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Tunable methods of long period fiber gratings

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Long period fiber grating is in-fiber device with the periodic structure and it is widely used in the area of optical fiber communication and sensing. With the more and more attention to the long period fiber grating in scientific research and application fields, the tunable long period fiber grating is developing as well. The paper mainly summarizes the design and achievement of tunable long period fiber gratings with electro-optic effect, magnetic-optic effect, thermo-optic effect and change of the surrounding in detail. And the LPFG in different tuning methods has different effects in tuning speed, tuning range, power consumption. With the efforts of many people, the tunable parameters can be improved and the application can be extended.

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Keywords: Long period fiber grating, Tunable, Electro-optic effect, Magnetic-optic effect; Thermo-optic effect

1. Introduction

Long period fiber grating (LPFG) is in-fiber device with periodic structure and the range of grating period is usually from 100 μm to 1 mm. LPFG is more sensitive to the environment than that of the short-period fiber grating called as fiber Bragg grating (FBG). It plays an important role in the field of the optical fiber communication and sensing, such as flat-gain fiber amplifier, band-rejection filter, the sensing of pressure and temperature. Since the period of LPFG is longer than that of FBG, the attenuation bands of the LPFG is formed by coupling between the propagating core mode and the different order of co-propagating cladding modes according to the couple theory. The advantages of LPFG include low insertion, low back-reflection, polarized light insensitivity, simple structure, convenient connection with fiber and strong wavelength selectability[1]. Tunable long period fiber grating is a long period fiber grating that the parameters can be controlled by external parameters through regular methods, such as the position of resonance wavelength, the strength of attenuation band and so on. The tunability of LPFG extends the applications of LPFG, makes the design more flexible and stronger adaptability. Many researches on the tunable long period fiber grating are to enlarge the tunable parameters, such as the tuning range of the resonance wavelength and the strength of the attenuation. Electro-optic effect, magnetic-optic effect, thermo-optic effect and change of the surrounding are applied to achieve the tuning of long period fiber grating.

2 The tuning methods of LPFGs

2.1 Electrically tunable LPFG

Q. Chen, *et al*[2, 3] presented an electrically tunable long-period fiber grating with a precise four-layer model using a very large electro-optic effect material, relaxor ferroelectric poly terpolymer (vinylidene fluoride-trifluoroethylene-chlorofluoroethylene). They added a small amount of zinc sulfide nanoparticles to adjust the refractive index of the nanocomposite to 1.4 ~1.5, and the nanocomposite retained a large electro-optic effect and high transparency. Then it matched the index of the optical fiber core to get a large tuning effect. From fig.1(a), there were four layer including a silica core layer, a thin silica cladding layer (~40μm), an ultrathin (~50nm) high refractive index indium-tin dioxide (ITO) inner electrode layer and a tunable electro-optic polymer layer. The nanocomposite was used as the second cladding layer of the electrically tunable LPFG, and an electric field was applied to the nanocomposite by adding electrode layers to the inner side and the outer side of the nanocomposite. Fig.1(b) showed the coating process of the nanocomposite winding around the fiber. The fiber was drawn slowly through a die with a hole and the polymer-nanoparticle solution, and then it was heated in the other side of the die. When the tunable LPFG was with a grating period of 400μm, grating length of 8mm, fiber core radius of 4.15μm, core index of 1.4491, cladding index of 1.4441, nanocomposite with ZnS of 1.5% in volume, the resonance wavelength of the electrically tunable LPFG shifted over 50nm under an electric field changing by 30V/μm and the change of the refractive index was $\Delta n/n \approx 0.4\%$. This tunable LPFG had low insertion, high tuning speed, low power consumption and high reliability and then it had great potential applications in the reconfigure communication systems, high sensitive optic sensors and optical spectrometers with low cost, compact and high speed.

