CHIN. PHYS. LETT. Vol. 35, No. 10 (2018) 104203

Magneto and Electro-Optic Intensity Modulator Based on Liquid Crystal and Magnetic Fluid Filled Photonic Crystal Fiber *

Yue-Lan Lu(吕月兰)[1], Fei-Ru Wang(王斐儒)[1,2], Chi Zhang(张弛)[1], Ji-Wen Yin(尹辑文)[2], Yu Huang(黄玉)[1], Wei-Min Sun(孙伟民)[1], Yong-Jun Liu(刘永军)[1**]

[1]*Key Lab of In-fiber Integrated Optics (Ministry Education), Harbin Engineering University, Harbin 150001*
[2]*Physics and Electronic Information Engineering, Chifeng University, Chifeng 024000*

(Received 20 July 2018)

We propose a novel light intensity modulator based on magnetic fluid and liquid crystal (LC) filled photonic crystal fibers (PCFs). The influences of electric and magnetic fields on the transmission intensity are theoretically and experimentally analyzed and investigated. Both the electric and magnetic fields can manipulate the molecular arrangement of LC to array a certain angle without changing the refractive index of the LC. Therefore, light loss in the PCF varies with the electric and magnetic fields whereas the peak wavelengths remain constant. The experimental results show that the transmission intensity decreases with the increase of the electric and magnetic fields. The cut-off electric field is 0.899 V/μm at 20 Hz and the cut-off magnetic field is 195 mT. This simple and compacted optical modulator will have a great prospect in sensing applications.

PACS: 42.81.Dp, 83.80.Xz, 61.30.Gd DOI: 10.1088/0256-307X/35/10/104203

Photonic crystal fibers (PCFs),[1,2] also known as microstructured optical fibers, have attracted the considerable attention of researchers over the past few years. A PCF is commonly composed of circular air holes arranged in a triangular lattice pattern along the fiber. The geometric structures of PCFs such as the lattice constants and air-hole diameters determine their optical properties. However, the presence of air holes in PCFs provides the possibility of changing the optical characteristics by filling air holes with a liquid. Therefore, tunable fibers and fiber-based devices for tuning, trimming, scrambling, and controlling light could be realized using this technique.[3–5] As one of the potential applications, PCF based modulators for scalar modulation[6,7] and phase modulation[8] have been achieved.

Compared to other filling materials, liquid crystal (LC) is considered to be a special material because its refractive index can be changed by adjusting the temperature. The outstanding tunability causes LC-based PCFs to be employed in various applications, such as light modulators,[9] switches,[10] interferometers,[11] and sensors.[12] Alkeskjold *et al.* proposed a serial of temperature sensors using a section of LC-filled PCF.[13,14] Du *et al.* demonstrated a tunable light switch by applying an external electric field to a PCF filled with LC.[15] Magnetic fluid (MF) is another particular filling material due to its high magnetic sensitivity. Miao *et al.* infiltrated Fe_3O_4 nanoparticle fluid in a PCF and proved that the transmission power could be modulated by changing the temperature.[16] Zu *et al.* reported a magneto-optical fiber sensor based on the bandgap tunability of an MF-filled PCF, which can reach a magnetic sensitivity of 1.56 nm/Oe.[17] However, most of the reported studies focused on the magnetically tunable reflective index of MF. As far as we know, the functional effect of MF on the molecular arrangement of LC has not been fully studied.

In this Letter, we present a new PCF based light intensity modulator, in which the PCF is filled with a mixture of LC and MF. When an electric or magnetic field is applied to this PCF, the transmission intensity is significantly modulated. Modulation principles are theoretically analyzed, and the influence of MF on the molecular arrangement of LC is discussed. The dependences of the transmission intensity on the electric field strength, electric field frequency, and magnetic field are experimentally investigated. Experimental results show that the transmission intensity decreases with the increase of the electric and magnetic fields. Larger electric field strength is needed to obtain the same attenuation in a higher electric field frequency situation.

