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Influence of the core size on light propagation in photonic liquid crystal fibers

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ABSTRACT

In this paper analyses of mode distribution, confinement and experimental losses of the photonic crystal fibers with different core sizes infiltrated with liquid crystal are presented. Four types of fibers are compared: with single-, seven-, nineteen- and thirty seven solid rods forming the core in the same hexagonal lattice of seven "rings" of unit cells (rods or capillaries). The experimental results confirming the influence of the core diameter on light propagation are also included. The diameter of cores determines not only the number of modes in the photonic liquid crystal fiber but also is correlated with experimentally observed attenuation. For fibers with larger cores confinement losses are expected to be higher, but the measured attenuation is smaller because the impact of liquid crystal material losses and scattering is smaller.

1. Introduction

Photonic crystal fibers (PCF) are two-dimensional structures made of silica glass with a periodically distributed refractive index. They consist of micro-holes which are surrounding a solid or hollow core [1–4]. Light propagation within such a structure depends on the ratio between the refractive index of the fiber core and the mean refractive index of the cladding. When the solid core is characterized by a higher refractive index than the index of a photonic crystal cladding, light is guided by the mechanism called modified total internal reflection (mTIR) also known as index guiding. When the refractive index of the solid core is lower than the cladding index, the photonic band gap (PBG) mechanism of light propagation is obtained. For the last years many different types of photonic crystal fibers, both hollow-core and solid-core have been demonstrated [5–7]. PCFs filled with liquid crystals (LCs) have a great number of potential applications in a new class of in-fiber devices such as polarization controllers, tunable filters or optical filters [8–11] whereas liquid crystals as anisotropic materials offer unusual optical properties (such as, e.g. tunable birefringence, optical activity, selective Bragg reflection, circular dichroism) that can be easily modified by external physical fields [12].

One of the serious issues related with any optical fiber and in particular with a PCF is attenuation, which is usually determined by absorption and material scattering (heterogeneity of the structure and spatial distribution of the refractive index) but also by a number of connectors or splices [13]. PCFs made of pure silica glass can have attenuation less than 0.48 dB/km at 1550 nm [14,15]. To increase the refractive index of the solid-core PCF, silica glass is doped with either erbium or germanium. Unlikely, attenuation of such a structure is higher up to 0.97 dB/km at the wavelength of 1.55 μm [16,17]. Moreover, not only doping but also modifications in the photonic structure, as well as infiltration of the air holes with different materials (as e.g. with LCs that scatter light strongly) may significantly increase fiber losses.

Despite of this, liquid crystals due to their very interesting anisotropic properties have been successfully used in the so-called photonic liquid crystal fibers (PLCFs), i.e. PCFs filled with liquid crystals [18–21]. It has been already showed that guiding properties of the PLCFs can be easily modified by an external electric field or by temperature. There are two important parameters that influence the light propagation in PLCFs, i.e. the core size and the scattering properties of the LC [22,23]. Scattering losses can be reduced by using a low birefringence LC [24]. In other works concerning PLCF, not only the attenuation properties, but also the waveguide dispersion can be elegantly tuned [25–27].

The aim of this study is to show that a change in the diameter of the fiber core can modify not only confinement losses of the PLCF, but also the amount of the optical power that is guided in strongly scattering LC-filled holes, by studying four fibers with a drastically varying core diameter. It is expected that fiber attenuation is smaller if propagation through the LC-filled holes is lower.

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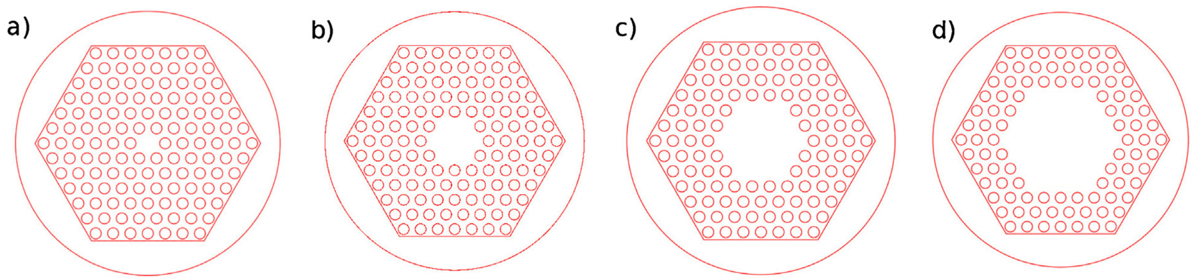

Fig. 1. Structures of the photonic crystal fibers. The core consists of (a) 1 rod (PCF 1), (b) 7 rods (PCF 7), (c) 19 rods (PCF 19), (d) 37 rods (PCF 37).

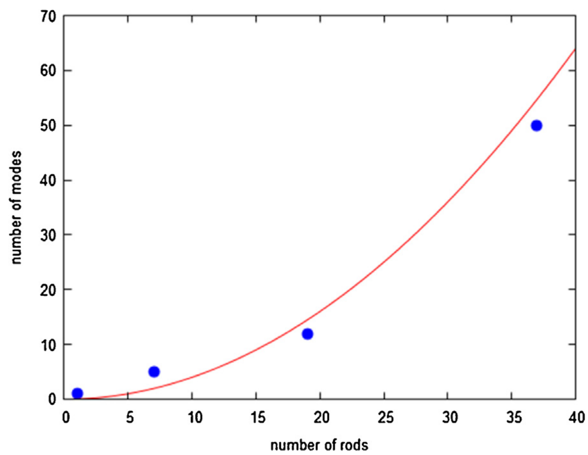

Fig. 2. Number of modes *vs.* number of rods forming the fiber core with quadratic fitting (red solid line).