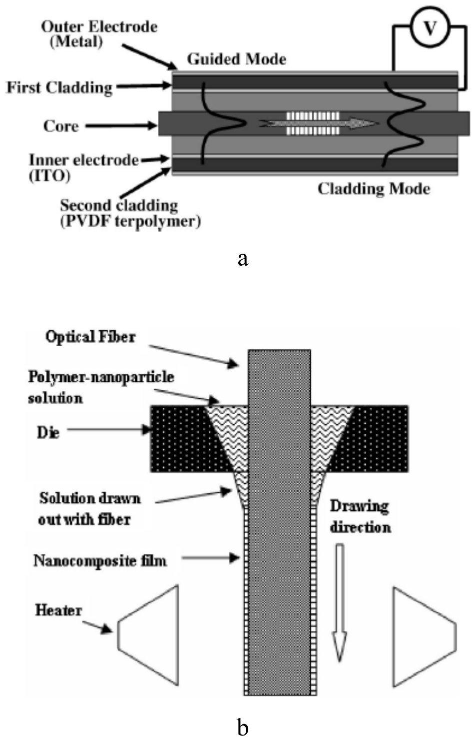


Fig.1 Electro-optic tunable LPFG (a) The schematic of the electro-optic tunable LPFG; (b) The coating process of nanocomposite

2.2 Magnetic tuning LPFG

2.2.1 Magnetic tuning LPFG based on the cover degree of grating section by magnetic fluid

W. Liao, *et al*[4] presented a method to tune the LPFG by changing the cover degree of the grating section by magnetic fluid under an magnetic field and the structure of it was as shown in fig.2. They utilized two solenoids winding around the fiber in both ends of LPFG to produce a magnetic field to move the magnetic fluid for a different degree of overlapping area around the grating section in a capillary. And then it caused the shift of resonance wavelength of the tunable LPFG. W. Liao achieved the shift of the resonance wavelength as large as 7nm and the switching response of the system was about 1 Hz. It just can be used in low speed environment, optical communication, biological sensing. In their research, they made two experiments to analyze and compare.

The first experiment used an LPFG (grating period: 570 μm, grating length: 35 mm, diameter of fiber core: 125 μm, center wavelength at 1536 nm) positioned in a capillary of 1 mm inner diameter. The gap between the grating and capillary was filled with water-based Fe_3O_4 magnetic fluid of 1.2% in volume. The grating section of the LPFG was coated between air and magnetic fluid under an external magnetic field. This tuning LPFG was shifted to shorter wavelength for 2.2 nm at max as shown in Fig.3(a). Fig.3(b) was the shift of resonance wavelength under different coating material of magnetic fluid, air and water. It found that the shift under full overlapping in Fig.3(a) was the same as that of covering with water because of the similar of the refractive index of the two materials .

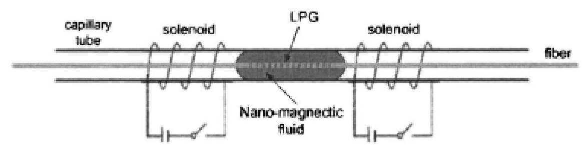


Fig.2. The schematic of magnetic tuning LPFG of W. Liao.

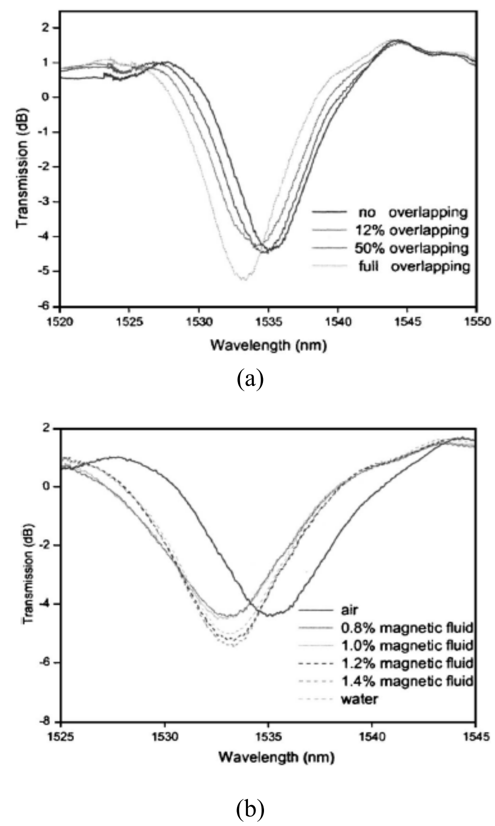


Fig.3 (a) The spectrum of different overlapping of LPFG with 570μm grating period; (b) The spectrum under different materials.

