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Letter

Fiber-to-fiber nonlinear coupling via a nematic liquid crystal

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Abstract
Nonlinear optical coupling between two single-mode fibers terminated coaxially in a nematic liquid crystal (NLC) was explored for the first time. Light-induced reorientation of nematic molecules can result in the stable self-collimation of light transmitted through the gap between fibers. Thus, high coupling efficiency can be achieved despite large fiber spacing. We demonstrated a coupling efficiency of up to ~0.7, achieved with spacing equal to four diffraction lengths. This feature opens up possibilities for the development of novel in-line fiber-optic elements based on NLCs. For instance, a polarization controller was proposed and considered.

Keywords: optical fiber, nematic liquid crystal, Fréedericksz effect, nonlinear coupling

(Some figures may appear in colour only in the online journal)

1. Introduction

Among various types of soft matter, liquid crystals have perhaps the most interesting and promising optical properties [1, 2]. Thus, the orientation order and anisotropy of nematic liquid crystals (NLCs) can be modified easily by applying relatively weak electromagnetic fields [3, 4], or by inducing weak thermal gradients [5]. NLCs have a high nonlinear optical susceptibility of a complex orientation electronic nature that can be exploited for efficient laser frequency conversion [6]. Good quality optical contact between NLCs and glass substrates is normally achievable. The listed features make NLCs an attractive optical medium for research into nonlinear photonics and the development of novel optic devices [7], including fiber-coupled ones. For instance, a miniature fiber-coupled NLC-based laser frequency converter was demonstrated recently [8]. It had a fiber input and a free-space output. An important task for further elaboration of such NLC-based nonlinear photonic devices is making the transition to an in-line (fully fiber-coupled) design. In-line NLC-based fiber-optic elements may be in demand for various applications, ranging from ultra-compact laser systems to telecom technologies.

2. Experimental

On the basis of the above, we studied experimentally the feasibility of nonlinear fiber-to-fiber coupling via a nematic liquid crystal (NLC). The experimental approach is illustrated in figure 1. Two identical telecom single-mode optical fibers (with core diameter ~8 μm) were terminated coaxially in a cylindrical sleeve filled with NLC. A room-temperature cyanobiphenyl-based (nCB) nematic mixture was used as the NLC. The spacing between the fiber end faces was adjustable from ~10 to 500 μm by means of a translation stage with a micrometer. A CCD camera with micro image optics was used to monitor the NLC-filled gap between the fiber end faces through a lengthwise slit in the sleeve. The slit also allowed

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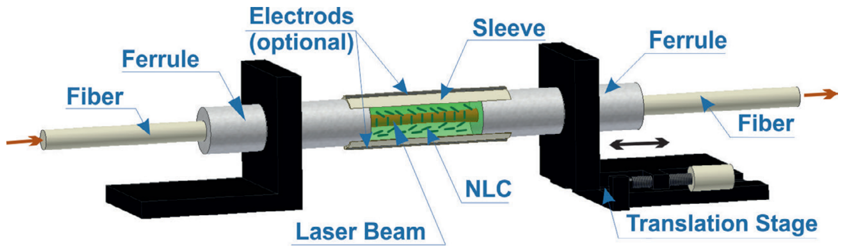

Figure 1. Experimental fiber coupling setup: NLC—nematic liquid crystal.

