Propagation characteristics of six-core photonic liquid crystal fibers*

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We demonstrate a new kind of multi-core photonic liquid crystal fibers (PLCFs) which have six liquid crystal cores arrayed in the ring-type geometry and separated by the air holes. Through analyzing the structure of this kind of PLCFs, it can be found that they have the ability to resist the structure deformation. Due to the effective index of the liquid crystal can be adjusted by temperature and wavelength, the energy in the six liquid crystal cores is increased with the temperature increasing and wavelength decreasing. The effective index of the PLCFs is decreased, the effective fundamental mode area is increased and the dispersion properties are gently affected with the wavelength increasing and temperature decreasing.

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For further enhancing the versatility of photonic crystal fibers (PCFs), many methods have been proposed and explored[1]. Fiber post-processing can be used to create longitudinal changes in core size and air filling fraction[2,3], and the hollow channels can be filled with materials such as polymers[4], liquid[5] or metals[6,7]. The embedded PCFs are widely used in PCFs mode converters, PCFs couplers and PCFs beam splitters. For example, our group[8] proposed the Ge dropped PCFs mode converters, J. Hou et al[7] used the PCFs with multi-metal cores to get single mode transmission by metallic reflection, S. K. Varshney et al[9] proposed the multi-core photonic crystal fiber-based 1×4 power splitters, and so on.

The liquid crystal (LC) is a kind of material whose index is sensitive to temperature and electromagnetic field[10]. Due to the index of LC can be adjusted, LC is widely used in dynamic scene projectors, laser beam steering, tunable bandgap photonic crystal fibers and millimeter-wave electronic phase shifters[11]. The photonic liquid crystal fibers (PLCFs) are special PCFs, whose holes are filled with the LC. This new kind of infiltrated PCFs has many novel properties and new applications in the area of temperature and electrically controlled fiber-optic sensing, as well as in all-optical data processing[12]. K. Satioh et al[13] obtained the tunable photonic crystal fiber couplers with a thermo-responsive liquid crystal resonator, S. Ertman et al[14] got tunable highly-birefringent photonic liquid crystal fibers based on PM-1550-01 PCFs which were filled with nematic liquid crystal, and L. Scolari et al[15] designed continuously tunable devices based on electrical control of dual-frequency liquid crystal filled photonic bandgap fibers. But the beam splitter based on PLCFs, which is sensitive to the temperature and wavelength, has not been proposed as our knowledge.

In this paper, we design a new kind of PCFs with six liquid crystal cores. First, we change the structure of PCFs to fix the optimal structure parameters. And then, we find that the effective index, dispersion properties, the mode field area of six liquid crystal cores and the intensity distribution are changed with varying wavelength and temperature. So this kind of PLCFs can be used as the fiber beam splitter, which is sensitive to temperature and wavelength.

The structure of the designed PLCFs is shown in Fig.1. The central core is an air hole instead of solid core to avoid the light power coupling between the central core and the six liquid crystal cores. Six air holes in the second ring of cladding are filled with LC to form the liquid crystal cores, and they are separated by air holes.

The electric field in each single core of PCFs can be expressed as[16]

$$\boldsymbol{E}_m(x,y,z)=E_m(x,y)\exp(\mathrm{i}\beta_m z)\ . \tag{1}$$

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Due to the coupling among all cores, the distribution of total electric field can be expressed as[17] ,

$$\boldsymbol{E}(x,y,z)=\sum_{m}A_m(z)\boldsymbol{E}_m(x,y)\exp(\mathrm{i}\beta_m z),$$
$$(m=1,2,\cdots,6)\ . \qquad (2)$$

In the multi-core fibers, the energy coupling happens in different cores. The modes which are transmitted in each core are determined by the material and geometry structure of fibers. So the multi-core, which couples with each other, can not produce high-order mode when they only transmit a single mode.

