Tunable magneto–optic modulation based on magnetically responsive nanostructured magnetic fluid*

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Magnetic fluid is a kind of functional composite material with nanosized structure and unique optical properties. The tunable magneto–optic modulation of magnetic fluid under external magnetic field, achieved by adjusting the polarization direction of incident light, is investigated theoretically and experimentally in this work. The corresponding modulation depth and response time are obtained. The accompanying mechanisms are clarified by using the theory of dichroism of magnetic fluid and the aggregation/disintegration processes of magnetic particles within magnetic fluid when the external magnetic field turns on/off.

Keywords: magnetic fluid, tunable magneto–optic modulation, modulation depth, response time

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1. Introduction

Magnetic fluid (MF) is a type of colloid consisting of magnetic nanoparticles scattered in liquid carriers with the aid of surfactants. The Brownian motion of magnetic nanoparticles prevents them from sticking to each other due to van der Waals attraction. The typical size of the magnetic nanoparticles, such as Fe_3O_4, $MnFe_2O_4$, and $CoFe_2O_4$, is around 3 nm–15 nm. The carriers are usually water, kerosene and heptane.[1] The stable, surfacted liquid ferromagnetic matter (called MF) was firstly made by Papell in the 1960s using the size reduction method.[2] Since then, methods for fabricating MF had a rapid development, which led to a great improvement of the stability and homogeneity of MF. Many magnetic and dynamic properties of MF, such as phase separation and aggregation, heat and mass transfer, hydrodynamics and polydispersity, have been discovered and investigated.[3−8]

It is well known that MF exhibits some conventional optical properties,[9−15] for instance, linear birefringence, linear dichroism, and Faraday rotation. Recently, some late-model optical properties of MF have been revealed, such as magnetically tunable optical scattering,[16−18] optical transmission,[19−26] clustering of nanoparticles,[27,28] tunable magnetic photonic crystals,[29−33] etc. Some optical devices based on MF have been proposed and demonstrated.[34−38] Most of them utilize the effect of magneto–optic modulation of MF, i.e., the incident light is modulated by the MF film under an external magnetic field. Thus, it is significant to understand the properties of magneto–optic modulation of MF in depth. Usually, the magneto–optic modulation of MF can be influenced by the strength and the gradient of the applied magnetic field, the concentration and the thickness of the MF sample and the intensity and the wavelength of the incident light.[39−42] To the best of our knowledge, the influence of polarization direction of the incident light has not been studied yet. In consideration of the MF-based photonic devices likely operating with polarized light, it is necessary to explore the detailed relationship between the magneto–optic modulation of MF and the polarization direction of the incident light. In this paper, a tunable magneto–optic modulation of MF achieved by adjusting the polarization direction of the incident light is studied. The corresponding modulation depth and response time[43] are studied.

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2. Experiments

Kerosene-based Fe_3O_4 MF with an average particle diameter of 10 nm is used. The volume fraction of the nanoparticles within the MF is 3.75%. The MF is sealed in a sample cell made of 20 mm × 15 mm glass plates with a spacing of 50 μm. Figure 1 shows the experimental layout for studying the tunable magneto–optic modulation properties of the MF, achieved by adjusting the polarization direction of the incident light. A single-mode He–Ne laser is employed to emit light with a wavelength of 632.8 nm. The superior linearly polarized light is obtained with a polarizer. The polarization direction of the incident light can be adjusted by tuning a halfwave plate. A special electromagnet is introduced to generate a uniform horizontal magnetic field parallel to the MF film. The strength of the magnetic field can be changed by tuning the magnitude of the supply current. The angle included between the polarization direction of the incident light and the magnetic field direction is denoted by θ. The incident light is perpendicular to the MF sample film and the transmitted intensity is detected by a photodiode. The electric signals of the photodiode are proportional to the transmitted intensity. They are amplified and then recorded by a computer.

