Novel optical fiber current sensor based on magnetic fluid

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A novel fiber optic Fabry-Perot (F-P) current sensor is developed based on magnetic fluid as the medium in F-P interference cavity. A signal demodulation method based on slanted fiber Bragg grating (FBG) wavelength measurement system is proposed. Theory and principle of electromagnetic-controlled refractive index of the magnetic fluid is described, as well as the structure of the sensor system. Preliminary experiments are carried out, and the results indicate that there is a fairly good linearity of the measurement characteristic. The thickness of magnetic fluid film and initial concentration will affect the measurement results.

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The traditional current measurement method is basically based on electromagnetic current transformers. But this method has some problems: when there is something wrong with the electric network, surge current will make the magnetic circuit of transformers be saturated; those current transformers with high voltages have the shortcomings of defective insulation, large size, and high cost; and it is dangerous to use oil as the insulating and heat-transfer medium. So, non-electromagnetic method for high voltage and high current measurement such as optical current transformers based on the polarized light detecting and processing technology has been proposed. But it needs a complex polarization-maintaining system.

Magnetic fluid is a special kind of nano functional material[1], which shows controllable rheological characteristics under the applied electromagnetic field. Magnetic fluid sensor is one of its important applications, such as the magnetic fluid tilt sensor[2−4], the sensor for very low gas flow rate measurement[5], and the capacitive transducer[6].

It is discovered that the magnetic-particle will be clustered when the applied electromagnetic field is increased to a certain value, resulting in the variation of the magnetic fluid refractive index. In this letter, based on the characteristic of controllable refractive index of magnetic fluid[7], a novel fiber optic electromagnetic sensor is proposed using fiber optic Fabry-Perot (F-P) resonant cavity as the sensing element and the slanted fiber Bragg grating (FBG) wavelength measurement system for signal demodulation.

If the applied magnetic field is perpendicular to the magnetic fluid film (MFF) whose thickness is about 10 μm, weakly flocculated structures in the magnetic fluid will increase with the increment of the applied magnetic field. The above physical process will lead to the change of the equivalent dielectric constant of the magnetic fluid system, and so will the variation of the refractive index. After the phase disengagement of the magnetic fluid, the height of the magnetic-column is the same with that of the MFF[8], so MFF system can be regarded as a two-dimensional two-phase system. Based on the earlier classical equivalent dielectric constant calculation method[9], the magnetic fluid equivalent dielectric constant ε_{M} can be described as

$$\varepsilon_{\mathrm{M}} = \Big\{ -\varepsilon_{\mathrm{col}}(1-f) - \varepsilon_{\mathrm{flu}}(f-1) + \sqrt{[\varepsilon_{\mathrm{col}}(1-f)+\varepsilon_{\mathrm{flu}}(f-1)]^2 + 4(1+f)^2\varepsilon_{\mathrm{col}}\varepsilon_{\mathrm{flu}}} \Big\} \Big/ [2(1+f)], \tag{1}$$

where $\varepsilon_{\mathrm{col}}$ is the dielectric constant of the magnetic-column, which is independent of external field; $\varepsilon_{\mathrm{flu}}$ is the dielectric constant of the fluid phase, which is related to the initial concentration, M_{s}, of the magnetic fluid, $\varepsilon_{\mathrm{flu}} = (0.1573M_{\mathrm{s}} + 1.3283)^2$; f is defined as $f = (A_{\mathrm{col}}/A)/(1 - A_{\mathrm{col}}/A)$, where A_{col} is the magnetic-column area in the given area A of the MFF.

According to the definition of the magnetic fluid refractive index $n_{\mathrm{M}} = \sqrt{\varepsilon_{\mathrm{M}}}$, the characteristic curve of n_{M} versus the applied magnetic-field intensity H can be obtained by experiments, as shown in Fig. 1[1].

The tunable fiber F-P filter is a multi-beam interference cavity, through which the light with a certain wavelength λ can pass, and this pass-band can be tuned by changing the length of the interference cavity or the refractive index of the medium in the interference cavity. Thus, if the magnetic fluid is used as the medium in the interference cavity, when the applied magnetic-field is changed, the refractive index of the magnetic fluid in the interference cavity will be changed as well, resulting in the output wavelength of the fiber F-P filter. Further, a kind of wavelength demodulation system can be used to measure the output wavelength of the fiber F-P filter. Then the magnetic-field measurement can be implemented. The sensor system is shown in Fig. 2.