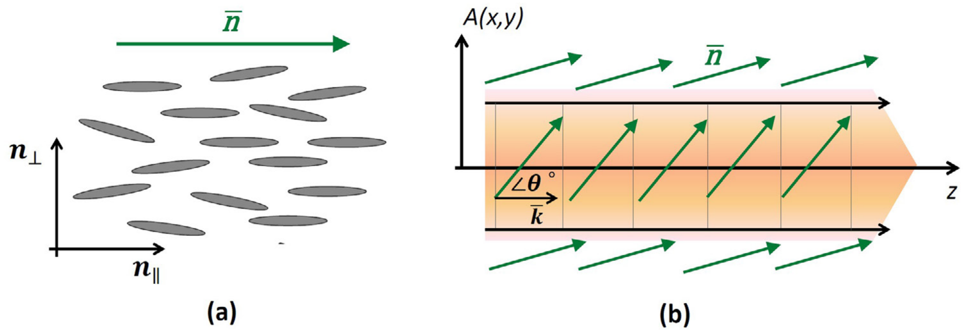

Figure 2. Molecular orientation ordering in NLCs. (a) The preferred average direction in a group of nematic molecules is denoted by a unit vector, the molecular director $\bar{\boldsymbol{n}}$ (which also indicates the optical axis direction). (b) A generic oscillating field of complex envelope $\boldsymbol{A}$ can affect the spatial distribution of the director (thereby modifying birefringence) in such a way that a light beam prorating along the z-axis becomes self-trapped in the waveguide sustained by the light-induced reorientation of molecules [4].

the NLC volume to be adjusted. A fiber-coupled laser diode at 1480 nm (Fitel FOL1425RUZ) with the output power tunable from a few to 400 mW was used as a light source. The optical power transmitted via the described NLC-based fiber coupler was measured by means of a power meter (Thorlabs PM100A with an S302C sensor).

Using the described setup, we discovered that strong optical coupling of two single-mode optical fibers separated coaxially by NLC can be achieved at a certain level of input optical power, despite a relatively large fiber-to-fiber spacing. This may result from light-induced reorientation of NLC molecules (figure 2) due to the light-induced *Fréedericksz* effect [3], which can cause the self-confinement of a propagating laser beam, as in a self-induced light guide.

The possibility of the self-confinement (self-collimation) of light in NLCs was previously demonstrated and studied in experiments with bulky NLC cells and free-space laser sources [4]. In our work this effect was exploited for the first time to achieve and study fiber-to-fiber nonlinear coupling via NLC and demonstrate the feasibility of novel NLC-based in-line fiber-optic elements on this basis.

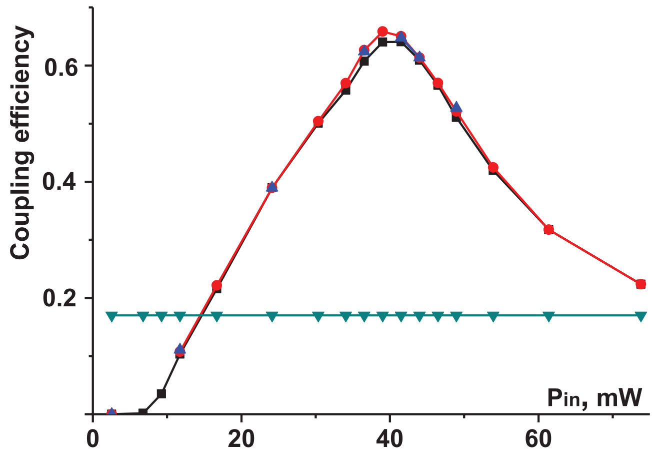

Figure 3. Experimental transmission curves (dependence of fiber-to-fiber coupling efficiency on the input optical power $\boldsymbol{P}_{\text{in}}$) measured three times for the same sample with $L \approx 320$ μm. The black curve with squares was measured when the input power was just increasing, the red curve with circles when it was decreasing back, and the blue curve with triangles when it was increasing again. The time intervals between the measurements did not exceed a few minutes. The green line with triangles is the transmission of the same gap filled with a refractive-index matching gel instead of NLC.

3. Results and discussions

To define the coupling efficiency, we varied the optical power injected into one of the fiber ports of the setup and measured the transmitted fraction of the optical power at the other fiber port. Figure 3 represents the most remarkable transmission curves measured for fiber-to-fiber coupling via the NLC-filled gap with a length (L) of ~320 μm.

Despite the huge fiber spacing equal to ~four diffraction lengths (defined for a beam with a core-sized waist), the transmission reached nearly 70% at a certain optical power level (~40 mW). The self-induced light guiding was stable enough over time and quite reproducible when it was examined within the input power range presented in figure 3. The largest fiber spacing which still allowed strong optical coupling was estimated experimentally to be nearly 400 μm. The coupling efficiency and stability decreased with larger spacing.

