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Low Loss Liquid Crystal Photonic Bandgap Fiber in the Near-Infrared Region

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We infiltrate a perdeuterated liquid crystal with a reduced infrared absorption in a photonic crystal fiber. The H atoms of this liquid crystal were substituted with D atoms in order to move the vibration bands which cause absorption loss to longer wavelengths and therefore reduce the absorption in the spectral range of 1–2 μm. We achieve in the middle of the near-infrared transmission bandgap the lowest loss (about 1 dB) ever reported for this kind of devices.

Keywords: photonic bandgap fiber, liquid crystals, absorption loss, all-in-fiber devices, tunability, near-infrared region

1. Introduction

Index-guiding photonic crystal fibers (PCFs) guide light in their silica core since the refractive index of the surrounding microstructured cladding is lower than that of silica.[1] The presence of air-holes in the microstructure gives the possibility to infuse liquids and therefore, create tunable all-in-fiber devices.[2,3] Liquid crystals (LCs) are a good candidate for the fabrication of tunable devices, since they exhibit extremely high electro-optic and thermo-optic effects due to high birefringence ($\Delta n \approx 0.8$)[4] and large dielectric anisotropy ($\Delta\epsilon \approx 70$).[5] If a typical index-guiding PCF is infiltrated with LCs, it will start guiding light by the bandgap effect, since LCs have an average refractive indice higher than that of silica. All-in-fiber devices based on LCs infiltrated PCFs have been demonstrated[6] and a variety of components have been developed, such as polarization controllers,[7] polarizers,[8] long-period gratings,[9] Gaussian filters[10] etc. All these fabricated devices possess both thermal and electrical tunability. Optical tunability of a LC-based PCF has also been achieved.[11] The typical insertion loss measured for these kinds of devices is in the range 2–5 dB for 10–20 mm infiltration. Such loss is normally caused by the sum of different contributions: scattering and absorption from the LC, coupling loss between the core mode of the unfilled fiber and that of the filled fiber, and propagation loss. The lower order bandgap in the near-infrared (IR) region shows normally a higher loss with respect to the higher order bandgaps in the visible region. This is because the guided modes of the LC rods are less confined at longer wavelengths than at shorter ones.[12] Furthermore, the absorption of most LC materials is higher at infrared wavelengths with respect to visible wavelengths. In the visible spectral region, in fact, most LCs are transparent while, in the mid- and long-infrared (IR) region, strong molecular vibration bands occur.[13] For example, the CH, CH2, and CH3 bands overlap closely in the 3.4–3.6 μm range, and the CN absorption band occurs at 4.45 μm. The overtones of these vibration bands fall into the near IR, at around 1–2 μm. This is a limitation for devices working in this range. In order to reduce the absorption in the near-IR region, a LC with deuterium (D) atoms instead of hydrogen (H) atoms is used in this experiment. The D atom has, in fact, a larger atomic mass with respect to the H atom, and therefore the CD stretching will occur at longer wavelengths with respect to that of the CH band, in this way reducing the absorption of the LC in the near-IR region.[14]

In this paper, we demonstrate a low loss LC-based PCF device. We use a LC named 5CB with H atoms exchanged with D atoms (D-5CB or perdeuterated 5CB)[14] and compare the obtained transmission spectrum with the one measured by using a standard LC 5CB, which contains H atoms. The reduction of the loss is considerable in the near-IR region. With D-5CB, we measure a loss of 1 dB in the middle of the bandgap, while with standard 5CB the loss is 3 dB. The reduction of the loss is critical for telecommunication devices, such as polarization controllers, polarimeters or filters in general.

2. D-5CB LC-Based PCF Device

We use a large mode area PCF (NKT Photonics, Denmark), with a solid core surrounded by four rings of air holes arranged in a triangular lattice. The hole size is 3.5 μm, the inter-hole distance is 9.1 μm and the outer diameter is 125 μm. Figure 1 shows the micrograph of its end-facet. This fiber is infiltrated with D-5CB for 20 mm by using capillary forces. We perform polarization microscopy observations on a 5 μm silica capillary infiltrated with this LC and we observe that the LC has a planar alignment, i.e., the LC is aligned along the axis of the capillary. Figure 2 shows two polarization micrograph of the LC infiltrated capillary at different angles with respect to the crossed polarizers of the microscope. The transmission is measured by butt-coupling the device to a single-mode fiber (SMF). A supercontinuum source is coupled to one end of the SMF and the transmission spectrum is recorded by an optical spectrum analyzer on the opposite side of the device, and then normalized to the spectrum of the empty fiber. Figure 3

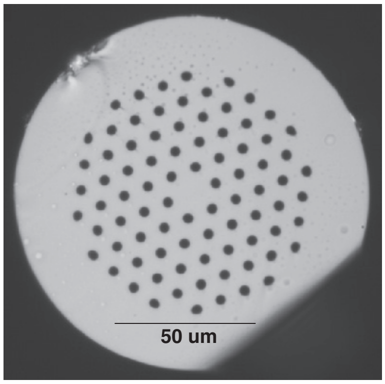

Fig. 1. SEM picture of the PCF end-facet used in this experiment.

