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基于金线填充的双芯光子晶体光纤偏振分束器

白育堃[1,2],王彪[1]

(1 天津理工大学 电气电子工程学院 通信器件与技术教育部工程研究中心,天津 300384)

(2 天津大学 精密仪器与光电子工程学院 太赫兹中心 光电信息科学技术教育部重点实验室,天津 300072)

摘　要:提出了一种基于金线填充的双芯光子晶体光纤超短偏振分束器,并进行了有限元分析.金线表面激发的表面等离子激元与双芯光子晶体光纤纤芯模之间的强烈耦合,导致更短的偏振分束器长度和更大的工作带宽.与同类的偏振分束器相比,所提出的偏振分束器能同时实现较短的长度和较高的消光比.数值结果表明,长度为 0.263 mm 的偏振分束器,在波长 1.55 μm 处消光比达 −70 dB,−20 dB 消光比带宽为 124 nm.

关键词:双芯光子晶体光纤;金线;表面等离子极化;偏振分束器;消光比

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Polarization Splitter Based on Dual-Core Photonic Crystal Fibers Filled with Gold Wire

BAI Yu-kun[1,2], WANG Biao[1]

(1 *Engineering Research Center of Communication Devices and Technology, Ministry of Education, School of Electrical and Electronic Engineering, Tianjin University of Technology, Tianjin* 300384, *China*)

(2 *Key Laboratory of Optoelectronic Information Science and Technology, Ministry of Education, and Center for Terahertz Waves, College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin* 300072, *China*)

Abstract: An ultra-short polarization splitter based on dual-core Photonic Crystal Fiber (PCF) with a gold wire filled into the air hole between the two cores has been proposed and analyzed with the finite element method. Surface Plasmon Polaritons (SPPs) excited on the surface of gold wire have strong resonant coupling with the guided core modes of PCF, which enables a short polarization-splitting length and broadband operation. Compared to its counterparts, the proposed polarization splitter exhibits a shorter length and higher Extinction Ratio (ER), simultaneously. Numerical results indicate that the 0.263 mm long polarization splitter can achieve an ER of −70 dB at the wavelength of 1.55 μm with −20 dB-ER bandwidth of 124 nm.

Key words: Dual-core photonic crystal fiber; Gold wire; Surface plasmon polaritons (SPPs); Polarization splitter; Extinction ratio

OCIS Codes: 230.5298; 240.6680; 250.5403; 240.3990; 260.1140

0 Introduction

Photonic Crystal Fibers (PCFs) have been widely used in modern communication system due to many advantages, such as endless single-mode[1], large mode area[2], low loss[3], high nonlinearity[4], high

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First author: BAI Yu-kun (1970−), male, associate professor, Ph. D. degree, mainly focuses on fiber grating sensing technology. Email: tjutbai_1@163.com

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birefringence[5] and controllable dispersion[6]. In recent years, many researchers have studied polarization beam splitter based on photonic crystal fiber. The splitter functions to separate the input light into two orthogonal polarization light. It can control two orthogonal-polarization modes refractive indices to achieve their different coupling lengths. Typically, PCF-based polarization splitting can be realized with one of the following two methods. The first one involves using of highly birefringent Photonic Crystal Fiber (PCF) structures such as dual-core or three-core PCFs, these structures can only allow one polarized mode couple between fiber cores[7-8]. The second one involves filling or coating the void cores of PCF with metal[9], water, liquid crystal[10] or polymer[11] to change the polarization properties of PCFs. In the metal-filled PCF, the Surface Plasmon Resonance (SPR) appears at certain resonance wavelength, where the Surface Plasmon Polariton (SPP) mode and the guided-core mode are strongly coupled as the phase matching condition is satisfied, and the energy contained in the guided-core mode is transferred to the SPP modes[12].

