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All-optical switch based on liquid-crystal infiltrated photonic bandgap fiber in transverse configuration

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We demonstrate optically controlled switching in a photonic bandgap fiber filled with liquid crystal using transverse coupling geometry. Fiber samples made from silica and lead silicate are studied. For the latter one, a continuous and fairly flat operating range from 600 to 1700 nm was achieved. The insertion loss was 3 dB and the extinction ratio better than 20 dB. [DOI: 10.2971/jeos.2007.07016]

Keywords: Photonic crystal fiber, liquid crystal, optical switch

1 INTRODUCTION

Photonic crystal or microstructured fibers offer interesting new possibilities for tailoring the transmission properties of optical signals through optical fiber [1]. Extra flexibility is gained by filling the open channels of the fiber by substances whose optical properties can be externally controlled. Liquid crystal (LC) materials pose an obvious choice for obtaining such functionality. These materials are composed of organic molecules that in their nematic mesophase are on average oriented along a particular direction leading into macroscopic anisotropy in the optical properties of the material. The molecular orientation becomes random when the LC is heated beyond the threshold to the isotropic mesophase [2, 3]. The refractive index contrast of the liquid and the fiber material can be high and thus lead to strong scattering of the light. Thus infiltration of LC in PCFs allows for switching between a transparent and a scattering state with very high extinction ratio. Optical switching has recently been demonstrated in PCFs filled with LC using thermal [4], external electric field [5, 6] or all-optical control mechanisms [7]. In all of these approaches an axial geometry is applied. Lately, also the use of PCFs in the transverse geometry has been explored [8]-[10].

In this paper, we present an optically controlled switch based on a photonic bandgap fiber filled with liquid crystal. The LC-filled fiber is transversally oriented between a conventional input and output fiber. The performance of the switch is investigated by conducting transmission measurements for two different types of photonic bandgap fibers.

2 EXPERIMENTAL SETUP

A schematic layout of the switching device is depicted in Figure 1. A standard single-mode fiber was used for coupling the input signal through the transversally oriented photonic bandgab fiber (PBF) filled with LC. A hotplate was applied to control and stabilize the temperature of the LC-filled fiber slightly below the isotropic mesophase transition temperature. A control signal through the LC-filled PBF is used to change the transmission properties of the fiber by raising the temperature of the LC to the isotropic mesophase. The signal light was then coupled into an output fiber that was either a standard single-mode or multi-mode fiber.

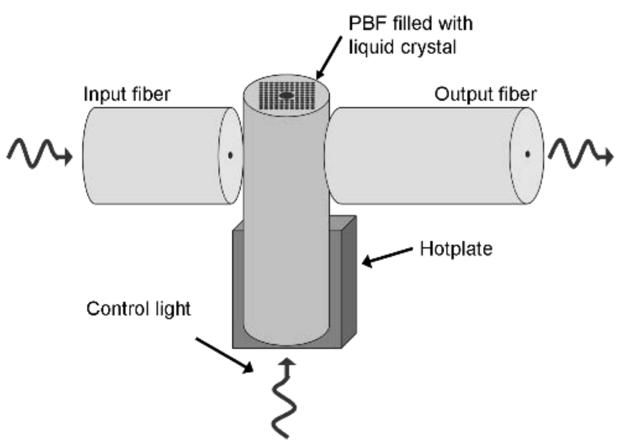

FIG. 1 LC-filled PBF transversally oriented between two conventional fibers. Control light sent into the PBF changes the transmission of the switch.

Two PBFs, labeled F1 and F2, were used to demonstrate the switching operation. Optical micrographs of the fibers are presented in Figure 2. Fiber F1 is fabricated at the Institute of Electronic Materials Technology in Warsaw, Poland from lead silicate glass SK222 having a refractive index of 1.51 at 1550 nm. The holes are arranged in a square pattern ranging across the entire fiber diameter of 230 μm. The diameter and pitch of the holes are 7 μm and 8.6 μm, respectively. Fiber F2 is a silica PBF

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(AIR-10-1550 from *Crystal Fibre A/S*) with a cladding diameter of 185 μm. The holes are confined to the fiber center within a radius of 24 μm in a triangular lattice pattern. The diameter of the holes is 2.7 μm and the pitch is 3.0 μm. The length of each PBF was $\sim$ 2 cm.