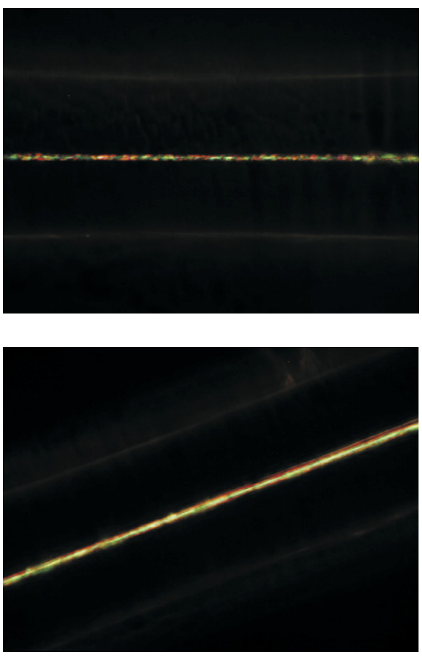

Fig. 2. (Color online) Polarization micrographs of a 5 μm silica capillary filled with D-5CB.

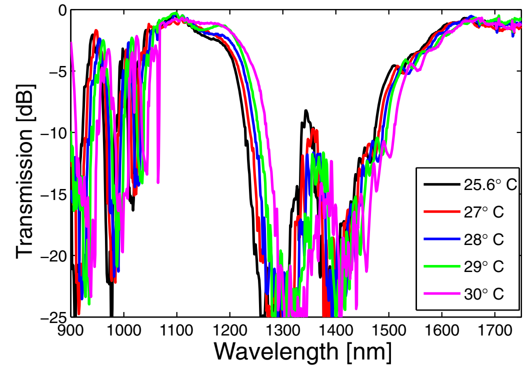

Fig. 3. (Color online) Transmission spectrum of a large mode area PCF infiltrated with the perdeuterated LC D-5CB for 20 mm.

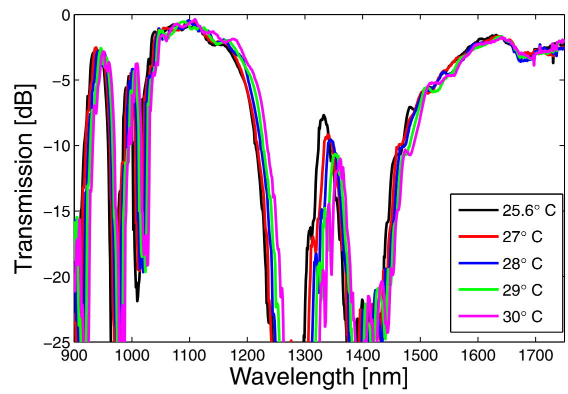

Fig. 4. (Color online) Transmission spectrum of a large mode area PCF infiltrated with the commercially available LC 5CB for 20 mm.

shows the transmission spectra of the D-5CB based PCF for different temperatures. We observe the formation of bandgaps and we notice that the loss in the middle of the near-IR bandgap is around 1 dB (with a peak of 0.8 dB). This is the lowest loss ever measured for a LC-based PCF device in the near-IR range. In ref. 9, for example, a higher loss of 3–4 dB was measured in the middle of the lower order bandgap by using a different LC infiltrated into a PCF for the same length as the one considered in this experiment.

3. 5CB LC-Based PCF Device

We now infiltrate the same PCF with the more standard LC 5CB with H atoms in order to compare its transmission spectrum with the one previously obtained. The infiltration length is again 20 mm. We perform polarization microscopy study with a 5 μm capillary infiltrated with this LC and we observe that the 5CB displays a planar alignment such as in the previous experiment with D-5CB. Figure 4 shows the transmission spectrum of this fiber device measured in the same way as the one presented before.