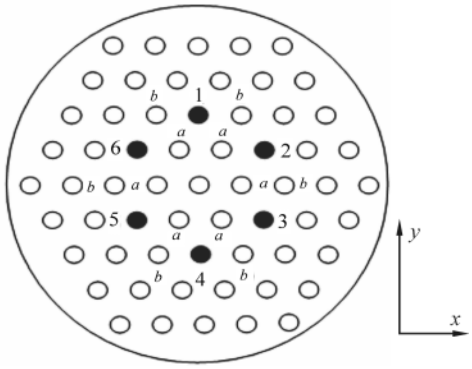


Fig.1 Structure of the designed six-core PLCF

We only consider the propagation along z direction and establish a vector as

$$\boldsymbol{E}(z)=\begin{bmatrix}A_1(z)\exp(\mathrm{i}\beta_1 z)\\A_2(z)\exp(\mathrm{i}\beta_2 z)\\\cdots\\A_6(z)\exp(\mathrm{i}\beta_6 z)\end{bmatrix}=\begin{bmatrix}E_1(z)\\E_2(z)\\\cdots\\E_6(z)\end{bmatrix}\ . \qquad (3)$$

Here, we assume that every core only couples with its neighbor cores. According to coupling mode theory, the coupling characteristics among different cores can be expressed as

$$\frac{\mathrm{d}\boldsymbol{E}(z)}{\mathrm{d}z}=\widetilde{\boldsymbol{C}}\cdot\boldsymbol{E}(z)\ , \qquad (4)$$

where $\widetilde{\boldsymbol{C}}$ can be expressed as

$$\widetilde{\boldsymbol{C}}=\begin{bmatrix}\mathrm{i}s_1 & \mathrm{i}k_{12} & 0 & 0 & 0 & \mathrm{i}k_{16}\\\mathrm{i}k_{21} & \mathrm{i}s_2 & \mathrm{i}k_{23} & 0 & 0 & 0\\0 & \mathrm{i}k_{32} & \mathrm{i}s_3 & \mathrm{i}k_{34} & 0 & 0\\0 & 0 & \mathrm{i}k_{43} & \mathrm{i}s_4 & \mathrm{i}k_{45} & 0\\0 & 0 & 0 & \mathrm{i}k_{54} & \mathrm{i}s_5 & \mathrm{i}k_{56}\\\mathrm{i}k_{61} & 0 & 0 & 0 & \mathrm{i}k_{65} & \mathrm{i}s_6\end{bmatrix}, \qquad (5)$$

where k_{mn} is the coupling coefficient between core m and core n, and s_n is the self-coupling coefficient of core n.

Six high index liquid cores are arrayed symmetrically around the central air hole. Because of the special structure of PLCFs, the self-coupling coefficients s_i are the same, so

$$s_1=s_2=s_3=s_4=s_5=s_6\ . \qquad (6)$$

In the relative perfect symmetrical structure, we can get an eigenvector [1,1,1,1,1,1], so all the powers distribute equally in the six liquid cores.

Based on the finite element method, we calculate the single mode condition of PLCFs at first. It can be found that the single mode cutoff wavelength is 1.0 μm when the ratio of the diameter d to the pitch Λ is 0.6. In other words, the PCFs keep single mode transmission when $d/\Lambda<0.6$, and the wavelength is larger than 1.0 μm. Considering above analysis and actual fabrication condition, d is set as 1.2 μm, and $d/\Lambda=0.45$. The material of PLCFs is SiO_2, and the effective index of SiO_2 is set as 1.45. The environment temperature is set as 25 °C, and the wavelength is set as 1.0 μm. The effective index of LC is 1.51 under these conditions.

Because the air holes, which are arrayed in the first ring of cladding and between the liquid crystal cores, have significant effect on the six liquid crystal cores, we analyze the effect of these air holes with different structure parameters on the six liquid crystal cores to fix the optimal PLCFs structure. First, the diameter of the air holes which are arrayed in the first ring of cladding and named "*a*" is changed in Fig.1. The diameter of "*a*" is changed from 1.6 μm to 0.8 μm. Due to the intensity distributions of six liquid crystal cores are the same, we only express the intensity distribution in two liquid crystal cores, which are arrayed in y direction. Fig.2 depicts the intensity distribution of six liquid crystal cores when the diameter of "*a*" is changed. We can find that the intensity distribution of six liquid crystal cores is decreased a little with the diameter of "*a*" increasing. And then we analyze the effect of the air holes named "*b*" shown in Fig.1. Without changing other structure parameters, we change the diameter of "*b*" from 1.6 μm to 0.8 μm. From Fig.3 we can know that the intensity distribution of six liquid crystal cores is gently increased by decreasing the diameter of

