Tunable magneto-optical wavelength filter of long-period fiber grating with magnetic fluids

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In this paper, the authors propose a magneto-optical tunable filter based on a long-period fiber grating (LPG) coated with magnetic fluids (MFs) as the ambient media. By applying a tunable magnetic field, the center wavelength shift of the attenuation band of LPG is found as large as 7.4 nm. The refractive index dependence of MF on the external magnetic intensity is measured and the simulation results show that it is well agreeable with the experimental observations. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2787970]

In-line tunable fiber-optic filters have important applications in optical communications and optical signal processing systems. The central attenuation wavelength of the long-period fiber grating (LPG) is highly sensitive to the ambient refractive index change[1–3] and, therefore, can be tuned by modulating the ambient refractive index via methods, such as thermo-optical,[4] electro-optical,[5] or magneto-optical effects. In recent years, many studies on the thermo-optical and electro-optical tunable filters have been carried out.[4–7] Up to date, there are few reports on the fiber-optic filters tuned by magneto-optical effect.

Magnetic fluid (MF) is a kind of homogeneous colloidal dispersion of ferromagnetic nanoparticles in a suitable liquid carrier.[8] Because the behaviors of ferromagnetic particles in MF are dependent on the external magnetic field, MF exhibits remarkable magneto-optical properties[9] and the refractive index of MF films is shown to be magnetic field dependent.[10–12] In this paper, tunable optical filter based on LPG by coating MF as the ambient medium is achieved by external applied magnetic field. In order to explain the experimental observations quantitatively, the field-dependent refractive indices of MF in bulk are investigated experimentally.

The magneto-optical tunable filter we proposed is based on the tuning of the coupling between the core mode and the cladding modes in the LPG through applying magnetic field on the MF, which is coated on the LPG as shown in Fig. 1. The LPG is fed through a capillary and then the MF is infused into the capillary. The external magnetic field is applied perpendicularly to the LPG at the region where MF stays.

The coupling between the core mode and copropagation cladding modes in LPG acts as spectral loss selection. The center wavelength λ_i of the ith attenuation band is given by the following phase matching condition between the core and cladding modes:

$$\lambda_i = (n_{co} - n_{cl}^i)\Lambda, \tag{1}$$

where n_{co} and n_{cl}^i are the effective indices of the core mode and the ith cladding mode, respectively. Λ is the grating period.[13] The refractive index sensitivity of LPG arises from the dependence of the effective refractive indices of the cladding modes upon the ambient refractive index. As the ambient index approaches the index of LPG cladding, the sensitivity of LPG increases sharply.[2,3] Thus by changing the refractive index of MF through the magneto-optical effect, the center wavelengths of the attenuation bands of LPG can be tuned correspondingly.

In our experiment, the LPG is fabricated using CO_2 laser irradiation on Corning SMF28 fibers, with the grating period of 400 μm, the grating region of 24 mm, and the center wavelength at 1540.5 nm in air. Water-based Fe_3O_4 magnetic fluids with the density of 1.2 g/ml are used as the ambient media. An amplified spontaneous emission light is used as the source. While the magnetic intensity applied perpendicularly on the LPG increases from 0 to 1661 Oe, the attenuation bands of LPG shift toward longer wavelengths. The transmission spectra are recorded by an optical spectrum analyzer with the precision of 0.1 nm. The measured spectra under different magnetic intensities are illustrated in Fig. 2.

Without external magnetic field, the center wavelength of the attenuation band after being coated with MF is 1524.8 nm. There is an about 15.7 nm shift in comparison with the one before coating. As the applied magnetic intensity increases, there are redshifts in the transmission spectra and the maximum center wavelength shift of 7.4 nm is achieved for an external magnetic intensity of 1661 Oe. The changing in depth of the attenuation band under different

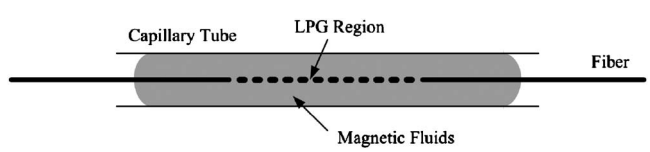

FIG. 1. Diagram of the magneto-optical tunable filter.

