Relaxation property of the magnetic-fluid-based fiber-optic evanescent field modulator

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The details about the modulation property of the magnetic-fluid-based fiber-optic evanescent field modulator are studied in this article. Experiments show that it needs some time for the outgoing light from the modulator to reach the final steady value when the external magnetic field is turned on or off (called the relaxation property of the modulator). Two exponential functions are employed to fit the experimental data of the falling and rising relaxation processes in order to achieve the falling and rising response times. By this method, the magnetic field dependent falling and rising response times are gained. The physical mechanisms of the relaxation property of the modulator are discussed qualitatively. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2709526]

I. INTRODUCTION

Ferromagnetic has many pragmatic applications due to its relatively very high permeability, which makes it have the ability to acquire high magnetization in a relatively weak magnetic field. Generally, ferromagnetic matter is in solid state. What about the properties and applications of liquid ferromagnetic matter? And is there any ferromagnetic matter in liquid state in nature? One may guess that the usual ferromagnetic matter will become liquid when it is heated above its melting point, but this method cannot realize the aim. The reason is that the melting point of the ferromagnetic matter is usually higher than its Curie point, above which the ferromagnetic matter becomes a paramagnetic one that has low magnetization property. So, liquid ferromagnetic matter must be synthesized artificially. This kind of work was initially done in the early 1930s and before.[1,2] But the stable liquid ferromagnetic matter (called magnetic fluid) in general used today was not obtained until the early 1960s.[3] From then on, the magnetic and dynamic properties of magnetic fluid (MF) have been investigated extensively[4–7] and it has been applied to rotary sealing, mechanical lubrication, damping, and magnetic flotation. Since the end of the last century, there is significant progress in optical information science and biomedicine and more and more research interests about MF are focused on these fields.[8,9]

With the development of nanoscale technology and material science, the quality of MF (e.g., stability, homogeneity) has been improved. This makes the MF have better optical properties. Because the MF possesses both the features of magnetism of solid ferromagnetic matter and fluid behavior of liquid matter, it exhibits unique optical properties—for example, refractive index tunability,[10–12] magnetochromatics,[13,14] thermal lens effect,[15,16] magneto-optic effects,[17,18] nonlinear optical effect,[19,20] etc. Based on these optical properties, many MF-based photonic devices can be made. Recently, some schemes for the applications of the MF to photonic devices have been proposed by some researchers and some sample photonic devices (for instance, MF light modulator,[21] MF optical switch,[22,23] MF coarse wavelength-division multiplexer,[24] MF Mach–Zehnder interferometer,[25] MF grating,[26] MF optical-fiber modulator,[27–29] etc.) have been demonstrated in the laboratories and their qualities have been experimented. An obstacle to the applications of the MF to practical use in the optical field is its relatively large extinction coefficient. Many of the earlier-mentioned MF photonic devices are transmission type, that is, the incident light must pass through the MF. And then, the outgoing light intensity is reduced due to the attenuation. So, designing a MF with high transparency is crucial to its optical applications. Some authors are working to achieve this goal.[30,31]

We have developed a fiber-optic evanescent field modulator using a MF as the cladding in our previous work.[29] This kind of MF photonic device is a nontransmission type, so it excels as a conventional one to some extent. Its operating principle is mainly based on the interaction between the evanescent field of the drawn fiber and the MF to attenuate the evanescent field intensity and the degree of interaction depends on the strength of the externally applied magnetic field. Accordingly, the transmitted light intensity from the drawn fiber can be modulated by the strength of the magnetic

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field. Hence, the MF fiber-optic evanescent field modulator can be constructed.[29] It is well known that the evanescent-field-based devices are very sensitive to ambient change,[32] so this kind of modulator may have a large modulation depth. Our previous research has shown a modulator with a modulation depth over 18%. Nonetheless, the modulation depth depends on the length and diameter of the drawn fiber. Nowadays, the techniques about drawing fiber to be sub-wavelength in diameter have been greatly developed since Tong *et al.* did pioneering work in the year of 2003.[33] Therefore, the modulation depth of this kind of modulator can be dramatically increased. And then, the desired modulation depth is easy to be obtained. Besides the modulation depth, another characteristic parameter about the MF modulator is its response characteristic to the external applied magnetic field. In this work, we will study this aspect in detail.

