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Published in:

Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, 2007. OFC/NFOEC 2007.

Link to article, DOI:

[10.1109/OFC.2007.4348726](https://doi.org/10.1109/OFC.2007.4348726)

Publication date:

2007

Document Version

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Noordegraaf, D., Scolari, L., Lægsgaard, J., Rindorf, L. H., & Alkeskjold, T. T. (2007). Electrically tunable long-period gratings in liquid crystal photonic bandgap fibers. In Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, 2007. OFC/NFOEC 2007. (pp. 1-3). Anaheim, LA, USA: IEEE. DOI: 10.1109/OFC.2007.4348726

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Electrically tunable long period gratings in liquid crystal photonic bandgap fibers

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Abstract: We demonstrate an all-electrically tunable long period grating in a photonic crystal fiber infiltrated with a nematic liquid crystal. The spectral dips and the resonance wavelengths are tuned electrically and thermally, respectively.

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OCIS codes: (060.2310) Fiber Optics; (230.3990) Microstructure Devices; (050.2770) Gratings; (230.3720) Liquid Crystal Devices

1. Introduction

Long period gratings (LPGs) have attracted a large amount of interest over the years, because of the wide range of applications, among others optical filtering [1], gain equalization [2], mode conversion [3] and temperature or strain sensors [4]. LPGs couple light from the core mode to copropagating higher order modes (HOM) of the fiber core or cladding. The phase matching condition is given by $\lambda_{res} = \Lambda_G(n_{eff,core} - n_{eff,HOM})$, where λ_{res} is the resonance wavelength, Λ_G is the grating pitch, $n_{eff,core}$ is the effective index of the core mode and $n_{eff,HOM}$ is the effective index of the higher order mode (HOM) that is coupled to by the grating [5].

Photonic crystal fibers (PCFs) are waveguides with holes running in the length of the fiber. This allows infiltration of various materials into the fiber, hereby creating highly tunable fiber devices. This was first done by Eggleton *et al.* to create highly tunable long period and fiber Bragg gratings [6]. The first tunable photonic bandgap fiber was demonstrated by Bise *et al.* [7], by infiltrating the air holes of a PCF with high index oil and tuning the bandgaps by temperature. Furthermore, photonic bandgap fiber devices with thermally, electrically or optically tunable bandgaps have been realized by infiltrating the holes of a PCF with a liquid crystal [8-11]. Recently long period gratings in photonic bandgap fibers have been realized by applying a periodic pressure to the length of the fiber [12, 13]. Furthermore electrically tunable LPGs have been realized in a single light guiding rod of liquid crystal [14] and in an index guiding fiber surrounded by four holes filled with liquid crystal [15].

In this paper we demonstrate the first, to our knowledge, purely electrically induced LPG in a liquid crystal photonic bandgap (LCPBG) fiber. The peak loss of the LPG is tuned by changing the strength of the applied electric field, and the resonance wavelengths of the grating can be tuned by temperature. The advantage is that no mechanical stress is applied to the fiber, resulting in a very stable grating. This enables small highly tunable fiber devices easily integrated into communication or sensor systems.

2. Electrically tunable LCPBG fiber

The fiber used in the experiment is a silica large mode area (LMA) fiber from Crystal Fibre A/S [16]. The diameter of the holes is $3.45 \mu\text{m}$, the inter hole distance is $7.15 \mu\text{m}$ and 7 rings of air holes are surrounding the fiber core. Fig. 1 left shows a scanning electron microscope (SEM) image of the fiber end facet.

The unfilled fiber is an index guiding fiber, i.e. guides light by the principle of modified total internal reflection. When the air holes of the fiber are infiltrated with a liquid crystal having a higher refractive index than that of silica, a high index hole region is created. The fiber now guides light in a finite number of wavelength bands due to anti-resonant reflections [17].

The liquid crystal used in this experiment is E7 from Merck, which has a wavelength dependent ordinary and extraordinary refractive index of $n_o=1.52$ and $n_e=1.75$, respectively, at 589.3 nm. The electrical permittivity at 1 kHz is $\epsilon_{\perp}=5.2\epsilon_0$ along the ordinary axis and $\epsilon_{\parallel}=19.3\epsilon_0$ along the extraordinary axis. All values are at 20°C. Within the holes of the PCF, the liquid crystal is planar aligned with its director along the fiber axis. An electric field applied to the liquid crystals inside the fiber results in a dielectric torque that aligns the liquid crystal molecules parallel to the electric field [9, 10].

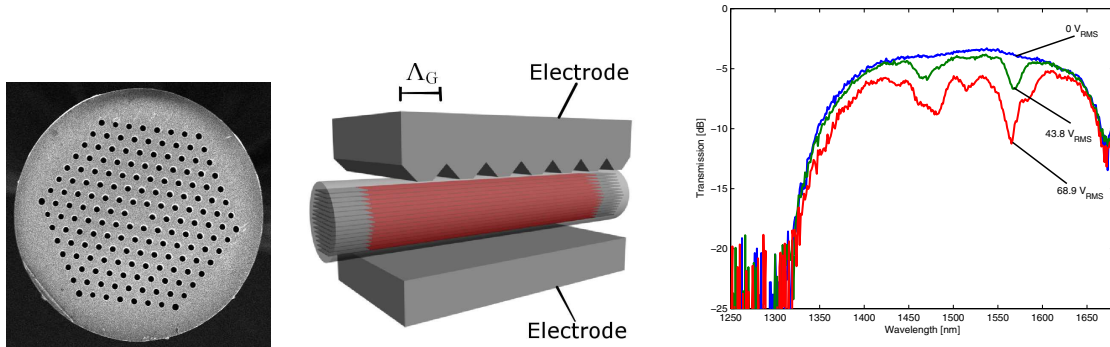


Fig. 1. Left: SEM image of LMA fiber end facet. Middle: Schematic illustration of LCPBG fiber sandwiched between electrodes used to create the LPG. No pressure is applied. The drawing is out of scale. Right: Long period gratings in a liquid crystal photonic bandgap fiber, the grating dips are tuned by varying the strength of the electric field at a constant temperature of 25°C.

