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Linear and nonlinear properties of photonic crystal fibers filled with nematic liquid crystals

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We investigate linear and nonlinear light propagation in the photonic crystal fibers infiltrated with nematic liquid crystals. Such a photonic structure, with periodic modulation of refractive index, which could be additionally controlled by the temperature and by the optical power, allows for the study of discrete optical phenomena. Our theoretical investigations, carried out with the near infrared wavelength of 830 nm, for both focusing and defocusing Kerr-type nonlinearity, show the possibility of the transverse light localization, which can result in the discrete soliton generation. In addition, we present the preliminary experimental results on the linear light propagation in the photonic crystal fiber with the glycerin-water solution and 6CHBT nematics, as the guest materials.

Keywords: photonic crystal fibers, optical nonlinearity in liquid crystals, solitons, discrete diffraction.

1. Introduction

In the last years, photonic crystal fibers (PCFs) have become the subject of growing interest and intensive theoretical and experimental investigations. Beside the conventional structures with a large number of air holes located in the silica cladding, the particular attention is recently paid to the PCFs infiltrated with different materials, including nematic liquid crystals (NLCs) [1–3]. The latter, being the new class of advanced microstructures called as photonic liquid crystal fibers (PLCFs), combine the passive PCF host structure and active NLC guest material. It was demonstrated, that such fibers can guide light in some range of the spectrum, which can be tuned by the thermal modification of the refractive index of NLCs [1]. Furthermore, nematic liquid crystals have been proven to be excellent materials for the nonlinear optics. It is possible to obtain optically induced changes of the refractive index of NLCs due to the reorientational and/or thermal nonlinear effects [4]. The idea of all-optical modification of photonic bandgap in PLCFs was recently presented [2]. On the other hand, the analyzed structure can guide light not only due to the existence of the photonic bandgap. Being out of the photonic bandgap, the light can be guided in the holes infiltrated with NLCs, which refractive index is higher than refractive index of the silica cladding. Such a structure corresponds to the hexagonal matrix of waveguides. Of course, the main difficulty in the experimental investigations in such fibers is to overcome the losses in NLC cores, which mainly result from the large light scattering in imperfectly oriented nematic phase. However, for very careful preparation of the holes surfaces and/or in isotropic phase (where the thermal nonlinearity is still significant) the light can successfully propagate in a few centimetre long fibers [5].

The described structure in form of the matrix of the coupled waveguides allows for the observation of a variety of new phenomena both for low power beam excitation (linear case) and with an existence of nonlinear effects (when the optical power is high enough). If the matrix consists of the nonlinear material the spatial soliton creation is possible [6–7]. It happens when the spatial profile remains constant and stable during propagation and then the beam is considered to be a discrete soliton or a lattice soliton. It is worth to underline here that the discrete systems require less optical power for solitons generation than comparable bulk homogenous media. Discrete diffraction and solitons were observed experimentally in different materials [8–11], and recently also in nematic liquid crystals [12]. The most of the theoretical and experimental works were concentrated on the one-dimensional systems but two-dimensional systems were also analyzed in photorefractive crystals [10], in optical fibers with multiple cores [13], in all-optically written arrays in silica [9] and in arrays of the optical fibers with partially removed cladding [14].

In this report we analyze the linear and nonlinear properties of the photonic crystal fibers with the silica cladding and the hexagonal matrix of holes filled with nematic liquid crystals. Depending on the refractive index of the medium in the micro-holes and on the geometrical parameters of the fiber, the analyzed structure can act as a typical photonic crystal fiber, guiding the light due to the existence of the photonic bandgap, or as the 2D optical lattice (matrix of waveguides) in which discrete light propagation is observed.

