Optics Communications 364 (2016) 1–8

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dispersion properties of transverse anisotropic liquid crystal core photonic crystal fibers

Naoki Karasawa

Chitose Institute of Science and Technology, 758-65 Bibi, Chitose 066-8655, Japan

ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form
12 November 2015
Accepted 13 November 2015

Keywords:
Photonic crystal fiber
Liquid crystal
Supercontinuum generation
Finite difference method

ABSTRACT

The dispersion properties of liquid crystal core photonic crystal fibers for different core diameters have been calculated by a full vectorial finite difference method. In calculations, air holes are assumed to be arranged in a regular hexagonal array in fused silica and a central hole is filled with liquid crystal to create a core. In this study, three types of transverse anisotropic configurations, where liquid crystal molecules are oriented in a transverse plane, and a planar configuration, where liquid crystal molecules are oriented in a propagation direction, are considered. The large changes of the dispersion properties are found when the orientation of the liquid crystal molecules is changed from a planar configuration to a uniform configuration, where all molecules are oriented in the same direction in a transverse plane. Since the orientation of liquid crystal molecules may be controlled by applying an electric field, it could be utilized for various applications including the spectral control of supercontinuum generation.

1. Introduction

The generation of a broadband light pulse in a photonic crystal fiber (PCF) using an optical pulse has been studied extensively [1]. Recently, liquid-filled PCFs for generating supercontinuum have been studied, where various liquids were selectively filled in PCFs [2–8]. Besides supercontinuum generation, liquid-filled PCFs and capillary fibers have been used to exploit their unique dispersive and nonlinear optical properties [9–14]. Various methods were proposed to fill liquid selectively in PCFs [15–18] and these methods may be used to create liquid crystal (LC) filled PCFs shown here by filling LC into a single hole in the clad region of PCFs with similar hole sizes and pitches shown here.

LC filled PCFs have been studied for various applications. Since the properties of LC filled PCFs can be controlled by changing temperature or applying an electric field, these PCFs can be used as variable optical filters [19–24] or sensors [25]. In addition to PCFs made of fused silica, LC filled PCFs made of polymer were reported [26]. When LC core PCFs are used for generating supercontinuum, it is expected that the spectra of the generated supercontinuum can be controlled by changing temperature or by applying an electric field since the dispersion properties of the PCFs can be controlled by these effects. The nonlinear refractive index for homogeneously aligned 5CB (4–cyano–4′ – n–pentylbiphenyl) LC is measured to be more than 100 times larger than that of fused silica [27]. The optical absorption of LC in the visible and near infrared wavelength regions is relatively low [28]. The optical loss due to the scattering in a nematic state is much higher than the absorption loss in the visible region. However, it is reported that the scattering loss can be reduced by filling LC in a glass capillary to be less than about 3 dB/cm at wavelength 633 nm [29]. Thus it is expected that LC core PCFs, whose lengths are about a few centimeters, can be utilized for generating supercontinuum in the visible and near infrared regions [30]. Here, we consider the dispersion properties of LC core PCFs because the generation of soliton pulses and the subsequent generation of dispersive waves are only possible when the GVD at the wavelength of an input optical pulse is negative. The ordinary and extraordinary refractive indices of E7 LC considered here are higher than the refractive index of fused silica. Thus it is possible to make an optical fiber with an LC core and fused silica clad. However, in that case, the effective refractive index of the propagation mode has to be between the refractive index of the LC and that of fused silica, and GVD values become always positive except for the cases with very small core diameters and long wavelengths. Thus, we consider the structure with maximum air fraction in clad such that the effective refractive index can take a value close to the refractive index of air ($n_{air} = 1$). In practice, the director reorientation of LC molecules may occur due to the intense optical field and it may modify the GVD of LC core PCFs [31]. However, for ultrafast optical pulses considered here for supercontinuum generations (pulse width ~100 fs and peak power ~10^4 W) in transparent LC, very small directorreorientation angle change, $2 \times 10^{-6}\theta_{ss}$ is expected where θ_{ss} is the steady state angle change by a continuous light (assuming 20 mW power and the response time of LC to be 25 ms). Thus the

E-mail address: n-karasa@photon.chitose.ac.jp

http://dx.doi.org/10.1016/j.optcom.2015.11.039
0030-4018/

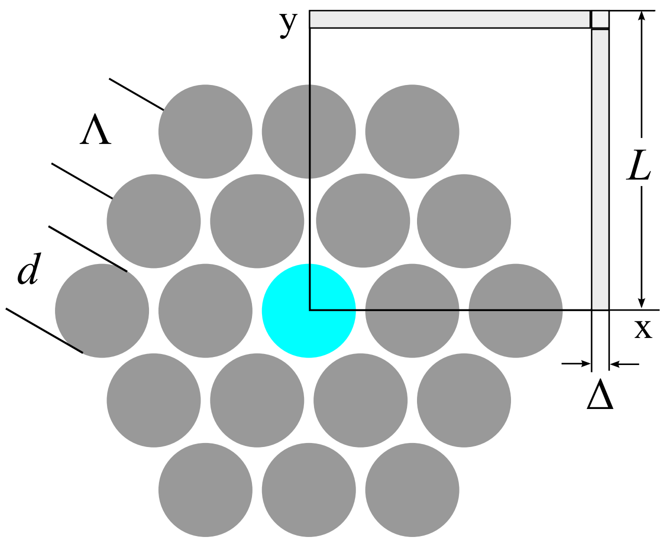

Fig. 1. The cross section of a LC filled PCF. Gray areas show air holes and a central hole is filled with LC. The pitch Λ is set to be $d + 0.1$ μm in calculations, where d is the hole diameter. Calculations were performed in a square region with a length L, where perfectly matched boundary layers with widths Δ were used.