II. EXPERIMENTS AND ANALYSIS METHOD

We have drawn a standard single-mode fiber to be around 19.3 μm in ultimate diameter by heating and the heated region is about 1.5 cm in length. This drawn fiber is used to construct the MF fiber-optic evanescent field modulator. The scheme of the modulator is shown in Fig. 1(a).[29] One can refer to Ref. 29 for details about the fabrication and operating principle of the modulator. The typical modulation properties of the modulator are shown in Figs. 1(b) and 1(c) for the magnetic field strength of 380 and 766 Oe, respectively.[29] From Figs. 1(b) and 1(c), we can find that when the external magnetic field is turned on or off, it needs some time for the transmitted light intensity from the drawn fiber to reach the final steady value, i.e., the change of the transmitted light intensity to the external applied magnetic field is not instantaneous, but varies with time. We call this phenomenon the relaxation property of the modulator, and the span for the transmitted light intensity to reach the final steady value from the time when the magnetic field is turned on or off is called its falling or rising response time.

Experiments indicate that the relaxation property of the modulator may follow exponential law. Thus, we design two exponential functions for fitting the falling and rising relaxation processes to get the falling and rising response times. It is worth noting that Chieh *et al.* have used the analogous method to investigate the dynamic response of their MF optical-fiber modulator.[28] For the falling relaxation process, the exponential function $P=P_f+P_a e^{-t/\tau_{\text{fall}}}$ is utilized for fitting it. Where P, P_f, and P_a represent light powers, t is time, and τ_{fall} is decay constant of the exponential function, which expresses the rate of change of its value with time. This decay constant (characteristic time) reflects the speed of the relaxation process and is considered as the falling response time. When the external magnetic field is just turned on, t equals zero, so $P=P_f+P_a$ is the initial value of the relaxation process. Whereas, when t becomes relatively large, $P \approx P_f$ is the final value of the relaxation process. So the experimental data of the relaxation process can be fitted to this exponential function, and then the falling response time τ_{fall} is obtained. Similarly, we have designed another exponential function $P=P_f-P_a e^{-t/\tau_{\text{rise}}}$ for fitting the experimental data of the rising relaxation process to get the rising response time τ_{rise}.

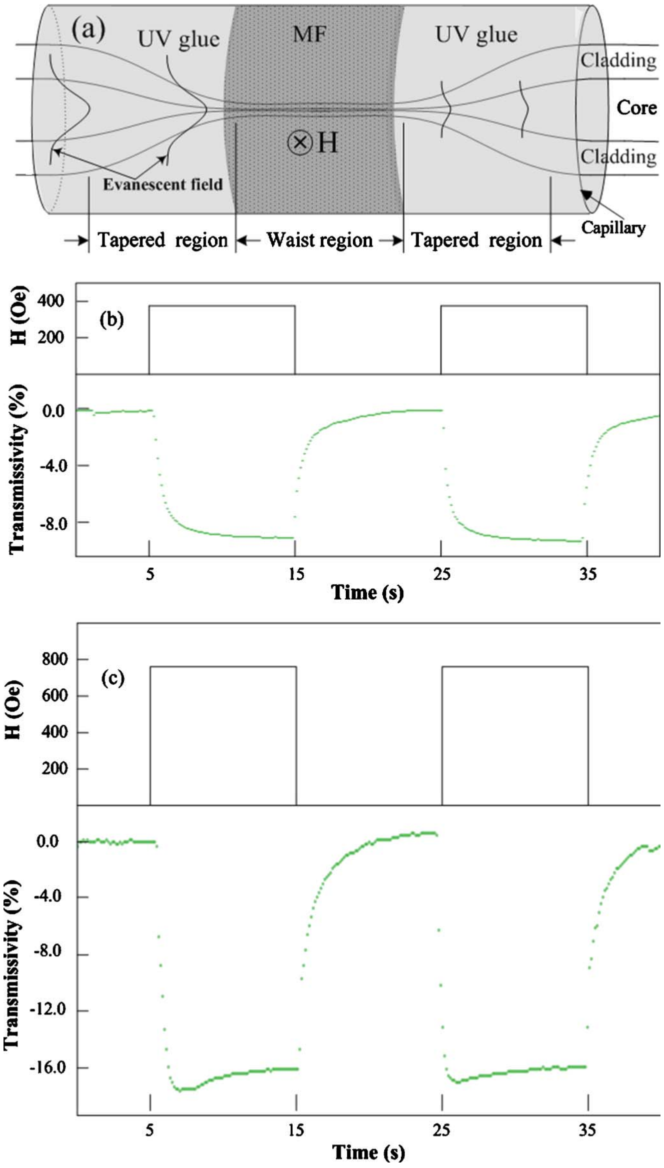

FIG. 1. (Color online) The scheme of the MF fiber-optic evanescent field modulator (a) and the typical modulation properties of the modulator at magnetic field strength of (b) 380 and (c) 766 Oe, respectively.