Figure 1(a) shows a scanning electron microscope (SEM) image of the PCF used in our experiments, in which five layers of circular air holes in a hexagonal pattern surround a solid core. The diameters of the PCF and air holes are 125 and 2 μm, respectively. The LC used in our experiment is a nematic LC 4-cyano-4'-pentylbiphenyl (5CB, at 25℃, $\lambda = 589.3$ nm, $n_e = 1.7063$, $n_o = 1.5309$), and the mass percentage of Fe_3O_4 nanoparticles in MF is 1%. The mixture of MF and LC with a weight ratio of 1:10 is filled into the air holes through a capillarity effect. The filling length in the PCF is controlled by the filling time. Due to the optical birefringence properties of this liquid mixture, the mixture in the PCF could be observed through a polarizing microscope, as shown in Fig. 1(b). The

*Supported by the Joint Research Fund in Astronomy under Cooperative Agreement between the National Natural Science Foundation of China and Chinese Academy of Sciences under Grant No U1531102, the Fundamental Research Funds for the Central Universities under Grant No HEUCF181116, and the National Natural Science Foundation of China under Grant Nos 61107059, 61077047 and 11264001.

**Corresponding author. Email: liuyj@hrbeu.edu.cn

© 2018 Chinese Physical Society and IOP Publishing Ltd

total length of the PCF is 100 mm and the length of the fully-filled section in this work is 10 mm. Figure 1(c) describes a schematic setup of this light intensity modulator. The PCF is spliced between two standard single-mode fibers (SMFs) using a conventional fusion splicer. Light from a laboratory-made broadband light source (BLS) with a wavelength range of 500–1000 nm passes through the PCF and is measured by an optical spectrum analyzer (OSA, YOKOGAWA, AQ6317C).

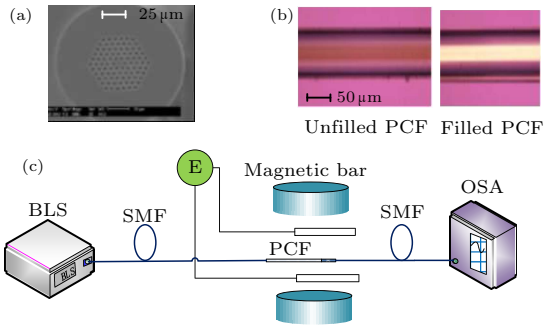


Fig. 1. (a) SEM image of a cross section of the PCF. (b) Images of the PCF under a polarizing microscope. (c) Schematic diagram of the experimental setup.

For electric field experiments, an ac signal with a maximum voltage of 400 V and a maximum frequency of 2 MHz is applied to the electrodes on the two substrates. The electrode gap is approximately 300 μm. Therefore, the electric field between two substrates could vary from 0 to 1.33 V/μm with a tunable frequency range of 0–2 MHz. For magnetic field experiments, the magnetic field is generated by two bar magnets and calibrated by a magnetometer whose probe is located very close to the PCF. The applied magnetic field could be adjusted by changing the distance between the magnetic bar and PCF. The room temperature is kept at 25℃ during the experiments. Furthermore, the LC and MF-filled PCF is placed in a V-groove slab to avoid bending effects. The validity time of this light intensity modulator is two weeks.

Figure 2 depicts the molecular arrangements of the LC within a mixture-filled hole in different situations. Without electric and magnetic fields, LC molecules show the typical distortions under normal boundary conditions, as illustrated in Fig. 2(a). LC molecules are aligned parallel to the wall at the center of the PCF hole and gradually twisted at a certain angle towards the wall along the direction of the radius.[18] The LC molecule angle is about 45° at the wall, and the Fe_3O_4 nanoparticles are uniformly distributed in the hole. In Fig. 2(b), when we apply an alternating electric field to the PCF, the alignment of the LC molecules changes from distortions to neat arrays, which results in a strong light scattering in filling holes and then light losses in the fiber core.

In Fig. 2(c), when a lab-obtainable magnetic field is employed to this PCF, the Fe_3O_4 nanoparticles in the PCF hole are arranged in chains along the direction of the magnetic field. The LC molecules are forced to array in lines along the chains and present a similar molecular arrangement pattern to that of the electric field. As a result, the light losses in the PCF lead to a significant change of the transmission intensity.

