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Fabrication and Application of Polymer Optical Fiber Grating Devices

Rui Min

Abstract

Grating devices in polymer optical fiber (POFs) have attracted interest due to various potential applications in recent years. This chapter presents the state of art about the fabrication technology of grating devices in different kinds of POFs and explores potential sensing application scenarios, focus on the fabrication of chirped POF FBG devices and the potential application of such devices. Present several typical applications with uniform POF FBG. Also present several typical applications based on Chirped POF FBG, which indicate POF FBG shown promising in the sensing area with show higher sensitivity and bio-compatibility than silica ones, and special grating in POF are attractive for future biomedical applications.

Keywords: polymer optical fiber, fiber Bragg grating, refractive index change, long-period grating

1. Introduction

Polymer Optical fiber (POF) is one kind of optical fiber made of polymer material. It has attractive characteristics such as low Young's modulus, high strain, high flexibility, and biocompatibility performance compared with silica optical fiber. The first commercially polymer optical fiber with deuterated polymer was reported in the early 1960s [1]. From the 1950s, optical fibers are under research due to the demand of transmission high-speed data. Silica fibers were also under intense research since their first proposal as a transmission medium by Kao et al. [2]. At that time the transmission loss of silica fibers was high and the theoretical predictions allow to propose pure glass as fiber material able to transmit light over a hundred kilometers. Then, the purity of silica material was significantly improved and losses were reduced up to 0.5 dB/km at 1300 nm, and 0.2 dB/km at 1550 nm after a few years [3]. Therefore, most of the research was shift to the silica optical fiber based transmission system, which forms the backbone of the modern telecommunications systems [4], the transmission loss of silica optical fiber, PMMA POF and CYTOP POF from 400 nm to 1600 nm wavelength shown in **Figure 1**.

The absorption loss of silica material is lower compared with polymer material although Rayleigh scattering is the main mechanism for both cases. The main absorption of polymer material contribution is due to the harmonics of the C-H vibration [5]. Researchers and companies in Japan did intense work to reduce the transmission loss of PMMA POF, also investigated perfluorinated polymer fibers (GI-POF) with

Figure 1. The transmission loss of silica optical fiber, PMMA POF and CYTOP POF, and from 400 nm to 1600 nm wavelength.

lower losses, which shown 50 dB/km loss over 650 nm ~ 1300 nm wavelength [6–8]. However, the fabrication expend of the fluorinated polymer optical fiber are still higher compared with silica optical fiber. So, the most common material for polymer optical fiber is still PMMA which is cheap with high transmission loss at the telecom band. Both GI-POF and step-index POF mentioned above are multimode fibers, until now the main commercial POFs with single-mode performance with low fabrication cost still under research.

In recent years, the use of POFs for varies sensing applications under research are growing [9–13]. Sensing technology based on POF are mainly divided into intensity modulation technology, Brillouin scattering technology, Grating devices technology. Intensity modulation technology is the basic optical fiber sensing technologies, the main disadvantage is the performance related to the stability of the photo detector and the source, which always introduces errors in the measurement [14]. Brillouin scattering is an attractive sensing technology based on optical fiber which has been explored with silica optical fiber for many years [15]. POF with the advantage such as high flexibility can be exploited under large strains. Brillouin scattering technology in POF are good candidate for structural health monitoring. Grating devices technology as one of the main sensing technologies in silica fiber with high resolution and repeatable performance already goes from lab to the industry [16–18]. Although the first FBG in POF was reported by Peng's group with a step-index polymer optical fiber before twenty years [19], one main challenge for grating device fabrication in POF is the multimode performance of fiber, make it is difficult to analyses the spectrum from different modes.

The mature of photonic crystal fiber (PCF) technology and the excellent performance of PCF attracted the attention of the researcher for POF fabrication and application, which was invested with silica structures in 1997 [20]. The Large et al. obtained the first PCF with polymer material with endless single-mode performance in 2001 [21]. Then, H. Dobb et al. [22] reported the first FBG in endless single-mode mPOF in 2005, open the research of grating devices fabrication research with POF. Different materials such as Zeonex [23, 24], TOPAS [25, 26], and polycarbonate [27, 28] were used to fabricate microstructured polymer optical fiber (mPOF), different kind of laser irradiation technology were investigated for POG

grating devices fabrication. Special grating such as Uniform FBG, Phase-shift FBG, Tilted FBG, Chirped FBG, LPG is investigated for various applications.