III. RESULTS AND DISCUSSION

The aforementioned techniques are used to quantify the MF modulator's relaxation properties under different magnetic field strengths. The strength of the external applied magnetic field ranges from 51 to 858 Oe. By fitting the experimental data of the falling/rising relaxation process to the exponential function $P=P_f+P_a e^{-t/\tau_{\text{fall}}}/P=P_f-P_a e^{-t/\tau_{\text{rise}}}$, the decay constant is achieved, so is the falling/rising response time $\tau_{\text{fall}}/\tau_{\text{rise}}$. When the external magnetic field is applied, the transmitted light from the MF modulator will reduce with time and the falling relaxation process will be formed. Figure 2 shows the typical falling relaxation processes and their fitting to exponential function $P=P_f+P_a e^{-t/\tau_{\text{fall}}}$ at the magnetic field strength of (a) 192 and (b) 474 Oe, respectively. Their corresponding falling response times τ_{fall} are obtained

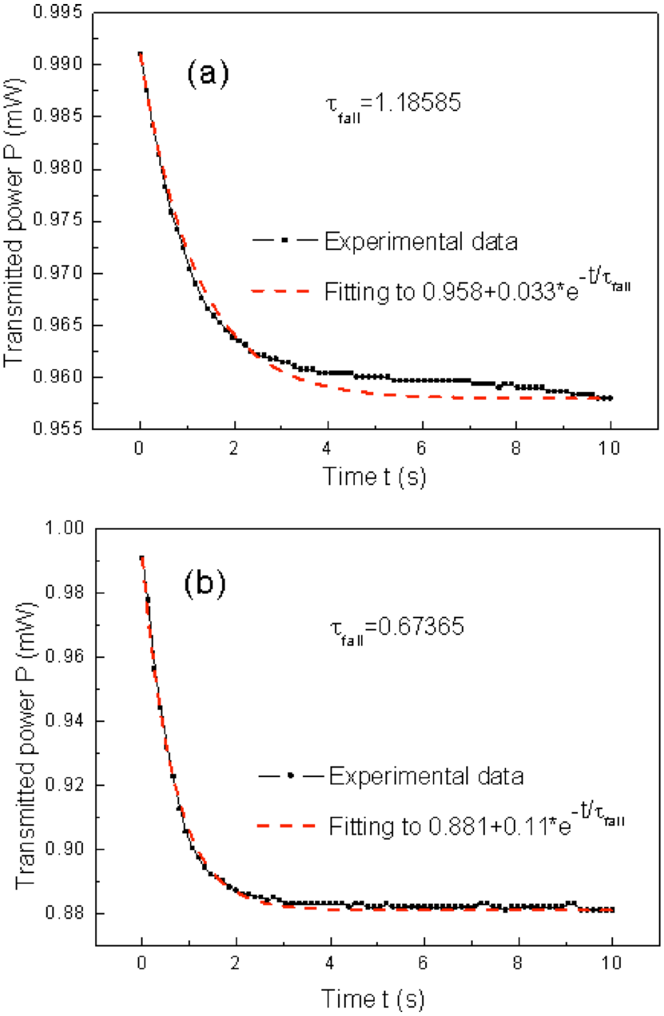

FIG. 2. (Color online) The falling relaxation processes of the MF modulator at magnetic field strength of (a) 192 and (b) 474 Oe, respectively, and their response times τ_{fall} are obtained to be 1.18585 and 0.67365 s, respectively, by fitting the experimental data to an exponential function.

