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journal or publication title	IEEE photonics technology letters
volume	26
number	6
page range	541-543
year	2014-03-15
URL	http://hdl.handle.net/10258/3824

doi: info:doi/10.1109/LPT.2013.2296592

Design of Polarization Splitter with Single-Polarized Elliptical-Hole Core Circular-Hole Holey Fibers

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***Abstract*—We propose a novel polarization splitter based on coupled elliptical-hole core circular-hole holey fibers (EC-CHFs). Utilizing the single-polarization nature of EC-CHFs, in the proposed polarization splitter, two orthogonally polarized waves couple only to different EC-CHFs and the crosstalk-free polarization splitting is realized. Also, the coupling length for two orthogonally polarized waves can be independently designed and this splitter is easy to design.**

***Index Terms*—polarization splitter, elliptical-hole core circular-hole holey fiber, single polarization property, vector finite element method**

I. Introduction

Novel optical fibers consisting of a single material with air holes have made remarkable advances over the past decade. The photonic crystal fibers (PCFs) [1],[2], which are composed of single-material fibers having a periodic air-hole lattice in the cladding, achieve the special properties that cannot obtained by the conventional fibers, such as endlessly single-mode behavior, very flexible dispersion control, zero-dispersion wavelength in the visible light band, hollow core propagation and so on [2]. One of the properties is absolutely single polarization transmission and several kinds of PCF structures which realize single polarization transmission have been proposed so far [3]-[6]. Recently a novel single-polarization circular-hole holey fiber with an elliptical-hole core, which is referred to as an elliptical-hole core circular-hole holey fiber (EC-CHF), has been proposed for achieving the single polarization regime easily [5],[6]. Polarization splitters [7],[8] are essential components for polarization division multiplexing (PDM) in coherent photonic network. In this research we offer a design of polarization splitter based on EC-CHFs, and investigate the polarization splitting property of the device. Compare with [7],[8], in our proposed device, utilizing single polarization nature of EC-CHFs, the x- and y-polarized waves essentially couple into different fibers without any crosstalk.

II. Polarization splitter with EC-CHFs

In this section, we explain the principle of single polarization transmission in the EC-CHF and introduce the design example of the polarization splitter.

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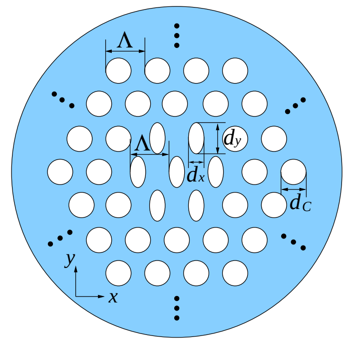


Fig. 1. Elliptical-hole core circular-hole holey fiber (The yEC-CHF).

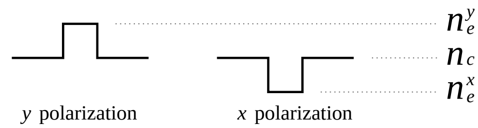


Fig. 2. Equivalent refractive index distribution in the radial direction through the core center of a yEC-CHF.

A. PRINCIPLE OF SINGLE POLARIZATION TRANSMISSION

A cross-section view of an EC-CHF with one-ring elliptical-hole core whose major axis is aligned along the y direction is indicated in Figure 1. This kind of EC-CHF is referred to as a yEC-CHF. When the circular holes of the cladding are isotropic, the birefringence only in the core region can be achieved by introducing elliptical-holes in the core region. The absolutely single polarization transmission also can be realized with appropriate air hole parameters. If $d_x < d_y$, the fiber will be a yEC-CHF that transmits only the y-polarized wave. Figure 2 shows the equivalent refractive index distribution for the x- and y-polarization in the radial direction through the core center of a yEC-CHF, respectively. For the y-polarized wave, compare with the cladding region, the core region has higher effective refractive index of fundamental space-filling mode (FSM). On the other hand, for the x-polarized wave, the core region has the lower effective refractive index of FSM. Therefore, the single-polarization transmission can be achieved. If $d_x > d_y$ by exchanging the directions of the major and minor axes of the elliptical-holes, only the x-polarized wave can be transmitted. This kind of EC-CHF is referred to as an xEC-CHF. In addition, if $d_x = d_y < d_C$, both of the x- and y-polarized waves can be transmitted simultaneously because there has no polarization dependence and we refer to it as a circular-hole core circular-hole holey fiber (CC-CHF) in this research.

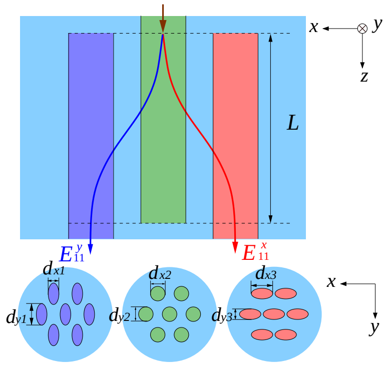


Fig. 3. Structure of the polarization splitter.

