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Photoactive photonic liquid crystal fiber polarization switches

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ABSTRACT

This study presents a light-controlled photonic liquid crystal fiber (PLCF) polarization switch. The solid-core PCF has an index-guiding effect that reduces the insertion loss produced by infiltrating liquid crystals (LCs) with a low refractive index (RI). The proposed approach achieves photoactive tuning through the trans–cis photoisomerization of doped azobenzene, which modulates the RI of infiltrated LCs. This design achieves an optically tunable extinction ratio of average 10 dB and photonic bandgap in the wavelength range of 1527–1538 nm under 30 mW laser illumination. The repeatable and switchable phase change is nearly 60°, corresponding to a response time of 100 ms, which is to date the fastest light-tunable PLCF polarization switch available.

1. Introduction

Photonic liquid crystal fibers (PLCFs) have attracted great interest because of their potential application in active photonic devices, such as electrically or optically tunable fiber attenuators, polarizers, and rotators [1–15]. Most PLCF devices are made by infiltrating LCs into solid-core photonic crystal fibers (PCFs). However, silica-made PCFs have a lower refractive index (RI) (approximately 1.475) than both ordinary and extraordinary RI of commonly used LCs. Therefore, the lightwave-guiding mechanism changes from index-guiding to photonic band-gap guiding, resulting in significantly higher scattering losses in solid-core PLCFs. Ertman et al. recently demonstrated the effective tuning of PLCFs by infiltrating commonly used LCs into specially designed PCFs made from multicomponent glasses with higher RIs (1.62 and 1.92) [16,17]. The fabricated PCFs retained the index-guiding effect after LC infiltration, greatly improving the light-coupling effects. However, fabricating a specially designed PCF is not an easy task. Most commercial solid-core PCFs (www.nktphotonics.com) are made from silica, and are less expensive than hollow-core PCFs. Therefore, other approaches should be available to achieve effective tuning and switching of PLCFs using commercially available solid-core PCFs.

This study is the first to present an optically tunable and switchable polarization rotator, based on an infiltrating lower RI of LCs into a commercially available solid-core PCF that retains the index-guiding effect after LC infiltration. This design achieves optically tunable polarization through the trans–cis photoisomerization of doped azobenzene molecules, which changes the orientation of infiltrated LCs and further modulates PLCF polarization. The fiber-phase difference is continuously tunable with 60° and switches on and off under an alternative on–off laser illumination of 100 ms. This photoactive PLCF can be used in an optically tunable and switchable polarization rotator in a fiber-optic communication system.

2. Experimental

The fiber used in this study is a large-mode area PCF (LMA-8, NKT Photonics, UK) with a solid 8.6-μm diameter core surrounded by 1.7-μm diameter air-holes with a pitch size of 4.7 μm. The infiltrated phototunable LC consists of 10 wt% azobenzene molecules (4-butyl-4′-methoxyazobenzene, BEAM Co., US) and 90 wt% nematic LC (LCM-1550.45, LCMatter Corp., US) with ordinary and extraordinary RI values of $n_o = 1.423$ and $n_e = 1.486$, respectively, at 633 nm and 25 °C. The LC mixture was infiltrated for 15 mm of the fiber length using capillary force, and the PLCF was placed in a V-shaped fiber mount. To obtain higher fiber-coupling quality, two lensed single-mode fiber (SMF) segments were separately positioned in a three-axis manual stage to ensure fiber alignment between the PLCF and lensed SMF fiber. Fig. 1a shows a schematic of the fiber positions and corresponding experimental setup. A Er^{+}-doped fiber amplifier (EDFA) light source and distributed feedback (DFB) laser diode (1550 nm) corresponding to an optical spectrum analyzer (OSA) and polarimeter (PAX5710IR3-T, Thorlabs) were used to analyze the spectral characteristics and the state of polarization (SOP) of the photoactive PLCF. A cylindrical lens was used to expand the 405 nm laser exposure area to 5 mm long, and a chopper operating at 10 Hz modulated the laser irradiation. Fig. 1b shows the orientation of phototunable LC under on–off switching of laser light.

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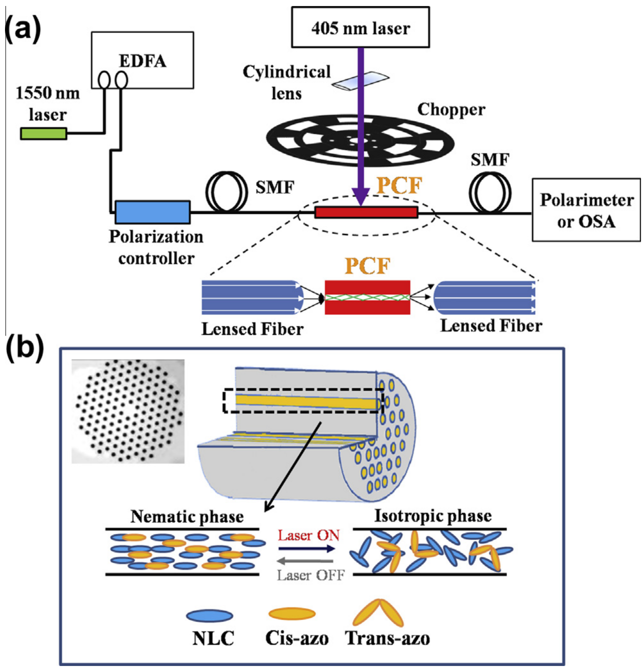

Fig. 1. (a) Experimental setup for characterizing the photoactive PLCF and (b) the photoresponsive LC orientation under laser light irradiation. The SEM image of commercial available PCF (Fig. 1b inset) is from NTK Photonics website.