to be 1.18585 and 0.67365 s, respectively. When the external magnetic field is turned off, the transmitted light from the MF modulator will increase with time and the rising relaxation process will be formed. Figure 3 shows the typical rising relaxation processes and their fitting to exponential function $P=P_f-P_a e^{-t/\tau_{\text{rise}}}$ at magnetic field strength of (a) 192 and (b) 474 Oe, respectively. Their corresponding rising response times τ_{rise} are obtained to be 0.95876 and 0.67910 s, respectively. In order to explore the relationship between the response times and the strength of the magnetic field, the falling and rising response times at several discrete magnetic field strengths are acquired through the earlier fitting method. Figure 4 depicts the falling response time of the modulator as a function of magnetic field and the magnetic field dependent rising response time is shown in Fig. 5. Figure 4 indicates that the falling response time decreases with the strength of the external applied magnetic field and it changes from 4.510 to 0.377 s under the given experimental condition. But the rising response time increases with the strength of the external applied magnetic field slightly as shown in Fig. 5 in the same experiment, which changes from 0.312 to 1.110 s and the average value is about 0.8 s. From Figs. 4 and 5, we can

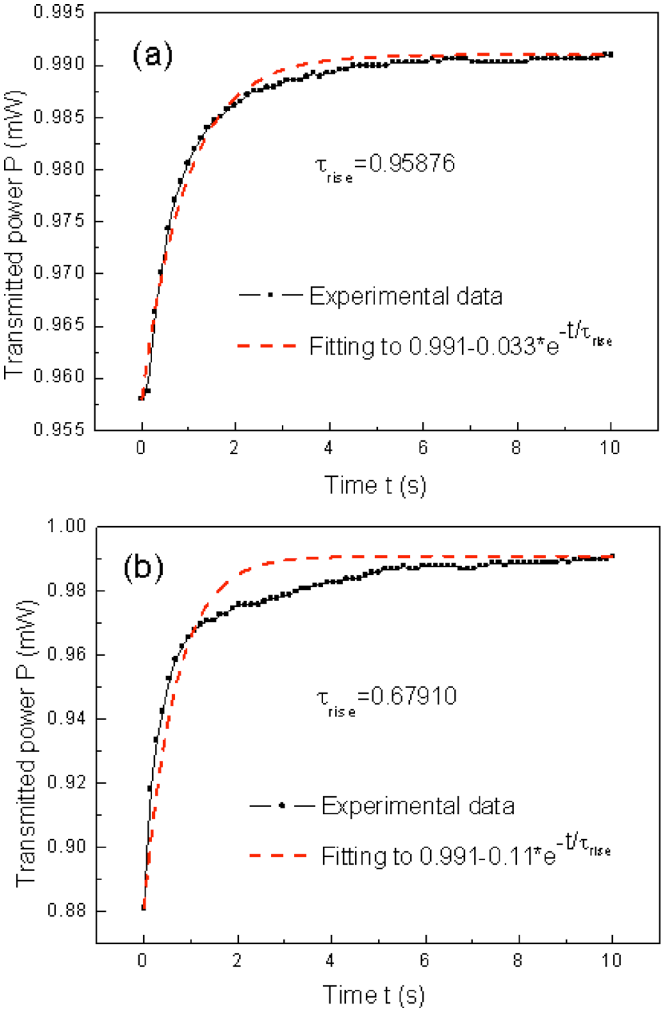

FIG. 3. (Color online) The rising relaxation processes of the MF modulator at magnetic field strength of (a) 192 and (b) 474 Oe, respectively, and their response times τ_{rise} are obtained to be 0.95876 and 0.67910 s, respectively, by fitting the experimental data to an exponential function.

find that there is a critical magnetic field strength H_c (around 160 Oe), which separates the magnetic field dependent response time into two regions. The degree of the dependency of the response time on the magnetic field under H_c (low

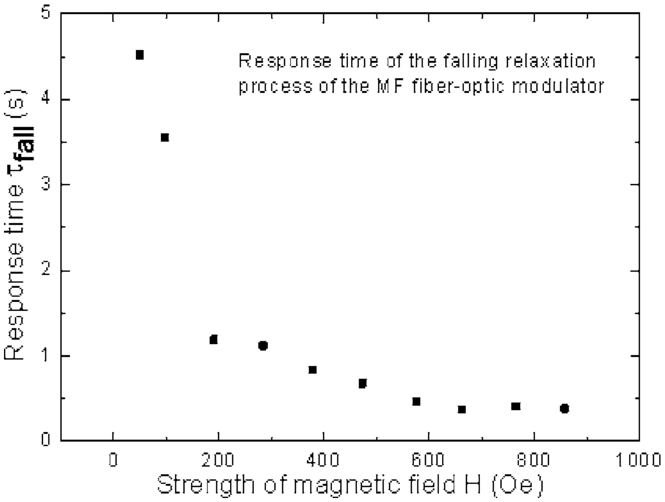

FIG. 4. The falling response time of the MF modulator as a function of the magnetic field strength *H*.

