG as a mux or demux, this thermal control is employed to minimize the spectrum shift caused by the ambient changes. In our work, the reversed way is used.

From (2-3), the center wavelength of an AWG channel can be described as

$$\lambda_c = \frac{n_a \Delta L}{m} \quad (2-7)$$

Due to the temperature dependency of both n_a and ΔL , the center wavelength shift is obtained by differentiating temperature on both sides of (2-7) [141]

$$\frac{d\lambda_c}{dT} = \frac{1}{m} \frac{d(n_a \Delta L)}{dT} \quad (2-8)$$

Since an AWG is fabricated with the material of silica, for an athermal AWG design, we have the temperature coefficient of both refractive index and delta of waveguides defined in [156]

$$\frac{d(n_a \Delta L)}{dT} = 10^{-5} \times \Delta L \quad (2-9)$$

Substituting (2-9) into (2-8), we obtain

$$\lambda_c(T) = \lambda_c(T_0) + \frac{10^{-5} \Delta L}{m} \Delta T \quad (2-10)$$

where $\lambda_c(T_0)$ and $\lambda_c(T)$ are the center wavelength of an AWG channel at the temperature T_0 and T respectively, and ΔT is the temperature difference between T_0 and T . From Eq. (2-10), it is seen that the center wavelength shifts linearly with the AWG temperature. According to the AWG operation principle, all the channels should be the same wavelength tuning capability.

Considering the heat control capability [164], the AWG temperature should be tuned within the range of 20-100 °C to cover the 0.8-nm spectrum range, which is the same as the channel spacing of a standard commercial AWG. Since all the AWG channels have the same wavelength tuning capability, the 20-100 °C temperature tuning range will cover the free

spectral range (FSR) of an AWG to keep the measurement range not reduced compared with a spectrum fixed AWG. Since the measurement resolution is dependent on the tuning temperature rather than the channel spacing, the spectrum tuning AWG can increase the measurement resolution and keep the measurement range at the same time.

2.2.2. Mechanical tuning

The mechanical tuning technique is based on the fact that the transmission wavelength of an AWG channel changes linearly with the beam position along the AWG input coupler (first focusing slab region). The mechanical tuning spectrum is achieved by either manually tuning with a position stage or automatically tuning with a PZT motor. This technique provides a mapping from the spatial position of the input light beam to the transmission wavelength of an AWG channel, which is regarded as the space-to-wavelength mapping.

Recall that (2-3) shows the fundamental principle of an AWG, it could also be described as [141]

$$\beta_s(\lambda_c) \frac{d_1 x_1}{f_1} - \beta_s(\lambda_c) \frac{dx}{f} + \beta_a(\lambda_c) \Delta L = 2m\pi \quad (2-11)$$

By differentiating (2-11), we can obtain the relationship between the output focal point x and the wavelength λ_c at a fixed input position x_1 as shown as

$$\frac{\Delta x}{\Delta \lambda} = - \frac{n_a f_1 \Delta L}{n_s d \lambda_c} \quad (2-12)$$

Since an AWG is a reciprocal device, the dependence of the wavelength λ on the input position x_1 for a fixed output focal point x could be expressed by

$$\left| \frac{\Delta\lambda}{\Delta x_1} \right| = \frac{n_s d_1 \lambda_c}{n_a f_1 \Delta L} \quad (2-13)$$

From (2-13), the center wavelength of an AWG channel is able to be tuned if the input light beam position is scanning along the AWG input coupler. The mechanical tuning spectrum is simulated using beam propagation method with the result of a selected AWG channel tuning spectrum shown in Fig. 2.2.

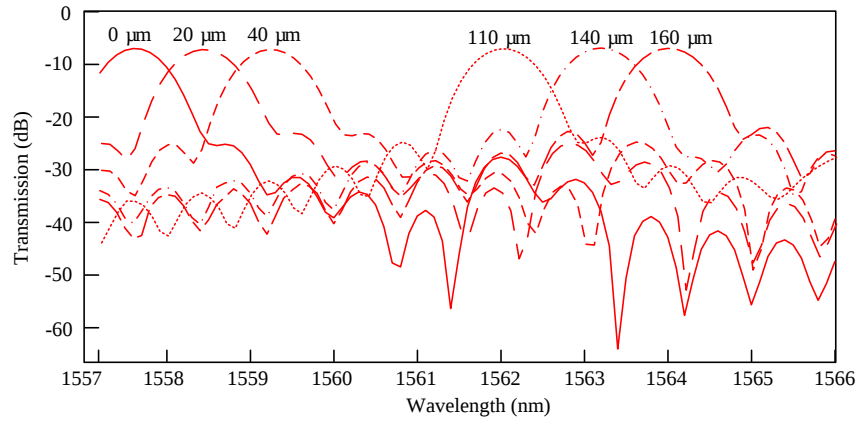


Fig. 2.2. Theoretical simulation of the spectrum shifts of a designated AWG channel with the input light beam position changes.

In the simulation, the AWG parameters are set by the default values in the BeamPro software, and the input light beam positions are set with six values. The spectrum of one designated AWG channel is calculated under these values. It is seen that a tuning spectrum is achieved by changing the input light beam position and the tuning range is much larger than the result achieved by the thermal tuning. The large spectrum tuning range in one AWG channel offers the capability of building a multi-channel interrogation unit with each channel covering the entire C and L band.

Though insertion loss in the butt-to-butt coupling between an optical fiber and planar waveguide with flat facet could be minimized using high-temperature epoxy [165], it has a challenge in coupling light from an optical fiber to an AWG input coupler, since the geometrical profile of the AWG input coupler is a Rowland Circle. Direct butt-to-butt coupling between an optical fiber and this Rowland Circle profiled input coupler will result in significant insertion loss. In our design, we cut the Rowland Circle into a slab waveguide to reduce the losses. A schematic of the interrogation methodology is shown in Fig. 2.3.

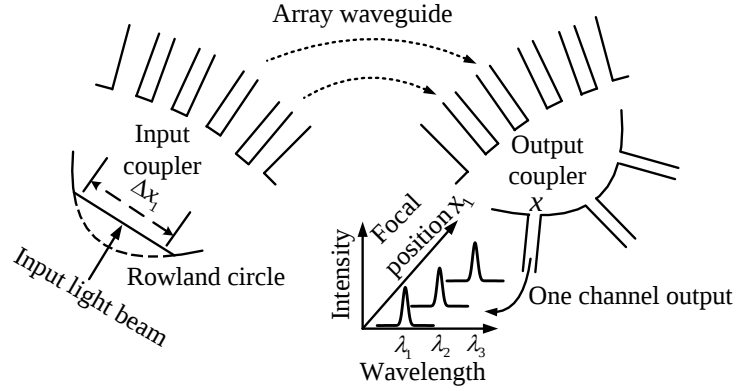


Fig. 2.3. Mechanical tuning spectrum of an AWG and the space-to-wavelength mapping.

2.3. Peak matching technique

The fundamental principle of our proposed wavelength interrogation technique is to get spectrum of an AWG or EDG tuning. The spectrum tuning techniques are described above. This session will discuss the peak matching technique, which is used to explore the peak from a reproduced reflective FBG spectrum [166]. As an AWG or EDG is using the same methodology to search the peak, the peak matching method will be discussed based on an AWG.

Assume that one AWG channel spectrum shifts via the thermal tuning, when it meets the reflective FBG spectrum, the light power travelling through the AWG and FBG will change accordingly to reproduce the FBG spectrum. By analyzing the reproduced spectrum and the linear relationship between the AWG spectrum and the temperature, the center wavelength of the FBG sensor can be obtained.

To simplify the mathematical processing, we assume that a Gaussian apodized FBG sensor has the reflective spectrum in a Gaussian profile [167], which can be expressed as

$$I_{FBG}(\lambda) = I_B \exp\left[-4\ln(2) \frac{(\lambda - \lambda_B)^2}{\Delta\lambda_B^2}\right] \quad (2-14)$$

where I_B is the peak transmittance at the center wavelength λ_B , and $\Delta\lambda_B$ is the full width at half maximum (FWHM) of the Gaussian profile.

A typical AWG spectrum also has a Gaussian profile and can be mathematically described as

$$A_j(\lambda) = a_j \exp\left(-4\ln 2 \frac{(\lambda - \lambda_{aj})^2}{\Delta\lambda_{aj}^2}\right) + a_0 \quad (2-15)$$

where a_j , λ_{aj} , and $\Delta\lambda_{aj}$ are the peak transmittance, center wavelength, and FWHM of the j th AWG channel. a_0 is the noise floor. Considering that the dynamic range of an AWG channel is larger than 30dB, the noise floor is low and can be neglected.

If we carefully design the center wavelength of all the FBG sensors, it is possible that the light received by the j th AWG channel is mainly from one FBG sensor. The contributions from the

other FBG sensors are very small and can be neglected. When the FBG and AWG are cascaded in tandem, the power detected by the j th AWG channel can be described as

$$I_j(\lambda) \approx k_j a_j I_B \Delta\lambda_{aj}^2 \Delta\lambda_B^2 \times \sqrt{\frac{\pi}{(\Delta\lambda_{aj}^2 + \Delta\lambda_B^2)4\ln 2}} \times \exp(-4\ln 2 \frac{(\lambda - \lambda_B)^2}{\Delta\lambda_{aj}^2 + \Delta\lambda_B^2}) \quad (2-16)$$

where k_j is a constant dependent on the source power and detector responsivity. It is seen that the received light power also has a Gaussian profile from (2-16), which can be simplified as

$$I_j(\lambda) \approx K_j \exp(-4\ln 2 \frac{(\lambda - \lambda_B)^2}{\Delta\lambda_{aj}^2 + \Delta\lambda_B^2}) \quad (2-17)$$

where K_j is the peak value and can be described as

$$K_j = k_j a_j I_B \Delta\lambda_{aj}^2 \Delta\lambda_B^2 \times \sqrt{\frac{\pi}{(\Delta\lambda_{aj}^2 + \Delta\lambda_B^2)4\ln 2}} \quad (2-18)$$

This peak value is achieved when the AWG center wavelength, λ , is equal to the center wavelength of the FBG sensor λ_B . By applying the thermal tuning technique, the AWG center wavelength changes with the temperature at a constant rate as discussed in 2.2.1. Thus, the AWG center wavelength can be expressed by

$$\lambda = \beta \times T + \lambda_0 \quad (2-19)$$

where T is the AWG temperature, β is the temperature dependent coefficient, and λ_0 is a constant representing the start wavelength. Substituting (2-19) to (2-17), the final expression of the received light power by the j th AWG channel can be written by

$$I_j(T) = K_j \exp\left(-4 \ln 2 \frac{(\beta \times T + \lambda_0 - \lambda_B)^2}{\Delta\lambda_{aj}^2 + \Delta\lambda_B^2}\right) \quad (2-19)$$

(2-19) shows that the received light power is also a Gaussian profile and the peak value is achieved by tuning the temperature T to make the center wavelength of the AWG channel the same as the one of the FBG spectrum to be tested. This peak matching method can be described as shown in Fig. 2.4.

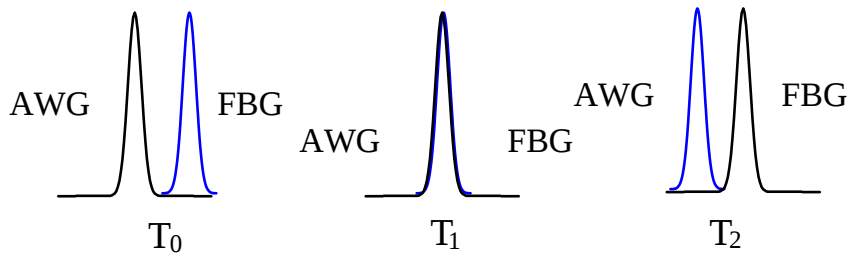


Fig. 2.4. Illustration of the peak matching method using a thermal tuning AWG spectrum.

Supposing that the center wavelength of AWG Channel A is shorter than the center wavelength of the FBG sensor at temperature T_0 , the light power from Channel A is received as P_0 by an optical power meter. When increasing the temperature of the AWG, the center wavelength of Channel A shifts. At temperature T_1 , the transmission wavelength of Channel A overlaps with the wavelength of the FBG sensor with the light power from Channel A measured as P_1 . Obviously, from temperature T_0 to T_1 , the received light power starts from P_0 and reaches the maximum value of P_1 at temperature T_1 . If continuously heating the AWG, the transmission wavelength of Channel A becomes larger than the wavelength of the FBG sensor. Meanwhile the received light power from Channel A decreases. Thus, by selecting the suitable transmission channel of an AWG and knowing the temperature corresponding to the maximum value of the

received light power, the wavelength of the FBG sensor can be precisely interrogated with the relationship between the temperature and the transmission wavelength discussed in (2-19).

CHAPTER 3 WAVELENGTH

INTERROGATION BASED ON AN AWG

For the applications of the FBG sensor technology, it is required that the wavelength interrogation unit has the features of easy portability, strong robustness, low cost, high measurement capacity, and high multiplexing capability. The wavelength interrogation techniques that are introduced in Chapter 1.1 have challenges to meet these requirements. In recent years, an AWG has been used to build the wavelength unit as the key component [141] to take the advantages of the matured fabrication of AWG chips. The use of an AWG in the wavelength interrogation units has the benefits of low cost, compact size, light weight, and high multiplexing capability. In the reported design, the wavelength interrogation is achieved by taking the ratio of the intensities in the two adjacent AWG channels [141]. This simple method yields a good performance but suffers from a limited measurement range and stringent requirement on the reflective FBG spectrum bandwidth. Since the FBG spectrum has to be located within the two adjacent channels, the measurement range and FBG spectrum bandwidth have to be smaller than the AWG channel spacing. These drawbacks are overcome by involving more AWG channels in measurement to increase the measurement range [168], and using heterodyne approach based on interferometric wavelength shift detection [121]. However, they make the interrogation system much more complicated.

To alleviate the drawbacks mentioned above, we propose to use spectrum tuning AWG instead of the spectrum fixed AWG in the wavelength interrogation unit. Two spectrum tuning methods are introduced, thermal tuning and mechanical tuning. The theoretical principles for these two

methods are described in Chapter 2.2.1 and Chapter 2.2.2 respectively. In this session, the characterization of the tuned spectrum and experimental results for each tuning method will be discussed.

3.1 Implementation of a thermal tuning AWG

The AWG chip used in the thermal tuning wavelength interrogation unit is a standard commercial product from NKT Integration. It has 32 output channels. Each channel has a Gaussian-type spectrum. The channel spacing is 100GHz (0.8nm). An illustration of the AWG chip is shown in Fig. 3.1.



Fig. 3.1. An illustration of the AWG chip used in the thermal tuning wavelegnth interrogation unit.

To achieve the thermal tuning spectrum, a thermal film heater is glued at the back of the AWG chip and used to adjust the AWG chip temperature. A resistance temperature detector (RTD) is bonded to the arrayed waveguide region of the AWG chip to monitor the AWG chip temperature. As discussed in Chapter 2.2.1, both the effective refractive index in input/output coupler and arrayed waveguide region affect the thermal tuning spectrum performance. As the major part of the phase difference is contributed by the numerous arrayed waveguides, we place the RTD at the arrayed waveguide region of the AWG chip rather than the input/output coupler

region. An illustration of the packaged AWG chip for thermal tuning wavelength interrogation is shown in Fig. 3.2.

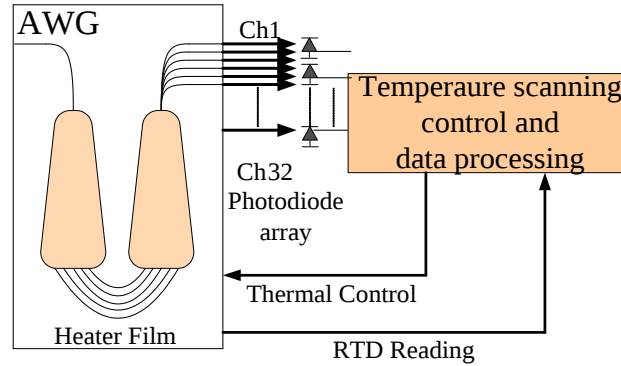


Fig. 3.2. An illustration of the packaged AWG chip with temperature control loop.

The temperature control signal is from an Analog Output port of a NI DAQ card. The RTD and AWG output readings are collected by a number of Analog Input ports of the same NI DAQ card. All the control is performed by a Labview program.

3.1.1. Characterization of a thermal tuning AWG

To verify the thermal tuning performance, the temperature effect on the transmission spectrum of a designated AWG channel is monitored by adjusting the AWG temperature from 25.4 °C to 98.8 °C. The transmission spectrum and its center wavelength of the AWG channel are monitored by an optical spectrum analyzer (OSA). Spectra at selected AWG temperature values are shown in Fig. 3.3(a) and the relationship between center wavelength of this AWG channel and the AWG temperature is shown in Fig. 3.3(b).

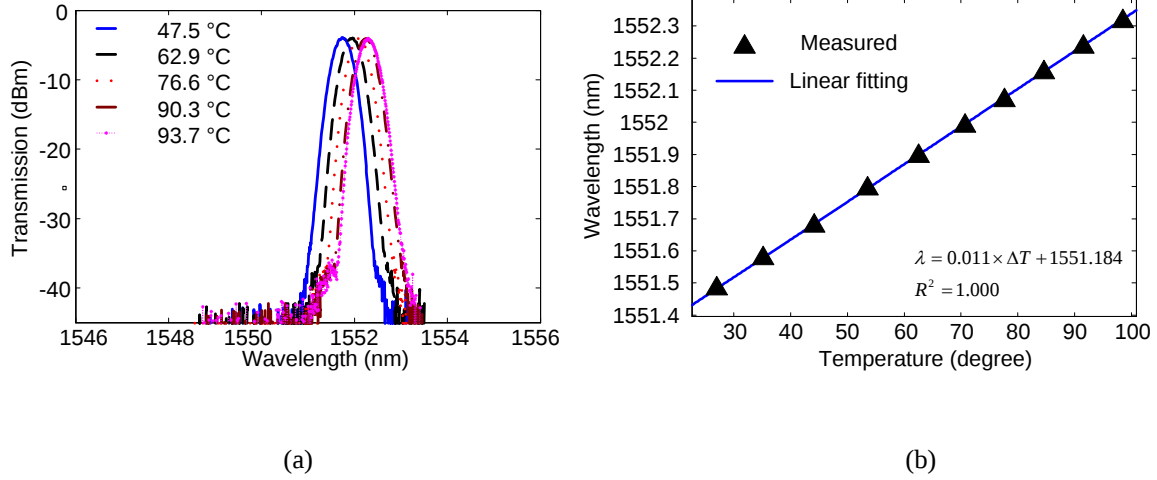


Fig. 3.3. Thermal tuning AWG. (a) Spectrum of the designated channel at selected AWG temperature values and (2) Linear relationship between center wavelength and the AWG temperature.

It is seen that the spectrum of the designated AWG channel shifts while the AWG temperature increases. Its spectrum profile keeps the same without any distortion during the shift, which indicates that the only the center wavelength changes when adjusting the AWG temperature. The linear temperature dependency of the AWG channel is experimentally verified. The temperature coefficient is calculated to be 11 pm/ °C. Due to the uniformity of the AWG [141], the other AWG channels should have the same tuning performance. Fig. 3.4 shows the linear temperature dependency of the other six selected AWG channels.

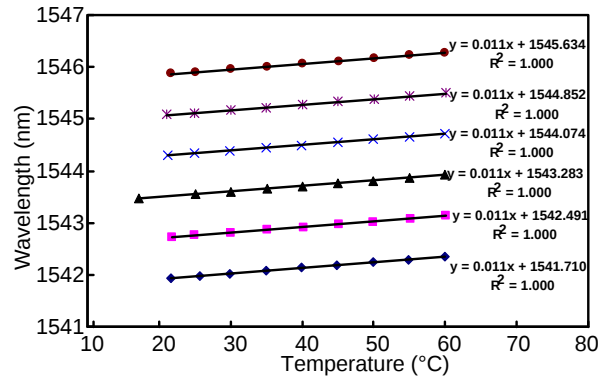


Fig. 3.4. Linear temperature dependency of the center wavelengths of six selected AWG channels.

It is seen that the center wavelength of the AWG channel changes linearly with the AWG temperature at a rate of 11 pm/ °C. Furthermore, all the six AWG channels have the same spectrum tuning rate and also the same as above single designated AWG channel. It validates our consumption that all the AWG channels should have the same spectrum tuning performance.

3.1.2. Wavelength interrogation for FBG sensors using thermal tuning AWG

AWG

In Chapter 3.1.1, six AWG channels are selected to verify the linear relationship between the center wavelength of AWG channel and AWG temperature, and the temperature coefficient is calculated to be 11 pm/ °C. As discussed in Chapter 2.3, the peaking matching method requires that the FBG sensor system is designed to meet the requirement that each AWG channel is used to interrogate a single FBG sensor. We now use a single-mode fiber (SMF) with six cascaded FBG sensors to test the wavelength interrogation of thermal tuning AWG and the peak matching method. The experimental setup is shown in Fig. 3.5.

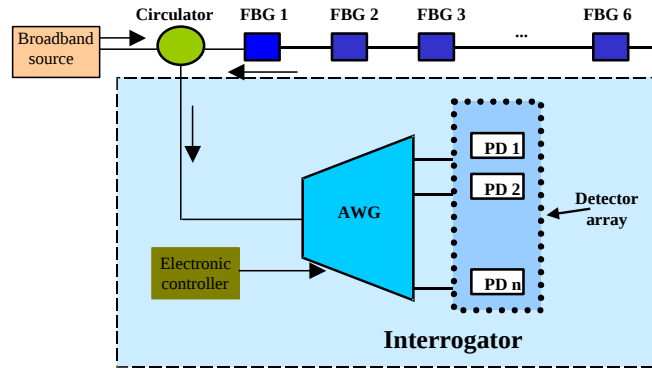


Fig. 3.5. Experimental setup for the demodulation of six FBG sensors using a thermal tuning AWG.

The setup includes a broadband light source, an optical circulator, six FBG sensors, and the developed interrogation unit, which consists of a 32-channel AWG with 0.8-nm channel

spacing, an eight-channel photodetector array and an electronic controller. The temperature tuning is performed by a film heater which is glued to the back of the AWG chip. A RTD is used to monitor the AWG temperature. With the assistance of the electronic controller, AWG temperature is able to be precisely adjusted. The six FBG sensors are supplied by Avensys Inc. with the wavelength spacing between neighboring FBG sensors as of 0.8 nm. All the six FBG sensors are separated with a distance.

The obtained results are the measured light power from six photodetectors with respect to the AWG temperature. Each photodetector is connected to one of the six AWG channels and used to monitor one FBG sensor. According to the wavelength interrogation principle as discussed above, the temperature corresponding to the peak light power is obtained. Then, the wavelengths could be calculated by introducing these temperature values into the linear relationship. In this experiment, the temperature values corresponding to the peak light power and the interrogated wavelengths are listed in Table 3.1, as well as the sensor wavelengths provided by the manufacturer in the same table for a comparison purpose.

TABEL 3.1. COMPARISON BETWEEN MEASURED WAVELENGTHS OF 6 FBG SENSORS AND THE DTA PROVIDED BY THE MANUFACTURER

Sensors	Peak Temperature (°C)	Measured Wavelength (nm)	Wavelength provided by Manufacturer (nm)
1	86.42	1542.661	1542.65
2	94.81	1543.534	1543.52
3	93.79	1544.316	1544.30
4	92.94	1545.096	1545.06
5	96.49	1545.913	1545.90
6	93.18	1545.659	1545.66

The measured results agree well with the data provided by the manufacturer and measured values by an OSA. The small variation between the two sets of data is believed to be attributed to the difference in measurement environments such as temperature and strain.

In the laboratory ambient condition, a better than 0.01 °C resolution can be obtained for the AWG temperature reading. This temperature resolution can lead to the wavelength resolution as high as 0.1 pm. In addition, the AWG chip used in this work has a dimension of 30 × 55 mm, the detector array has a dimension of 10 × 30 mm. It is possible to design and package the interrogating setup shown in Fig. 3.5 into a compact device. The small size of the AWG chip can also further improve the interrogation speed and the reliability of the device as only the arrayed waveguide region needs to be heated as discussed above. The smaller heating area equipped with a powerful heat film will accelerate the temperature change time cycle. Furthermore, heat film can be directly deposited on the arrayed waveguides of the device. It is reported that a 2-ms response time has been achieved for silica waveguide-based devices [144]. This potential improvement would make it possible for the thermal tuning AWG wavelength interrogation unit to meet the initial dynamic measurement needs.

3.1.3. Wavelength interrogation for LPG sensor using thermal tuning AWG¹

As we have presented in Chapter 2.2.1 and Chapter 3.1.2, the thermal tuning AWG is proved to be able to perform wavelength interrogation of FBG sensors via peak matching method. Similar to exploring the peak of the received light power for FBG sensors, we can transfer the methodology to the wavelength interrogation of a long period grating (LPG) sensor.

¹ This section is a revised version of the following published paper. Article title: Interrogation of a long period grating sensor by a thermally tunable arrayed waveguide grating. Authors: Honglei Guo, Gaozhi Xiao, Nezih Mrad, and Jianping Yao. Published in IEEE Photonics Technology Letters, vol. 20, no. 21, pp. 1790-1792, Nov. 2008.

I. Introduction

LPG sensors have been well documented for bio-chemical detection, industrial process monitoring and structural health monitoring due to their low back-reflection [169] and high sensitivities [44, 170-171]. The key practical challenge for LPG sensors is without doubt the wavelength interrogation of their large spectral band. So far, the current wavelength interrogation techniques for LPG sensors, including using OSA, FBG [172], and derivative spectroscopy [173], are not practical for most applications and can only be used in the laboratory environment because of the bulky size, high cost, poor robustness and non-portability. Especially for the bio-chemical applications, disposable sensor with portable interrogation unit is of great interest for field applications, such as water pollution detection [174-175]. In this session, thermal tuning AWG is applied to interrogate an LPG sensor. As shown by both theoretical and experimental analysis, the transmission wavelength of an AWG can be linearly tuned by changing the AWG chip temperature. Curve fitting and its first order derivative are performed to obtain the temperature corresponding to the minimum detected light intensity of the LPG sensor from one of the AWG channels. The center wavelength of the LPG is then calculated by interpolating the above obtained temperature in the temperature dependence curve of the AWG transmission wavelengths. Using this technique, 1-pm wavelength interrogation resolution and 25-nm interrogation range have been achieved.

II. Theory

Similar to the FBG spectrum profile, we assume that as a Gaussian-apodized LPG can be considered having a flip-flop Gaussian profile [176], its spectrum can be expressed as

$$I_{LPG}(\lambda) = I_0 - I_L \exp\left[-4\ln(2) \frac{(\lambda - \lambda_L)^2}{\Delta\lambda_L^2}\right] \quad (3-1)$$

where I_0 is a constant, $I_0 - I_L$ is the transmittance at the center wavelength λ_L FWHM of the Gaussian profile.

The LPG and AWG are cascaded in tandem. To simplify the mathematic analysis, we still use the j th AWG channel to receive the light travelling through the LPG, and the spectrum profile of the j th AWG channel is the same as (2-15). Similar to the mathematic processing in Chapter 2.3, the light detected by the j th AWG channel is given by

$$I_j(\lambda_{aj}) \approx I_c - P_j \exp\left[-4\ln(2) \frac{(\lambda_{aj} - \lambda_L)^2}{\Delta\lambda_L^2 + \Delta\lambda_{aj}^2}\right] \quad (3-2)$$

Where I_c is a constant and P_j is the peak of the second term on the right side of (3-2), which is dependent on the optical source power, photodetector sensitivity and the FWHM of both AWG and LPG.

As the AWG has the same temperature dependency, the linear relationship between the center wavelength and AWG temperature still keeps the form in (2-18). Substituting this linear relationship into (3-3), the final expression of the received light from the j th AWG channel can be described by

$$I_j(T) \approx I_c - P_j \exp\left[-4\ln(2) \frac{(\beta \times T + \lambda_0 - \lambda_L)^2}{\Delta\lambda_L^2 + \Delta\lambda_{aj}^2}\right] \quad (3-3)$$

(3-3) shows that the $I_j(T)$ has a flip-flop Gaussian profile with the minimum value of $I_c - P_j$, which is achieved when the AWG temperature is adjusted to a value that the center wavelength

of the AWG channel is equal to the center wavelength of the LPG sensor. Therefore, by knowing the temperature corresponding to the minimum of the detected light intensity and the temperature dependence of AWG center wavelength, the center wavelength of an LPG can be determined.

III. Experimental results and discussion

To evaluate the feasibility of the proposed interrogation scheme, an experimental interrogation setup illustrated in Fig. 3.6 is built.

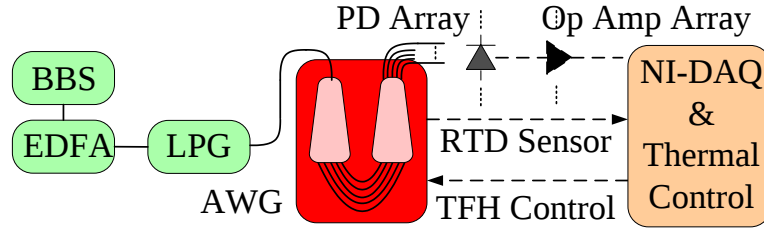


Fig. 3.6. Experimental setup for LPG interrogation based on a thermal tuning AWG.

The experimental setup shown in Fig. 3.6 consists of a broadband light source (BBS), an erbium doped fiber amplifier (EDFA), a thermal film heater (TFH), a RTD and a 32-channel AWG with 0.8 nm uniform channel spacing. The TFH is bonded at the back of the AWG chip and controlled by a Labview program. The RTD is implemented for the purpose of monitoring the temperature variation. Also, an array of photodetectors (PD) and operational amplifiers (Op AMP) are used to acquire and amplify the light intensity from the AWG channels. A National Instrument data acquisition (NI-DAQ) card is used to perform the data acquisition for both temperature and light intensity. For simultaneous data acquisition, the Labview based triggering function is initiated so that temperature and light intensity are obtained at the same sampling points in each AWG output channel.

As shown in Fig. 3.7, one dedicated channel (Channel 8 in this case) with the tuning temperature from 60 °C to 98 °C is capable of obtaining the center part of the LPG spectrum, which is decided by the 3-dB bandwidth of the LPG being studied and the temperature dependence of the AWG transmission wavelengths. As to the other LPG with larger 3-dB bandwidth, the flexibility of the proposed interrogation technique allows for the use of two, three or more AWG channels to obtain the LPG spectrum, since a continuous 25-nm scannable range can be achieved as discussed above.