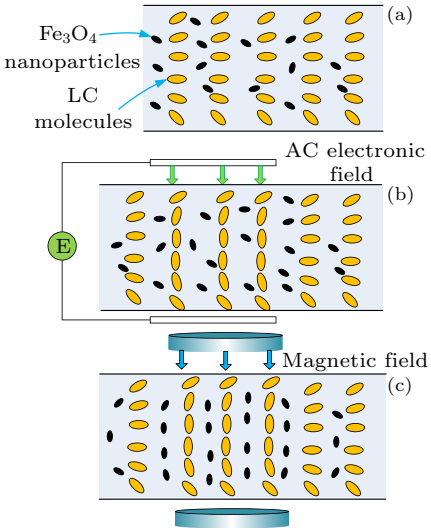


Fig. 2. Schematic diagrams of the alignment of LC molecules and Fe_3O_4 nanoparticles in one hole of the PCF filled with LC and MF (a) without electric and magnetic fields, (b) in an electric field, and (c) in a magnetic field.

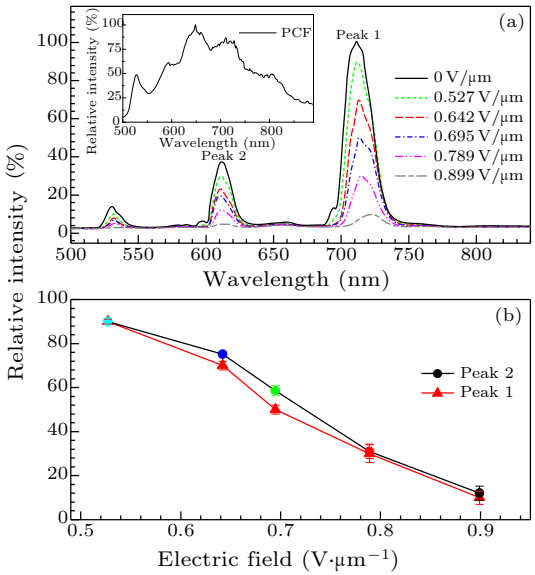


Fig. 3. (a) Transmission spectra of the PCF filled with the LC in different electric fields with a frequency of 20 Hz. (b) Peak intensities of peaks 1 and 2 in different electric fields. The inset is the transmission spectrum of an unfilled PCF.

To prove the effect of the electric field on the LC molecules, we first only fill the LC into the PCF. An electric field with a frequency of 20 Hz is applied to the PCF. The transmission spectra in the wavelength range 500–800 nm in different electric field strengths are shown in Fig. 3(a), in which three peaks with peak wavelengths of 530 nm, 611 nm (peak 2), and 711 nm (peak 1) are observed. When the electric field strength increases, the wavelengths of all these three peaks are almost invariable, whereas the peak intensities significantly decrease. Taking the highest peak 1 of

711 nm as an example, the peak intensity in the original state (0 V/μm, 20 Hz, black curve) is set as 100%. The intensity remains constant when the electric field strength is smaller than 0.5 V/μm. When the electric field increases to 0.53 V/μm (green curve), the peak intensity drops to 90%. As the electric field reaches 0.899 V/μm (grey curve), the peak intensity decreases to 10%. However, the peak wavelength shifts no more than 2 nm. We have demonstrated that different reflective indices in air holes would change the transmission modes in the PCF and the peak wavelengths as well.[19] This experimental result proves that the reflective index of the LC is not affected by the change of the molecular arrangement of the LC. When the electric field is larger than 0.899 V/μm, the peak intensity is too weak to be distinguished from the background. Therefore, we set the cut-off electric field of this kind of optical modulator to a value at which the peak intensity drops to 10%. The inset is the transmission spectrum of an unfilled PCF. The transmission spectra of unfilled and filled PCFs look very different because the guiding mechanism of the PCF changes from the modified total internal reflection to the photonic bandgap guidance when we fill a liquid into the PCF.

Figure 3(b) presents the dependence of the peak intensities of peaks 1 and 2 on the electric field. Both peaks are normalized by the peak intensities in the original state to show the decreasing tendency. The electro-optical modulator remains at almost the same function at these two peaks. Repeated experiments indicate that the discrepancy of the peak intensities is less than 9%, which shows a good reliability. These results prove that the intensity of light can be modulated by an electric field.

