Fall 2011

Simultaneous measurement of temperature and strain by three-section phase-shift long period fiber grating

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SIMULTANEOUS MEASUREMENT OF TEMPERATURE AND STRAIN BY THREE-SECTION PHASE-SHIFT LONG PERIOD FIBER GRATING

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2011

Approved by

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ABSTRACT

Long period fiber gratings (LPFGs) have found many applications as sensors to measure strain, temperature, refractive index and other physical parameters. In various sensing applications, the cross-sensitivity between two parameters, especially the temperature cross-sensitivity, has been a major difficulty to achieve high accuracy measurement. One of the solutions is to develop LPFG sensors for simultaneous, multi-parameter measurements.

In this thesis, three-section phase-shift (PS) LPFGs were fabricated and investigated for simultaneous measurement of temperature and strain. Compared with a two-section PS-LPFG, a three-section PS-LPFG has two deeper resonance sub bands and a larger separation between the two bands. The strain, temperature and refractive index sensitivities of the two resonance sub bands are independent and significantly different. As such, it has the potential for measurement of two parameters simultaneously. We fabricated high-quality three-section PS-LPFGs using CO_2 laser point-by-point radiations, characterized and calibrated the strain and temperature sensitivities of the two resonance sub bands, and for the first time to our knowledge demonstrated its effectiveness for simultaneous measurement of temperature and strain.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank all those people who helped me with the successful completion of my research and M.S. program. First, I would like to express my gratitude to my advisor Dr. Hai Xiao who gave me guidance in this research and the M.S. program. I thank him for giving me a chance to work with him and for his continued support with valuable advice and encouragement. His guidance with unbelievable patience has made a great impact on this research and me.

I am grateful to Dr. Steve Watkins, Department of Electrical and Computer Engineering and Dr. Hai-Lung Tsai, Department of Mechanical Engineering for being my committee members.

Additionally, I would like to take this opportunity to thank my colleagues, Xinwei Lan, Tao Wei, Yinan Zhang, Xia Fang and Baokai Cheng in my group for being supportive all the time.

I would also like to thank my parents for everything they have done for me. Finally, I would like to thank the sponsors for this project. They are the U.S. Department of Energy through the National Energy Technology.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

1.1. BACKGROUND

1.1.1. Long period fiber gratings. A long period fiber grating (LPFG) consists of a periodic refractive index variation in the fiber core along the longitudinal axis. The refractive index modulation couples light from a forward-propagating core-guided mode to forward-propagating cladding-guide modes near certain resonance wavelengths. The optical power coupled into the cladding modes eventually attenuate due to the high loss of the cladding modes. As a result, the transmission spectrum of a LPFG has a series discrete attenuation bands near the resonance wavelengths. The periods of LPFGs are commonly in the hundreds of micrometers to produce resonance wavelength in the communication wavelength centered around 1550nm.

LPFGs have found many applications ranging from filters in optical communications and fiber optic sensors to measure various physical, chemical and biological parameters [1]. In optical communications, LPFG has been used as filters to flatten the gain spectrum of erbium-doped fiber amplifiers, monitor power levels transmitted in optical fibers, and compensate dispersion in an optical communication system [2-4]. LPFGs have been developed into sensors to measure various physical (e.g., stress, temperature, strain, refractive index, etc.) and chemical (e.g., pH, chemical concentration, humidity, etc.) parameters [5]. As an optical fiber sensor, a LPFG has the unique advantages for sensing such as immunity to electromagnetic interference, high sensitivity, resistance to corrosion, and high temperature survivability.

As shown in Figure 1.1, for LPFGs inscribed in single-mode fiber (SMF), mode coupling happens when the phase-matching between the fundamental core mode and a particular cladding mode is satisfied. The phase-matching condition required for coupling is given by

$$\beta_{core} - \beta_{clad}^{mn} = \frac{2\pi}{\Lambda} \tag{1}$$

where β_{core} is the propagation constant of the core mode, known as the LP01 mode, the β_{clad}^{mn} is the propagation constant of the mn-th order cladding mode, and Λ is the period of the LPFG.

An alternative form of the phase-matching condition is given by

$$\lambda_{re}(n_{core} - n_{clad}^{mn}) = \Lambda \qquad (2)$$

where n_{core} is the effective index of the guided core-mode, n_{clad}^{mn} is the effective index of the mn-th order cladding mode, and λ_{re} is the center wavelength of the resonance. Figure 1.2 shows the transmission spectrum of a LPFG of 5th order cladding mode. The LPFG was fabricated by CO_2 laser irradiations with a laser power of 7.5W and pulse duration of 100ms. The device had a small loss (~2dB) and a strong resonance band (~27dB).

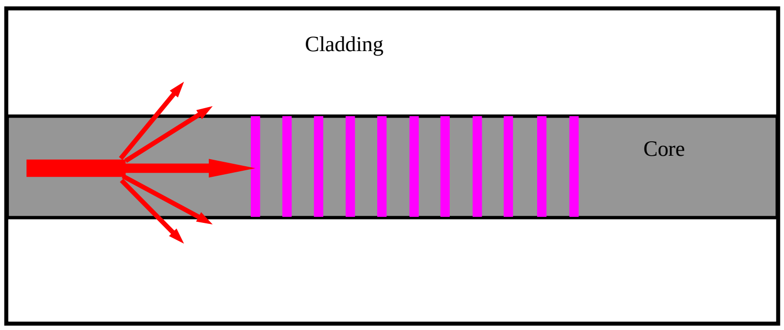


Figure 1.1. Coupling between the guided core mode and cladding mode in LPFG

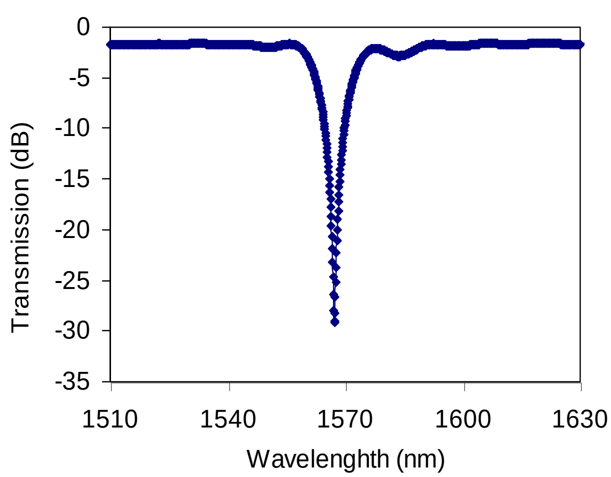


Figure 1.2. Transmission spectrum of 5th order LPFG

As indicated in Equation (2), the resonance wavelength of a LPFG is a function of the fiber properties, grating period, and the order of the corresponding cladding mode. When these parameters changes as a result of environmental parameters (e.g., temperature, strain, pressure, refractive index, etc.), the resonance wavelength changes correspondingly. As such a LPFG can be used as a sensor to measure various parameters by monitor the change in its center wavelength.

1.1.2. Cross-sensitivity of LPFG sensor. A main difficulty in applying LPFGs for some sensing applications is its large temperature cross-sensitivity. A LPFG is typically very sensitive to environmental temperature variations, which could result in an overwhelmingly large error for some intended applications such as the case of using an LPFG for strain measurement in structural health monitoring (SHM).

Three general methods have been explored to eliminate or minimize the measurement error caused by the temperature cross-sensitivity. One method involves athermal-packaging or temperature-compensated sensor design to reduce the temperature cross-sensitivity of the device to an acceptable level. However, athermal-packing may change during sensor installation and the delicate packaging may also complicate the sensor deployment. The second general approach is to measure temperature using an independent temperature sensor and deduct the temperature effect from the sensor output based on the calibrated curve. The issue of using a separate temperature sensor is that it is sometimes difficult to place the two sensors at exactly the same location. As a result, the measured temperature might not the same as the other sensor sees. The third method is to use a single sensor for simultaneous measurement of temperature and the parameter of interest. This is the preferred method because the temperature is measured exactly at the same location of the other parameter.

In the case of LPFG-based sensing, various techniques have been explored to perform temperature compensation [6-9]. In one case, two independent LPFGs with different thermal and strain sensitivities [6] have been used to measure these two parameters simultaneously. In another report, Rego [7] proposed to use two resonances of difference cladding modes in one LPFG to discriminate temperature and strain response. The strain sensitivities of the two modes were modified by changing the electric current of the arc discharge used in LPFG fabrication. Bhatia [8] proposed using the temperature and strain sensitivity differentials between two resonance bands of a single LPFG to separate their effects; Han [9] reported successful measurement with respect to strain and temperature of spectral sensitivity of two adjacent LPFG resonant dips inscribed on the polarization-maintaining fiber. However, If two gratings of different cladding modes are used to measure temperature and strain simultaneously, the sensor device will be too long. If two different cladding modes of the same grating are used, two different resonance bands must be interrogated in a wide spectrum, which would be difficult due to the limited bandwidth of the source.

1.1.3. **Phase-shift LPFG.** As shown in Figure 1.3, a two-section phase shift (PS) LPFG can be made by inserting a disturbance into an otherwise a continuous grating. By introducing a phase shift in the LPFG, destructive mode coupling is converted to constructive mode coupling, and one grating resonance is split into two or more resonances based on the number of phase shift sessions and the length of the grating [10]. As shown in Figure 1.4, a PS-LPFG has two resonant peaks that have different sensitivity towards the environmental parameters and it could potentially be used for simultaneous measurement of two parameters.

