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Periodic micro-structures in optical microfibers induced by Plateau-Rayleigh instability and its applications

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Abstract: A periodic micro-structure on optical microfibers induced by Plateau-Rayleigh instability (PRI) was investigated and a potential application for long period gratings (LPGs) fabrication was given. The linear relation between the average periods of micro-structures and the diameters of optical microfibers was demonstrated first. By brushing a glass rod with a Teflon droplet suspended at the end tip along microfibers, a continuous film of Teflon was formed at once, then the film broke up into a series of periodic droplets due to PRI. Periodic Teflon nodes were left after the evaporation of the solvent. A LPG structure based on polymer was finally formed by this method on a microfiber with a diameter of 5.5 μm. An attenuation transmission dip of 15 dB around 1447 nm was achieved. Investigation of the strain and temperature response characteristics of the grating presented a strain sensitivity of −2.5 pm/με and a temperature sensitivity of −157 pm/°C. The technique proposed here provides a versatile technique for polymer-based LPGs fabrication. Benefiting from the high sensitivities, LPGs based on numerous polymers fabricated in this way could have potential applications in optical and biological sensing.

OCIS codes: (060.2370) Fiber optics sensors; (060.2340) Fiber optics components.

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1. Introduction

Optical microfibers have aroused enormous attentions in recent years because of their large evanescent field, low insertion loss, compact size and great mechanical property. Many optical devices including fiber couplers, resonators and gratings have been fabricated based on microfibers. Among all these applications, long period gratings (LPGs) play an important role in optical fiber communications and sensors. LPGs fabricated in optical microfibers have been proved to have greater potential for integrating and sensing because of their compact size and strong interaction with the environment when compared to LPGs fabricated in standard single mode fibers (SMFs) [1]. To our knowledge, LPGs in optical microfibers are mainly based on silica material fabricated by the methods including femtosecond laser processing [2], CO_2 laser machining [3], helical coiling [4] and chemical etching [5]. Another popular way to realize LPGs is through a microfiber side-coupling with an external metal gratings [6]. Recently, the polymer-based LPGs become an interesting issue. Polymers exhibit many applications in optical sensing because of their particular biocompatibility and sensitivity to ultraviolet illumination, strain, humidity and temperature. Point by point dip-coating [7] is a primary method to fabricate polymer-based LPGs, but the whole process is complex and requires accurate position control.

As a widely-used approach to form periodic array of spindle-nodes, the Plateau-Rayleigh instability (PRI) [8] effect has been used to fabricate many useful devices. A fluid film on a fiber is generally unstable for even very small disturbances. Because of the liquid surface tension and the environmental perturbations, fluid film spontaneously undulates and finally breaks into a periodic array of droplets within a characteristic growth time, such effect is called PRI. Joseph Plateau was the first to study the instability of cylindrical films. Plateau showed that when the free surface of a liquid cylinder undulates with a spatial perturbation, its area decreases, provided that the axisymmetric perturbation length scale larger than the circumference of the fluid cylinder. Lord Rayleigh [9] revisited and extended the work of Plateau, and showed that the instability of cylindrical films is established with a well-defined wavelength, and thus explained the regularity in spacing of the drops that form. H. Bai et al. [10] uses periodic polymethyl methacrylate (PMMA) spindle-nodes to collect water under a fog flow. Velez-Cordero et al. [11] succeeds to control the motion of drops in micro-channels through a periodic array of pearls along the capillary. Kaufman et al. [12] utilizes fluid instability in-fiber to generate structured spheres. Optical microfibers possess the characteristics of high fractional evanescent fields, which lead to a strong interaction with the surrounding medium. Therefore, it is expected that the PRI effect can be applied to fabricate mode-coupling devices in optical microfibers.

