# Highly birefringent microstructured fiber selectively filled with lossy material

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**Abstract**—Photonic crystal fibers (PCFs) filled with various substances can be used as all-in-fiber tunable devices. Due to their optical anisotropic properties, liquid crystals (LCs) are one of the best solutions for these devices. However, numerical modeling and design may be a very challenging task in this case if LC anisotropy is considered. Moreover, LCs are characterized by much higher losses than silica glass and it is not clear how it will affect the modal properties. In this paper we investigate theoretically highly birefringent PCFs selectively filled with lossy materials characterized by a wide range of extinction coefficients.

In the last decade photonic crystal fibers have attracted significant attention of many researchers all over the world. In these fibers light can be guided by two different mechanisms: the index-guiding and the photonic bandgap (PBG) effect [1]. It is possible to tailor their properties by playing with the holes size and their distribution. A change in the fiber microstructure geometry is one way to modify its guiding properties. Another method is PCF infiltration with substances whose refractive indices can be dynamically influenced by external physical fields. This gives us an opportunity to create dynamically tunable PCFs. Liquid crystals are especially interesting as a filling material since their optical properties can be easily modified external fields. Generally, both refractive indices of LCs are higher than the refractive index of silica glass and in the majority of cases light is guided in the core by the photonic bandgap effect. Recently, it has been experimentally demonstrated that the properties of liquid crystal photonic bandgap fibers (LC PBFs) can be tuned with temperature [2] or electric field [3]. Electric tuning has been also demonstrated in index-guiding hollow-core PBG fiber filled with a liquid crystal [4]. Optical tuning in PCF filled with a dye-doped LC has been reported in [5]. By filling PCFs with unique LC mixture (characterized by extremely low ordinary refractive index) dynamic tuning from index-guiding to PBG mechanism was possible [6]. Dynamic birefringence tuning in selectively filled highly birefringent (HB) PCF has been also experimentally demonstrated [7].

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Although all the results mentioned above are very interesting and promising, it is quite difficult to analyze them theoretically. This difficulty originates from the complex physical properties of LCs. Firstly, LCs are characterized by very high (in comparison to other materials) optical anisotropy – depending on their molecular structure it can vary from 0.05 to even 0.9. The second issue is that the optical properties of LCs strongly depend on a molecular orientational order parameter, which should be also taken into account in theoretical investigations. And finally, LCs attenuation is many orders of magnitude higher than the attenuation of silica glass. This could have a strong impact not only on modal losses but also on the values of modal effective refractive indices.

Several attempts to explain theoretically the propagation effects in LC-filled PCFs have already been reported [8-15]. In some of them, LC anisotropy and orientation has been taken into account. However, effects of LC attenuation on the light propagation has never been discussed so far.

The motivation for this paper was to investigate how LC attenuation influences the modal properties of an LC-filled HB PCF [7]. A full vectorial Finite Element Method (FEM) with Perfectly Matching Layers (PML) boundary conditions was applied [14], and fiber structure was characterized by a complex refractive index:

$$m = n + i\kappa \qquad (1)$$

where n is a refractive index, and $\kappa$ is an extinction coefficient. The extinction coefficient $\kappa$ can be used to calculate material attenuation by using the following formulae:

$$\alpha_{dB} = \frac{20}{\ln 10}\frac{2\pi}{\lambda}\kappa \qquad [\alpha_{dB}] = \frac{dB}{[\lambda]} \qquad (2)$$

where $\lambda$ is the wavelength (all results in this paper were obtained for $\lambda$ = 1500 nm).

As mentioned before, LCs' attenuation is much higher than the attenuation of silica glass. Losses in high-grade pure silica glass are about 0.15 dB/km at 1500 nm, which corresponds to a very low value of extinction coefficient $\kappa$ - in the order of $10^{-12}$. Generally, it is quite difficult to measure liquid crystals extinction coefficients and special techniques are required in which LCs molecules are usually oriented in a planar cell with thickness of few tens of microns. Moreover, extinction coefficients do not play a crucial role in the most of applications, so there is lack of papers presenting values of the LCs extinction coefficients. Reported values can be in the order from 0.001 [16] up to 0.01 [17], or in some special conditions reaching the value of 0.5 [18].