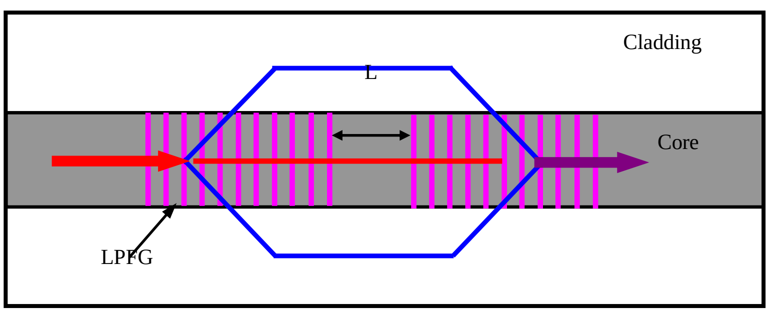


Figure 1.3. Schematic illustration of a two-section phase shifted long period fiber grating

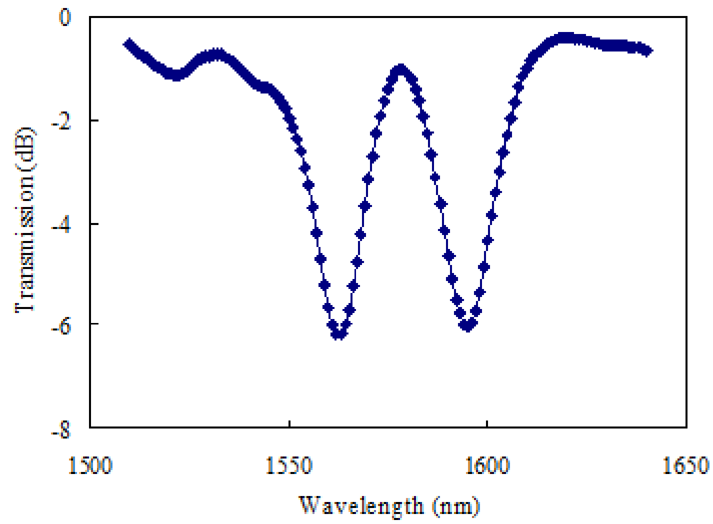


Figure 1.4. Typical transmission spectrum of a two-section PS-LPFG

Based on a PS-LPFG, Han [11] demonstrated simultaneous measurement of bending and temperature by controlling initial coupling strength using ultraviolet light; Falate [12] proposed a refractometric sensor fabricated by electric-arc discharges. However, in the reported work, the sensitivity difference between the two resonance bands was not large enough. As a result, the measurement accuracy is limited.

1.2. RESEARCH OBJECTIVE

The main objective of this thesis is to investigate fabrication of high-quality PS-LPFGs and develop methods to use PS-LPFGs for simultaneous measurement of multiple parameters, especially by using three-section PS-LPFG sensors. To be detailed, the specific objectives are:

1. Fabricate and characterize PS-LPFGs for sensing application,

2. Compare the characteristics of regular LPFGs, two-section PS-LPFGs and three-section LPFGs,

3. Demonstrate three-section PS-LPFGs for simultaneous measurement of temperature and strain.

1.3. THESIS OVERVIEW

This thesis focuses on fabrication, calibration and application of two-section and three-section PS-LPFGs for simultaneous measurement of environmental temperature and strain. The thesis contains 5 Chapers:

Chapter 1 is the introduction and background of the thesis work.

Chapter 2 focuses on fabrication process of LPFG by point-by-point CO_2 laser irradiation method. The sensitivities of different order LPFGs to temperature, strain and refractive index were characterized experimentally.

Chapter 3 introduces two-section PS-LPFGs. The fabrication process and characteristics of two-section PS-LPFG are described and discussed in detail.

Chapter 4 focuses on simultaneous measurement of temperature and strain by three-section PS-LPFGs. Based on the calibrated the temperature and strain sensitivities of the two resonances bands, a single three-section PS-LPFG is used to measure temperature and strain simultaneously.

Section 5 summarizes thesis work, draws a few conclusions and lay out the future work.

2. CHARACTERISTICS OF LONG PERIOD FIBER GRATING

2.1. FABRICATION OF LPFG BY CO_2 LASER IRRADIATION METHOD

A number of techniques have been developed for fabrication of LPFGs. Just like fiber Bragg gratings (FBGs), LPFGs can be fabricated by exposing photosensitive optical fibers to UV light under a phase mask. The UV exposure introduces a permanent and periodic refractive index change in the fiber core. Similar to UV exposure, LPFG has been created by ion implantation (bombardment) through a metal amplitude mask [13]. Electric arc discharge and focused infrared femtosecond laser pulses have also been used to write LFPG on a point-by-point basis [14-16]. Both of the two methods can achieve a permanent density variation on optical fiber which helps create a permanent modification of the refractive index of the core periodically. Pressing on an optical fiber with a grooved plate is another method by which an LPFG can be temporarily created. This is based on the physical deformation on optical fiber which also changes the refractive index of the fiber core [17, 18]. Another method used for fabrication of LPFG is CO_2 laser irradiation [19, 20]. A focused CO_2 laser beam heats the fiber point-by-point at the glass transition temperature and produces a periodic change of refractive index in the fiber core. Compared to those fabricated using UV irradiations, LPFGs fabricated by CO_2 lasers have the advantage of surviving high temperatures, up to 1200ºC as reported [21, 22].

In this thesis, long period fiber grating was fabricated by point-by-point CO_2 laser irradiation method. As shown in Figure 2.1 and Figure 2.2, a tunable laser (HP81642A) and an optical power meter (HP 81618A) were used to monitor the grating transmission spectrum. A CO_2 laser (SYNRAD, Inc.) with a free space wavelength of 10.6μm and a maximum output power of 20W was used in the system. A ZnSe cylindrical lens with a focal length of 50mm was used to shape the CO_2 laser beam into a narrow line. The CO_2 laser was controlled by the computer through the laser controller to produce a desired power. The optical fiber (Corning SMF-28) with its buffer stripped was placed on a motorized translation stage, which moved the fiber to CO_2 exposure point-by-point controlled by a computer.

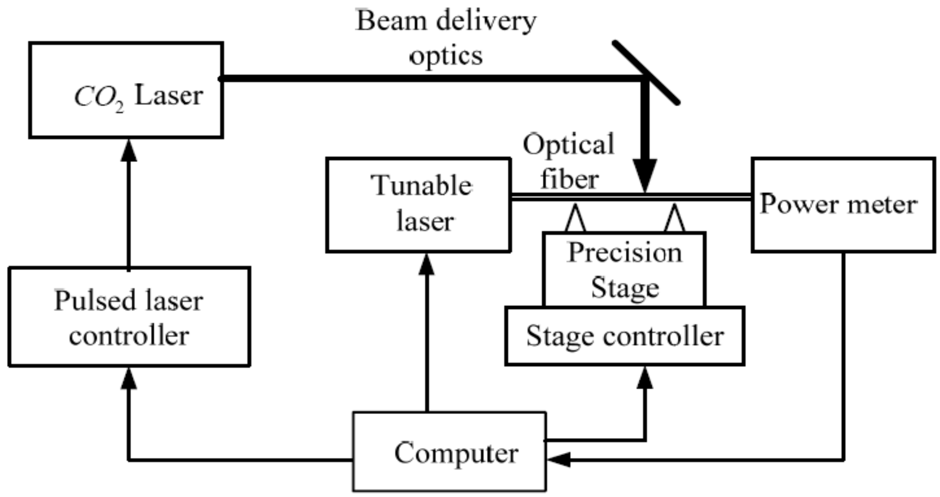


Figure 2.1. Schematic setup of the CO2 laser based LPFG fabrication system

Figure 2.2. Photograph of LPFG fabrication system

Figure 2.3 shows the 5th order long period fiber grating under microscope of this LPFG. The distance between two adjacent laser irradiation points (i.e., the grating period) was 510µm.

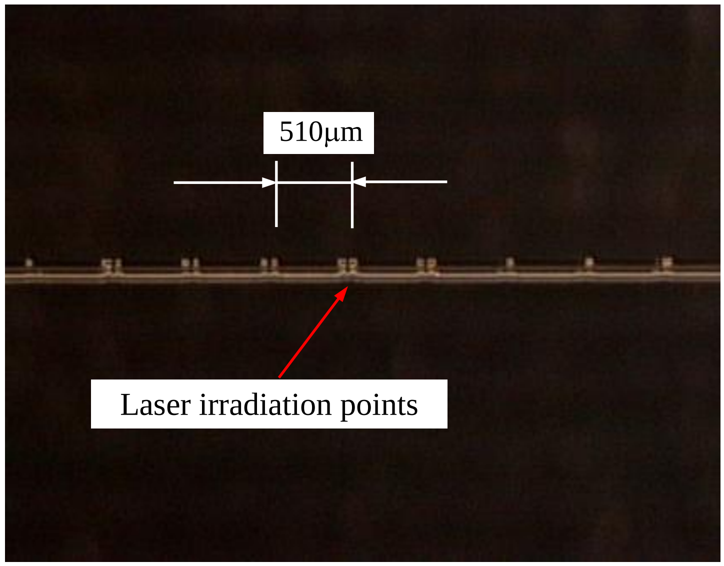


Figure 2.3. Laser irradiations on fiber under microscope

2.2. CHARACTERISTICS OF LONG PERIOD FIBER GRATING

The sensing and sensitivity characteristics of LPFGs fabricated by UV laser were described in details by Shu [23]. Using a home-integrated CO_2 laser system, we were able to fabricate LPFGs of various cladding modes.