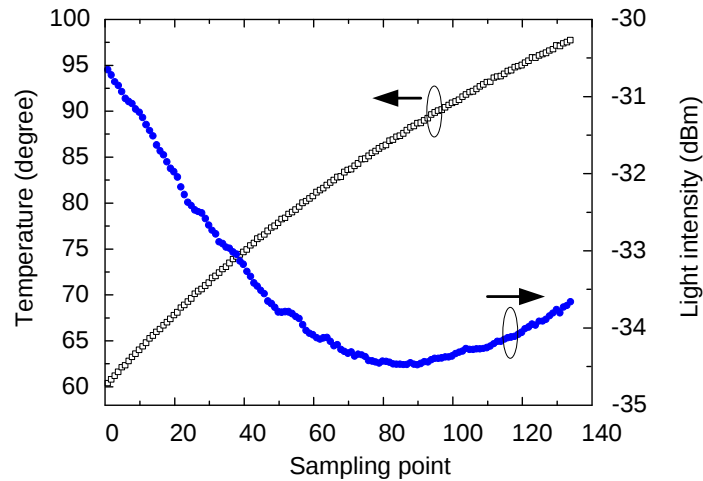


Fig. 3.7. Experimental results for LPG interrogation measured from the DAQ card.

Curve fitting of the detected light intensity and its first order derivative with respect to the temperature are shown in Fig. 3.8 in solid and dashed lines, respectively. The temperature corresponding to the minimum light intensity is measured as 86.98 °C by analyzing the first order derivative. Using the temperature dependence of the AWG transmission wavelengths discussed above, an LPG center wavelength of 1552.202 nm is obtained. The obtained results correlate well with the ones provided by the manufacturer and denoted as 1552.2 nm. Five repeating tests within 2 hours show that the maximum variation obtained is 26 pm, which is

believed to be partly attributed to the drifting of the ambient conditions during the experiment period, since a typical LPG has the sensitivity to strain and temperature almost an order-of-magnitude higher than $1 \text{ pm}/\mu\epsilon$ and $10 \text{ pm}/^\circ\text{C}$ respectively, denoted as that of an FBG [169].

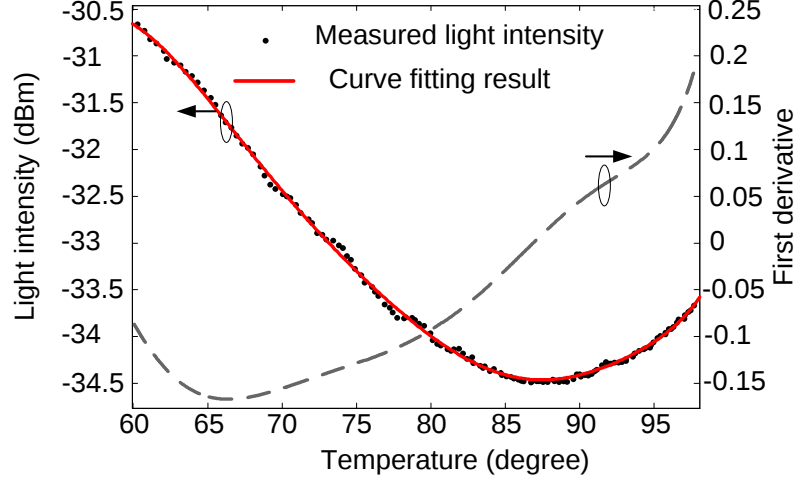


Fig. 3.8. Detected light intensity, curve fitting and the first order derivative versus the chip temperature.

Additionally, an AWG transmission spectrum of a Dirac delta function with an infinite height and a unity area would be ideal for the scanning of the LPG spectrum. In this work, a commercial AWG demultiplexer chip from IgnisPhotonix is used. The chip has a 3-dB bandwidth of $\sim 0.4 \text{ nm}$ (a typical performance of commercially available AWG devices). This could also contribute to the measurement variation discussed above. According to the analysis in [177], the narrower the AWG transmission bandwidth, the less the measurement error will be. Therefore, using an AWG with a narrower transmission bandwidth could potentially improve the measurement accuracy.

Moreover, AWG chip temperature dependence coefficient is $11 \text{ pm}/^\circ\text{C}$ and its resolution is 3.16 pm for TFH temperature increment step of 0.27°C . If the curve fitting is employed, calculating its first order derivative with the temperature increment step of 0.1°C , an interrogation

resolution of 1 pm can be achieved. A better than 1 pm resolution will be theoretically achieved by reducing the temperature increment step in calculating the first order derivative.

The presented high resolution AWG based approach employed for the interrogation of LPG would be particularly attractive for the refractive index estimation in chemical sensors, such as a chemical concentration sensor which requires a spectral resolution of 10 pm in a 60-nm range [174-175, 178]. The 25-nm interrogation capacity of the presented device in this paper can be increased by stacking several properly designed AWGs, providing added flexibility for the applications requiring wide spectral interrogation range.

IV. Conclusion

The interrogation of an LPG sensor was achieved by thermal scanning an AWG. The experimental results showed that the transmission wavelengths of AWG channels shifted linearly with the temperature. By calculating the temperature corresponding to the minimum of the detected light intensity and employing the temperature dependence curve of the AWG transmission wavelengths, the center wavelength of the LPG sensor was successfully measured. It was also shown that the use of the proposed thermal tunable AWG technique provided a 25-nm interrogation range at resolution of 1 pm with the additional features of compact size, low cost and suitability for practical applications.

3.2 Implementation of a mechanical tuning AWG

In this session, a novel spectrum tuning technique for the wavelength interrogation is introduced, which is based on the space-to-wavelength mapping. Experimental tests using the AWG chip shown in Fig. 3.9 have been implemented to verify the performance. Initial results show that

this technique could successfully perform the wavelength interrogation for FBG, LPG, and TFBG sensors [148-152, 179]. Compared with the thermal tuning spectrum, the mechanical tuning spectrum has advantages of a broader measurement range and a faster measurement speed.

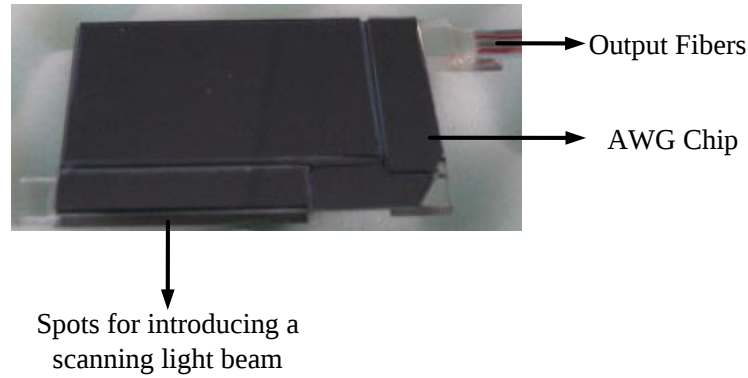


Fig. 3.9. Illustration of the mechanical tuningAWG for the wavelength interrogation unit.

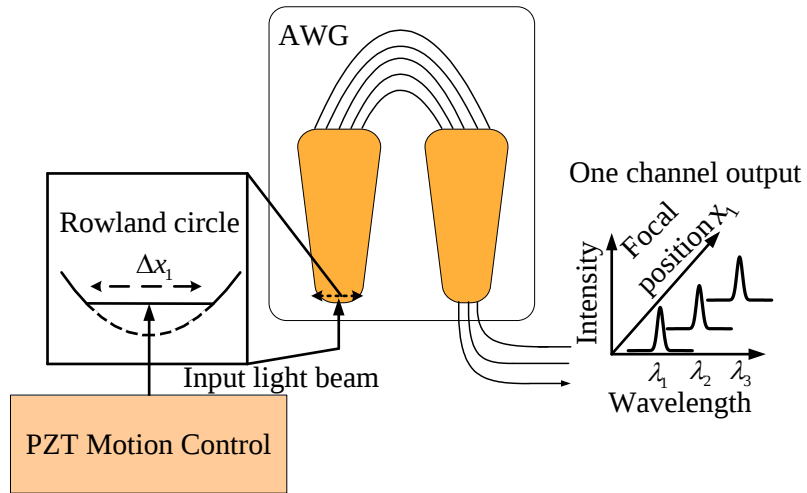


Fig. 3.10. Illustration of the mechanical tuningAWG methodology.

It is noted that the AWG shown in Fig. 3.9 does not have the input waveguide and the facet of the input coupler is right on the edge, facilitating the position scanning of an optical fiber along the side of the AWG chip. In addition, the Rowland Circle has been partly cut off to minimize

the insertion loss of the coupling between the optical fiber and the input coupler as discussed and shown in Fig. 2.3.

To achieve the mechanical tuning spectrum, a piezo motor (PZT) is introduced to change the input light position along the cut AWG input coupler as shown in Fig. 3.10.

For a fixed AWG output channel, (2-13) shows that its center wavelength has a linear relationship with respect to the input light beam position. Thus, by knowing the input light position which corresponds to the maximum value of the received light and this linear relationship, the center wavelength of FBG sensor can be interrogated. There are two types of PZT motion control methods, open-loop and closed-loop. Compared with the two methods, open-loop motion control has a significantly lower cost as it does not have the position sensor. Thus, in the open-loop motion control, only the start and end position are known, the acceleration, deceleration, and travel speed are unknown. In this case, there is no position feedback from the PZT motion control, making it hard to determine the input light position corresponding to the peak value of the received light. The advantages of using open-loop motion control are the low cost and easy implementation of the setup. To overcome this drawback, we introduce a wavelength reference component into the system, which is a sampled chirped FBG (SCFBG). Detail and demonstration will be discussed in Chapter 3.2.2. Though we are able to use open-loop motion control in the mechanical tuning AWG wavelength interrogation unit, it is always of great interest to obtain the input light position in real time. The real time position feedback can then be used to reproduce the detailed changes of the FBG spectrum. Therefore, we also develop a closed-loop mechanical tuning AWG wavelength interrogation unit. In this unit, a position sensor is installed into the PZT motor head and used to provide the real time input light position. Then, the physical input light position and the center

wavelength of the designated AWG channel can be associated by the space-to-wavelength mapping. FBG and tilted FBG (TFBG) sensors are used to show the closed-loop mechanical turning AWG has the features of high resolution and broadband range with high accuracy in Chapter 3.2.3 and 3.2.4 respectively.

3.2.1. Characterization of a mechanical tuning AWG

The linear relationship between the center wavelength of a designated AWG channel and the input light position is first tested by continuously adjusting the input light position from 0 μm to 100 μm and measuring the spectrum of this AWG channel. The result is shown in Fig. 3.11.

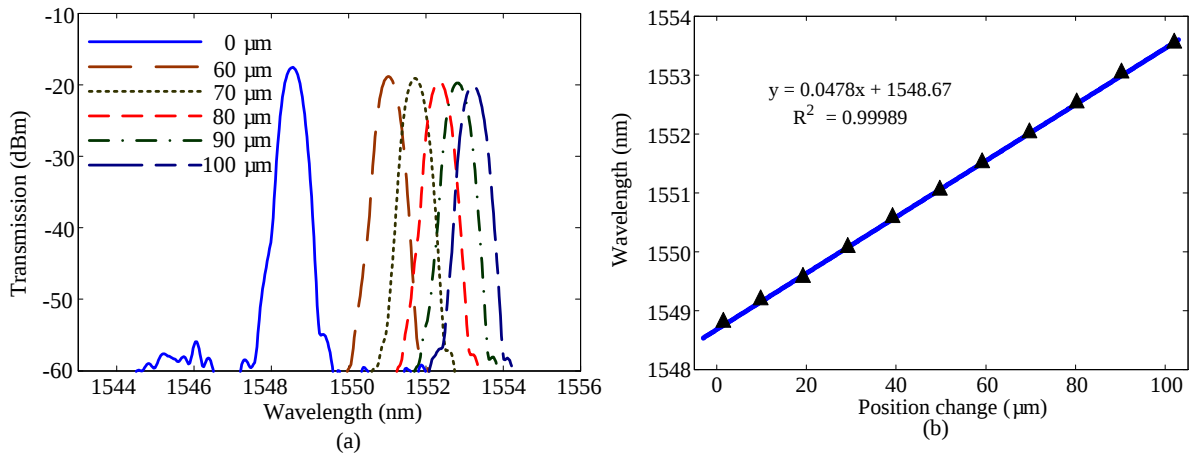


Fig. 3.11. Illustration of the space-to-wavelength mapping. (a) Shifted spectrum of one designated AWG channel with changes of the input light beam position. (b) Relationship between the transmission wavelength of the AWG channel and the input light position.

As it shows in Fig. 3.11(a), the center wavelength of the designated AWG channel is shifted while the input light beam position changes. During the shifting, the spectrum profiles remain unchanged, validating our assumption that the operation of the AWG is not affected by the structure changes when slightly cutting part of the Rowland Circle into a slab waveguide. In addition, Fig. 3.11(b) shows the experimental result that the wavelength shifts at a constant rate,

meaning that the space-to-wavelength mapping has a linear relationship as the theoretical simulation shown in Fig. 2.2 and (2-13). The different power level of the shifted spectrum is believed to be attributed to the non-uniform gain profile of the optical amplifier used in this test. Therefore, the proposed space-to-wavelength mapping is verified and the relationship is set up for the wavelength interrogation.

3.2.2. Wavelength interrogation using an open-loop mechanical tuning AWG for an LPG sensor²

In this work, an open-loop mechanical tuning AWG is used to build the wavelength interrogation unit for an LPG sensor. The use of open-loop mechanical tuning AWG has the advantages of low cost and simple setup on the PZT motion control. Since it does not have the real time position feedback, a sampled chirped FBG (SCFBG) is used to provide the wavelength reference.

I. Introduction

Previous studies shows the advantages of using spectrum tuning technique for the wavelength interrogation instead of conventional techniques, including fixed AWG spectrum technique, for the LPG and FBG sensors. In Chapter 3.1, we summarize the benefits for using thermal tuning spectrum of an AWG. However, the current major difficulty associated in this method is the low speed limited by the response time of the thermal film heater. In this work, we propose and demonstrate a novel technique to interrogate an LPG sensor. The technique is implemented

² This section is a revised version of the following published paper. Article title: Interrogation of a long period grating using a mechanically scannable arrayed waveguide grating and a sampled chirped fiber Bragg grating. Authors: Honglei Guo, Yitang Dai, Gaozhi Xiao, Nezhir Mrad, and Jianping Yao. Published in OSA Optics Letters, vol. 33, no. 15, pp. 1635-1637, Aug. 2008.

based on space-to-wavelength mapping by mechanical scanning the input light beam along the input coupler facet of an AWG.

Open-loop motion control is used in this work which decreases the cost and simplifies the motion control setup, but meets the challenge of determining the input light position along the input coupler of the AWG. To solve this problem, an SCFBG is employed into the system. The SCFBG is connected into a paralleled arm of the LPG sensor, which does not affect the simple setup of the motion control. The SCFBG is a special fiber grating with multiple peaks, which are used to build a mapping between the wavelength and the number of sampling points. Basically, the SCFBG can be regarded as a multichannel comb filter which is fabricated by sampling a regular chirped FBG with a specific sampling period to achieve the required wavelength spacing [180]. Due to the position uncertainty introduced by the hysteresis and the scanning speed non-uniformity, a space-to-wavelength mapping should be established for each scan, which is realized by comparing the SCFBG peak wavelengths with the measured sampling points.

When the input light beam is scanning along the input coupler facet of the AWG, the transmission wavelength of the AWG is shifted. The received light intensity will reach its minimum when the AWG transmission wavelength is located at the center wavelength of the LPG. Then, the received light intensity will increase as the input light beam moves further. Thus, by knowing the position of the input light beam corresponding to the minimum light intensity with the assistance of the reference SCFBG, the center wavelength of the LPG can be measured.

II. *Experimental result*

To evaluate the feasibility of the proposed scheme, an experimental interrogation setup illustrated in Fig. 3.12 is built, consisting of a broadband source (BBS), an erbium-doped fiber amplifier (EDFA), an AWG, a PZT, an SCFBG, and two photodetectors (PDs). The fiber tail at the output of the EDFA is mounted on a piezo motor which is moving along the input coupler facet of the AWG. The output light is split into two channels via a 3dB fiber coupler, with one channel connected to the LPG under interrogation and the other connected to the SCFBG. A thermal electrical cooler (TEC) is used to control the temperature of the SCFBG to eliminate its wavelength drifts due to the environmental temperature variations. A data acquisition (DAQ) card is employed to record the electrical voltages representing the light intensity. With the same trigger provided by the DAQ card itself, the measured data are acquired from the two channels at the same time, establishing the relationship between the wavelengths and sampling points within each scan. The position uncertainty introduced by the hysteresis of the open-loop piezo motor and non-uniformity of the scanning speed are overcome by the space-to-wavelength mapping implemented by the SCFBG. Finally, the center wavelength of the LPG is interrogated by interpolating the measured data to find a sampling point representing the LPG dip with the space-to-wavelength mapping.

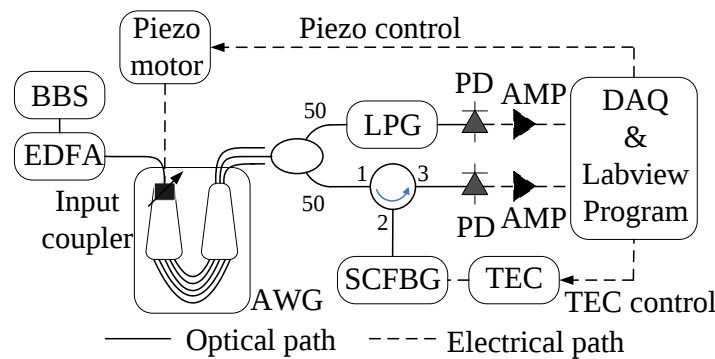


Fig. 3.12. Experimental setup for the wavelength interrogation of an LPG sensor based on open-loop mechanical tuning AWG.

The dependence of the wavelength on the input light position is measured to be 47.8 pm/ μ m, as shown in Fig. 3.11 (b). Fig. 3.13 shows the reflective spectrum of the SCFBG measured by an OSA with a resolution of 10 pm, with the selected peak wavelengths labeled in the figure.

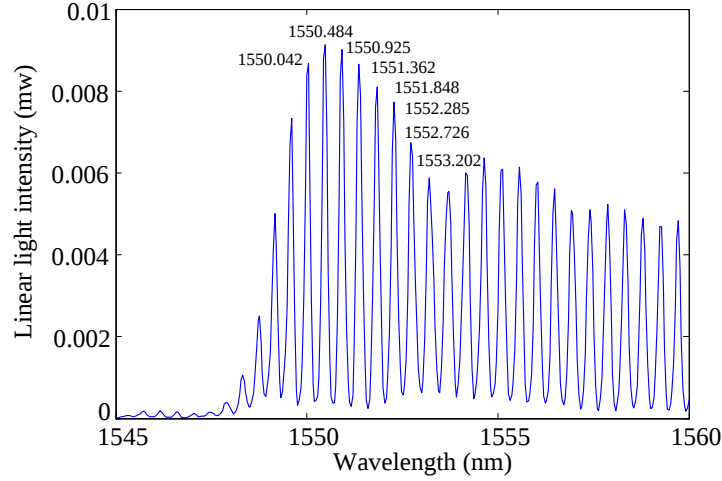


Fig. 3.13. Reflective spectrum of the SCFBG measured by an OSA.

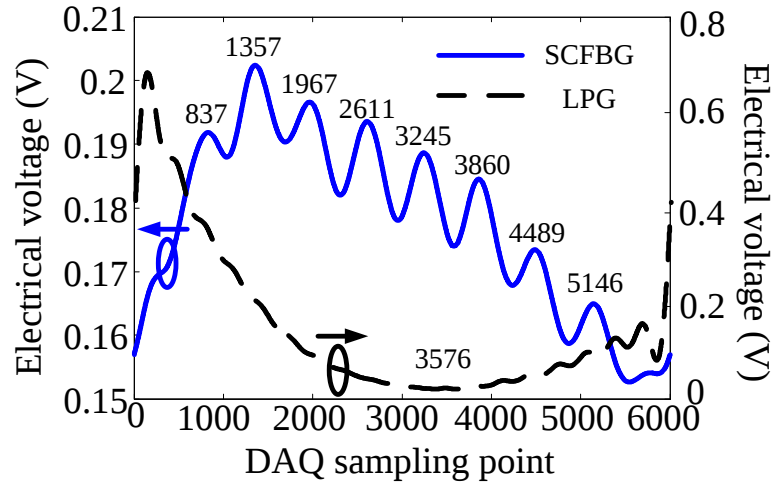


Fig. 3.14. Experimental interrogation results of an LPG sensor by open-loop mechanical tuning AWG.

Fig. 3.14 shows the experimental results. The peak wavelengths and their corresponding sampling points are obtained by comparing the solid line in Fig. 3.14 with Fig. 3.13. The DAQ sampling point corresponding to the minimum value of the dashed line in Fig. 3.14 is measured

as 3576. The center wavelength of the LPG is measured to be 1552.083 nm as discussed above. Compared with the center wavelength of 1552.080 nm at room temperature supplied by the manufacturer, a good agreement is achieved. The small variation is believed to be due to the determination of the desired sampling point because the minimum range is broad.

III. Discussion

The piezo motor applied in this experiment has a maximum speed of 500 mm/s. A physical distance along the input coupler of 1 mm is required to achieve a spectral scanning range of 50 nm based on the AWG wavelength tunability of ~ 0.05 nm/ μm . If the piezo motor works at its maximum speed, a physical scanning distance of 1 mm can be completed within 2 ms. Therefore, the scanning speed can be as high as 500 Hz with a spectral scanning range of 50 nm, which would make the proposed interrogation technique feasible for most applications where a large measurement range and fast speed are required.

In this experiment, the DAQ card is set at a sampling speed of 60k samples per second (kS/s). For the sake of simplicity of demonstrating the concept, 6k sampling points representing a spectral range of ~ 4 nm, as shown in Fig. 4 and 5, are obtained within 100 ms, which provides a resolution of 0.67 pm and a scanning speed of 10 Hz. However, the resolution achieved in this experiment is restricted to 10 pm by the OSA resolution. The resolution of the proposed interrogation technique can be highly improved if the reference SCFBG spectrum is calibrated by a state-of-the-art interrogator with sub-pm resolution. Meanwhile, the resolution, as well as the accuracy, can be improved if an AWG with a smaller 3-dB bandwidth is applied. The AWG used in this experiment has a 3-dB bandwidth of 0.4 nm, which is the maximum value that is suitable for the scanning of the current SCFBG, because the wavelength spacing of the SCFBG

is around 0.4 nm. If an SCFBG with smaller wavelength spacing is employed, an AWG with an equal to or smaller 3-dB bandwidth should be used. Furthermore, the maximum sampling speed of the current DAQ card is ~300 kS/s in the condition that only two input channels are in operation. Compared with the sampling speed of 60 kS/s incorporated in this work, the resolution will be 5 times higher if the DAQ card is working at 300 kS/s

IV. Conclusion

A new technique to interrogate an LPG sensor by mechanical tuning the input light position along the input coupler of an AWG has been demonstrated. By using the space-to-wavelength mapping provided by an SCFBG, the center wavelength of the LPG with a resolution of 10 pm was interrogated. The proposed system has the potential to operate at an interrogation resolution better than 1 pm and an interrogation range of 50 nm with a scanning speed up to 500 Hz.

3.2.3. Wavelength interrogation using a closed-loop mechanical tuning AWG for FBG sensors³

Previous studies shows a technique for wavelength interrogation based on space-to-wavelength mapping, in which an open-loop motion control is employed to scan the input light along the AWG input coupler. Since the beam position was not known, an additional wavelength reference device, such as an SCFBG, is used. The use of an additional wavelength reference makes the interrogation wavelength range, resolution, and accuracy limited by the additional wavelength reference device. To overcome these technical challenges, we propose and

³ This section is a revised version of the following published paper. Article title: Wavelength interrogator based on closed-loop piezo-electrically scanned space-to-wavelength mapping of an arrayed waveguide grating. Authors: Honglei Guo, Gaozhi Xiao, Nezih Mrad, Jacques Albert, and Jianping Yao. Published in Journal of Lightwave Technology, vol. 28, no. 18, pp. 2654-2659, Sep. 2010.

demonstrate an AWG based interrogation technique based on space-to-wavelength mapping using a closed-loop motion control.

I. Introduction

The proposed interrogation technique is evaluated with single channel and multiple channels respectively. First, a single FBG sensor is used for the wavelength interrogation. Since the proposed technique provides an absolute position of the input light beam, experimental results indicate that an accurate measurement with a high resolution of 3 pm is achieved. Then, a multichannel measurement of our proposed interrogation technique is tested by simultaneously interrogating 4 distributed FBG sensors with the use of four designated AWG channels.

II. Experimental result

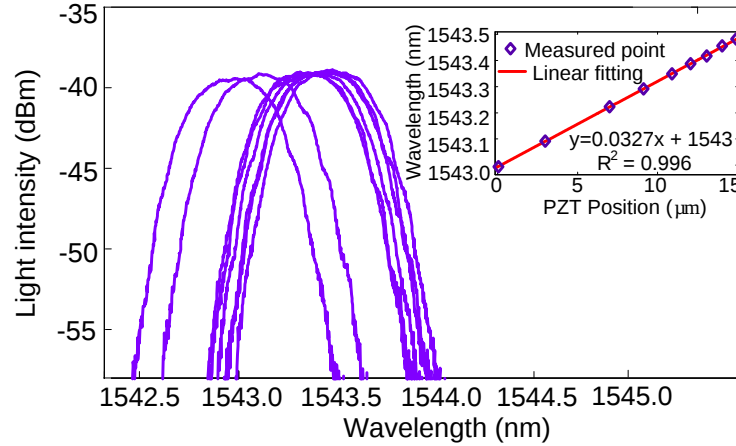


Fig. 3.15. Spectrum and wavelength shift of a designated AWG channel as a function of the beam position.

First, the space-to-wavelength mapping of this setup needs to be performed as a calibration step. When the position of the input light beam is varied from 0 to 15 μm, we obtain the transmission spectrum. The AWG transmission spectrum is measured using a photodetector (PD) and a

tunable laser source with a tuning step of 1 pm. As shown in the inset of Fig. 3.15, a linear fitting function is obtained which gives the space-to-wavelength mapping coefficient κ_A ,

$$\lambda_A(x_1) = 1543.000 + 0.0327\Delta x_1 \quad (3-4)$$

A tuning spectral range of 0.49 nm is obtained within a 15- μm travel range of the input light beam and the coefficient is measured to be 32.7 nm/ μm .

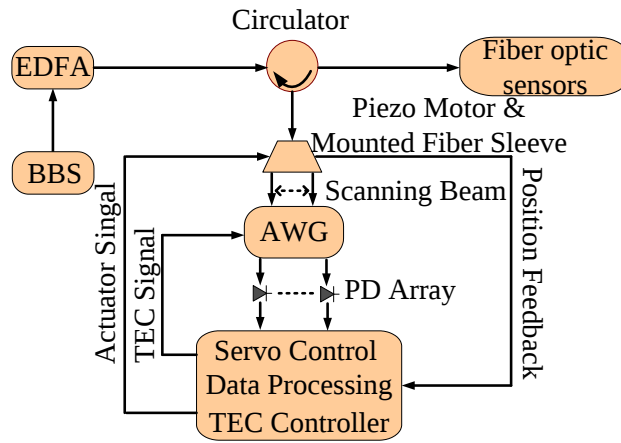


Fig. 3.16. Experimental setup of the closed-loop mechanical tuning AWG for FBG sensor wavelength interrogation.

The experimental setup is shown in Fig. 3.16. A light beam from a broadband source (BBS) is amplified by an erbium-doped fiber amplifier (EDFA), and then sent to the fiber optic sensors through a circulator. The output fiber tail of the circulator is mounted on top of a closed-loop piezo motor, fixed and protected by a fiber sleeve, which is pre-aligned with the input coupler of an AWG using a positioning stage. The piezo motor moves horizontally driving the fiber tail to scan along the input coupler. A capacitive position encoder is embedded in the piezo motor to provide the absolute position of the scanning fiber tail. With the position feedback, an actuator signal is properly set to drive the piezo motor to reach the specified position. This is regarded as

the closed-loop (servo) control. Due to the temperature dependence of the AWG transmission wavelength (reported as 11 pm/°C [148]), a thermal electrical cooler (TEC) is attached to the base of the AWG to compensate for the thermal variations due to the temperature drift. The output light power of the AWG is detected by a PD array. A Labview program is developed to collect and process the measurement data, and implement servo control of the piezo motor.

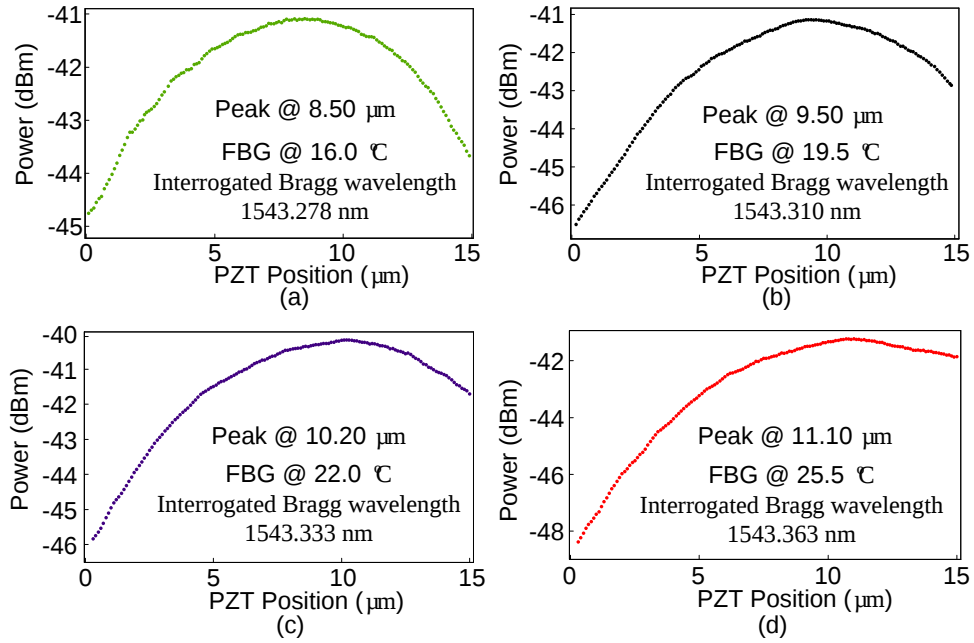


Fig. 3.17. Interrogation result of a single FBG sensor under four different temperatures, (a)-(d), as a function of the beam position.

Only one AWG channel is used in the above experiment. As discussed, one significant feature of applying an AWG for the wavelength interrogation is that it has multichannel measurement capability. In a second experiment, the interrogation of four distributed FBGs using four designated AWG channels is performed, in which the output powers of the four AWG channels are monitored.

