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Colloidal crystal cladded microfiber for refractive index sensing

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We investigate the evanescent field of a microfiber wrapped by colloidal crystals. The microfiber has the diameter of about 1 μm that is drawn from a single-mode fiber with an alcohol lamp. The colloidal spheres are further attached to the microfiber through thermal evaporation, then they self-assemble to crystal-like structures. The 400 nm, 590 nm, and 710 nm-diameter SiO_2 colloidal spheres are used, respectively. The spectral responses are studied theoretically and experimentally, and the results agree with each other. It is revealed that the evanescent field of a microfiber could be modulated by the photonic band-gap of colloidal crystals. This characteristic is very useful in refractive index sensing for liquids.

Keywords: microfiber, colloidal crystals, refractive index sensing.

1. Introduction

An evanescent field plays an important role in various optical sensing technologies. In particular, the evanescent field-based optical fiber sensor has been investigated extensively in the past years [1–3]. The optical field outside the microfiber or inside the holes of a photonic crystal fiber is sensitive to the environmental index. Therefore either active modulation or positive sensing could be realized. Normally, the corresponding fiber may act as the main light transmission path or an arm of an interferometer, depending on the system architecture. All-fiber robust sensors thus can be constructed. Two methods have been reported to obtain the microfiber. One is to strip the cladding of a fiber [4, 5] and the other is to draw a fiber into a small diameter, usually from sub-micrometers to tens of micrometers [6, 7]. After these procedures, more guided light in the fiber may penetrate outside the fiber and interact with the environment for sensing. Modulation of the evanescent field could further enhance the sensing properties significantly [8, 9].

Recently, some researchers reported a new approach to fabricate microfiber structures, which is based on the growth of colloidal crystals inside or outside optical fibers [10, 13]. Both dip-coating and chemical vapor deposition approaches have been demonstrated to produce large-area colloidal crystal films surrounding cylindrical fibers [14]. The prepared colloidal crystals become hollow macro-porous cylinders and can be used as an air-core optoelectronic component with a 3-D structure for sensing.

In this paper, the microfiber is fabricated through heating and drawing a single-mode fiber. The microfiber with ~1 μm diameter is selected for the experiment, which has a strong evanescent field. Modulated by a self-assembled colloidal photonic crystal, the characteristics of the fiber are studied. The applications in refractive index sensing are discussed.

2. Designed and fabricated

Figure 1 shows the schematic diagram of the experiment. The coating of a standard single-mode silica optical fiber (SMF-28) is removed. The fiber is heated by an alcohol blowtorch, then drawn with motorized linear stages. The obtained microfiber diameter is about 1 μm after drawing. At the same time, different colloidal solutions are prepared

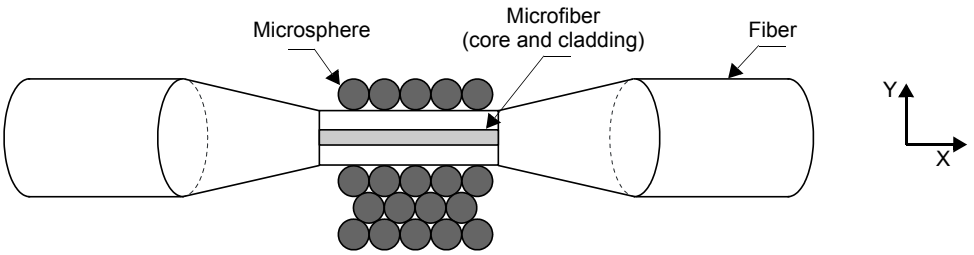

Fig. 1. The sketch of a colloidal crystal cladded microfiber.

with 1.5 wt% silica microspheres in water/ethanol (volume ratio 1:4) mixture. The corresponding microspheres have the diameters of 400, 590 and 710 nm (standard deviation of about 2%), respectively. The microfibers are clamped and immersed in the colloidal solution so that the microspheres are adhered on the surface of the microfiber. After that, colloidal silica microspheres are self-assembled forming a crystal -like structure during the process of isothermal heating evaporation at 50 °C. The accumulated vapor pressure, together with interfacial forces, is a critical parameter for the colloidal crystal self-assembling. The 2–3 cm colloidal crystal cladded fibers are obtained after two hours. Then, the fiber is annealed in a muffle at 350 °C for about 5 minutes to stabilize the structures.