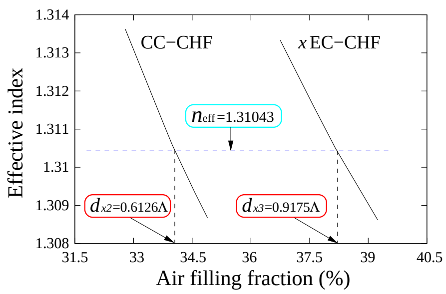
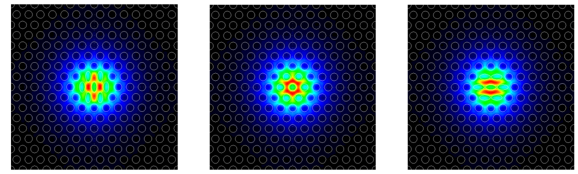


Fig. 4. Effective refractive indices n_{eff} of the CC-CHF and xEC-CHF as a function of the air filling fraction.

B. DESIGN OF PHASE MATCHED EC-CHFs

The structure of the polarization splitter that proposed in this research is shown in Figure 3. We observed that three EC-CHFs are placed in parallel, the waveguide on the left side is a yEC-CHF, the center is a CC-CHF, and the right side is an xEC-CHF. Because of the single-polarization nature of EC-CHFs, if a y-polarized light is incident on the CC-CHF, that will couple only to the yEC-CHF on the left. Similarly, an x-polarized light couples only to the xEC-CHF on the right. Therefore, arbitrarily polarized light is incident on the CC-CHF, it can be separated to the x-, y-polarization and couples to the xEC-CHF, yEC-CHF respectively without crosstalk.

In practical design, in order to reduce the insertion loss, it is necessary to satisfy the phase matching condition according to the coupled mode theory. In this study, in order to estimate the modal effective index, we employ the full-vectorial finite element method [9]. Here, the parameters of the yEC-CHF refer to Ref. [6]. The lattice pitch is $\Lambda = 1.24$ μm, a circular hole diameter in the cladding region is $d_C = 0.65\Lambda$, an elliptical hole size in the core region of the yEC-CHF is $d_{y1} = 0.9\Lambda$, and the ellipticity is $d_{y1}/d_{x1} = 2$. The refractive index of silica and air holes are $n_1 = 1.45$ and $n_2 = 1$, respectively. The operating wavelength is set to $\lambda = 1.55$ μm. In such conditions, the phase matching condition determines the air hole size in the core region of the CC-CHF and xEC-CHF. Figure 4 shows the effective refractive indices n_{eff} of the CC-CHF and xEC-CHF as a function of air filling fraction. Here, the ellipticity of the xEC-CHF is considered as $d_{x3}/d_{y3} = 2$. The dashed line represents the effective refractive index of the yEC-CHF. The air hole size that meets



(a) yEC-CHF (b) CC-CHF (c) xEC-CHF

Fig. 5. Magnetic field distribution in each EC-CHF.

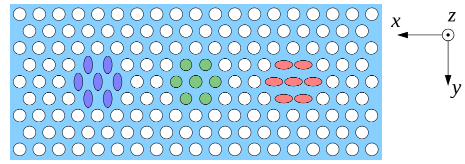


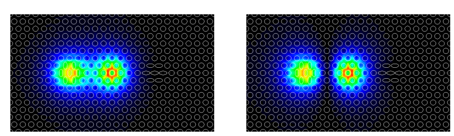
Fig. 6. Cross-sectional structure of the polarization splitter.

the phase matching condition corresponds to $d_{x2} = 0.6125\Lambda$ for the CC-CHF, and corresponds to $d_{x3} = 0.9175\Lambda$ for the xEC-CHF. The magnetic field distributions in each EC-CHF are shown in Figure 5. The mode field diameters in all structures are almost the same.

So far, three EC-CHFs which satisfy the phase matching condition have been designed, then we will determine the device length of the polarization splitter. In this polarization splitter, the device length is determined by the coupling lengths of the EC-CHF directional couplers, so we first calculate the coupling length of them. Figure 6 shows the cross-sectional structure of the polarization splitter. Each core is separated from the adjacent cores by two air holes. Figure 7 shows the modal field distributions of the y-polarized even- and odd-symmetric modes, respectively. We can observe that there is no light coupling to the xEC-CHF. The modal field distributions of the x-polarized modes are shown in Figure 8, on the contrary, there is no light coupling to the yEC-CHF. The effective refractive indices of the even and odd modes are obtained, then the coupling length L_c can be calculated by

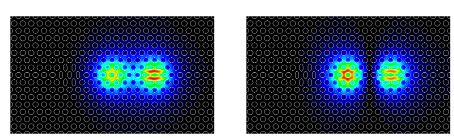
$$L_c = \frac{0.5\lambda}{n_{\mathrm{eff},1} - n_{\mathrm{eff},2}} \tag{1}$$

where $n_{\mathrm{eff},1}$ and $n_{\mathrm{eff},2}$ are the effective refractive indices of even- and odd-modes, respectively.