Fig. 3.19(a) shows the spectrum of each AWG channel when the input light beam is located at four different positions (0 μm , 5 μm , 10 μm , and 15 μm) along the AWG input coupler. It is seen that the transmission wavelength of an AWG channel is shifted while the spectrum shape remains unchanged and the wavelength shift in each AWG channel keeps the same. The different power levels of the four AWG channels are believed to be attributed to the non-uniform gain profile of the EDFA. The interrogation of the four-FBG-based sensor is performed by measuring its temperature sensitivity, in which the sensor temperature is modified by an oven. As shown in Fig. 3.19(b), the temperature sensitivity is measured to be ~ 10 pm/ $^{\circ}\text{C}$ near the wavelength of 1550 nm for each FBG based sensor, which accords well with the results reported in [55].

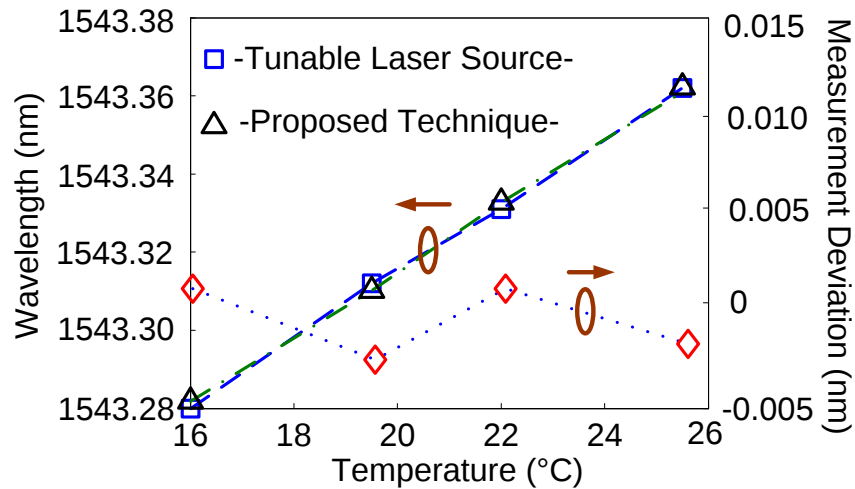


Fig. 3.18. Measured Bragg wavelength by the proposed technique and the use of a PD and a tunable laser source.

The experimental results in Fig. 3.19 show that the proposed interrogation technique has the capability of multichannel measurement and all the channels are able to constitute a zoom-in spectrum to reflect a small-scale wavelength shift.

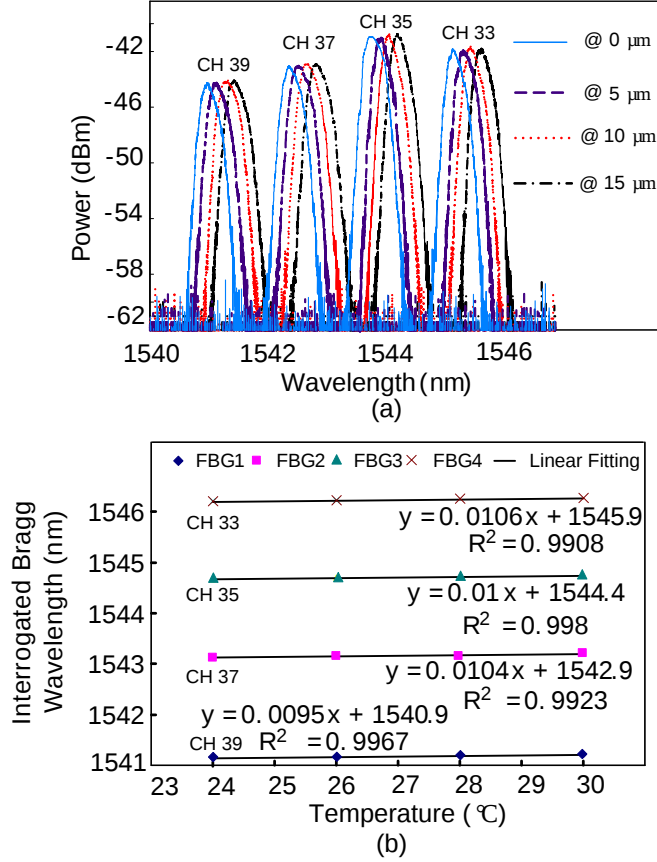


Fig. 3.19. Interrogation of a four-distributed-FBG sensor. (a) Shifted spectrum of each AWG channel with changed position of the input light beam. (b) Measured temperature sensitivity.

III. Discussion

The key difference between this technique and the one discussed in Chapter 3.2.2 is that the wavelength is accurately interrogated here by reading the beam position provided by the closed-loop control. While in the previous study, since the beam position was not known, a wavelength reference must be used to estimate the Bragg wavelength. Clearly, the use of the proposed technique in this paper would increase the interrogation accuracy and resolution. Since no wavelength reference device is needed, the proposed system has a smaller size with a reduced system complexity and increased system robustness.

To increase the wavelength interrogation range, a solution is to extend the travel range of the piezo motor, as discussed above. If the travel range is extended to 2 mm, a wavelength range of ~65 nm will be achieved, which covers the entire C band and part of the L band - a wavelength range that is wide enough for most of FBG sensor applications. The wavelength interrogation range can also be extended by cascading multi-AWG-channels. Our current AWG has a channel spacing of 0.8 nm. Since all the AWG channels have the same wavelength tuning capability, a PZT motor travel range of 25 μm will allow each AWG channel cover an interrogation range of 0.8 nm. In such a case, cascaded multi-AWG-channels will cover a broader interrogation range. Compared to the first method to increase the interrogation range, this method is not vulnerable to the size of the cut Rowland Circle and it further decreases the requirements of the PZT motor and the fiber-to-waveguide coupling due to reduced PZT motor travel range. Furthermore, the reduced PZT motor travel range can increase the interrogation speed. Our current PZT motor has a maximum travel speed of 400 mm/s (PI, M-663.465). It could provide an interrogation speed of 16 kHz if a travel range of 25 μm is needed as discussed above. The broad interrogation range and fast interrogation speed are particularly suitable for the vibration measurement using a TFBG sensor.

In this paper, a positioning stage is still required for the light coupling from the input fiber into the input coupler of an AWG. The butt-to-butt coupling results in a high attenuation of 25 dB, as shown in Fig. 8, which reduces the performance of the entire interrogation system. The use of a recently developed sub-wavelength grating coupler could be a solution. In a sub-wavelength grating coupler, the light is designed to be coupled into the input coupler of an AWG from its top surface with the coupling grating structure fabricated directly onto the input coupler. As a

result, positioning stage is no longer required. A simple configuration with better robustness and higher coupling efficiency has been reported [181].

IV. Conclusion

We have demonstrated a wavelength interrogation technique based on space-to-wavelength mapping implemented by an AWG and a closed-loop controlled piezoelectric motor. The interrogation was performed by scanning the light beam along the AWG input coupler, with the beam position controlled by a closed-loop piezoelectric motor. A fixed relationship between the beam position and the transmission wavelength of the AWG channel was established, making it possible to interrogate the wavelength by simply measuring beam positions. The key contribution of this technique was the use of a closed-loop controlled piezoelectric motor which could increase the wavelength range and resolution of the interrogation system. Since no additional wavelength reference device was needed, the system was greatly simplified. Four-distributed FBGs were successfully interrogated, which confirmed the multichannel measurement capability of the proposed technique. The proposed AWG based interrogation technique has a high potential to be packaged into a miniaturized, light weight and cost-efficient device with high performance.

3.2.4. Wavelength interrogation using a closed-loop mechanical tuning AWG for a TFBG sensor⁴

Previous studies show the performance of the closed-loop mechanical tuning AWG spectrum in FBG sensor wavelength interrogation. The measurement range is limited by the travel range of the piezo motor. The maximum travel range of the PZT motor used before is 15 μm . Now we use a new PZT motor to extend the travel range from 15 μm to 1 mm. As the space-to-wavelength mapping coefficient is 47.8 pm/ μm , the measurement range can increase up to 47.8 nm. Due to the large measurement range, we apply this for the wavelength interrogation of a TFBG sensor.

I. Introduction

Previous studies show the open-loop and closed-loop mechanical tuning AWG. In this work, we extend the travel range of the PZT motor from 15 μm to 1 mm, which significantly increases the measurement range as discussed in Chapter 3.2.3. By involving the space-to-wavelength mapping, the overall interrogation range is determined by the travel range of the input beam and the specific space-to-wavelength coefficient. In our experiment, the wavelength tunability is first measured with respect to the position of the input light beam. A spectral scanning of 4.78 nm is achieved by changing the input light position of 100 μm . Thus, the coefficient is 47.8 pm/ μm for this particular AWG channel. According to the AWG principle [141], all the AWG channels should have the same wavelength tuning capability. Therefore, the coefficient for all the AWG channel is defined as 47.8 pm/ μm in this experiment. The total travel range of the

⁴This section is a revised version of the following published paper. Article title: Wavelength interrogation of a tilted fiber Bragg grating sensor using space-to-wavelength mapping of an arrayed waveguide grating with closed-loop piezo-electrical control. Authors: Honglei Guo, Liyang Shao, Gaozhi Xiao, Nezih Mrad, and Jianping Yao. Published in IEEE Sensors 2010 Conference, pp. 1152-1155, Nov. 2010.

input beam has a maximum value of 1 mm, which makes the overall interrogation range up to 47.8 nm. However, only portion of this maximum value is enough for the measurement of refractive index using a TFBG sensor according to its sensing principle as described above.

In this design, the real-time position of the input beam is obtained by a position encoder which is integrated into a closed-loop piezoelectric motor. Therefore, the position can be accurately measured. By employing the calibrated space-to-wavelength mapping relationship, the wavelength can be achieved by substituting the position into the linear relationship. In the comparison with previously reported TFBG sensor interrogators, our proposed technique has features of (1) broad interrogation range, (2) high resolution, (3) multi-channel measurement capability, (4) fast speed, and (5) cost-effective solution.

II. Experimental result

Fig. 3.20 shows the experimental setup. Similar to the one used in Chapter 3.2.3, A broadband source (BBS) is used as the light source. Its output light is amplified by an erbium-doped fiber amplifier (EDFA), and then directly sent to a TFBG sensor. The output fiber tail of the sensor is mounted on top of a closed-loop piezo motor, fixed and protected by a fiber sleeve. A positioning stage is used to achieve the pre-alignment between the fiber and the AWG. When the piezo motor moves horizontally, it drives the fiber tail to scan along the input coupler of the AWG. The absolute position of the scanning fiber tail is provided by a position encoder embedded in the piezo motor. With the real-time position feedback, an actuator signal is properly set to drive the piezo motor to move a specific step. This is regarded as the closed-loop (servo) control. Since the transmission wavelength of an AWG is temperature dependent, the AWG needs a temperature compensation device for accurate measurement. In our experimental

setup, a thermal electrical cooler (TEC) is attached to the base of the AWG for this purpose. The output light power of the AWG is detected by a PD array and amplified by an operational amplifier (AMP). All the controls, data acquisition and processing are implemented by a Labview program.

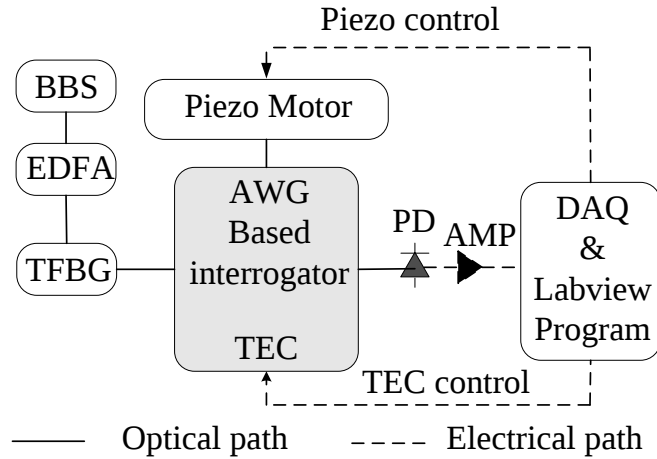


Fig. 3.20. Experimental setup of the closed-loop mechanical tuning AWG with extended travel range for the TFBG sensor wavelength interrogation.

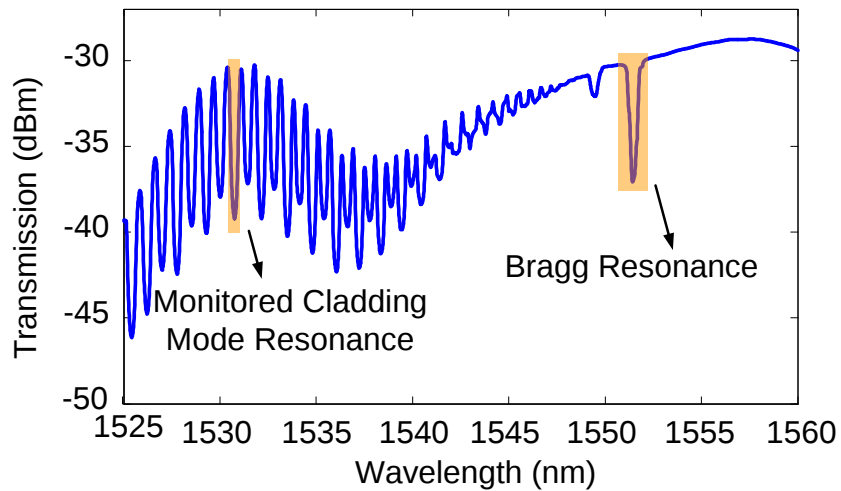


Fig. 3.21. Measured transmission spectrum of the TFBG sensor.

With the same techniques discussed in Chapter 3.2.3, the transmission spectrum of the TFBG sensor is obtained and shown in Fig. 3.21.

The TFBG sensor used in this paper is written in a hydrogen-loaded Corning SMF-28 optical fiber using a pulsed KrF excimer laser. The tilted angle of the grating planes is achieved by rotating the phase mask of 6° with respect to the optical fiber with a rotation stage. As described above, a relative wavelength spacing is measured to reflect the refractive index changes. In our experiment, both the Bragg resonance (1551.506 nm) and a cladding mode resonance (1536.008 nm) are selected. Higher order cladding mode resonances are located further away from the Bragg resonance. Since these modes are more sensitive to the refractive index of the surrounding medium, they are of great interests in measuring the refractive index. However, it is also facing a challenge of the wavelength interrogation. The wavelength spacing is 15.498 nm measured when the TFBG sensor is present in the air.

For refractive index measurement, water-sugar solutions with different weight concentrations are used to provide a wide range of refractive indices. The weight concentration starts from 10% to 40% with steps of 5%. The refractive indices are measured using an Abbe refractometer. The results show that the refractive indices vary from 1.35 to 1.40 with steps of 0.0083, corresponding to the weight concentration varying from 10% to 40% with steps of 5%. The TFBG sensor is immersed in the solutions and transmission wavelength of target resonances are obtained with the principle described in detail in [150]. The corresponding wavelength spacing is then obtained and shown in Fig. 3.22.

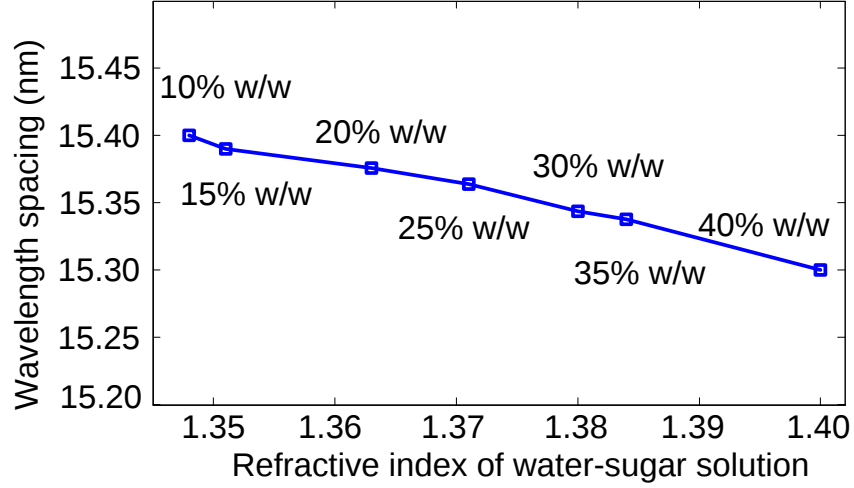


Fig. 3.22. Experimental wavelength spacing measured by the proposed interrogator between the cladding mode resonance and the Bragg resonance as a function of the refractive index of water-sugar solutions.

Fig. 3.22 shows the measured wavelength spacing with our proposed and developed interrogator. Comparing this result with the one measured by an OSA, the deviations are within ± 0.01 nm. Therefore, agreement has been achieved between the results measured by our interrogator and an OSA, and our interrogator is approved to have the capability to measure the transmission wavelengths of a TFBG sensor, which is then used for refractive index measurement purpose.

III. Discussion

Initial results show that (1) the interrogation range is determined by the wavelength tunability, which has a maximum value of 47.8 nm in our design with this particular AWG, given that the travel range of the piezo motor is 1 mm and the space-to-wavelength mapping coefficient is 47.8 pm/ μ m. This range is broad enough for most TFBG sensor applications; (2) the spectrum resolution is determined by the spatial tuning step of the closed-loop piezo motor, which is 4.78 nm in this experiment by setting the spatial tuning step of 0.1 μ m. Higher resolution could be reached by a smaller spatial tuning step; (3) the multi-channel measurement capability is

determined by the characteristics of the AWG. All the AWG channels have the same wavelength tunability. If each AWG channel is used for monitoring a single TFBG sensor, a total of 32 TFBG sensors could be simultaneously monitored in our present design with this particular AWG; (4) the interrogation speed is determined by the travel speed of the piezo motor. The present piezo motor has a maximum speed of 500 mm/s, which makes the interrogation speed up to 1 kHz; (5) since a commercial standard AWG is used in this experiment, there is no need to design and fabricate an AWG chip with new structures, which significantly decreases the total cost.

IV. Conclusion

We have successfully achieved the wavelength interrogation of a TFBG sensor in the refractive index measurement with our proposed and developed interrogator based on an AWG. By using a closed-loop control mechanism, the input beam position was obtained. The space-to-wavelength mapping was tested and used to convert the positions into the transmission wavelength of target resonances in the TFBG transmission spectrum. Since each AWG channel was capable to monitor one TFBG sensor in our design, a multichannel measurement capability could be achieved by using multiple AWG output channels. Besides that our interrogator had a potential to reach advanced performance, another important advantage of our AWG based interrogator was cost-effective, since the AWG used in our design was a standard commercial product, which implied obvious cost effects. Furthermore, our interrogator was miniaturized in size and light in weight, which could be packaged into a palm-size device.

CHAPTER 4 WAVELENGTH INTERROGATION BASED ON EDG

Previous studies discuss the use of an AWG for the wavelength interrogation of fiber grating sensors with the spectrum tuning technique and peak matching technique. Similar to an AWG, an EDG is another major type of PLCs that has already been widely used in the optical communication systems as mux and demux components [182-183]. The operation principle of an EDG is fully detailed in [184-185]. As an EDG uses the reflection light rather than the transmission light to build the phase difference, which is used to spatially separate lights with different wavelengths, it has a size at least half of the AWG chip. Considering the requirement for the wavelength interrogation unit from the aircraft SHM applications, the smaller size of the PLCs will lead to additional advantages, such as fast response speed, low power consumption, and improved portability. Therefore, employing a similar wavelength interrogation principle of thermal tuning spectrum, we have also prototype miniaturized interrogation units based on a monolithically packaged EDG device [152-153, 186-187].

The EDG device we use is a standard commercial product with monolithically packaged PDs and fiber tail. Thus, only thermal tuning technique is used in the prototypes. In this session, the thermal tuning performance of an EDG is first analyzed. Then, the wavelength interrogation applications for an FBG sensor and FBG/LPG sensor pair are demonstrated. Third, the advanced model of the EDG based miniaturized wavelength interrogation unit is present with the capability to measure both static and dynamic strain changes.

4.1. Characterization of a thermal tuning EDG

The EDG device consists of a 1×32 EDG demultiplexer, a detector array, a thermal electric cooler (TEC), and a RTD. The whole device is made on an indium phosphide (InP) chip. Fig. 4.1(a) shows the inside of the EDG device with a dimension of $20 \text{ mm} \times 7.3 \text{ mm}$. Fig. 4.1(b) illustrates the EDG device packaged inside a house with 60 electrical pins. The whole packaged device has a weight of less than 60 g and a miniaturized dimension of $45 \text{ mm} \times 30 \text{ mm} \times 15 \text{ mm}$, making it ideal for the development of a micro interrogation unit in the aircraft SHM applications.

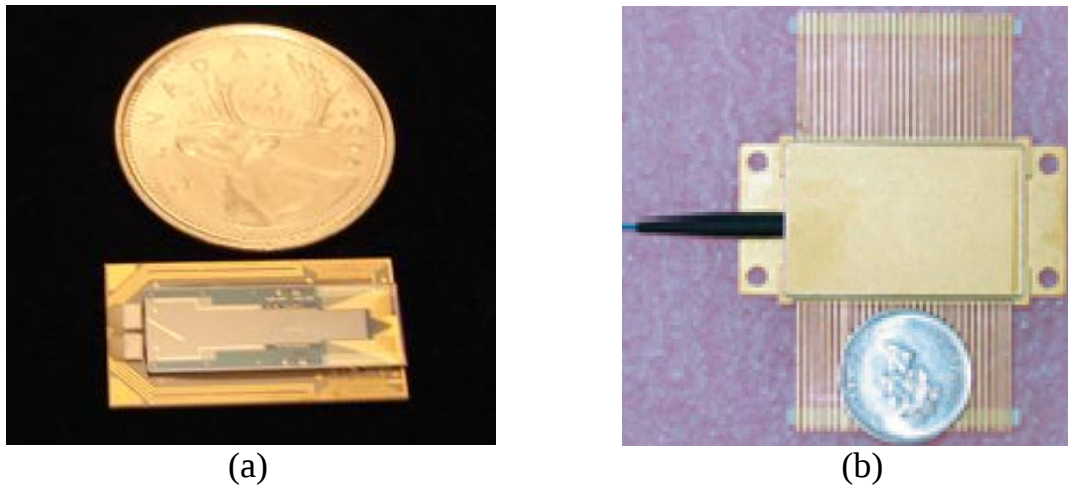


Fig. 4.1. Monolithically integrated EDG device. (a) Open box (chip dimension: $20 \times 7.3 \text{ mm}$) and (b) closed box (box dimension: $45 \text{ mm} \times 30 \text{ mm} \times 15 \text{ mm}$).

The full spectrum of this EDG device with 32 channels is shown in Fig. 4.2.

Our first design has a 16-channel data acquisition module. Since one analog input channel is assigned to detect the EDG temperature, only 15 EDG channels can be connected. In order to achieve a broad measurement range, we connect the odd number EDG channels in our first

prototype. Since the channel spacing of the EDG demultiplexer is 0.8 nm [183], the channel spacing in our first prototype is enlarged into 1.6 nm.

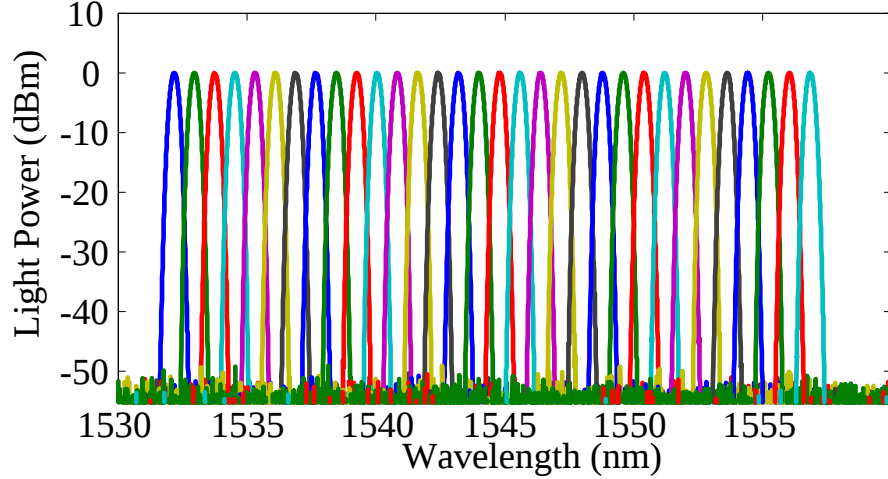


Fig. 4.2. Spectrum of the 32-channel EDG at ambient room temperature.

To further miniaturize the package dimension, the detector array is also integrated with the EDG multiplexer on the InP chip using semiconductor processing techniques. As the refractive index of the InP changes linearly with the chip temperature in the range of 10-60 °C, the center wavelength of an EDG channel should also change linearly with respect to the EDG temperature at a constant rate [186]. Since this rate is much higher than the one of an AWG, which is ~ 11 pm/°C [148], the temperature tuning range is significantly reduced. Thus, in this design, a TEC is used to replace a film heater to control the temperature. By changing the electrical input to the TEC, the EDG temperature could be precisely controlled and tuned. The RTD performs the same function of providing the temperature feedback in the closed-loop temperature control.

To validate the linear temperature dependency of the center wavelength, the relationship between the center wavelength and EDG temperature for all the 15 EDG channels are measured with the result shown in Fig. 4.3.

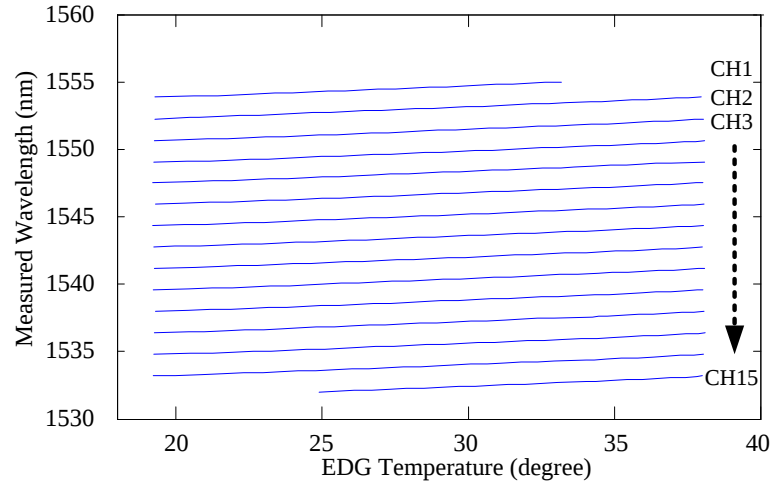


Fig. 4.3. Relationship between the EDG temperature and the transmission wavelengths of the 15 EDG channels.

The linear relationship between the center wavelength and EDG temperature is measured as ~ 90 pm/ $^{\circ}\text{C}$. Fig. 4.3 shows that the EDG has the same linear temperature dependency of the center wavelength with a larger rate.

For wavelength interrogation applications, as discussed in Chapter 2.2, the EDG spectrum should keep constant during the spectrum shifting. To validate this assumption, three EDG channels are selected to show the shifting spectrum while adjusting the EDG temperatures with the result shown in Fig. 4.4.

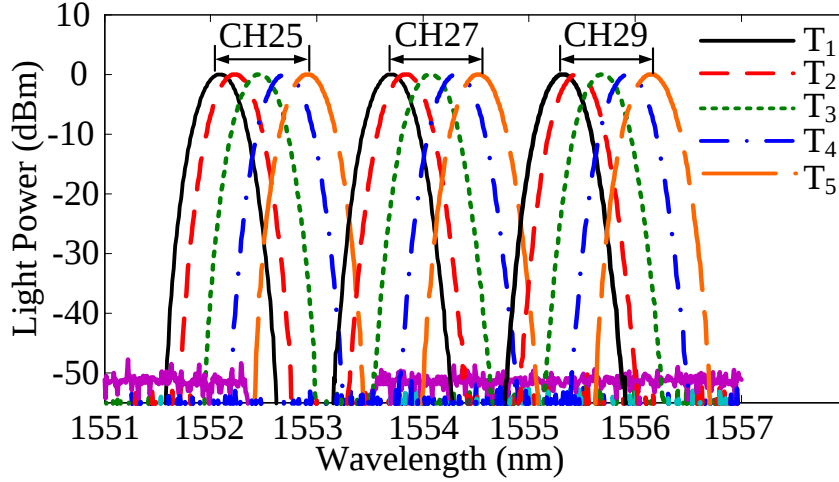


Fig. 4.4. Spectrum shift of the selected EDG channels versus temperature changes.

Five discrete temperature values (T_1 to T_5) between 19 °C to 29 °C are chosen to test the sweeping spectrum of the modified EDG based interrogator. It is seen that the sweeping spectrum profile of each channel keeps constant while the EDG temperature changes.

It is seen that a linear relationship between the center wavelength of an EDG channel and EDG temperature is achieved and its spectrum profile keeps undistorted during the spectrum shifting. Thus, the EDG is verified to be able to use for the wavelength interrogation with the same methodology as the AWG used in Chapter 3.

4.2. Wavelength interrogation using a thermal tuning EDG

Two lab prototypes are developed based on this EDG device. The operation principle of the interrogation unit is shown in Fig. 4.5 and the two lab prototypes are shown in Fig. 4.6.

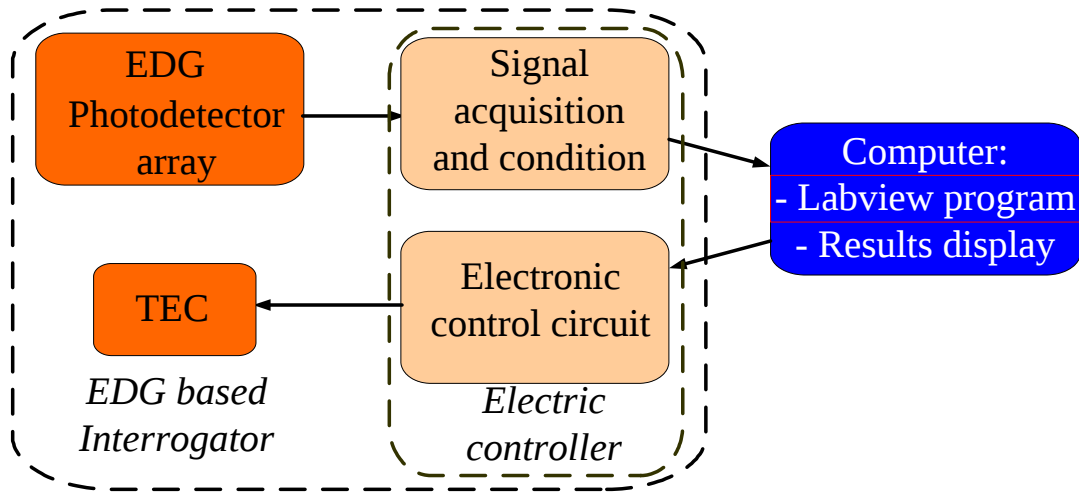


Fig. 4.5. Illustration of the operation principle of the EDG based interrogation unit.