Here, we propose a simple and versatile method to fabricate polymer-based LPGs in optical microfibers based on the fluidic PRI effect. The optical microfiber with a proper diameter is coated with a continuous film of liquid Teflon by brushing a glass rod, at the end of which a Teflon droplet is suspended, along the waist of the microfiber. After the characteristic time [13], the continuous film breaks up into periodic droplets due to the PRI effect. The surface of the microfiber is periodically modified by the left Teflon nodes after the solvent evaporates. The theoretical value of the selected wavelength (which often corresponds to the distance between droplets) is found to be $\sim 2\pi\sqrt{2}r$ in Rayleigh's work [14], where r is the radius of the fiber. The linear relation between average periods of the nodes and the diameters of the optical microfiber is demonstrated experimentally by coating fibers of different diameters under the same condition. The periods of general LPGs are in the range of tens of micrometers to hundreds of micrometers. According to the theoretical formula, the period of microstructure formed on a microfiber with a diameter of few micrometers is around tens of micrometers, which fits well with LPGs. In our experiment, A LPG with 15 dB attenuation dip around 1447 nm is achieved in a microfiber with a diameter of 5.5 μm based on the PRI effect. The strain and temperature response characteristics are investigated, and the sensitivity is up to −2.5 pm/με and −157 pm/°C, respectively. The polymer-based LPGs proposed here present potential applications in optical sensing. More specific applications in chemical and biological sensing are available by using functional polymers to modify the surface of microfibers.

2. PRI effect in optical microfibers

The schematic of the experimental setup to form periodic nodes on optical microfibers is showed in Fig. 1(a). A microfiber is drawn from a commercial SMF(cladding diameter ~125 μm,core diameter ~9 μm) by the flame brushing method. The two pigtails of the microfibers are clamped at two linear translation stage stages. The waist of the microfiber is brushing-coated with Teflon AF solution using a travelling glass rod with a velocity of 1 cm/s. The Teflon solution with a refractive index of 1.31 is composed of Teflon dissolving in C5-18-Perfluoro compounds with a gram weight of 11.4 in 100 ml solution. The viscosity of the Teflon is 0.2 Pa·s. After coating, a uniform film of Teflon on the microfiber is formed at first, as shown in Fig. 1(b). The formation of the film is the result of the liquid viscosity, the thickness of which is largely affected by the viscous force and coating speed. The details of film formed at different speeds region have been discussed in Quéré's work [15]. Due to the PRI effect, the solution film is observed to be unstable within a short time (less than 1 s). The film completely breaks up into periodic droplets within 10 s. After the evaporation of the solvent, the surface of the microfiber is distributed with periodic Teflon nodes, as shown in Fig. 1(c). In this way, a polymer-based micro-structure with an appropriate period is fabricated on the microfiber. The transmission spectrum is monitored with a super-continuum broadband light source (BBS) covering a wavelength from 1200 nm to 1600 nm and an optical spectrum analyzer(OSA) with a resolution of 20 pm.

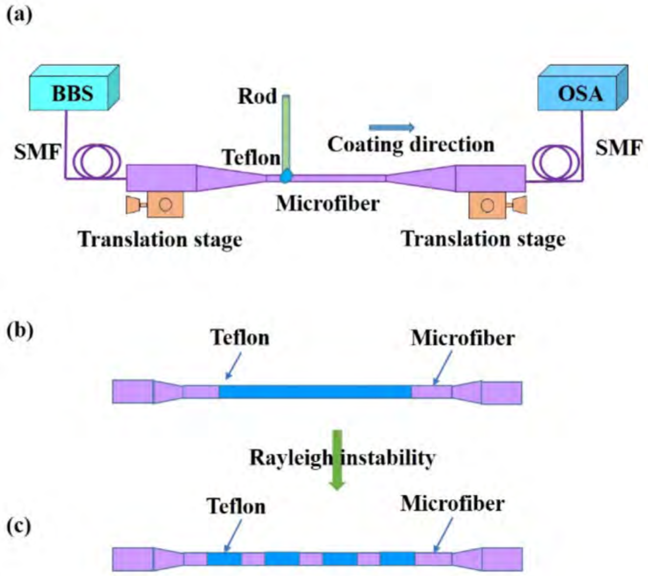

Fig. 1. Schematic of the experimental setup to form periodic nodes on optical microfibers. (a) Schematic of the setup for fabricating periodic micro-structure on optical microfiber and monitoring of transmission spectrum of the modified optical microfiber. (b) Schematic of an optical microfiber with a continuous film of Teflon. (c) Schematic of an optical microfiber with periodic Teflon nodes induced by the PRI effect.