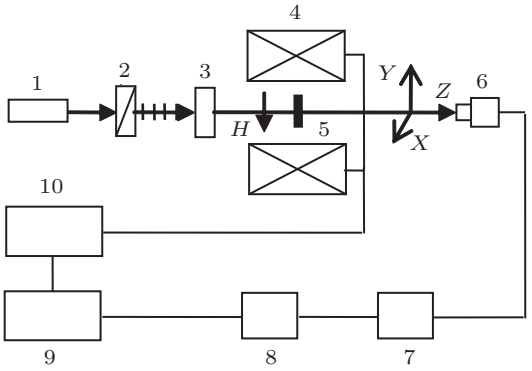


Fig. 1. Schematic diagram of the experimental setup for studying the tunable magneto–optic modulation properties of the MF, achieved by adjusting the polarization direction of the incident light: 1: laser source; 2: polarizer; 3: rotatable halfwave plate; 4: electromagnet; 5: sample; 6: photoelectric cell; 7: amplifier; 8: data acquisition card; 9: computer; 10: power supply.

3. Results and discussion

The time-dependent electric signals of the outgoing light are recorded when the magnetic field is turned on and off alternately. The typical results are shown in Fig. 2 for different polarization directions of the incident light at a magnetic field strength of 3.9×10^{-2} T. From Fig. 2, one can see that the electric signal of the transmitted light is stable at a constant value at the initial stage (zero magnetic field). The voltage value of this electric signal is referred to as V_s, which is proportional to the power of the transmitted light P_s at zero magnetic field. When the magnetic field is applied, the electric signal of the transmitted light will reach another steady value and the corresponding voltage value is referred to as V_f, which is proportional to the power of the transmitted light P_f when the magnetic field is turned on. Afterwards, the electric signal of the transmitted light comes back to the initial value (V_s) when the magnetic field is turned off. In our experiment, the temporal period of the magnetic field is set to be 20 s. Experiments indicate that the regular variation of transmitted light with time is repeatable when the temporal period of the magnetic field is appropriate. Detailed work on the relationship between the repeatability of the transmitted light with time and the temporal period of the magnetic field is ongoing and will be presented in another paper.

From Fig. 2, it is obvious that V_f (when the magnetic field is turned on) remarkably depends on the polarization direction of incident light, while V_s (when the magnetic field is zero) is always constant in different polarization directions. This manifests that the variation of the transmitted light can be tuned by adjusting θ. Moreover, the variation of the transmitted light has a negative value and is inversely proportional to θ for $0^\circ \le \theta < 45^\circ$. However, it has a positive value and increases with θ for $45^\circ < \theta \le 90^\circ$. For $\theta = 45^\circ$, transmitted light becomes invariable.

This particular magneto–optic modulation can be expounded with the dichroism of MF under external magnetic field. Magnetic nanoparticles within the MF are magnetic single domains and in random state of thermal motion under zero magnetic field.[38] As soon as the magnetic field is applied, magnetic nanoparticles like small magnets will undergo Brownian and/or Neel rotation,[44,45] which results in the formation of chain-like structures parallel to the magnetic field direction. This leads to the polarization direction-dependent attenuation (assigned to the emergence of the dichroism of MF) when the incident light passes through the MF. The attenuation of the incident light with polarization direction parallel to the field direction ($\theta = 0^\circ$, extraordinary light) increases with the strength of the external magnetic field increasing. On the contrary, the attenuation of the incident light with

polarization direction perpendicular to the field direction ($\theta = 90°$, ordinary light) decreases with the strength of the magnetic field increasing.[46−48] When $0° \leq \theta < 45°$, the extraordinary light is stronger than the ordinary one. So, the negative variation of the transmitted light happens when the externally magnetic field is applied. Moreover, the larger the strength of magnetic field and/or the smaller the value of θ, the smaller the intensity of the transmitted light is. At the special polarization of $\theta = 45°$, the transmitted light is constant regardless of the magnetic field. This is attributed to the equality between the extraordinary light and the ordinary one. When $45° < \theta \leq 90°$, the ordinary light is stronger than the extraordinary one and the intensity of the transmitted light will increase when the externally magnetic field is applied. This positive variation of the transmitted light is proportional to the strength of magnetic field and the value of θ. When the external magnetic field is turned off, the thermal agitation in the MF makes the magnetic particles in chain-like structures dispersed into the random state,[38] which leads to the disappearance of dichroism of MF. As a result, the intensity of the transmitted light comes back to the initial stable value. In a word, the attenuation of the incident light under a fixed external magnetic field is inversely proportional to θ. So, the variation of the transmitted light increases with θ for 0° (the smallest negative variation) $\leq \theta \leq 90°$ (the biggest positive variation).