It is notable that the coupling efficiency in the low power range ($\boldsymbol{P}_{in} < 15$ mW) is suppressed below the level defined by diffraction and Fresnel losses. Most probably, this is due to the light scattering effected by thermal fluctuations of the NLC director [9]. In stronger light fields the scattering becomes negligible, because the ordering parameter of the NLC increases.

The physics of self-triggered light guiding in NLCs is supposed to be based on the balance between diffraction and self-focusing. However, it differs from nonlinear light propagation in solids because of the highly nonlocal response of NLCs. The critical power (P_c) for the above balance in NLCs is defined by a relation that is different from the Kerr case that is typical for solids. In NLCs the critical power is supposed to feature the following dependence on the beam waist [4]:

$$P_c \sim \frac{\lambda^2}{8\pi^2 w_0^2 n_0^2 n_{NL}^2} \tag{1}$$

where λ—wavelength of the transmitted light, w_0—waist of the beam, n_0—linear refractive index and n_{NL}—nonlinear refractive index (which is supposed to be a constant that is independent of the waist). Self-focusing weakens (the critical power increases) as the spot size reduces, thereby preventing collapse and stabilizing the self-trapped wavepacket in the NLC. This explains the observed stability of coupling via self-induced light guides in NLCs. However, such coupling is also subject to the slow response feature of reorientation nonlinearity and nonlocality in NLCs. The typical response times of optical effects related to reorientation nonlinearity are much longer than 10 ms. In some cases, associated with spatial solitons, light-induced reorientation evolution can take as long as several seconds [4].

In our experiment we could not make precision measurements of the response time for the fiber-to-fiber nonlinear coupling. The experimental time scale was affected by the relatively long response time (3 s) of the thermal sensor used to measure the power of the transmitted light. Relatively slow push-button control of the laser diode current also contributed to the time scale. Nevertheless, we measured how much time it takes to tune the coupling efficiency from pure diffraction-limited transmission (sustained at $\boldsymbol{P}_{in} \sim 15$ mW) to the highest transmission of the self-induced light guide (sustained at $\boldsymbol{P}_{in} \sim 40$ mW) by continuously increasing the input power. The measured time was about 12 s. This is just an overall time scale for the whole experimental setup. At least the half of this time is due to the above-mentioned delays in the power meter and laser diode control. So far, we can just suppose that light-induced reorientation of NLC molecules, which results in the emergence of a self-induced light guide between fibers, is completed within a time scale of a few seconds ($\leqslant$6 s). This rough evaluation matches the relevant time scale (at the stage of beam self-trapping) presented in [4] for the temporal evolution of two counter propagating beams in NLC.

For more physics details regarding light self-confinement caused by the reorientation of NLCs, one can refer to the extensive review article [4] by the leading NLC experts Marco Peccianti and Gaetano Assanto.

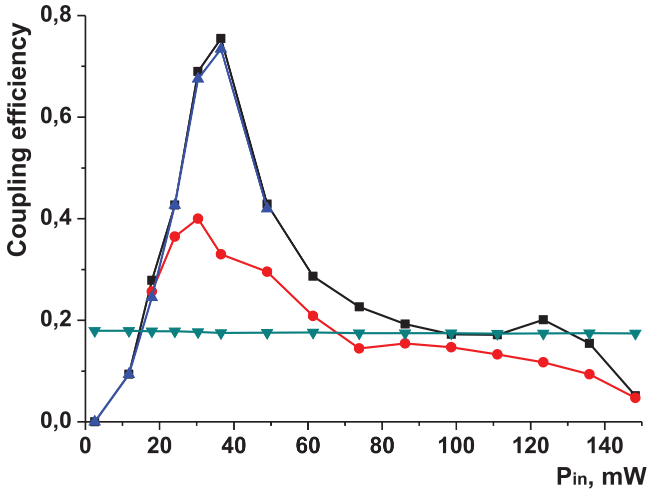

Figure 4. Experimental transmission curves acquired over an extended range of input power for the sample with $L \approx 320$ μm. The black curve with squares was measured when the input power was just increasing, the red curve with circles when it was decreasing back, and the blue curve with triangles when it was increasing again. The time intervals between the measurements did not exceed a few minutes. The green line with triangles is the transmission of the same gap filled with a refractive-index matching gel instead of NLC.