In recent years, many researchers have successfully fabricated metal-filled PCF polarization beam splitter[13]. For example, Nagasaki et al. investigated the coupling properties between the core modes and SPP modes for PCFs with metal wires filled into the air holes[13]. Zhang et al. theoretically studied the dual-core photonic crystal fiber filled with a metal wire in the center air hole[14]. Sun et al. proposed a polarization splitter filled with a silver wire in the air hole, which is 6.3 mm long and the −20 dB-Extinction-Ratio(ER) bandwidth is 146 nm[16]. Liu proposed a broadband polarization splitter using a dual-core PCF filled with gold wires in four air holes, which is 0.585 mm long and has a −20 dB-ER bandwidth of 400 nm[9]. However, the ER is only about −23 dB at 1.55 μm. Jiang L et al. proposed an ultra-broadband polarization splitter based on a square-lattice dual-core photonic crystal fiber filled with a gold wire, which is 4.036 mm long and the −20 dB-ER bandwidth is 430 nm[17]. Fan Z et al. compared the results of the gold-wire-filled and gold-layer-coated DC-PCFs, which indicated that with corresponding lengths of 0.542 mm and 2.605 mm, the bandwidth of the former is twice as much as that of the latter, and ERs of −84 dB and −62 dB at the wavelength of 1.55 μm[13] can be obtained, respectively.

In this paper, we propose a polarization splitterbased on a dual-core PCF with a gold wire filled into the air hole between two cores. In this work, we study the polarization characteristics of the structure based on the supermode theory and the Finite Element Method (FEM)[18]. The metal wire can greatly change the coupling characteristics of the cores. Compared to conventional dual-core PCFS, the coupling lengths is significantly decreased. With a length of 0.263 mm, the proposed polarization splitter exhibits an ER of −70 dB at the resonance wavelength of 1.55 μm and −20 dB-ER bandwidth of 124 nm, simultaneously.

1 Structure designed and basic theory

The cross-section of the proposed PCF polarization splitter is shown in Fig. 1. The air holes are arranged in a hexagonal lattice with lattice pitch $\Lambda=2.5$ μm. The parameters of the elliptical air holes are $a=1.4$ μm and $b=2$ μm with ellipticity of $\eta=a/b$. The dark air hole is filled with a gold wire, the diameter of the gold wire is $d_1=1.16$ μm. The diameters of the small and large air holes are $d_2=1.6$ μm and $d_3=2$ μm, respectively. The background material is pure silica with the refractive index set as 1.45. The refractive index of air is set as 1. In the numerical simulation, a Perfectly Matched Layer (PML) [20] is used for absorbing the radiation energy. The relative permittivity of the gold wire is approximated in the visible and near-IR region by using the Drude-Lorentz model with five Lorentz oscillators as follows[21]

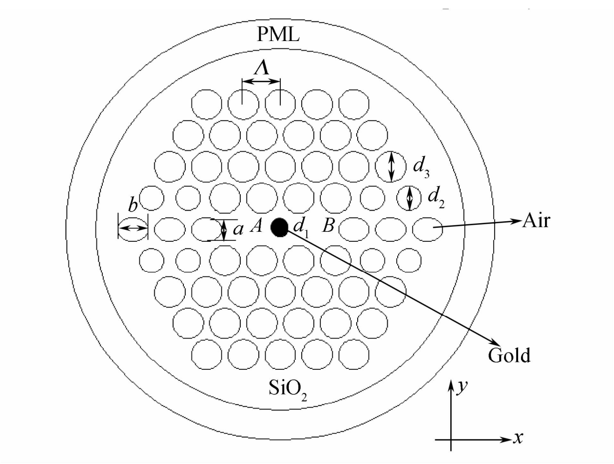


Fig. 1 Cross-section of the proposed DC-PCF. The background material is silica, and the black center hole is filled with gold wire

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\gamma D)} - \frac{\Delta\varepsilon \cdot \Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L \omega} \tag{1}$$

where, $\varepsilon_\infty = 5.9673$ is the relative permittivity in the high frequency, ω_D is the plasma frequency, $\omega_D/2\pi = 2113.6$ THz, γ_D is the damping frequency, $\gamma_D/2\pi = 15.92$ THz, ω is the angular frequency of transmitting light, $\Delta\varepsilon = 1.09$ can be regarded as a weighting factor, $\Omega_L/2\pi = 650.07$ THz and $\Gamma_L/2\pi = 104.86$ THz represent the frequency and the spectral width of the Lorentz oscillator, respectively.