Based on the first experiment, the second experiment changed to use the LPFG of grating period of 625 μm, grating length of 9 mm, fiber core diameter of 125 μm, center wavelength at 1532 nm, and the capillary of 0.3 mm inner diameter. So the thickness of magnetic fluid was less than 200 μm and less than that of the first experiment. The resonance wavelength of this LPFG shifted 7.1 nm to the shorter wavelength as shown in fig.4 and the response of the tuning systems was about 1Hz under a light source of 1mW and current of 750 mA. Compared with the first experiment, the same partial overlapping had large different in the shift of the resonance wavelength. The large difference between the two experiments was the thickness of the magnetic fluid. When the refractive index of the magnetic fluid with the thickness of 200 μm was 1.43 and that of the magnetic fluid in bulk was 1.33. So it could be conluded that the different thickness of the magnetic fluid caused different result of the tuning effect. The 3dB band of the second experiment was wider than that of the first experiment and the change of the the attenuation strength between no overlapping and overlapping of the two experiments was about 1 dB.

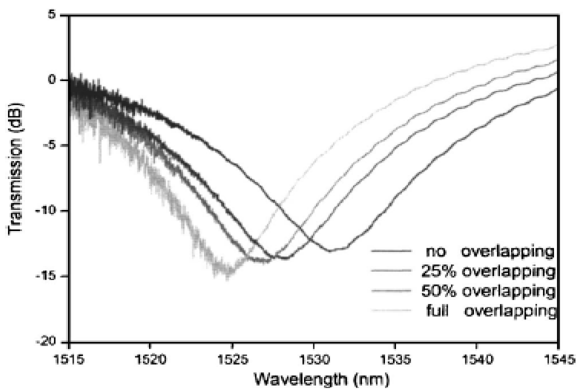


Fig.4 The spectrum of different overlapping of LPFG with 625μm grating period.

2.2.2 Magnetic tuning LPFG based on the magneto-optic effect of magnetic fluid

T. Liu, *et al*[5, 6]utilized a magnetic field to tuning the LPFG through the magneto-optic effect of magnetic fluid. Fig.5(a) showed the structure of the LPFG and it was similar to that of 2.2.1. From fig.5(b), it could found that the different direction of magnetic field with Liao. The magnetic field of Liao was parallel to the light direction and that of Liu was prependicular to the light direction. And the principles of the two tuning methods were not the same. Liao just changed the overlapping of the magnetic fluid in the grating section, while Liu utilized the magneto-optic effect to tuning the LPFG. When the magneto-optic tuning LPFG was grating period of 400 μm, grating length of 24 mm, center wavelength at 1540.5 nm in air and water-based magnetic fluid was 1.2 g/ml, it achieved 7.4 nm shift of resonance wavelength to longer wavelength with the magnetic field changing from 0 Oe to 1661 Oe as shown in fig.5(c). Compared with the method of 2.2.1, the shift direction was different, and the mainly reason could be the different tuning principle of the refractive index of surrounding, and it could be used in the field of optical communication and sensors as well.