4. Comparison between the Two Devices

In Fig. 5 we compare the transmission spectrum obtained with D-5CB with the one achieved with 5CB. Both the spectra were measured at 25.6 °C and the LCs were infiltrated for a length of 20 mm. We notice that the loss for 5CB is about 3–4 dB in the wavelength range of 1650–1750 nm, while by using D-5CB the loss can be reduced to 1 dB. Therefore, an improvement of more than 2 dB has been achieved in the near-IR region by using a perdeuterated LC. Figure 6 shows the measured optical density of D-5CB and 5CB infiltrated in a 1-mm-thick quartz.[14] One can notice that D-5CB displays a reduced absorption in the near-IR region with respect to the more standard 5CB and that there is a correspondence between the absorption shown in Fig. 6 and the transmission spectra of Fig. 5. The use of a LC with a reduced absorption is particularly useful for long infiltration lengths (>10 mm). In this specific case, in fact, the absorption of the LC can give rise to high losses, which might decrease the performance of the device. The reduction of the absorption loss is particularly useful, for example, for

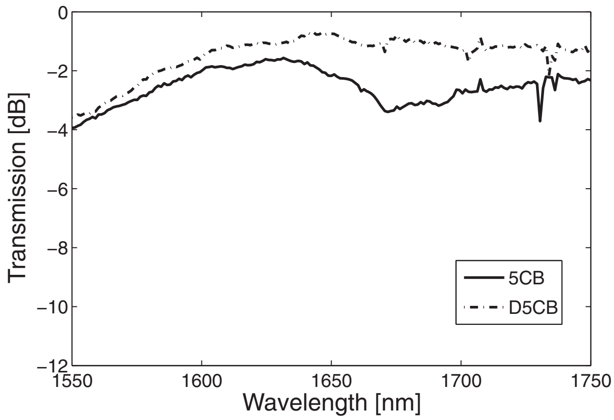

Fig. 5. Comparison between the transmission spectra of a large mode PCF infiltrated with D-5CB and 5CB at 25.6 °C in the wavelength range of 1550–1750 nm.

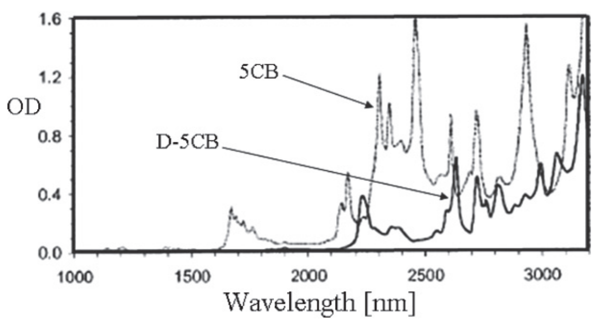

Fig. 6. Measured optical density (OD) of 1 mm quartz cell filled with D-5CB and 5CB in the near-IR region.[14)]

polarization controllers devices which need to be infiltrated for more than 20 mm and have stringent limitations concerning the loss. Concerning the temperature tunability of the two developed devices we observe by comparing Fig. 3 with Fig. 4 that the fiber infiltrated with D5CB exhibits a slightly higher thermal tunability than that of 5CB. This can be explained by the fact that the clearing temperature of D5CB is slightly lower than that of 5CB (32.1 °C for D5CB versus 34.2 °C for 5CB) and both measurements of the transmission spectra were taken within the same temperature range 25.6–30 °C. Both LCs present a planar alignment inside the capillaries of the fiber and it is therefore mainly the ordinary refractive index which plays a role in the temperature tunability of the devices. In ref. 15 the typical behavior of both ordinary and extraordinary refractive indices as a function of temperature is shown for many LCs, including 5CB. In proximity of the clearing temperature the ordinary index increases rapidly and the closer we get to the clearing temperature the higher the temperature gradient becomes. Therefore, the higher temperature tunability of D5CB in comparison to 5CB is a consequence of the fact that, for the temperature interval considered, the thermal gradient of D5CB is higher than that of 5CB, since the temperatures at which the measurements were taken lie closer to the clearing temperature of D5CB than 5CB.

5. Conclusions

We have infiltrated an index-guiding PCF with a perdeuterated 5CB LC. The hydrogen atoms of this LC have been substituted with deuterium ones. This procedure reduces the absorption of the LC in the near-IR spectrum. We have measured and compared the transmission spectra of two different devices. The first device has been fabricated by infiltrating a large mode area PCF with a perdeuterated 5CB, while the second consists of the same PCF filled with a normal 5CB LC. The loss in the middle of the lower order transmission bandgap is considerably lower for the perdeuterated LC device. In fact, a loss of less than 1 dB in the middle of the near-IR bandgap is achieved for the PCF infiltrated with 20 mm perdeuterated 5CB, while 3–4 dB losses have been measured with the standard 5CB. This is the lowest loss ever reported for this kind of devices in the near IR region and it allows the fabrication of low loss all-in-fiber LC devices.

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