(a) Even mode (b) Odd mode

Fig. 7. Modal field distribution of the y-polarization.



(a) Even mode (b) Odd mode

Fig. 8. Modal field distribution of the x-polarization.

Table I shows the even and odd mode effective refractive indices of the coupled system and the estimated coupling lengths for the x- and y-polarization. The coupling lengths of the x- and y-polarized waves are slightly different. Consequently, in this research the average length has been adopted and the device length is set to $L = 630\ \mu$m. If the difference of the coupling lengths between the x- and y-polarized waves is not negligible, the coupling lengths can be independently designed for the x- and y-polarization by adjusting the air hole radius between the cores.

TABLE I
EVEN AND ODD MODE EFFECTIVE REFRACTIVE INDEX AND THE ESTIMATED COUPLING LENGTH

	Effective refractive index		L_c [μm]
	Even mode	Odd mode	
x-pol.	1.311040	1.309825	638
y-pol.	1.310982	1.309736	622

The propagation behavior in the polarization splitter is shown in Figure 9. If a 45-degree polarized light is incident on the CC-CHF, using the full-vector finite element beam propagation method [10], we can observe that the light is separated and moves to left and right side depending on the field components. The y-polarized component (H_x) couples only to the left side yEC-CHF, and the x-polarized component (H_y) couples only to the right side xEC-CHF. The light power of the CC-CHF is almost zero at the device length of 630 μm. The calculated crosstalk is about the same as the computer's round-off error. Actually, there is difference between the coupling lengths of the x- and y-polarization. In order to investigate the extent of the influence, the normalized power along propagation distance has been estimated, as seen in Figure 10. Assuming that a 45-degree polarized light is incident on the CC-CHF, there is a slight deviation in the graph of the xEC-CHF and yEC-CHF according to the difference of the coupling length. However, the normalized power at 630 μm of each waveguide is about 49.98%, the loss due to the difference of the coupling length is almost negligible. In another numerical simulation, if all of the hole sizes deviate 1%, the coupling efficiency degrades around 3%, and if only the hole sizes in a specific core deviate 0.2%, the coupling efficiency degrades around 5%. In practical application, there is a splice loss at the input and output edges, and it is necessary to consider the impact. Although the modal field distribution of an EC-CHF is unlike the Ganssian shape, the splice loss between an EC-CHF and a conventional single mode fiber (SMF) is not so large by adjusting the mode field diameter of the EC-CHF and SMF [11].

III. CONCLUSION

We proposed and designed a novel polarization splitter using the EC-CHF, and investigated its polarization splitting property. In the future, we are planning to study more about the polarization controlling device using the EC-CHF.

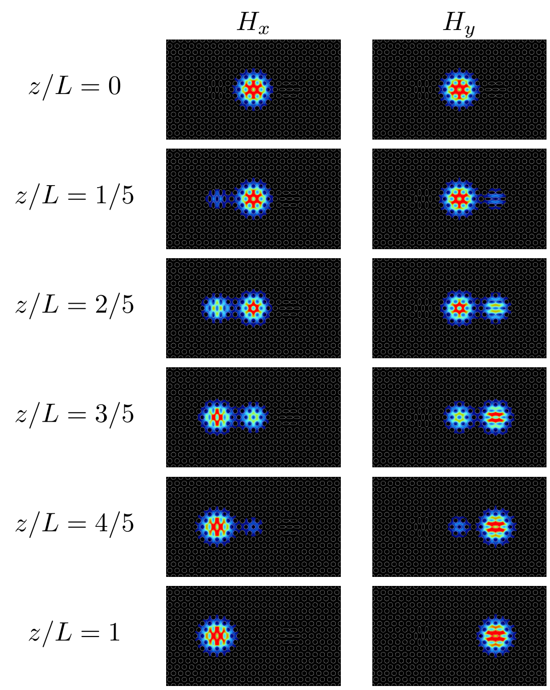


Fig. 9. Propagation behavior in the polarization splitter.

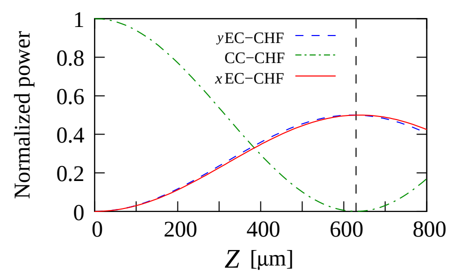


Fig. 10. Normalized power along the propagation distance.

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