Tunable Polarization Splitter Based on Asymmetric Dual-core Liquid Photonic Crystal Fiber

B. M. Younis, Mohamed Farhat O. Hameed*, and S. S. A. Obayya*

Center for Photonics and Smart Materials, Zewail City of Science and Technology, October Gardens, 6th of October City, Giza, 12578 Egypt. E-mail: mfarahat@zewailcity.edu.eg, sobayya@zewailcity.edu.eg

Abstract— **An asymmetric dual core photonic crystal fiber (ADC-PCF) tunable polarization splitter is reported and analyzed. The left core of the DC-PCF is infiltrated with nematic liquid crystal (NLC) material to control the wavelength at which coupling occurs between the dual cores of the proposed structure. Moreover, the suggested design can be tuned to split out the x and y-polarized modes by rotating the NLC molecules by rotating the NLC molecules through an external electric field. Additionally, the wavelength at which the coupling between the two cores occur can also be tuned by changing the temperature of the NLC material. The geometrical parameters of the reported splitter are studied by full vectorial finite difference method (FVFDM) via Lumerical software package to achieve high wavelength selectivity with an average device length of 602 µm at λ=1.3 µm. Therefore, the suggested design can be a good candidate for the integrated photonic devices.**

***Index Terms*— Photonic crystal fibers, Liquid crystals, Polarization splitters, Coupled mode theory.**

Through optical data communications, many advantages can be achieved including very high data capacity and low transmission loss with negligible effect of external electromagnetic interference. One of the most important components of modern optical communication systems is polarization splitter that can separate two orthogonal polarized beams[1–3]. Photonic crystal fibers (PCFs)[4] are commonly used in designing highly tunable and compact optical devices because of their unprecedented light control mechanisms and high design flexibility. Further, selective infiltration to the cladding holes of PCFs with fluid materials such as polymer, oil, or liquid crystal (LC)[5–7] is performed to tailor the polarization and birefringence properties of PCFs. As their refractive indices can be tuned by changing the temperature or applying an external electric field, LC materials have an increasing interest. Therefore, high tunable LC PCF devices can be obtained.

Directional couplers[8], polarization beam splitters[9], mode converters[10], and multiplexers-demultiplexers[11] can be designed by increasing the number of PCF cores to more than one. Based on dual-core PCFs, many promising designs for polarization splitting function have been proposed for efficient and compact optical communication systems[9,12–19]. While most of the proposed splitters in literature have their own advantages and properties, the tunability of these devices is still a big challenge.

The operation of the proposed device is different from the conventional PCF splitters with symmetric cores[1]. In this work, the proposed design is based on the asymmetry between the two cores. The coupling between the two cores is required to occur only at a single wavelength that is called resonance wavelength (λ_r) at which phase matching condition can be achieved. So, one of the two cores is infiltrated with the NLC material while the other one is a solid core to establish an asymmetric cores PCF where the two cores are not identical. Here, the asymmetry is used to attain the required behavior at a certain wavelength that can be tuned through the NLC parameters. Therefore, only one of polarization is coupled from the input core to the other one while the other polarization keeps propagating in the launching core. The geometrical parameters and NLC parameters (rotation angle and temperature) can be engineered to control λ_r to induce the required tunable behavior.

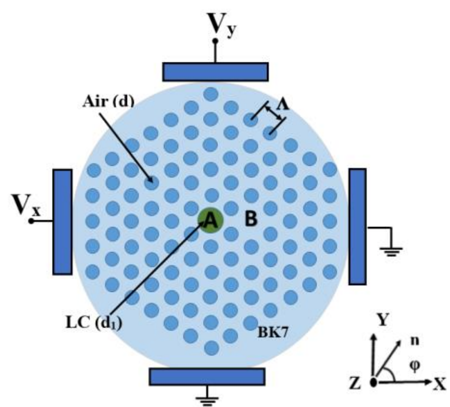

Fig. 1. Cross section of the proposed ADC-PCF.