Figure 2.4 shows the measured central resonance wavelength shift of LPFGs of different cladding modes as a function of temperature from 20ºC to 500ºC. The LPFG was made on a SMF (Corning SMF-28e) by the CO_2 laser irradiation method. The temperature sensitivities of the gratings were nonlinear. The center wavelengths of the attenuation bands of all LPFGs shifted to the long wavelength region as temperature increased. However, the temperature sensitivity of different cladding-mode LPFG was different. As shown in the Figure 2.4, the temperature sensitivity increased from 5th order mode to 8th order mode. The 5th order mode LPFG had the smallest temperature sensitivity.

The high sensitivity of cladding modes to surrounding refractive index values makes LPFGs suitable for chemical sensing [24-29]. Figure 2.5 shows the resonance wavelength shift as the environmental refractive index changes. Similar to the temperature sensitivity, the refractive sensitivity of the LPFG is also mode dependent. The higher the cladding mode is, the higher the sensitivity of the grating towards refractive index changes. In addition, the LPFGs responded to the refractive index changes quite nonlinearly.

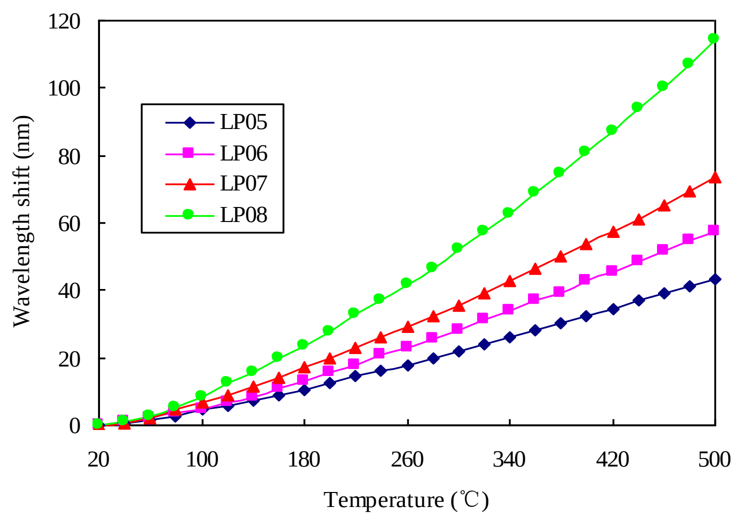


Figure 2.4. Wavelength shift of LPFGs with different modes as function of temperature

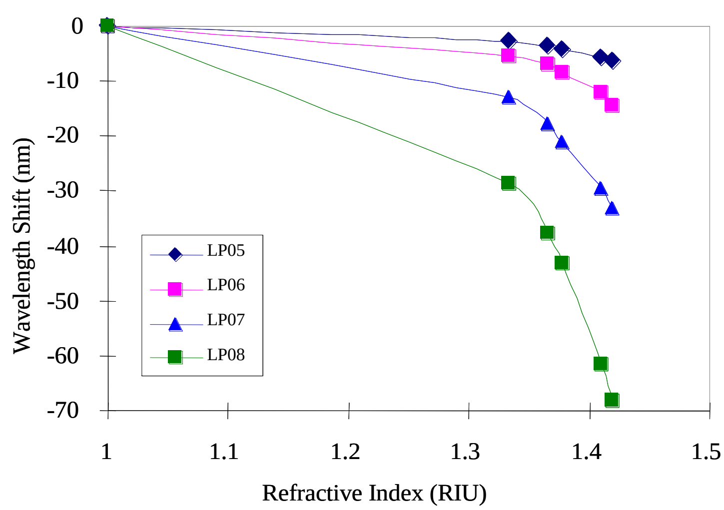


Figure 2.5. LPFG Mode-RI Sensitivity Relations (LP05-LP08)

2.3. SUMMARY

Long period fiber grating can be fabricated by CO_2 laser point by point irradiation method. The LPFG fabricated by CO_2 laser irradiation method can survive in high temperature environment. LPFG can be used as sensor for environmental temperature and refractive index by detecting resonance wavelength shift. The temperature and refractive index sensitivity of LPFG will increase as the cladding mode increases from 5^{th} order to 8^{th} order.

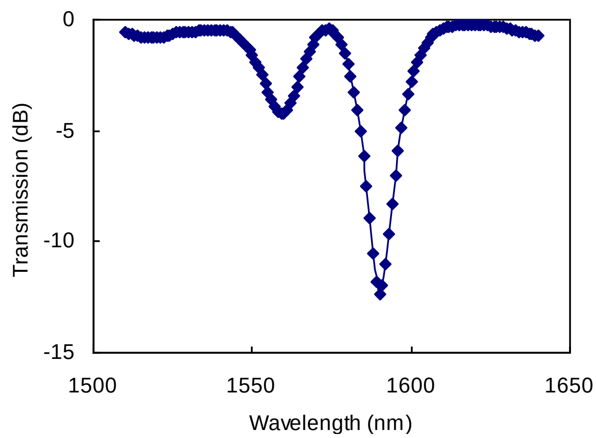
3. CHARACTERISTICS OF PHASE-SHIFT LPFG

3.1. FABRICATION PROCESS OF TWO-SECTION PS-LPFG

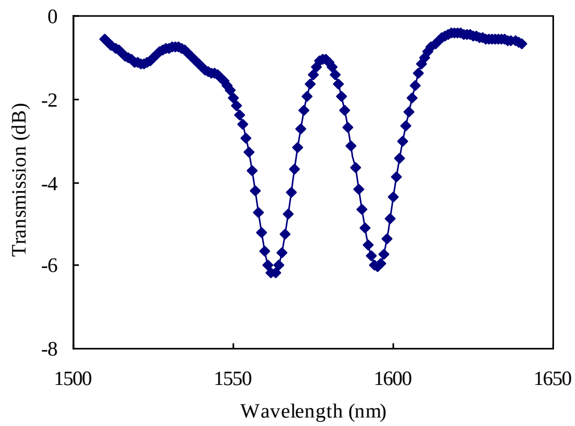
PS LPFGs can be made by inserting a disturbance into an otherwise continuous grating. The inserted length (L in figure 1.3) is typically a fraction of the grating period. As such, the phase of the grating becomes a fraction of 2π at the discontinuity and thus the name of phase-shift LPFG.

Using the same laser parameters, a number of PS-LPFGs of 5th order mode were fabricated with different amount of phase shifts between two sections of 30 points each. The period of all these gratings was 520μm. The transmission spectra of three PS-LPFGs are shown in Figure 3.1. As expected, the transmission spectra of these PS-LPFGs have two resonance bands split from the original one band when small phase disturbances were inserted. The strength of two attenuation bands varied as the gap distances changes. As the amount of phase shift increased, one attenuation band increased its strength while the other decreased correspondingly. In our case, the left side sub attenuation band increases its strength while the right side sub attenuation weakened as the separation distance increased. When the inserted length was about half of the period (L = 286μm), the two sub attenuation bands had approximately equal intensity.

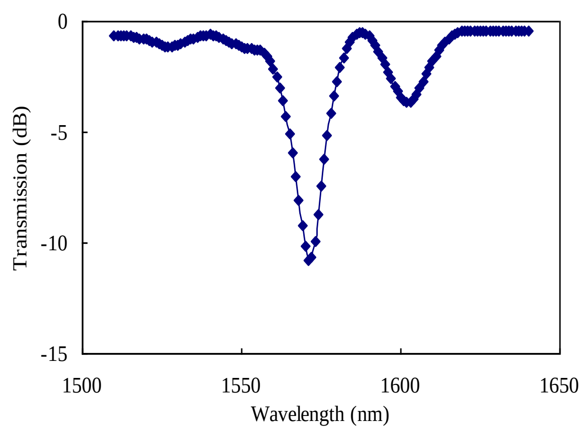
The percentage of left sub band strength to the two sub bands total strength as a function of the gap distance (in percentage of the LPFG period) is shown in Figure 3.2.