The relation between the average periods of Teflon nodes and the diameters of optical microfibers is investigated first. Figure 2 shows the microscope images of the periodic Teflon nodes formed on a microfiber at multiple sections with different diameters. The periodic nodes were observed through an optical microscope. A charge coupled device was used to measure the distances between adjacent periodic nodes. The measurement error of the microscope is about 0.5 μm. The figure at the top is the waist of the microfiber, the rest of the figure are chosen from the transition area with different diameters. The figure shows the adjacent distances increase with the increase of the diameter of the microfiber. This result is consistent with Rayleigh’s work [14]. The top of the figure shows that the distances between the adjacent nodes at the uniform waist are not exactly equal. The undulation of period results from the variation of the velocity of brushing and the thickness of the film during the whole brushing process. Five adjacent distances were recorded for each diameter of the microfiber. The average period shown by black squares is calculated using a Gaussian fitting curve, the detail is given in the next section. The bars in Fig. 3 are standard deviations of each group of data. The average periods increase with the increase of the diameters of microfibers. The blue line in Fig. 3 shows a linear relation between the periods of Teflon and the diameters of microfibers. To demonstrate the compatibility of this fabrication technique, the experiment of coating microfibers with PDMS was performed with the same coating speed. The refractive index of the PDMS is 1.40 and the viscosity is 0.9 Pa·s. Figure 3 shows that the slope of PDMS is higher than the slope of Teflon. This result is due to the difference of viscosities between these two fluids. When compared to PDMS, Teflon is more applicable to the fabrication of LPGs because of its lower refractive index and smaller viscosity. However, PDMS is more sensitive to organic liquids and gases, so it is more suitable for certain sensor applications.

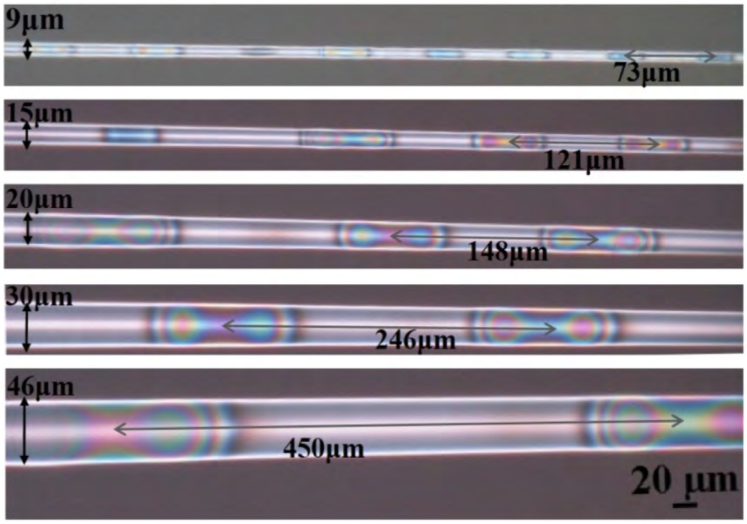

Fig. 2. Microscope images of the periodic Teflon nodes formed on a microfiber at multiple sections with different diameters.

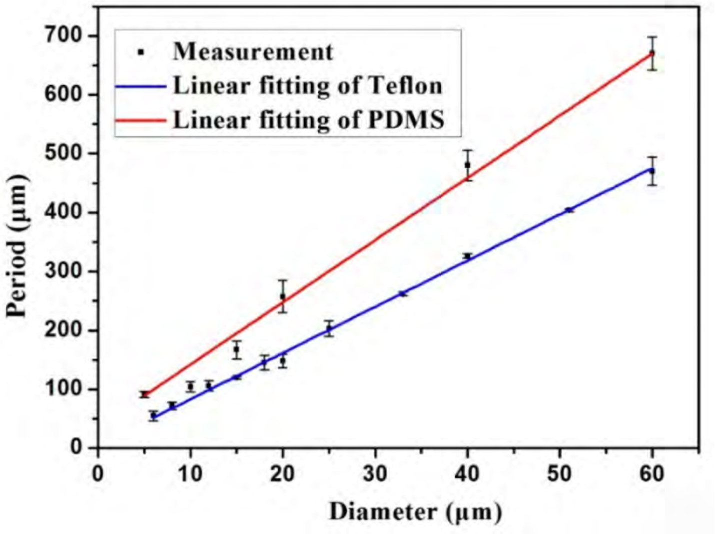

Fig. 3. The evolution of the period when the microfibers with different diameters are modified by Teflon (blue line) and PDMS (red line). All the experiments were performed at the same coating speed.