In the experimental system, the output light power of the broad-band source (BBS) is 20 mW. After passing through the F-P filter, light with a certain wavelength will be demodulated by a slanted FBG wavelength measurement system. The input light with a certain

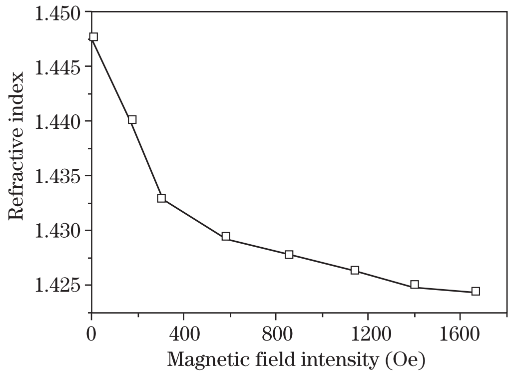

Fig. 1. Relationship between the magnetic fluid refractive index and the applied magnetic-field intensity. Wavelength $\lambda = 1550$ nm, temperature $T = 20$ °C.

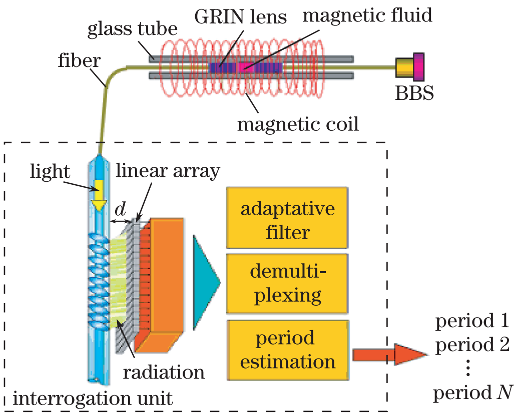

Fig. 2. Structure of the sensor and the wavelength measurement system.

wavelength from the F-P filter is led into the slanted FBG. The radiation from the slanted FBG with a certain angle will be captured by the optoelectronic linear array. If the output wavelength from the F-P filter changes, the angle of the radiation will change as well, and thus the light spot position on the optoelectronic linear array will vary[10]. If we can measure this light spot position variation, the output wavelength, that is, the measured magnetic field will be detected. The F-P resonant cavity of the filter is composed of a pair of coated gradient index (GRIN) lenses, the space between which is filled with magnetic fluid. The F-P cavity and the magnetic fluid cell are mounted in a capillary glass tube.

The sensor signal from the F-P filter is coupled into a coupler and then transmitted to a slanted FBG, which is placed parallel to a photodetector linear array. As all the measurements are carried out in the near-field region, the distance between these two elements is only a few millimeters (typically 4–5 mm). This fact ensures the compactness of the design since the main constituents of the system can be packed into a very small space. The operating principle relies on the widely known fact that slanted FBGs are able to extract light to the outer medium in a very wide wavelength range, provided the tilt angle is high enough. Therefore, with the slanted FBG and the photodetector linear array arranged in the way described above, the light radiated by the former can be captured by the array. Thus, since the characteristics of that radiation are highly wavelength dependent, the Bragg wavelengths reflected by the gratings can be recovered by analyzing several parameters of the image obtained by the linear array, namely its shape and position. Therefore, the measurement process can be described as follows. The varied measured magnetic field will lead to the variation of the output wavelength of the fiber F-P filter sensor. The position of the light spot radiated by slanted FBG and detected by the photodetector linear array is corresponding to the output wavelength of the fiber F-P filter sensor. Each position of light spot radiated by the slanted FBG will correspond to a certain magnetic field, thus the measured magnetic field can be obtained by recording the output wavelength of the fiber F-P filter sensor.

To verify the feasibility of the proposed idea, preliminary experiments were carried out. An amplified spontaneous emission (ASE) light source was used as the BBS, which had the wavelength range from 1525 to 1565 nm and the output light power of 23 mW. The turn number of the magnetic coil was 100, the internal diameter was 10 mm, and the length was 60 mm. The length of the fiber F-P cavity was 12.7 μm. Figure 3 shows the picture of the fiber F-P filter.

