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Fiber-optic evanescent field modulator using a magnetic fluid as the cladding

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A kind of fiber-optic modulation-depth-tunable modulator is developed in this paper. In this modulator, a magnetic fluid is used as the cladding of the drawn fiber, which attenuates the evanescent field when the light is guided in the fiber. Because the attenuation depends on the strength of the applied external magnetic field, the emergent light intensity from the fiber is modulated with the change of the magnetic field strength. The response times, i.e., the span for the light intensity to reach the final steady value from the time when the magnetic field is turned on or off, are evaluated quantitatively. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2195016]

I. INTRODUCTION

Evanescent field is attractive in the field of optical sensing owing to its high sensitivity. In particular, evanescent-field-based optical fiber sensor has been investigated extensively in the past years. The fiber of the sensor is used as both optical transmission line and sensing arm, and then the all-fiber sensor can be constructed.[1–4] This kind of sensor may have the advantages over conventional one, e.g., more sensitive, on-line analysis, geometrical versatility, remote monitoring, etc. There are two methods to fabricate the sensing fiber. One is to strip the cladding of the fiber and the other is to draw the fiber to be thin in diameter (usually from tens or hundreds of nanometers to tens of micrometers). After these treatments, more guided light in the fiber will penetrate outside the fiber and becomes evanescent field for sensing. It is well known that the higher the fraction of the guided energy as evanescent field, the more sensitive the sensor is.[5] So the techniques about drawing fiber to be subwavelength in diameter have been developed recently and they have been used for microphotonic integration and biological analysis.[6–9]

Magnetic fluid (MF) is a kind of homogeneous colloidal dispersion of very fine magnetic nanoparticles (usually 3–15 nm in diameter) in a suitable liquid carrier with the aid of a molecular layer of surfactant coated on the surface of the particles, which will prevent the particles from sticking to each other due to van der Waals attraction. The sizes of the magnetic particles are so small that the thermal energies are comparable to their gravitational forces, and then the sedimentations are avoided. MF has been applied to dynamic sealing, damping, cooling in audio speakers, and drug delivery in medicine successfully and broadly.[10] The optical properties of MF have been emphasized since the late part of the 20th century.[11–15] Nowadays, with the dramatic progress of integrated optics, photonic devices, and the studying about the optical properties of MF, MF receives a lot of interest and the potential applications to optical devices based on MF have been proposed in laboratory by some researchers.[16–18] Lately, Horng *et al.* have used the MF to design an optical fiber modulator successfully.[19] In their modulator, they use a bare fiber core (the cladding is etched away) surrounded by a MF, and the refractive index of the MF is slightly smaller than the fiber core at zero magnetic field. It has been found that the refractive index of the MF is proportional to the strength of the external magnetic field.[20] So it is easy to control the occurrence of total reflection at the interface between the fiber core and the MF when the light is guided in the fiber. Thus the intensity of the outgoing light can be modulated by varying the strength of the applied magnetic field. In their design, it is vital to select the proper concentration of the MF to make its refractive index slightly smaller than that of the fiber core. In this work, we will develop another kind of MF-based modulator, whose modulation depth can be tuned by changing the strength of the applied magnetic field.

II. OPERATING PRINCIPLE

The modulator we fabricate in this paper is based on the modulation of the evanescent field of the guided light in the optical fiber through applying magnetic field on the MF, which encloses the fiber as shown in Fig. 1. When the light is guided in the standard single-mode optical fiber, there is no evanescent field outside the cladding of the fiber. In order to make an evanescent-field-based modulator, a fiber with thin diameter should be employed because in this case more evanescent field is outside the fiber. We heat a part of the single-mode fiber and draw it to make it thin in diameter. The length of the heated part is about 1.5 cm and its diameter is almost uniform at last (about 19.3 μm in this experiment), which becomes the waist region of the drawn fiber. Two

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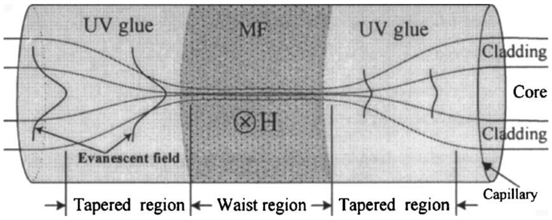

FIG. 1. Diagrammatic sketch of the operating principle of the fiber-optic evanescent field modulator using a MF as the cladding.