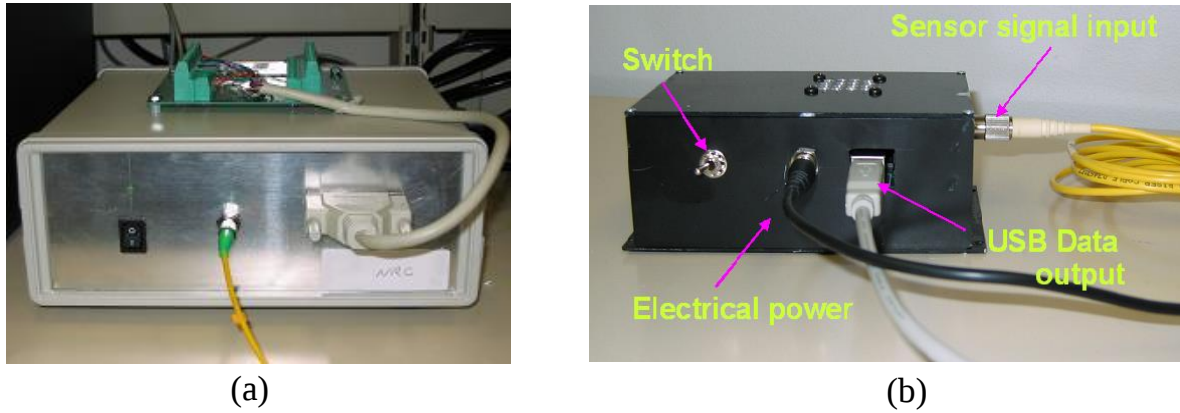


Fig. 4.6. Prototypes of the EDG based interrogation units. (a) Prototype based on NI-DAQ system, (b) Prototype based on Micro-Controller.

In Fig. 4.5, an electric controller is used to perform the data acquisition, signal amplification, temperature control, and A/D conversion. First, we use a data acquisition (DAQ) card and a signal conditioning board from National Instrument as the electric controller in the first lab prototype as shown in Fig. 4.6(a). It has a dimension of $250 \times 250 \times 110$ mm. In order to miniaturize the dimension, we develop the second lab prototype as shown in Fig. 4.6(b), which uses a micro-controller and a more sophisticated electric circuit to perform the electric

controller. Therefore, the dimension is reduced to $125 \times 73 \times 50$ mm. To demonstrate the performance of the prototypes, a variety of tests are implemented.

4.2.1 Wavelength interrogation for an FBG sensor using a thermal tuning EDG

In this test, the developed interrogation unit is used to monitor the load applied to an aluminum coupon. An FBG sensor is glued on this coupon with the standard M-bond AE10 adhesive, and placed at the mid-span of the coupon, where the strain distribution is known to be uniform. The coupon is then mounted in a 20 kips MTS Load Frame for the test. The test setup is shown in Fig. 4.7.

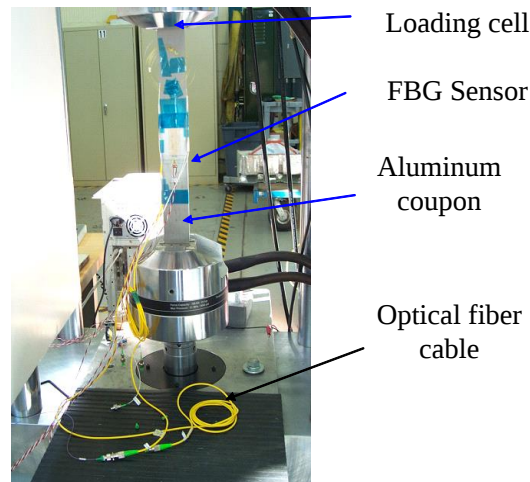


Fig. 4.7. Setup for testing the EDG based interrogation unit with an FBG bonded on an aluminium coupon.

Loads are applied to the coupon from 0 N to a maximum value of 31000 N (~ 3500 $\mu\epsilon$ of the coupon) at a step of 400 N with a 3-minute holding period after each load increasing.

The channel spacing of the EDG device is 0.8 nm. Limited by the number of PDs in your first prototype, only odd-number of EDG channels are connected, making the channel spacing of the

wavelength interrogation 1.6 nm. As the EDG temperature changes from 20 °C to 40 °C, each EDG channel can cover a maximum of 1.8 nm given the temperature coefficient is 90 pm/°C. The maximum strain of 3500 $\mu\epsilon$ applied on an FBG sensor usually makes the center wavelength of the FBG sensor change 3.5 nm with the strain coefficient of 1 pm/ $\mu\epsilon$ [55]. Obviously, the measurement range of a single EDG channel is not wide enough. Thus, two or more EDG channels have to be used to monitor this strain change applied on the FBG sensor. In this test, Channel 5, 6, and 7 of the interrogation unit are used to monitor the FBG wavelength changes. Fig. 4.8 shows the EDG temperatures corresponding to peak received light power at each load and the measured wavelength converted from these EDG temperatures.

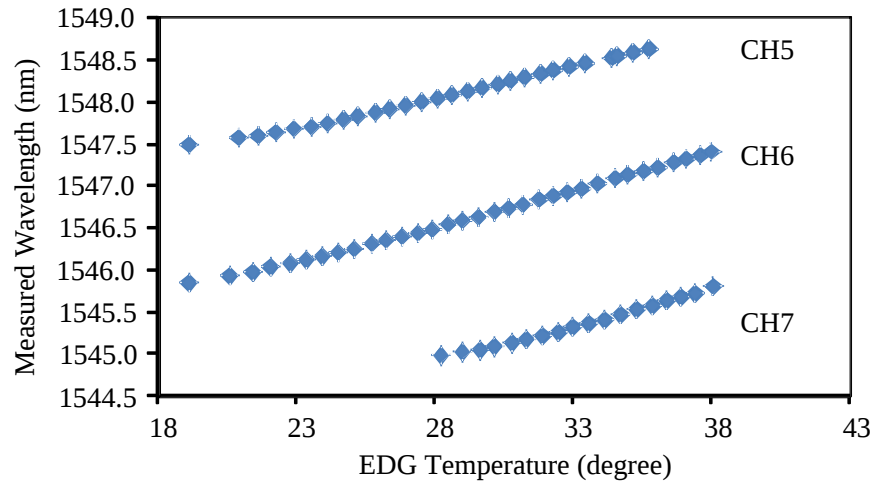


Fig. 4.8. EDG temperatures corresponding to the peak received light at each load and the measured wavelength.

Fig. 4.9 shows the relationship between the wavelengths measured by our developed interrogation unit and the applied loads. In order to evaluate the performance of our developed interrogation unit, the wavelength of the two FBG sensors is also measured by a multi-wavelength meter (HP 86120C) and the comparison between the two systems is shown in Fig. 4.10. As it shows, a strong correlation between the two systems has been achieved, which

confirms that our developed interrogation unit can be used in the strain measurement and operational load monitoring.

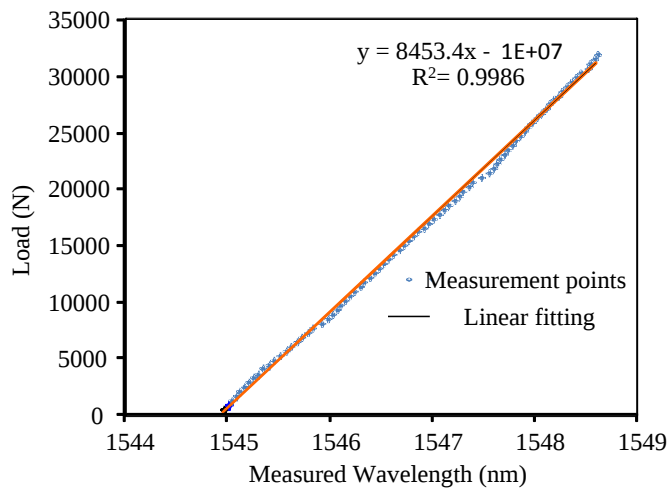


Fig. 4.9. Measured center wavelength of FBG sensor with respect to the applied load.

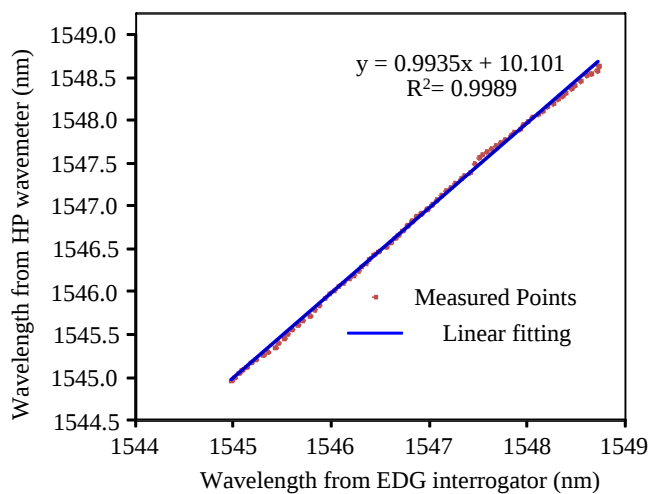


Fig. 4.10. Comparison between the measured wavelength and readings from an HP wavemeter.

4.2.2 Wavelength interrogation for FBG/LPG sensor using a thermal tuning EDG⁵

Previous studies show that thermal tuning EDG can successfully perform the wavelength interrogation for FBG sensors. In Chapter 4.2.1, the EDG temperature increases by a 0.01 °C step. In this work, the EDG temperature sweeps from the start value directly to the end value without introducing a number of steps. The measurement time for each EDG channel to scan 1.6 nm spectrum range is reduced from 30 sec to 10 sec.

I. Introduction

The FBG/LPG pair is selected to verify the new EDG temperature control. The selection of FBG/LPG pair is usually used for refractive-index (RI) sensor [63]. The use of single LPG sensor suffers from distinguishing wavelength shifts introduced by the cross sensitivity between RI and temperature [44-46]. Considerable effort has been devoted to develop techniques for the RI/temperature discrimination, such as dual-wavelength LPG sensors [188-189], LPG sensors packaged in two sections with different coatings [190], sandwiched LPG sensors [191] and hybrid FBG/LPG sensor pairs [63]. All the proposed techniques are based on the different temperature and RI responses of the two gratings or two sections of a single grating sensor. As a consequence, the RI/temperature discrimination effect significantly depends on these values. Due to the larger RI and temperature responses of LPG sensors, as compared to FBG sensors [192-193], and the simple configuration, the hybrid FBG/LPG is one of the most suitable approaches for the RI/temperature discrimination in the RI measurement. However, the key challenge for such an effective hybrid approach is the availability of wavelength interrogation

⁵ This section is a revised version of the following published paper. Article title: Simultaneous interrogation of a hybrid FBG/LPG sensor pair using a monolithically integrated Echelle diffractive grating. Authors: Honglei Guo, Gaozhi Xiao, Nezhir Mrad, and Jianping Yao. Published in Journal of Lightwave Technology, vol. 27, no. 12, pp. 2100-2104, Jun. 2009.

technique that is capable of simultaneously providing both high resolution and large wavelength range [46, 178].

The performance of the wavelength interrogation of an FBG sensor using thermal tuning EDG is demonstrated in Chapter 4.2.1. In this session, three EDG channels are used to cover a total measurement range larger than 3.5 nm, which is good for an LPG sensor wavelength interrogation. With the modified EDG temperature control, we are able to simultaneously perform the wavelength interrogation for FBG/LPG pair with high resolution and large measurement range.

II. Experimental result

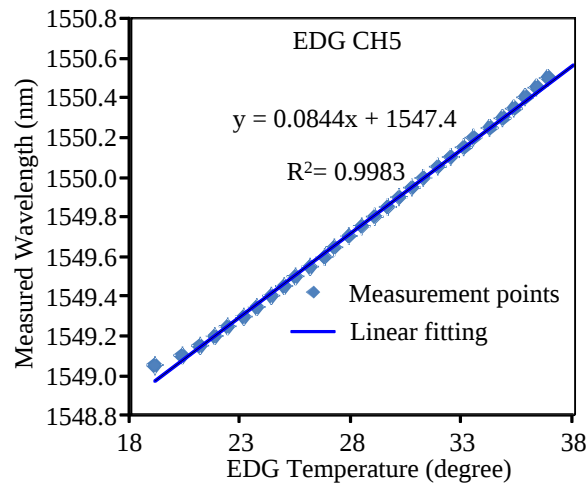


Fig. 4.11. Thermal tuning spectrum of a selected EDG channel with the new EDG temperature control.

Though the EDG temperature control is changed to reduce the temperature scan time cycle, the temperature coefficient of the center wavelength of EDG channels is an intrinsic characteristic determined by the structure and material of the EDG chip. This temperature coefficient should keep the same as the value measured in Chapter 4.2.1. To confirm this assumption, the

relationship between center wavelength of EDG channel and EDG temperature is re-measured for all the 15 EDG channel, the temperature coefficient is $84.4 \text{ pm/}^\circ\text{C}$, which is very close the number in Chapter 4.2.1. The thermal tuning spectrum of a selected EDG channel is shown in Fig. 4.11.

To further demonstrate the feasibility of the proposed interrogation technique, an experimental setup is established as in Fig. 4.12.

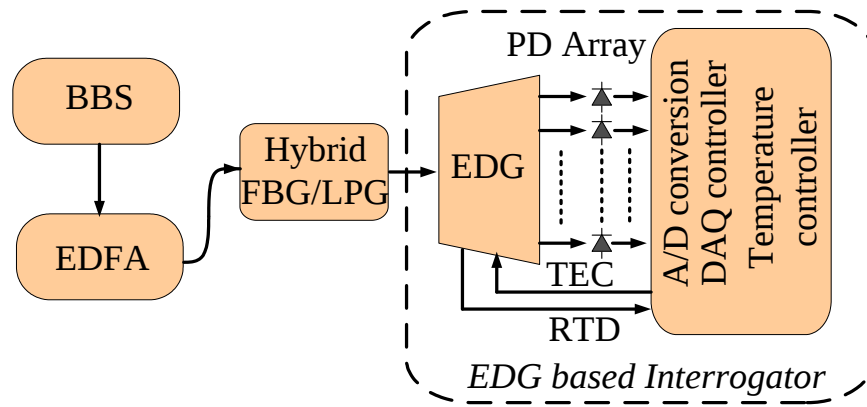


Fig. 4.12. Experimental setup for the hybrid FBG/LPG interrogation using a thermal tuning EDG.

The setup consists of a broadband source (BBS), an erbium doped fiber amplifier (EDFA) and an EDG based interrogator. The EDG based interrogator, which has a channel spacing of 1.6 nm , is controlled by a Labview program which performs the analog-to-digital conversion, data acquisition, temperature detection and control.

Considering the $84.4 \text{ pm/}^\circ\text{C}$ EDG temperature sensitivity as shown in Fig. 4.11, the proposed interrogation technique presents a wavelength resolution of better than 1 pm due to the temperature resolution of $0.01 \text{ }^\circ\text{C}$ provided by the TEC and RTD. Meanwhile, a transmission wavelength shift of 1.7 nm at each EDG channel can be obtained by tuning the EDG chip

temperature of 20 °C. Since the tunable range of each channel is larger than the channel spacing, the proposed interrogation system can provide a continuously scanning spectral range of 24 nm. Therefore, the proposed interrogation technique can meet the challenges posed by the hybrid FBG/LPG based RI sensors and would be able to make the RI/temperature discrimination.

Fig. 4.13 shows the spectrum of the hybrid FBG/LPG measured by an optical spectrum analyzer (OSA) with wavelength resolution of 10 pm. It is noted that the wavelength spacing between the FBG and LPG (4.2 nm) is larger than a EDG channel (1.6 nm). Therefore, the spectra of the two gratings are located in two different EDG transmission channels.

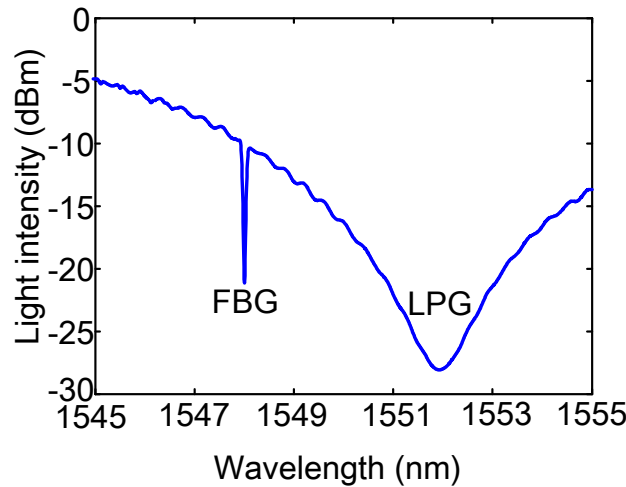


Fig. 4.13. Spectrum of the hybrid FBG/LPG measured by an OSA.

Since the bandwidth of the FBG is relatively small, as shown in Fig. 4.13, one dedicated channel (Channel 5) is capable of obtaining the spectrum (received light power with respect to the sampling points) shown in Fig. 4.14(a). Although the bandwidth of the LPG is larger than the EDG channel spacing, the flexibility of the proposed interrogation technique allows for the use of three or more EDG channels (Channel 2-4 in this case) to obtain the LPG spectrum, as shown in Fig. 4.14(b)-(d), where the minimum light intensity is obtained at Channel 3.

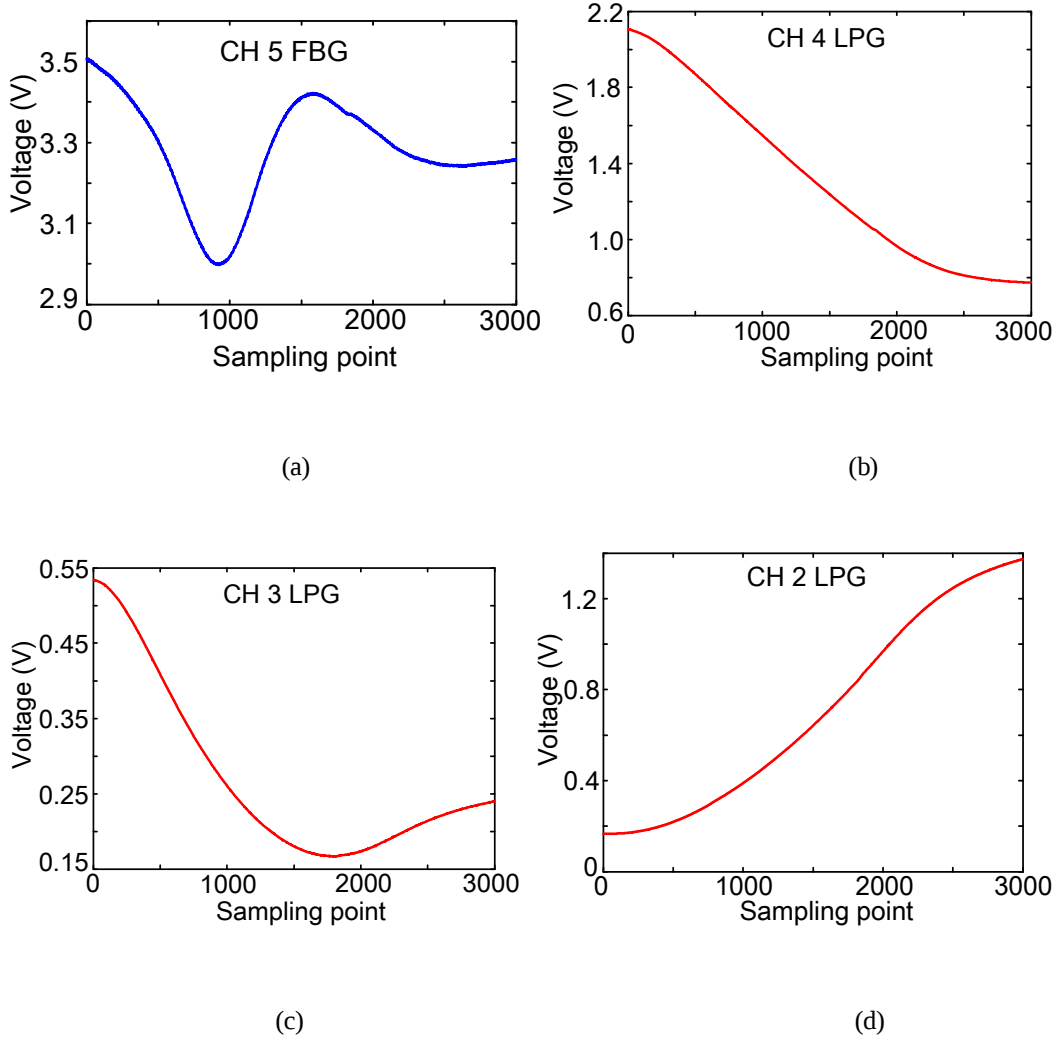


Fig. 4.14. Measured light power with respect to the sampling points. (a) FBG sensor, (b) – (d) LPG sensor.

In this work, the EDG temperature, measured by the RTD, is simultaneously fed back to the Labview program together with the light intensity. Fig. 4.15 shows the measured EDG temperature with respect to the sampling points.

In the data processing, the sampling points representing the minimum value of the detected light intensity in the dedicated channels are obtained from Fig. 4.14(a) and (c) for the FBG and LPG respectively. Then, the EDG temperatures are calculated by interpolating the above obtained sampling points in the processed curve in Fig. 4.15. Finally, the center wavelengths of the

hybrid FBG/LPG pair are achieved by correlating the obtained EDG chip temperatures to the wavelengths using the pre-measured temperature coefficient. Three Experiments were performed within 1 hour to verify the proposed interrogation technique. Table. 4.1 illustrates the results and a very good agreement is achieved with those manufacturer provided wavelengths, validating the proposed interrogation technique.

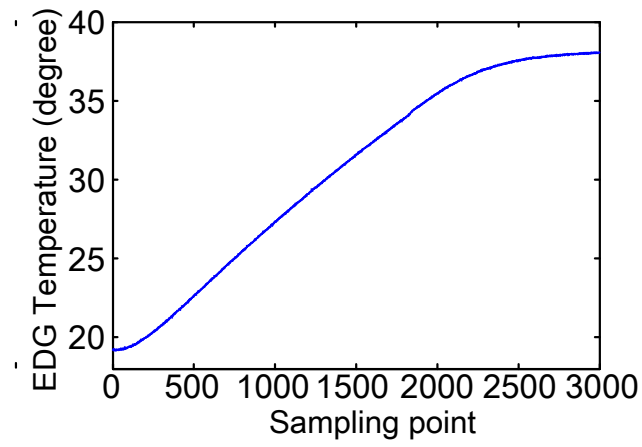


Fig. 4.15. Measured EDG chip temperature with respect to the DAQ sampling points.

TABEL 4.1. INTERROGATION RESULTS FOR THE FBG/LPG SENSOR PAIR

Measurement	1	2	3	Actual*
FBG (nm)	1548.021	1548.019	1548.023	1548.01
LPG (nm)	1552.214	1552.210	1552.180	1552.20

* supplied by the manufacturer

III. Discussion

The maximum variation is 14 pm between the measurement results and the actual wavelength values measured by an OSA and referenced with the manufacturer's numbers as shown in Table. 4.1. This small variation is believed to be partly attributed to the drifting of the ambient conditions, such as strain and temperature, during the testing processes. A typical FBG sensor

has the strain and temperature sensitivity of 1 pm/ $\mu\epsilon$ and 10 pm/ $^{\circ}\text{C}$ respectively at the Bragg wavelength of 1550 nm; whereas the ones of a typical LPG is almost an order-of-magnitude higher [63]. In addition, even though the spectra of the gratings are assumed to be of Gaussian profiles in the theoretical analysis, practically, they are not an absolute requirement. As can be seen from Fig. 4.13, the spectrum of the hybrid FBG/LPG is not truly Gaussian but closely resembles a Gaussian distribution. This is described in detail in [166] from the mathematical view. Thus, the assumption of the grating spectra with the Gaussian profiles might slightly introduce error in the measurement. Finally, the Gaussian profile of the EDG transmission spectrum might also induce some errors. Mathematically, an EDG transmission spectrum of a Dirac delta function with an infinite height and a unity area is preferable in scanning the spectrum of the hybrid FBG/LPG. However, for real implementation, the EDG involved in this experiment has a 3-dB bandwidth of ~ 0.8 nm. Compared with the ideal Dirac delta function, it might slightly affect the measurement accuracy. Better measurement accuracy could be achieved by introducing an EDG with a smaller 3dB bandwidth according to the analysis presented in [177].

The proposed interrogation technique was shown to be capable of providing a better than 1-pm resolution and 24-nm interrogation range. It has the potential to stack several EDG based interrogators together to increase the interrogation capacity beyond the current device capability for increased flexibility, in the use of the hybrid FBG/LPG for RI/temperature discrimination, at reduced weight, size and cost.

IV. Conclusion

A simultaneous interrogation technique based on a monolithically integrated EDG was proposed and demonstrated for the interrogation of hybrid FBG/LPG based sensor pairs to perform discrimination of refractive-index (RI)/temperature in the RI measurement. It has been noted that the transmission wavelength of an EDG can be monotonically tuned by changing the EDG temperature with a modified EDG temperature control. Therefore, by knowing the monotonic temperature dependence of the EDG transmission wavelengths and the temperatures representing the dips of the transmission spectra of the FBG and LPG respectively, the center wavelengths of the hybrid FBG/LPG sensor pair can be determined by a single measurement. A resolution of 1 pm and wavelength range of 24 nm are achieved by the proposed interrogation technique. This type of performance would be ideal for the RI/temperature discrimination of a hybrid FBG/LPG refractive index sensor pair. Furthermore, the interrogator presented here is capable of being applied in interrogating other sensor systems, such as tilted FBG sensors, superstructure FBG sensors and Fabry-Perot based sensors

4.2.3 Advanced model of the EDG based wavelength interrogation unit⁶

As discussed in Chapter 1.1, two major aspects in the aircraft SHM applications are operational load monitoring and impact damage detection [14]. FBG sensors can be used for either operational load monitoring (changes of strain) [62] or impact damage inspection (detection of acoustic signals) [83]. In addition, FBG sensors also offer the possibility in fulfilling the two tasks at the same time [84], which is regarded as a superior advantage for FBG sensors in the aircraft SHM applications. However, the lack of a suitable interrogation system hinders the use of FBG sensors from doing both the load monitoring and the damage detection. Currently

⁶ This section is a revised version of the following published paper. Article title: Echelle diffractive grating based wavelength interrogator for potential aerospace application. Authors: Honglei Guo, Gaozhi Xiao, Nezhir Mrad, and Jianping Yao. Published in Journal of Lightwave Technology, vol. 31, no. 13, pp. 2099-2105, Jul. 2013.

available sensor interrogators can only perform one of the two SHM tasks as described in Chapter 1.1. For operational load monitoring, it is required to measure large changes (thousands of $\mu\epsilon$) at a low speed (static). While for impact damage detection, the capability of measuring acoustic signals, i.e., small changes (tens of $\mu\epsilon$) at an ultrafast speed (50 kHz - 500 kHz), is usually required for a standard FBG sensor with a 10-mm grating length [87].

To address this issue, we introduce the advanced model of the miniaturized interrogator that operates in two operation modes, i.e., the sweeping mode and the parked mode, to a miniaturized interrogation system previously developed. This system is based on a monolithically integrated EDG device [153, 186], which is fabricated by the PLC technology and with the features of small size, light weight, and strong reliability proved by the stringent telecommunication standards. The sweeping mode, in which the transmission wavelength of the EDG channel is tuned by adjusting the EDG chip temperature, can be used for the load monitoring, while the parked mode, in which the transmission wavelength of all the EDG channels is fixed, can be used for the damage detection.

In order to achieve the dual functions required, the previously developed EDG based interrogator is modified. In the previous design, only the odd number EDG channels are connected in order to reduce the electronic complexity [153]. In this design, all the 32 channels of the EDG, including the odd and even number EDG channels, are used with the EDG spectrum shown in Fig. 4.2. In the sweeping mode, the transmission wavelength of each EDG channel is tuned by changing the EDG temperature. The wavelength interrogation principle is the same as the one described in [153]. By monitoring the light power and recording the EDG temperature, the EDG temperature corresponding to the peak light power could be found. With

the proven linear relationship between the EDG transmission wavelength and its temperature, the Bragg wavelength of an FBG sensor can be accurately interrogated. The use of 32 channels makes the channel spacing be 0.8 nm instead of 1.6 nm used in the previous design. Thus, the EDG temperature tuning range required to move one EDG transmission wavelength from one channel to its neighboring channel is reduced by half, resulting in a lower power consumption in the sweeping mode operation and an increase in the measurement repeatability. As demonstrated in Chapter 4.2.1 and Chapter 4.2.2, this sweeping mode can be used for large strain variation, which is suitable for the interrogation of load monitoring FBG sensors.

Also, due to the reduction of the channel spacing from 1.6 nm to 0.8 nm, the two neighboring EDG channels have an overlapped region. This makes it possible for the interrogator to be operated in the parked mode based on the principle described in [103, 117]. In this mode, the FBG sensors are interrogated by using a linear wavelength-dependent optical filter consisting of two adjacent EDG channels as shown in Fig. 4.16. Only small variation of strain recorded by an FBG sensor can be accurately interrogated using this method, but at a very high speed. In [103], an interrogator based on an AWG reaches a speed up to 300 kHz, and is used to interrogate FBG acoustic sensors for the aircraft SHM damage detection. Our EDG device has the same spectrum profile as that of an AWG. Thus, it has the same interrogation capability of using a fixed spectrum in the parked mode for the interrogation of FBG acoustic sensors, which can be further implemented in the impact damage detection.

Therefore, the modified EDG interrogator can operate at both the sweeping mode and the parked mode, which can be used for the interrogation of FBG sensors for operational load monitoring and for impact damage detection in the aircraft SHM applications.

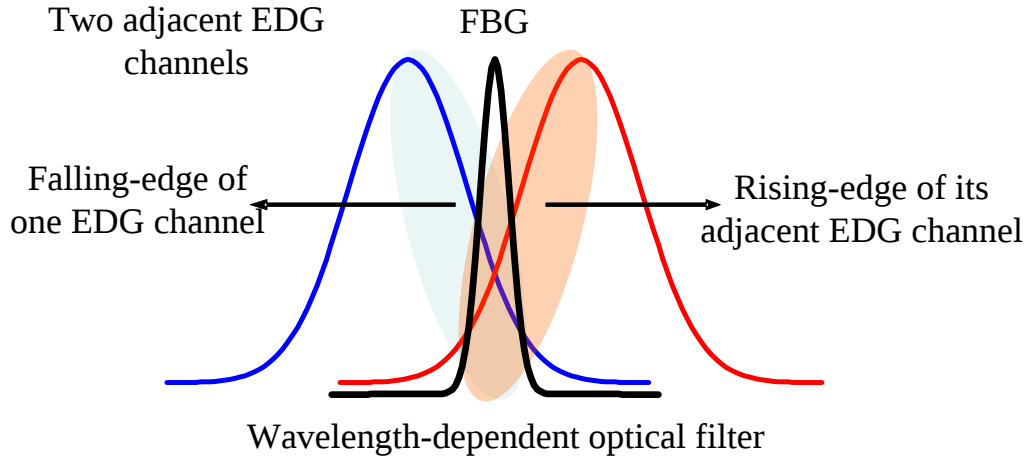


Fig. 4.16. Wavelength-dependent optical filter with two EDG channels used as parked mode wavelength interrogation.