3. Polymer-based LPGs fabrication based on the PRI effect and its applications

The periods of LPGs are usually in the range of a few tens of micrometers to hundreds of micrometers. The average distance between adjacent nodes formed by the PRI effect in optical microfibers with a diameter of several micrometers locates in such range just right. So a Teflon-based LPG device on a microfiber induced by PRI effect is fabricated in our experiment using the setup shown in Fig. 1. Figure 4(a) shows the microscope images of the periodic Teflon structure in a microfiber with a diameter of 5.5 μm, the details of the surface modification can be seen from the scanning-electron-microscope (SEM) images in Fig. 4(b), from which it can be seen that the node has a height of 6.5 μm and a length of 38 μm. Figure 4(a) shows that the distance between adjacent nodes is not strictly equal because of the fluctuation of velocity and thickness of Teflon during the whole process of brushing. Statistical data for periods is shown in Fig. 5 and a Gaussian fitting is used to reveal the central periods. The average period is around 73 μm.

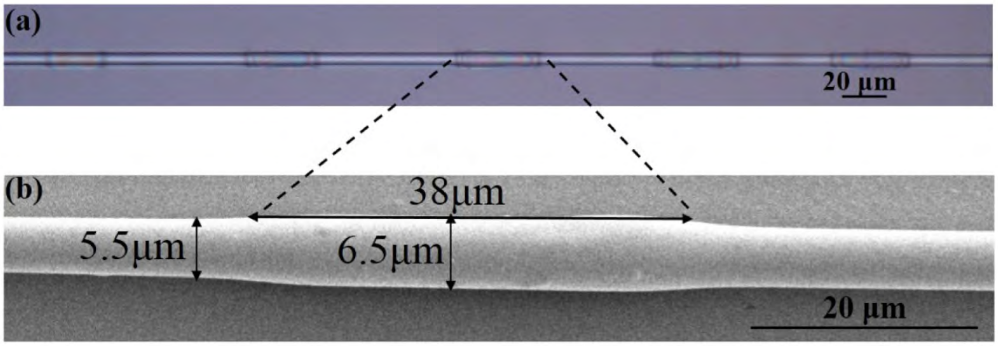

Fig. 4. (a)The microscope images of the periodic Teflon structure in an optical microfiber with a diameter of 5.5μm. (b) SEM images for the details of the surface of modified optical microfiber.

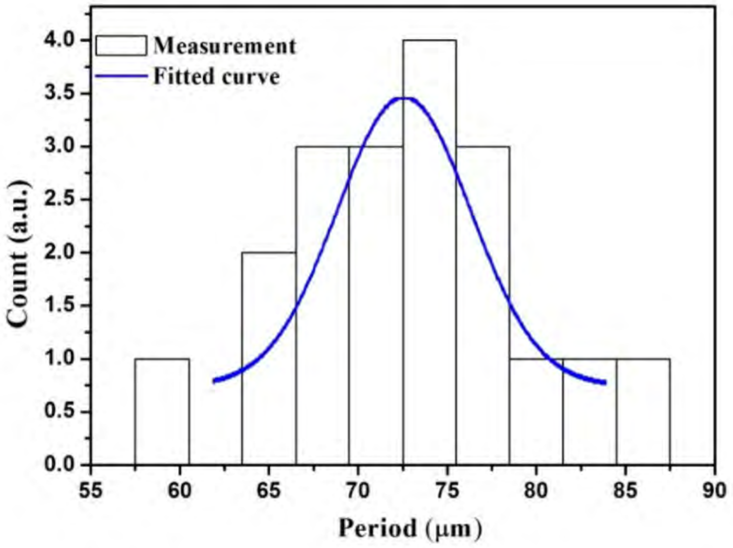

Fig. 5. Statistical data for periods of a LPG in a microfiber with a diameter of 5.5μm. A Gaussian fitting curve (blue line) is used to calculate the average period.

