Modeling of polarization behaviour of LC filled photonic crystal fibers

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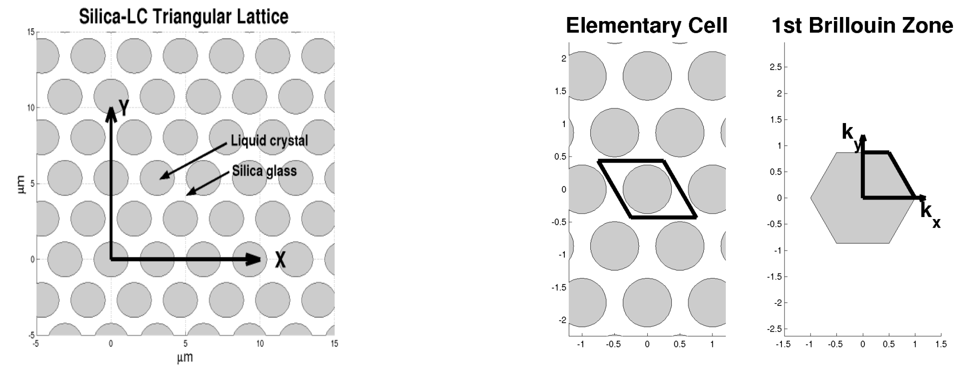
We present the modeling results on the polarization properties of silica-LC photonic crystal fibers. We investigate how the material anisotropy induced when the LC is oriented by an externally applied static electric field, modifies the bandgap structure of the fiber cladding, compared to the isotropic situation. The polarization dependent shift of the out of plane bandgap may enable the construction of novel polarization controllers or switching devices.

Introduction

Photonic crystals containing liquid crystal (LC) inclusions have recently brought a lot of interest [1] as they represent a novel tunable material. The tunability of the optical properties of LC with temperature or external electric field makes it easy to modify the photonic bandgap (PBG) of the crystal.

Bandgap guiding photonic crystal fibers [2] (PCF) with a silica-LC microstructure have been experimentally demonstrated by Larsen et al [3]. In their work, the LC has been overgoing a change of refractive index and a phase transition with the variation of temperature, allowing to tune the wavelength range guided by the PCF.

In this paper we investigate the polarization properties of a LC-silica fiber, when the LC is highly birefringent giving rise to a modified bandgap structure. We base our study on the plane wave method formulated for binary birefringent materials [4,5].



a) b)

Fig. 1. a) The triangular lattice used to model the properties of the cladding of the LC-silica PCF. **b)** The elementary cell and the corresponding part of the 1st Brillouin zone used in simulations.

PBGs of the silica lattice with a birefringent material in the capillars

In this section we analyze the bandgap structure of a silica-LC triangular lattice in a LC-filled PCF cladding. For the sake of simplicity, we assume the LC to be a spatially uniform uniaxial material. This obvious simplification provides good physical insight into the role of birefringence in the modification of the bandgap structure. On the other hand, it becomes a resonable model for a LC-silica 2D photonic crystal, with the LC oriented by an externally applied static electric field. The latter situation is practically interesting, as the rotation of the orientation of the applied field, and the following rotation of the refractive index ellipsoid of the LC, allows to tune the bandgap differently for the two polarizations. It is straightforward to construct a polarizer or a switching device based on this principle.