We can obtain the coupling characteristics by calculating the propagation constants of the x-polarized and y-polarized even and odd supermodes, the coupling lengths of the x-polarized and y-polarized modes of the polarization splitter are defined as[22]

$$L_{x,y} = \frac{\lambda}{2 \mid n_{\text{even}}^{x,y} - n_{\text{odd}}^{x,y} \mid} \tag{2}$$

where, $n_{\text{even}}^{x,y}$ denotes the refractive indices of the x-polarized and y-polarized even modes, respectively, and $n_{\text{odd}}^{x,y}$ denotes that of the odd modes. The two orthogonally-polarized modes launched into one core can be separated between the two cores, when the relation $L_C = mL_x = nL_y$ is satisfied, with m and n being positive integers and of opposite parities. The optimal value of the coupling length ratio is either $m:n = 1:2$ or $m:n = 2:1$ to realize a compact polarization splitter[23].

Assuming the incident light with power $P_{\text{in},A}$ is launched into core A, the output power normalized to $P_{\text{in},A}$ for the x-polarized and y-polarized light in core A with a length of L_C can be calculated as[17]

$$P_{A,\text{out}}^{x,y} = \cos^2\left(\frac{\pi \cdot L_C}{2 \cdot L_{x,y}}\right) \tag{3}$$

Extinction ratio is a key parameter to characterize the performance of a polarization splitter, which is defined as follows[19]

$$\text{ERA} = -10 \log_{10}\left(\frac{P_{A,\text{out}}^y}{P_{A,\text{out}}^x}\right) \tag{4}$$

where, $P_{A,\text{out}}^y$ and $P_{A,\text{out}}^x$ denote the normalized output powers of the y-polarized mode and x-polarized mode, respectively.

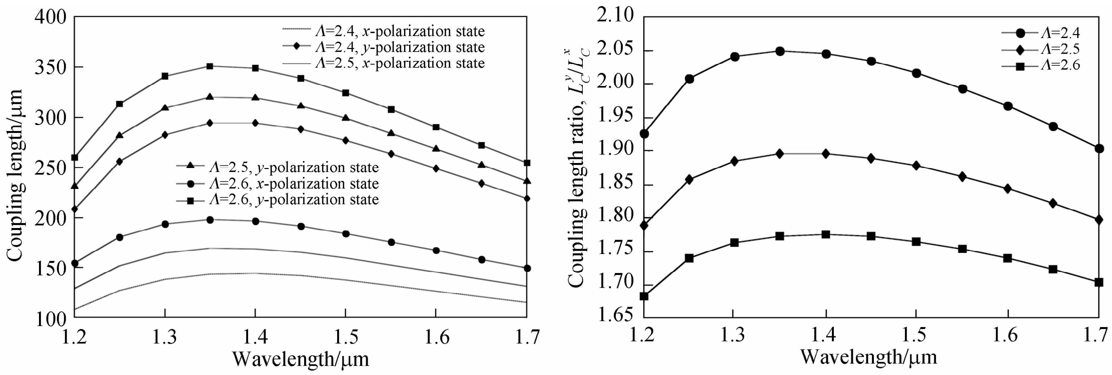
To characterize the modal propagation length, the mode loss[13] is defined as

$$\alpha = 8.686 \times \frac{2\pi}{\lambda} \text{Im}(n_{\text{eff}}) \times 10^4 \tag{5}$$

where, λ is the operation wavelength, $\text{Im}(n_{\text{eff}})$ is the imaginary part of the mode effective index, the units of the mode loss and the wavelength are dB/cm and micrometer, respectively[20].

2 Simulation results and analysis

In order to reveal the coupling characteristics of the polarization splitter, the effects of DC-PCF parameters, namely Λ, d_3 and η, on the coupling length ratio are investigated. As shown in the Fig. 2(a), when the $d_3 = 2$ μm and $\eta = 0.8$, the increase of the air-hole pitch Λ from 2.4 μm to 2.6 μm leads to the coupling-length increase of both polarizations. Fig. 2(b) shows the coupling length ratio within the wavelength range, and it is shown that the coupling length ratio approaches 2 when $\Lambda = 2.4$ at the wavelength of 1.55 μm.