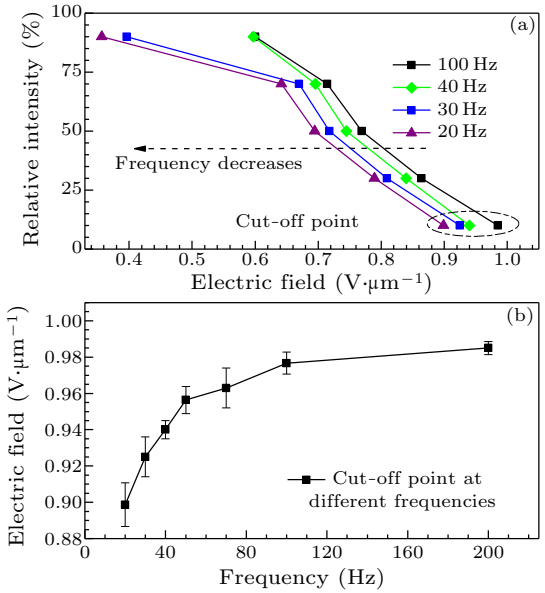


Fig. 4. (a) Peak 1 intensities of LC-filled PCF in electric fields with different frequencies. (b) Dependence of the cut-off electric field on the electric field frequency.

In addition, the effect of the frequency of the electric field on the peak intensity is also investigated. Figure 4(a) exhibits the peak intensities of peak 1 in electric fields with different frequencies, in which a stronger electric field is required to acquire the same attenuation for a higher electric field frequency. The dependence of the cut-off electric field on the electric field frequency is shown in Fig. 4(b). The cut-off electric field rapidly increases when the frequency rises from 20 to 50 Hz, and then the cut-off electric field stabilizes between 50 and 200 Hz. The discrepancy of the cut-off electric field is less than 5%. If we apply an electric field with a frequency smaller than 10 Hz, the transmission intensity will not remain stable.

As discussed above, the frequency of the electric field has an effect on the intensity modulation. The reason can be explained through the dynamic coherent light-scattering which appears in liquid crystal cells, reported in 1970.[20] In the dynamic coherent light-scattering, a stronger electric field is needed to gain the same hydrodynamic instabilities for a higher frequency.[21] The molecular arrangement of the LC in the PCF is the same as that in liquid crystal cells. Therefore, the electric field frequency will cause a similar effect on the LC filled PCF, which is in good agreement with our experimental measurement.

We also try to utilize magnetic bars to generate a magnetic field of 200 mT to influence the LC-filled PCF. However, the transmission spectrum shows no response to the magnetic field. As the magnetically insensitive LC molecules, the relationship between electric and magnetic fields for the LC transform[22] is defined by

$$E = (4\pi\Delta\chi/\Delta\varepsilon)^{1/2}H, \tag{1}$$

where $\Delta\chi$ is the difference between magnetic susceptibilities of $n_{\rm o}$ and $n_{\rm e}$, and $\Delta\varepsilon$ is the difference between dielectric constants of $n_{\rm o}$ and $n_{\rm e}$, and 5CB LC, which is used in our experiment, has $\Delta\varepsilon$ and $\Delta\chi$ of 13.3 and 10^{-7} cgs (cm·g·second), respectively.

Based on Eq. (1), if we intend to obtain the same influence as the electric field of 0.899 V/μm, the magnetic field will be about 1.82 T. The magnetic field of 200 mT is much lower than the value that can cause an effect on the light intensity. Therefore, we filled the PCF with a mixture of the MF and the LC. Compared to the black curve in Fig. 3(a), which is the transmission spectrum of an LC-filled PCF without magnetic and electric fields, the blue curve in Fig. 5(a), which is the transmission spectrum of a mixture-filled PCF without magnetic and electric fields, exhibits a completely different spectrum. The reason is that the LC and the mixture have different reflective indices, which results in different transmission modes in the fiber and then various peaks in the transmission spectra. There are three peaks of 501 nm (peak 3), 549 nm, and 688 nm in the blue curve. However, the effects of the electric field on the transmission spectrum of mixture-filled PCF are the same as those of the LC-filled PCF, i.e., the peak intensity decreases as the electric field increases, and a stronger electric field strength is demanded to generate the same intensity attenuation for a higher frequency.

In Fig. 5(a), the mixture-filled PCF shows a remarkable intensity response to the magnetic field. Although the molecular arrangement of the LC is driven to rotate towards the direction of the magnetic field by Fe_3O_4 nanoparticles, the reflective index of the LC has no change. Therefore, all the peak intensities decrease with the increase of the magnetic field whereas the peak wavelengths change by no more than 2 nm. The inset is the transmission spectrum of an unfilled PCF. The dependence of the peak 3 intensity on the magnetic field is presented in Fig. 5(b). Its goodness of fit is 0.97487. The discrepancy of the peak intensity is less than 6%, and the cut-off magnetic field of this optical modulator (10% of the maximum intensity) is 195 mT. Therefore, the light intensity can be modulated by a magnetic field.