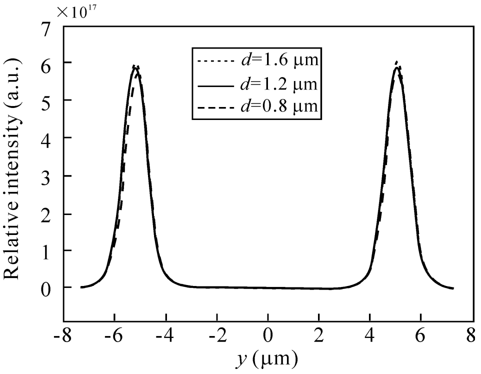


Fig.2 Effect of the diameter of the air holes named "*a*"

"*b*". Based on above analysis, the diameters of air holes named "*a*" and "*b*" have little effect on the intensity distribution of six liquid crystal cores, so this kind of PLCFs has immunity somewhat to the structure deformation. For fabricationg easily, we fix the ratio of diameter to pitch at 0.45, and the diameter of all air holes and six liquid crystal cores is 1.2 μm.

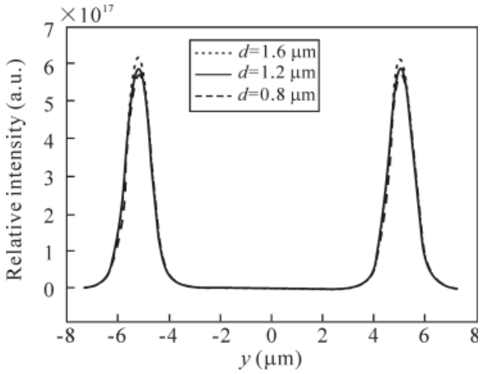


Fig.3 Effect of the diameter of the air holes named "*b*"

Without changing other conditions, we only increase the incident wavelength from 1.0 μm to 1.4 μm in step of 0.2 μm, and the intensity distribution in the six liquid cores is decreased a lot. The intensity distribution is changed from 5.90 × 10^{17} at 1.0 μm to 2.95 × 10^{17} at 1.4 μm, and the intensity is decreased 50% as shown in Fig.4. Thus we know that the intensity distribution in six liquid crystal cores can be adjusted by changing wavelength.

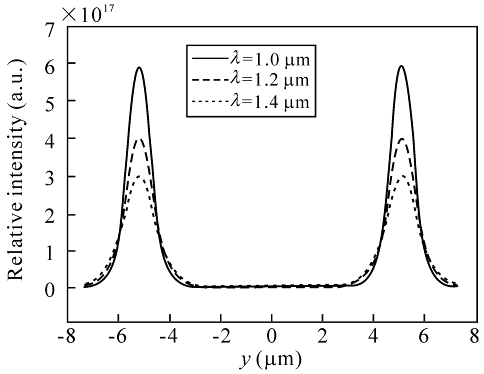


Fig.4 Effect of the incident wavelength

The index of LC can be expressed by Cauchy equation. When the wavelength range is between visible and infrared radiation (IR) wavelengths, it only needs to keep up to the λ^{-4} terms. The wavelength and thermo-optical dispersion characteristics for LC molecules are considered as the following type[2,5]

$$n_i(T,\lambda) = A_i(T) + \frac{B_i(T)}{\lambda^2} + \frac{C_i(T)}{\lambda^4}\ , \tag{7}$$

where n_i (i=o or e) is the ordinary (n_o) and extraordinary (n_e) refractive indices. $A_i(T)$, $B_i(T)$, $C_i(T)$ are the wavelength dependent Cauchy coefficients. Eq.(7) can be applied well to both high and low birefringence liquid crystal materials. For low birefringence liquid crystal mixtures, the λ^{-4} terms are insignificant and can be omitted, so n_o and n_e have only $A_i(T)$ and $B_i(T)$ parameters. The wavelength is set to 1.0 μm, and the environment temperature is set to 25 °C, 35 °C and 45 °C, respectively. Fig.5 depicts that the intensity distribution of six liquid crystal cores is increased with temperature increasing. When the environment temperature is changed from 25 °C to 45 °C, the intensity distribution is raised from 5.90 × 10^{17} to 7.42 × 10^{17}, and the intensity is increased by 25%. So the intensity of six liquid crystal cores is sensitive to temperature, the intensity can be controlled by changing temperature, and the change of temperature can be determined by analyzing the intensity variation.