(a)



(b)



(c)

Figure 3.1. Transmission spectra of PS-LPFG of various phase-shifting lengths (L). (a) L = 208μm, (b) L = 286μm, and (c) L = 364μm

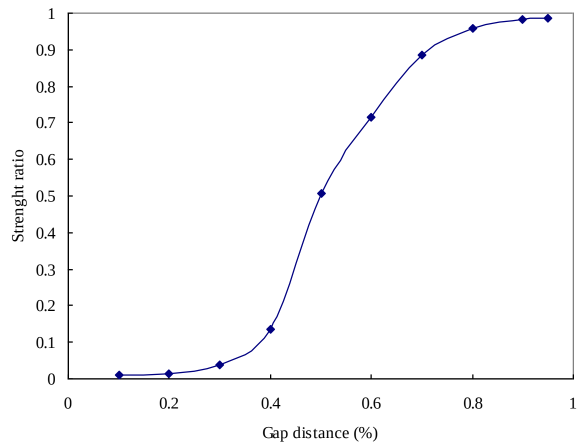


Figure 3.2. Percentage of left sub band strength to the two sub bands total strength as a function of the gap distance (in percentage of the LPFG period)

3.2. TEMPERATURE CHARACTERISTICS OF TWO-SECTION PS-LPFG

The temperature sensitivity of two-section PS-LPFG with inserted length about half of the period (L = 286µm) was tested by placing them into an electrical oven. The temperature of the oven was increased from 20ºC to 160°C at a step of 10ºC per set point. The transmission spectra at these temperature set points were recorded using an optical spectrum analyzer (OSA). Figure 3.3 shows the grating spectra of the PS-LPFG with L = 286µm at 20 and 160ºC, respectively.

The spectra at these two temperatures were very similar except that there was a lateral shift towards the long wavelength region as the temperature increased. Figure 3.4 plots the shift in center resonance wavelengths of the blue (left) and red (right) sub bands as a function of temperature. The two response lines are almost the same, indicating that the two sub bands had almost the same sensitivity towards temperature. There is a slight difference at high temperature region where the red sub band has a slightly higher sensitivity than that of the blue sub band.

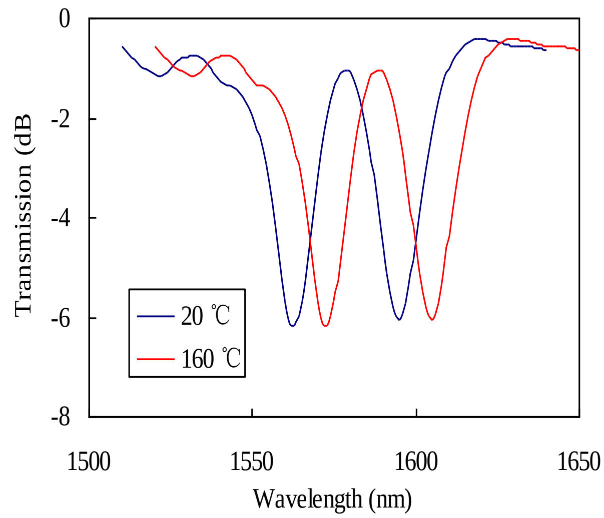


Figure 3.3. Transmission spectra at 20 ºC and 160ºC of a 5th order two-section PS-LPFG

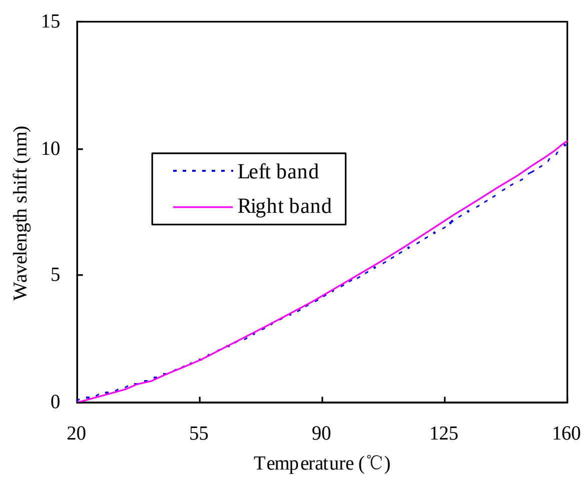


Figure 3.4. Spectral shift of the two sub bands as a function of temperature of the 5th order two-section PS-LPFG shown in Figure 3.4

The temperature sensitivity of the two-section PS-LPFG was also investigated. A two-section PS-LPFG with the period of 520μm and the gap distance of 0.26mm was installed into an electric furnace and increased the temperature from 20°C to 500°C. The PS-LPFG transmission spectrum at different temperature is shown in Figure 3.5. Figure 3.6 shows the shifts of two sub bands wavelengths as a function of temperature. Although the two attenuation bands drifted towards the long wavelength region, the spectral separation (Figure 3.7) between the two sub attenuation bands kept almost unchanged as the temperature increased.

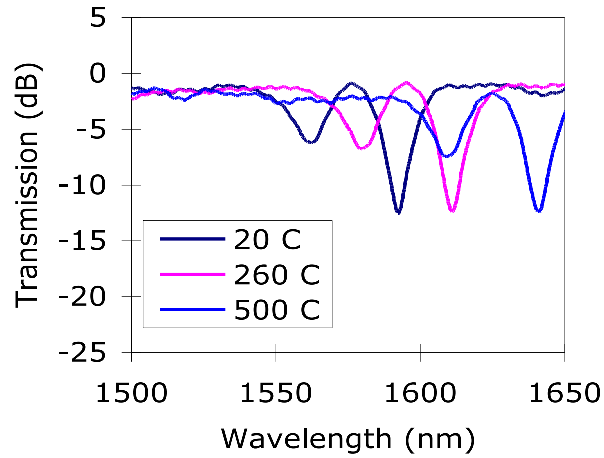


Figure 3.5. Transmission Spectra of a PS-LPFG with gap distance of 0.26mm

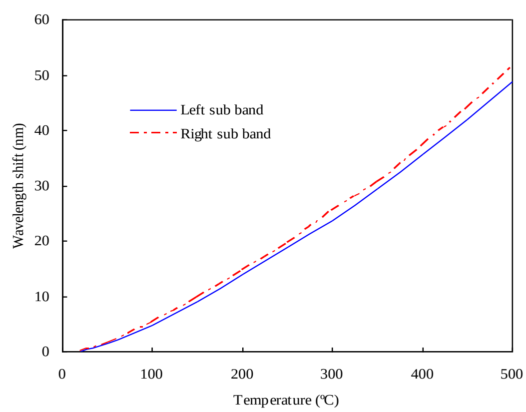


Figure 3.6. Shifts of the two sub bands wavelengths of a PS-LPFG with gap distance of 0.26mm as a function of temperature

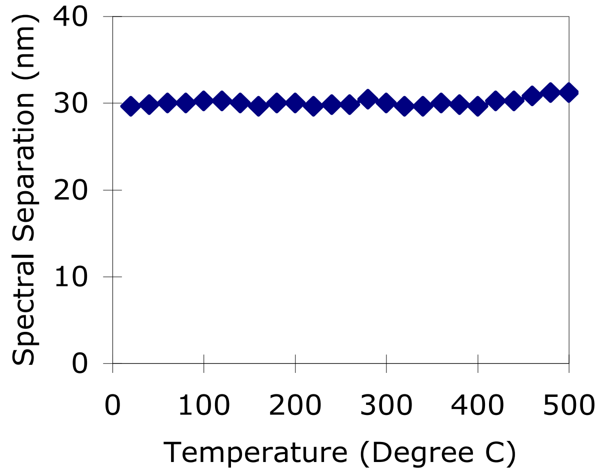


Figure 3.7. Spectral separation of the two sub attenuation bands as a function of temperature

3.3. REFRACTIVE INDEX SENSITIVITY OF TWO-SECTION PS-LPFG

The sensitivity of two-section PS-LPFGs towards ambient refractive index changes were also investigated experimentally. The same PS-LPFG with L = 286µm was used in the experiment. During the experiments, the grating was immersed into different liquids of known refractive index (water, acetone and isopropanol) at room temperature while the transmission spectra were recorded correspondingly using an OSA. Figure 3.8 shows the transmission spectra of the grating in air and water (n = 1.333), respectively.

As seen from the Figure 3.8, the entire resonance spectrum of the grating shifted towards short wavelength region as the ambient refractive index increased while the intensities of the two sub bands remained almost the same. Figure 3.9 plots the resonance wavelength shifts of the blue and red sub bands as a function of the ambient refractive index. In general, the resonance wavelengths of the two attenuation sub bands of the PS-LPFG shifted to the shorter wavelength region as external refractive index increased. As expected, the refractive index sensitivities of the two sub bands were nonlinear. The two sub bands changed almost the same as a function of the refractive index changes, indicating the two sub bands had almost the same sensitivity.