3.Experiment and discussion

The colloidal crystal cladded microfiber is observed under a scanning electronic microscope (SEM). Results are shown in Fig. 2. From Fig. 2**a**, the final fiber diameter

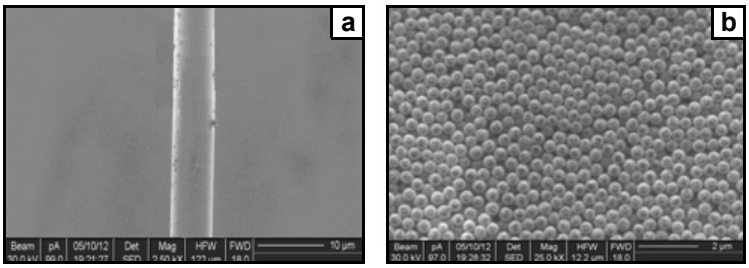

Fig. 2. SEM photograph of the colloidal crystal cladded microfiber (see text for explanation).

is 4–5 μm with a colloidal crystal cladding. The microstructure shows good integrity. Figure 2**b** is another SEM photograph of higher magnification. A continuous large -area colloidal crystal film can be clearly observed. The exhibited colloidal sphere diameter is ~0.59 μm as shown in Fig. 2**b**.

The colloidal crystal cladded microfibers are packaged, then characterized optically. Figure 3 shows the transmission spectra of the colloidal crystal cladded microfibers measured using an optical spectrum analyzer (OSA). Three kinds of colloidal crystals are studied, with diameters of 400, 590 and 710 nm, respectively. The curves show remarkable transmission peaks with the contrast of around 2.5 dB. They locate at 870.2, 1290.6, and 1542.5 nm, respectively. The peak half-width is about 60 nm. This phenomenon can be used in broadband optical filters.

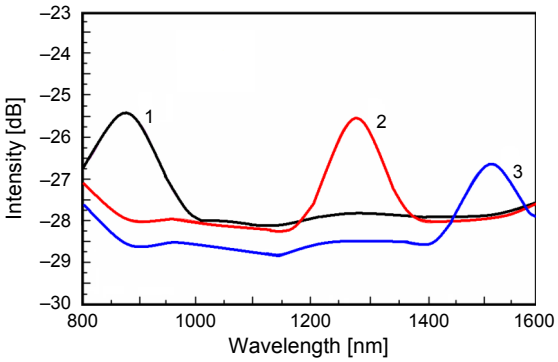

Fig. 3. Transmission spectra of three colloidal crystal cladded microfibers. Curves 1–3 correspond to colloidal crystals with diameters of 400, 590, and 710 nm, respectively.

As we know, the spectrum response of a naked microfiber is quite flat with no evident peaks or valleys. The transmission peak should result from the colloidal crystal structure. If the light wavelength is right at the photonic band-gap, the optical field thus could be trapped inside and close to the core. In another word, the core area just acts as a defect line inside the photonic crystal structure. However, for other wavelengths, the evanescent field is scattered continuously during propagation showing strong attenuation. As shown in Fig. 2**b**, the crystal structure is not very uniform, which

may further enhance the scattering and attenuation. Therefore, a transmission peak emerges, which coincides with the expected photonic band-gaps for 400, 590, and 710 nm-diameter colloidal crystals. The microfiber coated colloidal crystals are formed.

In order to affirm the structure's properties, we do a theoretical analysis of the structure. This structure can be divided into the core and cladding of the microfiber, and colloidal crystals close to the microfiber. The equivalent refractive index method is used to solve the coupling behavior between the microfiber and the colloidal crystals. The microfiber had a fixed transmission mode before the colloidal crystals cladded the optical fiber. Here, the colloidal crystals are decomposed into two dimensions, one direction (X) is parallel to the microfiber, and another direction (Y) is perpendicular to the microfiber (Fig. 1). The distribution of the refractive index is periodical in both directions. So, the colloidal crystals can be seen as a two-dimensional periodically corrugated waveguide. And then, the structure can be a simplified, symmetrical five-layer structure. The core of the microfiber is a central layer, the cladding of the microfiber is a middle layer, and the colloidal crystals are the outmost layer. The colloidal crystals can be treated as a perturbation unit to the microfiber.

We assume that the propagation constant of the microfiber is β_i, the refractive index of the core and the cladding are n_o and n_c, respectively. The colloidal crystals propagation constant is β_0, the effective refractive index is n_{avg}. The period of Λ (direction X and Y) is same, the length is L_X and L_Y. When the microfiber coupling with colloidal crystals occurs in the X direction, the incident and reflected coupling waves A and B satisfy the following formulas:

$$\frac{\mathrm{d}A}{\mathrm{d}x} = K_c B \exp(-2i\nabla\beta_x) \tag{1}$$

$$\frac{\mathrm{d}B}{\mathrm{d}x} = K_c^* A \exp(2i\nabla\beta_x) \tag{2}$$

$$\frac{\mathrm{d}^2A}{\mathrm{d}x^2} + i2\beta_x\frac{\mathrm{d}A}{\mathrm{d}x} - |K_c|^2 A = 0 \tag{3}$$

where K_c is the coupling coefficient. When the phase-matching condition is met, $\Delta\beta_x = \beta_i - \beta_0 = \beta_i - m\pi/\Lambda = 0$. Using the boundary conditions, we can obtain:

$$A(x) = B(0)\frac{K_c}{|K_c|}\frac{\sinh\left[|K_c| - (x-L)\right]}{\cosh\left(|K_c|L\right)} \tag{4}$$

$$B(x) = B(0)\frac{\cosh\left[|K_c|(x-L)\right]}{\cosh\left(|K_c|L\right)} \tag{5}$$