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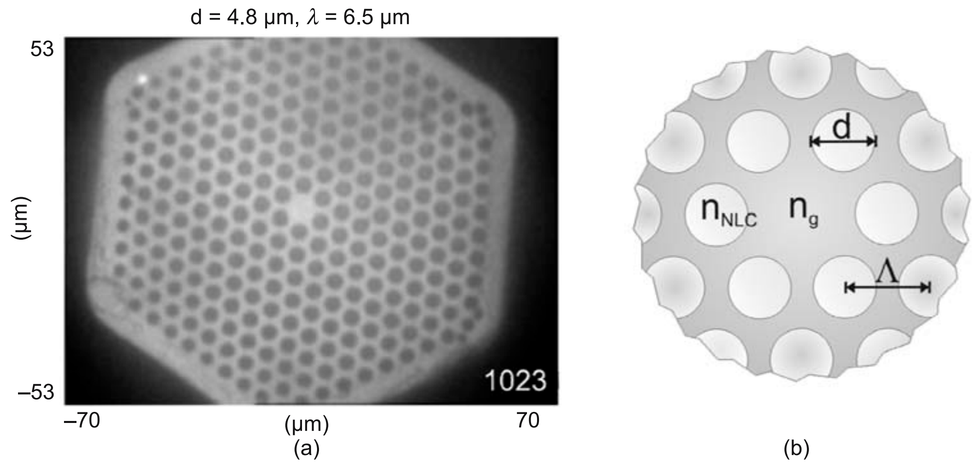

Fig. 1. Cross section of an investigated 1023 PCF and a sketch of the analyzed structure in the form of hexagonal matrix of waveguides.

The picture and the scheme of the analyzed PCF, called as 1023 and fabricated at Maria Curie Skłodowska University in Lublin (Poland), are shown in Fig. 1. The geometrical parameters of such a fiber are as follows, the distance between neighbouring holes Λ = 6.5 μm and the holes diameter d = 4.8 μm.

2. Numerical results

Numerical simulations of the light propagation in the analyzed structure were carried out by using beam propagation method (BPM) and by injecting Gaussian beam. Calculations were performed using the squared-shaped grid with a period of 0.1 μm and the calculating window size was 150×150 μm. Additionally, the mode solver was implemented to estimate an effective refractive index of the fundamental mode in analyzed configurations. The value of refractive index of the silica cladding was taken as n_g = 1.4528 at the wavelength of 830 nm. The scalar BPM and an assumption that the holes are infiltrated with the isotropic liquid were used. These simplifications give qualitatively reasonable results especially for NLC in the isotropic phase and as an approximation in the nematic phase.

Figure 2 shows the light propagation in the linear (i.e., for low input optical power) regime, when light beam with initial waist w_0 = 10 μm is launched into the glass core of the structure. The refractive index of the infiltrated liquid n_{NLC} = 1.4542 was chosen in the way to fulfil the single-mode operation for each of the NLC core. The light is coupling and spreading into increasing number of NLC