(a) Coupling length (b) Coupling length ratio

Fig. 2 Coupling length and coupling length ratio versus wavelength for different pitches Λ

With $\Lambda = 2.4$ μm and $\eta = 0.8$, we adjust the parameter d_3 to realize a shorter coupling length. As shown in Fig. 3, the coupling length will increase with the increase of d_3 and the coupling length ratio is very close to 2 at the wavelength of 1.55 μm when the diameter $d_3=2$ μm.

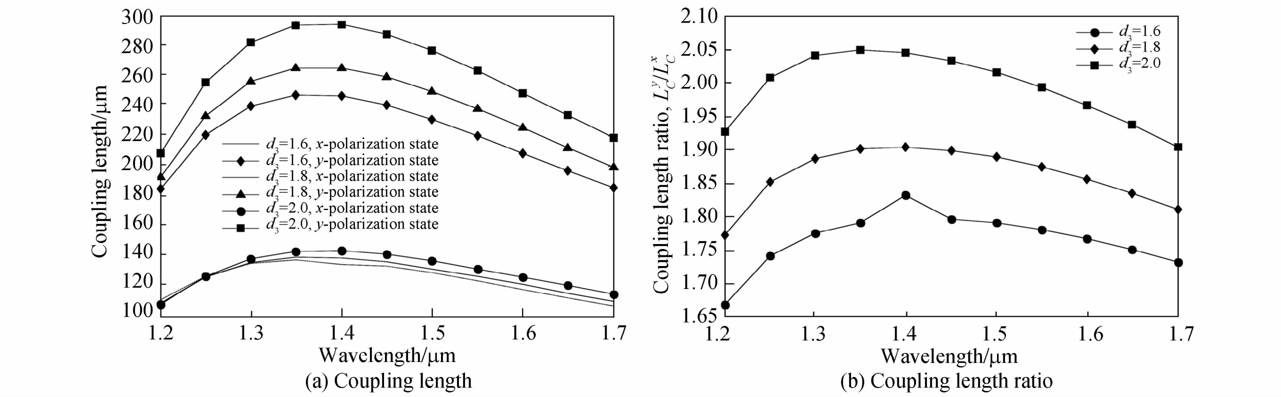


Fig. 3 Coupling length and coupling length ratio versus wavelength for different d_3

It can be seen from Fig. 4 that the ellipticity η also affects the coupling length ratio to a small extent, and the coupling length ratio approach 2 at the wavelength of 1.55 μm when $\eta=0.8$. Through the above analysis, we ultimately obtain a set of optimal parameters, i.e. $\Lambda=2.4$, $d_3=2$ μm, $\eta=0.8$ to achieve polarization splitting at 1.55 μm.

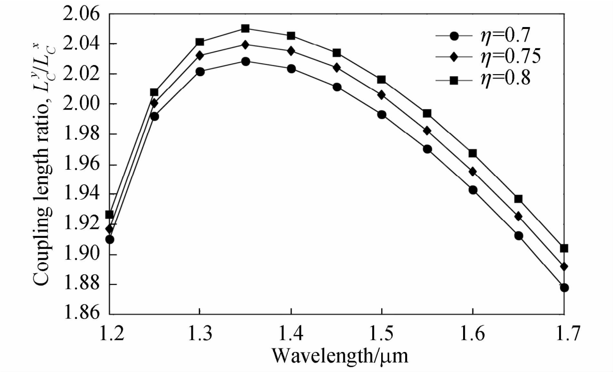


Fig. 4 Coupling length ratio versus wavelength for different η

In order to study the coupling characteristics of polarization splitter with gold wire, we have calculated the dispersion diagram of the DC-PCF structure, in which the effective indices of the 1st-SPP and 2nd-SPP modes excited on the surface of

SPP and 2nd-SPP modes excited on the surface of gold wire and the x-polarized and y-polarized supermodes of DC-PCF are presented. It can be seen from Fig. 5 that the phase matching condition is satisfied for the x-polarized and y-polarized 2nd-SPP modes and odd supermodes, respectively, at the resonance wavelength 1.13 μm. It results in a sudden increase of the effective indices of odd supermodes in both x- and y-polarizations. We can see that the same direction of effective index D-value $|n_{\text{even}}^x-n_{\text{odd}}^x|$ and $|n_{\text{even}}^y-n_{\text{odd}}^y|$ increase obviously as the wavelength increases, which will lead to an ultra-short coupling length for the orthogonal polarizations. While the 1st-SPP modes' effective index are much higher than that of the corresponding core-guided supermodes, the phase matching condition can't be met.