It is important to note that the initial (prior to light injection) orientation structure of the NLC in the presented experimental setup corresponds mainly to the so-called homeotropic alignment of NLC-filled cells [1, 2]. This is the case if completely clean and perfectly polished ferules are used in the experimental arrangement. The above feature ensures a low threshold for the light-induced Fréedericksz effect and eliminates the need to pre-tilt NLCs via external electric field or a special surface coating. We also suppose that the thermal orientation effect [5] may play a certain role in the observed nonlinear coupling. However considering it is rather complicated and lies beyond the scope of this paper.

The above experimental arrangement ($L \approx 320$ μm) enables strong nonlinear optical coupling with stable and repeatable characteristics within a relatively narrow range of input power (with maximum efficiency at ~40 mW). Figure 4 illustrates the transmission curves acquired over an extended range of input power. The measurements were performed with the same sample (but a few days before acquiring the data for figure 3).

Optical coupling between the fiber ports decays drastically when the input power rises beyond ~75 mW. Moreover, the transmission becomes less stable over time: continuous measurement of the output power manifested its stochastic fluctuations (up to ±15% of the average) at a constant input power in excess of ~75 mW. The underlying process for the coupling degradation at high input power has not yet been categorically revealed. It probably differs from the pure self-focusing collapse of the beam. Coupling may be affected by local heating, convection and the thermo-optic response of NLCs [4], which may cause distortion and instability for the light-induced orientation ordering in NLCs. Another issue related to high input power is the appearance of hysteresis in the transmission

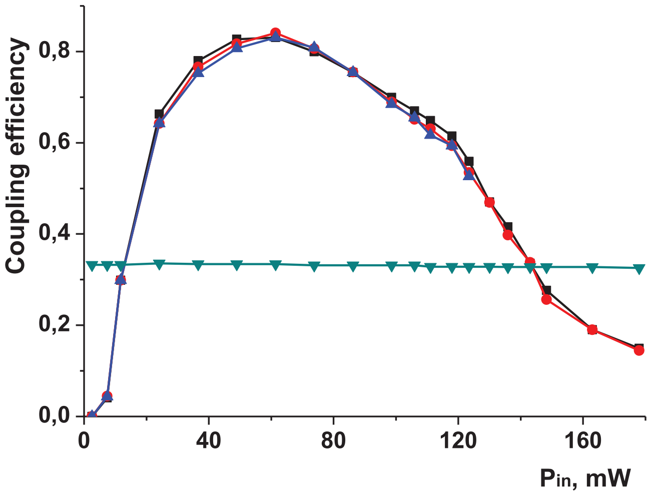

Figure 5. Experimental transmission curves acquired over an extended range of the input power for the sample with $L \approx 200$ μm. The black curve with squares was measured when the input power was just increasing, the red curve with circles when it was decreasing back, and the blue curve with triangles when it was increasing again. The time intervals between the measurements did not exceed a few minutes. The green line with triangles is the transmission of the same gap filled with a refractive-index matching gel instead of NLC.

characteristic. If the input power was increased to in excess of ~100 mW, when it was decreased later the coupling efficiency did not reach the demonstrated maximum. The coupling efficiency recovered completely after the input power was reduced to a few mW and then increased again up to ~40 mW. Such hysteresis behavior may be considered to be indirect evidence for the dominance of the thermal contribution to coupling degradation at high input powers.

Thus, there will be a certain limitation of the power-handling capacity for practical NLC-based fiber-optic devices. We have, however, found that the operating power range (where strong and stable nonlinear coupling is enabled) extends with decreased fiber spacing (L). For example, figure 5 illustrates the transmission curves measured for another sample where the fiber spacing was reduced to approximately 200 μm. This small-gap sample sustained high-performance coupling even at higher input powers compared to the 320 μm-gap sample. Moreover, the small-gap transmission characteristics obtained when the input power was tuned within 0 ÷ 180 mW do not manifest any evident hysteresis. These features of the small-gap sample may be explained by the reduction of thermal absorption in the smaller volume of NLC due to the shorter interaction length. Furthermore, coupling in the small-gap coaxial arrangement is less sensitive to the angular misalignment and angular instability of the NLC-guided beam.