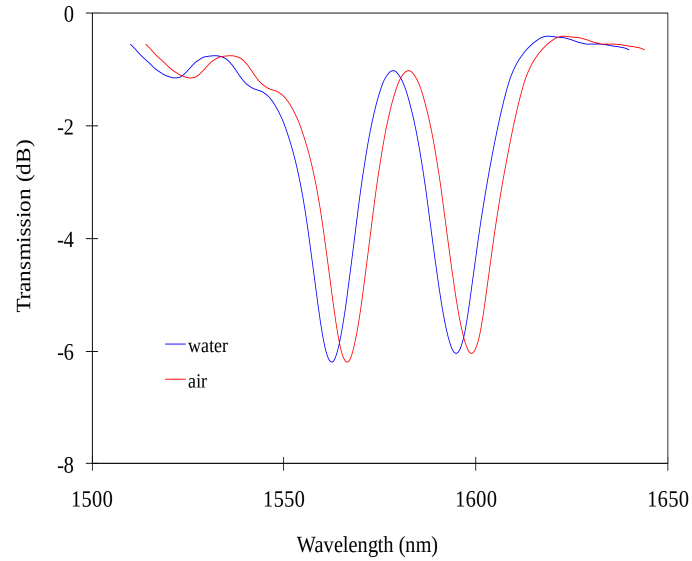


Figure 3.8. Refractive index sensitivity of a 5th order Two-Section PS-LPFG

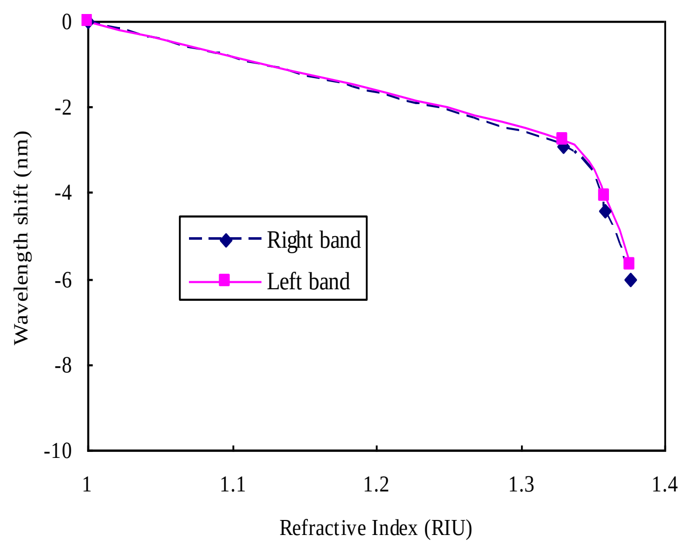


Figure 3.9. Spectral shift of the two sub bands as a function of ambient refractive index

3.4. SUMMARY

In general, the two sub bands of two-section PS-LPFGs had almost the same sensitivity towards temperature and refractive index. The resonance wavelengths of the two attenuation sub bands of the two-section PS-LPFG shifted to the long wavelength region as temperature increased while it shifted to the shorter wavelength region as external refractive index increased. As expected, the t refractive index sensitivities of the two sub bands were not linear. However, the two sub bands changed almost the same as a function of temperature and the refractive index changes, indicating the two sub bands had almost the same sensitivity. As a result, the two-section PS-LPFG is not suitable for simultaneous measurement of multiple parameters.

4. SIMULTAMEOUS MEASUREMENT OF TEMPERATURE AND STRAIN BY USING THREE-SECTION PHASE-SHIFT LPFG

4.1. EVOLUTION PROCESS OF THREE-SECTION PS-LPFG

Based on the discussion in section 3 of this thesis, the two sub bands of two-section phase-shift long period fiber grating have almost the same sensitivity towards temperature. So it is not suitable to be used as sensor for simultaneous measurement of multiple parameters. The exploration was thus continued to investigate a three-section PS-LPFG.

Figure 4.1 shows the schematic illustration of the three-section PS-LPFG studied, in which three equal-length LPFGs are separated by two identical phase shifts.

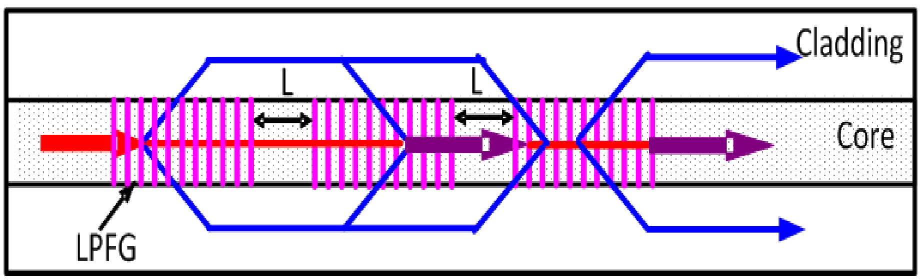


Figure 4.1. Schematic illustration of a three-section PS-LPFG

Figure 4.2 shows the transmission spectrum of a 5th order three-section PS-LPFG with the L equals to 50% of the period, fabricated on a single mode fiber (Corning SMF28e) using the aforementioned CO_2 laser irradiation method. The period of the grating was 520μm and each grating section consisted of 30 points of laser irradiations. The grating had three attenuation sub bands. Compared with two-section PS-LPFG, the three-section PS-LPFG had a larger spectral separation between the two major attenuation sub bands and the strength of the grating was also larger.

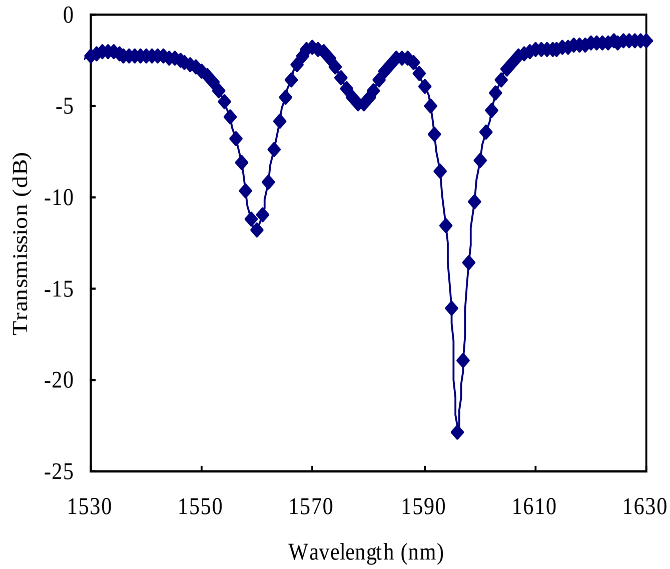


Figure 4.2. Transmission spectrum of a 5th order three-section PS-LPFG with L = 50% of the grating period

Figure 4.3 shows the spectral evolution of a three section PS-LPFG during fabrication. The grating had a period of 316μm which had a resonance peak of the 8^{th} order mode (LP08 mode) in the 1550nm region. The fabrication started by first creating a 3dB grating (the gray line in Figure 4.3) with 50 points of irradiations. After inserting a gap of half period, another section of grating with 50 points of irradiations was added, which resulted in a two-section PS-LPFG as shown in the purple line in Figure 4.3. The two-section PS-LPFG had two resonance bands with about 8 dB depth in strength. Then, another half-period gap was inserted and the third section of grating with 50 points of laser irradiations was added. The resulted three-section PS-LPFG had a transmission spectrum shown as the green line in Figure 4.3. The three-section PS-LPFG had three resonance sub bands, one small dip at the center and two large resonances on two sides.

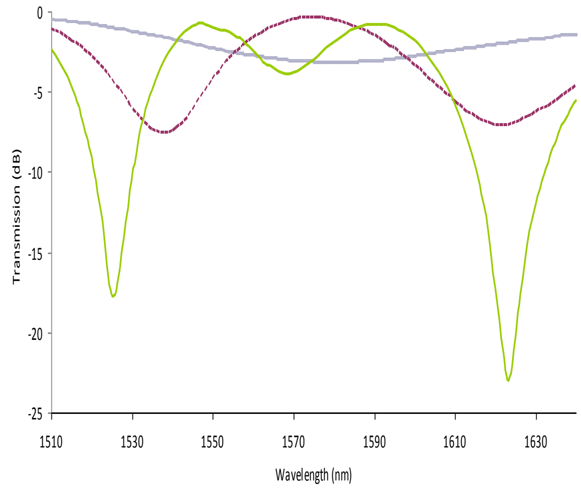


Figure 4.3. Evolution process of three sections long period fiber phase shift grating

Compared with the two-section PS-LPFG, there are two obvious features in the three section grating. One is the resonance dips on both sides become deeper, which is beneficial for sensing application due to higher signal noise ratio. The other is the separation of two rejection bands becomes larger, whose effects on sensing are yet to be discovered.

4.2. REFRACTIVE INDEX SENSITIVITY OF THREE-SECTION PS-LPFG

To characterize the sensitivity of three-section PS-LPFG towards ambient refractive index, gratings of various cladding modes (from 5^{th} order to 8^{th} order) were fabricated and tested using liquids of different refractive indices. Figure 4.4 shows the transmission spectra of these gratings in air and water. Figure 4.5 plots the change of the resonance wavelengths of the two major sub bands as a function of the ambient refractive index. It is clear that the entire grating spectrum of all gratings shifted nonlinearly towards the short wavelength region as the ambient refractive index increased. However, the two sub bands shifted different amount given the same amount of refractive index change. The sensitivity of the blue band was lower than that of the red band. It is also interesting to note that the blue band of the three-section PS-LPFG had almost the same sensitivity as the two-section PS-LPFG. However, the red band of the three-section PS-LPFG had a noticeable higher sensitivity than that of the two-section PS-LPFG.