Since there is about ten orders of magnitude difference between pure silica glass and LCs extinction coefficients, it is not so clear how such a big difference in the material attenuation will result in modal properties of the fiber. To explain this we decided to perform a series of simulations in which refractive index of filling material was fixed as a constant (and equal to the index of silica glass), whereas the extinction coefficient has been systematically changed in the wide range: from $10^{-12}$ to 10. The values of $\kappa$ in the order of 10 are typical for metals, for example, the complex refractive index of aluminum at 1550 nm is equal to (1.44 + i16) [19].

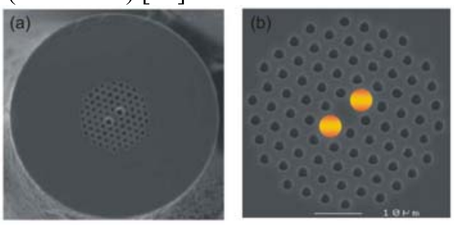


Fig. 1. Cross section of the *Blazephotonics* PM-1550-01 fiber a) an empty PCF, b) two big holes selectively filled with lossy material.

As a host structure in our theoretical investigations we used a commercially available HB PCF (PM-1550-01 – Fig1). In our simulations we assumed that only two big holes are filled with a lossy material (Fig. 1b). We have chosen this model, because by using the PM-1550-01 fiber selectively filled with a low-index LC, thermal birefringence tuning was experimentally observed [7], but theoretical analysis appeared somehow difficult [9,10].

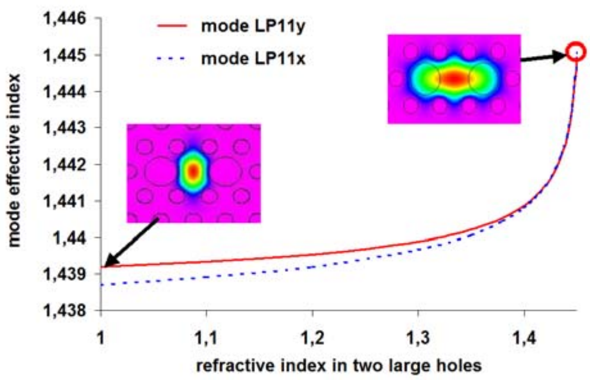


Fig. 2. Modal effective indices change in the function of the filling material refractive index $n_H$ (extinction coefficient $\kappa_H$ equal to 0).

Figures 2 and 3 show the results of simulations in which only the refractive index of two big holes ($n_H$) was varied in the range from 1.0 to 1.45, and the extinction index ($\kappa_H$) was equal to 0. Fig. 2 shows that modal effective indices for both polarizations increase when $n_H$ rises. At the same time the difference between the values of both effective indices gets smaller – so the phase birefringence decreases and changes its sign (Fig. 3).

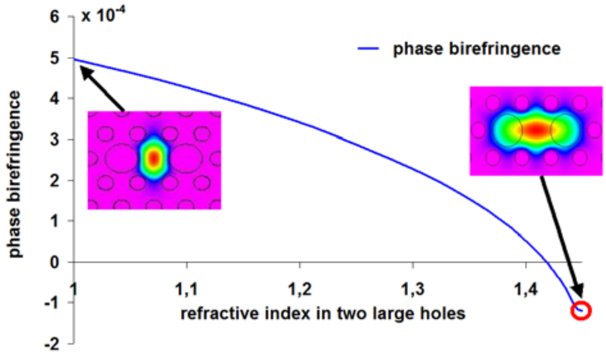


Fig. 3. Phase birefringence in the function of $n_H$ ($\kappa_H$ equal to 0).

It could be also noticed that the mode area increases with $n_H$, and for $n_H \sim 1.45$ the mode covers both the core and two holes. Similar values of $n_H$ were used in [7], so to investigate how filling material attenuation would influence modal properties, in next step we decided to fix $n_H$ equal to the glass refractive index (1.45) and change the value of $\kappa_H$ from $10^{-12}$ to 10 (however, the results presented in Fig. 4 are limited to the $10^{-6}$ – 10 range, because for $\kappa_H$ smaller than $10^{-6}$ results were the same as for $\kappa_H = 10^{-6}$).