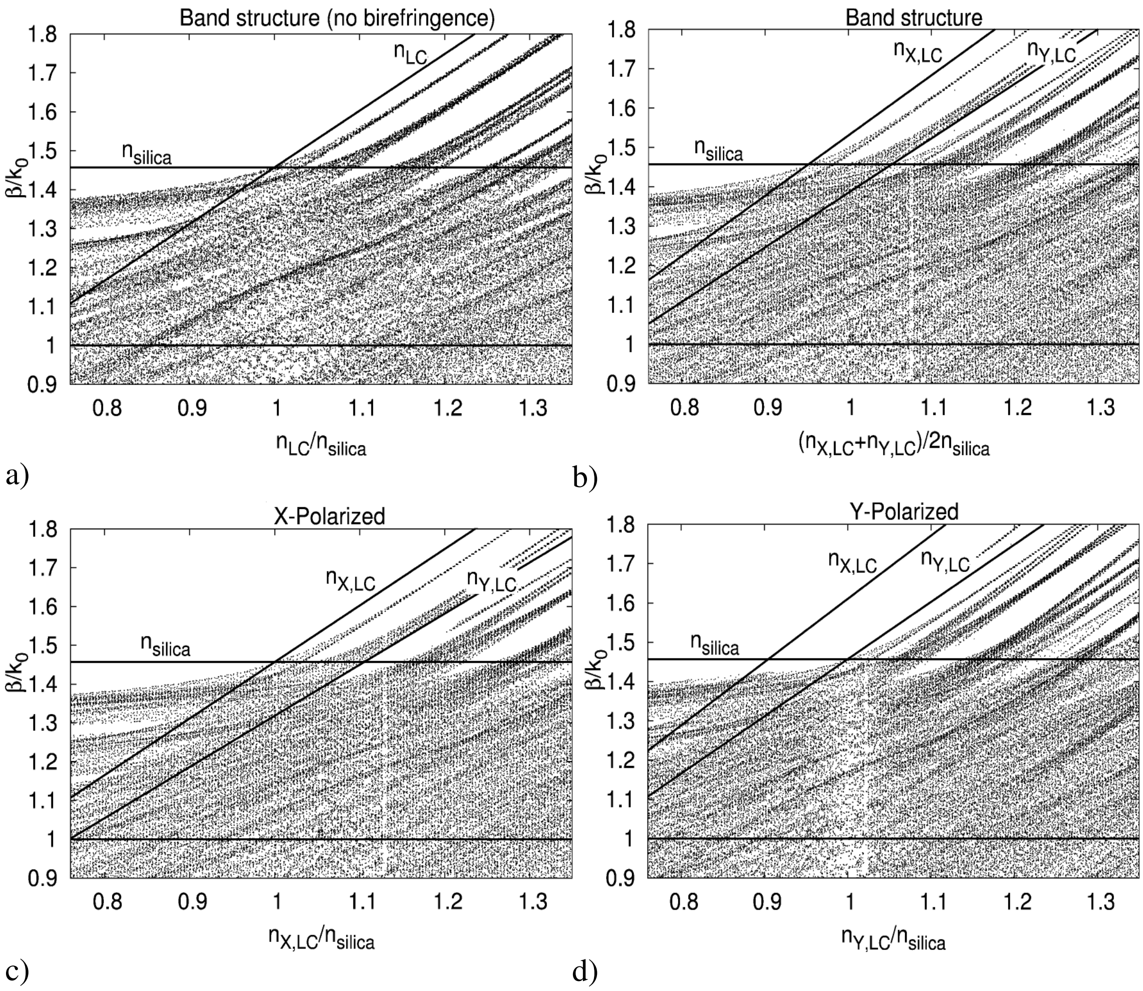


Fig. 2. The photonic bandgap structure of a silica triangular lattice with circular holes filled with an isotropic (a) or birefringent (b,c,d) liquid crystal vs refractive index contrast ($\Lambda/\lambda=2$, filling factor=0.5). Solid lines correspond to the refractive indices of silica glass, air, and the indices of LC ($n_{LC,X}>n_{LC,Y}$). The full bandgap structure is shown in a) and b), while c) and d) represent the bandgaps for the x, and y polarizations respectively.

In the bandgap calculations we use an in-house implemented solver based on the plane-wave method [4]. The problem is formulated as an eigenequation for the transverse magnetic field and the corresponding propagation constants:

$$\hat{L}\cdot h_t=\beta^2 h_t \qquad (1)$$

In addition to previous work based on this formulation [6,7,8], in our model, we also account for material birefringence $\varepsilon_{ij}=\varepsilon_i\delta_{ij}$, which is sufficient for modeling of uniform biaxial fiber profiles. We note that our model is also applicable to other birefringent structures than PCF, and for instance we have recently used it to analyze the polarization losses in surface relief VCSELs [9].

