Magnetic field tunability of optical microfiber taper integrated with ferrofluid

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Abstract: Optical microfiber taper has unique propagation properties, which provides versatile waveguide structure to design the tunable photonic devices. In this paper, the S-tapered microfiber is fabricated by using simple fusion spicing. The spectral characteristics of microfiber taper integrated with ferrofluid under different magnetic-field intensities have been theoretically analyzed and experimentally demonstrated. The spectrum are both found to become highly magnetic-field-dependent. The results indicate the transmission and wavelength of the dips are adjustable by changing magnetic field intensity. The response of this device to the magnetic field intensity exhibits a Langvin function. Moreover, there is a linear relationship between the transmission loss and magnetic field intensity for a magnetic field intensity range of 25 to 200Oe, and the sensitivities as high as 0.13056dB/Oe and 0.056nm/Oe have been achieved, respectively. This suggests a potential application of this device as a tunable all-in-fiber photonic device, such as magneto-optic modulator, filter, and sensing element.

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1. Introduction

Optical microfiber tapers, due to their unique geometry with low dimension, large surface-to-volume ratio, and versatility for electrical and optical detection, have been attracting considerable attention in the areas of physical, chemical, and biological sensing [1–4]. At present, microfiber tapers can be fabricated in many different ways, including scanning flame, electric arc, and CO$_2$ illumination [5,6], which have exhibited excellent propagation properties. Related microfiber-based devices have been developed, including interference-based tapered fiber, gas detection, refractive index sensor, and so on [7, 8]. Due to the small dimension of the fiber and high fraction of the evanescent field, this kind of fibers is promising for high-sensitivity sensing with small footprint and fast response. It is significant to investigate a photonic device integrating the microfiber and functional material, considering the physical effect of functional material tuned by the surroundings, which results in high tunability of the microfibers.

On the basis of physical properties of functional materials, microfiber-based photonic devices integrated with functional materials have been widely studied [9, 10]. Recently, ferrofluid, namely magnetic fluid (MF), possessing tunable optical characteristics have attracted considerable research interest as a sensing material [11–14]. It is a stable colloidal suspension of ferromagnetic nanoparticles in certain suitable liquid carriers. The nanoparticles form chains along the magnetic field direction under external magnetic field. It has flexible optical properties, such as magneto-optical effect, tunable refractive index (RI), birefringence, magnetochromatics and nonlinear optical effect [15–18]. The unique optical characteristics of ferrofluid exhibit great potential in application as tunable photonic devices.
With the fast development of fiber photonics, the magneto-optic characteristics of ferrofluid, as an important physics phenomena and a way of controlling propagation properties, have been widely studied in the field of fiber optics [19]. Fiber-based devices have been proposed on the basis of its unique optical properties. For example, a sensor with high sensitivity was proposed by Zu with a MF film inserted into the Sagnac loop owing to the birefringence generated by the applied magnetic field [20]. The magnetic-field-dependent transmission loss was in Gao’s work [21], etc. From the present reports, the microstructure and mode field property of the optical fiber, as a key supporter of ferrofluid, affect the physical property of ferrofluid.

Micro-fiber tapers, on the basis of the modal Mach-Zehnder interferometer, possessing the advantages of simple structure, compactness, ease of fabrication, low cost, have become the subjects of numerous studies [22]. As an excellent modal interferometer, the S-tapered fiber interferometer was reported recently [23–26]. These studies indicate that the S-tapered fiber interferometer exhibits a high sensitivity to the external RI. Therefore, it is a good candidate for the ferrofluid to construct a fiber-based photonic device with high sensitivity. Owing to its above advantages, it will find potential applications in the area of magnetic field detection and tunable photonic devices.

In this paper, combining the evanescent field propagation property of microfiber tapers with tunable refractive index property of ferrofluid, we proposed a magnetic-field-tunable photonic device based on the S-tapered fiber and ferrofluid. The S-tapered fiber is simply fabricated by applying off-axis pull while tapering the fiber by a fusion splicer and then sealed with the ferrofluid. The transmission characteristics of the proposed device in response to the magnetic field intensity have been theoretically analyzed and experimentally investigated. The transmission and the interference wavelength can be tuned by changing the applied magnetic field intensity. This characteristic makes the device particularly attractive as sensing elements and telecommunication devices.