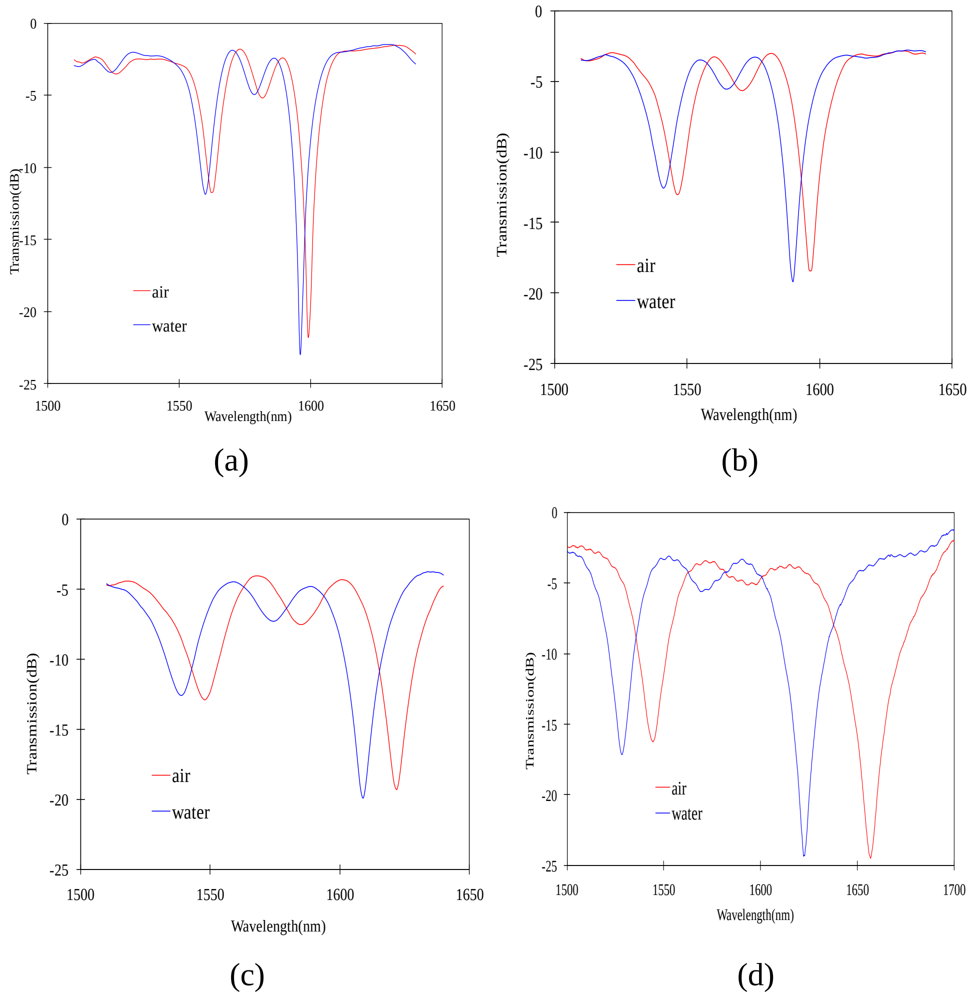


Figure 4.4. Transmission spectra in air and water of three-section PS-LPFG. (a) 5th order. (b) 6th order. (c) 7th order. (d) 8th order

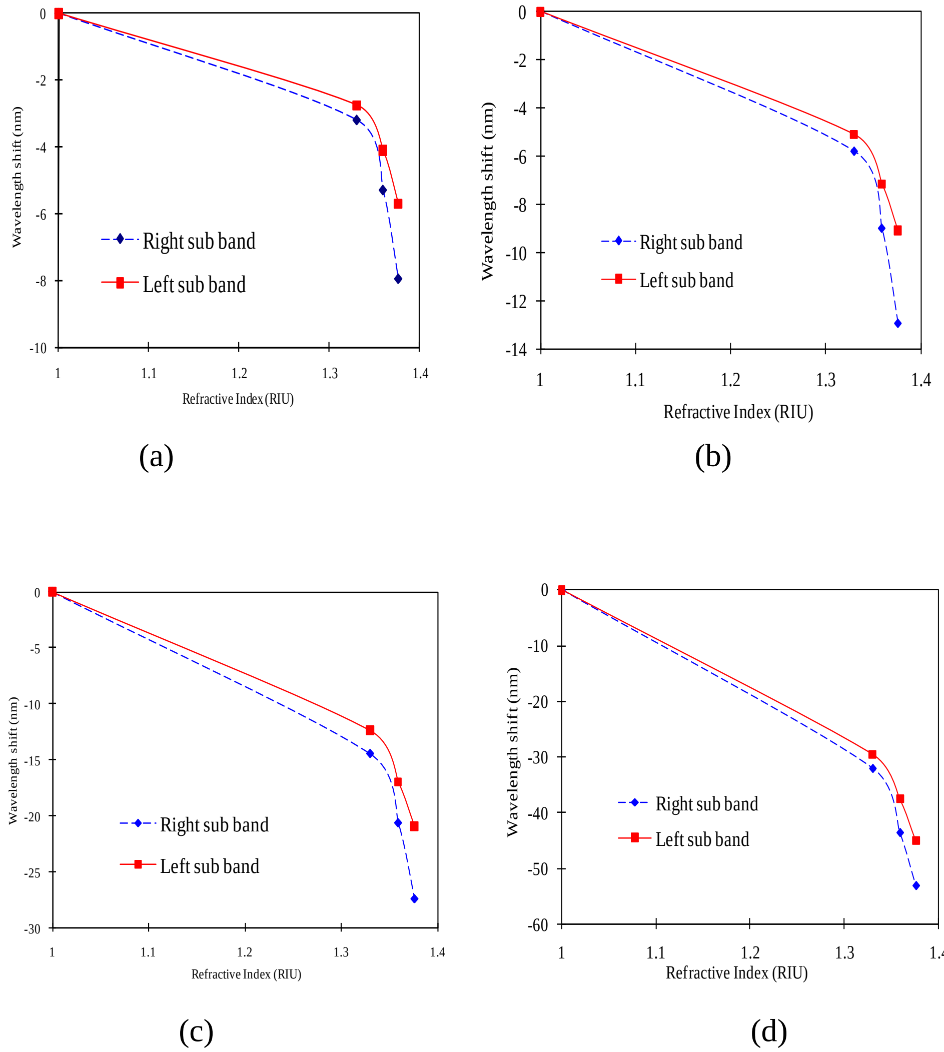


Figure 4.5. Spectral shifts of the two sub bands of three-section PS-LPFG as a function of ambient refractive index. (a) 5th order. (b) 6th order. (c) 7th order. (d) 8th order

4.3. TEMPERATURE AND STRAIN SENSITIVITY

Investigations were also conducted experimentally on the three-section PS-LPFG in response to temperature and strain. Figure 4.6 shows the experimental setup used sensor calibration and simultaneous temperature and strain measurements. The three-section PS-LPFG fiber sensor was firmed epoxied on two motorized translation stages (Newport PM 60082) for strain measurement. The stages have resolution of 0.1μm. When the two stages moved apart, stain was applied to the grating. The applied strain was calculated by dividing the stage movement by the separation distance between the two exploy points. For temperature tests, an electric tubular furnace was used and the grating was positioned in the center of the furnace. A quartz tube was used to host the grating to decrease the air flow effect and keep the temperature more stable. A broadband optical source (Agilent 83437a) was connected to the grating to provide the optical power, and the transmission spectrum was monitored by an OSA (AQ6319). The spectrum was acquired by a computer for signal processing.

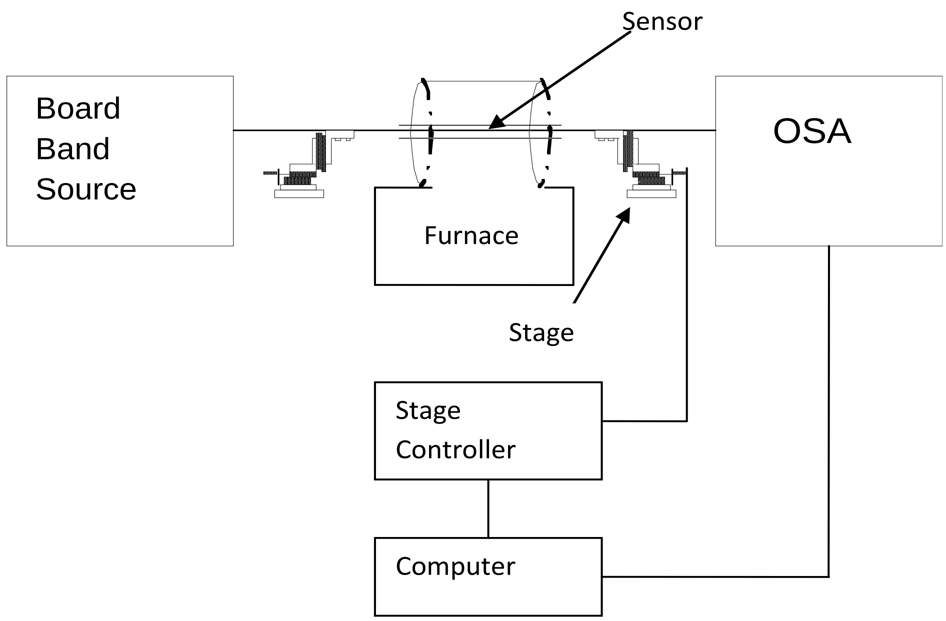
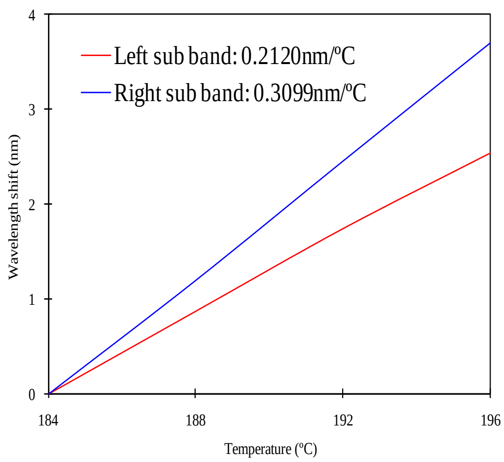