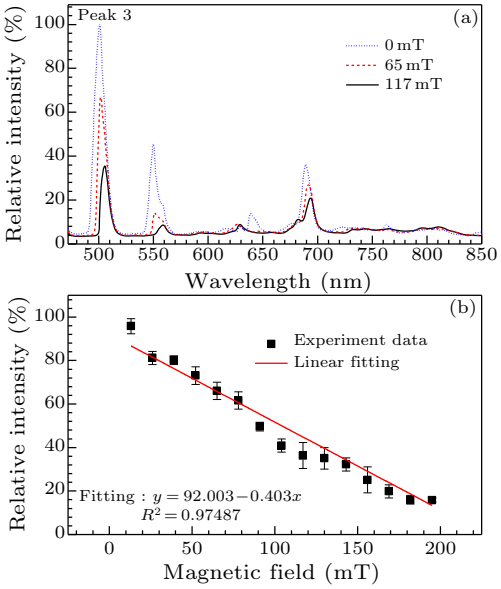


Fig. 5. (a) Transmission spectra of a mixture-filled PCF in different magnetic fields. (b) Peak intensities of peak 3 in different magnetic fields. The inset is a transmission spectrum of an unfilled PCF.

In conclusion, we have presented a light intensity modulator based on a magnetic fluid (MF) and liquid crystal (LC) filled photonic crystal fiber (PCF). The transmission light in the PCF can be attenuated by increasing the electric or magnetic field. The cut-off electric field at 20 Hz is 0.899 V/μm and the cut-off magnetic field is 195 mT. In addition, for an electric field with a higher frequency, stronger electric field strength is required to gain the same extinction. This light intensity modulator has a great application prospect for an integrated electric and magnetic sensor.

References

[1] Russell P 2003 *Science* **299** 358
[2] Birks T A, Knight J C and Russell P St J 1997 *Opt. Lett.* **22** 961
[3] Peng Y, Hou J, Zhang Y et al 2013 *Opt. Lett.* **38** 263
[4] Dhara P and Singh V K 2015 *Opt. Fiber Technol.* **21** 154
[5] Gangwar R K and Singh V K 2015 *Photon. Nanostruct. Fundam. Appl.* **15** 46
[6] Harvey J D, Leonhardt R, Coen S et al 2003 *Opt. Lett.* **28** 2225
[7] Wong G K L, Chen A Y H, Ha S W et al 2005 *Opt. Express* **13** 8662
[8] Lenihan S A, Salem R, Murphy T E et al 2006 *IEEE Photon. Technol. Lett.* **18** 1329
[9] Li X P, Hu W S and Yu H L 2017 *Chin. J. Liq. Cryst. Displays* **32** 234
[10] Liu X Q, Liu Y G and Wang Z 2017 *Liq. Cryst.* **44** 479
[11] Luo X P, Wang F R, Chen C L et al 2017 *Chin. Phys. Lett.* **34** 124203
[12] Hu D J J, Lim K J L, Cui Y P P et al 2012 *IEEE Photon. Technol. Lett.* **4** 1248
[13] Alkeskjold T T, Laegsgaard J, Bjarklev A et al 2006 *Appl. Opt.* **45** 2261
[14] Alkeskjold T T, Laegsgaard J, Bjarklev A et al 2004 *Opt. Express* **12** 5857
[15] Du F, Lu Y Q and Wu S T 2004 *Appl. Phys. Lett.* **85** 2181
[16] Miao Y P, Liu B, Zhang K L et al 2011 *Appl. Phys. Lett.* **98** 021103
[17] Zu P, Chan C C, Gong T X et al 2012 *Appl. Phys. Lett.* **101** 241118
[18] Scolari L, Alkeskjold T T, Riishede J et al 2005 *Opt. Express* **13** 7483
[19] Wang J L, Du M Q, Zhang L L et al 2015 *Acta Phys. Sin.* **64** 12070 (in Chinese)
[20] Orsay Liquid Crystal Group 1970 *Phys. Rev. Lett.* **25** 1642
[21] Gennes D P 1973 *The Physics of Liquid Crystal* (Oxford: Oxford University)
[22] Maier V W and Saupe A 1960 *Teil II. Naturforsch* **15a** 287