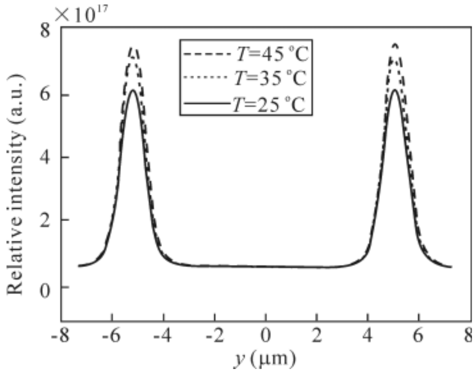


Fig.5 Effect of the environment temperature

We analyze the effective index of six liquid crystal cores of PLCFs in different wavelengths. At certain temperature, the effective index of PLCFs is decreased with wavelength increasing, and the effective index of PLCFs is increased with temperature increasing at certain wavelength as shown in Fig.6. The mode field distribution of six-core PLCF is shown in Fig.7. Fig.8. depicts that the effective mode field area of each liquid crystal core is increased with wavelength increasing and temperature decreasing. So the size of the effective

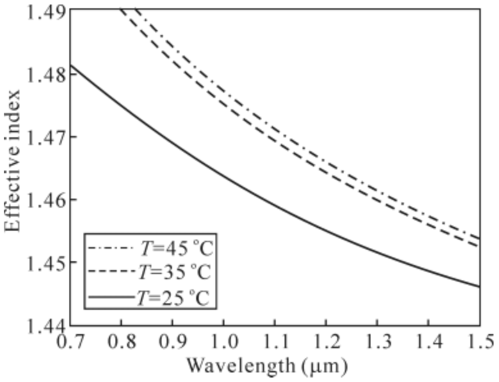
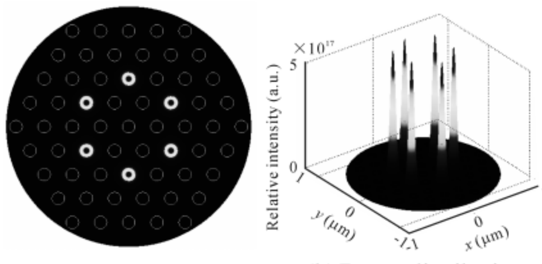


Fig.6 Change of effective index with wavelength in different temperatures

mode field area can be adjusted by controlling temperature and wavelength. Finally, we analyze the dispersion properties of PLCFs. From Fig.9 it can be known that the dispersion value is increased with wavelength increasing, but the trend becomes gentle with temperature increasing.



(a) Mode field distribution (b) Energy distribution

Fig.7 Distributions of the mode field and energy in the six-core PLCF

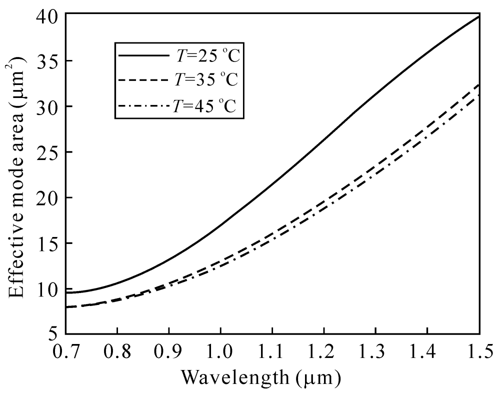


Fig.8 Change of the effective mode field area with wavelength in different temperatures

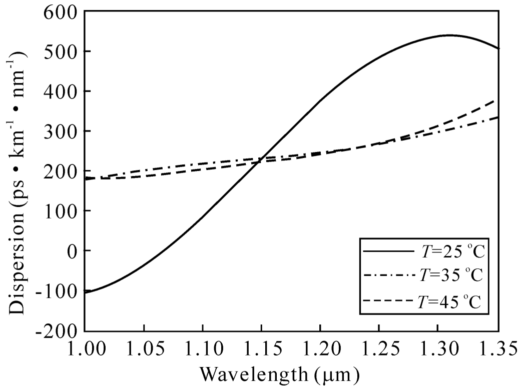


Fig.9 Change of the dispersion with wavelength in different temperatures

In this paper, we propose a new kind of PLCFs with six liquid crystal cores. Due to the effective index of liquid crystal is sensitive to temperature and incident wavelength, the intensity distribution and effective mode area of six liquid crystal cores are increased with temperature increasing and wavelength decreasing. The trend of dispersion curve becomes gentle with temperature increasing. Based on these characteristics, this kind of PLCFs is a good candidate for wavelength and temperature tunable 1×6 splitter and splitter sensor, which is sensitive to temperature.

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