Different from previous studies, both odd and even number channels are connected in this advanced model wavelength interrogation unit, 5 channels are selected to show the temperature dependency of their center wavelength. Fig. 4.17 shows the result.

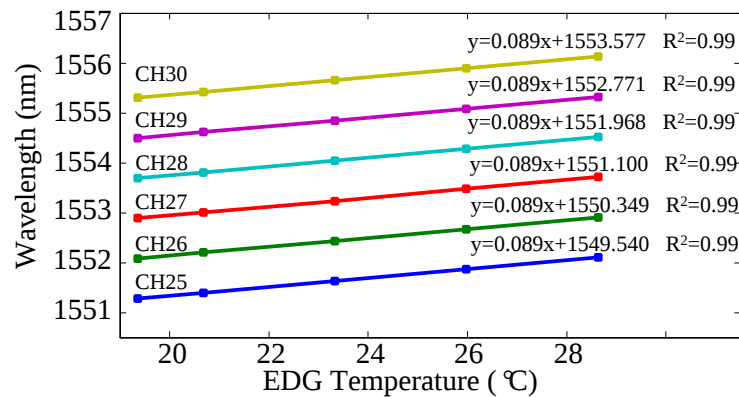


Fig. 4.17. Relationship between the transmission wavelength of each EDG channel and its temperature.

In Fig. 4.17, it is seen that all the EDG channels have the same spectrum sweeping capability in the modified EDG based interrogator, which is similar to the results obtained in our previous studies [153]. The sweeping coefficient is measured to be 89 pm/ °C. The use of all the 32 EDG

channels makes the channel spacing be reduced from 1.6 nm to 0.8 nm, which also reduces the EDG temperature tuning range. In our previous studies, the EDG temperature needs to be tuned from 20 °C to 40 °C in order to achieve a 1.6-nm spectrum range for each EDG channel, which is used to cover the channel spacing and perform the full-spectrum sweeping. In this work, an EDG temperature tuning range of ~ 10 °C is enough for each EDG channel to cover the 0.8-nm channel spacing. Fig. 4.18 shows the sweeping spectrum of CH 26 at the five discrete temperature values and the spectrum of CH 27 at the initial temperature of 19.36 °C.

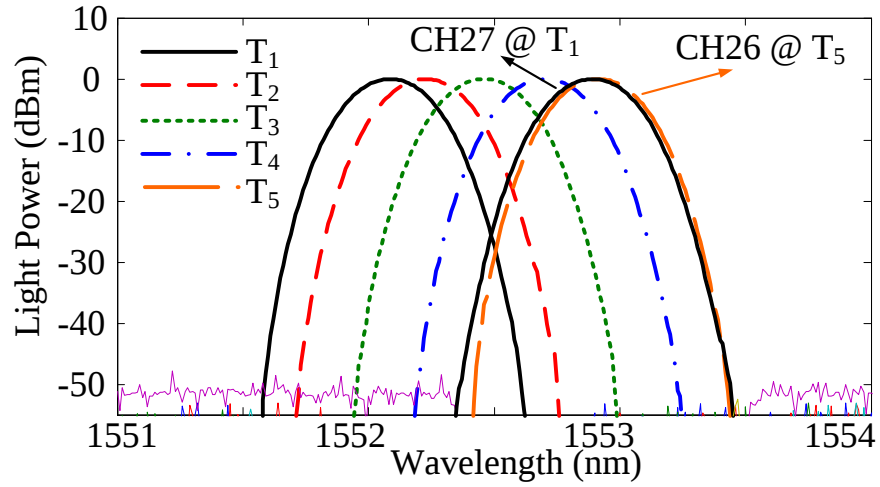


Fig. 4.18. Sweeping spectrum of CH 26 and the spectrum of CH 27 at the initial temperature.

It is seen that the spectrum of CH 26 at the temperature of 28.63 °C has already exceeded the spectrum of CH 27 at the initial temperature of 19.36 °C, which means that an EDG temperature tuning range from 19.36 °C to 28.63 °C is able to provide a full-spectrum interrogation range. Compared with the temperature tuning range of ~ 20 °C in the previous work [153], the power consumption is reduced. Furthermore, as described in [186], the measurement error could be decreased if a faster wavelength sweeping is applied. In this paper, the temperature tuning range

is reduced by half, resulting in a smaller period in each sweeping cycle. Therefore, the measurement error could be decreased by using the modified EDG device.

The experimental setup is shown in Fig. 4.19. An FBG sensor is mounted on a closed-loop piezo motor, which is used to precisely apply a strain on the FBG sensor. A broadband source (BBS) is used as the light source. The reflected signal from the FBG sensor is then introduced into the proposed interrogation system. A Labview program is developed to perform the temperature control, light power acquisition, and data processing with a friendly user interface.

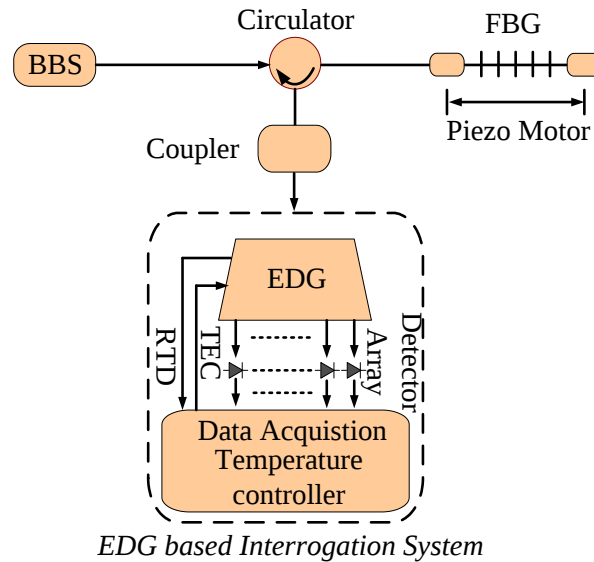


Fig. 4.19. Illustration of the advanced model of the thermal tuning EDG wavelength interrogation unit.

As discussed above, two operation modes are studied to confirm their potentials for operational load monitoring and impact damage detection. In the sweeping mode, the EDG temperature is tuned from 19.36 °C to 28.63 °C, which is achieved by changing the TEC control voltage from 1.055 V to 1.091 V. Within the 36-mV TEC tuning range, a step of 0.4 mV is applied, which is performed by the analog output function of a data acquisition card (National Instrument, DAQ PCI-6081). Thus, a temperature tuning step of 0.1 °C is obtained, which makes a wavelength

sweeping step of 9 pm. During each temperature tuning step, the EDG temperature from the RTD is acquired by 10 measurement points, resulting in a temperature resolution of 0.01 °C. Furthermore, a built-in peak searching function in the Labview program is applied to determine the temperature corresponding to the peak light power. Therefore, a resolution of better than 1 pm is achieved.

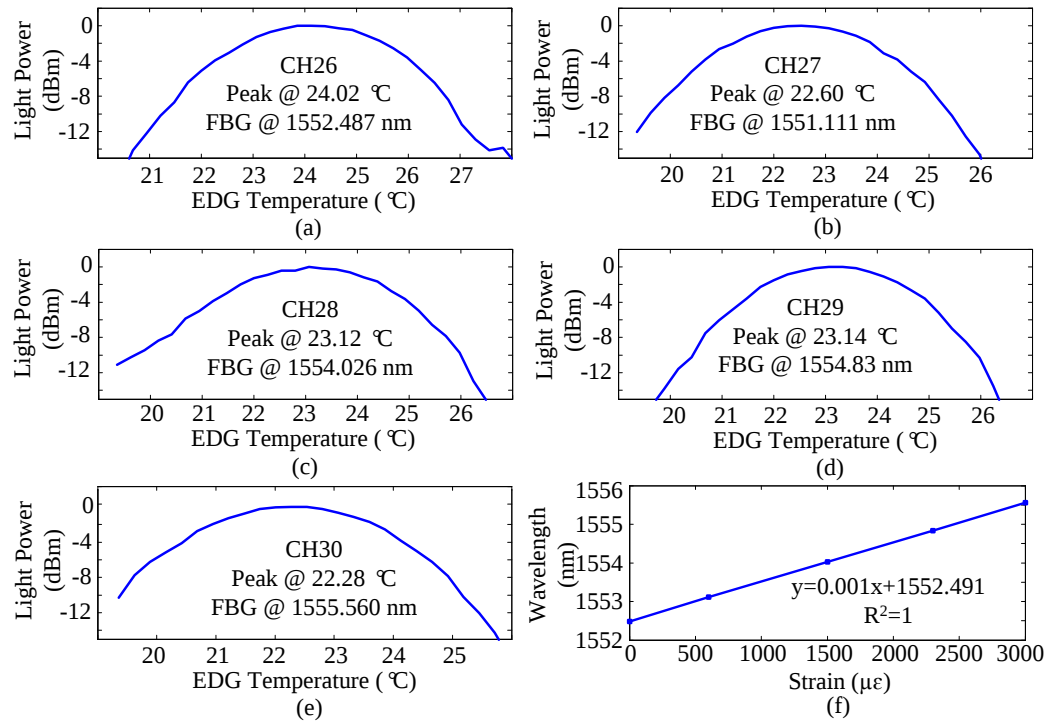


Fig. 4.20. Interrogation results of the FBG sensor under five different strains. (a) – (e) Light power with respect to the EDG temperature of the designated EDG channels. (f) Interrogated Bragg wavelength as a function of the strain applied.

The interrogation of an FBG sensor under five different strains (0 με, 600 με, 1500 με, 2300 με, and 3000 με) is demonstrated. Fig. 4.20(a) - (e) shows the light power with respect to the EDG temperature of the designated EDG channels. Each EDG channel has a measurement range of 0.8 nm, which is defined by the temperature tuning settings and the EDG channel spacing. Therefore, the Bragg peak positions of the FBG sensor corresponding to the five different

strains are located within different EDG channels. The temperature representing the peak light power in each EDG channel is obtained by the built-in Labview peak searching function. By employing the reference shown in Fig. 4.17, we are able to calculate the Bragg wavelength of the FBG sensor under the five strains. Fig. 4.20(f) shows the relationship between the interrogated Bragg wavelength and the strain applied. It is seen that the Bragg wavelength increases with the strain at a rate of 1 pm/ $\mu\epsilon$, which is typical for FBG sensors working at around 1550 nm [55]. Moreover, the repeatability of the proposed interrogation system prototype is also tested. In this test, a certain strain is constantly applied on the FBG sensor. For simplicity, three measurements are taken with a time interval of 5 minutes. The experimental result is shown in Fig. 4.21.

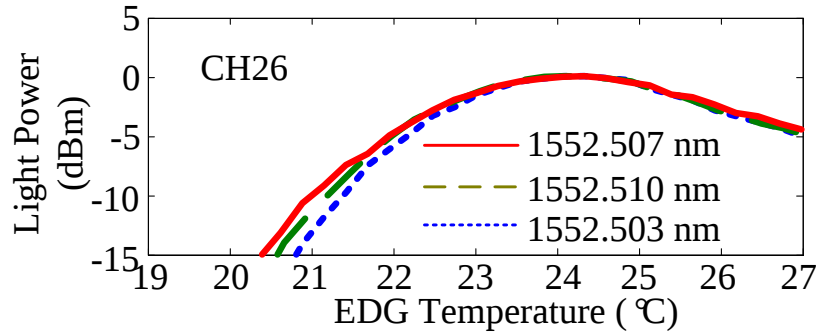


Fig. 4.21. Experimental result for the repeatability test.

It is seen that better than 10-pm repeatability is achieved. As discussed above, the channel spacing is reduced from 1.6 nm to 0.8 nm in this work, resulting that the EDG temperature tuning range is from 20 °C to 30 °C rather than from 20 °C to 40 °C in our previous studies. By using the best operation range of the TEC, to avoid the use of higher temperature range, and to reduce the time period of each sweeping cycle, the repeatability is improved.

Next, the parked mode of the proposed interrogation system is tested. In the parked mode, the EDG spectrum is fixed by keeping the EDG temperature constant at 30 °C, at which the TEC is tested to have the best performance. Due to the lack of an acoustic signal generator, the parked mode is tested by monitoring the movement of a piezo motor. In the parked mode, two adjacent EDG channels are used to function as a wavelength-dependent optical filter. The Bragg wavelength shifts are converted into the light power changes from the two channels. By monitoring the ratio of the light power from the two channels, the Bragg wavelength is measured [122]. The experimental result is shown in Fig. 4.22.

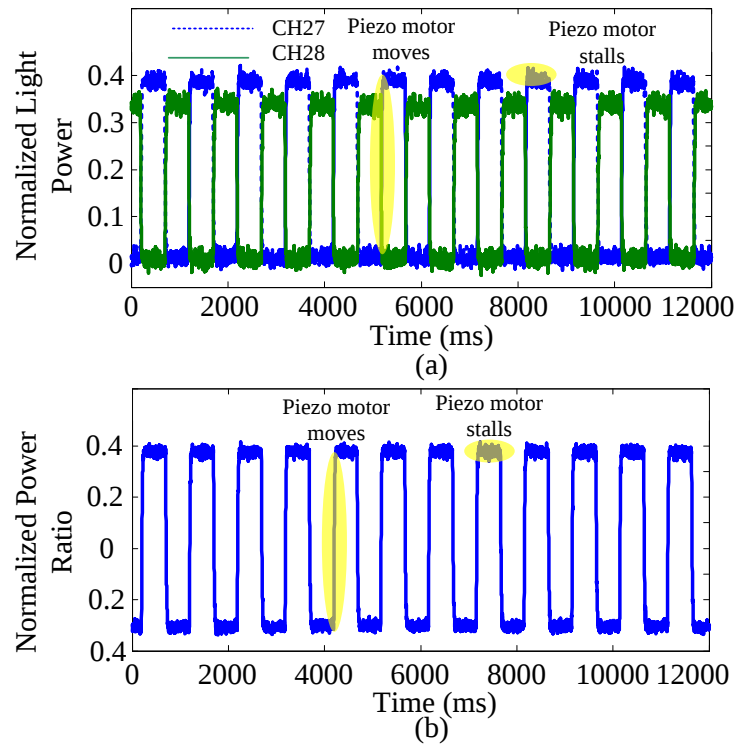


Fig. 4.22. Experimental result of monitoring the movement of a piezo motor. (a) Light power from two designated EDG channels. (b) Illustration of the movement.

Two EDG channels, CH 27 and CH 28, are used in this test. Fig. 4.22(a) shows the light powers from the two channels while the piezo motor is moving, and Fig. 4.22(b) shows the ratio of the

light powers, which could be used to reflect the Bragg wavelength shifts and the movement of the piezo motor. Based on the data processing methods in [103] and [122], the Bragg wavelength shift is measured to be from 1553.810 nm to 1554.290 nm. Thus, when the piezo motor moves from one end to the other end, a strain of 480 $\mu\epsilon$ is applied to the FBG sensor. Considering the length of 42 cm between the two ends of the FBG sensor fixed on the stage, the travel range of the piezo motor is measured to be 200 μm . As shown in Fig. 4.22, the piezo motor takes 10 ms to travel from one end to the other. The measured piezo motor movement agrees well with the initial settings. Since the EDG has the same spectrum as an AWG as shown in Fig. 4.2, and a similar technique to achieve an interrogation speed of 300 kHz has been demonstrated in [103], the parked mode has a potential to reach an ultrafast speed for acoustic wave measurement in the damage detection.

The measurement error from this interrogator system is believed to be attributed to the broad bandwidth of the EDG channel and the power fluctuations, mainly from the broadband light source. Ideally, in the sweeping mode the EDG spectrum has a Dirac delta function profile with an infinite height and a unity area. In real implementation, however, the EDG spectrum has a 3dB bandwidth of 0.4 nm, which is comparable or even larger than the bandwidth of the FBG sensor. Better accuracy could be achieved by reducing the EDG spectrum bandwidth. In the parked mode, the EDG spectrum bandwidth is tested to be proportional to the measurement resolution and error [122]. Thus, better results could be obtained by using an EDG with a smaller 3-dB bandwidth. The impact due to the power fluctuations on the measurement error mainly comes from the broadband light source. As discussed in [186], a fast wavelength tuning or the use of one EDG channel as the reference will alleviate this impact and a more accurate result could be obtained.

The proposed interrogation system is proven to have a small size and light weight, as shown in Fig. 4.19. In addition to the application for both operational load monitoring and impact damage detection, it also features a low power consumption. The packaged EDG device is operated with a +5 V power supply, which can be powered by a battery. This feature allows the integration of energy harvesting techniques into the proposed interrogation system and makes it self-powered. Furthermore, a total of 32 EDG channels provide a capability to perform a multichannel interrogation for multiplexed FBG sensors, which is also a favorite feature for the aircraft SHM applications.

4.3. Multichannel RF receiver based on a thermal tuning EDG⁷

Besides the use of an FBG sensor and its wavelength interrogation unit in the aircraft SHM applications, we also propose to use the same setup as a multichannel RF receiver.

I. Introduction

Photonic techniques have been well documented for generating, distributing, controlling and processing microwave signals for radar and other electronic warfare (EW) applications due to their numerous advantages, such as high bandwidth, low loss, light weight and immunity to electromagnetic interference [194]. One of the basic requirements for EW applications is to estimate the frequency of an unknown microwave signal over a large bandwidth. Conventional microwave architectures usually make the measurement systems very bulky and costly. Thus, considerable effort has been devoted to develop novel techniques for microwave frequency

⁷This section is a revised version of the following published paper. Article title: Measurement of microwave frequency using a monolithically integrated scannable Echelle diffractive grating. Authors: Honglei Guo, Gaozhi Xiao, Nezih Mrad, and Jianping Yao. Published in IEEE Photonics Technology Letters, vol. 21, no. 1, pp. 45-47, Jan. 2009.

measurements using photonic techniques, such as Fabry-Perot etalon based scanning receiver [195], integrated hybrid Fresnel lens systems [196], parallel phase-shifted FBGs based photonic channelizers [197] and optical power monitoring of two optical carriers with power penalties introduced by different dispersions [198].

In this section, a novel approach with multi-microwave frequency measurement capability is proposed. The approach is based on a monolithically integrated echelle diffractive grating (EDG) [182-183] interrogator having 15 measurement channels. One of those channels is used to demonstrate the feasibility of the proposed approach. Some initial experimental results are also presented in this letter.

II. Theory

In modulating a microwave signal with unknown frequency on an optical carrier, two sidebands in the optical domain can be generated while the optical carrier can be suppressed by properly setting the bias of a Mach-Zehnder modulator (MZM) [199]. If a fiber Bragg grating (FBG) is introduced as a notch filter [200] to filter out one of the two sidebands, the center wavelength λ_s of the remaining sideband can be related to the frequency of the microwave signal f by

$$f = |\nu_c - \nu_s| = c \left| \left(\frac{1}{\lambda_c} - \frac{1}{\lambda_s} \right) \right| \quad (4-1)$$

Where ν_c and ν_s are the frequencies of the suppressed optical carrier and the remaining sideband, respectively, c is the light speed in vacuum and λ_c is the wavelength of the suppressed optical carrier. Therefore, by knowing the wavelength of the sideband passing through the FBG filter, it is possible to determine the frequency of the microwave signal. Now, similar to the AWG

spectrum profile discussed in Chapter 2.3, the transmission spectrum of the j th channel of an EDG interrogator is given by

$$I_j = I_0 \exp\left[-\frac{4 \ln 2 (\lambda - \lambda_{Ej})^2}{\Delta \lambda_{Ej}^2}\right] \quad (4-2)$$

where I_0 , λ_{Ej} , and $\Delta \lambda_{Ej}$ are the peak transmittance, center wavelength, and full-width at half-maximum (FWHM) of the j th output channel of an EDG. In this study it is assumed that the transmission wavelength of the j th EDG channel is shifting monotonically with the EDG interrogator chip temperature as follows

$$\lambda_{EDGj} = M(T) + \lambda_0 \quad (4-3)$$

Where $M(T)$ is the monotonic temperature dependent function, T is the EDG chip temperature, and λ_0 is a constant.

It is further assumed that the light intensity detected by the j th channel of the EDG is mainly from the sideband under measurement, while the contributions from the filtered out sideband and suppressed optical carrier are very small and can be neglected. This assumption can be realized by properly designing the FBG spectrum and setting the MZM bias. Then, based on the analysis presented in [153], the detected light intensity of the j th channel of the EDG will reach the maximum value when λ_{EDGj} reaches λ_s by tuning the EDG chip temperature. Therefore, by measuring the EDG chip temperature corresponding to the maximum light intensity output of channel j , the center wavelength of the sideband passing through the FBG filter can be determined using equation (4-3), while the frequency of the microwave signals can be calculated using equation (4-1) and (4-3).

III. Experimental result

A proof-of-concept experiment with the setup illustrated in Fig. 4.23 is carried out to demonstrate the feasibility of the proposed approach

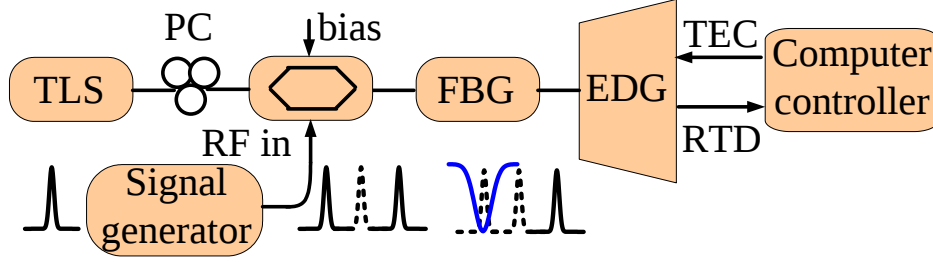


Fig. 4.23. Experimental setup of the proposed approach.

The light signal from the tunable laser source (TLS) is used as the optical carrier and modulated by an MZM. By properly setting the MZM bias, the optical carrier is suppressed and two sidebands are generated, one of which is filtered out by the FBG notch filter as shown in Fig. 4.24, while the remaining sideband is characterized by an EDG based interrogator. This interrogator, developed based on a monolithically integrated InGaAsP/InP chip consists, as detailed in [153], of a 1×15 EDG demultiplexer, an array of photodetectors (PD), a thermal electric cooler (TEC) and a resistance temperature detector (RTD). The TEC and RTD are integrated in the chip for the purpose of adjusting and monitoring the EDG chip temperature. However, to improve the response speed of the interrogator, a different temperature control technique from the one used in [153] is employed in this work.

Fig. 4.25 shows the mapping relationship between the RTD readout and the wavelength by tuning an Agilent tunable laser source (81640B) with a step of 5 pm. Considering that the center wavelength of the FBG is 1548.858 nm (shown in Fig. 4.24) and to simplify the data processing, the center wavelength of the optical carrier is selected to be 1548.964 nm and a 0.5 nm linear

range is applied in this experiment. The linear coefficient in this selected linear region is measured as 84.4 pm/ °C. Since the temperature reading resolution of the RTD used is 0.01 °C, a better than 1-pm wavelength interrogation resolution can be achieved.

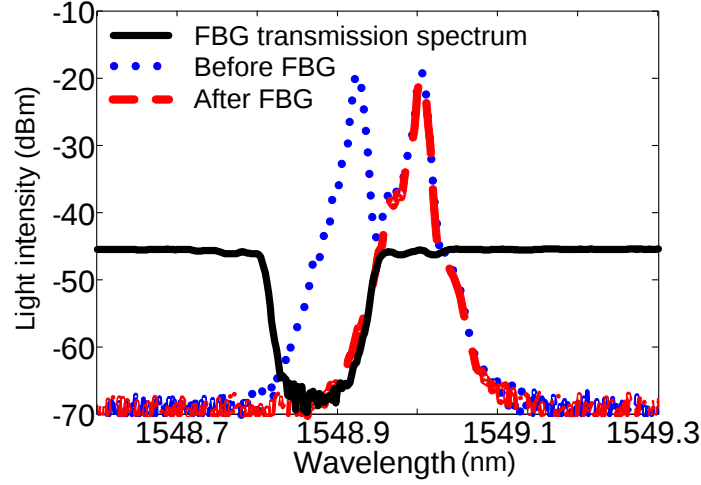


Fig. 4.24. Spectra of the FBG and the sidebands before and after the FBG with 5 GHz microwave signal applied on the MZM.

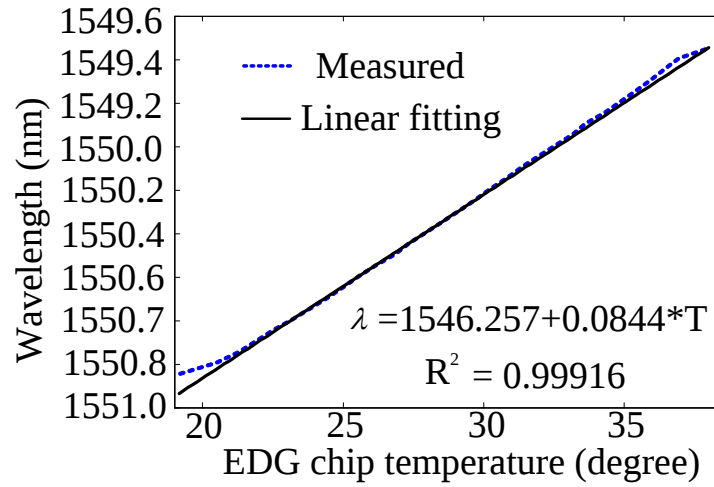


Fig. 4.25. Temperature dependence of the center wavelength of the selected EDG channel.

The power of the input microwave signal is set as 5 dBm and the scanning frequency is from 0 GHz to 15 GHz with a step of 1 GHz. Fig. 4.26 shows the selected sideband spectra with

respect to the EDG chip temperature under different microwave frequencies applied to the MZM. The optical carrier wavelength used in this experiment is selected slightly larger than the optimal number. Thus, the FBG cannot completely filter out the left sideband when lower microwave frequencies are applied. With the increase of the input microwave frequency, the left sideband shifts into the dip of the FBG spectrum as shown in Fig. 4.24. Hence, the contribution of its residual to the detected light intensity and the measured spectrum is decreasing, which results in the lowering of the power intensity and the narrowing of the bandwidth. This effect can be overcome by properly selecting the optical carrier wavelength.

By applying the above discussed process, the EDG chip temperatures representing the maximum value of detected light intensity and the corresponding center wavelengths of the remaining sideband under different input microwave frequencies are obtained and the results are shown in Fig. 4.27.

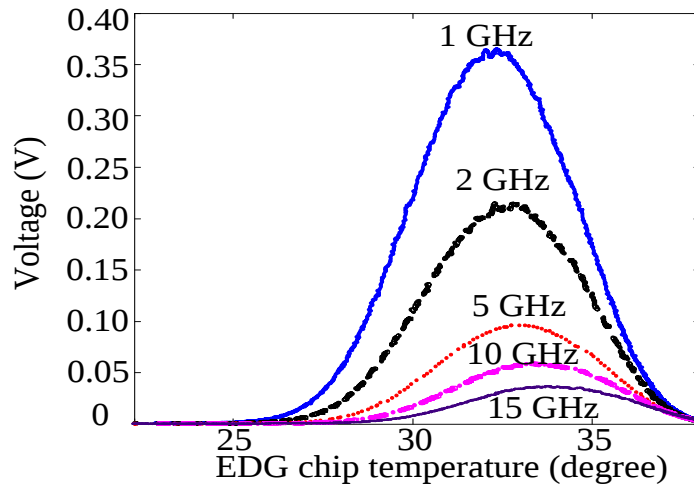


Fig. 4.26. Samples of the sideband shift measured by the EDG based interrogator.

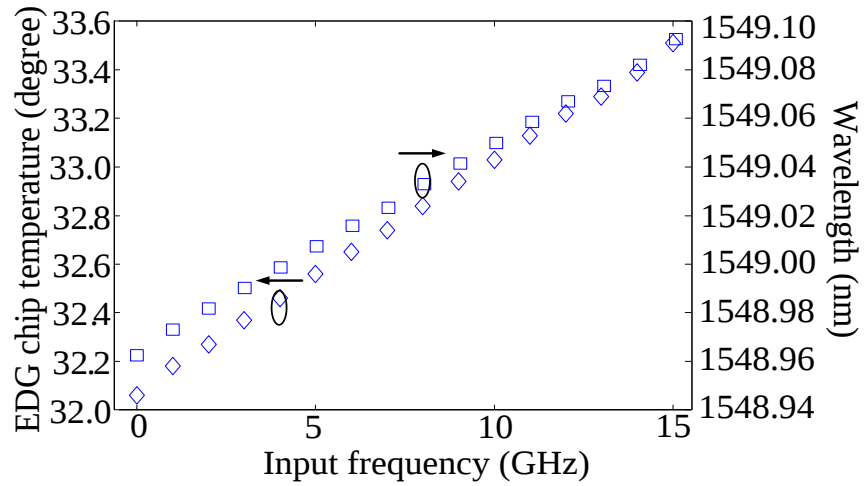


Fig. 4.27. Measured EDG chip temperatures and the corresponding wavelengths with different input microwave frequencies.

By substituting the above obtained wavelengths and the optical carrier wavelength in (4-1), the frequencies of the microwave signals can be obtained. The experimental results are correlated to the actual microwave frequencies and their relation is shown in Fig. 4.28.

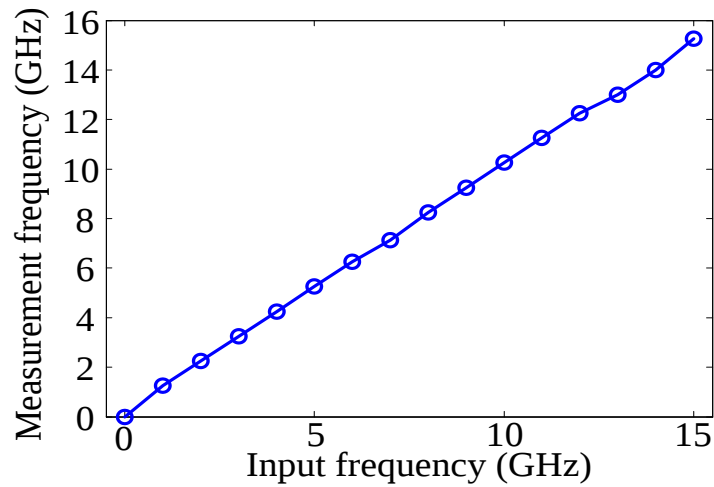


Fig. 4.28. Correlations of the measured and the actual frequencies.