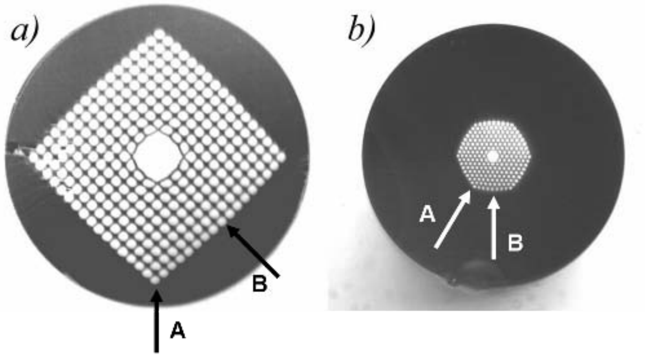

FIG. 2 Optical micrographs of (a) lead silicate fiber (F1) and (b) silica fiber (F2). The directions in which the signal light is applied are marked with arrows.

The holes of these fibers were filled with LC (BM400, Beam Co.) by immersing one end of the fiber sample into the liquid whereby the capillary forces soaked it into the holes. The LC is a uniaxial birefringent medium with ordinary, extraordinary and isotropic refractive indices of 1.52, 1.75 and 1.60, respectively, at λ = 1064 nm. The refractive index of the LC is higher than refractive index of the fiber material which means that the guiding mechanism for the control beam is index guiding. Below the threshold temperature of $\sim$ 35 °C, the LC is in the nematic mesophase. Several orientations of the LC molecules are possible in this phase. The refractive index profile of small air-holes infiltrated with LC is highly anisotropic depending both on the LCs and the anchoring properties of hole-surface material [2]. Consequently, transmitted light is heavily scattered from its original propagation direction. Above the threshold temperature, the LC is in an isotropic mesophase which reduces the transmission losses drastically.

3 RESULTS

The performance of the switch was studied by conducting transmission measurements. The signal light was delivered by a linearly polarized external-cavity laser (Nettest Tunics) operating at 1550 nm. It was directed through the transversally oriented LC-filled PBF between the input and output fiber and it was detected with a photodetector at the end of the output fiber. The temperature of the LC-filled fiber was raised to 30 °C ($\sim$ 5 °C below the threshold temperature) with the hotplate. The optical control signal was 4 s long pulses with a repetition rate of 6 s from a high-power Erbium-doped fiber amplifier (EDFA) (Southampton Photonics). Relatively small power levels of $\sim$ 10 mW were sufficient to operate the switch when the temperature of the hotplate and the PBF was close to the threshold temperature. To optimize the transmission, index-matching oil was used at the interfaces of the three fibers so that the alignment was not so critical. Without index-matching oil, the in- and output fibers needed to be positioned to the optimal distance to utilize the filled PBF as a lens. This reduces the thermal capacity of the setup as only the LC-filled fiber is heated but it makes the transmission more susceptible to vibration and poor alignment.

Transmission of 0.3 mW of signal light in the time domain for fiber F1 is presented in Figure 3. The output power of the EDFA was 40 mW.

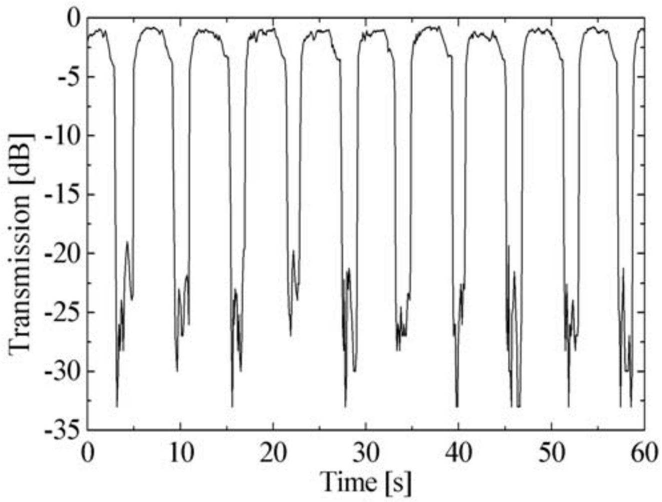

FIG. 3 Transmission of 0.3 mW, 1550 nm signal light when 4 s long control pulses at a repetition rate of 6 s are sent into the LC-filled PBF fiber (F1).

Cooling of the LC utilizing the hotplate is rather slow. Better switching characteristics can be obtained by using a lower temperature and more intense control pulses instead. The maximum switching speed was 1 Hz and 0.5 Hz for fiber F1 and F2, respectively.