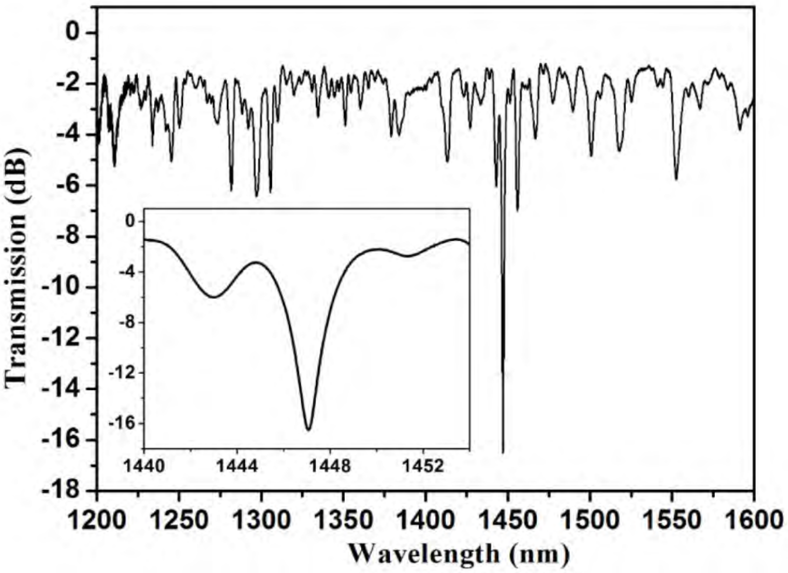

Fig. 6. Transmission spectrum of a LPG in a microfiber with a diameter of 5.5 μm. Inset: transmission spectrum around an attenuation wavelength.

The transmission spectrum of the LPG above-mentioned is monitored by an OSA and showed in Fig. 6. It is a classical transmission spectrum of a LPG device. An attenuation transmission dip of 15 dB is achieved. The central wavelength of the attenuation dip locates around 1447 nm. The detail around the attenuation wavelength is shown in the inset. The 3 dB bandwidth of the attenuation dips is about 2 nm, much narrower than that of LPGs in conventional SMFs [5]. The insertion loss is around 1.5 dB, and it can be further reduced by optimizing the fabrication process.

The microfiber used in our experiment can support dozens of modes. The effective indexes of the first ten modes in Teflon-clad silica microfiber with a diameter of 5.5 μm are calculated by Comsol Multi-Physic Software. A LPG is formed when the coupling between fundamental and higher-order modes is satisfied by the phase matching condition [16]:

$$\lambda = \left(n_0 - n_m\right)\Lambda. \tag{1}$$

Where λ is the coupling wavelength, Λ is the grating period, n_0 , n_m are the effective refractive indexes of the fundamental and the m-order mode. The index differences between fundamental HE_{11} mode and TM_{01} mode is around 0.0197. According to the Eq. (1), for a grating period of 73.5 μm, the attenuation dip would be formed around 1447 nm. The result is consistent with the experimental measurement.

The strain response characteristics of the above LPG is investigated by stretching both ends of the microfiber with two high-precision translation stages. As shown in Fig. 7(a), the attenuation wavelength moves towards the short wavelength when increasing the applied strain, which can be explained by photo-elastic effect [4,17,18]. The measured attenuation wavelengths under different strain are shown by the squares in Fig. 7(b), and the solid red line is the linear fitting result of the measurement, which gives a strain sensitivity of –2.5 pm/με in the strain range of 0-4500 με, the strain sensitivity is about 6 times larger than that of the conventional LPG [19].