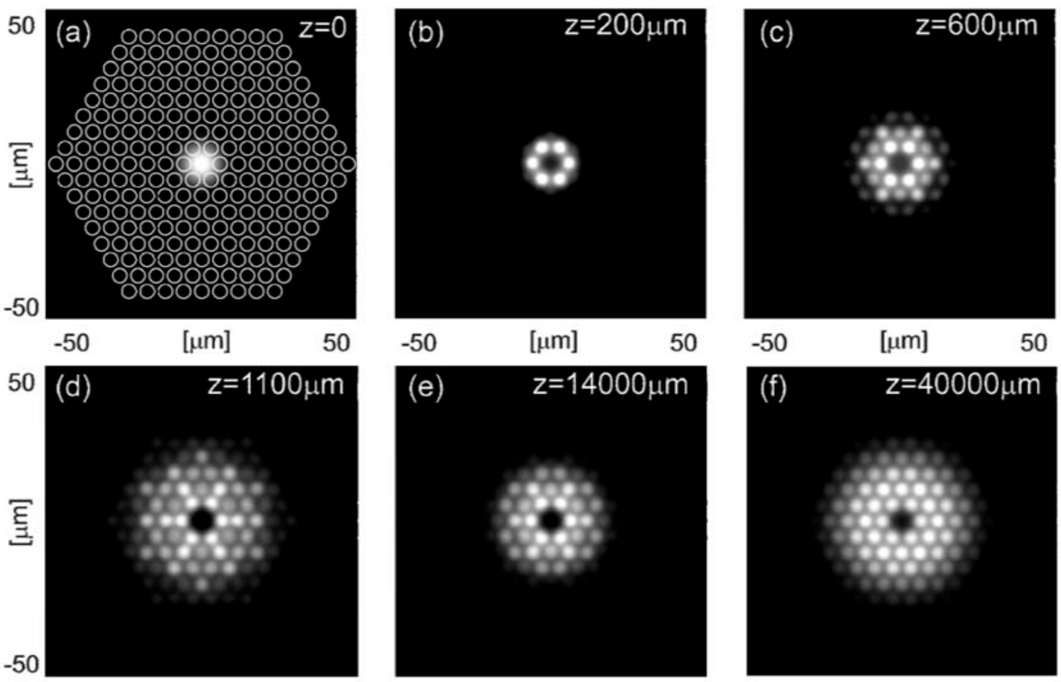

Fig. 2. Light intensity distribution in x-y plane for different propagation distances z, showing the character of discrete diffraction in the analyzed structure (which shape is given for z = 0) for the low-power Gaussian optical input of waist w_0 = 10 μm.

waveguides as it propagates, broadening its own spatial distribution. As a consequence of the discrete diffraction, the energy redistributes among the neighbouring NLCs guiding cores, as it is clearly visible in Fig. 2, showing the beam transverse profiles in the *x*-*y* plane along propagation *z*. Due to the finite size of discrete structure, the light reaching its border comes back to the core region. In this way the propagating light beam is alternately broadening and narrowing in space, resulting in the intensity profile that is repeating on the way of propagation. This recurrence is determined by the coupling length and in our configuration the typical length scale of its period is of the order of 1 cm.

In the analyzed structure, optimization of such parameters as the optical properties of infusing material (i.e., refractive indices of NLCs), the holes size and their location, allows to obtain properly coupled NLC waveguides. In this way also the magnitude and character of the discrete diffraction can be controlled. As it is shown in Figs. 3(a) and 3(b), the change in the value of refractive index of NLCs within the PCF holes allows for the magnificent changes in the optical properties of the fiber. The linear propagation effect can be tuned thermally while the temperature has an important impact on NLCs refractive indices [4,15]. As intuitive, an increase in refractive index of NLCs reduces angular divergence of the beam; light is more confined within the NLC waveguides region. By increasing the value of the refractive index of NLC, an increase in the contrast between holes and cladding region refractive indices is obtained. It results in the increasing width of photonic gap [16]. For n_{NLC} = 1.4604, the light beam of the initial waist of 10 μm is confined in the region of the glass core [Fig. 3(b)]. By increasing the initial width of the beam, the character of the propagation can change again, resulting in the discrete diffraction [Fig. 3(c)], with better light localization within NLC waveguides than in the case of the lower refractive indices contrast.

As the power of the propagating beams increases, the refractive index of excited NLC waveguides is modified by nonlinearity. In the nonlinear cases, numerical simulations were performed using the standard Kerr-like dependence $n = n_0 + n_2 I$, i.e. for refractive index, which changes linearly with the light intensity. In the case of nematics, both positive and negative nonlinearity occurs having its origin in molecular reorientation and in thermal effects, respectively.

In the nonlinear regime, the light induces a defect in the periodic structure of the matrix. The increase in the light power causes the beam confinement. The growth of the difference between refractive indices of the adjacent cores leads to the difference of propagation constants. It causes a detuning of the launched NLC cores from the others and finally leads to the coupling decrease. Moreover, for positive (focusing) nonlinearity, the increase in the difference between NLC waveguides and glass cladding refractive indices results in stronger guiding of the beam in the region of NLC cores. In the case of defocusing nonlinearity, the difference between waveguides and glass refractive indices decreases and beam guidance becomes weaker for the higher light intensities. As a result, the soliton observation is possible only in the case of the focusing nonlinearity. In the case of defocusing nonlinearity, the generation of the bright soliton is possible only in the regime of negative discrete diffraction [6].