Figure 1 depicts the reported ADC-PCF structure. The left core (A) has a large hole with a quite large diameter d_1 and infiltrated with the NLC material while the right core (B) is obtained by removing an air hole. Further, borosilicate crown glass of type BK7 is used as the background material in which the cladding air holes are arranged in a hexagonal lattice with lattice constant Λ and a hole diameter d as may be seen in Fig. 1. Furthermore, the Sellmeier equation of the BK7 material is taken from[9]. The NLC has two refractive indices; ordinary index (n_o), and extraordinary index (n_e). The temperature dependent n_o and n_e of the E7 material can be calculated using Cauchy models as in[8]. In addition, the dielectric permittivity tensor of the NLC material is taken as[8] and depends on n_o, n_e, and the rotation angle (ϕ) of the NLC molecules as shown in the inset of Fig. 1. The proposed in-plane alignment of the NLC material can be exhibited through an appropriate homeotropic anchoring conditions[20]. Additionally, by applying external voltage that fulfills the Fredrick's threshold[21] between two pairs of electrodes as may be seen in Fig. 1, the in-plane alignment of the NLC material molecules can be achieved.

According to the coupled mode theory[22], each single core in the DC-PCF structure, as shown in Fig. 1, is treated as an independent waveguide. For ADC-PCF, the power transfer will only occur at a wavelength that achieves the complete phase matching (λ_r). At λ_r, the power is transferred periodically from one core to the other, and maximum power transfer occurs at the coupling length L_C. However, the coupling strength is reduced by moving away from λ_r due to the absence of phase matching.

In this investigation, the material dispersions of BK7 and the NLC materials are considered. At ϕ=90°, the wavelength at which the effective index of the TE mode supported by the air-PCF is equal to that of the NLC-PCF can be controlled through the temperature. At T=25°C, the phase matching between the two modes supported by the two cores can be obtained at the telecommunication wavelength, λ=1.3 µm. Therefore, in the ADC-PCF, the TE mode in core A is expected to have the same n_{eff} of that in core B and hence a strong coupling between the two modes occurs at λ=1.3 µm and ϕ=90° while the TM modes in this case makes no mutual coupling due to the absence of phase matching. Further, at ϕ=0°, the TM modes in the two cores will have a strong coupling.

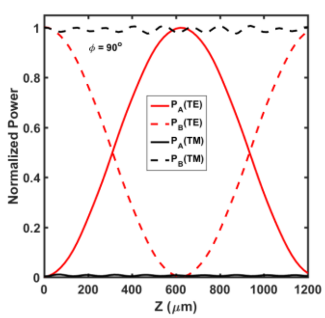

Fig. 3 Normalized powers for both polarizations in cores A and B at ϕ=90° at λ=1.3 µm.

The ADC-PCF is studied to show the power coupling characteristics of the TE and TM modes. The propagation is performed using Lumerical software package [23] based on the coupled mode theory [22]. Figure 2 shows the normalized power evolution for both TE and TM modes in the two cores at ϕ=90° and λ=1.3 µm. It may be seen from this figure that there is a strong coupling between the two TE modes in the dual cores at ϕ=90° while the TM modes have no coupling.

REFERENCES

[1] M. F. O. Hameed and S. S. A. Obayya, "Polarization splitter based on soft glass nematic liquid crystal photonic crystal fiber," *IEEE Photonics J.*, 2009.

[2] Y. Sun, Y. Bai, and X. Ma, "Dual-core photonic crystal fiber polarization splitter based on lead silicate glass," *Optoelectron. Lett.*, vol. 11, no. 3, pp. 170–173, 2015.

[3] H. L. Chen, S. G. Li, Z. K. Fan, G. W. An, J. S. Li, and Y. Han, "A Novel Polarization Splitter Based on Dual-Core Photonic Crystal Fiber With a Liquid Crystal Modulation Core," *IEEE Photonics J.*, 2014.

[4] J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," *Opt. Lett.*, vol. 21, no. 19, pp. 1547–1549, 1996.

[5] M. F. O. Hameed and S. S. A. Obayya, "Analysis of polarization rotator based on nematic liquid crystal photonic crystal fiber," *J. Light. Technol.*, 2010.

[6] A. Boltasseva, T. Nikolajsen, K. Leosson, K. Kjaer, M. S. Larsen, and S. I. Bozhevolnyi, "Integrated optical components utilizing long-range surface plasmon polaritons," *J. Light. Technol.*, vol. 23, no. 1, p. 413, 2005.