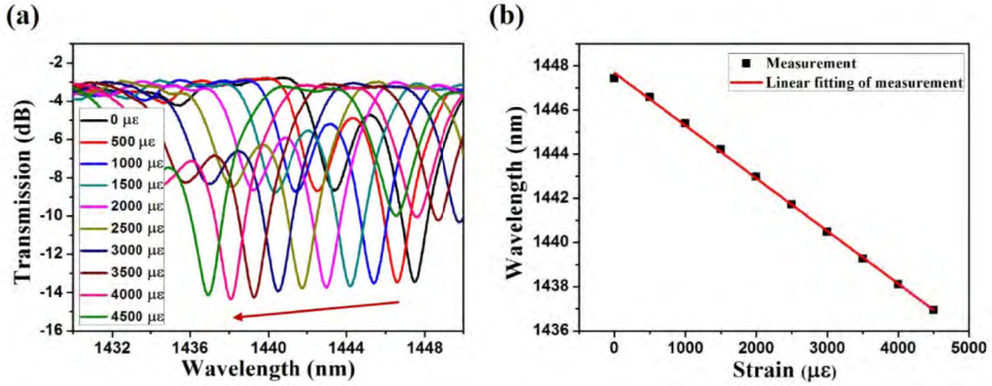

Fig. 7. (a) Spectral responses of the LPG to strain ranging from 0 to 4500με. The red arrow represents the increase of the strain. (b) The measurement attenuation dip wavelength (square scatters) at different strain and the linear fitting result. The linear fitting curve presents a strain sensitivity of –2.5 pm/με.

The temperature response characteristics of a LPG formed in a 4.5 μm diameter microfiber with an average period of 55 μm is measured by placing the LPG on a digital controlled heater stage. The LPG is heated in the temperature range of 30 – 70 °C. The evolution of the transmission spectrum at different temperature is shown in Fig. 8(a). The attenuation wavelength also has a blue-shift with the increase of the temperature [7]. The relationship between the dip wavelength and the temperature is shown in Fig. 8(b), corresponding to a temperature coefficient of ~157 pm/°C. The sensitivity is higher than that of the LPG fabricated in SMF [20].

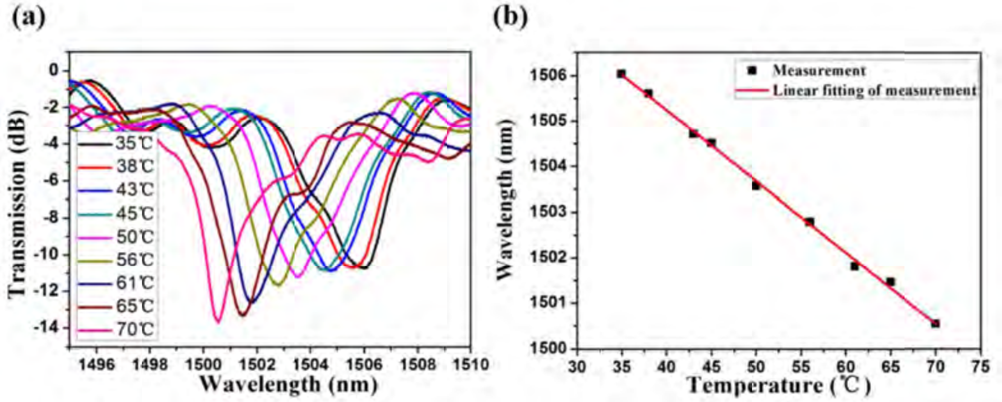

Fig. 8. (a) The temperature responses of a LPG in a microfiber with a diameter of 4.5 μm. The average period of the LPG is 55 μm. (b) The measurement attenuation dip wavelength (square scatters) at different temperature and the linear fitting result. The linear fitting curve presents a temperature sensitivity of –157 pm/°C.

4. Conclusion

In conclusion, a versatile technique to fabricate polymer-based LPGs on optical microfibers based on the PRI effect is proposed. This provides a low cost and simple method to fabricate microfiber LPGs. The surface of the microfiber is periodically modified by the Teflon micro-structure. The relation between the average periods of micro-structures and the diameters of microfibers was demonstrated to be linear both for Teflon and PDMS. By introducing a micro-structure satisfying the phase matching condition for modes coupling, a LPG is implemented. A LPG with 15 dB attenuation transmission dip around 1447 nm is achieved in our experiment. The strain and temperature response sensitivity is investigated and up to −2.5 pm/με and −157 pm/°C, respectively. Other than these demonstration, LPGs fabricated by our method can also be combined with more functional materials, such as graphene, quantum dots and liquid crystal. Applications in chemical and biological sensing are promising. However, compared to LPGs based on silica material, the polymer based LPGs cannot apply to high-temperature environments and many factors in producing process need to be controlled to improve the repeatability.

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