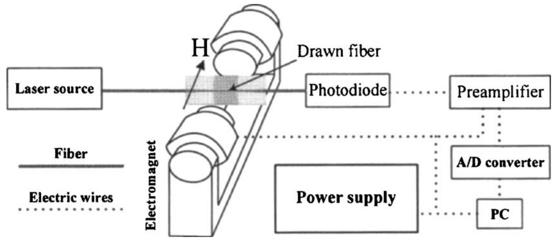

FIG. 2. Schematic diagram of the experimental setup for investigating the properties of the modulator. The solid and dashed lines represent the fiber and the electric wires, respectively.

tapered regions are formed at each side of the waist region (see Fig. 1). The drawn fiber is fed through a capillary. The UV glue is used at one end of the capillary (where the tapered region stays) to fix the drawn fiber in the center of the capillary, and then the MF is infused into the capillary (where the waist region stays). Finally, the UV glue is used again at the other end of the capillary (where another tapered region stays) to fix the drawn fiber and seal the MF inside the capillary. The external magnetic field is applied at the waist region (where the MF stays) and perpendicular to the optical fiber.

When the guided lights reach some point at the tapered region, a part of light will leave the fiber and extend into the region outside the fiber (called evanescent field) as shown in Fig. 1. The lights continuously go forward until the waist region, where higher fraction of guided light as evanescent field exists. The magnetic particles and their aggregations (when a proper external magnetic field is applied) in the MF in this region will attenuate the intensity of the evanescent field due to absorption, scattering, and decrease of the optical transmission. Meanwhile, the degree of attenuation can be tuned by changing the strength of the applied magnetic field. The reason is that when the external magnetic field is applied over certain critical value, agglomerations will be formed within the MF.[21] This will raise the absorption and scattering coefficients of the MF (Ref. 22) and decrease the optical transmission of evanescent field through MF.[23] So the total emergent light intensity can be modulated by changing the strength of the applied external magnetic field. Quantitatively, the loss of the incident light passing through the modulator can be given by[1]

$$P_H = P_0 \exp(-r\alpha L), \tag{1}$$

where P_H and P_0 are the transmitted powers in the presence and absence of the magnetic field, respectively; r is the ratio of the power of the evanescent field to that of the total propagating field; α is the extinction coefficient of the MF; and L is the length of the MF in the capillary along the optical axis. From Eq. (1), we know that there are three parameters (r, α, and L) we can use to tune the transmitted power, i.e., the modulation depth of the modulator. In general, the diameter and length of the fiber are fixed for a given drawn fiber. But the extinction coefficient (α) of the MF can be tuned by applying an external magnetic field, so the modulation-depth-tunable modulator can be constructed when using MF to attenuate the evanescent field of the drawn fiber. Moreover, increasing the length and thinning the diameter of the waist region of the drawn fiber will enhance the values of L and r, and then the modulation depth of the modulator will be raised.

III. EXPERIMENTAL DETAILS

The MF we use to make the modulator in this paper is water-based magnetite MF with volume fraction of 2%, which is commercially available. The average diameter of the magnetic particles is about 10 nm. The refractive index of the MF is about 1.3458 at 1550 nm,[24] which is much smaller than that of the fiber (the refractive index of the fiber is around 1.46). The increase of the refractive index of the MF due to applying an external magnetic field is much smaller than the index difference between the fiber and the MF.[20] So the condition of total reflection is always satisfactory at the interface between the fiber and the MF through our experiment. Figure 2 shows the schematic diagram of the experimental setup for investigating the properties of the modulator. One end of the drawn fiber is connected to the laser source emitting a wavelength of 1550 nm, and the other end is connected to the photodiode. The waist region of the drawn fiber is placed in the middle of the poles of the electromagnet, which generates a uniform magnetic field in the waist region of the drawn fiber. The strength of the magnetic field is adjusted by tuning the magnitude of the supply current. The light intensities passing through the drawn fiber are detected by the photodiode and the electric signals of the photodiode are amplified by the preamplifier. Then, they are recorded by the personal computer via an analog-to-digital converter.