Numerical results showing the influence of the optical nonlinearity on the beam propagation in the analyzed structure are shown in Figs. 4 and 5. Please note that for the Kerr coefficient $n_2 = 10^{-10}$ m^2/W, the product $n_2P = 0.1$ μm^2 corresponds to the optical power of 1 mW.

As it is shown in Fig. 4, in the case of positive (focusing) nonlinearity ($n_2 > 0$) the increasing optical power leads to the self-localization of light and to the elimination of diffractive broadening. Finally, when the input beam is intense enough, nonlinearity balances diffraction and the light propagates being localized in the limited region of the array. When the light beam is launched into the centre of the one of the NLC cores [Fig. 4(d), 4(e), and 4(f)] and its power is high enough, it is possible to obtain the light localization in this core (as it happens in the case of 2D optical lattice). Such a beam, which propagates maintaining an invariant transverse profile during propagation, is called discrete spatial soliton.

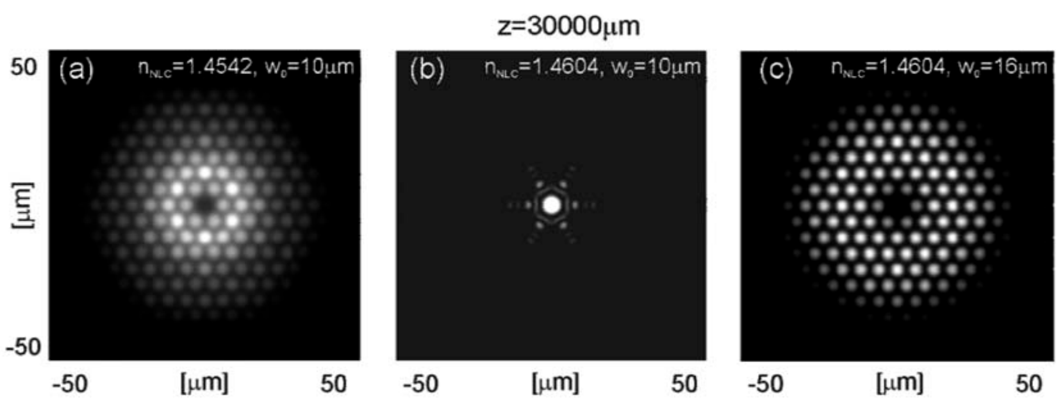

Fig. 3. Numerical results for a low-power Gaussian optical input obtained for the propagation distance of 30 mm for different refractive indices of NLC: n_{NLC} = 1.4542 (a) n_{NLC} = 1.4604 (b, c) and for the different input waist of the beam: w_0 = 10 μm (a, b) and w_0 = 16 μm (c).