Table 1
The parameters for the extended Cauchy equations off E7 LC at 298 K used in calculations for ordinary (n_o) and extraordinary (n_e) refractive indices [42].

	n_o	n_e
A	1.4994	1.6933
B	0.0070	0.0078
C	0.0004	0.0028

Table 2
Parameters used for finite difference calculations (in μm) of LC core PCFs for different hole diameters (d). In calculations, Δy was set to be equal to Δx.

d	L	Δx	Δ
0.5	2.35	0.005	0.2
1.0	3.2	0.01	0.2
1.5	4.25	0.01	0.2
2.0	5.5	0.015	0.21

effect of director reorientation is not considered in this study. The dispersion properties of liquid core PCFs were calculated using a multipole method [32] and those of LC core PCFs were calculated using the modified multipole method to treat anisotropic inclusions rigorously for a planar configuration [30] to understand the difference between the nematic and isotropic states since the planar configuration was observed in experiment [22]. Previously, the dispersion properties of LC core PCFs were calculated by a perturbative scheme for the planar and the axial geometries of LC [33]. Also, modal properties of LC filled PCFs were calculated by a finite difference method [34,35] when an electric field was applied.

In this study, dispersion properties of LC core PCFs are calculated by a mode solver for anisotropic waveguides based on a full vectorial finite difference method [36] for the transverse anisotropic configurations of LC, where all LC molecules are aligned in the transverse plane of a PCF, as well as for a planar configuration. The results of calculations by a finite difference method are compared with those by a modified multipole method for a planar configuration, since only uniaxial PCFs can be treated by a multipole method at present. When an electric field is applied in the perpendicular direction of a fiber, it is expected that LC molecules align in the same direction as the electric field, which we call a uniform configuration. Since this configuration may be realized experimentally, the changes of dispersion properties between

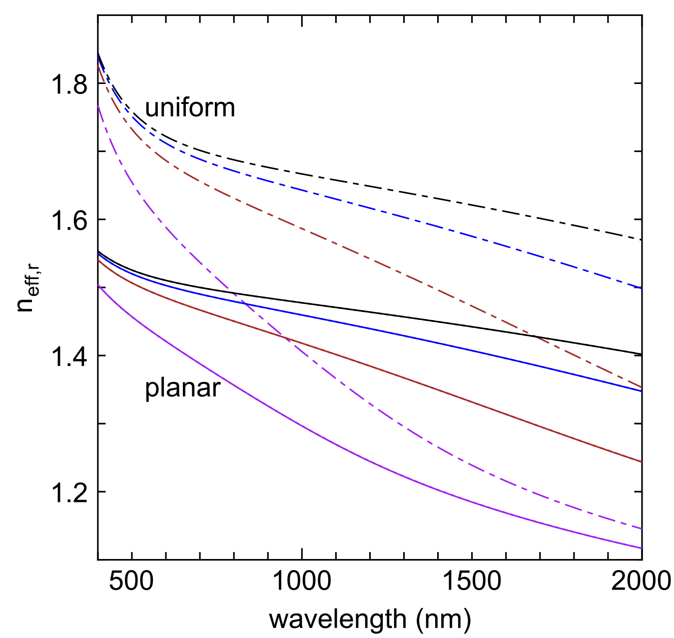

Fig. 3. Effective refractive indices ($n_{eff,r}$) versus wavelength for LC core PCFs with different hole diameters for a planer (solid and dotted curves) and uniform (dot dashed curves) configurations. For planar configurations, both results by a multipole method (solid curves) and those by a finite difference method (dotted curves) are shown. However, these curves overlap almost completely. Here, hole diameters are 2.0, 1.5, 1.0, and 0.5 μm from top to bottom for both uniform and planar configurations.

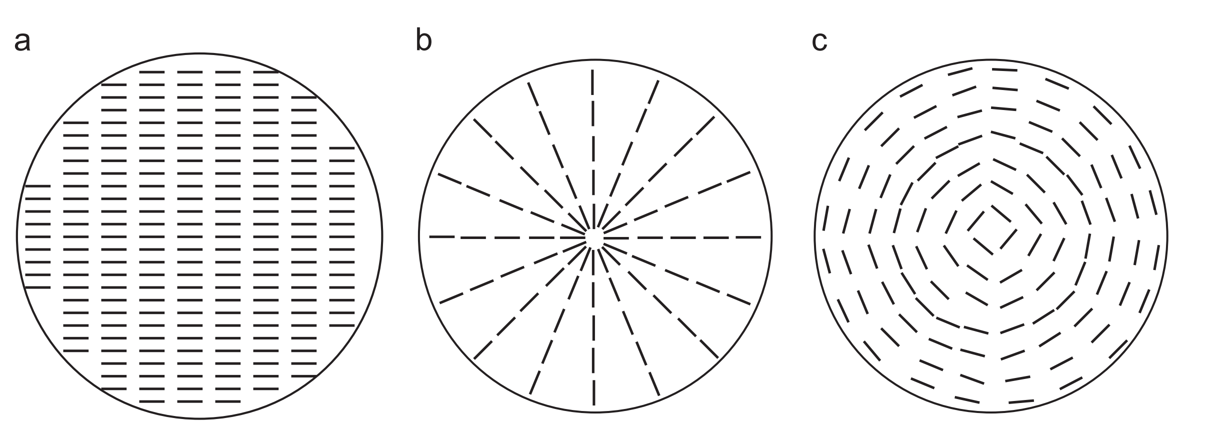

Fig. 2. The configurations of transverse anisotropic LC molecules in a central hole of a PCF for (a) uniform, (b) radial, and (c) circular director configurations.