The loss and extinction ratio were for each fiber sample measured for the two microstructure directions indicated in Figure 2. The extinction ratio was determined for both the optimal and worst-case state of polarization using a polarization controller. The results are presented in Table 1.

Fiber	Direction	Insertion loss [dB]	Extinction ratio (max) [dB]	Extinction ratio (min) [dB]
F1	A	3.3	26.2	14.5
F1	B	4.6	24.9	8.9
F1*	B	1.9	12.9	11.1
F2	A	4.5	11.8	0.3
F2	B	3.2	3.6	0.8

* multi-mode fiber used as output fiber

TABLE 1 Measured insertion loss and extinction ratio for optimal and worst-case polarization.

In the measurements, the insertion losses (i.e. loss when the switch is open) was 3-5 dB for both types of fiber samples irrespectively of the polarization state. By applying a multi-mode fiber as the output fiber, insertion losses as low as 1.9 dB could be achieved. The multi-mode fiber collects more scattered light in the nematic mesophase since its core is larger. Extinction ratios better than 10 dB were, however, hard to reach.

The performance of the device over a broad wavelength range was also investigated by employing a nanosecond supercontinuum (SC) source as the light source [11]. The total optical output power of the SC was ~ 8 mW in the wavelength range from 600 nm to 1700 nm. In this experiment, the transmission of the SC signal was recorded in the isotropic and nematic mesophase. The measurement was performed by keeping the temperature of the fiber ~ 5 °C above or below the transition temperature for more than 10 min. The transmission spectrum of the signal light at the output fiber was recorded with an optical spectrum analyzer. Back-to-back measurements were carried out to normalize the spectra. Measurement results for the A and B direction of fiber F1 are presented in Figure 4.

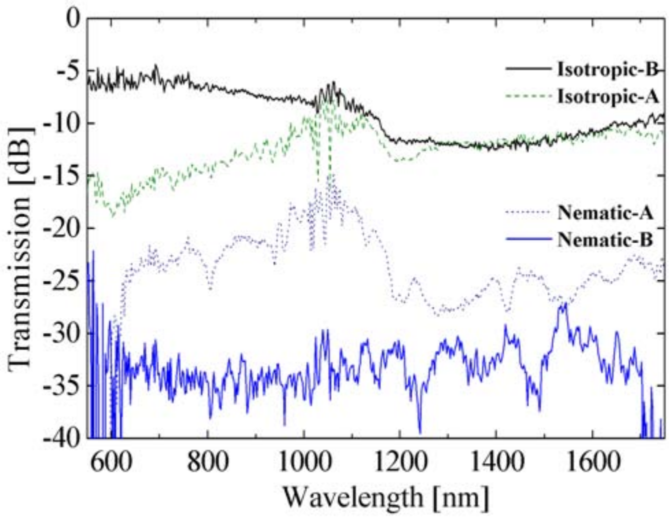

FIG. 4 Transmission spectra for the nematic and isotropic mesophase for the A and B direction of fiber F1 using a nanosecond supercontinuum source.

An extinction ratio of 20 - 30 dB and insertion loss of 5 - 12 dB were obtained over a continuous operating wavelength range from 600 to 1700 nm. The insertion losses were slightly higher for the SC measurements compared to those made using the external cavity laser since the distance, and consequently the coupling loss, between the input and output fiber was larger. In addition, compared to the laser measurement the output of the SC was unpolarized. By applying a highly birefringent photonic crystal fiber in generating the SC [12] a better agreement could be obtained.

4 CONCLUSION

We have demonstrated a novel switching concept based on a liquid-crystal filled photonic crystal fiber transversally oriented between a conventional input and output fiber. It was found that the performance of the fiber made of lead silicate glass was better. It is believed to result from two factors. Firstly, the fiber has a larger cladding area of holes and the holes are larger than in the silica fiber, thus the light is scattered more in the nematic mesophase. Secondly, the refractive index of the lead silicate glass matches better with the index of the isotropic mesophase of the LC. It can be seen as fairly small insertion loss even though the cladding hole-area is larger than in the silica fiber. Moreover, the device can operate over a broad wavelength range which has not been achieved with previous switches based on LC-filled PCFs [7].

This switch-concept does not need any additional optical components such as couplers or filters, because the control beam is not guided along the same path as the signal light as in many other designs. Furthermore, by designing the liquid-filled fiber to have large scattering for only one polarization could result in a single polarization device [3].

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