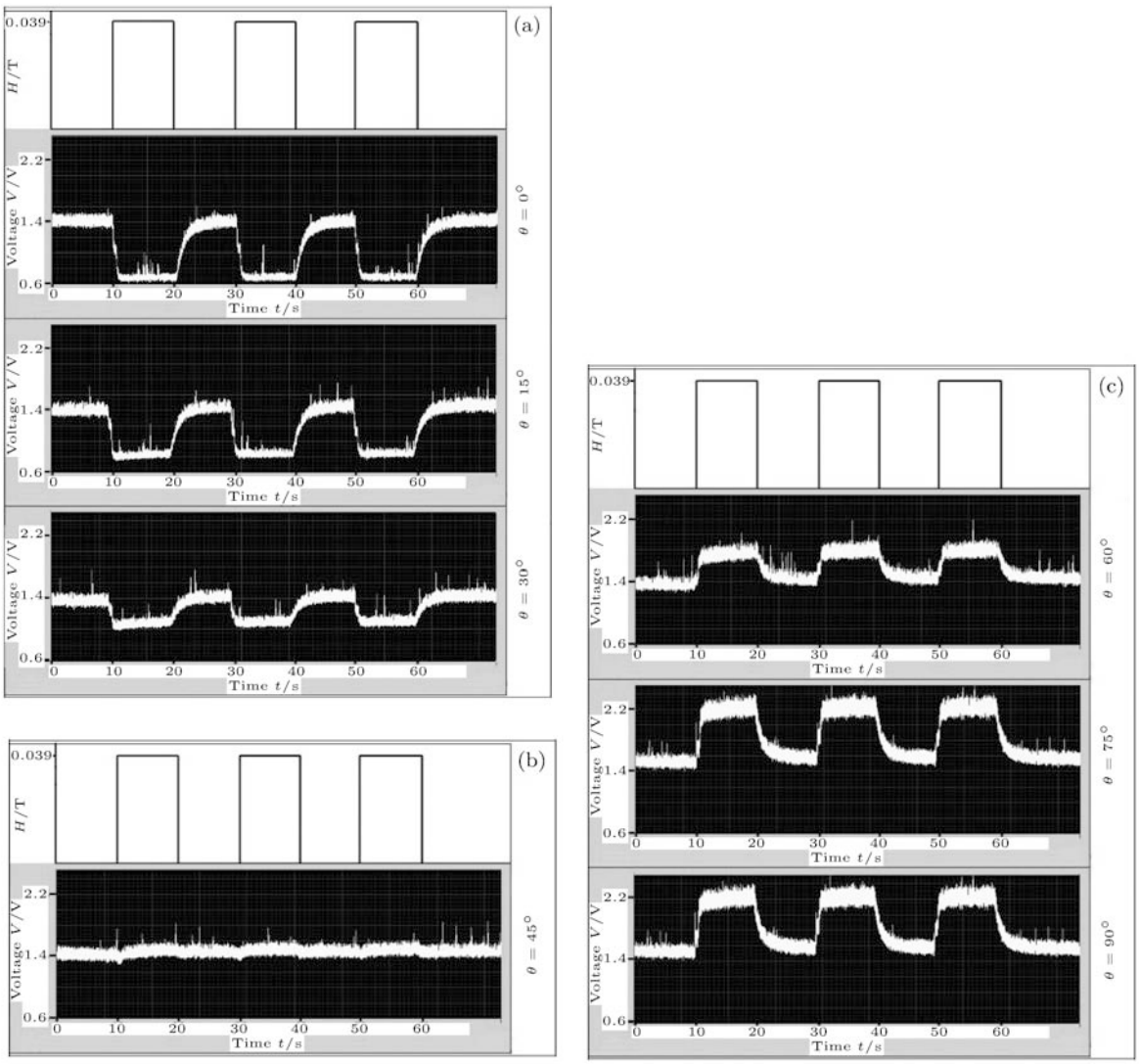


Fig. 2. Typical variations of the electric signals of the outgoing light with time when the external magnetic field is turned on and off alternately. The values of angle (θ) included between the polarization direction of the incident light and the magnetic field direction are (a) 0°, 15°, 30°; (b) 45°; and (c) 60°, 75°, 90°. The strength of the magnetic field is 3.9×10^{-2} T.