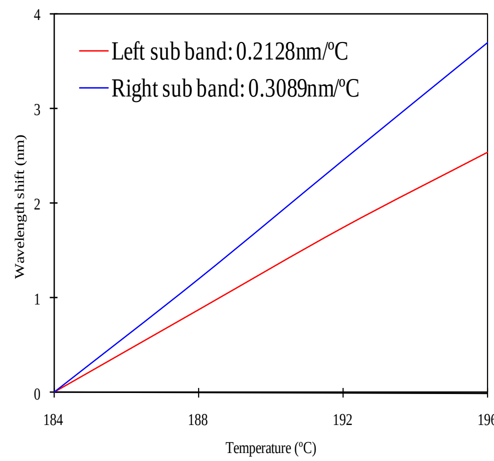
Figure 4.6. Experimental set up for simultaneous measurement of strain and temperature by three-section phase-shift long period fiber grating

LPFGs, including the PS-LPFGs, fabricated using CO_2 laser irradiations can survive high temperatures. In this research, we chose the temperature range of 180-200^{0}C to minimize the nonlinearity. The main reason to choose this temperature range was to consider the stability of the electric furnace, which was unstable in either low or high temperature regions. Other reasons included the nonlinear responses and the large temperature sensitivity of the gratings.

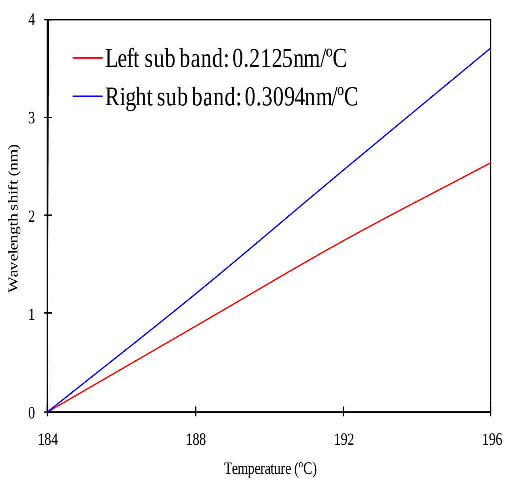
Figure 4.7 shows the spectral drifts of the two sub bands of an 8th order three-section PS-LPFG as the environmental temperature increased from 184 to 196 ^{0}C at different of strain values (i.e., 360.35, 720.70, 1081.50 and 1441.40με) applied to the grating. During the tests, the applied strain was kept unchanged when temperature varied. To increase the measurement accuracy, the grating was heated to 210 ^{0}C and then cooled down slowly. Measurement data were taken at each degree. Table 4.1 shows temperature sensitivity of 8th order three-section PS-LPFG at various applied strain.



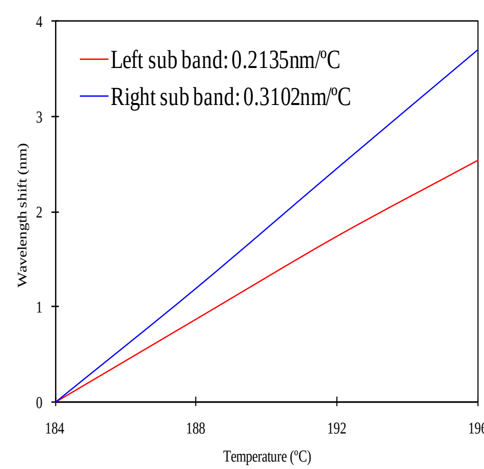
(a) Strain=360.35με



(b) Strain=720.70με



(c) Strain=1081.50με



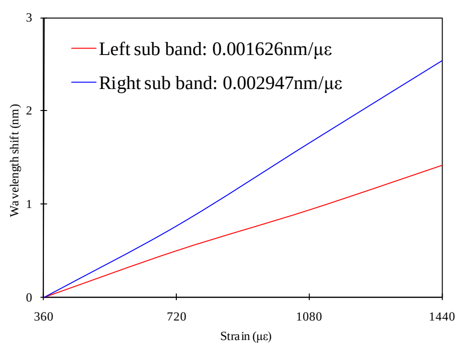
(d) Strain=1441.40με

Figure 4.7. Shift of left and right attenuation bands as temperature increases.

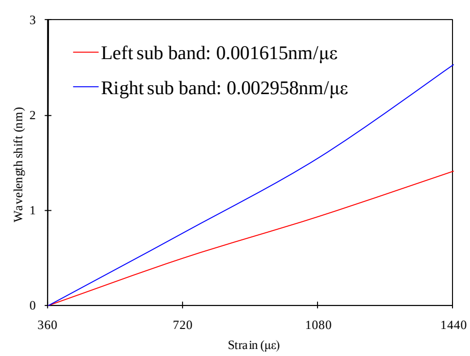
Table 4.1. Temperature sensitivity of the 8th order three-section PS-LPFG at various applied strain

	360.35με	720.70με	1081.50με	1441.40με
Left sub band	0.2120 nm/^{0}C	0.2128 nm/^{0}C	0.2125 nm/^{0}C	0.2135 nm/^{0}C
Right sub band	0.3099 nm/^{0}C	0.3089 nm/^{0}C	0.3094 nm/^{0}C	0.3102 nm/^{0}C

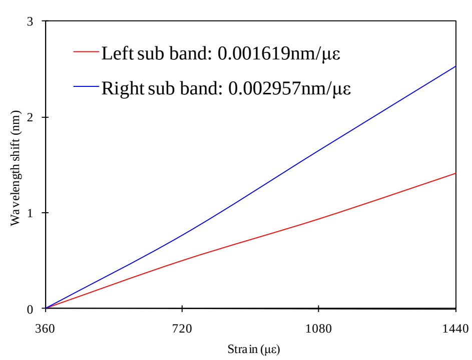
With the same experiment setup, the strain sensitivity of 8th order three-section PS-LPFG two sub bands was investigated. Figure 4.8 shows the center wavelength drift of the two sub bands as the strain applied on sensor increased from 360.35με to 1441.40με at a step of 360.35με. The experiments were repeated at different environmental temperatures (from 184 ^{0}C to 196 ^{0}C). During strain measurements, the temperature was kept constant. Table 4.2 shows the strain sensitivity of the 8th order three-section PS-LPFG at various temperatures.



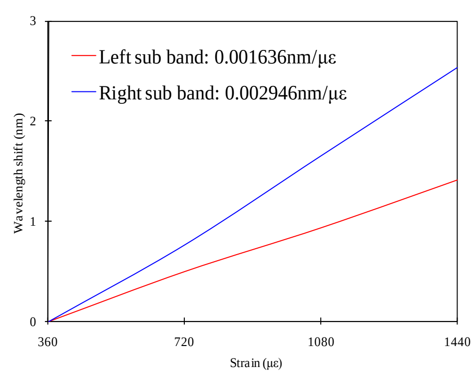
(a) Temperature=184^{0}C



(b) Temperature=188^{0}C



(c) Temperature=192^{0}C



(d) Temperature=196^{0}C

Figure 4.8. Shift of left and right attenuation bands as strain increases

Table 4.2. Strain sensitivity of the 8th order three-section PS-LPFG at various temperatures

	184^0C	188^0C	192^0C	196^0C
Left sub band	0.001626 nm/με	0.001615 nm/με	0.001619 nm/με	0.001636 nm/με
Right sub band	0.002947 nm/με	0.002958 nm/με	0.002957 nm/με	0.002946 nm/με

4.4. SIMULTANEOUS MEASUREMENT OF TEMPERATURE AND STRAIN

From the experiments, we clearly noticed that the two sub bands of the 8^{th} order three-section PS-LPFG had different sensitivity to temperature and strain. The temperature and strain sensitivities of the two sub bands are significantly different. Additionally, the temperature and strain sensitivities were quite linear in the specific temperature and strain ranges. These make it possible to use the PS-LPFG for simultaneous measurement of temperature and strain.

To elucidate the principle of operation of simultaneous measurements, let's assume that the two resonance wavelengths of the two sub bands are λ_1 and λ_2, respectively. Let A and B be the coefficients of temperature and strain induced wavelength shifts (i.e., temperature and strain sensitivities), respectively, of one sub band at wavelength λ_1, and C and D be those of another sub band at wavelength λ_2. Assuming a linear system, the wavelength shifts $\Delta\lambda_1$ and $\Delta\lambda_2$ of the two sub bands can simply be expressed as:

$$A\Delta T + B\Delta\varepsilon = \Delta\lambda_1 \tag{3}$$

$$C\Delta T + D\Delta\varepsilon = \Delta\lambda_2 \tag{4}$$

ΔT and $\Delta\varepsilon$ are the changes in temperature and strain respectively.

Here $\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1}$ is called as sensitivity matrix and it is normally obtained from calibrations. In Equations (3) and (4), a non-trivial solution exists when $AD - BC \neq 0$.