Equations (4) and (5) show that the coupling exists between the microfiber and colloidal crystals, and the coupled intensity is related to the coupling coefficient and the phase-matching condition. Therefore, we select the appropriate parameters of the colloidal crystals, and the colloidal crystals can modulate the evanescent field of the microfiber.

The band-gap wavelength of FCC photonic crystals can be estimated using a modified form of Bragg's law [15]

$$\lambda_{\max} = \frac{2d_{hkl}}{m} n_{\text{avg}} \tag{6}$$

where $\lambda_{\max}$ is the wavelength of the reflection peak (*i.e.*, the center wavelength of the photonic band-gap), d_{hkl} is the interplanar spacing between *hkl* planes, m is the order of the Bragg diffraction, n_{avg} is the average refractive index of the photonic structure. For silica colloidal photonic crystals in air at 25 °C, $n_{\text{avg}} = n_{\text{silica}} f_{\text{silica}} + n_{\text{air}} f_{\text{air}}$, where $n_{\text{silica}} = 1.450$, $n_{\text{air}} = 1.000$, f_{silica} and f_{air} are the volume fractions occupied by silica spheres and air in the structure (generally taken as 74% and 26%, respectively, for a FCC lattice). In the case of the first order Bragg diffraction from FCC [111] planes, $d_{hkl} = 0.8165D$, Eq. (6) is simplified to be

$$\lambda_{\max} = 1.633 D n_{\text{avg}} \tag{7}$$

where D is the silica microspheres diameter.

Substituting the quantity values into Eq. (7), the reflection peak wavelengths are obtained with $\lambda_{\max} = 870.7$, 1306, and 1545.5 nm, respectively. From Fig. 3, the experimental results agree well with our theoretical calculation. The minor errors of the band-gap wavelengths should come from the un-uniformity of the colloidal crystal structure. For example, the diameters of the colloidal spheres may have some variation; there might be some defects in the structure; and, sometimes, the colloidal crystal may form a body-centered cubic (BCC) structure rather than the expected FCC structure.

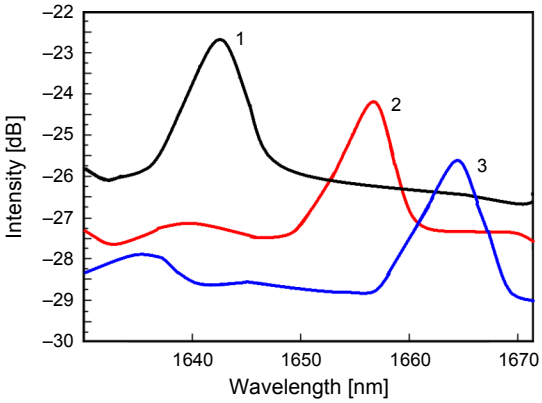

Fig. 4. Transmission spectra of a 710 nm colloidal crystal cladded microfiber immersed in water (curve 1), isopropanol (curve 2) and alcohol (curve 3).

In order to validate the colloidal crystal cladded microfiber, the sensing properties [16–18] are characterized based on 710 nm-diameter microspheres. The transmission spectra of the fiber immersed in water, isopropanol and ethanol are measured as shown in Fig. 4.

From the curves in Fig. 4, the band-gap of the colloidal crystals locates at 1643.5, 1657.4, and 1664.1 nm, respectively. An evident wavelength shift takes place, in comparison with the results obtained in the air. The corresponding environmental refractive indexes are calculated at 1.325, 1.371, and 1.393, respectively. These values agree well with the actual materials' parameters. The measured sensitivity is 302 nm/RIU (RIU – refractive index unit). The application of this structure in refractive index sensing is thus demonstrated.

4. Conclusions

We have designed and prepared colloidal crystal cladded microfibers with different parameters. The transmission properties are studied, showing that a colloidal crystal can modulate the microfiber's evanescent field through the photonic band-gap enhancement effect. The application of the structure in sensing is also demonstrated with a sensitivity of ~300 nm/RIU. Applications in chemical and biomedical areas thus are expected.

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