The transmissivity of the incident light is defined as $T = [(P_f - P_s)/P_s] \times 100\% = [(V_f - V_s)/V_s] \times 100\%$, which is also called modulation depth. It is obvious from Fig. 2 that the modulation depth of the magneto–optic modulation of MF increases with θ at a fixed magnetic field, which can be clearly seen in Fig. 3. Figure 3 shows the curves for the modulation depth of the MF sample as a function of θ under three different magnetic fields (2.1×10^{-2} T, 3.0×10^{-2} T, and 3.9×10^{-2} T) . From Fig. 3, we can find that the modulation depth increases with the strength of magnetic field increasing when $\theta(\neq 45°)$ is constant. The degree of aggregation of the magnetic particles within MF increases with the strength of magnetic field increasing, so does the dichroism of MF. This leads to a larger variation of the transmitted light at higher magnetic field. Hence, the modulation depth increases with the strength of magnetic field increasing in a fixed polarization direction of the incident light.

Figure 3 also displays that the absolute value of the modulation depth for $\theta = 0°$ is larger than that for $\theta = 90°$. This is due to the larger variation of the attenuation of the incident light for $\theta = 0°$ than that for $\theta = 90°$ as shown in Fig. 2. Therefore, the deepest modulation depth of MF can be achieved when the polarization direction of the incident light is parallel to the field direction ($\theta = 0°$). These results give a guideline for designing the corresponding (tunable) photonic devices and improving their quality.

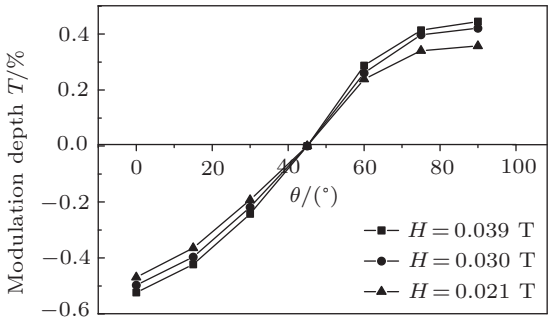


Fig. 3. Curves for modulation depth T of the magneto–optic modulation of an MF as a function of θ under three different magnetic field strengths: 2.1×10^{-2} T, 3.0×10^{-2} T , and 3.9×10^{-2} T.

Figure 2 also indicates that it needs some time for the electric signals of the transmitted light to reach the final steady value, when the external magnetic field is turned on or off. That is to say, the change of the transmitted light intensity with respect to the external applied magnetic field is not instantaneous, but varies with time. We call this delay time the response time of the magneto–optic modulation. 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 the first or second response time. The corresponding processes are called the first or second response process.

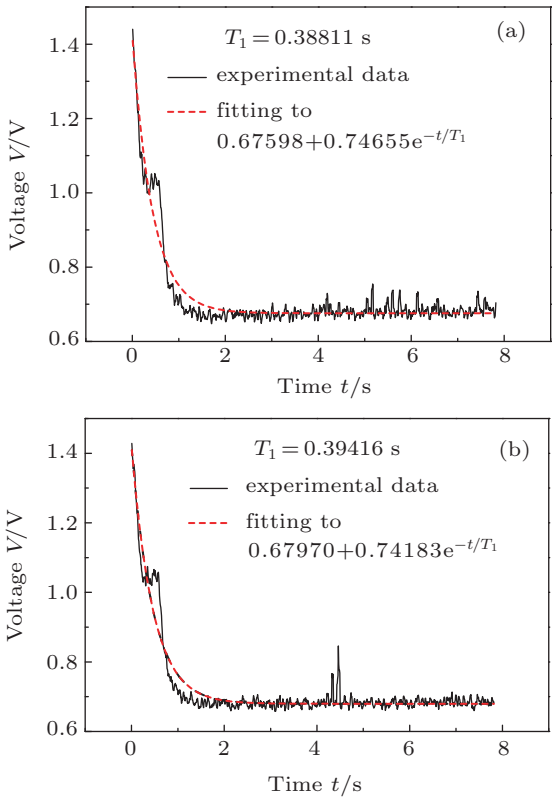


Fig. 4. The first response processes of the magneto–optic modulation at a magnetic field strength of 3.9×10^{-2} T for (a) $\theta = 0°$ and (b) $\theta = 30°$. The values of response time T_1 are obtained to be 0.38811 s and 0.39416 s, respectively.