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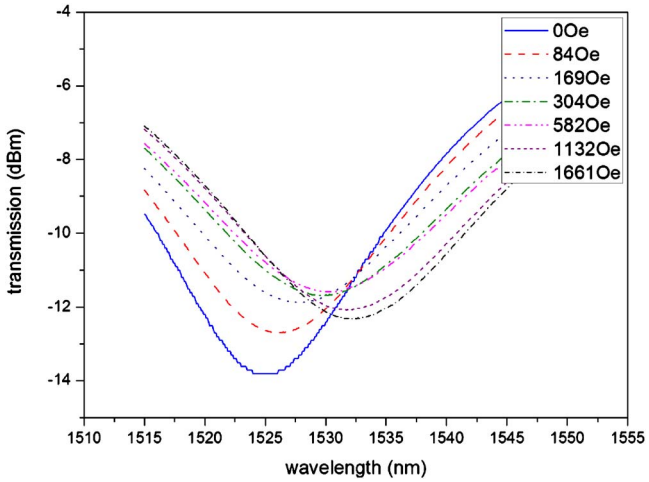

FIG. 2. (Color online) Transmission spectra of the magneto-optical tunable filter based on long-period fiber gratings and magnetic fluids.

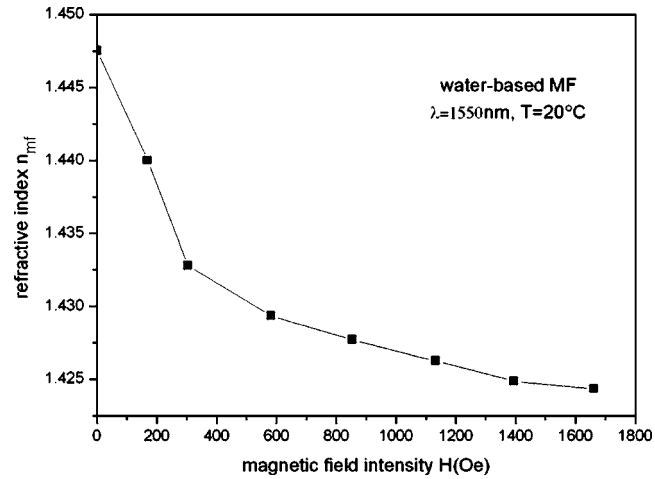

FIG. 4. Dependence of refractive indices of MF in bulk on the external magnetic field.

magnetic fields is attributed to the differences in absorption of the MF under applied magnetic field.

In our experiment, it is observed that the attenuation bands of LPG shift toward longer wavelengths with the increase of the applied magnetic field, which implies that the index of the surrounded MF decrease with the applied magnetic field according to the LPG coupling theory. The magnetically tunable refractive index of MF films has been measured by total reflection method,[10–12] their study shows that the index increase when the applied magnetic field becomes stronger. In order to clarify our experimental observations, it is necessary to measure the field-dependent refractive index of MF in bulk. Figure 3 shows the schematic diagram of the experiment setup with an efficient method developed by Pu *et al.*[14]

The magnetic fields of variable intensity are applied on MF by an electromagnet. The operation wavelength is 1550 nm and the room temperature is 20 °C. The refractive indices of air, water, and the fiber core are $n_{air}=1.0003$, $n_{water}=1.3330$, $n_{fc}=1.46$, respectively. The detecting tip is immersed into air, water, and MF under magnetic fields of different intensities and the power of the reflected light is measured under each condition. Using the experimental data, the field-dependent refractive indices of MF can be calculated[14] as shown in Fig. 4.

