Polarization properties of liquid-crystal infiltrated photonic crystal fibers

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Introduction – Photonic Crystal Fibers

Light guidance in photonic crystal fibers is achieved by two distinct mechanisms:

- **index-guiding** by a modified form of total internal reflection
- **bandgap-guiding** due to the bandgap effect originating from the periodic cladding structure.

- In **index-guiding** PCFs the solid defect core exhibits a higher refractive index than the effective index of the air-hole cladding.


- In **bandgap-guiding** PCFs light is confined in a lower index defect core due to the full bandgaps of the periodic cladding that prevent transversal leaking.

Introduction – Nematic Liquid Crystals

- Nematic liquid crystalline materials consist of rod-like molecules that exhibit macroscopically orientational order along the “director”.

- When confined in cylindrical cavities the local director’s pattern is determined by the physics of elastic theory and the anchoring conditions at the cavity’s walls.

- Two commonly observed patterns for homeotropic anchoring conditions are the planar-polar and the escaped-radial.

- A very common pattern for homogeneous anchoring conditions is the axial or planar (molecules aligned along the cylinder axis).

- The director pattern can be controlled by an external electric field.

Liquid Crystal Photonic Crystal Fibers – Keypoints

LC-PCFs : Boosting the fiber’s polarization properties

- The inherent anisotropic properties of LCs are exploited to achieve extensive polarization control: single-polarization and polarization-maintaining (highly birefringent) fiber properties are targeted.
- The thermo-optic and electro-optic response of the LC molecules allow for the dynamical control of the fiber’s polarization properties.
- Tunable transition among different operational states is also feasible.

LC-PCFs : Key technological features

- Infiltration (capillary forces, vacuum pump) – Selective infiltration.
- Electrical control of the LC molecule pattern – Electrodes and applied voltage.
- LC compounds with tailored properties – Highly birefringent LCs ($\Delta n \sim 0.4$).
- Non-silica fiberglasses (Fluorine, Metal oxide, Tellurite).
**Liquid Crystal Photonic Crystal Fibers – Experimental milestones (1)**

- **Thermal switch with 60 dB extinction ratio for $\Delta T = 0.4^\circ C$ around LC phase-transition temperature**
  

- **All-optical thermal tuning of photonic bandgaps and modulation with dye-doped LCs**
  

- **Electrically tunable, polarization-dependent fiber optical power transmission**
  

Liquid Crystal Photonic Crystal Fibers – Experimental milestones (2)

- Extremely sensitive (27nm/°C) thermal tuning of photonic band-edges with highly thermo-optic LCs
  

- Switching between index guiding and PBG guiding
  

- Electrically controlled broadband fiber polarimeter
  
Main points addressed in this talk

Theoretically investigate the propagation mechanisms in LC-PCFs in order to achieve single-polarization and/or polarization-maintaining (highly birefringent) guidance:

- Exploiting index guiding (m-TIR).
- Exploiting photonic bandgap (PBG) guiding.
- Exploiting hybrid guiding: i.e. on polarization is index guided whereas the orthogonal is PBG guided.
Index-guiding LC-PCFs - Structural layout

- Selection of proper materials so that the fiberglass index matches the extraordinary index of the nematic LC.
- Light is guided through the infiltrated defect core due to index guiding.

The orientation of the nematic director is controlled via an external electric field.

\[ V_y = V, \quad V_x = 0 \]

The effective core index “sensed” by \( x \)- and \( y \)-polarized light is \( n_o \) and \( n_e \), respectively.
Index-guiding LC-PCFs – Single polarization properties

Material and Structural Parameters

- Fiberglass of $\text{n}_g=1.68$
- Nematic compound E7 ($\text{n}_o=1.5$, $\text{n}_e=1.68$)
- Y-aligned nematic director or planar polar profile
- Defect radius $r_{\text{def}}=0.5\Lambda$, hole radius $r=0.2\Lambda$

- The HE$_y$ mode senses: a matched index ($\text{n}_g=\text{n}_e=1.68$) for y-aligned director; a high index with $\text{n}_{\text{eff}}<1.68$ for the PP profile. Index-guidance is supported in either case.
- The HE$_x$ mode senses a low-index core and radiates into the cladding.

