Tuneable liquid crystal asymmetric dual-core photonic crystal fiber mode converter

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Abstract. In this work, a novel and compact mode selective coupler based on an asymmetric dual core photonic crystal fiber with a thermo-responsive core is proposed and numerically studied. Simulation results show that high conversion efficiencies are achieved between LP\textsubscript{01} and LP\textsubscript{11} modes in the O-band with a wide bandwidth of 24.55 nm and a mode conversion efficiency over 60% when it has a total length of 3.15 mm and the operating wavelength is 1310 nm. In addition, the thermally tunability was evaluated when this device was submitted to thermal changes from 15°C to 35°C. The results evidence that thermal effect allows to control the operating wavelength and the mode coupling efficiency of the mode converter when it is used to couple energy from the LP\textsubscript{01} mode to the LP\textsubscript{11} mode. Therefore, the proposed device could be useful in high-bandwidth mode division multiplexed communication systems.

1. Introduction

The traffic in optical communications networks has presented an exponential growing, close to 50% to 60% per year, as reported by Bell Labs in [1,2]. These data are associated to the ever-growing number of users and devices connected through Internet of Things around the world [3,4]. To solve the problem associated to the transmission capacity of optical links, spatial division multiplexing (SDM) techniques based on multi-core optical fibers or spatial modes have been employed in order to transmit independent data streams and increase the number of channels [1,5]. One interesting alternative to solve this problem is the implementation of mode selective converters, which are based on multi-core fibers. The main objective with these devices is the coupling between the fundamental mode with high order modes such as LP\textsubscript{11}, LP\textsubscript{21} and others [6–9]. Some of them use photonic crystal fiber (PCF) structures based on total internal reflection (TIR) guiding mechanism [7,10], photonic band gap (PBG) [6,11] or hybrid mechanism [8,12].

2. Methodology

Figure 1(a) shows the proposed mode converter based on an asymmetric dual-core silica PCF structure. The proposed structure has two different cores separated by an air hole of diameter \(d_2 = 0.8 \mu m\). The right core is a micro-hole of diameter \(d_3 = 1 \mu m\) infiltrated with a highly thermo-responsive nematic liquid crystal (LC), E7 [13], while the left core is a Ge-doped solid core of diameter \(d_1 = 4.2 \mu m\) (Ge concentration of 19.3% mole). Ge doping increases the refractive index (RI) of the solid core, allowing interaction with the LC core. As the RI of each core is higher than in the microstructure cladding (pure silica), the light-guiding mechanism in both cases is based on total internal reflection (TIR). The other
holes of the hexagonal microstructure have a diameter ($d$) of 2 μm and the pitch ($\Lambda$) of the whole structure is 3.5 μm. The background silica and the germanium-doped core RI are calculated using the Sellmeier’s equation and the coefficients were taken from [14]. On the other hand, because the E7 NLC RI has a strong dependence on the light wavelength and the temperature, the impact of both parameters on the device characteristic is considered by using the model presented by Li, et al. [13]. Based on this model, the ordinary and extraordinary components of the LC RI are computed.

![Figure 1](image)

Figure 1. (a) Schematic of the tunable PCF mode converter with a thermo-responsive LC core, (b) electric field distribution of the $y$-polarized LP$_{11}$, left core, and (c) electric field distribution of the $y$-polarized LP$_{01,o}$ mode, right core.

The operating principle of the modal converter is based on the coupled mode theory [15]. In this theoretical model, each core is analyzed as an independent waveguide, and the electric field of the entire system as the superposition of the individual core fields could be expressed by Equation (1).

$$E(x, y, z) = A_1(z)e^{-i\beta_1 z}E_1(x, y) + A_2(z)e^{-i\beta_2 z}E_2(x, y),$$

(1)

where the subscripts 1 and 2 refers to the Ge-doped and LC core, respectively. In addition, $E_{1,2}(x, y)$, $A_{1,2}$ and $\beta_{1,2}$ are the electric field distributions, electric field amplitudes and propagation constants of the propagating modes in each isolated core, respectively. The coupled modes equation can be written as is observed in Equation (2).

$$\frac{d}{dz}A_1 = i\beta_1 A_1 + i\kappa_{12} A_2,$$

$$\frac{d}{dz}A_2 = i\kappa_{12} A_1 + i\beta_2 A_2,$$

(2)
where, $\kappa_{12}$ are the coupling coefficients, which are calculated using Equation (3) [15].

$$
\kappa_{jl} = \frac{k_0}{2A_{\text{coj}}} \int_A (n^2 - n_{\text{coj}}^2) E_j^* E_l dA,
$$

where $(j,l) = (1,2)$ or $(2,1)$, $k_0$ is the vacuum wave number, $n$ is the refractive index profile of the whole system, $n_l$ is the refractive index profile of the system for the each isolated $l$-th core, $n_{\text{coj}}$ is the refractive index of the $j$-th core, and $A$ is the fiber cross-section. Due to the complex geometry of the PCF it is not possible to analytically calculate the coupling coefficients, then, numerical modeling such as the vector finite elements method (FEM) should be used. Finally, it was assumed as an initial condition that the light is injected into the LC-core that only transmits the fundamental mode ($LP_{01}$), and the evanescent field is gradually coupled to the $LP_{11}$ mode of the Ge-doped core.

The effective coupling between the $LP_{01,o}$ mode of the right core (Figure 1(c)) and the $LP_{11}$ mode of the left core (Figure 1(b)) requires a phase-matching condition for these two interacting modes. In order to identify the condition to obtain the phase-matching condition, the effective RI and the electric field distribution of each mode were calculated using COMSOL Multiphysics. Next, these parameters were employed in combination with the coupling mode theory to analyze the behavior of our proposed mode converter device.