In this chapter, we report the basic theory of grating devices, and the latest results about POF grating devices fabrication and potential applications. Section 2 will focus on the basic theory of grating devices such as FBG and LPG. Recent results on POF gratings fabrication with different kind of fibers and UV lasers will be reported in Section 3 and Section 4 will focus on introduce the potential applications of POF grating devices. Finally, the last section summarizes the main conclusions.

2. The basic theory of POF grating devices

Grating devices in optical fibers normally belong to two main types, which depending on the mode-coupling mechanism, counter-directional coupling is the responsible mechanism in fiber Bragg gratings (FBGs) and co-directional coupling as main mechanism for long-period gratings (LPG).

FBG is a device due to periodic modulation of the refractive index along the optical fiber, normally obtained through the exposure of the optical fiber core with an intense optical interference pattern [29]. The periodic structure in an FBGs as a selective mirror, and the wavelength satisfies the Bragg condition expressed as:

$$\lambda_{\text{Bragg}} = 2n_{\text{eff}} \Lambda \tag{1}$$

where n_{eff} is the average effective refractive index along the fiber and Λ is the grating period. Then, **Figure 2** shown a component reflects one wavelength and transmits all others with a wavelength-specific dielectric mirror response.

The ability of the FBGs shown optical communication applications such as band stop filters in Raman amplifiers [30] dispersion compensators [31], and wavelength division multiplexers [32]. Also, FBG can be used for sensing purposes, such as humidity, strain and temperature measurements.

As **Figure 3** shown, LPG is based on a periodic modulation of the refractive index of the fiber core along of the direction of propagation of the light, and the core mode couples to co-propagating cladding modes, different attenuation bands are obtained when the resonance condition is satisfied the equation below:

$$\lambda_{\text{res}} = \Lambda * \Delta n \tag{2}$$

Figure 2.
The transmission and reflection spectrum of a broad light go through one fiber with FBG inside.

Figure 3.
LPG transmission graph.

Where $\Delta n = n_{co} - n_c$ shown the difference between the effective refractive indices of the fundamental mode in core and the i th mode in cladding. As can be seen from the relation of the resonance wavelength, which is determined by the effective refractive indices of the core and cladding modes, so that any photo-induced, thermal-induced, geometrical, or mechanically induced periodic change will modify the position of the resonance wavelength. Which makes LPFGs are useful for the applications in fields as biological, chemical and optical sensing.

3. Fabrication of POF grating devices

POF FBG devices are normally obtained with direct writing technology [33], and phase mask technology [34]. Direct writing shown the advantage such as flexibility performance in terms of structure and wavelength, but the high cost femtosecond laser system is required for irradiation, and the resolution imposes limitations for the low wavelengths. LPG are normally obtained by heat imprinting [35], direct writing [36], and amplitude mask [37]. Here, we present several typical achievements obtained recently in the optimization of the fabrication process, grating devices inscription in a different kind of POF.

The fabrication process of POF grating devices has been reported by using different kind of lasers system such as 800 nm Ti:sapphire femto-second laser system [38], 532 nm Nd:YVO4 laser system [35], 387 nm Ti:sapphire femto-second laser system [39], 355 nm Nd:YAG laser system [40], 325 nm He-Cd laser [41], 266 nm Nd-YAG laser system [42] and 248 nm KrF excimer laser system [43]. Although 325 nm was the first irradiation wavelength for POF reported by the researchers in The University of New South Wales [44] and initially 248 nm and 266 nm wavelength were not considered suitable for POF grating writing due to high absorption of POF material at such wavelength, the first POF Bragg grating devices successful inscription less than one minutes with low flow and repetition rate 248 nm UV pulse opened a novel field of interest for POF grating irradiation [43]. Since then, the research about POF grating devices fabrication use 248 nm and 266 nm wavelength UV pulse has been continuously growing. A typical POF Bragg grating devices fabrication system is shown in **Figure 4**, where the pulse repetition rate and power can be optimized to modify the fabrication process, as shown in **Figure 4**.