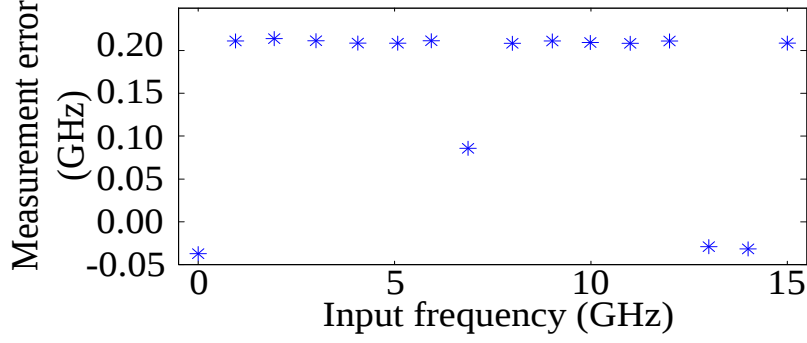


Fig. 4.29. Measurement errors.

Ideally, those two sets of values are equal. For this proof-of- concept work (as shown in Fig. 4.29), we find the measurement variation is mainly around 0.2 GHz from the one-to-one relationship, which accords well to the measurement accuracy of 10 pm in [153]. This accuracy level is also comparable with those reported in the literature [195-198]. The variations are believed to be attributed to two major error sources. The first error source is from the Gaussian spectra of the EDG interrogator. In a theoretically ideal case, the spectral function of the EDG transmission channels, implemented in the spectrum scanning, should be mathematically a Dirac delta function with an infinite height and a unity area. As discussed in [153], an EDG with a relative smaller bandwidth is preferable to perform better spectrum scanning and yield better measurement accuracy. However, the EDG interrogator used has a 3-dB bandwidth of 0.4 nm, which would contribute to the measurement variation. Better measurement accuracy could be achieved by introducing an EDG with a smaller 3-dB bandwidth (< 0.4 nm). Secondly, the spectrum of the conventional FBG is susceptible to drifting 10 pm for 1 °C temperature change, which will affect the measured light intensity as well as the frequency. Finally, the Gaussian profile assumption for the sidebands and the EDG transmission channels might induce error in the measurement, but referring to the analysis in [133], this error can be neglected.

The EDG interrogator used in this work has 15 channels. If the wavelengths of the optical carriers are properly selected, 15 microwave signals can be monitored simultaneously. In addition, since the EDG based interrogator is in a miniaturized form and no other microwave components except an MZM was used in the system, the proposed approach could potentially lead to a system of compact size, reduced complexity and low cost.

IV. Conclusion

The feasibility of microwave frequency measurement based on a monolithically integrated EDG interrogator was demonstrated. Initial results from a proof-of-concept experiment showed that the measured frequencies were in very good agreement with the actual frequencies.

CHAPTER 5 FIELD APPLICATIONS OF AN FIBER BRAGG SENSOR SYSTEM FOR THE AIRCRAFT STRUCTURE HEALTH MONITORING

In Chapter 1, we have described that operational load monitoring and impact damage detection are the two major aspects of the aircraft SHM [12-15]. In Chapter 3 and Chapter 4, we have shown that miniaturized wavelength interrogation units based on PLCs, such as an AWG and EDG, are developed and used to build fiber optic sensing systems in the lab environment. In order to assess the performance, reliability, and readiness level for an in-service implementation (in real operation conditions) of the aircraft SHM systems, our developed fiber optic sensing system perform the tests in the field applications. These tests are carried on a platform that is built by the National Research Council of Canada (NRC) and Defence Research and Development Canada, Department of National Defence (DRDC-DND). Our systems are involved to identify, assess, integrate, and determine the suitability of fiber optic sensors for potential aircraft SHM applications.

The initial objective of this project is to conduct SHM on the aircraft structural component, in particular the monitoring of loads and detection of cracks and corrosions in the metallic structures using our developed fiber optic sensing system. The specific objectives are

- (1) To demonstrate fiber optic sensor (FOS) system for the strain, load, crack, corrosion, impact monitoring in aircraft metallic structures.

(2) To explore fiber optic acoustic sensing technology.

(3) To investigate a temperature compensated fiber optic humidity sensing technology.

For Objective (1), an FBG sensor system for strain and load monitoring of metallic structures is demonstrated. For Objective (2), the demonstration of using an FBG to receive acoustic signal is performed. For Objective (3), a temperature-compensated FBG humidity sensor is used for successfully measuring the chamber humidity.

5.1. Introduction to the aircraft SHM testing platform

The aircraft SHM testing platform is built by the Atlantic Air Vehicles Research Section (AVRS) of the Defence Research and Development Canada, the Department of National Defence (DRDC-DND), and the Structures and Materials Performance Laboratory (SMPL) of the Institute for Aerospace Research (IAR), the National Research Council of Canada (NRC). This platform, as shown in Fig. 5.1 and Fig. 5.2, is representative of aircraft structures and ranges in complexity from a simple aluminium beam subjected to bending, torsion, or a combination of both, in both quasi-static and dynamic conditions, to a complex CF-188 wing loaded by multiple hydraulic actuators. They also simulate real aircraft operating scenarios and are fully instrumented with Linear Variable Displacement Transducers (LVDTs) and strain gauges in order to establish comparative baselines for the SHM systems being assessed. For this work, it is made possible to demonstrate our FBG sensor systems on the load monitoring platform.

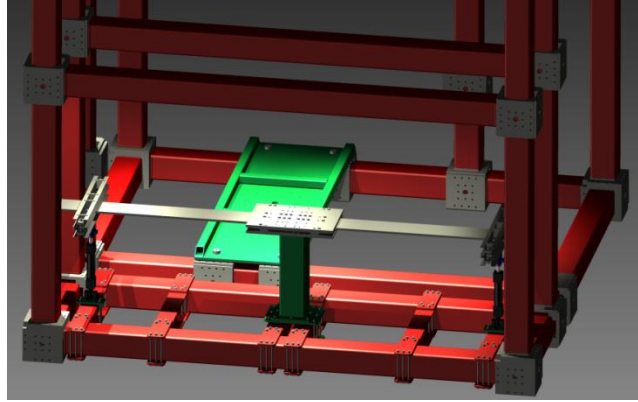


Fig. 5.1. Illustration of the SHM testing platform.

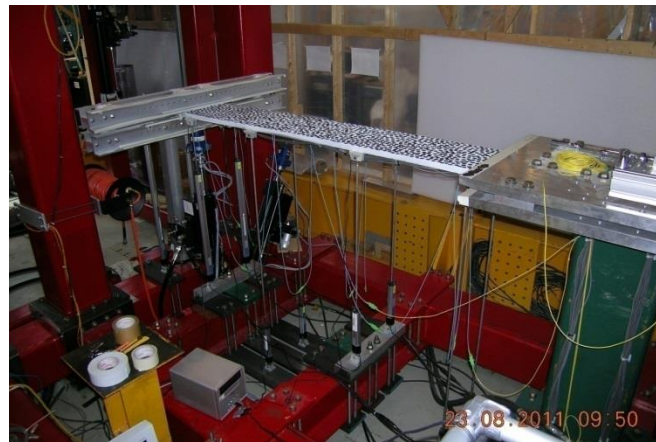


Fig. 5.2. Picture of the SHM testing platform.

The above platform simulates the loads on aircraft wings during a flight. It consists of two simple aluminum cantilever beams, made of aluminum alloy 6061-T6. The beams are 2.7607 m (108.7 in) long and with a constant rectangular cross section of 0.3045 m (12 in) in width and 0.0254 m (1 in) in thickness/height. These beams are fixed to a central stiff pedestal and are loaded close to their opposite tips.

5.2. Demonstration of the operational load monitoring

For monitoring the load, the FBG sensor is glued on the bottom surface of the left part of the platform beam, which is located next to an existing attached strain gauge. The results from the FBG sensor are obtained and compared with the results from the strain gauge.

The Beam shown in Fig. 5.2 is loaded at the edge with a ramp movement from 0 in $\rightarrow$ 4 in $\rightarrow$ 0 in $\rightarrow$ (-2) in $\rightarrow$ 0 in with a step of 0.5 in. The Bragg wavelengths of the sensor corresponding to the strain changes are monitored and validated with the strain data from strain gauges. The results are shown in Fig. 5.3 to Fig. 5.6.

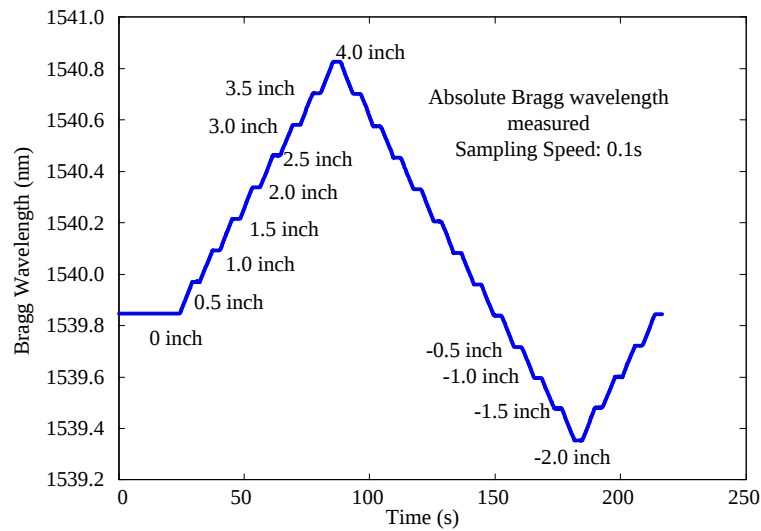


Fig. 5.3. Changes of the Bragg wavelength of the FBG sensor during the ramp movement from 0 in $\rightarrow$ 4 in $\rightarrow$ 0 in $\rightarrow$ (-2) in $\rightarrow$ 0 in.

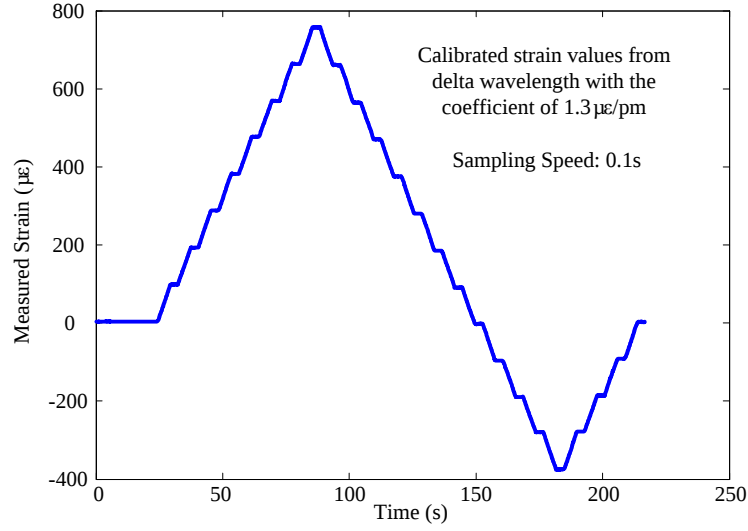


Fig. 5.4. Strain values converted from the Bragg wavelengths with the calibration coefficient of $1.3 \mu\epsilon/\text{pm}$.

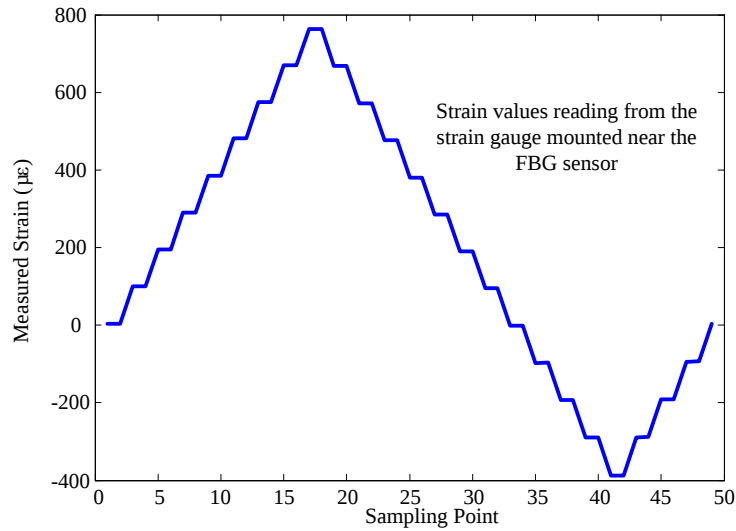


Fig. 5.5. Measured results from the strain gauge next to the FBG sensors.

Fig. 5.3 presents the changes of the absolute Bragg wavelength of the FBG sensor with respect to the time during which the deflection of the beam is executed. The results clearly show that the FBG sensor records every deflection change occurred at the beam edge. Through a proper calibration process, we find that the strain correlation factor for this FBG sensor is $1.3 \mu\epsilon/\text{pm}$. By introducing this parameter into the data shown in Fig. 5.3, we obtain the strain at the FBG sensing point. The results are shown in Fig. 5.4. As it shows, the strains at the testing point

change accordingly with the deflection of the beam. To verify the FBG sensor data, a strain gauge next to the FBG sensor is also used to monitor the loads and the results are shown in Fig. 5.5. They seem identical with those obtained from the FBG sensor system. The correlation of the strain results from the FBG sensor system and the strain gauge are shown in Fig. 5.6. It confirms that the results from two techniques are in a very good agreement.

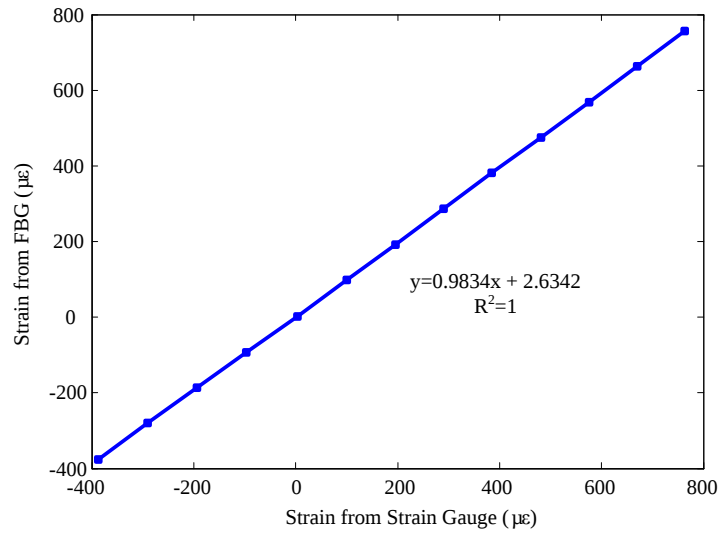


Fig. 5.6. Comparison between the strain values from our FOS system and the strain gauge.

We also perform two types of dynamic strain measurement, including (1) fixed amplitude and vibration frequency, and (2) varied amplitude and frequency.

For the dynamic test with fixed amplitude and frequency, the load is applied with the displacement following a sine wave of 1Hz frequency and constant amplitude of 1 in. The monitoring results from the FBG sensor system are presented in Fig. 5.7. For comparison, the corresponding results measured from the strain gauge are shown in Fig. 5.8.

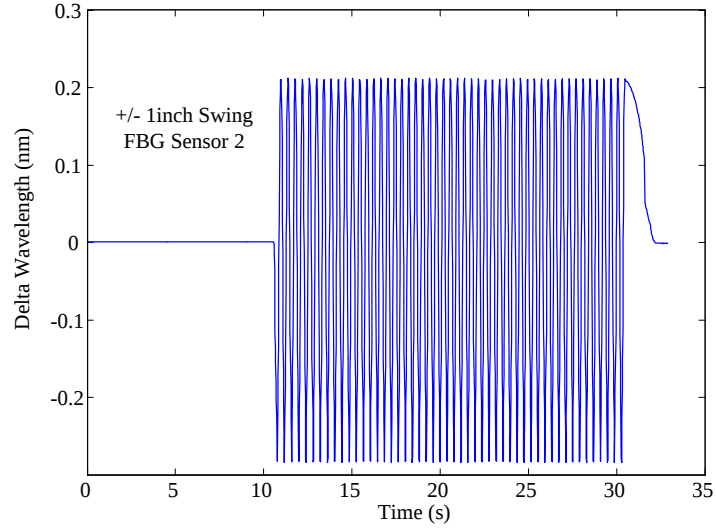


Fig. 5.7. Beam vibration monitoring using FBG sensor system.

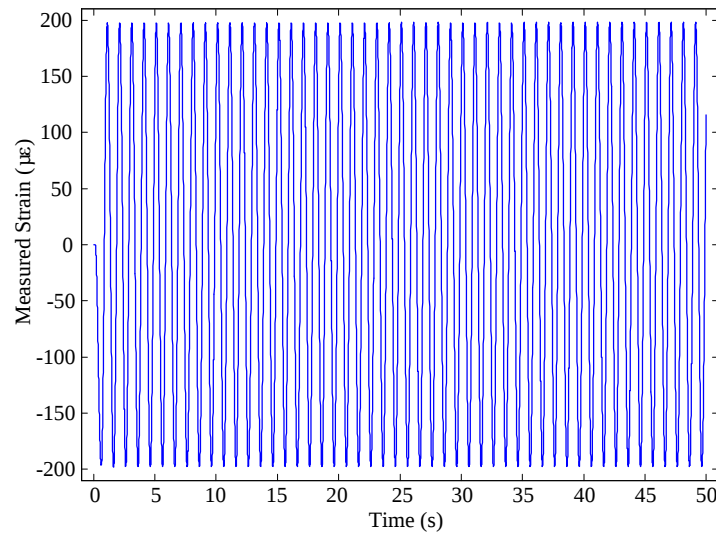


Fig. 5.8. Beam vibration monitoring using strain gauge.

It is seen that the results from the FBG sensor system and strain gauge are matching well.

For the dynamic test with the varied amplitude and frequency, load is applied with the displacement following a sine wave of the varying frequency (1-3 Hz) and amplitude (0-5 in).

The strain results from the FBG sensor system are shown in Fig. 5.9. It clearly shows that our FBG sensor system is capable of obtaining the amplitude and correctly.

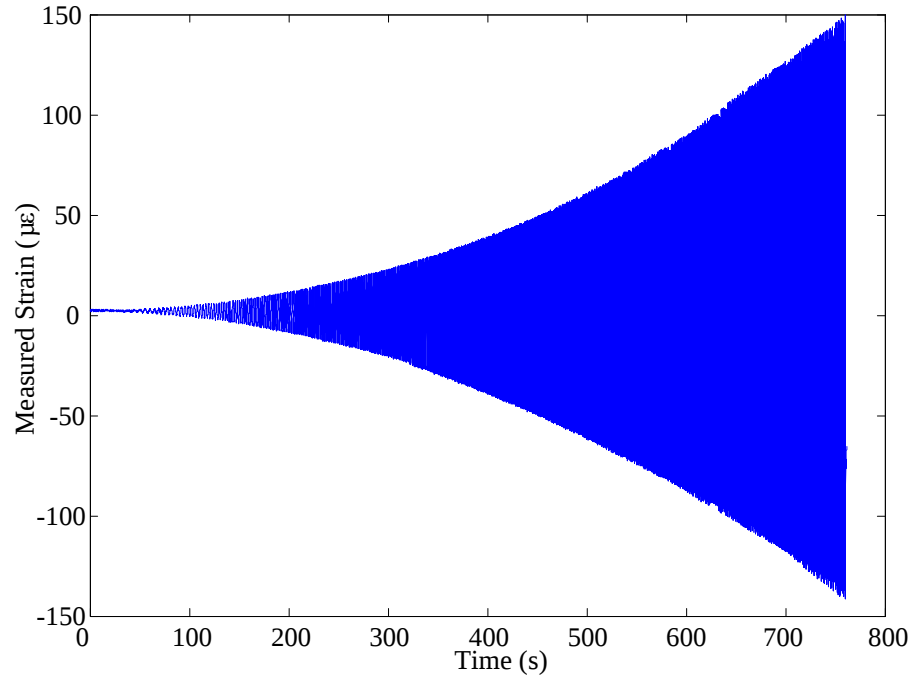
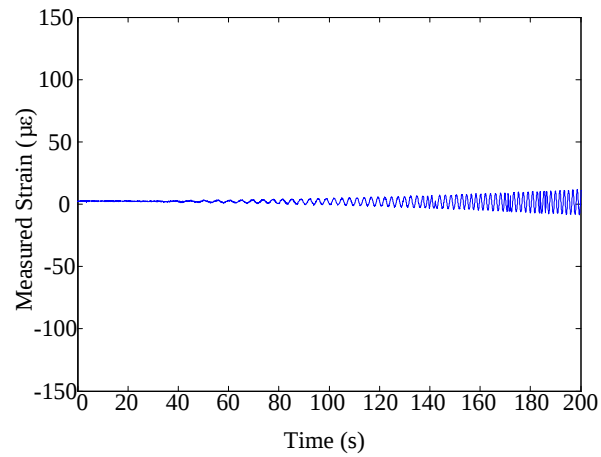


Fig. 5.9. Beam vibration with varied amplitude and frequency using FBG sensor system.

Three samples in Fig. 5.10 are the zoom-in figures of Fig. 5.9 to show the FBG sensor system in monitoring the dynamic strain.



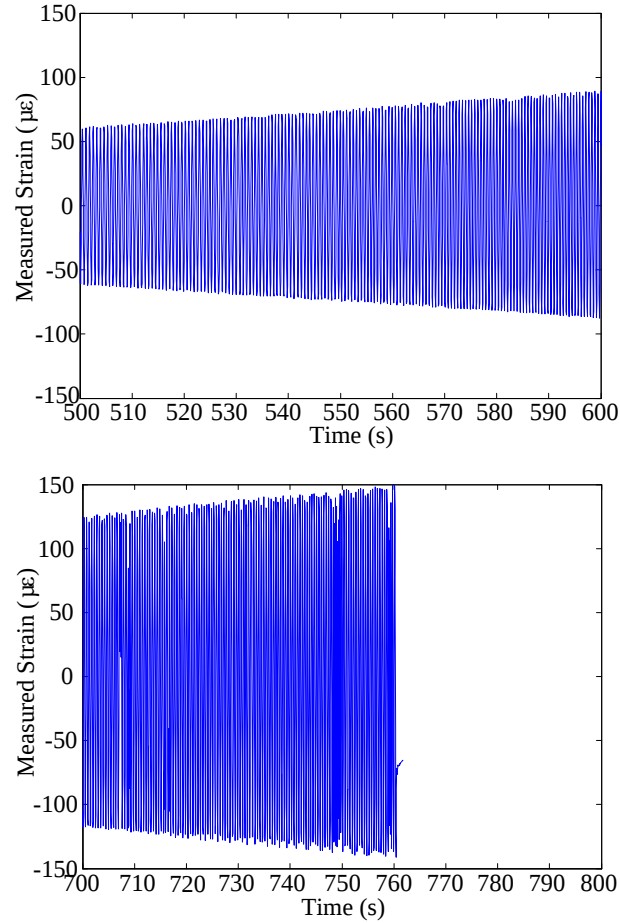


Fig. 5.10. Zoom-in sample figures showing varied amplitude and frequency using FBG snesor system.

The above results show that our developed FBG sensor system could be used for the static and dynamic strain measurement, which proves that it could also be used for the operational load monitoring.

5.3. Investigation of the acoustic signal detection

As described in Chapter 1.1 and Chapter 4.2.3, acoustic sensing technology has been the most promising technology for the impact damage detection in aircraft SHM applications. Fiber optic acoustic sensing technology is currently at a very low Technology Readiness Level (TRL), but shows a great potential of moving towards a higher TRL. There are many challenges the FBG

acoustic sensing technology has to face, including the acoustic FBG sensor design and data interrogation. In this thesis, we push the TRL level of this technology higher by checking the feasibility of using an FBG sensor to detect the acoustic signals in the aircraft SHM testing platform.

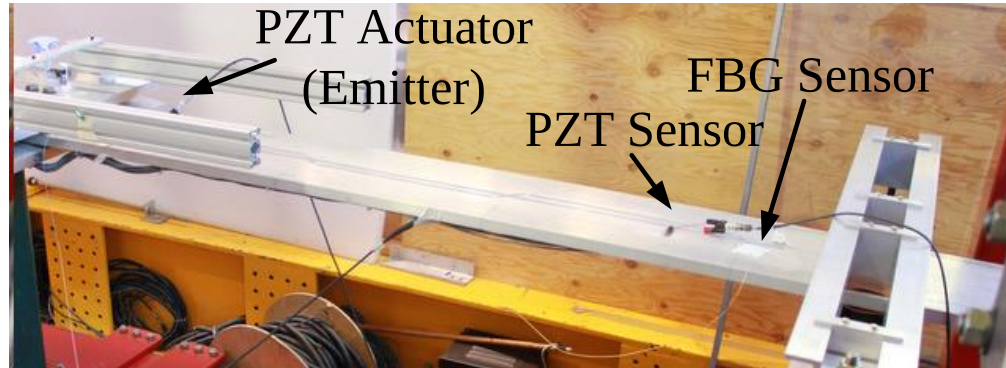


Fig. 5.11. Illustration of the attachments of PZT actuator and FBG sensor.

The experimental setup is shown in Fig. 5.11. The beam shown in the figure is 6061-T6 aluminum beam with a thickness of 25.4 mm (1 in.) (simulating thicker aircraft structural components in this case). Actually, this thickness makes it very challenging to effectively generate and propagate an acoustic wave, and in particular a Lamb wave. It introduces considerable damping in Lamb wave propagation. In the literature related to the damage detection, the generation, propagation, detection, and application of Lamb waves are performed in structural components of considerably smaller thicknesses - usually around 2 mm. Regarding acoustic wave propagation in beam structural elements, the studies are usually performed considering body wave propagation, assuming fairly constant wave propagation velocities independent of the applied wave frequencies. This considerably facilitates the tuning of the actuation, acquisition system, and applied waves. Considering that this testing platform is originally designed for the operational load monitoring in the aircraft SHM and it is used to

simulate the actual aircraft wing structural, we decide to perform the acoustic sensing test with our developed fiber sensing system on this platform for a proof-of-concept result.

Regarding the FBG sensors, it is concluded through reported experimentation that the ideal FBG length to detect and enable the reconstruction of Lamb waves propagating through the sensor location was of $1/7$ of the wavelength to detect [96-97]. This relationship between sensor length and wavelength to detect (for an optimum detection) is related with the desire to use infinite small sensors to sense the infinitesimal strain fields induced and within the propagating strain waves. The FBG reflected light spectrum is related with the strain field sensed along the entire FBG length, with the Bragg wavelength shift being proportional to the average of such sensed strain field. Thus, a longer FBG sensing localized strain fields present a reflected light spectrum with increased bandwidth, generating increased difficulties on relating such reflected light spectrum with the localized strain field. The use of infinite small sensors would enable an accurate reconstruction of the propagating waves. However, the power of the FBGs reflected light is related with the number of fringes (optical fiber cross sections with altered refractive index) in the grating. As a consequence, a grating with a higher length will present an increased number of fringes and then a higher reflected light power.

With the relationships established between wavelength to detect and dimensions of PZT actuators and FBG sensors, the first conclusion is that the length of the applied FBG should be $1/3.5$ the diameter of the PZT actuator disc. Consequently, the applied PZT actuator (diameter) and FBG sensor (length) are non-optimal for this application due to the lab instrument limitation. The generation of the acoustic waves is performed by an Accellent PZT actuator of 6.35 mm ($1/4$ inch) diameter which is attached to the upper surface of the beam in the platform (as show

in Fig. 5.11). The actuator input signals are generated by a commercially available arbitrary waveform generator, capable of output voltage amplitudes of ± 150 V.

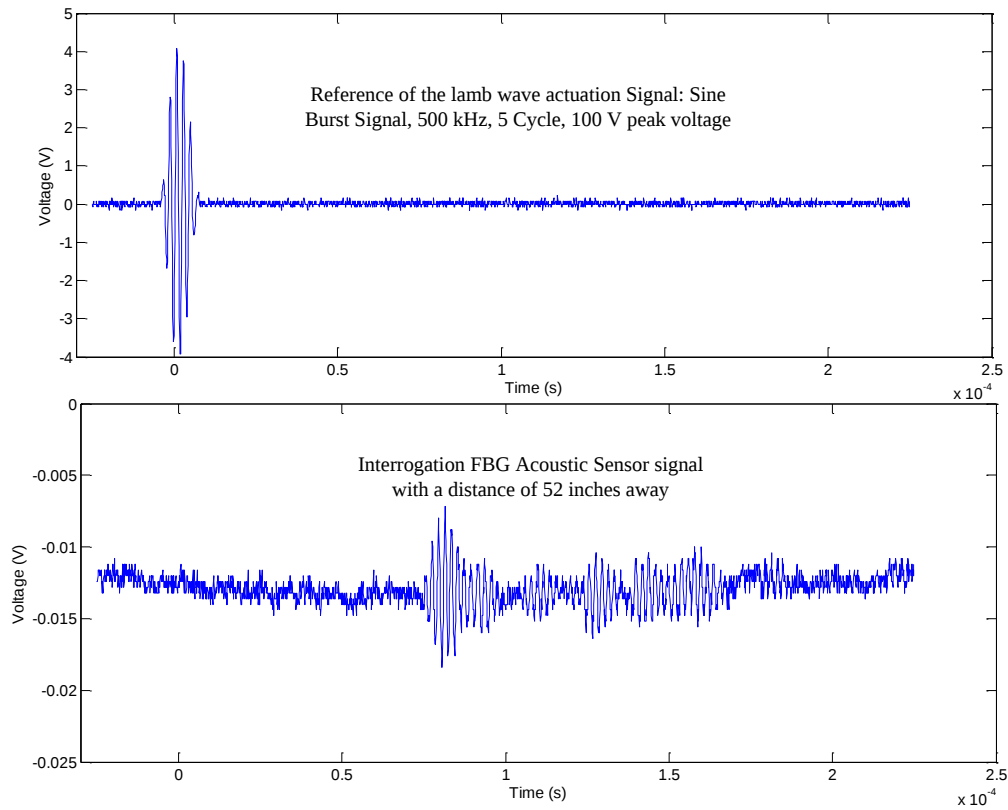


Fig. 5.12. Demonstration of receiving acoustic signal with FBG sensor system.

For the detection of the generated and propagating Lamb waves, an FBG sensor is glued to the upper surface of the beam at a distance of 1.32 m (52 in) away from the PZT actuator (as shown in Fig. 5.12). The FBG sensor is oriented (with its length, pointed) to the wave actuation locale, for a maximum sensitivity to the generated and propagating strain waves. The FBG sensors glued to the beam has a grating length of 3 mm.

The results shown in Fig. 5.12 clearly demonstrate that FBG sensor is able to detect acoustic signals generated with an acoustic transducer at a distance of 52' apart with our developed

interrogation unit. This is important since it may be possible to detect damage within a structure from a remote distance which would eliminate the requirement for knowing the exact damage location. This capability would also allow for the placement of the sensor in an accessible location, which would allow for easy replacement if problems arise.