Based on the research results shown in Fig. 4 and Table 1, the characteristics are different for different initial concentrations and thicknesses of the magnetic liquid film. The thickness of the liquid film was changed by adjusting the length of the F-P cavity under a microscope. When the initial concentration of the magnetic liquid is low, the linearity of the characteristics is not very good, as shown in Fig. 4(a). And as the thickness increases (12, 85, and 195 μm), the linearity between the refractive index variation and the measured magnetic field within a certain measurement range will become worse and worse. Figure 5 shows the relationship between the output wavelength of the fiber F-P filter sensor and the measured magnetic field. In the experiments, the thickness of MFF was 11.8 μm and the initial concentration was 0.39 emu/g (emu is the electromagnetic unit).

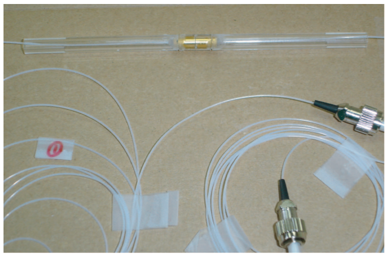

Fig. 3. Picture of the fiber F-P filter.

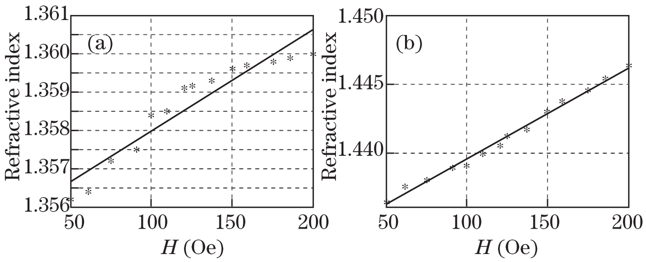

Fig. 4. Characteristics of refractive index variation versus the measured magnetic field of the filter with different initial concentrations: (a) 0.17 emu/g; (b) 0.68 emu/g.

Table 1. Experimental Data of the Field Dependent Refractive Index under Various Thicknesses

H (Oe)	n (12 μm)	n (85 μm)	n (195 μm)
50.0	1.4626	1.4644	1.4689
61.4	1.4627	1.4654	1.4710
75.0	1.4630	1.4669	1.4739
90.9	1.4635	1.4685	1.4768
100.0	1.4638	1.4696	1.4785
109.3	1.4641	1.4707	1.4801
120.5	1.4644	1.4718	1.4817
125.0	1.4648	1.4723	1.4823
137.3	1.4651	1.4735	1.4834
150.0	1.4654	1.4744	1.4841
159.1	1.4659	1.4748	1.4844
175.0	1.4661	1.4754	1.4849
185.6	1.4663	1.4756	1.4852
200.0	1.4664	1.4759	1.4853

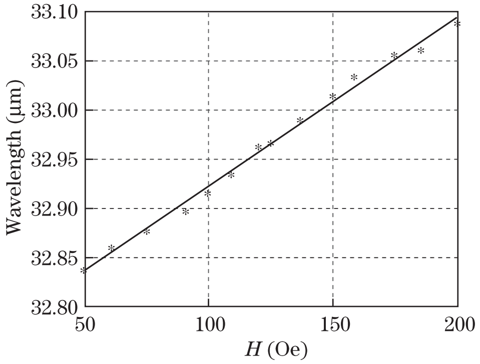

Fig. 5. Output wavelength of the fiber filter sensor versus the measured magnetic field. $M_s = 0.39$ emu/g.

In conclusion, a novel magnetic measurement method is proposed. The fiber F-P filter is used with the magnetic fluid being the medium in the resonant cavity of the filter. Based on the magnetic-field-controlled refractive index characteristics of the magnetic fluid, the magnetic field can be recorded by measuring the output wavelength of the fiber F-P filter sensor. The wavelength demodulation method for the output wavelength of the fiber F-P filter sensor is also introduced. Preliminary experimental results indicate the feasibility of the proposed idea.

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