2. Principle and devices fabrication

The experimental setup for the magnetic field tunability test is shown in Fig. 1(a). It consists of a supercontinuum broadband source (SBS, wavelength ranges from 600nm to 1700nm), an optical spectrum analyzer (OSA: Yokogawa AQ6370C), a sensor probe, two electromagnets to generate the magnetic field (H) perpendicular to the fiber axis (i.e. the direction of the incident light electric field E) and a tunable voltage source (TVS) to tune the intensity of the external magnetic field. A Gauss meter is used to measure the intensity of the magnetic field with a resolution of 0.1Gs. The sensor head is fabricated by an S-tapered fiber immersing in the EMG605 (Ferrotec, Japan) carried by the capillary with two ends sealed with paraffin. The S-tapered fiber is fabricated by applying off-axis pull while tapering the single mode fiber (SMF) in a fusion splicer (FiTel S178A, Japan). The relative axial off-set is controlled by the manual operation of the fusion splicer clamps. The length and the width of the S-tapered fiber are controlled by the discharge current and time of the fusion splicer, respectively. Here, the parameters of this S-tapered fiber are L = 583.88μm, W = 65.50μm and Δd = 57.20μm.
Fig. 1. (a) Schematic diagram of the experimental setup for magnetic field tunability test; (b) optical microscopic image of the S-tapered fiber; (c) schematic diagram of the S-tapered fiber mode interference.

Figure 1(b) shows the microscopic image of S-taper fiber. The schematic diagram of the S-tapered fiber mode interference is presented in Fig. 1(c). When the incident light propagates into the tapered region, high-order modes are excited due to the perturbation in the front of S-tapered fiber. The fundamental mode and the high-order modes propagate in the fiber core and cladding, respectively. When the light propagates out of the tapered region, the high-order modes couple back and interfere with the fundamental mode. The transmission could be expressed as:

\[ I_{\text{out}}(\lambda) = I_f(\lambda) + I_h(\lambda) + 2\sqrt{I_f(\lambda)I_h(\lambda)} \cos(2\pi\Delta n_{\text{eff}}L / \lambda) \]  

where, \( I_f \) and \( I_h \) are the amplitudes of the fundamental mode and high-order modes, respectively. \( \Delta n_{\text{eff}} \) is the effective refractive index difference of the fundamental mode and the high-order modes. \( L \) is the length of the S-tapered region. The minima of the spectrum appear at the following wavelengths:

\[ \lambda_{\nu} = \frac{2\Delta n_{\text{eff}}L}{2N+1} \]  

where, \( N \) is integer.

The transmission could be written as:
\[ I_{\text{min}}(\lambda_n) = \sqrt{I_j(\lambda_n) - I_k(\lambda_n)}^2 \]  
\[ I_j(\lambda_n) = \kappa_{f-j}^2 I_{\text{in}}(\lambda_n) \]  
\[ I_k(\lambda_n) = \kappa_{f-k}^2 I_{\text{in}}(\lambda_n) \]  
\[ I_{\text{min}}(\lambda_n) = [\kappa_{f-j} - \kappa_{f-k}]^2 I_{\text{in}}(\lambda_n) \]  

where, \( \kappa_{f,f} \) is the self-coupling efficiency and \( \kappa_{f,h} \) is the coupling efficiency of the fundamental mode to the high-order mode:

\[ \kappa_{f-h} = \frac{\alpha}{4} \iint \left| E_f(x,y) \Delta \varepsilon(x,y) E_h(x,y) \right|^2 dx dy \]

where, \( \Delta \varepsilon \) is the change of dielectric constant, which is depended on the effective refractive index difference between the core and cladding modes (\( \Delta n_{\text{eff}} \)); \( E_f(x,y) \) is the field profile of the modes involved in the mode coupling process. The effective refractive index of cladding mode could be tuned by the external refractive index. As a result, \( \Delta n_{\text{eff}} \) and \( \kappa_{f,h} \) will change accordingly. The wavelength shift and intensity variation is observable according to Eqs. (2) and (6). Therefore, it is potential to effectively tune the propagation properties by integrating the tapered fiber with functional materials. The spectra of the S-tapered fiber before and after immersing into the ferrofluid are presented in Fig. 2. Based on the coupling between the core mode and high-order mode, red shift of the interference fringes could be observed due to the positive change of \( \Delta n_{\text{eff}} \) with the SRI increasing when the S-tapered section is immersed into ferrofluid [26, 27]. \( I_{\text{min}} \) will also increase with the variation of \( \kappa_{f,h} \).

3. Experimental results and discussion

During the measurement of the magnetic field intensity, both two ends of the sensor head are held straight and fixed by the fiber holder to prevent the influence of strain. A Gauss meter is used to measure the magnetic field intensity as a reference value. By adjusting the tunable voltage source, different magnetic field intensities are applied. The transmission characteristics of the S-tapered fiber are given in Fig. 3.

![Fig. 3. Transmission spectral responses to the magnetic field intensity.](image)