5.4. Exploration of temperature compensated FBG humidity sensor

Relative humidity (RH) is a critical parameter in the aircraft SHM applications. Most of the conventional RH sensors are resistive and capacitive types, which are based on the electrical properties of the sensing materials [201-202]. Though these conventional electrical RH sensors offer the advantages of low cost and fast response, they have limitations in the multiplexing and deployment in the harsh environment. The unique features of an FBG sensor, such as light weight, small size, immunity to EMI, and multiplexing capability, make it of great interest in the RH measurement. Over the years, FBG RH sensors have been designed and developed [203-221].

It is seen that all these sensors need coatings, which are sensitive to the RH values in the surrounding medium. Considering the operation mechanism, these techniques could be classified into two types. First, the Type I FBG RH Sensors have a coating with the refractive index dependent on the RH values [203-218]. The changes in the RH value will result in a variation in the transmission characteristics of these sensors. By monitoring the power or spectrum, the RH measurement could be achieved. Second, the Type II FBG RH Sensors convert the RH changes into the strain changes applied on the FBG sensors as described in [219-221]. In this scheme, the coating, usually the polyimide material, is a moisture sensitive

material. The water absorption and desorption will result in the volume expansion and shrinkage, which induces the strain changes applied on the FBG sensors. Thus, the Bragg wavelength of FBG sensors is shifting accordingly. By measuring the wavelength shift, RH value can be obtained. Similar operation principle can also been successfully applied in the salinity measurement with a different type of coating (hydrogel) [222]. An illustration of this operation principle is shown in Fig. 5.13. As a conclusion from the overview, the Type II FBG RH sensor is recommended for the aircraft SHM applications due to the following features:

- It is fabricated based on a regular FBG sensor with a special coating. Thus, it has all the features that a regular FBG sensor has.
- It could use our developed wavelength interrogation units.
- It has a strong wavelength multiplexing capability, making it ideal to be used with other FBG sensors, such as strain, temperature, and vibration.

An experimental demonstration of this Polyimide material coated FBG RH sensor is implemented. Fig. 5.14 shows the experimental setup.

The pictures of the RH FBG sensor with a 30 μm thick Polyimide coating material are shown in Fig. 5.15.

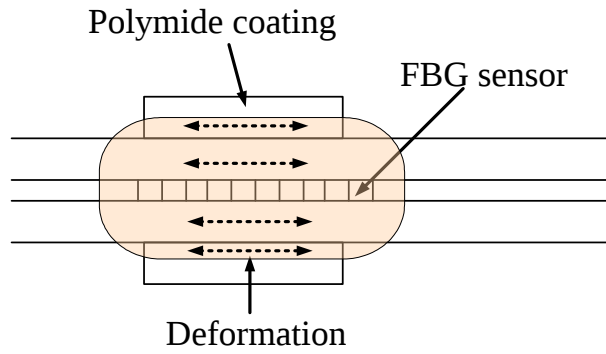


Fig. 5.13. Illustration of the operation principle of polymide material coated FBG sensor in RH measurement.

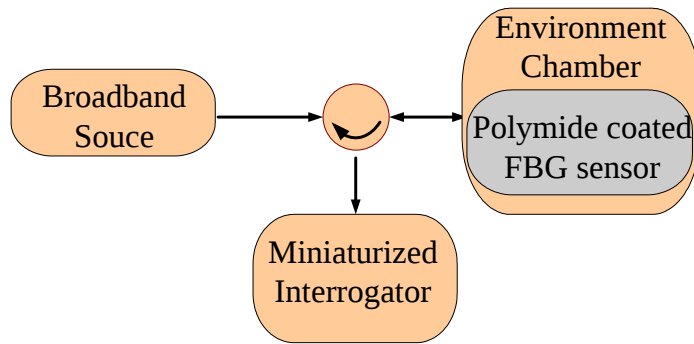


Fig. 5.14. Experimental setup of polymide material coated FBG sensor in RH measurement.

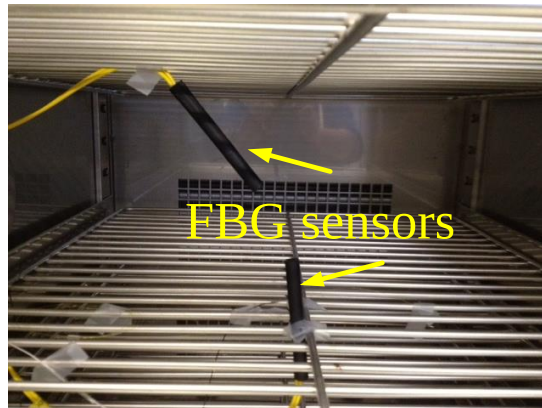


Fig. 5.15. Polymide material coated FBG sensor placed in the environment chamber.

The experimental results are listed below:

- Step 1. The temperature is fixed and humidity is changing from 20% to 90%. Three temperatures, 20 °C, 50 °C, and 90 °C, are selected with the same humidity changing range.

Results are shown in Fig. 5.16.

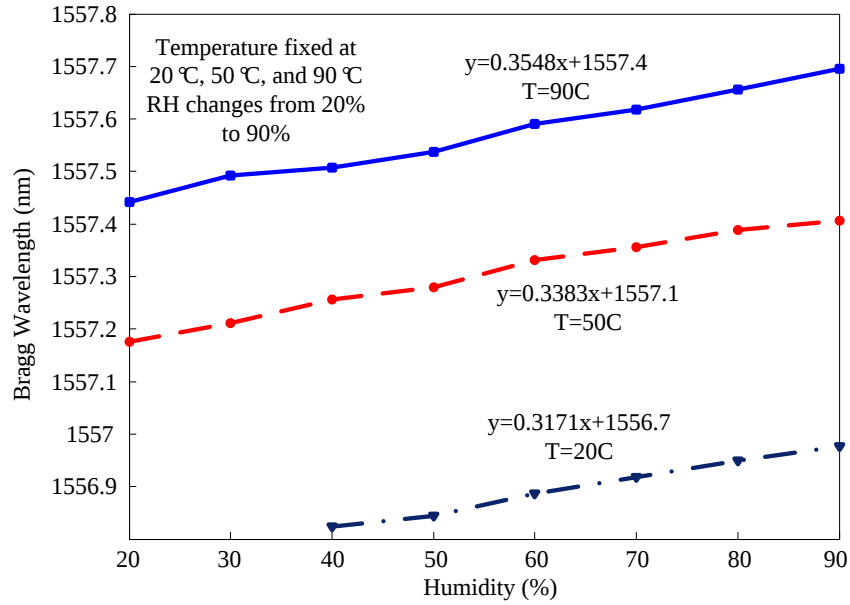


Fig. 5.16. Experimental results of the polyme coated RH FBG sensor. Fix temperature and change RH.

From Fig. 5.16, it is seen that at each temperature the Bragg wavelength shift is linear with respect to the humidity. The coefficient becomes larger when the temperature increases. It is mainly due to the coating material that has a stronger transforming capability at a higher temperature. Meanwhile, it is seen that the temperature also introduces a wavelength shift to the FBG RH sensors, which means that a temperature compensated FBG RH sensor should be used in the aircraft SHM applications.

- Step 2. Fix the RH at 50%, and change the temperature from 20 °C to 90 °C. Results are shown in Fig. 5.17.

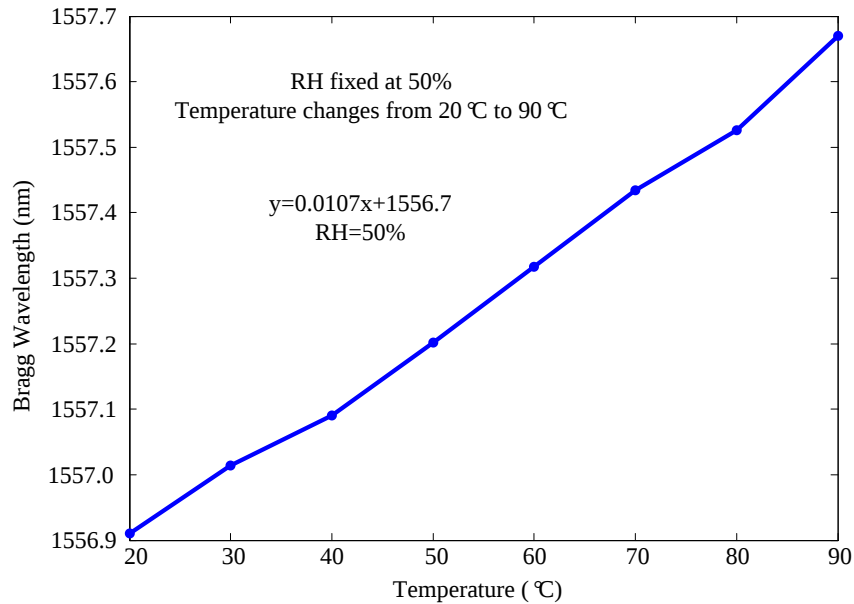


Fig. 5.17. Experimental result of polyme coated RH FBG sensor. Fix RH and change temperature.

From Fig. 5.17, it is seen that the 30 μm thick Polyme coating does not affect the temperature coefficient for the humidity sensor. It has the typical 10pm/°C temperature coefficient as an FBG sensor.

- Step 3. Bare FBG sensors and FBG sensors with regular coating materials (200 - 300 μm thickness).

Results show that bare FBG sensors and the ones with regular coating materials (200 – 300 μm) are not sensitive to the humidity.

- Step 4. Bare tilted FBG and long period grating sensors.

Results show that bare tilted FBG sensors and long period grating sensors are not sensitive to the humidity.

With the experimental results, we could obtain the following conclusions:

- (1) Polyimide coated FBG sensors can be used for the humidity measurement.
- (2) The wavelength shift with respect to the humidity can be regarded as a constant when the temperature is fixed. This coefficient becomes larger when the temperature increases.
- (3) The FBG RH sensor is also sensitive to temperature with the typical temperature coefficient.
- (4) Considering (2) and (3), temperature compensated FBG RH sensors should be used in the aircraft SHM applications.

CHAPTER 6 INTEGRATION OF PLANAR LIGHTWAVE CIRCUITS INTO OPTOFLUIDICS CHIP

In the previous chapters, our developed miniaturized wavelength interrogation units are used in the aircraft SHM applications in association with the FBG sensors. Besides the applications of FBG sensors in the aircraft SHM, they are also used in the biomedical sensing field [25-27, 72, 77]. Therefore, the developed wavelength interrogation units can convert the optical sensing signal into the biomedical information. In Chapter 3.2.4, these wavelength interrogation units are used to interrogate the optical sensing signal from a tilted FBG sensor, which is one of the most powerful tools in the optofluidic analysis [50]. Same wavelength interrogation units can also be used for the evanescent optical sensors [207, 212], which are strong candidates for the optofluidic analysis. Therefore, the developed wavelength interrogation units can be used to interrogate grating-structured optical sensors in the optofluidic analysis.

In addition, the recent progress in the microfluidics for biomedical applications shows a great promise to evolve the microfluidic devices from single function to complex functions which include mixing fluids, sorting particles, sensing particles, and much more [223]. This trend greatly stimulates the integration of optics and microfluidics to form a field commonly referred to as “optofluidics”. During the development of the PLCs based wavelength interrogation units, we find that the advantages of the PLCs, as described in [139-145], show that the integration of the PLCs into the microfluidic devices has a great potential to build the Lab-on-a-Chip device, which is able to synthesize these novel functionalities [224]. Therefore, we propose to use the PLCs to build an optofluidic device to meet this requirement.

6.1. Proposal of the optofluidic device

The proposed optofluidic device is shown in Fig. 6.1, which has three major parts.

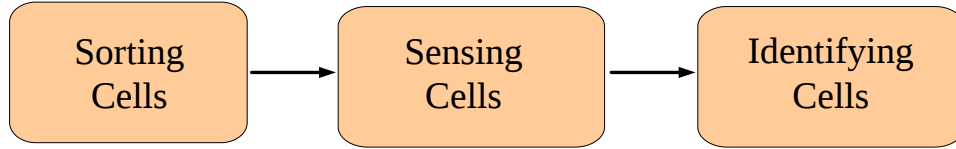


Fig. 6.1. Structure of proposed microchip based optofluidic platform

The functionalities of each part are: (1) sorting and concentrating a single cell type of interest from a mixed cellular population, (2) converting the biological responses of biomolecules released from individual cell types into readable optical signals, and (3) analyzing the feedback signal and identifying the biomolecules.

PLCs are the key components in the proposal optofluidic device.

In the first part, we use PLCs to introduce the light into the device and perform beam forming to increase the photon-solid interaction efficiency, resulting in an enhanced capability of manipulating cells. We first propose and develop a hybrid optofluidic chip (SU-8/PDMS) with monolithically integrated on-chip lens sets for manipulating particles. In this optofluidic chip, cross-type optically driven transport architecture is selected due to its capability of continuously maneuvering particles and its simple configuration. The components, including the fibre groove, microfluidic channel, and on-chip lens sets, are defined in a single PLCs layer of SU-8 by one-step photolithography. The incorporation of on-chip lens set is proposed and demonstrated for the first time to achieve a smaller light beam waist at the microfluidic channel for an increased particle displacement, hence enhancing particles manipulation performance. By

distributing a number of the on-chip lens sets along the microfluidic channel, the manipulation of a particle to a specific position has been achieved.

In the second part, we propose an optical biosensor based on grating structures. The grating architecture could be written on an optical fibre embedded in the device or directly on the bottom of the device fabricated with photosensitive polymeric material via the PLC technology. When the light interacts with some bound cells which usually rest on the surface of the sensor, the local effective refractive index at the surface of the sensor will increase. The light experiencing this slightly varied effective refractive index will have a larger phase change than the case that the cells are not been bound to the sensor. The presence of the phase change will shift the transmission spectrum of the light propagating through the sensor. Therefore, the biological response of cells is converted into an optical signal that could be interrogated by monitoring the spectrum shifts.

In the third part, the optical sensing signal is interrogated from the spectrum shift to the corresponding biological responses with our developed miniaturized wavelength interrogation units. We plan to use a thermal tuning EDG or a mechanical tuning AWG as described in this thesis.

We have numerous achievements, such as PLCs based optofluidic device for the particle manipulation and miniaturized wavelength interrogator for the optical signal interrogation. However, due to the time limitation, not all of the proposed works are fully completed. The realization of the proposed optofluidic device as a fully functional prototype will be scheduled in the future work.

6.2. PLCs based optofluidic device for the particle manipulation⁸

In this work, an SU-8/PDMS microfluidic chip incorporating a monolithically integrated on-chip lens set for transport and manipulation of microparticles is developed. The components, including the on-chip lens set, the microfluidic channel and the fibre grooves, are defined in a single layer of SU-8 by one-step photolithography. The design of the on-chip lens set and the fabrication of the microfluidic chip are fully described. The influence of the beam waist radius on the manipulation performance is theoretically analyzed and experimentally verified for the first time. In the cross-type optofluidic architecture, the evaluation is performed by measuring the particle displacement with different beam waist radii under different fluid flow rates. The on-chip lens set is designed to have a specific dimension to achieve the required beam waist radius. It is revealed that the particle displacement is counter proportional to the beam waist radius. An experiment is performed. The results show that the particle displacement is increased by reducing the beam waist radius. The optical manipulation of microparticles is also demonstrated by using two counter-propagating light beams that are perpendicularly to the fluid flow direction with the beam waist radius determined by two on-chip lens sets placed on the two sides of the microfluidic channel. The proposed architecture could be used to enhance the performance in particle transport, separation and concentration.

I. Introduction

The potential of integrating photonic and microfluidic elements into a ‘Lab-on-a-Chip’ system or a miniaturized total analysis system (μ TAS) has opened new routes to improve the

⁸This section is a revised version of the following published paper. Article title: Optical manipulation of microparticles in an SU-8/PDMS hybrid microfluidic chip incorporating a monolithically integrated on-chip lens set. Authors: Honglei Guo, Ping Zhao, Gaozhi Xiao, Zhiyi Zhang, and Jianping Yao. Published in IEEE Journal of Selected Topics in Quantum Electronics, vol. 16, no. 4, pp. 919-926, Jul. 2010.

performance of the particle transport and manipulation [224-225]. These systems can be accomplished by various methods [226]. The well-known optical tweezer, achieved by using a tightly focused light beam, has already been proven to be a valuable research tool in the fields of biomanipulation [227] and flow cytometry [228]. However, this technique is restricted by the very short focal depth and the large light beam diffraction, which limit its capability in continuously transporting particles and its overall strength in trapping particles [229]. To overcome these drawbacks, a range of near-field methods have recently been demonstrated by using planar optical waveguide [230], high magnification total internal reflection (TIR) microscope objective [231] and sub-wavelength slot waveguides [229]. Although the use of the near-field methods would improve the transport and manipulation performance, the technique has limitations in two aspects. First, the very shallow penetration depth limits the height of the microfluidic channel [232]. Second, the waveguide structure has to be properly designed and fabricated to avoid the multimode distribution in the core waveguide [233]. The technique of optical chromatography is then developed to overcome these limitations. The first type of optical chromatography technique is defined as axial-type optical chromatography [234], where the scattering force resulted from the optical radiation and the fluid drag force act on the particles in the opposite direction. Due to the sensitivity of the scattering force to the particle size and refractive index, this technique has been successfully applied to particle separation [235] and concentration [236]. The architecture has also been extended by using a core waveguide [237] and a hollow core waveguide [238]. Fundamentally, however, the axial-type optical chromatography is not capable of continuously manipulating particles and requires additional devices to deliver the target particles out of the control region. A more recent cross-type optical chromatography technique is developed [239] as a solution to the problems, in

which the light beam propagation is perpendicular to the fluid flow direction. This orthogonal arrangement can manipulate particles in a continuous manner without the need for additional devices to move the target particles away [240]. Similar to other methods, the manipulation performance is highly dependent on the particle size and the refractive index, which have been fully described in [241-242]. On the other hand, the manipulation performance of the orthogonal arrangement relies on the light beam waist radius at the microfluidic channel as well.

All microfluidic chips can be generally classified into two categories based on the materials used for the fabrication of the chips: the optical-planar-waveguide-based architectures and the poly-dimethylsiloxane- (PDMS) based architectures. Optical-planar-waveguide-based architectures can be fabricated by using the thin-film deposition or the anisotropic etching technique, which usually requires two or four photolithographic steps, with a procedure usually lasting up to a couple of weeks [243]. The fabrication process can be simplified by using the polymeric material [244], such as the SU-8 (negative photoresist). The use of PDMS-based architectures can also significantly reduce the complexity in the chip fabrication. However, a duration of at least two days is required to finish the steps of master mold fabrication and the PDMS molding [245]. In addition, the incorporation of other optical elements, such as an on-chip lens, into the PDMS-based architectures will lead to the undesirable fabrication interactions. Especially, a high risk of distorting the optical elements during the processes of peeling off the PDMS layer from the master mold and bonding it on the substrate would be resulted due to the micro features of the chip. In developing the ‘Lab-on-a-Chip’ or μ TAS system, the ability to fabricate a microfluidic chip in a fast manner with low complexity is highly desirable.

In this work, we demonstrate a novel microfluidic chip with an improved particle transport and manipulation performance by incorporating a monolithically integrated on-chip lens set or a few on-chip lens sets in the microfluidic chip. The fundamental principle in the performance improvement is the reduction of the beam waist radius by the on-chip lens set. A theoretical analysis of the operation, the design of the on-chip lens set, and the fabrication of the proposed SU-8/PDMS hybrid microfluidic chip are fully described in this paper. Especially, the influence of the light beam waist radius on the manipulation performance in a cross-type optofluidic architecture is discussed for the first time. Starting from the particle velocity (which is different from [239]), we obtain an analytical expression of the particle displacement induced by an ideal cross-type optically driven propulsion where the flow rate is assumed to have a constant value instead of a parabolic profile. The design of the on-chip lens set is then discussed and the modification of the light beam waist radius is demonstrated. The fabrication of the chip is also detailed. Since the on-chip lens set, the microfluidic channel and the fibre grooves are all defined in the same SU-8 layer, the chip fabrication and packaging are greatly simplified with a much shorter processing time.

II. *Theory*

The radiation forces applied to a particle resulted from the momentum transfer between the photon and the particle could be classified into two categories: the gradient force and the scattering force. The gradient force drives the particle to the center of the light beam, and eventually, retains all the particles at the focal point of the light beam. The scattering force drives the particle in the light beam propagation direction. Given the assumption that the particle size is smaller than the light beam size, the gradient force is small and could be ignored. Therefore, the dominant force is the scattering force.

Based on the ray-optics model [246] and the equation for the calculation of the scattering force [240], the particle displacement from the fluid flow direction can be analytically derived from the particle velocity. Fig. 6.2 is a simplified illustration of the particle deflection, which is used to perform our analysis.

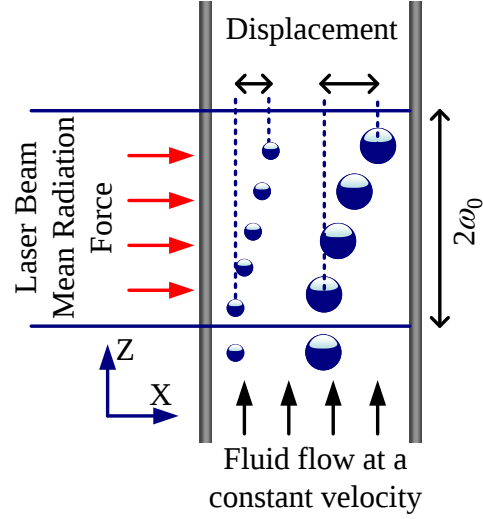


Fig. 6.2. Schematic of the optically driven transport.

Assuming the light beam has an energy distribution of a Gaussian profile, the scattering force at the position of z is given by

$$F(z) = \frac{2nP}{c} \left(\frac{r_p}{\omega_0} \right)^2 Q \exp\left(-\frac{2z^2}{\omega_0^2}\right) \quad (6-1)$$

where P is the power of the light beam, ω_0 is the light beam waist radius, r_p is the particle radius, n is the refractive index of the surrounding medium, Q is a dimensionless factor which is dependent on the refractive indices of both the particle and the surrounding medium, and z is the distance between the center of the particle and the light beam axis.

The mean value of the scattering force is obtained by integrating (6-1) within the light beam region, which is given by

$$F_M = \frac{1}{2\omega_0} \int_{-\omega_0}^{\omega_0} F(z) dz \quad (6-2)$$

Substituting (6-1) into (6-2), we have

$$F_M = \sqrt{\frac{\pi}{2}} \text{erf}(\sqrt{2}) \frac{n^P}{c} \left(\frac{r_p}{\omega_0}\right)^2 Q \quad (6-3)$$

where $\text{erf}(\cdot)$ represents the error function resulted from the integration of the Gaussian function.

As shown in Fig. 6.2, the particles are flowing upwards into the light beam region, from $-\omega_0$ to ω_0 along the z direction. When the particle reaches the light beam region, it is driven along the light beam axis by the force described in (6-3) which gives the particle a velocity along the x direction, denoted as V_p . If we only consider the x -directional components of the vectors, such as the velocity and forces, the equation representing the particle motion in the x direction can be written as

$$m_p \frac{dV_p}{dt} = F_M - F_D \quad (6-4)$$

According to the Stokes's law, the drag force, denoted as F_D , applied to the particle moving at a velocity of V_p is given by

$$F_D = 6\pi\eta r_p V_p \quad (6-5)$$

where η is the viscosity of the surrounding medium. Substituting (6-5) into (6-4), the particle velocity along the x direction is given by [247]

$$V_p = \frac{F_M}{3\pi r_p \eta} (1 - e^{-t/\tau_p}) \quad (6-6)$$

where τ_p is the particle relaxation time and its value is in the order of 10^{-9} s. Since it is relatively small, the term of e^{-t/τ_p} in (6-6) can be neglected. Thus, the maximum particle velocity along the x direction can be obtained by

$$V_{pM} = \lim_{\tau_p \rightarrow 0} V_p = \frac{F_M}{3\pi r_p \eta} \quad (6-7)$$

Considering that the initial particle velocity along the x direction is zero, the displacement along the x direction can be calculated as

$$x = \frac{1}{2} V_{pM} T \quad (6-8)$$

where T represents the time period within which the particle travels through the light beam region from $-\omega_0$ to ω_0 at the z -directional velocity of U , which is regarded as the fluid flow rate. As a pressure driven fluid, the flow rate has a parabolic profile within the microfluidic channel, where the fluid that is closer to the microfluidic channel wall has a lower flow rate. The non-uniform flow rate distribution is due to the viscous force between the fluid and the microfluidic channel [248]. In this paper, the theoretical model is set up for validating the proposed theory, that is, the particle displacement could be increased by reducing the light beam waist radius. In addition, surface treatment is applied to the microfluidic channel to reduce the viscous force between the fluid and the microfluidic channel, which could be used to keep the flow rate constant, to some extent, rather than having a parabolic profile. Thus, for the sake of simplicity, we assume that the fluid flow rate could be considered as a constant value within the

area where the particles are deflected by the incoming light beams. Therefore, for a time period of $T = 2\omega_0/U$, substituting (6-3) and (6-7) into (6-8), we obtain the displacement given by

$$x = \sqrt{\frac{\pi}{2}} \operatorname{erf}(\sqrt{2}) \frac{nP}{3\pi\eta U c} \frac{r_p}{\omega_0} Q \quad (6-9)$$

It is seen that the displacement is counter proportional to the light beam waist radius at the microfluidic channel. This conclusion is important since we can increase the displacement by using an on-chip lens set to reduce the waist radius rather than increasing the input light power.

III. Design and Fabrication

The key significance of the current work is the incorporation of a monolithically integrated on-chip lens set into a microfluidic chip, by which the beam waist radius is reduced, which leads to an improved performance in the optofluidic transport and optical manipulation. An on-chip lens [249] is originally designed to enhance the detection efficiency of a scattered light [250-251]. In our earlier study, we have shown that the particle displacement can be increased by using a light beam with a reduced waist radius modified by an on-chip lens set [243]. In this section, the design of an on-chip lens set is described and the use of an on-chip lens set to reduce the beam waist radius is demonstrated. The chip fabrication is also detailed in this section. The schematic of a microfluidic chip is shown in Fig. 6.3.

As illustrated in Fig. 6.3, two on-chip lenses (such as On-Chip Lens 1 and On-Chip Lens 2) are used as an on-chip lens set (such as On-Chip Lens Set 2) to achieve a specific light beam waist radius. On the right side of the microfluidic channel, three sets of lenses with different lens dimensions are fabricated and placed along the channel, as shown in Fig. 6.3. These three

different light beam waist radii can be achieved by the on-chip lens sets. The lens dimension settings for the On-Chip Lens Set 2 illustrated in Fig. 6.3 are listed in Table 6.1.

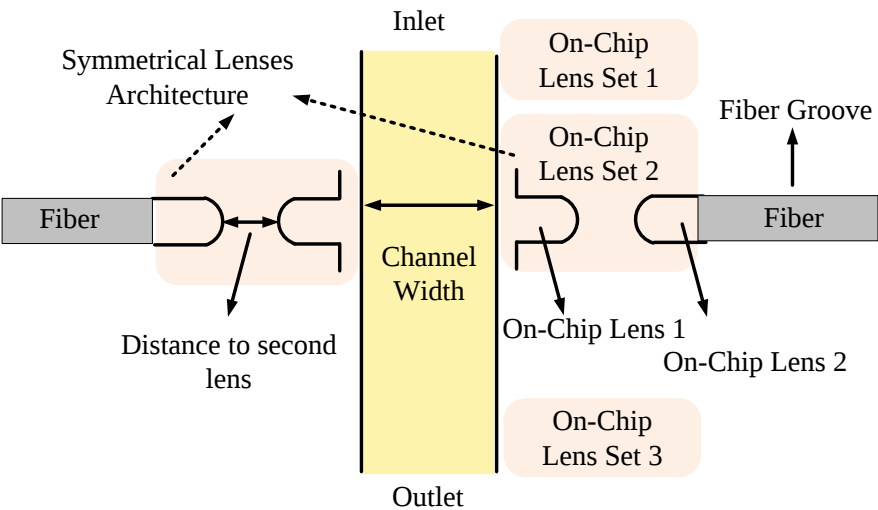


Fig. 6.3. Schematic of a microfluidic chip incorporating on-chip lens sets.

In order to achieve the optical manipulation by using two counter-propagating light beams, a symmetric architecture by incorporating on-chip lens sets on the other side of the microfluidic channel is designed, which is denoted as “Symmetrical Lenses Architecture” in Fig. 6.3.

TABEL 6.1. DIMENSIONS OF THE ON-CHIP LENS SET 2 STRUCTURE^A

Lens 1	Curvature	-300 ^B
	Aperture	500
Distance to second lens		300
Lens 2	Curvature	190
	Aperture	500

A. unit is μm .

B. Negative curvature means a concave lens while positive curvature means a convex lens

The width of the microfluidic channel is designed to be $100\ \mu\text{m}$ and the height is $130\ \mu\text{m}$, which are determined by the size of the external optical fibre. The fibre used in this work has a

core radius of 52.5 μm and a cladding radius of 60 μm . The input light beam is introduced into the on-chip lens by butt coupling. The fibre groove is used to fix the fibre, which avoids the use of a high-precision positioning stage and simplifies the alignment.

Take the On-Chip Lens Set 2 for example, Fig. 6.4 illustrates the overall field view of the fiber groove and the lens structure in both bright and dark fields.

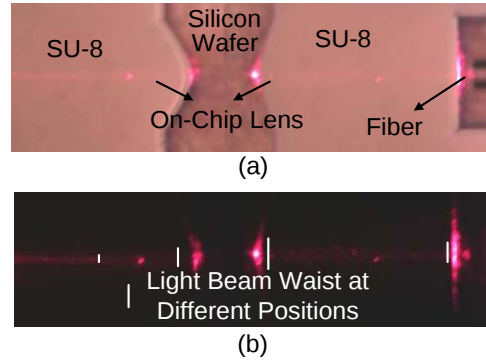


Fig. 6.5. Microscope images of the On-Chip Lens Set 2 (the microfluidic channel is on the left side of the images and is not shown here due to the limited vision field). (a) Bright field image. (b) Dark field image with the incident light beam of He-Ne laser (632.8 nm, 20 mw).

All the three on-chip lens sets are shown in Fig. 6.5(a) and the resultant light beam waists on the microfluidic channel are shown in Fig. 6.5(b). The light beam waist radius on the microfluidic channel can be estimated in each on-chip lens set with the assistance of the known channel width, which is fixed at 100 μm (defined by the photomask). By comparing the distance of the channel width and light beam waist radius obtained from Fig. 6.5(b), the light beam waist radii are measured to be $\sim 75 \mu\text{m}$, $\sim 50 \mu\text{m}$, and $\sim 100 \mu\text{m}$ (total light beam size of $\sim 150 \mu\text{m}$, $\sim 100 \mu\text{m}$, and $\sim 200 \mu\text{m}$) for the On-Chip Lens Set 1, 2, and 3 respectively.