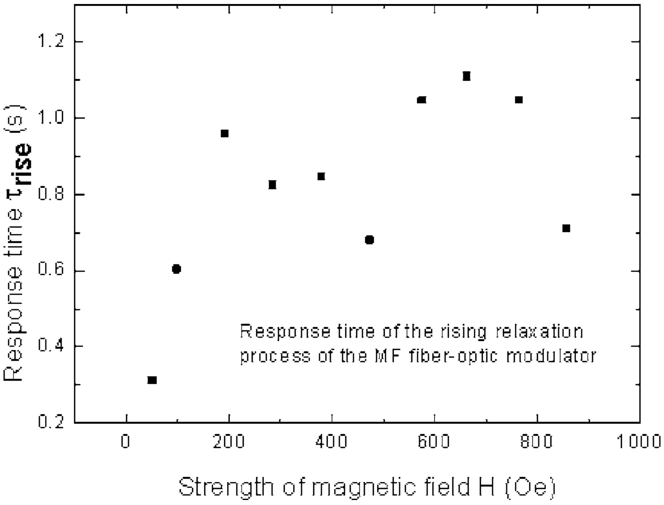

FIG. 5. The rising response time of the MF modulator as a function of the magnetic field strength *H*.

magnetic field region) is higher than that above H_c (high magnetic field region). Meanwhile, the response time tends to saturate at a very high magnetic field strength.

The modulation property of the modulator is based on the interplay between the evanescent field of the drawn fiber and the MF and the degree of the interplay depends on the agglomeration of the magnetic particles within the MF. So the falling response time of the modulator corresponds to the span for the magnetic particles to agglomerate to form the final steady clusters from the time when the magnetic filed is just turned on and the rising response time of the modulator corresponds to the span for the magnetic particles within the clusters to be dispersed into the MF evenly from the time when the magnetic field is just turned off. There are two main factors to determine the agglomeration or dispersion process, that is, magnetic attraction and thermal agitation. The former make the magnetic particles agglomerate, while the latter make the magnetic particles to be dispersed. During the falling relaxation process, the magnetic energy of the magnetic particles is comparable to their thermal energy when the external applied magnetic field is low. This results in the long time for the magnetic particles within MF to agglomerate to the final steady state, hence, the falling response time is long. When the external applied magnetic field is relatively high, the magnetic energy of the magnetic particles is much larger than their thermal energy, and then the agglomeration factor is dominant over the dispersion one. This results in the relatively short time for the magnetic particles within MF to agglomerate to the final steady state, hence, the falling response time is short. The larger the magnetic field is, the higher the magnetic energy of the magnetic particles, and the shorter the falling response time is. When the external applied is too high, the magnetization of the magnetic particles tends to saturate, so does the falling response time. These phenomena coincide with the experimental results as shown in Fig. 4. We would like to point out that Hong *et al.* have found the same dependency on the magnetic field of the diameters of and distances between the clusters.[34,35] During the rising relaxation process, only the thermal agitation exists in the MF when the external magnetic field is turned off. And then every magnetic particle of a cluster will disperse into the MF at the same time. Therefore, the rising response time seems to have nothing to do with the magnetic field. But when the preceding magnetic field is high, more clusters have been formed within the MF. A little more time is needed for all the magnetic particles disperse into MF until the last homogenous state is formed. Consequently, the rising response time of the modulator only increases with the magnetic field slightly, as shown in Fig. 5. From the experimental results and the earlier analysis, we can know that the total response time (falling and rising response time) in a period decreases with the external applied magnetic field. Besides, we believe that the response time of the modulator depends on many other parameters, for example, the viscosity and temperature of the MF. Thus there is some room for enhancing the quality of the modulator for potential practical applications.

IV. CONCLUSIONS

In conclusion, the relaxation property of the evanescent-field-based MF fiber-optic modulator is investigated. Falling and rising response times are used to characterize the falling and rising relaxation processes, respectively. Both of the two kinds of response times depend on external applied magnetic field strength. For our previous developed modulator, the falling response time changes from 4.51 to 0.38 s when the magnetic field increases from 51 to 858 Oe. While the rising response time increases slightly in the same field strength range and the average value is about 0.8 s. Magnetic attraction and thermal agitation are employed to clarify the physical mechanisms of the magnetic field dependent response times. The modulation property of the modulator can be improved for potential applications by taking some measures.

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