Pure PMMA POF with low photosensitivity performance make it is difficult to obtain strong POF grating device, doped POFs have attracted the researchers' interest to enhance photosensitivity performance. Researchers in The University of New South Wales employed a step-index multimode PMMA POF doped with organic dye in the core for grating devices irradiation with 325 nm wavelength UV

Figure 4.
 Typical fabrication setup for POF FBG.

beam. The same group investigated benzyl methacrylate doped step-index multi-mode POF which lead a -28 -dB transmission spectrum with 85 mins exposure [45]. Researchers in The Hong Kong Polytechnic University investigated a step-index PMMA POF doped with TS (1% w.t.) and diphenyl sulfide (DPS) (5% mole) in the core and a pure $150\text{ }\mu\text{m}$ diameter PMMA cladding, obtained the FBG spectrum with -10 dB in transmission after 10 mins [46]. The researcher at Aston University reported a highly photosensitive mPOF doped with BDK in the core, FBG with -23 dB in the transmission was achieved after 13 mins [47]. The researchers in Belgium improved the optical fiber drawing technology with selected center hole doped with BDK in mPOF, a rapidly growing process of FBG with 83% reflectivity with 40 s [48]. Recently, the researcher in Hongkong investigated a new dopant material, named as diphenyl disulphide, which enables a fast and positive refractive index change with a low ultraviolet dose and leads to FBG fabrication with 7 ms under 325 nm wavelength UV beam irradiation [49].

The researchers optimized the fabrication process of FBGs in BDK doped POF with 248 nm and 266 nm wavelength, obtained strong grating with a single short pulse (15 and 8 ns of duration), the short time is even suitable for the fiber drawing process [42]. R. Min et al. also reported two, three, and five rings structure undoped PMMA POF fabricated with 266 nm Nd:YAG laser in the 850 nm region and using commercial ferrule connectors for POF connecting with silica fiber [50], the rend face and the reflected spectrum shown in **Figure 5**.

POF special grating devices such as tilted FBG and Chirped FBG are under research due to attractive applications. The first tilted POF FBG was investigated by the researcher's in Belgium, use of TS-doped photosensitive step-index PMMA POF with scanning phase mask technique, the transmitted amplitude spectrum evolution of a 3° angle is analyzed for the surrounding refractive index varies [51]. The first chirped POF FBG was irradiated with a KrF excimer laser operating at 248 nm wavelength and a 25-mm long chirped phase mask which customized for telecom-band FBG inscription in 2017 [52]. The laser pulse rate was 1 Hz and several shots were used for the grating response with a 1.2 nm/cm chirp and 3.9 nm bandwidth. The chirped phase mask technology offers good stability with the high cost and no flexibility as main drawbacks. Since then, different kind of techniques have been demonstrated for obtain chirped gratings in POF. The researchers in Cyprus used the femtosecond direct writing method for fabricate chirped FBG in commercial CYTOP POF [53], obtained 2000 periods with 10 nm bandwidth and a total length of around 4.5 mm . Femtosecond laser direct writing used for flexible chirped grating writing, although with the disadvantage as limit for low wavelengths. The first tunable chirped FBG was obtained with a tapered BDK doped mPOF by using a

uniform phase mask under strain performance [54]. The spectral reflected power of a 10 mm bandwidth with a chirp of ~ 0.26 nm/mm under 1.6% strain, and the strain and temperature sensitivity obtained with 0.71 ± 0.02 pm/ $\mu\epsilon$ and 56.7 pm/ $^{\circ}\text{C}$. Then, Chirped POFBGs have been also obtained by hot water-assisted gradient thermal annealing, where one grating device with around 1.1 nm/mm chirp performance was obtained as **Figure 6** shown [55]. The simplicity of this method is one of the main advantages since no special phase mask or additional etching is needed, and enables easy control of the chirp characteristics and the central wavelength.

Finally, regarding LPG in POF, the extensive literatures with different methods and mechanisms appeared in the last years. Recently, the researcher in Spain [56]

Figure 5.
The end face and the reflected spectrum of three types mPOF.

Figure 6.
The spectrum and the bandwidth varies of the chirped POF FBG fabrication with strong gradient annealing.

demonstrated a – 20-dB transmission LPG in mPOF with point by point method use a slit width of 0.2 mm; the beam was shifted 1 mm for inscribing each point and 25 steps were implanted. And the researchers in Cyprus reported an LPG in a CYTOP POF using a femtosecond laser inscription method. The LPG was inscribed directly in the center of the optical fiber core, tailored for operation at 1560 nm, which was characterized in transmission, and the response for relative humidity and temperature was also measured [57].