From Fig. 4, we can see that the refractive indices of MF in bulk decrease significantly while the magnetic intensity increases from 0 to 1400 Oe and tends to saturate in the high intensity range. Under our experimental conditions, the magnetic field range is between 0 and 1661 Oe, which means that the ambient indices of LPG change from 1.4244 to 1.4475, making the attenuation bands of LPG shift.

With the refractive index data from our measurements, we calculated the center wavelength shifts theoretically,[15] as shown in Fig. 5. It can be seen that the experimental results are in good agreement with the theoretical results.

Our experiments show that the refractive indices of MF in bulk decreases while the magnetic intensity increases, which seems in contradiction with the results of the study by Yang *et al.*[10–12] The contradiction can be attributed to the magnetoelectric directive effect of ferrofluid.[16] The electric susceptibility χ of ferrofluids is dependent on the magnitude of the magnetic field and on the relative direction between the electric field E and magnetic field H. When E is perpendicular to H, χ decreases with the increasing magnetic field, and when E is parallel to H, χ increases with the increasing magnetic field. Since the refractive index $n=\sqrt{\varepsilon_r}=\sqrt{1+\chi}$, the changing tendency of the refractive indices of MF with the increasing external magnetic field will be dependent on the relative direction between the electric field E of the light source and H. Thus the magnetic field-dependent refractive indices of MF are susceptible to the polarization of the light

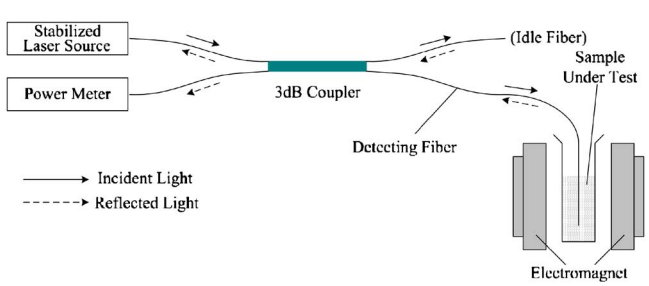

FIG. 3. (Color online) Schematic diagram of experimental setup for measuring the field-dependent refractive index of MF in bulk.

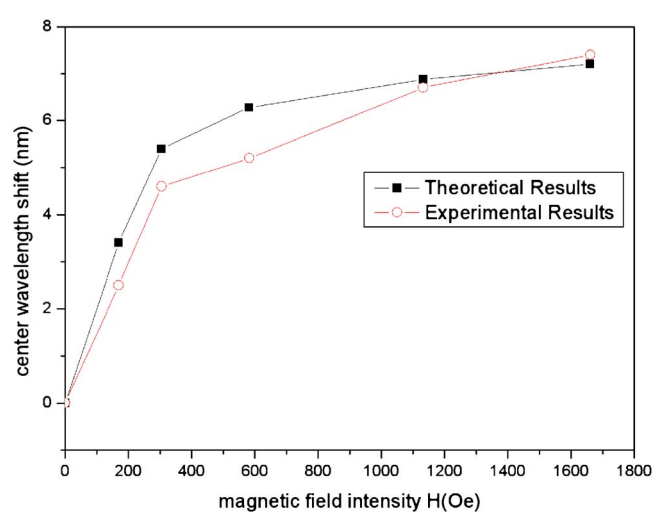

FIG. 5. (Color online) Theoretical and experimental center wavelength shift dependence on external magnetic field.

source, which may lead to the contradictions between our results and the results by Yang *et al.*

It is worthy to mention that the tuning range of the proposed magneto-optical tunable filters can be enlarged through more carefully choosing of magnetic nanoparticles and the carriers of MF to closely match the refractive index with that of the fiber cladding.

In conclusion, based on the long-period fiber grating and the magneto-optical effect of magnetic fluids, we proposed and implemented a magneto-optical tunable filter. The center wavelength shift with the external magnetic field was experimentally observed and the results are in good agreement with the theoretical calculation by the measured data of magnetic field-dependent refractive indices of MF. A tuning range of 7.4 nm is achieved and it can be improved by carefully choosing the magnetic nanoparticles and the carriers of MF.

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