IV. RESULTS AND DISCUSSION

When the magnetic field is applied, the intensity of the light passing through the modulator will decrease. The larger the strength of the magnetic field, the smaller the transmitted light intensity is. Figure 3 displays the modulation property of the modulator at different magnetic field strengths: (a) 98, (b) 380, (c) 766, and (d) 858 Oe. The transmissivity in Fig. 3 is defined as $[(P_H - P_0)/P_0] \times 100\%$. We can see from Fig. 3 that the modulation depth (equals the negative value of the transmissivity) of the modulator increases with the applied magnetic field strength. When the strength of the magnetic field is low, the modulation property is not obvious, while the modulation depth tends to saturate in the high field range. We assign the operating principle of the modulator to the attenuation of the evanescent field by the MF when the external magnetic field is applied, and the attenuation is attributed to

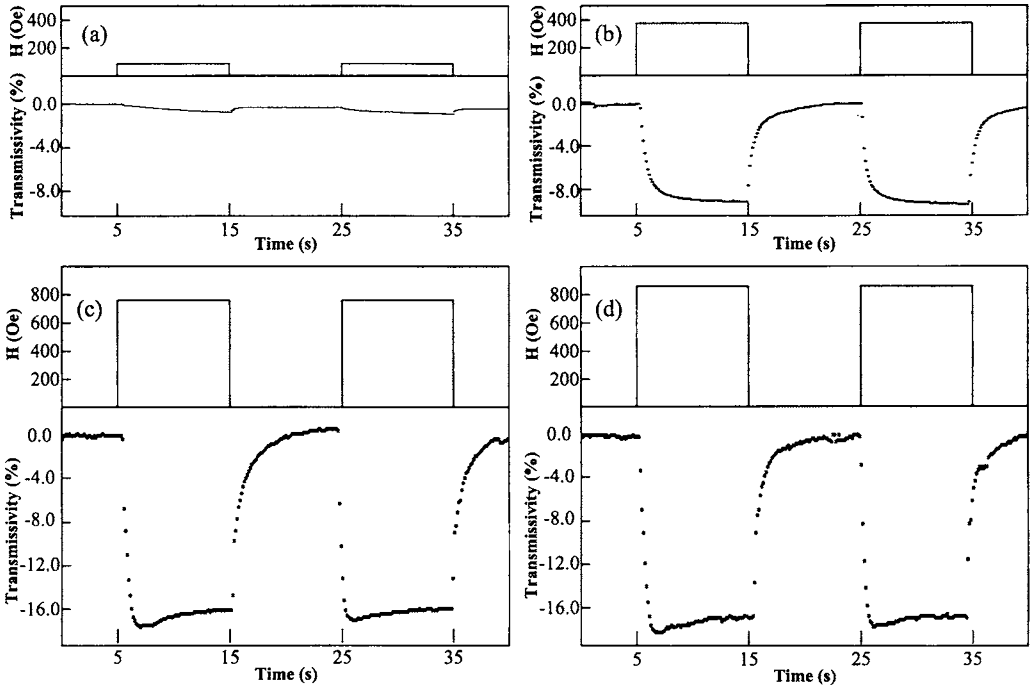

FIG. 3. Modulation properties of the modulator at different magnetic field strengths: (a) 98, (b) 380, (c) 766, and (d) 858 Oe.

absorption, scattering, and decrease of the optical transmission of the evanescent field. When the external magnetic field is applied over some critical value, the magnetic particles in the MF will agglomerate to form chains. The chains in MF will increase the absorption and scattering of the evanescent field. Furthermore, the larger the magnetic field strength is, the more the chains are formed, and the larger the volumes of the chains are, the larger the attenuation is. At the same time, the refractive index of the MF will increase with the strength of the magnetic field. So the index difference between the fiber and the MF will reduce, and then more evanescent field is guided in the MF,[25] which can be seen in Fig. 4. This will result in the increase of the attenuation of the evanescent field and then in the total energy of the guided light. Figure 4 calculates the fractional power of the guided light outside the fiber (evanescent field), η, as a function of the refractive index of MF (n_{MF}) approximately using the method as Tong *et al.* used.[26] $n_{\mathrm{fiber}}=1.46$ is taken as the refractive index of the fiber, and n_{MF} is set in the reasonable range from 1.34 to 1.37 (depends on magnetic field strength). From the above analysis, we know that the absolute value of the transmissivity is proportional to the magnetic filed strength and so is the modulation depth of the modulator. Accordingly, it is convenient to change the modulation depth to be the desired value by adjusting the magnetic field in certain extent. Figure 5 shows the modulation depth of the modulator as a function of magnetic field. The inset of Fig. 5 depicts the transmitted light powers (P_{out}) at various magnetic field strengths. It is well known that the agglomeration does not occur when the magnetic field strength is very low and saturation will happen when the magnetic field strength is very high. So the transmissivity and the modulation depth of the modulator should be analogous. These are proven in our experiment and shown in Figs. 3 and 5.