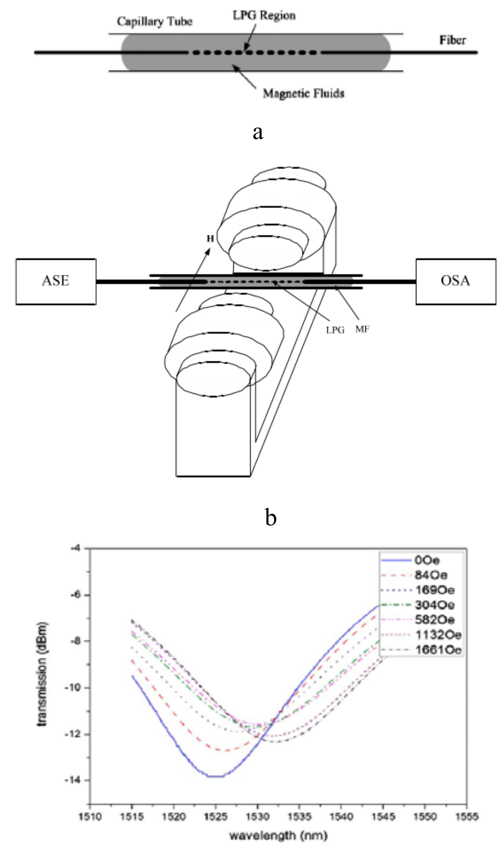


Fig. 5 The schematic of magneto-optic tuning LPFG of T. Liu (a) The structure of tuning LPFG; (b) the schematic of tuning LPFG system (c) The spectrum of the tuning LPFG

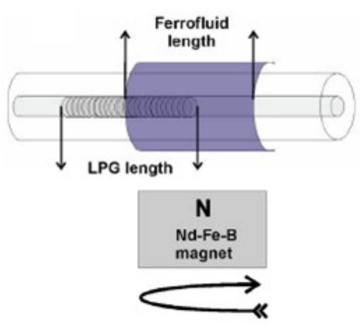
2.2.3 Magnetic tuning LPFG based on the control of magnetic fluid by bulk magnet

M. Konstantaki, *et al*[7, 8] presented two tuning methods of magnetic tuning LPFG coating with the water-based and the hydrocarbon based magnetic fluid respectively.

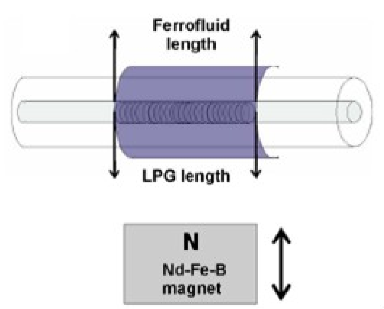
Fig.6(a) was the first tuning method of LPFG, using the water-based magnetic fluid EMG605 as the out-cladding of the LPFG by a bulk magnet. It obtained 7.5 nm tuning range and more than 6.5dB attenuation in intensity of light by an bulk magnet as shown in fig.7(a). And the important of the first tuning method was the repeatability, which was not mentioned in or before the Ref.[4]. They increased the hydrophobicity of cladding surface, employed water-based magnetic fluid to reduce the residue of the magnetic fluid, and then the system got a well repeatability. The LPFG (grating period of 407μm, grating length of 16 mm, written in Boron doped germanosilicate fiber) passed through a glass tube of 70 mm length and 5 mm inner diameter, and the gap was filled with 2/5 water based ferrofluid (EMG605) and 3/5 of a mixture of Carbon Teltrachloride (CCl_4, n_D=1.460) and Silicone Oil (Dow Corning-705, n_D=1.579). Using a Nd-Fe-B magnet of 50 mm × 25 mm ×10 mm dimension at a distance of about 4 mm from the capillary to move precise positioning along a straight travel line to change the degree of overlapping by magnetic fluid. It was similar to the method of 2.2.1 in the structure and the principle. It improved the method of 2.2.1, emphasized the repeatability as shown in fig.7(b) and the magnetic field's direction of the two methods was different and the direction of the method of 2.2.1 was parallel to the light and that of the other was perpendicular.