- The HE$_y$ modal profile exhibits hexagonal symmetry for y-aligned director; for the PP profile optical power concentrates along the y-axis.
- The fiber supports single mode/single polarization guidance. The polarization axis may be controlled by the applied electric field.
Index-guiding LC-PCFs – Highly birefringence properties

- The fiber’s material parameters are kept the same and molecules are y-aligned.
- The reduction of the defect core radius raises the core’s effective index for x-polarized light.
- For $r_{\text{def}} \sim 0.25 \Lambda$ the dispersion curve of the $\text{HE}_x$ mode enters the waveguiding region.

- The $\text{HE}_x$ mode for $r_{\text{def}} \sim 0.25 \Lambda$ exhibit significant radiation into the cladding as its dispersion curve lies very close to the radiation line.
- As the value of $r_{\text{def}}$ is further reduced, the $\text{HE}_x$ mode gets more localized in the central defect core.
The values of modal birefringence can be finely adjusted by varying the central defect radius $r_{\text{def}}$.

Especially high birefringence values can be obtained: up to $\sim 1.5 \times 10^{-2}$ at $\Lambda/\lambda = 1.1$ for $r_{\text{def}} = 0.25\Lambda$.

The fiber still does not allow for the propagation of higher-order modes.

The fiber supports single mode/highly birefringent guidance. The two orthogonal polarization axes may be controlled via the applied electric field.

Bandgap-guiding LC-PCFs – Structural layout

- **Honeycomb lattice** photonic bandgap fiber.

- Selection of proper materials so that the fiberglass index is higher than both refractive indices ($n_e$, $n_o$) of the nematic LC.

- Light is guided through the air defect core owing to the **bandgap effect**.

The orientation of the nematic director is controlled via an **external electric field**.

\[ V_y = V, \ V_x = 0 \]

The effective index “sensed” by $x$- and $y$-polarized light in the cladding holes is $n_o$ and $n_e$, respectively.
Bandgap-guiding LC-PCFs – Single polarization properties

Material and Structural Parameters

- Fiberglass of $n_g=2.1$ (Tellurite).
- Nematic isothiocyanato–based compound: $n_o = 1.5624$, $n_e = 2.09$.
- Y-aligned nematic director.
- Cladding hole radius $r = 0.25\Lambda$.

The fiber supports single polarization guidance.

- The fundamental $HE_y$ mode senses $n_e=2.09$. The contrast $n_g/n_e$ is too low to allow for full bandgaps for $\beta\Lambda < 15$.
- The fundamental $HE_x$ mode senses $n_o=1.5624$ and its dispersion curve can be adjusted by varying the core radius.
- The fiber remains single-mode for $4.5<\beta\Lambda<9$. 
Bandgap-guiding LC-PCFs – Highly birefringence properties

Material and Structural Parameters

- Fiberglass of $n_g = 2.1$ (Tellurite).
- Nematic LC: E7 - $n_o = 1.5024$, $n_e = 1.697$ @ 25°C, 1 μm.
- Y-aligned nematic director.
- Cladding hole radius $r = 0.25\Lambda$.

- No losses or material dispersion issues; guidance in the LC-free core.
- Modal profiles for both x- and y-polarized light exhibit hexagonal symmetry.

- The $HE_y$ mode senses $n_e = 1.697$, while the $HE_x$ mode $n_o = 1.5024$.
- Different effective bandgaps open for light of x- or y-polarization; different modal dispersion curves and high birefringence values.
- The fiber remains single-mode for $5.5 < \beta\Lambda < 8.5$. 

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Bandgap-guiding LC-PCFs – Highly birefringence properties

- The values of modal birefringence can be adjusted by varying the cladding hole radius $r$.
- Especially high birefringence values can be obtained: up to $\sim 2.25 \times 10^{-2}$ at $\beta\Lambda = 5.5$ for $r = 0.3\Lambda$.
- The fiber remains single-mode for $5.5 < \beta\Lambda < 8.5$.

The fiber supports highly birefringent guidance.

The fiber’s dispersive properties depend on the form of the nematic director pattern.

The planar polar pattern varies between strong ($\xi = 0$) and weak ($\xi = \infty$) anchoring.

The value of $\xi$ affects the fiber’s birefringent properties.

Control over the director could be exerted by an external field, or by operating around the nematic to isotropic temperature of the LC.