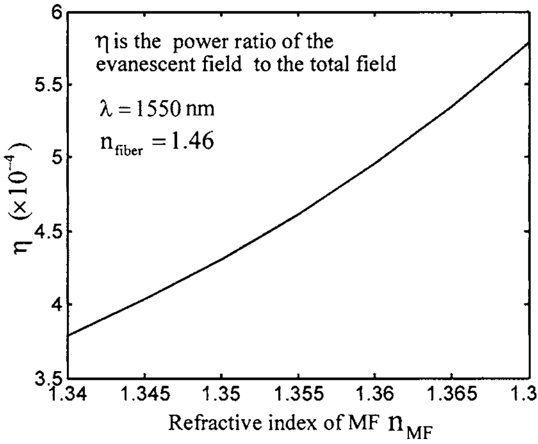

FIG. 4. The fractional power of the guided light outside the fiber (evanescent field), η, as a function of the refractive index of MF (n_{MF}).

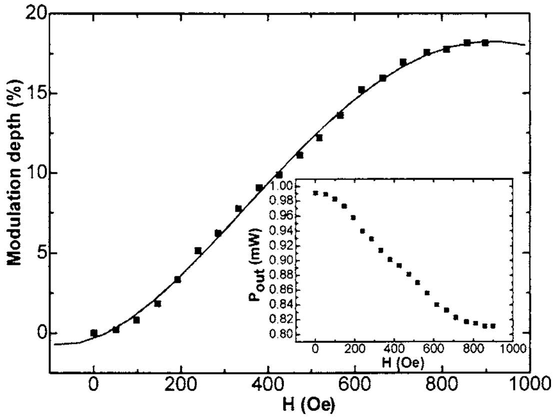

FIG. 5. Modulation depth of the modulator as a function of the magnetic field strength H. the inset shows the transmitted powers at various magnetic field strengths used to calculate the modulation depth.

We find that when the external magnetic field is turned on or off, it needs some time for the transmitted light intensity to reach the final steady value. We call this time falling or rising response time. We use the method developed by Chieh *et al.* to quantify the response times.[27] Experiments show that the falling response time decreases with the strength of the applied magnetic field. It changes from 4.51 to 0.377 s corresponding to Figs. 3(a) and 3(d), respectively. Experiments also show that the rising response time increases with the strength of the applied magnetic field very slightly in the range of the magnetic field strength in our experiment and the average value is about 0.8 s. We believe that the response times depend on the concentration and viscosity of the MF and other parameters. Optimizing these parameters can reduce the response times and enhance the modulation property of the modulator. Detailed work about the relationship between the modulation property (response time and modulation depth) and the correlative parameters (for example, the thickness and length of the drawn fiber; the concentration, viscosity, and kinds of the MF; the strength of the applied external magnetic field; and the wavelength, spectrum, and state of the polarization of the incident light, etc.) is ongoing. Finally, we would like to point out that the response time of the modulator may be too slow for high-speed applications, but it reveals another principle and method for constructing a modulation-depth-tunable modulator, which may be useful for some cases.

V. CONCLUSIONS

In summary, we have constructed an evanescent-field-based modulation-depth-tunable optical fiber modulator using a MF as the cladding of the drawn fiber. The operating principle of the modulator is analyzed. The modulation depth and the response time of the modulator depend on the strength of the applied magnetic field. The maximum modulation depth and the minimum response time of the modulator in this work are over 18% and below 0.4 s, respectively. Some parameters of the modulator can be optimized to get better results. The modulator presented in this paper may be useful for some low-speed applications.

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