Fig.6(b) showed the second tuning method and it utilized the magneto-optic effect of magnetic fluid to tuning the LPFG by changing the refractive index of the magnetic fluid with an bulk magnet. The schematic of the tuning method of LPFG was similar to that of 2.2.2. The LPFG positioned in a capillary of 40 mm length and 1 mm inner diameter and the gap was filled with oil based magnetic fluid (EMG900) diluted down to 20%. Under a static magnetic field of 400 Gauss, the refractive index of the magnetic fluid was changed in order of 10^{-2} and the strength of the resonance wavelength of LPFG was changed by more than 10% (0.5dB) at 1540.8 nm without any wavelength shift as shown in fig.8. The result was different to the experiment of 2.2.2 and the reason was that the absorption of the 20% emg900 was strong.

These two methods could be applied in the high-efficient magnetic sensors and the magnetic actuators.

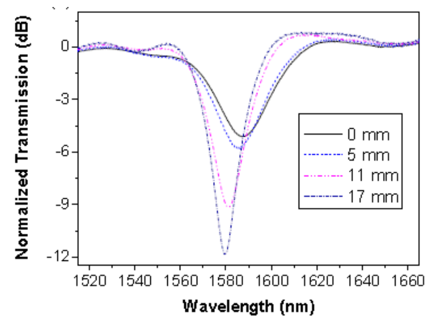


(a)



(b)

Fig.6. Two kinds of tunable LPFG (a) Tunable LPFG with magnetic fluid moving along the LPFG by magnet; (b) Tunable LPFG with static magnetic fluid tuning by moving magnet.



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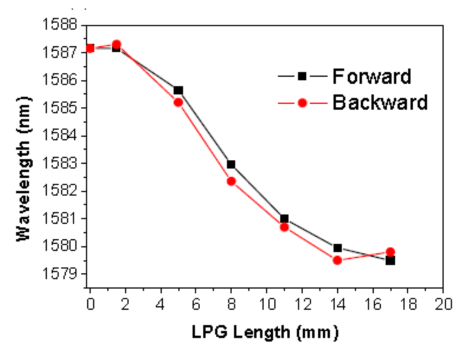


b

Fig.7 The first tuning method

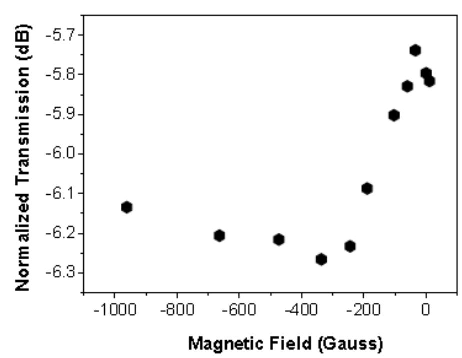


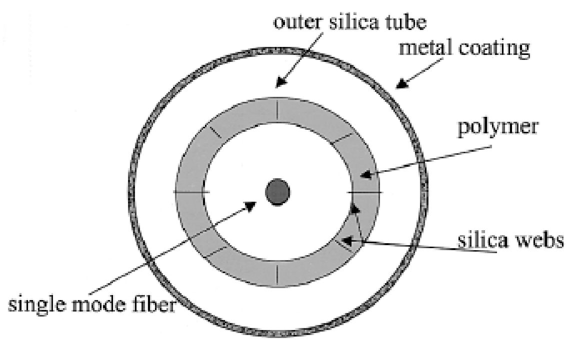
Fig.8. The spectrum result of the second tuning method

2.3 Thermo-optic tuning LPFG

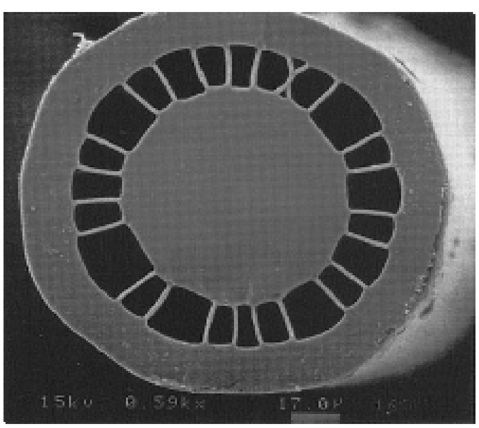
2.3.1 Thermo-optic tuning LPFG based on the air-cladding structure