3. Results

A mode analysis of both cores demonstrates that the LC core allows the propagation of the $LP_{01,o}$ and the $LP_{01,e}$ modes, while the germanium-doped core support the $LP_{01}$ and the $LP_{11}$ modes due that it has a bigger size. However, the device with these parameters only allows the interchange of energy between the $LP_{01,o}$ mode of the right core and the $LP_{11}$ mode of the left core.

![Figure 2](image-url)  
**Figure 2.** Dispersion curves of the Ge-core guided mode (black line) and the LC-core guided mode (red line). The insets are the electric field distribution of the Ge-core guided modes at three selected wavelengths.

Figure 2 shows the dispersion curves of the two interacting modes ($LP_{11}$ and $LP_{01,o}$ modes) of the Ge-core and LC-core modes at 25°C, respectively. In this figure, three wavelengths are highlighted, corresponding to 1286 nm (I), 1306 nm (II), and 1326 nm (III), where (II) is the wavelength of maximum coupling at the phase matching condition between the two cores, as evidenced by the electric field.
distributions in the figure insets. It is evident that at the three analyzed wavelengths there is always coupled light between the Ge-core to the LC-core. However, as expected, this coupling is partial for wavelengths (I) and (III), while it is optimal only for wavelength (II) (the operating wavelength). Based on these results, we analyze the normalized power in both cores when the light is initially injected into the LC-core [15,16].

Figure 3 shows the normalized power as a function of the fiber length. The results show that almost 100% of the optical power is coupled between both cores at 1306 nm (II). Similarly, the proposed device requires only 3.15 mm to couple the total energy between the cores. On the other hand, the power coupled between the cores is reduced for the wavelengths (I) and (III), where the coupling is weak.

The thermally tunability of this device was also evaluated. The dispersion curves of the modes involved in the operation of the mode converter in the wavelength range 1280 - 1315 nm at different temperatures were calculated to identify the phase-matching conditions as shown in Figure 4. It can be seen that for the left core, the effective RI of the LP_{11} mode decreases linearly as the wavelength increases and fundamentally does not change with the temperature due to the low dependence of the Ge-doped silica RI with the temperature, which facilitates the coupling with the LP_{01,0} mode of the right core.

On the other hand, the dispersion curve of the thermo-responsive LC core mode presents a displacement due to the RI changes of the LC because of the temperature variations [13]. Therefore, the phase matching condition, and hence the optimum operating wavelength to which the device operates, can be thermally tuned. As mentioned before, the dispersion curves of LP_{01} mode for the extraordinary component of the LC do not appear in the Figure 4, because it has higher effective RI values and the phase-matching condition is never fulfilled. Therefore, the coupling energy between both cores is only possible for the y-polarization, and therefore, the mode conversion. As can be seen from the operating wavelengths highlighted in Figure 4, the proposed method allows obtaining a tunable mode converter between the LP_{01,0} and LP_{11} modes, which always operates into the O-band of optical communications.

Finally, the mode coupling efficiency was evaluated using the Equation (4) [7,17].

\[
\text{Coupling Efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\kappa_{1}^{2}}{\kappa_{2}^{2} + \delta} \sin^{2} \left( \sqrt{\kappa_{2}^{2} + \delta} z \right); \quad \delta = \frac{\beta_{1} - \beta_{2}}{2}
\]  

(4)
where, $z$ is the length of the device. Figure 5 shows the coupling efficiency as a function of the wavelength for a 3.15mm long device. To calculate the modal coupling efficiency, the intensity distribution of the $LP_{01,0}$ mode was taken as reference to obtain modal coupling efficiency when this mode is converted to $LP_{11}$ mode. The analysis was performed from 1250 nm to 1350 nm and the numerical results reveals that for each temperature there is a wavelength where maximum coupling between the y-polarized modes $LP_{11}$ and $LP_{01,0}$ can be achieved. These maximum coupling wavelengths match the crossing points of the dispersion curves shown in Figure 4. In addition, the proposed device presents a conversion efficiency greater than 60% at 1310 nm when the applied temperature is between 20°C and 35°C, which means that the proposed mode converter could be implemented into O-band with an excellent performance. Moreover, the bandwidth remains each constant for all temperatures, which is approximately 24.55 nm.

**Figure 4.** Dispersion curves of the modes involved in the operation of the PCF mode converter at different temperatures.

**Figure 5.** Coupling efficiency analysis as a function of wavelength for a 3.15 mm long mode converter. This analysis was carried out at different temperatures to evidence the tunability of the proposed device.
4. Conclusions

In conclusion, a compact mode selective coupler based on mode coupling in an asymmetric dual-core PCF with a thermo-responsive liquid crystal core was proposed and numerically analyzed. Thermal tuning capability of the phase matching condition was evaluated when the mode conversions was made between the LP_{01,a} and LP_{11} modes. Therefore, we demonstrated that it is possible to control the operating wavelength of mode converter through thermal changes. For temperatures above 20°C, a wavelength of 1310 nm and a total length of 3.15 mm, the coupling efficiency reaches at least 60% when the proposed mode converter is employed to couple energy from the LP_{01,a} mode to LP_{11} mode. Likewise, the coupling mode efficiency and the operating wavelength could be controlled due that the LC-core properties have a strong dependence with thermal variations. Then, the proposed mode converter could be useful for further development of high bandwidth mode division multiplexed communication system.

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