As shown in Fig. 3, the blue shift of the wavelength and the increasing transmission are observed with the increment of magnetic field intensity. It is because the refractive index of external ferrofluid is tuned by the magnetic field intensity. The magnetic particles in the ferrofluid will form column patterns when the field is applied. As a result, the phase separation, which occurs in ferrofluid under external magnetic fields, results in the variation of the refractive index [28]. Since the refractive index of the ferrofluid \( n = \sqrt{\varepsilon} = \sqrt{1 + \chi} \), the electric susceptibility \( \chi \) of ferrofluids is related to the intensity of the magnetic field and the
relative orientation between the electric field $E$ and magnetic field $H$ as well. $\chi$ decreases with the increase of the magnetic field intensity when $E$ is perpendicular to $H$; $\chi$ increases with the increment of the magnetic field intensity while $E$ is parallel to $H$ [17]. Here, the external magnetic field $H$ is applied along the perpendicular direction while the optical electric field $E$ is applied along the fiber axis. Therefore, with the increment of external magnetic-field intensity, the refractive indices of ferrofluid will decrease according to the relative orientation between the electric field $E$ of the light source and $H$. Considering Eqs. (3) and (7), $\Delta n_{\text{eff}}$, $\kappa_{f-f}$ and $\kappa_{f-h}$ will change with the decrease of refractive index. For the high-order mode case, the transmission spectrum will shift toward short wavelength region. These experimental results are in good accordance with the above theoretical analysis.

With the wavelength shift, the transmission loss changes gradually with the variation of the applied magnetic field intensity. Here, Dip A and B are selected to analyze the tunability of S-tapered fiber and the spectral response to the magnetic field intensity. The relationship between the wavelength of dip A/B and magnetic field intensity is given in Fig. 4. It can be found that the wavelengths of the dip A and B experience some blue shift by about 10nm as the magnetic field intensity increases to 500Oe. From the Eq. (2), the relationship between the resonance wavelength and refractive index is linear. However, the refractive index of ferrofluid and magnetic field satisfy the Langvin function [29]. Therefore, the curves in Fig. 4 indicate that the wavelength shifts exhibit a nonlinear behavior. The wavelengths corresponding to coherent cancellation decrease with the increment of magnetic field intensity until the magnetic field intensity increase to a saturated value of 200Oe, beyond which the resonance wavelength tends to stand still. There are two sensitive regions according to the resonant wavelengths for different applied magnetic field intensities. When the magnetic field intensity is less than 200Oe, the magnetic field is more sensitive with linear relationship, A: $y = 1437.9-0.042x$, $R^2 = 0.972$; B: $y = 1564.8-0.057x$, $R^2 = 0.98$. The slope coefficients are about 0.042nm/Oe and 0.056nm/Oe, respectively. When the magnetic field intensity is larger than 200Oe, the resonant wavelength shift also becomes slow as the refractive index of magnetic fluid gets saturated. Therefore, the magnetic field sensitivity could achieve 0.042nm/Oe and 0.057 nm/Oe for the low magnetic field intensity range, respectively.

![Fig. 4. Wavelength shift of the transmission spectrum with the variation of the magnetic-field intensity: (a) dip A; (b) dip B.](image)

Figure 5 shows the transmission responses of dip A and B to the applied magnetic field intensity. These responses exhibit nonlinear behaviors similar to the Langvin function as described in [27]. The transmission losses increase from $-47.559\text{dB}$ to $-30.522\text{dB}$ for dip A, and from $-44.233\text{dB}$ to $-28.211\text{dB}$ for dip B with the increment of magnetic field intensity from 0Oe to 500Oe, respectively. Due to the initial magnetization, the transmission losses change slightly with the magnetic field intensity below 250Oe. The transmission losses tend to be constant for the magnetic field intensity range beyond the saturation value of 200Oe. Thus, the measurement range of the S-tapered fiber covers a magnetic intensity range of 25Oe to 500Oe.
200Oe. For the range from 25Oe to 125Oe, the experiment data could be linearly fitted with the coefficients of determinations of 0.99901 for dip A and 0.99922 for dip B, respectively, and the sensitivities as high as 0.13056dB/Oe and 0.056nm/Oe have been achieved respectively. Therefore, the spectral property of S-tapered fiber could be effectively tuned by the applied magnetic field intensity, and in other words, it could be exploited in developing the magnetic tunable devices based on the S-tapered fiber, such as high sensitivity magnetic sensors and magnetic-controlled optical filters. Moreover, the experimentally acquired sensitivity could be further optimized by choosing appropriate structure parameters of the tapered fiber.

Fig. 5. Transmission responses of dip A (black) and dip B (red).

4. Conclusion

In conclusion, the transmission characteristics of the S-tapered fiber in response to the magnetic field intensity have been investigated from an experimental as well as theoretical perspective. The results show that both of the transmission loss and the interference wavelength are adjustable by changing the magnetic field intensity. Due to the high sensitivity of the S-tapered fiber to the external refractive index, the magnetic sensitivities as high as 0.13056dB/Oe and 0.056nm/Oe have been achieved, respectively. It suggests the potential application of this device as the tunable all-in-fiber photonic devices, such as filters and all-optical switching. Considering the large number of available magnetically tunable ferrofluid and the flexible design of micro-fibers, micro-fiber-integrated-ferrofluid-based photonic devices would provide promising and underexplored possibilities for both fundamental and applied studies paving new perspectives in optical telecommunication and fiber-optic sensing applications. The proposed method possesses several advantages, including compact size, low cost, high sensitivity, good integrated level, flexible maneuverability, etc. It is expected that the ferrofluid can be widely applied in tunable photonic devices.

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