Qualitatively, the experimental data of the electric signals of the transmitted light in Fig. 2 indicate that the response process of the magneto–optic modulation may follow exponential law with time. Thus, the exponential function $V = V_a + V_b\, e^{-t/T_1}$ (equivalent to $P = P_a + P_b\, e^{-t/T_1}$, where P, P_a, and P_b represent light powers) is designed to fit the experimental data of the first response process to obtain the first response time, where V, V_a, and V_b are the corresponding voltage values proportional to P, P_a, and P_b, respectively, t is the time, and T_1 is the decay constant of the exponential function. T_1 expresses the change rate of V (P) with time and reflects the speed of the first response process, i.e. the first response time. When the external magnetic field is just turned on (t equals zero), $V = V_a + V_b$ ($P = P_a + P_b$) is the initial value of the first response process. When t becomes relatively large, $V = V_a$ ($P = P_a$) is the final value of the first response process. Figure 4 shows

the typical first response processes and their fitting to exponential function $V = V_a + V_b\,e^{-t/T_1}$ at magnetic field strength of 3.9×10^{-2} T for (a) $\theta = 0°$ and (b) $\theta = 30°$. The values of corresponding first response time T_1 are obtained to be 0.38811 s and 0.39416 s, respectively. Similarly, another exponential function $V = V_a - V_b\,e^{-t/T_2}$ (equivalent to $P = P_a - P_b\,e^{-t/T_2}$) is designed to fit the experimental data of the second response process to obtain the second response time T_2. The typical second response processes and their fitting to exponential function $V = V_a - V_b\,e^{-t/T_2}$ at a magnetic field strength of 3.9×10^{-2} T is shown in Fig. 5 for (a) $\theta = 0°$ and (b) $\theta = 30°$. The values of corresponding second response time T_2 are obtained to be 1.04864 s and 1.04636 s, respectively.

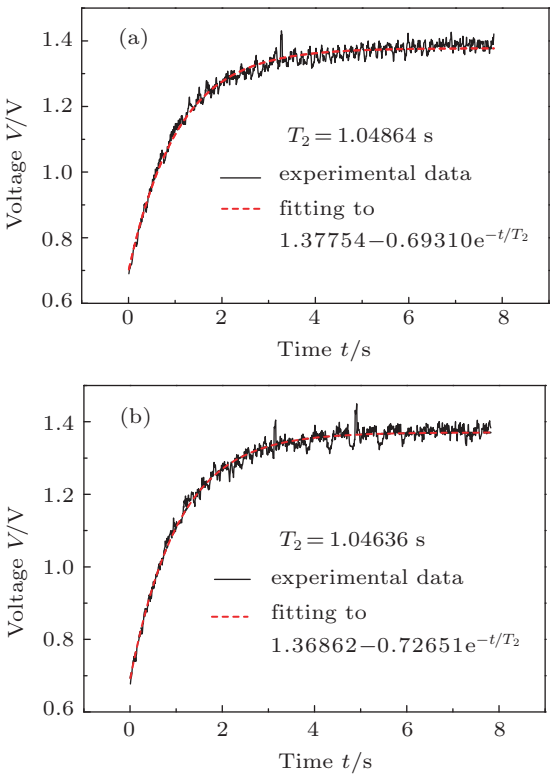


Fig. 5. The second response processes of the magneto–optic modulation at a magnetic field strength of 3.9×10^{-2} T for (a) $\theta = 0°$ and (b) $\theta = 30°$. The values of response time T_2 are obtained to be 1.04864 s and 1.04636 s, respectively.