A. A. Abramov, *et al*[9] presented an tuning LPFG with air-cladding structure through thermo-optic effect. And the air-cladding of the special LPFG (grating length of 50 mm, grating period of 260 μm) was filled with a high thermo-optic effect polymer and it achieved a tuning range of 60 nm under an electrical power of 0.17W as shown in fig.10(c). Fig.9 showed the structure of the LPFG. It was written in a deuterium loaded single-mode fiber coated with an air-cladding layer and was protected by a silica tube. The out surface of silica tube was coated with metal (titanium of 50 Å in thickness and gold of 3000 Å in thickness) and current passing through the gold film was to heat the LPFG. The refractive index of material with high thermo-optic effect changed, and then the resonance wavelength shifted. This air-cladding structure enabled the power efficient operation of the device and ensured that it was insensitive to the surrounding environment and was not affected by metal coating as shown in fig.10(a). Fig.10(b) showed the different curves of resonance wavelength under different temperature (lower than 100℃).

This thermo-optic tuning LPFG had high tuning efficient in low power consumption, insensitivity of the refractive index of surrounding, resistance to the environmental and aging influences. It can be potentially applied in dynamic flat-gain filter, wavelength multiplexing decomposition device and the other communication systems and sensors.



(a)



(b)

Fig.9 Tuning LPFG with air-cladding structure a) The tuning LPFG structure of Abramov; (b) The SEM photograph of LPFG

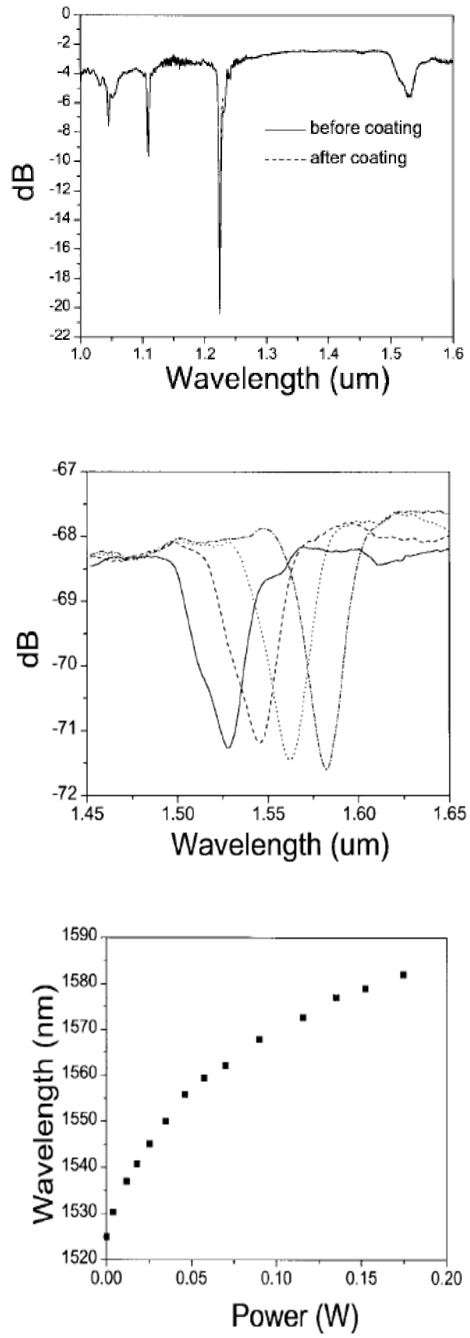


Fig.10(a) The spectrum of LPFG before and after coating by metal: (b) The spectrum shift of LPFG under different temperature ; c) The relative between resonance wavelength and the electric power