The contents of the sensitivity matrix were obtained from the slopes of the response curves shown in Figure 4.7 and Figure 4.8. Linear regression was applied to the curves and the calculated slopes were used as the sensitivity data. The temperature coefficient A of left sub band was 0.2127nm/0C and temperature coefficient C of right sub band was 0.3096nm/0C. Because the wavelengths shift to the right as temperature increased, the temperature coefficients were positive. The strain coefficient B of left sub band was 0.001624nm/με and strain coefficient D of right sub was 0.002952nm/με. Because the wavelengths shifted to right with increasing strain, the strain coefficients were also positive. The coefficients A, B, C and D are the average value from experiment as shown in Figure 4.7 and Figure 4.8. The value of $AD - BC$ is 0.0001251 not equal to zero. So there is a non-trivial solution exit for equation (3) and (4).

To verify the simultaneous measurement capability of the three-section PS-LPFG, we used the system to set the grating to a combination of temperature and strain values. Using the calibration matrix, Equations (3) and (4), we obtained the measured values of temperature and strain based on the amount of wavelength shifts of the left and right sub bands of the grating. The results are plotted in Figure 4.9, where the set-point values are also presented for comparison. Table 4.3 lists the data regarding the set values, measured values and difference between them. The maximum temperature difference is only 0.40% and the maximum strain difference is 4.41%. Both of them are acceptable.

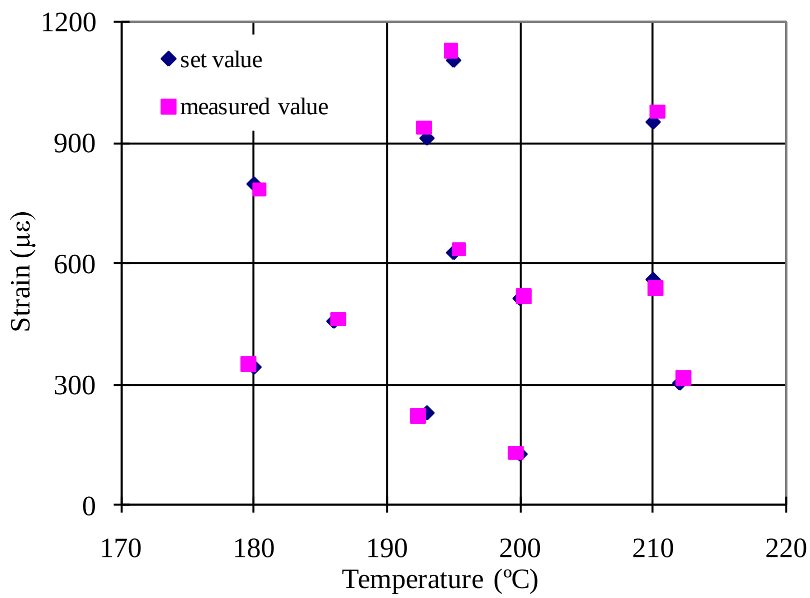


Figure 4.9. Comparison between the results from set-point and PS-LPFG measurement

Table 4.3. Set-point value and PS-LPFG measurement data comparison

Temperature (^{0}C)		Error (%)	Strain (με)		Error (%)
set value	measured		set value	measured	
180	179.61	-0.21	342.42	349.16	+1.97
195	195.45	+0.23	627.77	647.61	+3.25
200	200.52	+0.26	513.63	522.85	+1.83
193	192.33	-0.34	228.28	219.03	-4.12
210	210.36	+0.17	953.46	977.45	+2.53
195	194.52	-0.25	1107.16	1116.61	+0.85
193	192.58	-0.22	913.12	930.64	+1.92
180	180.38	+0.21	798.98	785.14	-1.73
210	210.49	+0.23	560.77	540.39	-3.61
212	212.31	+0.15	302.37	315.72	+4.41
186	186.29	+0.16	456.65	461.87	+1.14
200	199.21	-0.40	125.53	130.15	+3.62

The differences between the actual and the measured perturbation values can be attributed to the inaccuracy and uncertainty in the bands wavelength measurements and the errors during the calibration process. The maximum error in strain measurement value was attributed to difference between temperature sensitivity and strain sensitivity.

4.5. SUMMARY

In this chapter, we successfully fabricated three-section PS-LPFGs of various cladding modes. The grating responses to refractive index, temperature and strain were measured experimentally. Compared with the two-section PS-LPFG, the resonance sub bands of the three-section PS-LPFG have significant difference in sensitivity towards different parameters, which makes it possible to use the PS-LPFG for simultaneous measurement of two parameters. Based on the different sensitivities, simultaneous measurement of temperature and strain were successfully demonstrated.

5. CONCLUSION AND FUTURE WORK

Optical fiber sensors have a number of unique advantages such as immunity to electromagnetic interference, high sensitivity, resistance to corrosion, and high temperature survivability. They have been widely used to measure various physical (e.g., stress, temperature, strain, refractive index, etc.) and chemical (e.g., pH, chemical concentration, humidity, etc.) parameters. Among the various optical fiber sensors, long period fiber gratings have the additional advantages of small insertion loss, low retro-reflection, good sensory property and low cost fabrication. Most of the existing LPFGs are made by UV laser irradiation. However, the UV induced refractive index changes are found difficult to survive high temperatures. In this thesis, a CO_2 laser has been used for fabricating LPFGs. The CO_2 laser irradiation technique is simple and flexible and provides a high thermal stability.

In this thesis, the characteristics and applications of conventional LPFG, two-section PS-LPFG and three-section PS-LPFG fabricated by point-by-point CO_2 laser irradiation were investigated. It was found that the LPFG sensitivity to temperature and refractive index depends on the order of the cladding mode. The higher the LPFG mode is, the more sensitive of the grating to temperature and refractive index.

In the fabrication process of two-section PS-LPFG, the transmission spectrum of two-section PS-LPFG has two resonance bands split from the original one band. The strength of two attenuation bands varies as the gap distances changes. As the amount of phase shift increased, one attenuation band increased its strength while the other decreased correspondingly. The two sub attenuation bands have equal strengths when the gap distance is about half of period. Additionally, the two sub bands of two-section PS-LPFG have almost the same sensitivity towards temperature. The resonance wavelengths of the two attenuation sub bands of the two-section PS-LPFG shifted to the shorter wavelength region as external refractive index increased. As expected, the refractive index sensitivities of the two sub bands were not linear.

In the investigation of three-section PS-LPFG, fabrication and evolution process were described. Its characteristics and application in refractive index, temperature and strain sensing were also investigated. Compared with two-section PS-LPFG, there are two obvious evolution changes in three-section PS-LPFG. One is the resonance dips on both sides become deeper, in other words, the full-width-at-half-maximum (FWHM) gets improved, which is benefit for the sensing application with higher signal noise ratio. The other is the separation of two rejection bands becomes larger, this bigger difference between two rejection bands.

The refractive index sensitivity of three-section PS-LPFG two sub bands has been evaluated experimentally from 5^{th} order to 8^{th} order. As same as two-section PS-LPFG, the resonance wavelengths of the two attenuation sub bands of the PS-LPFG shifted to the shorter wavelength region as external refractive index increased. As expected, the refractive index sensitivities of two sub bands of three-section PS-LPFG are different, but the refractive index sensitivities are not linear.

Further exploration to investigate the temperature and strain sensitivities of three-section PS-LPFG two sub bands is also done. The significant result shows that three-section PS-LPFG two sub bands have noticeable difference in both temperature and strain sensitivities. Furthermore, both temperature and strain sensitivities of two bands are linear.

Towards simultaneous measurement of multiple parameters using a single PS-LPFG, the two-section and three-section LPFG was studied. The two sub bands of a two-section 5^{th} order PS-LPFG had shown almost same sensitivity to temperature and refractive index. However, the three-section PS-LPFG had a noticeable difference in the two bands sensitivity for refractive index, temperature and strain. The right sub band of a three-section PS-LPFG had larger sensitivity to refractive index, temperature and strain than the left sub band.

Simultaneous measurement of multiple parameters was demonstrated using a single three-section PS LPFG. The mathematical models of the simultaneous measurement were established. The temperature and strain sensitivity coefficients were obtained by calibrations. To validate the effectiveness of proposed method, the temperature and strain were set randomly and compared with the results from experiments. It was confirmed that two resonance wavelength in a three-section PS-LPFG could be used for simultaneous measurement of strain and temperature.

In this thesis, the characteristics of three-section PS-LPFG were investigated experimentally. The sensitivity difference of two sub bands was applied to simultaneous measurement of temperature and strain. Thus the future work should include the theory analysis to explain why there is sensitivity difference of two sub bands. It also includes investigation of relationship between sensitivity difference and initial resonance wavelength of two sub bands. We also need to investigate the relationship between fabrication process (e.g., irradiation point number, phase shift length, period length, power of CO_2 laser, etc.) and spectrum of three-section PS-LPFG. Although it is able to obtain the temperature and strain through a non-trivial solution from equation (3) and (4), but for the same sub band temperature sensitivity is so higher than strain sensitivity that it will increase the inaccuracy. So in the future work, we need to investigate the method to reduce the difference between temperature and strain sensitivity for the same sub band. In the future work, it is also necessary to investigate the method to reduce the inaccuracy and uncertainty in the sub bands resonance wavelength measurement and the errors during the calibration process.

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