4. Applications of POF grating devices

POF FBG already goes to industry measurement such as used for water content detection in aviation fuel as shown in the **Figure 7**, the water content in Jet-A1 was measured by using POF FBG sensing technology which calibrated with both coulometric titration and environmental chamber. The results indicate a better performance compare with coulometric titration [58].

POF FBG can be also used to monitor the strain of human arteries with pulse wave signals. A variety of different vital signs including blood pressure can be derived from the signals, which show a higher signal to noise than silica FBG [59], the experimental measurement as **Figure 8** shown.

POF FBG can be used as health equipment for dynamic monitoring of gait. Five FBGs inscribed in CYTOP POF was embedded in a cork insole, as shown in **Figure 9**. The advantages of POF such as higher flexibility and robustness enabled monitoring patients with higher body mass, compared the results obtained with similar systems based on silica fiber, a mean sensitivity of ~8.14 PM/kPa was obtained, which is much higher compared with FBGs in silica optical fiber [60].

Consider the special POF grating applications, due to polymer special characteristics, strain sensing is the most attractive and reliable applications. There is a lot of literature reported POF FBG for strain sensing [61–63]. However, strain sensing under variable humidity and temperature conditions is always an issue for POF sensing technology go to real applications. The researchers in Spain demonstrated

Figure 7.
Schematic of the bench test rig [58].

Figure 8.
Experimental measurement of blood pressure uses silica FBG and POF FBG [59].

Figure 9.
Experimental measurement of blood pressure uses silica FBG and POF FBG. (a) Foot plantar area designation and sensing point. (b) Polymer optical fiber Bragg grating embedded cork insole [60].

one method use the effective bandwidth of the tunable chirped POFBG, which is highly dependent on the strain and remains practically constant with temperature and humidity changes, can be implemented combine with wavelength measurement, for strain sensors under temperature and humidity variable environments, the spectrum varies under strain condition as **Figure 10** shown [64].

Due to the polymer characteristics, POF grating devices are attracting attention for biomedical applications. An essential feature of these systems is the possibility to detect temperature spatial distributions, which also name as thermal maps. A linearly chirped POF FBG reported as a semi-distributed temperature sensor for monitor the temperature profile along the grating length as **Figure 11** shown [65]. The grating device has been placed close to the radiofrequency applicator, which have one tip inserted in situ of the target. The reflection spectrum of the chirped

Figure 10.
Chirped POF FBG spectrum varies with strain. (a) Spectral reflected power vs strain; (b) Wavelength shift vs strain; (c) Bandwidth vs strain [64].

Figure 11.
Schematic of thermal ablation experiment [65].

POF FBG was detected by LUNA OBR 4600 and the temperature gradient was estimated use the Gaussian model method. The results indicate that chirped POF FBG can provide significant improvement in thermal detecting for biomedical applications.

Also, a high spatial resolution distributed strain sensing approach based on Chirped POF FBG was reported by researchers in China [66], through spatial wavelength encoded characteristic of Chirped POF FBG, a fully distributed high resolution strain measurement can be achieved by optical frequency domain reflectometry method, which is a promising approach for short-range fully distributed sensing systems, schematic of the experiment setup shown in **Figure 12**.

Figure 12.
Schematic of the experiment setup for fully distributed strain measurement [66].

5. Conclusion and outlook

Significant progress has been demonstrated for POF grating devices fabrication during the last years, such as to allow fast fabrication of POF grating devices under 248 nm and 266 nm wavelength UV, one 15 ns pulse for POF FBG fabrication. Besides the benefit as potential grating fabrication technology in the optical fiber drawing process, special grating structures such as Chirped FBG also take advantage of the short irradiation time, such as the benefit to reduce the stability requirements for the irradiation setup.

Besides strain and temperature sensitive devices as the main applications of POF FBG, special grating devices open new perspectives. As the main relevant examples, chirped POF FBGs used for high-resolution thermal detection in the biomedical area with a higher sensitivity and bio-compatibility than silica ones, special grating in POF are attractive for future biomedical applications, which also make special POF grating fabrication technology have room to improve.

To conclude, grating devices in POF show attractive performance for sensing applications. However, most of the POF for grating devices fabrication are still homemade, which need time and research to make this technology mature for real applications. From this point of view, grating devices fabrication in commercial CYTOP POF are promising, also the investigated for low cost single-mode commercial CYTOP POF and grating on such fiber.

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Conflict of interest

The authors declare no conflict of interest.

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