In this paper we consider a silica fiber with circular LC-filled holes arranged in a triangular lattice. In the absence of material birefringence, the hexagonal symmetry of this lattice leads to polarization mode degeneracy [10]. Even then, the fiber could be highly birefringent, provided that the shape of the core does not fulfill the same symmetry. We have earlier demonstrated numerically and experimentally the presence of high birefringence for an index guiding PCF effecting only from the assymetry of the core shape [5]. However, as the PBG structure of the cladding shows no preference to any particular polarization state in that case, we could expect similar cut-offs for the polarizations of the bandgap guided modes. On the other hand, the change of geometry of the lattice or the presence of material birefringence breaks the degeneracy of the bandgap structure with respect to polarization, leading to a distinct behavior of bandgap guided polarization modes. In a separate paper at this conference [11], we analyze the case of birefringence introduced through squeezing the lattice, while here we consider a perfect hexagonal lattice but composed of birefringent materials.

Figure 1 shows the triangular lattice consisting of silica glass with LC circular holes together with the reduced Brillouin zone. We assumed that the filling factor is equal to $f=0.5$, the ratio of the pitch to wavelength is $\Lambda/\lambda=2$, and the simulations have been done for $\lambda=1.55\mu\mathrm{m}$. Figure 2(a). presents the PBG structure of the lattice from fig. 1 as a function of the index contrast, with the assumption that the LC is isotropic. Clearly, the respective locations of the bandgaps, and the lines representing the refractive index of silica glass, LC, and air indicate the possibility of achieving effective index guidance in a LC core (for $n_{LC}>n_{silica}$, when the fundamental space filling mode is below n_{LC}), or PBG guidance in a silica core (around $n_{LC}\approx1.53$ or $n_{LC}\approx1.63$). On the other hand, bandgap guidance in air is not possible.

Figure 2(b) represents an analogous simulation for the birefringent case, when the LC is uniaxial with axis oriented transversally along $\hat{\mathbf{x}}$, and the the ratio of the principal refractive indices $n_{X,LC}$ and $n_{Y,LC}$ is equal to $n_{X,LC}/n_{Y,LC}=1.1$. Further in fig. 2(c) and 2(d) the bandgaps for the X and Y linear polarizations are drawn independently vs $n_{X,LC}/n_{silica}$, and $n_{Y,LC}/n_{silica}$ based on the same vectorial simulation that is presented in fig. 2(b). The bandgaps have been plotted with the assumption that less than 0.1% of energy is present in the given polarization state.

It is easy to identify in fig. 2(b)-(d) some practically interesting regions that allow for: effective index guidance in LC for a single polarization only ($n_{X,LC}>n_{silica}>n_{Y,LC}$), effective index guidance in LC for both polarizations ($n_{silica}<n_{Y,LC}$). Also for a core made of silica glass, it is possible to acheive bandgap guidance for one polarization only (e.g. for $n_{X,LC}\approx1.52$), or for a very high refractive index of LC, bandgap guidance for both polarizations ($n_{Y,LC}\approx1.68$).

A direct comparison of fig. 2(a) with 2(c) or with 2(b), illustrates the significance of the vectorial effects in PBG calculation. Without the polarization coupling one should expect all the three figures to be exactly equivalent. Clearly, except for small index contrast ratios it is risky to assume that the bandgaps could be determined independently for the two polarizations through two isotropic simulations. The same remark applies to any attempt of determining the full bandgap structure in the anisotropic situation shown in fig. 2(b), by superimposing the structures from fig. 2(a) with contrast ratios corresponding to the normal and anomalous refractive index of the LC.

Finally, we would like to mention the noticable decrease of the density of states observed in fig. 2(d) when $n_{Y,LC} \approx n_{silica}$. This effect will be further studied in the future.

Conclusions

We have investigated the photonic band structure of triangular silica-LC lattice for a large range of refractive index contrasts under the assumption that the LC is highly birefringent and spatially uniform. More in particular, we have shown how the release of the hexagonal symmetry due to the material birefringence leads to the separation of the bandgap structure for the two linear polarizations oriented along the principal axis of the LC refractive index ellipsoid. In a PCF with such a cladding, different guidance regimes can be identified for the two polarization modes. This could find application in novel switching or polarizing devices, where the bandgap is tuned with the appliance of a static external electric field.

Acknowledgments

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