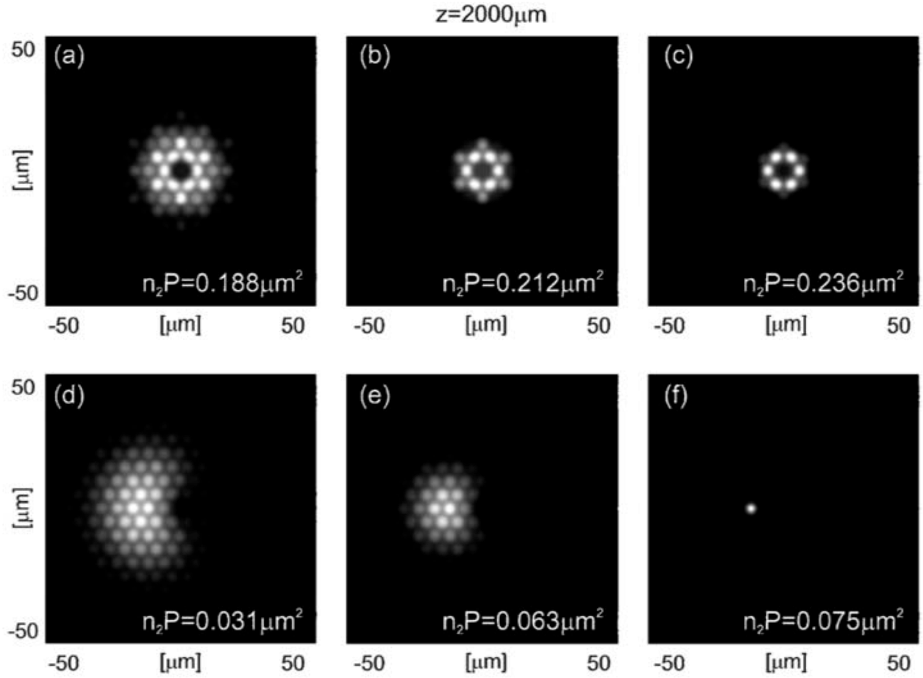

Fig. 4. Light intensity distribution for the propagation distance z = 2 mm as a function of input optical power P in the case of focusing Kerr-type nonlinearity ($n_2 > 0$). The 10 µm-waist Gaussian beam is initially launched into the glass core of the fiber (a-c) and to the centre of the one of the NLC cores (d-f); n_{NLC} = 1.4542.

Figure 5 presents the behaviour of the light beam in the case of negative nonlinearity. Initial value of NLC refractive index n_{NLC} = 1.4604 and the input waist of the beam w_0 = 10 µm, guarantee the light confinement in the glass core region in the case of linear regime. When the optical power increases, the stronger guiding of the light within NLC cores is obtained. Eventually, the discrete diffraction can be balanced by the power-induced detuning of the launched cores from the rest of the matrix and the light propagates localized in the limited region of the structure. High power excitation leads to the situation in which the light leaves the region of the central glass core. In the case of negative nonlinearity, the refractive index decreases with the optical power in such a way that the bandgap is shifted. The incident beam with a frequency initially within the bandgap is then turned outside the bandgap resulting in the change of the propagation effect for the total internal reflection [17]. In this situation, the decreasing value of NLC refractive index due to the negative nonlinearity is so high that the nonlinear detuning of the launched holes is similar to the situation of the light localization in the case of positive nonlinearity shown in Fig. 4(c).

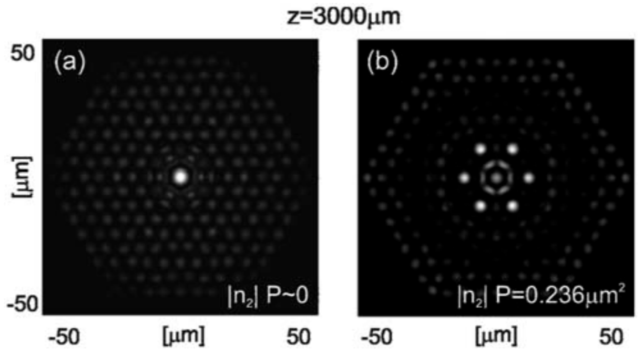

Fig. 5. Dependence of the beam propagation on the beam power P in the case of negative Kerr-type nonlinearity. The spatial intensity distribution was calculated after 3 mm of propagation of the input Gaussian beam of the initial waist of 10 µm; n_{NLC} = 1.4604.

As one can see, the light localization in the case of negative nonlinearity requires higher power than for positive one (maintaining the value of the absolute value of the Kerr coefficient $|n_2|$ as a constant).

3. Experimental results

Experiments were carried out in the 1023 PCF of the length of few centimeters. Parameters of the analyzed structure (i.e., PCF filled with the NLCs) were optimized to observe discrete diffraction in the linear regime, and potentially the creation of discrete spatial soliton in the high powers regime (with assumption of thermal or orientational nonlinearity in NLCs). Investigated liquids were introduced into the micro-holes by the capillary effect but the molecular orientation was not controllable. The linearly polarized beam from the near infrared (λ = 830 µm) semiconductor laser, pigtailed to the single mode fiber and operating with the maximum optical power of 30 mW, was launched into the analyzed sample. The output of PCF was observed trough the microscope objective connected to the CCD camera. Light distribution at the output surface of the samples was analyzed for various infiltrating liquids, different temperatures, and for different initial beam positions.