[7] S. Obayya, M. F. O. Hameed, and N. F. F. Areed, "Computational Liquid Crystal Photonics: Fundamentals, Modelling and Applications," *John Wiley Sons*, 2016.

[8] B. M. Younis, A. M. Heikal, M. F. O. Hameed, and S. S. A. Obayya, "Coupling Enhancement of Plasmonic Liquid Photonic Crystal Fiber," in *Plasmonics*, 2017, vol. 12, no. 5, pp. 1529–1535.

[9] B. M. Younis, A. M. Heikal, M. F. O. Hameed, and S. S. A. Obayya, "Highly wavelength-selective asymmetric dual-core liquid photonic crystal fiber polarization splitter," *J. Opt. Soc. Am. B*, vol. 35, no. 5, p. 1020, May 2018.

[10] M. Y. Chen and J. Zhou, "Mode converter based on mode coupling in an asymmetric dual-core photonic crystal fibre," *J. Opt. A Pure Appl. Opt.*, vol. 10, no. 11, p. 115304, 2008.

[11] M. F. O. Hameed, R. T. Balat, A. M. Heikal, M. M. Abo-Elkhier, M. I. Abo El Maaty, and S. S. A. Obayya, "Polarization-Independent Surface Plasmon Liquid Crystal Photonic Crystal Multiplexer-Demultiplexer," *IEEE Photonics J.*, 2015.

[12] L. Zhang and C. Yang, "A novel polarization splitter based on the photonic crystal fiber with nonidentical dual cores," *IEEE Photonics Technol. Lett.*, vol. 16, no. 7, pp. 1670–1672, 2004.

[13] M.-Y. Chen, B. Sun, Y.-K. Zhang, and X.-X. Fu, "Design of broadband polarization splitter based on partial coupling in square-lattice photonic-crystal fiber," *Appl. Opt.*, vol. 49, no. 16, pp. 3042–3048, 2010.

[14] D. Mao, C. Guan, and L. Yuan, "Polarization splitter based on interference effects in all-solid photonic crystal fibers," *Appl. Opt.*, vol. 49, no. 19, pp. 3748–3752, 2010.

[15] J. Zi, S. Li, G. An, and Z. Fan, "Short-length polarization splitter based on dual-core photonic crystal fiber with hexagonal lattice," *Opt. Commun.*, vol. 363, pp. 80–84, 2016.

[16] H. Chen, S. Li, G. An, J. Li, Z. Fan, and Y. Han, "Polarization splitter based on d-shaped dual-core photonic crystal fibers with gold film," *Plasmonics*, vol. 10, no. 1, pp. 57–61, 2015.

[17] Q. Liu *et al.*, "Numerical analysis of ultrabroadband polarization splitter based on gold-filled dual-core photonic crystal fiber," *Opt. Commun.*, vol. 334, pp. 46–50, 2015.

[18] Z. Fan, S. Li, Q. Liu, J. Li, and Y. Xie, "Plasmonic polarization beam splitter based on dual-core photonic crystal fiber," *Plasmonics*, vol. 10, no. 6, pp. 1283–1289, 2015.

[19] H. Wang, X. Yan, S. Li, G. An, and X. Zhang, "Ultra-short polarization beam splitter based on dual core photonic crystal fiber," *J. Mod. Opt.*, vol. 64, no. 5, pp. 445–450, 2017.

[20] D. C. Zografopoulos, E. E. Kriezis, and T. D. Tsiboukis, "Photonic crystal-liquid crystal fibers for single-polarization or high-birefringence guidance," *Opt. Express*, vol. 14, no. 2, pp. 914–925, 2006.

[21] M. F. O. Hameed, A. M. Heikal, B. M. Younis, M. Abdelrazzak, and S. S. A. Obayya, "Ultra-high tunable liquid crystal-plasmonic photonic crystal fiber polarization filter," *Opt. Express*, vol. 23, no. 6, p. 7007, Mar. 2015.

[22] W.-P. Huang, "Coupled-mode theory for optical waveguides: an overview," *JOSA A*, vol. 11, no. 3, pp. 963–983, 1994.

[23] "Lumerical Software Package." [Online]. Available: https://www.lumerical.com/.