2.3.2 Thermo-optic tuning LPFG based on high thermo-optic fiber with coils

B. Jun Kye*, et al* [10]presented a tuning method that using coils around the LPFG to heat the LPFG to tuning the LPFG. Fig.11 showed structure of the tuning LPFG, which was inscribed in a boron-codoped germanosilicate (B–Ge) fiber with grating period of 428 μm, grating length of 40 mm. The boron-codoped germanosilicate (B–Ge) fiber is more sensitive to the temperature than the normal fiber and it can enhance the tuning effect. There were 20 individual coil heaters (8 turns, 1800 μm length, 120 μm line diameter, 120 μm distance between two coils, 200 μm distance between two coil sections) winding around the LPFG. And it achieved 35 nm tuning range with 1.2W electric power. The thermo-optic tuning LPFG is high efficient tuning with individual controlled by symmetrical heating each section of LPFG. Compared with the method of 2.3.1, it was not advanced in the tuning range and the power consumption, and it was more sensitive to the surrounding, but it was simpler in fabrication.

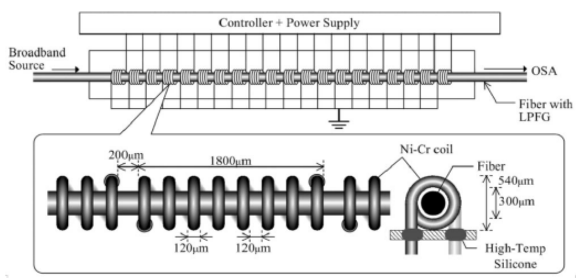


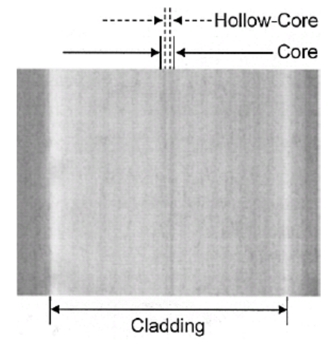
Fig.11 The tuning LPFG schematic of B. Jun Kye.

2.4. Special tuning LPFG

The tuning methods above are based on the ready-made long period fiber grating. They try different ways to change the refractive index of the surrounding or the cladding. While some tuning methods are just based on a fiber by a flexible design and they can obtain the specification similar to the tuning LPFG above.

2.4.1 Electrically tuning LPFG based on liquid crystal

J. Yoonchan, *et al* [11]utilized the electro-optic effect and presented a electrical tuning long period liquid crystal grating (LPLCG). As shown in fig.12(a), there was a hollow-core in the fiber core of LPLCG and the hollow-core was filled with nematic liquid crystal as shown in fig.12 (b), and a long-period-combed electrode was placed on one side of the LPLCG and a whole electrode was placed on the other side as shown in fig.12 (c) and fig.12 (d). Under different strength of the electric field, the different resonance wavelength and attenuation of the LPLCG could achieve because of the electro-optic effect of liquid crystal. When the external voltage was 250V (the period of combed electrode was 483 μm), a 15 nm bandwidth and 6dB band rejection had been obtained. This tuning LPFG should overcome its packaging problem and improve its tuning range in practice, and this tuning LPFG can be more flexible that its grating period can be changed by adjust the period of electrode after fabrication compared with the tuning method of 2.1. It can be widely used in many optical systems.



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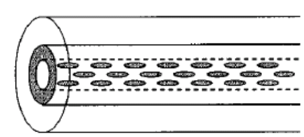

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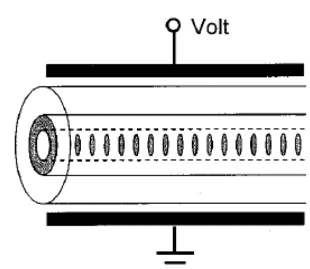