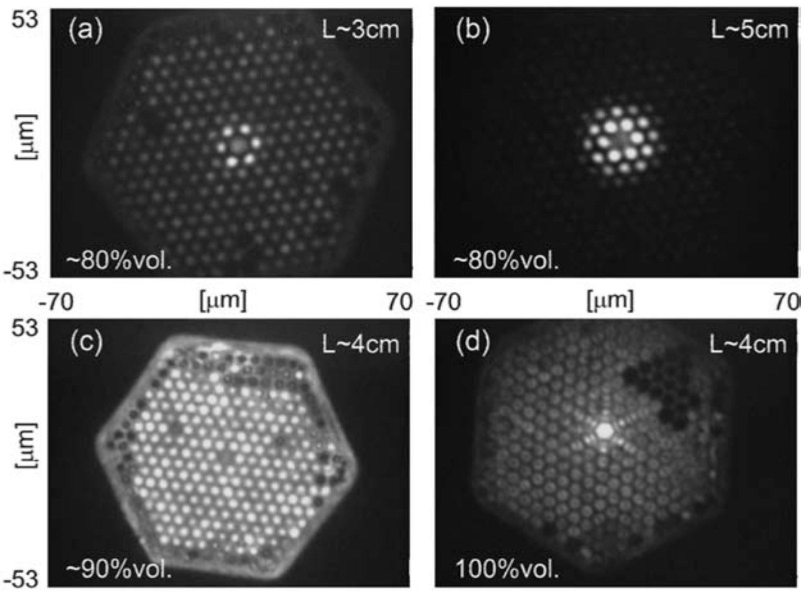

Fig. 6. Experimental results showing the low power beam (< 1 mW) propagating in the PCF of the different length *L* and infiltrated with different concentration of the glycerin-water solution.

In the preliminary experiments, the glycerin-water solution was introduced into PCF as a guest material. It was motivated by the great possibility of the tuning of the refractive index, depending on the glycerin concentration and the temperature [18] and by the lower scattering losses in glycerin than in the nematic liquid crystals.

Figure 6 shows the experimental photos of the linear light propagation ($P < 1$ mW) in the PCF filled with different glycerin-water solutions, when the input beam is injected into centre of glass core. For the first one (i.e., ~80% vol.), characterized by the refractive index close to the refractive index of silica glass at the wavelength of 830 nm and room temperature, performed experiments have shown that keeping the input power constant and changing the length *L* of the analyzed fiber it is possible to change the number of the waveguides being coupled at the output [Fig. 6(a) and 6(b)]. By increasing the concentration of the glycerine, its refractive index increases. Infiltration of the air-holes with the different liquid mixtures changes the guiding properties of the infiltrated area. In the case of ~90% vol. solution the light beam propagates in the form of discrete diffraction, widening into all holey region after the propagation distance of about 4 centimetres [Fig. 6(c)]. Further increase in the refractive index of the mixture leads to the