The curves for response time of the magneto–optic modulation of an MF sample as a function of θ under three different magnetic fields (2.1×10^{-2} T, 3.0×10^{-2} T , and 3.9×10^{-2} T) are shown in Fig. 6. The entire response time T_{res} in Fig. 6(c) is defined as $T_{res} = T_1 + T_2$. Figure 6 indicates that the first (T_1) and second response time (T_2) under a fixed magnetic field are constant except for the abrupt jump near $\theta = 45°$. The entire response time T_{res} is always constant for all θ values. For a specific MF sample at a

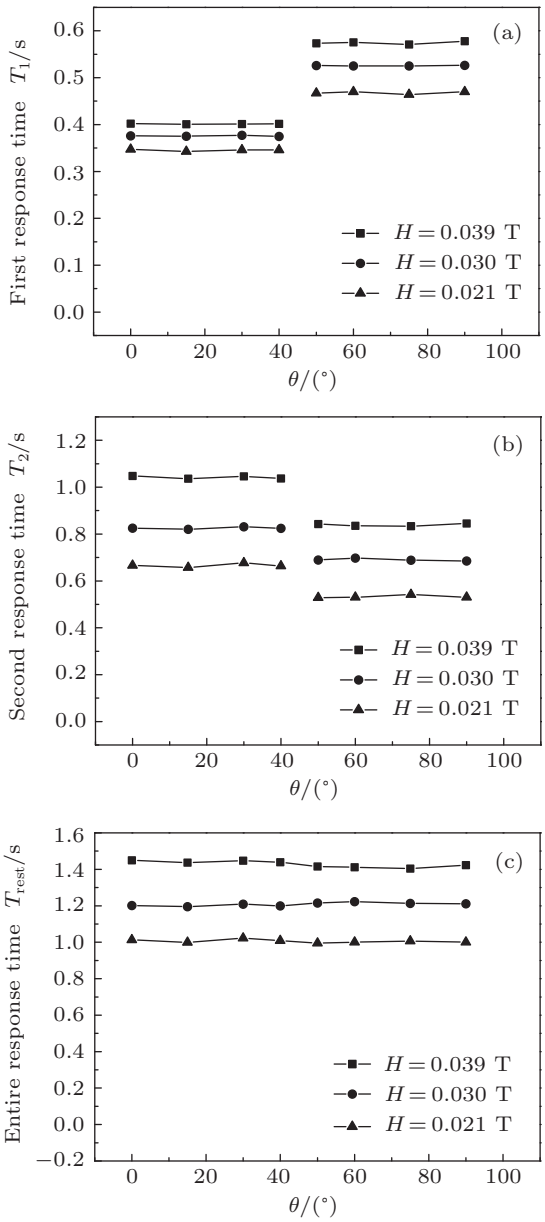


Fig. 6. The (a) first response time T_1, (b) second response time T_2, and (c) entire response time T_{res} of the magneto–optic modulation of an MF sample, each as a function of θ, under three different magnetic field strengths: 2.1×10^{-2} T, 3.0×10^{-2} T , and 3.9×10^{-2} T.

fixed ambient temperature, the motions of the magnetic particles (aggregation and dispersion, which are crucial to the response times) depend mainly on the strength of the external magnetic field and has nothing to do with the angle included between the polarization direction of the incident light and the magnetic field direction. Thus, the response times T_1, T_2, and T_{res} are invariant with θ. The degree of aggregation of magnetic particles within the MF increases with the magnetic field increasing, which leads the response process to last a long time at high magnetic field. So,

the response time increases with the strength of magnetic field increasing as shown in Fig. 6.

4. Conclusions

The tunable magneto–optic modulation of MF under external magnetic field is achieved by adjusting the polarization direction of the incident light. The corresponding modulation depth and response time are investigated in detail. It is found that the modulation depth of this kind of magneto–optic modulation can be tuned by changing the angle included between the polarization direction of the incident light and the magnetic field direction. Besides, it increases with the strength of the applied magnetic field increasing in a fixed polarization direction of the incident light. Under an external magnetic field of 3.9×10^{-2} T, the deepest modulation depth (-52.35%) is obtained when the polarization direction of the incident light is parallel to the field direction. The response time of the process of the magneto–optic modulation does not vary with the polarization direction of the incident light except for the abrupt jump at 45° polarization, and it is directly proportional to the magnetic field strength. This tunable optical property of MF under external magnetic field can be used to develop the newfashioned tunable photonic devices, such as optical switch, logic device, light modulator, etc.

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