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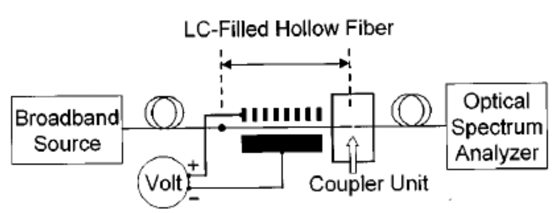
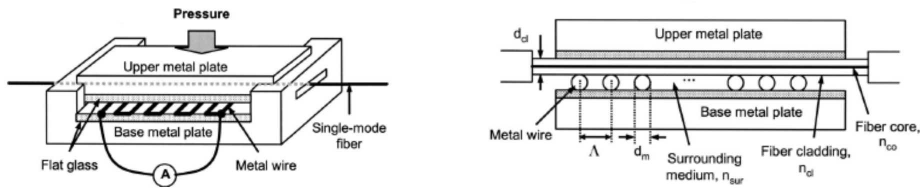


d

Fig.12 Long period liquid crystal fiber grating (a) Hollow-core fiber; (b) Liquid crystal state without electric field; (c) Liquid crystal state under an electric field; (d) The schematic of long period liquid crystal fiber Grating.

2.4.2 Thermo-optical tuning LPG based on mechanically formed LPFG

K. R. Sohn[12] used a mechanical structure to form an LPFG with two plates (one upper metal plate, the other base plate with long period structure metal wire) by adding an pressure to the upper metal plate as shown in Fig.13. When the pressure increased, the tuning depth of refractive index of fiber increased periodically, and then formed a LPFG. A large thermo-optic effect material (one or two orders of magnitude larger than that of the fiber) was filled into the gap between the two plates. When the current passed through the wire, the wire heated the material. Under the electric power of 17W, the 50 nm shift of resonance wavelength had been obtained. Compared with the methods of 2.3.1 and 2.3.2, it could find that Sohn's method was greatest in the power consumption, was second at the tuning range and was low reliability than others's.



a b

Fig.13 Electrically tunable of MFLPFG (a) The mechanically formed LPFG; (b) The cross section of tunable MFLPFG

3. Conclusions

In conclusion, people made deep research on the tuning LPFG, and the most fundamental principle was changing the resonance wavelength of LPFG by external control of the temperature and the surrounding refractive index. Tab.1 shows the tuning methods of LPFG. Based on ready-made LPFG, the electrically tuning LPFG can obtain 50nm shift of wavelength, the magneto-optic tuning method can achieve 7.5nm shift and thermo-optic tuning method can get 60 nm shift. Just from the tab.1, the thermo-optic tuning method can get the largest tuning range of 60nm, the electro-optic tuning method is second, and the magneto-optic is the last in tuning range of resonance wavelength's shift. The electrically tuning method is in high speed, while others are in low speed. We should not overlook the application environment. The electro-optic tuning LPFG can measure the electric field and voltage. The magneto-optic tuning LPFG can measure the current and magnetic field. The thermo-optic tuning LPFG can measure the temperature of the surrounding. They can not be replaced by any other, and then we should use it according to the situation. Based on none LPFG, Yoonchan achieved 15 nm wide of band rejection and 6dB in the strength of attenuation. Sohn obtained 50nm tuning range under a electric power of 17W in his thermo-optically tunable LPG using mechanically formed LPFG.

With the developing of the research on the tunable LPFG, the parameters of the tunable LPFG will optimize and its application will be extended.

Table 1 The comparison of each tuning methods.

	Tuning methods	Tuning range	Power consumption	Speed
Chen, Q.	Electro-optic tuning LPFG	50nm	low	high
Liao, W.	Magnetic tunable LPFG	7nm	low	low
Liu, T.	Magneto-optic tunable LPFG	7.4nm	low	low
Konstantaki, M.	Magnetic tunable LPFG by bulk magnet	7.5nm	low	low
	Magneto-optic tunable LPFG by bulk magnet	0.5dB Attenuation	low	low
Abramov, A.A.	Thermo-optic tunable LPFG with air-cladding	60nm	0.17W	low
B. Jun Kye	Thermo-optic tunable LPFG with heating by coils	35nm	1.2W	low
Yoonchan,	Electrically tunable LPLCG	15 nm wide band	low	low
K. R. Sohn	Themro-optic tunable LPFG formed by mechanical structure	50nm	17W	low

Acknowledgments

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