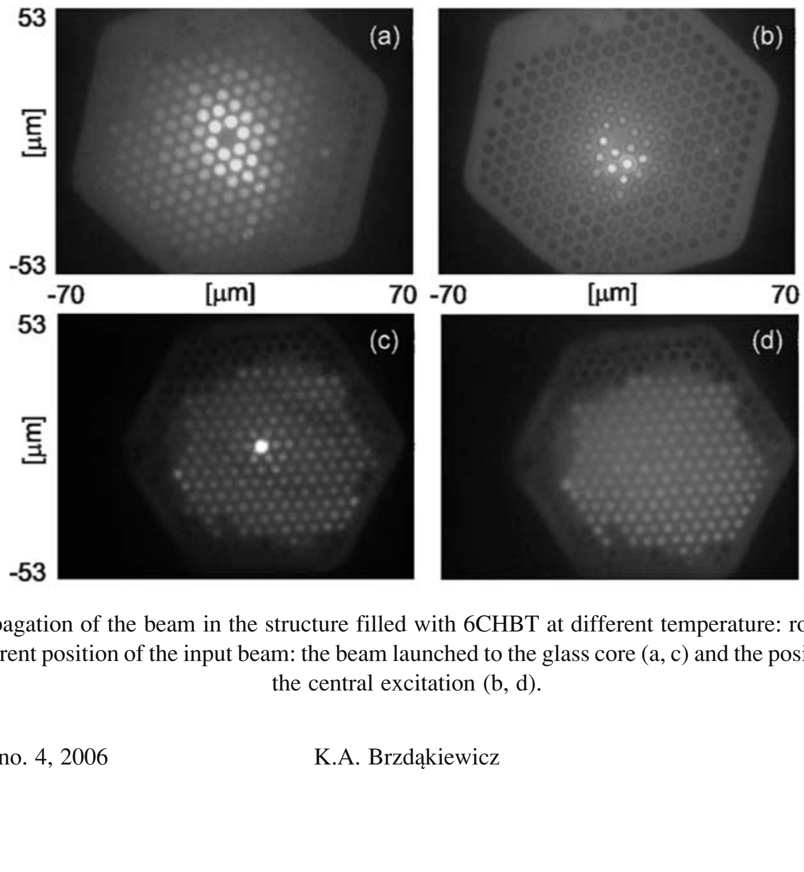

Fig. 7. Experimental propagation of the beam in the structure filled with 6CHBT at different temperature: room temperature (a, b) and ~50°C (c, d); and the different position of the input beam: the beam launched to the glass core (a, c) and the position slightly different from the central excitation (b, d).

situation in which the light beam propagates mainly in the glass core region due to the photonic bandgap creation [Fig. 6(d), for pure 100% vol. glycerine].

Experimental results obtained in 3.5 cm-long fiber infiltrated with 6CHBT (4-trans-4'-n-hexyl-cyclohexyl-isothiocyanatobenzene) NLC for low optical power, different positions of the input beam and different temperature are presented in Fig. 7. Figures 7(a) and 7(b) present the output intensity profiles obtained at the room temperature, for which an ordinary and extraordinary refractive index at λ = 830 nm is close to 1.5 and 1.7, respectively. In this case, the beam propagates in the NLC holes.

By increasing the temperature over the value characteristic for the nematic-isotropic phase transition (that is equal to 43°C for 6CHBT), the refractive index within holes increases respectively to the value of the ordinary refractive index and obtains the value of about 1.6. In this case, the slight difference in the initial position of the beam leads to the light propagation in or out of the glass core [Fig. 7(c) and (d)]. The guidance of the light in the core is possible only in the case of the perfectly central beam launching to the sample [Fig. 7(c)]. Please note that the initial waist of the beam in the cases 7(a), 7(b), 7(c), and 7(d) are not the same.

4. Conclusions

We have presented thermal and all-optical controlled structure, which enables one to investigate the transition from discrete diffraction to the light localization, leading to the discrete soliton generation. The investigated geometry, in the form of the multi-core optical fiber, takes advantage of the thermal dependence of NLCs refractive indices, as well as of the all-optical response of NLCs, offering considerable flexibility both in the linear and in the nonlinear regimes. Large variety of the temperature-tunable configurations could enable the potential applications in the sensing systems to be achieved in PCFs infiltrated with NLCs. The giant nonlinear response, which is characteristic for the molecular reorientation in NLCs, allows for observation of discrete spatial solitons at mW levels, giving the possibility of the routers and signal processors in liquid crystals. Theoretical predictions are in agreement with the preliminary experimental results and further work is continued to observe nonlinear phenomena including discrete solitons generation.

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