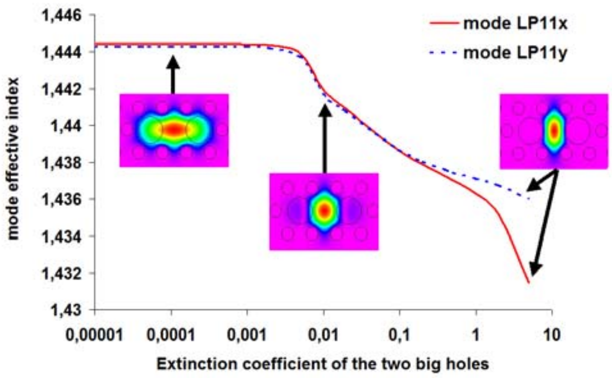


Fig. 4. Effective indices in the function of the filling material extinction coefficient $\kappa_H$ ($n_H$ fixed to 1.45)

Fig. 4. shows modal effective indices for different values of $\kappa_H$ for both polarizations. For $\kappa_H < 0.01$ the mode effective refractive indices remain almost constant. However, for higher values of $\kappa_H$ they start to fall down. Moreover, for very high attenuations ($\kappa_H \sim 1$) a significant difference between both polarizations is

 

observed. Also it could be noticed that the mode profile also changes with the increasing value of $\kappa_H$. For low values of $\kappa_H$ the mode deeply penetrates the holes area, but for higher $\kappa_H$ values the mode is "pushed away" from the highly attenuated area and propagates mainly in the core.

A change in the effective indices for both polarizations means that the phase birefringence also changes with increasing value of $\kappa_H$ – most significant changes are visible for very high attenuations (Fig. 5). It suggests that by using materials with optically tunable attenuation (such as saturable absorbents know from passively Q-switched lasers) all-optical birefringence tuning may be possible.

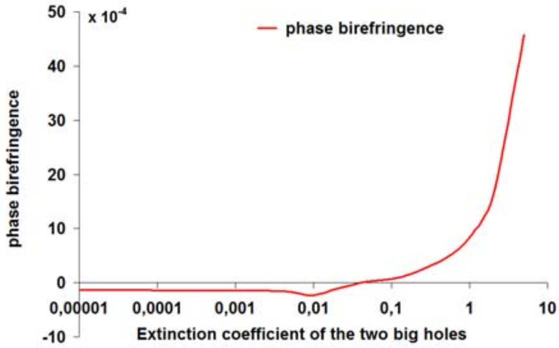


Fig. 5. Phase birefringence in the function of $\kappa_H$ ($n_H$ fixed to 1.45).

To give a full view how the increase of $\kappa_H$ modifies the guiding properties of fiber, the characteristics of modal confinement losses is shown in Fig. 6. It could be noticed that confinement losses strongly depend on $\kappa_H$ – even for small values, where both effective refractive indices were constant.

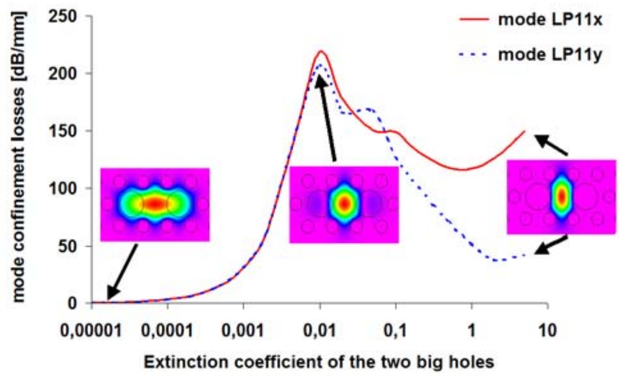


Fig. 6. Confinement losses for the fundamental mode in the function of the filling material extinction coefficient $\kappa_H$ ($n_H$ fixed to 1.45).

For very high values of $\kappa_H$ the mode is localized in the core (however, losses are still high) and also confinement losses are different for both polarizations – relatively high Polarization Dependent Losses (PDL) appear. It suggests that short sections of the HB PCF selectively filled with a metal (for example, aluminum) may be used as an in-fiber polarizer. However in practice selective filling with metals may be a very challenging task. Moreover to determine precisely properties of the PCFs filled with metals more advanced numerical method should be applied, which deals with surface plasmons. It is also worth to mention that single polarization guiding may be obtained much easier in the PCF with similar geometry to the fiber discussed in this paper, but with different diameters of small and big holes [20].

To conclude, the properties of an HB PCF selectively filled with lossy materials (including LCs) depend not only on the refractive indices of a filling material, but also on its extinction coefficient. Its impact on confinement losses is quite natural and could be deducted qualitatively without any simulations. However, significant changes in the mode profiles, effective indices and birefringence are not so trivial to predict.

In the context of theoretical investigations of PCFs filled with LCs it can be concluded that, to ensure a good agreement with experiments, numerical models should deal not only with LC anisotropy and molecular orientation, but also losses of the LC filling material.

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