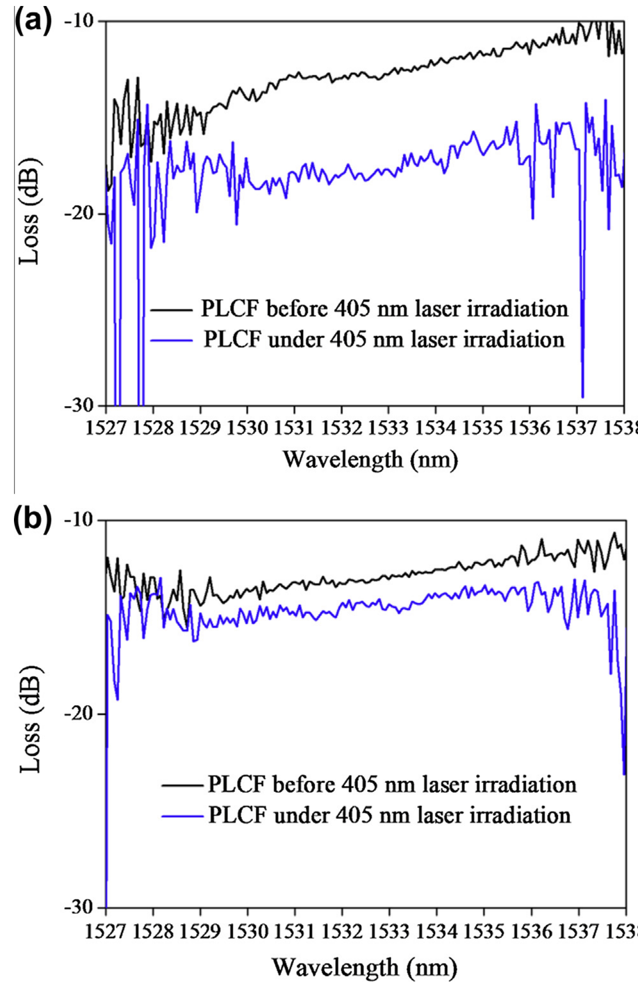

Fig. 2. Normalized transmission spectra of photoactive PLCF before and under laser irradiation. The initial polarization of light was controlled at (a) linear and (b) circular polarization using fiber-based polarization controller. The PLCF was irradiated with 30 mW, 405 nm laser diode.

3. Results and discussion

The performance of the photoactive PLCF was first characterized using a broadband light source (i.e., the EDFA), and the transmission spectrum was measured by OSA. Fig. 2 shows the optical spectrum of the EDFA light source passing through photoactive PLCF before and under 405 nm laser illumination. An insertion loss of 10–15 dB was measured when placing the PLCF device between two SMFs. The insertion loss is from the coupling loss of two lensed fibers that the loss may be reduced by mechanically spicing the PCF and SMF. Using 405 nm laser irradiation, it is possible to generate the photoisomerization of doped azobenzene in the photoresponsive LCs and further control the transversal orientation of LC molecules. This in turn enables the photoactive tuning of the optical spectrum of the PLCF, which is normalized to the spectrum without infiltrating LC into PCF. The change of initial SOP of probe beam has no obvious effect on output spectrum; however, using linearly polarized light achieves large optical power tuning and photonic bandgap in the communication wavelength. The results from Fig. 2 also confirmed that the capillary force-infiltrated LC is aligned in the fiber axis [14].

To investigate the polarization tuning and switching effect from a photoactive PLCF, a DFB laser diode was used as a light source, and changes in the output fiber polarization were analyzed by the polarimeter. Continuous phase changes from the PLCF could be induced at various levels of laser power irradiation. The changes of phase birefringence induced by the photoactive PLCF depending on the power of laser irradiation can be expressed as follows [16]:

$$\Delta B = \frac{\Delta\phi}{2\pi} \cdot \frac{\lambda}{L} \tag{1}$$

where ΔB is the change of phase birefringence in the photoactive PLCF, L is the exposure length of the fiber, λ is the wavelength of the probe beam, and $\Delta\phi$ is the phase difference measured from the polarimeter. Fig. 3 shows the change in phase birefringence at a 1550 nm wavelength for the PLCF sample. The phase birefringence increases almost linearly at a lower laser power (20 mW) and becomes saturated as the laser irradiation increases. Under 30 mW laser irradiation, the tuning range of phase birefringence from PLCF is almost 5×10^{-5} at the 1550 nm wavelength. Compared to previous simulation results [17], the 30 mW laser power generates a 60° tilt of the LC molecules.

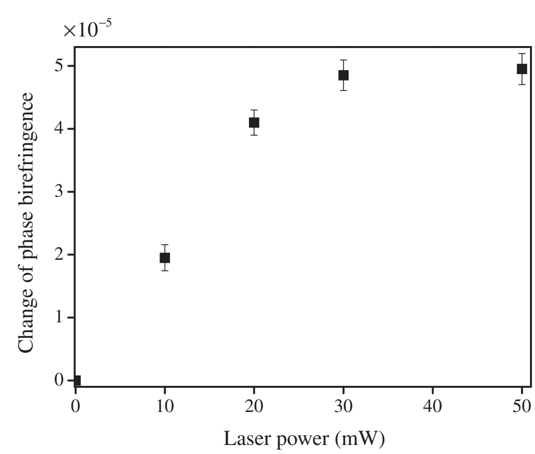

Fig. 3. Phase birefringence tuning at the 1550 nm wavelength in the photoactive PLCF at various levels of laser irradiation.