The LCPBG fiber is sandwiched between two electrodes, where the top electrode has a periodic pattern of 26 V-grooves with a pitch of $\Lambda_G=800 \mu\text{m}$. Fig. 1 middle shows an out of scale image of the electrodes and fiber. When a 1 kHz sinusoidal voltage is applied to the electrodes, the periodic pattern of the top electrode results in a periodically varying electric field along the fiber length. This results in a periodic variation of the orientation of the liquid crystals inside the capillary tubes, and gives a periodic modulation of the refractive index of the liquid crystal infiltrated fiber cladding. Fig. 1 right shows the transmission bandgap around 1500 nm when a voltage is applied to the electrodes. The temperature is fixed at 25°C. At a voltage of $V_{RMS}=43.8 \text{ V}$ two distinct dips are observed, one at 1565 nm and one at 1480 nm. When the voltage is increased to $V_{RMS}=68.9 \text{ V}$ two more dips appear, one at 1515 nm and a small one at 1440 nm.

By tuning the temperature of the liquid crystals inside the fiber, the refractive index is changed, and therefore the position of the loss peaks can be tuned, as seen in fig. 2 left. The loss peaks move towards shorter wavelengths when the temperature is changed from 25°C to 40°C, and towards longer wavelengths from 40°C to 59°C. In the temperature interval from 55°C to 59°C the resonance wavelengths move approximately 6 nm/°C.

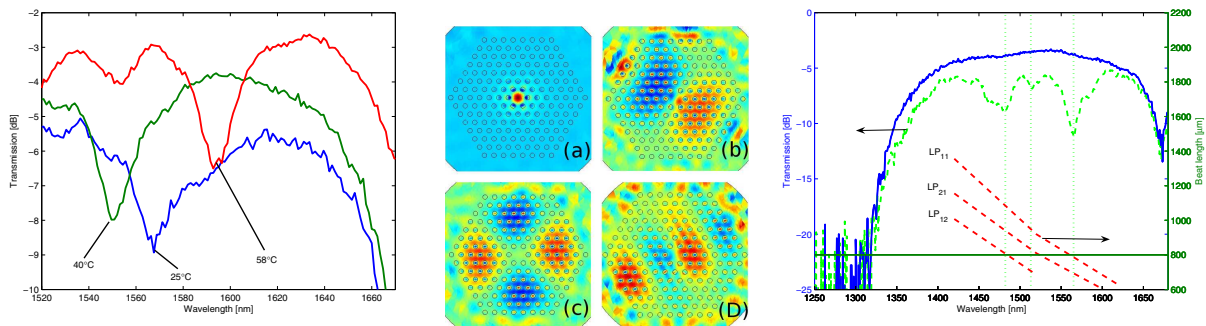


Fig. 2. Left: Tuning of the resonance wavelengths of the long period grating by changing the temperature of the liquid crystal at a constant applied electric field of $V_{RMS}=63.6 \text{ V}$. Middle: Transverse mode profiles of (a) LP_{01} core mode, (b) LP_{11} , (c) LP_{21} and (d) LP_{12} mode of the microstructured cladding. The plots show the dominant y-component of the magnetic field. Right: Transmission spectrum of the long period grating in the LCPBG fiber, superimposed with the simulated resonance wavelengths of the LP_{02} , LP_{11} and LP_{12} like cladding modes. The simulated resonances are shifted 30 nm in order to match the experimental measurements.

Simulations using COMSOL Multiphysics™ are performed in order to numerically determine the position of the spectral dips of the LPG in the LCPBG fiber. The dips appear where the phase matching condition is fulfilled for coupling of the fundamental LP_{01} core mode to HOM of the fiber. Fig. 2 middle shows the transverse mode profile of the fundamental core mode of the fiber (a) and the profiles of the cladding modes that, we believe, the core mode couples to (b-d). The simulated phase matching curves do not agree fully with the measured spectral dips, a slight shift of 30 nm towards longer wavelengths is observed. This is because the simulations are made for a perfect uniform cladding structure, and because of uncertainties in the value of the refractive index of the liquid crystal. The

refractive index of the liquid crystal is measured at visible wavelengths and then extrapolated using Cauchy equations to infrared wavelengths [18]. Furthermore, the refractive index is measured in a standard planar cell, in which the liquid crystals are oriented differently than in a capillary tube of a few micron.

Fig. 2 right shows the experimentally measured transmission together with the simulated phase matching curves when the simulation is shifted 30 nm to match the measurements, both are at a temperature of 25°C. The figure shows that even though the simulations show a phase match shift towards longer wavelengths, the relative position of the simulated phase match coincides with the positions of the spectral dips.

3. Conclusion

To our knowledge, this paper demonstrates the first electrically tunable LPGs in a PBG fiber device. The dips of the grating are tuned by changing the strength of the applied electric field, and the resonance wavelengths are tuned by changing the temperature of the liquid crystals inside the fiber. By using numerical simulations we show that the relative position of the loss peaks can be determined, but that a more accurate measure of the refractive index of the liquid crystal and fiber structure is needed in order to fully simulate the position of the loss peaks. We believe that, by using a different liquid crystal, deeper spectral dips and higher temperature tunable devices can be fabricated. We also believe that the overall loss in the fiber device can be decreased by filling a shorter section of fiber.

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