Via the application of the external field the fiber may operate in a selective (x- or y-) single-polarization or tunable highly birefringent state.
Hybrid-guiding LC-PCFs – Structural layout

- Triangular lattice solid core fiber with LC infiltrated lattice capillaries: hole radius $r=0.25\Lambda$.

- Selection of proper materials so that the fiberglass index lies between the refractive indices of the nematic LC ($n_o < n_g < n_e$): $n_g=1.595$ (Schott F2 fiberglass), $n_o=1.51$, $n_e=1.86$.

The NLC molecules in the cladding capillaries are switched at a constant angle $\theta$ under the application of an electric field.
Hybrid-guiding LC-PCFs – Periodic cladding properties

- The tilt angle \( \theta \) determines the polarization-dependent properties of the periodic cladding (radiation line and photonic bandgaps).
- X-polarized light senses a low-index cladding characterized by the radiation line.
- As \( \theta \) obtains higher values full photonic bandgaps open in the periodic cladding for y-polarized light that senses high-index capillaries.
- Hybrid-properties: x-polarization \( \rightarrow \) index-guidance, y-polarization \( \rightarrow \) bandgap-guidance.
For zero value of the tilt angle $\theta$ the LC molecules align along the fiber axis: both polarizations sense the same low-index effective cladding and the fundamental mode is index-guided and degenerate.

For $\theta$ up to $\sim 25^\circ$ the dispersion curve of the $y$-polarized mode rises.

The fiber operates in a highly-birefringence state.
For $\theta$ around 30° the y-polarized mode cannot propagate.

For $\theta > 35^\circ$ the effective hole index sensed by y-polarized light is high enough to allow for full photonic bandgaps.

The fiber operates in an extremely highly-birefringence state due to hybrid-guidance: x-polarized mode is index-guided and unaffected by the LC switching, while y-polarized mode is tunably guided within the $\theta$-dependent bandgaps.
The fiber passes progressively from a zero-birefringence (ZB) state ($\theta=0^\circ$) to high-birefringence (HB) ($\theta<30^\circ$), single-polarization (SP) ($\theta\sim30^\circ$) and finally wavelength-selective extremely high-birefringence operation (EHB) ($\theta>30^\circ$).

In the HB state, birefringence values of up to $7\times10^{-3}$ may be achieved, while values of up to $5\times10^{-2}$ are predicted in the EHB state.

Low levels of switching are required ($\theta=50^\circ$) in order to induce SP, HB or EHB properties.
The Freederickz-like transition of the LC molecules in a capillary is modeled by minimizing the free total energy.

Realistic nematic director patterns are produced, correlated to an average tilt angle $\theta_{av}$ in the material’s bulk.

The dispersion curves for $\theta_{av}$ are compared to those under the assumption of a constant $\theta$. 
All principal characteristics of the fiber’s modal and polarization properties are preserved in the case of modeling realistic nematic director profiles as well.

Low values of applied voltage ($V<5$ V) are enough to induce the full transition (ZB $\rightarrow$ HB $\rightarrow$ SP $\rightarrow$ EHB) of the fiber’s operational state.

Bandgap guidance in the first-order bandgap for y-polarized light

Bandgap guidance in the second-order bandgap for y-polarized light

Index guidance for both x- and y-polarized light

Hybrid-guiding LC-PCFs – Summary & Keypoints

Electrically switchable hybrid-guiding liquid-crystal photonic crystal fibers exhibit the following attractive elements, not achieved by other types of proposed polarizing fibers:

1. Light is guided in a solid glass core minimizing thus material scattering and absorption loss or dispersion issues owing to the presence of the NLC.
2. There is no need for selective infiltration of the cladding's capillaries.
3. No specific anchoring conditions and therefore surface treatment of the capillary walls is required.
4. It is not necessary to fully switch NLC molecules so that single-polarization or highly-birefringent properties are induced; even relatively low levels of switching are sufficient.
5. The dependence of polarization properties on both the applied field and the operating wavelength provides extensive control capabilities, which might be particularly exploited in novel switching or polarizing devices.
Summary

(1) Though at an early stage, LC-PCFs are now recognized as a special class of infiltrated Photonic Crystal Fibers. In excess of 150 publications over the last five years.

(2) From the demonstration of basic concepts the research is now moving towards more elaborate functional devices.

(3) Applications in the area of optical fiber communications and fiber optic sensors are most likely.