The loss spectra of x-polarized and y-polarized supermodes for the DC-PCF with gold wire is shown in Fig. 6. It is obvious that high losses are exhibited at the resonance wavelength , because at this wavelength

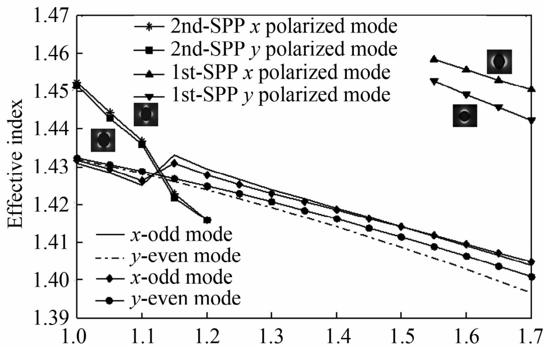


Fig. 5 Dispersion diagram of the x- and y- polarized super-modes and SPP modes for designed DC-PCF with gold wire

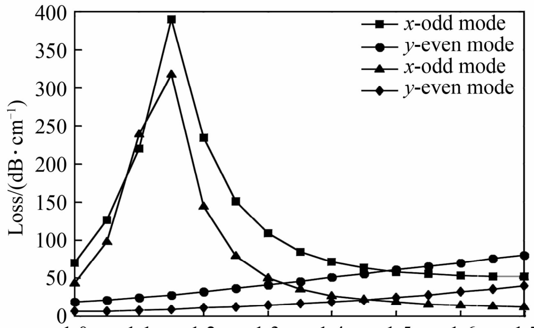


Fig. 6 Wavelength dependence of the losses in x- and y-polarized η supermodes for the designed dual-core PCF with gold wire

the 2nd-SPP mode and the odd core-guided modes satisfy the phase matching condition and the power of core-guided modes is coupled into that of the 2nd-SPPs with the same polarization, forming the resonance coupling. But the losses of even supermodes are always low in the wavelength range, no coupling occurs between even supermodes and SPP modes[14,18].

The electrical field distributions of the four supermodes in the DC-PCF at the resonance wavelength 1.13 μm are shown in Fig. 7. As seen in the figure, the power of odd supermodes is transferred to that of the 2nd-SPPs with the same polarization, while the power of the even supermodes remains confined in the cores. It is consistent with the previous results.

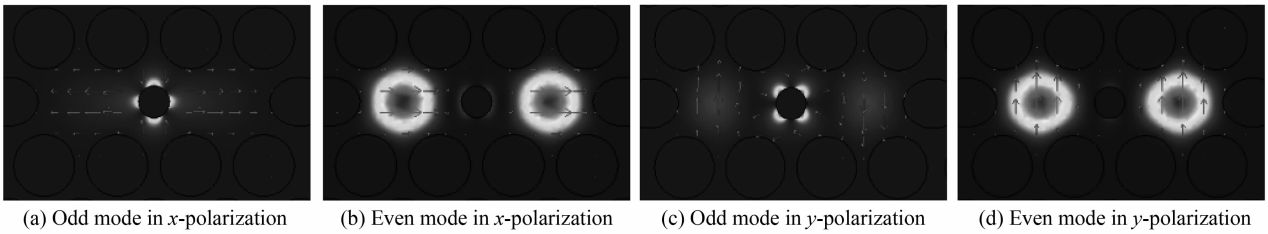


Fig. 7 Electric field distributions of odd and even supermodes in the DC-PCF with gold wire at the wavelength of 1.13 μm

To compare to the conventional unfilled DC-PCF polarization splitter, Fig. 8 shows the coupling lengths of the DC-PCF with and without a gold wire. The coupling lengths of DC-PCF without gold wire decrease sharply with the increase of wavelength, whereas that of DC-PCF with gold wire are much smaller and display insignificant variation over the entire wavelength range. It features the advantage of the gold-wire filled DC-PCF to achieve a broadband polarization splitting.