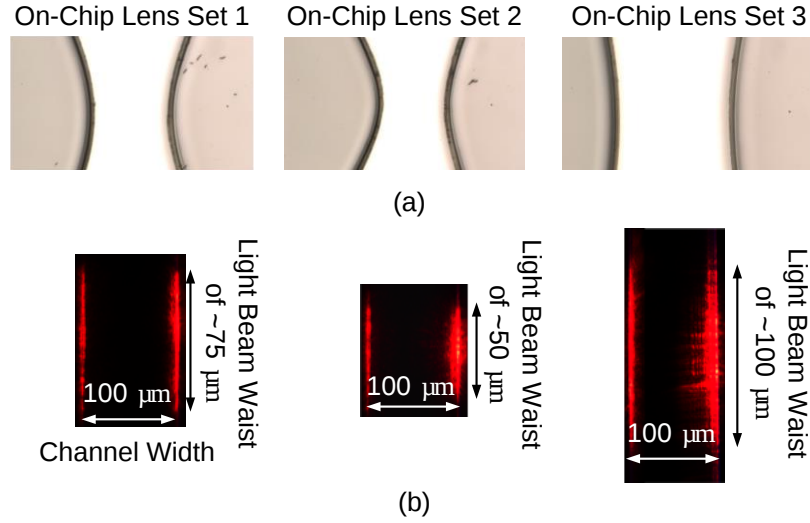


Fig. 6.5. Illustration of the three on-chip lens structures. (a) on-chip lens structure. (b) light beam waist on the microfluidic channel. (a) and (b) are not in the same scale.

The architecture of the proposed microfluidic chip is illustrated in Fig. 6.6. It is fabricated with the photolithography technique [252]. In general, the on-chip lens set, the microfluidic channel and the fibre grooves are defined in the same layer of SU-8 (SU-8 2075, MicroChem). All these components are fabricated based on a 4-inch silicon wafer as the substrate. The use of a silicon wafer makes it simple to fabricate the 130-μm-thick architecture. During the fabrication process, the silicon wafer is first cleaned in a ‘Piranha’ solution ($\text{H}_2\text{O}_2:\text{H}_2\text{SO}_4=1:4$) for 30 min and is then thoroughly washed by distilled water, followed by a dehydration process in a 250 °C oven for 3 h to improve the adhesion of the SU-8. The 130-μm-thick SU-8 layer is spun onto the wafer with a rotation speed of 1500 rpm after the wafer is cooled down to the room temperature. The microstructures are defined on the SU-8 layer by UV photolithography. The post-exposure bake is implemented by putting the microfluidic chip on a hotplate with the temperature of the hotplate being increased to 100 °C at a temperature ramp of 10 °C/min and then keeping the temperature at 100 °C for 30 min. The microfluidic chip is then cooled down to the room temperature again. The microfluidic chip is developed in the SU-8 developer for 30

min. Finally, our newly home-developed bonding technique [253] is applied to seal a layer of pre-made PDMS on top of the SU-8 based microstructures as a cover. Our home-developed bonding technique makes the whole fabrication process easier to handle compared with the technique applying spring-mounted screws in [250]. Since only one mask is required in the fabrication process and the architecture is fabricated on SU-8, the proposed SU-8/PDMS hybrid microfluidic chip can be made, packaged and tested in a single fabrication step, which would significantly reduce the processing time compared with other existing methods where a long processing time of a few days is usually needed. In addition, the fabrication complexity is also significantly reduced.

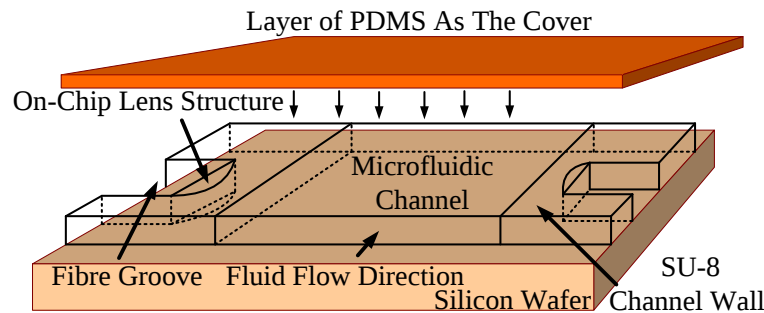


Fig. 6.6. Illustration of the proposed microfluidic chip architecture.

After the proposed SU-8/PDMS microfluidic chip is fabricated, surface treatment should be applied to the microfluidic channel for two reasons [254]. First, surface treatment is used to reduce the viscous force between the fluid and the microfluidic channel, achieving a constant flow rate, to some extent, within the channel rather than having a parabolic profile. Second, surface treatment can prevent the samples (microparticles) from attaching on the microfluidic channel. Surface treatment is implemented first by introducing 3% Pluronic F68 into the

channel. Then, the channel is rinsed with phosphate buffered saline (PBS) to remove any residue of Pluronic F68 before introducing any sample.

IV. Experimental results and discussion

Polystyrene particles (Polystyrene Microsphere, refractive index of 1.59, Polysciences) are used in this work to evaluate the performance of the developed microfluidic chip for microparticle transport and manipulation. The radii of the polystyrene particles are 1 μm and 3 μm . The particles are first diluted to a concentration of 105 samples/ml, and then introduced into the microfluidic chip with a 1 ml syringe and a syringe pump (Pump 33, Harvard apparatus).

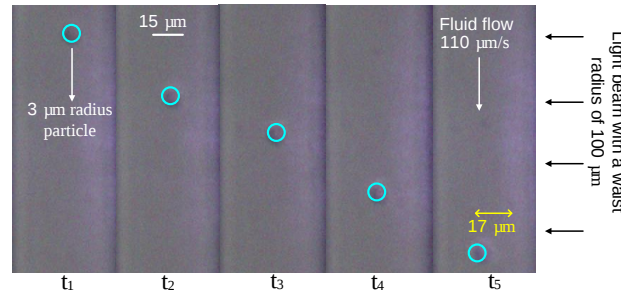


Fig. 6.7. Snapshots of the transport of a 3- μm -radius particle with the light beam waist radius of 100 μm at a flow rate of 110 $\mu\text{m/s}$. The cropping location is the same in each time-lapse image.

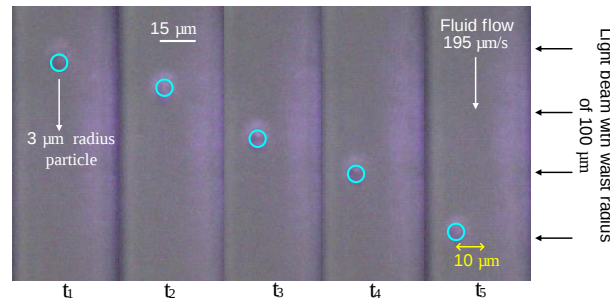


Fig. 6.8. Snapshots of the transport of a 3- μm -radius particle with the light beam waist radius of 100 μm at a flow rate of 195 $\mu\text{m/s}$. The cropping location is the same in each time-lapse image.

A continuous-wave fiber laser (Custom designed, fibre tail of AFS 105/125Y, NA=0.22, WT&T) with a operating wavelength of 1064 nm and an output power of 0.5 W is employed to

provide the input light beam. The motions of the particles are captured using an imaging system that consists of a microscope (Nikon), a $20\times$ microscope objective (Infinity-Corrected long working distance objective, Mitutoyo), and a CCD camera (Infinity 2-2, Lumenera).

The performance of the optofluidic transport is evaluated by measuring the particle displacements. A light beam with a beam waist radius of 50 μm , 75 μm or 100 μm achieved using one of the three on-chip lens sets is applied to perform the measurement. Although the light beam is loosely focused by the on-chip lens set, the light beam waist radius is still larger than the particle radius. Therefore, the assumption that the gradient force is negligible and the scattering force is the dominant radiation force is still valid.

The optofluidic transport of microparticles with a radius of 3 μm is first performed. Experimental results are shown in Figs. 6.7 and Fig. 6.8, where the flow rates are 110 $\mu\text{m/s}$ and 195 $\mu\text{m/s}$ respectively.

The fluid flows downwards in the microfluidic channel, and the input light beam with a modified waist radius of 100 μm is introduced into the microfluidic channel from the right to the left, which drives the particle to the left direction. This orthogonal arrangement is defined as the cross-type optofluidic transport as discussed above. A series of snapshots obtained at different instants, starting from t_1 to t_5 , is shown. It is seen that the 3- μm -radius particles have been driven with different displacement at different flow rates.

Particle displacements are also measured with the other two light beam waist radii at different flow rates. A comparison between the theoretical and experimental results is shown in Fig.6.9.

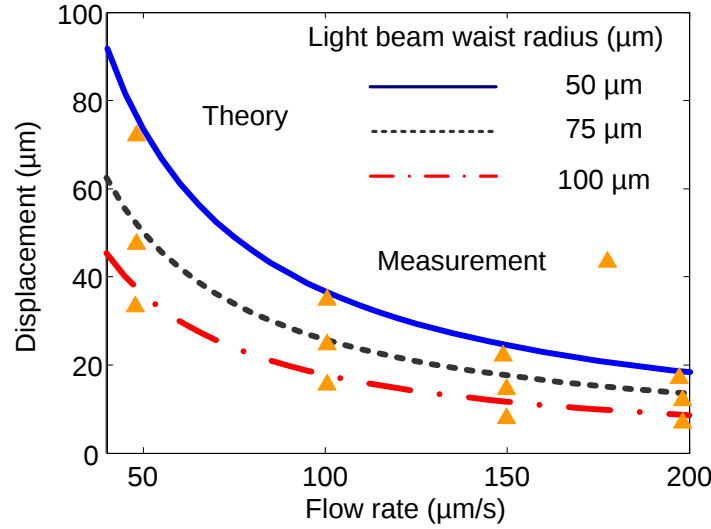


Fig. 6.9. Measured and simulated displacement as a function of the flow rate and the light beam waist radius. The comparison is made for a microparticle with a 3- μm radius.

In Fig. 6.9, the particle displacement is evaluated as a function of the light beam waist radius and the flow rate. In all cases, the measured displacements agree well with the theoretical predictions. As can be seen the displacement is increased by reducing the light beam waist radius. This conclusion is important since it provides a potential solution to enhance the performance of a microfluidic chip for the optofluidic transport and optical manipulation by defining its architecture rather than using a high power laser. It is also seen that a small deviation exists between the measured and theoretical displacements, which is believed to be mainly resulted from the assumption that the fluid flow rate keeps constant within the microfluidic channel, whereas it should have a parabolic profile as discussed in the theory section. However, as can be seen from Fig. 6.9, it is deemed sufficient for the purpose of demonstrating that the displacement could be enhanced by reducing the light beam waist radius.

Then, the optofluidic transport of the 1- μm -radius particles is experimented. Fig. 6.10 shows the experimental result, which is obtained using a light beam with a waist radius of 50 μm and the particles are moving at a flow rate of 105 $\mu\text{m/s}$. A comparison between the experimental and

theoretical displacements of the 1- μm -radius particle is shown in Fig. 6.11. Again, a reduced waist radius leads to an increased displacement in the optofluidic transport.

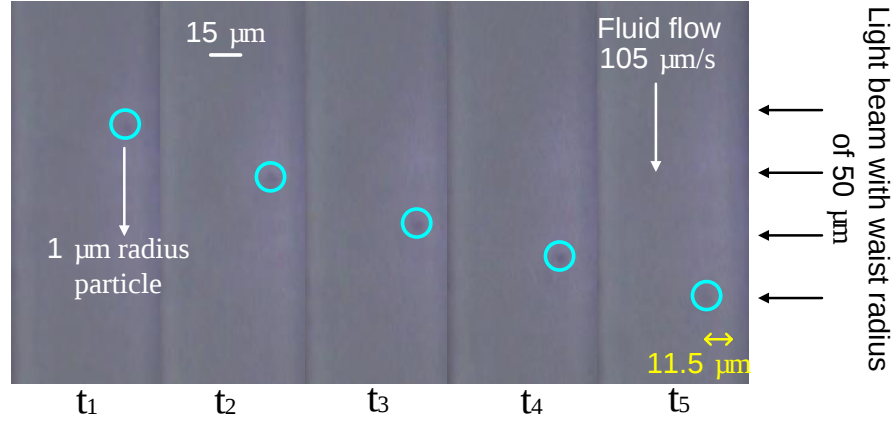


Fig. 6.10. Snapshots of the transport of a 1- μm -radius particle with the light beam waist radius of 50 μm at a flow rate of 105 $\mu\text{m/s}$. The cropping location is the same in each time-lapse image.

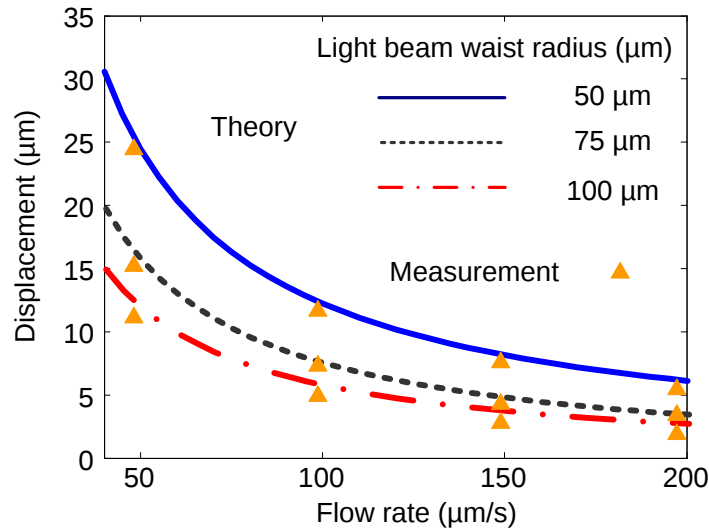


Fig. 6.11. Measured and simulated displacement as a function of the flow rate and light beam waist radius. The comparison is made for a microparticle with a 3- μm radius.

Third, the optofluidic transport of mixed particles with two different radii is experimented. The experimental results are shown in Fig. 6.12. Again, the measured displacements of the particles with different radii agree well with the theoretical predictions as shown in Fig. 6.9 and Fig.

6.11. If we compare the displacements of the particles with different radii, we will find that the displacement of the 3- μm -radius particle is three times that of the 1- μm -radius particle, which confirms the relationship between the particle size and the displacement as shown in (9).

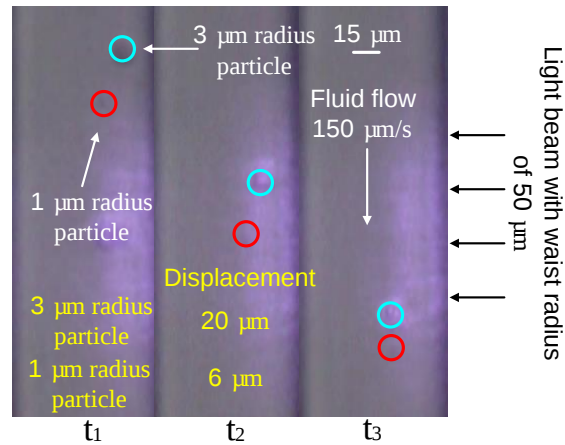


Fig. 6.12. Snapshots of the transport of mixed particles of radii of 1- μm and 3- μm with the light beam waist radius of 50 μm at a flow rate of 150 $\mu\text{m/s}$. The cropping location is the same in each time-lapse image.

Finally, the optical manipulation of a 3- μm -radius particle is demonstrated using the developed microfluidic chip. The motion of the particle is controlled by two counter-propagating light beams introduced to the microfluidic chip from two opposite sides, both propagating perpendicularly to the fluid flow direction. The second light beam is provided by a fibre laser source (Custom designed, standard single mode fibre, WT&T) with an operating wavelength of 1067 nm and an output power of 150 mw. The two output fibres of the two laser sources are fixed in the fibre grooves on each side of the microfluidic channel, as shown in Fig. 6.6. The On-Chip Lens Set 2 as shown in Fig. 6.3 is used to achieve a light beam waist radius of 50 μm , and another on-chip lens set on the opposite side is used to achieve a light beam waist radius of 10 μm . The use of the two counter-propagating light beams is different from the optical trapping reported in [255], where a pair of single mode fibers or a pair of multimode fibers was used to achieve the optical trapping. In this work, however, the optical manipulation of a

microparticle is performed by the optofluidic transport which is different from the optical trapping. In addition, the optical manipulation ability is important for the assembly techniques and optically driven bioanalysis [256]. Furthermore, the analysis of the mode distribution in the cross section of the two light beams and the precise control of their output power, as required for the optical trapping in [255], are not necessarily considered in the proposed optical manipulation scheme, because we are only considering the mean value of the radiation forces as illustrated in (2). Therefore, it is a simple process to achieve optical manipulation.

The optical manipulation is shown in Fig. 6.13 with six steps from Fig. 6.13(a) to (f). Fig. 6.13(a) shows the area of the control region. At the beginning, the two lasers are off. After the particle flows into the control region at Position A, Laser 2 is switched on and input light beam 2 drives the particle to the left as shown in Fig. 6.13(b). After the particle has been driven with a displacement to the left direction, Laser 2 is off and the particle continues to flow along the microfluidic channel as shown in Fig. 6.13(c). Then, Laser 1 is turned on and input light beam 1 pushes the particle to the right, as shown in Fig. 6.13(d). When the particle reaches a position as shown in Fig. 6.13(e), Laser 1 is turned off. The particle then leaves the control region at Position B, as shown in Fig. 6.13(f).

It is seen that the output position and the moving path inside the control region can be defined by the two lasers. The architecture for the manipulation of the particle shown in Fig. 6.13 can be considered as an optical manipulation unit. By placing a number of these units along the microfluidic channel, the transport of a particle to a specific position can be accomplished. With the modified waist radius of the input light beams, the optofluidic transport performance can be maximized in each unit. This will improve the performance of the optical manipulation.

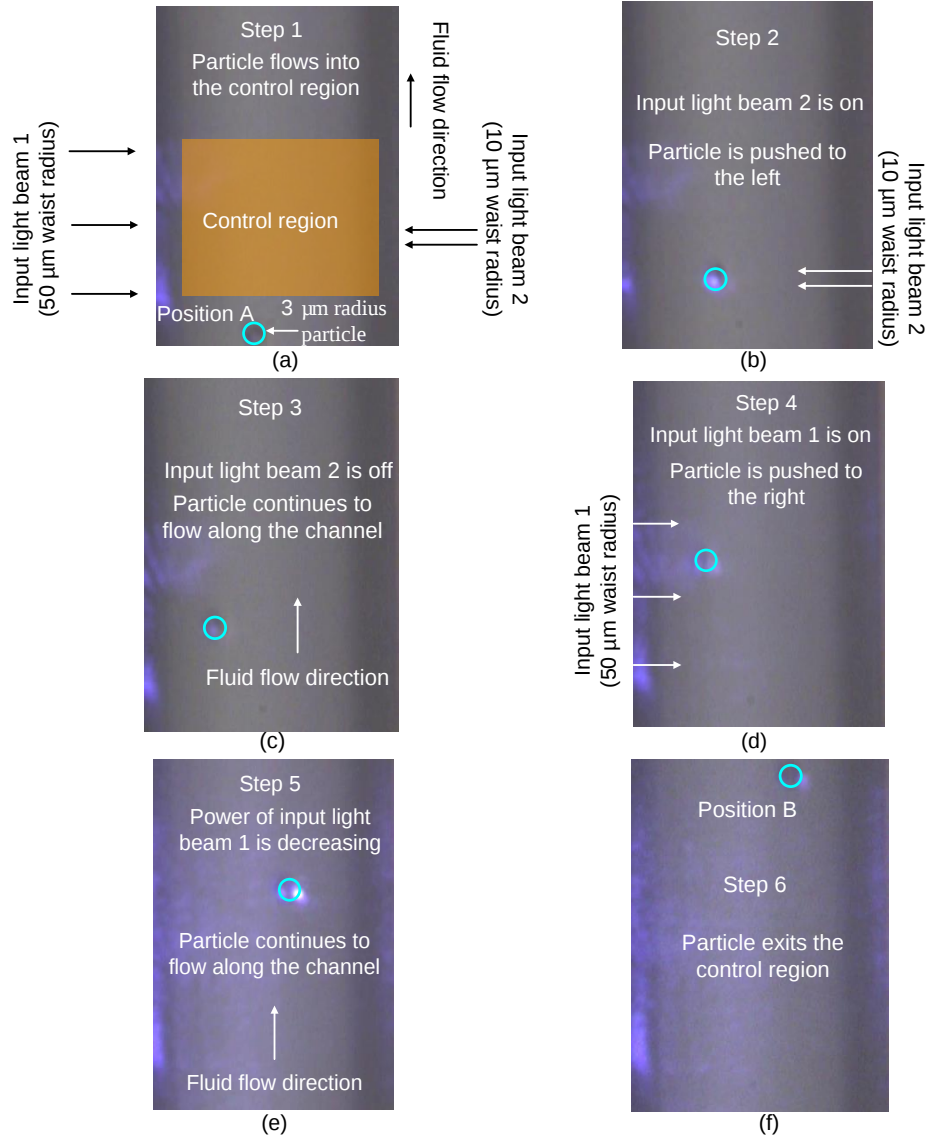


Fig. 6.13. Optical manipulation of a 3-μm radius particle by controlling the powers of the two light beams.

In addition, a further expected performance for this device is that the particle displacement could be further increased to over 200 μm by designing a compound on-chip lens structure while keeping a low power of the input light beam. For this displacement, it is believed to be sufficient for separating the target particles. In such a case, the proposed SU-8/PDMS microfluidic chip with a monolithically integrated compound on-chip lens structure is expected

to have a potential to be applied in the optofluidic sorting and switching applications [257] with its capability of manipulating particles demonstrated in Fig. 6.13.

V. Conclusion

Beside the use of PLCs in the wavelength interrogation unit as discussed in previous chapters, its application is extended to biophotonics in this chapter. More specifically, an SU-8/PDMS microfluidic chip incorporating a monolithically integrated on-chip lens for the transport and manipulation of microparticles was developed and experimentally demonstrated. The design of the on-chip lens sets and the fabrication of the microfluidic chip were fully described. The dependence of the optofluidic transport on the light beam waist radius using an on-chip lens set was evaluated for the first time. It was shown that an increased particle displacement was achieved with a reduced light beam waist radius. The displacements of particles with different radii under different flow rates were also measured. The experimental results agreed well with the theoretical analysis. In addition to the transport of a microparticle using the developed microfluidic chip, the use of the microfluidic chip for the optical manipulation of a particle was also demonstrated, which was achieved by introducing two counter-propagating light beams into the microfluidic chip using two on-chip lens sets placed on the two sides of the microfluidic channel. The incorporation of multiple on-chip lens structures with the compound lens design in the microfluidic chip would make the proposed microfluidic chip to have an improved functionality for the transport and manipulation of microparticles for different optofluidic sorting and switching applications.

CHAPTER 7 SUMMARY AND FUTURE WORK

7.1. Summary

In this thesis, the research efforts have been focused on the development of miniaturized wavelength interrogation units for fiber grating sensors, which met the requirements of the aircraft structural health monitoring applications and optofluidic analysis. Two types of PLCs, arrayed waveguide gratings and Echelle diffractive gratings, were selected to build the prototypes. Theoretical analysis was performed and experimental verifications were demonstrated in this work.

AWG based wavelength interrogation unit was first presented. Instead of reported wavelength interrogation techniques, spectrum tuning techniques were introduced to increase the measurement resolution and range. Two spectrum tuning techniques were used, thermal tuning and mechanical tuning. In the thermal tuning, the AWG temperature was controlled. As the center wavelength of an AWG channel spectrum had a linear relationship with the AWG temperature, the AWG spectrum could be linearly tuned, which was then used to scan and retrieve the sensor spectrum. By knowing the AWG temperature corresponding to the peak of the received light power and the temperature dependency of the AWG spectrum, the sensor spectrum peak could be obtained. Mechanical tuning had a similar operation principle, where the tuning spectrum was achieved by adjusting the input light position along the AWG input coupler. The linear dependency of the AWG spectrum with respect to the input light position existed, which was named as the space-to-wavelength mapping in this thesis. By using the same peak searching methodology, sensor spectrum peak could be obtained by substituting the input

light position corresponding to the peak of the received light power into the space-to-wavelength mapping.

The miniaturized wavelength units were also built based on an EDG, which was the other type of the PLCs. Due to the intrinsic characteristics of an EDG, it had a size at least half smaller than the size of an AWG, making it more ideal for the aircraft SHM applications and Lab-on-a-Chip optofluidic analysis. As the EDG used in this work was a commercially monolithically packaged device, only thermal tuning could be used. The spectrum of an EDG was proved to have the same temperature dependence, but at larger rate compared with the one of an AWG due to the EDG material. In addition, an advanced model of an EDG based interrogation unit was built. It had two operation modes, sweeping mode and parked mode, which were for the two major aspects of the aircraft SHM applications, operational load monitoring and impact damage detection. Besides the applications in the wavelength interrogation, the EDG based wavelength interrogation unit also showed a potential capability as a multichannel RF receiver.

Field tests in the aircraft SHM applications were performed of using an FBG sensor system on a platform which simulated the aircraft wing structure. Dynamic strain and acoustic signal measurement were performed for the operational load monitoring and impact damage detection respectively. In addition to the above measurement, an FBG based humidity sensor was developed and used to monitor the humidity with our developed interrogation units, which was also a major environmental parameter in the aircraft SHM applications.

In conclusion, the developed AWG and EDG based wavelength interrogation units, to a certain extent, overcame the current limitations of deploying fiber optic sensors, especially FBG sensors, in the aircraft SHM applications. Results have shown that these interrogation units had

the features of compact size, light weight, broad measurement range, high measurement resolution, and multichannel measurement capability, making them ideal for the aircraft SHM applications.

Besides the uses of PLCs based wavelength interrogation units in the aircraft SHM applications, they could also be used for the optofluidic analysis in our proposed optofluidic device. The proposed optofluidic device had three parts and each part was built with the PLC technology, which combined optics and microfluidic to achieve novel functionalities. In the first part of the proposed device, PLCs were used to introduce light into the device and perform beam forming to enhance the manipulating capability of the small particles and cells. PLCs in this part were made together with the fluidic channels using the SU-8, including the straight waveguides for introducing the light and on-chip lens structures for focusing the light. By introducing these PLCs, the input light beam could be focused, which was verified to increase the performance of manipulating small particles with the diameter in μm level. Theoretical and experimental results have shown that the performance was successfully enhanced by reducing the beam size with the on-chip lens structures. The second part of the proposed device was the sensing part, which consisted of grating-structured sensors to convert the biomedical information into readable optical signals. The last part of the proposed device was the developed wavelength interrogation units, which could interrogate the optical signals and recover the biomedical information. By the time of finishing this thesis, we had achieved initial results for the first part and experimental results for the third part. Due to the time limitation, the development of the second part and the assembling of the three parts together were left to the future work. However, the current results showed that our proposed optofluidic device had a great potential to be packaged as a Lab-on-a-Chip device for the optofluidic analysis.

7.2. Future work

In this thesis, AWG and EDG based wavelength interrogation units have been developed and shown good performance in the fiber optic sensor interrogation in both aircraft SHM applications and optofluidic analysis.

The advanced EDG based wavelength interrogation unit is able to operate under two working modes, the sweeping mode and parked mode. In the sweeping mode, thermal tuning technique is used and the performance has already been verified. In the parked mode, we have reached an interrogation speed up to 200 Hz in the field tests and 500 kHz in a proof-of-concept test. Based on the theoretical analysis and experience from published studies, the interrogation speed up to 500 kHz is enough for the acoustic signal in the impact damage detection in the aircraft SHM applications [103, 117]. The continuous investigation and development of this advanced EDG based interrogation unit will be done in the further work.

In addition, the space-to-wavelength mapping of an AWG is proposed and experimental results show that it has a great potential to build a multichannel wavelength interrogation unit with 32-channel measurement capacity, larger than 60 nm measurement range per channel, and 1-pm resolution. The current barrier is the light coupling while the input light travels along the AWG input coupler in the range of 1 - 1.5 mm. Top surface light coupling has been recently reported with a good coupling efficiency [181]. It would be of great interest if the top surface light coupling can be used in the AWG based wavelength interrogation unit in the near future.

In the optofluidic analysis, the proposed device as described in Chapter 6.1 is scheduled to be built upon available resources.

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PUBLICATION LIST

Refereed journal papers

- 1 **H. Guo**, G. Xiao, N. Mrad, and J. P. Yao, "Echelle diffractive grating based wavelength interrogator for potential aerospace applications," *J. Lightwave Technol.*, vol. 31, no. 13, pp. 2099-2105, Jul. 2013.
- 2 **H. Guo**, G. Xiao, N. Mrad, and J. P. Yao, "Fiber optic sensors for structural health monitoring of air platforms," *Sensors*, Special Issue on State-of-the-art Sensors in Canada, vol. 11, no. 4, pp. 3687-3705, Mar. 2011 (Invited paper).
- 3 **H. Guo**, G. Xiao, N. Mrad, J. Albert, and J. P. Yao, "Wavelength interrogator based on closed-loop piezo-electrically scanned space-to-wavelength mapping of an arrayed waveguide grating," *J. Lightwave Technol.*, vol. 28, no. 18, pp. 2654-2659, Sep. 2010.
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- 5 **H. Guo**, G. Xiao, N. Mrad, and J. P. Yao, "Simultaneous interrogation of a hybrid FBG/LPG sensor pair using a monolithically integrated echelle diffractive grating," *J. Lightwave Technol.*, vol. 27, no. 12, pp. 2100-2104, Jun. 2009.
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Conference papers and talks

- 1 **H. Guo**, G. Xiao, N. Mrad, and J. P. Yao, "Static and dynamic strain fiber Bragg grating sensor interrogation using a monolithically integrated echelle diffractive grating," *The 21st International Conference on Optical Fiber Sensors*, 15-19 May 2011, Ottawa, Canada.
- 2 G. Xiao, **H. Guo**, N. Mrad, and J. P. Yao, "Fiber optic Bragg grating sensing systems for potential air vehicle structural health monitoring," *OIDA/NRC Photonics Sensor Symposium*, 8 Dec. 2010, Boston, US.
- 3 **H. Guo**, G. Xiao, N. Mrad, J. Albert, and J. P. Yao, "Wavelength interrogation of a tilted fiber Bragg grating sensor using space-to-wavelength mapping of an arrayed waveguide grating with closed-loop piezo-electrical control," *Proc. IEEE Sensors 2010*, 1-4 Nov. 2010, Waikoloa, US.
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Other contributions

- 1 **H. Guo**, N. Mrad, G. Xiao, and J. P. Yao, “Miniaturized fiber Bragg grating sensor systems for potential air vehicle structural health monitoring applications,” Chapter 8 in *Photonic Sensing: Principles and Applications for Safety and Security Monitoring*, Edited by: Gaozhi Xiao (National Research Council Canada) and Wojtek J. Bock (University of Quebec), John Wiley & Sons, 2012.
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