Interesting results were reported in Ref. [28] where a PLCF with a very large core had a very low attenuation in the PBG mechanism compared to a similar structure with a single-defect core. In this work analyses of mode distribution, confinement and experimental losses for different fiber core diameters and also experimental results with designed fibers are presented.

The paper is organized as follows: in Section 2 fibers' parameters, theoretical analysis of four types of PCF structures infiltrated with LC are presented and in Section 3 experimental results obtained are compared with the theory.

2. Numerical simulation

Structures of different PCFs under consideration are presented in Fig. 1. All the structures are based on a similar lattice consisting of seven rings of solid rods or capillaries, with the lattice constant $\Lambda = 8.4\,\mu m$ and the diameter of the holes $d = 5.7\,\mu m$. The first one is a typical fiber with the core consisting of a single rod (named PCF 1) surrounded by six rings of holes. The second one has the core consisting of 7 rods (named PCF 7) surrounded by 5 rings of holes. The third one has the core consisting of 19 rods (named PCF 19) surrounded by 4 rings of holes. The last one has 37 rods (named PCF 37) surrounded by 3 rings of holes. The PCF1 is a single mode fiber, while PCFs 7, 19 and 37 are multimode photonic crystal fibers.

The PCF structures and fiber modes were analyzed by using the commercially available software Comsol 3.5a which is based on a fully vectorial finite-element algorithm [29,30]. Simulations were performed for the wavelengths within the range of 200 ÷ 850 nm. Liquid crystal dispersion was not taken into account, whereas dielectric anisotropy was represented by the diagonal tensor of dielectric permittivity $\varepsilon_{xx} = \varepsilon_{yy} = 1.4614$, $\varepsilon_{zz} = 1.5225$ (planar orientation was assumed) at 25 °C, characterizing the 1550 nematic liquid crystal mixture used in the experiment [31,32]. The PCF structure was represented by the refractive index of the fused silica determined from the Sellmeier equation and it is equal to 1.45 at 0.6 μm [33]. A typical mode field area of the fundamental mode for PCF37 core is ~2525 μm^2, for PCF19 is ~1140 μm^2, PCF7 is 411 μm^2 and PCF1 is 74 μm^2.

The PCF37, PCF19, and PCF7 are multimode fibers in both cases when the holes are either empty or filled with liquid crystal. For example, for the empty PCF 37 it was possible to find more than 100 modes. For the fibers filled with the LC, multimode photonic bandgap propagation has been obtained numerically. In the following part of the paper the PLCFs stand for photonic crystal fibers infiltrated with liquid crystals (i.e. PLCF1, PLCF7, PLCF19, and PLCF37).

For PLCF37 it was usually more than 50 modes (which were thoroughly analyzed), for PLCF19 it was about 12 modes, for PLCF7 it was 5 modes. PLCF 1 guides only a single mode but for particular wavelengths (e.g. $\lambda = 645$ nm) second mode was observed with high losses. It is worth to mention that the position of the PBGs is determined by properties of the cladding holes infiltrated with the LCs. The higher order modes are guided in the same range of wavelengths as the fundamental mode. The criterion of the modes number results from the observation of modes' profiles depending on the wavelength, until the moment when cladding modes appear, (i.e. when the power of light propagating in the holes filled with LCs, expressed as a percentage of the total power, is higher than

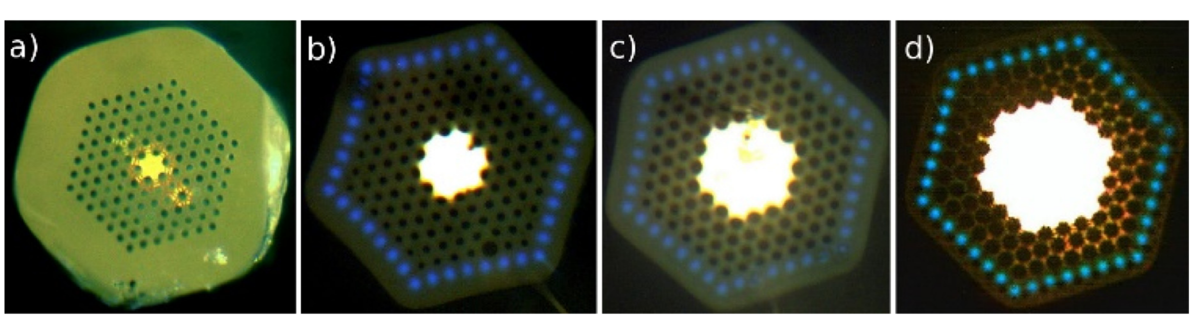

Fig. 3. Microscope images of the cross-section of empty photonic crystal fibers with different cores. (a) PCF1 (b) PCF7, (c) PCF19, (d) PCF37, (The mTIR mechanism of light propagation in fibers is observed).