Fig. 9 indicates the power evolution in core A along the length of proposed polarization splitter at the wavelength of 1.55 μm, with $\Lambda=2.4$ μm, $d_1=1.16$ μm, $d_2=1.6$ μm, $d_3=2$ μm, $a=2$ μm, $b=1.6$ μm. As shown in this figure, at the transmission distance $L_C=2L_x=L_y=263$ μm, the separation of light with orthogonal polarizations can be achieved.

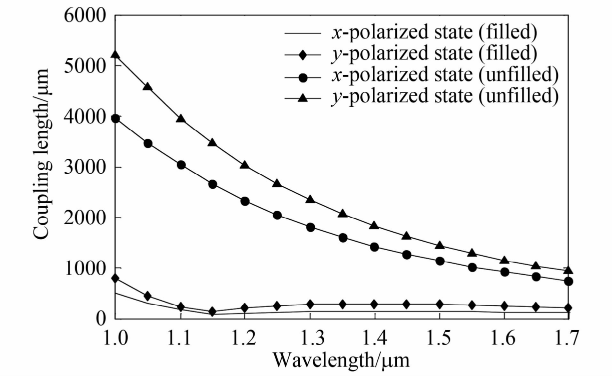


Fig. 8 Comparison of the coupling lengths of a DC-PCF with and without a gold wire

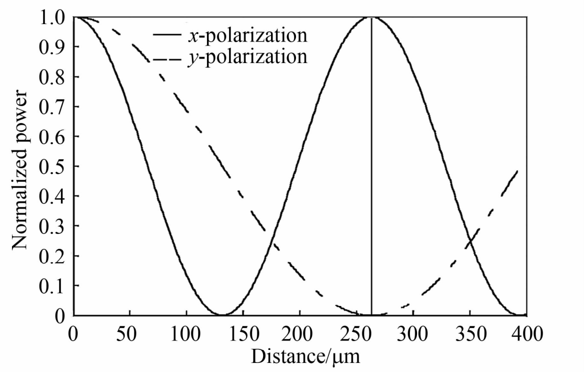


Fig. 9 Normalized power evolution for x- and y-polarizations in core A along the fiber length at 1.55 μm

Extinction ratio of the polarization splitter is shown in Fig. 10. At the wavelength of $\lambda=1.55$ μm, the extinction ratio of core A is −70 dB and core B −42 dB. Furthermore, the −20 dB-ER bandwidths are 124 nm and 60 nm, respectively. Therefore, broadband polarization splitting is demonstrated.

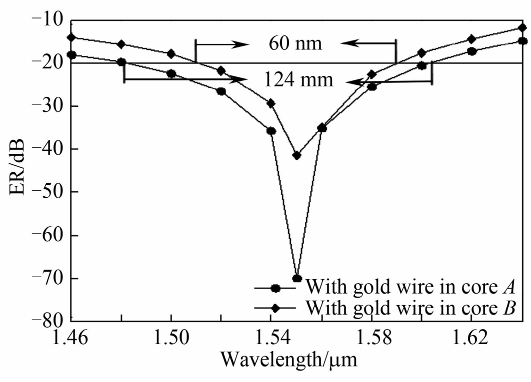


Fig. 10 Extinction ratios in core A and core B as a function of wavelength

3 Conclusion

In this paper, we proposed a novel polarization splitter based on DC-PCF filled with gold wire. We studied the coupling characteristics of the polarization splitter with the supermode theory and the finite element method . It is found that a broadband ultra-short polarization splitter can be realized. With a length of 0.263 mm, the extinction ratio of the input core is−70 dB at the wavelength of 1.55 μm and its −20 dB-ER bandwidth is 124 nm. The design exhibits ideal polarization-splitting performances.

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