On the basis of the above, one can find an optimal fiber spacing which will provide a desirable balance between the light-NLC interaction length and the operating power range in a practical device.

It should be noted also that the reproducibility of the transmission characteristics in different samples can be affected by the inaccuracy of the fiber spacing adjustment and random angular misalignments (coaxiality misalignments). Therefore, any practical design of prospective fiber-optic elements based on nonlinear coupling via NLC will have to feature high-precision alignment and a rigid structure.

3.1. Proposal

The obtained results prove the feasibility of efficient fiber-to-fiber nonlinear optical coupling via a nematic liquid crystal. This opens up possibilities for the development of novel NLC-based in-line fiber-optic elements with functionalities such as laser frequency conversion, power limitation and polarization control. In what follows we consider a possible design for an in-line fiber-optic polarization controller based on the above arrangements and effects.

To implement an electronically controlled variable retarder (a variable phase plate) we propose to add a couple of electrodes to the experimental arrangement depicted in figure 1. The electrodes must be located lengthwise on the outer surface of the sleeve. Such a retarder can be driven (to modify the polarization state of the transmitted light) by voltage applied to the electrodes. The applied electric field will cause a fractional change of the light-induced reorientation of the NLC molecules. Thus, the birefringence of the self-induced light guide in the NLC will be affected. In a rough approximation, one can estimate the sensitivity of the proposed variable retarder as follows.

The birefringence strength in NLCs governs the phase difference $\Delta\psi$ between extraordinary and ordinary waves and depends on the tilting angle θ. This is the angle between the radiation wave vector $\bar{\boldsymbol{k}}$ and the NLC director $\bar{\boldsymbol{n}}$ (see figure 2). There is a relation between these parameters [2]:

$$\Delta\Psi = 2\pi\frac{L}{\lambda}\left(\frac{n_\perp n_\parallel}{\sqrt{\varepsilon_\parallel - \varepsilon_a \sin^2\theta}} - n_\perp\right) \xrightarrow[\varepsilon_a/\varepsilon_\parallel \ll 1]{} \pi\frac{L}{\lambda}n_\perp\frac{\varepsilon_a}{\varepsilon_\parallel}\sin^2\theta \quad (2)$$

where L is the NLC length (equal to the fiber spacing in figure 1)and $n_{/\!/} = \varepsilon_\parallel^{1/2}$, $n_\perp = \varepsilon_\perp^{1/2}$ are the refractive indices and permittivities ($\varepsilon_a = \varepsilon_{/\!/} - \varepsilon_\perp$) associated with the electric fields parallel and normal to the NLC optical axis (the NLC director), respectively. Thus, the tilting angle for the quarter-wave retardation ($\Delta\psi = \pi/2$) can be found via the following relation:

$$\sin^2\theta_{\lambda/4} = \frac{\lambda}{2\,L}\frac{\varepsilon_\parallel}{n_\perp\varepsilon_a}.$$

If the NLC length L is a given value (~320 μm), and typical values of the NLC parameters are substituted into the above relation, it will yield (approximately) an angle of ~6° ÷ 7°.

As is well known, the tilting angle θ of the NLC director can be adjusted within almost the whole range $0 < \theta(E) < 90°$ by transverse electrostatic field (E) due to the Fréedericksz effect. To this end, the voltage applied to the opposite NLC surface boundaries has to be adjusted from approximately 1–2 V (threshold range) to approximately 3–4 V (saturation range), independently of the NLC thickness in the case of a planar cell [2]. If one relies on such a dependence of the tilting angle θ on the applied electrostatic field (E), as estimated in [2] for the Fréedericksz effect, one can expect that a voltage of not higher than ~2.2 V will be sufficient to induce quarter-wave retardation. However, it is necessary to take the actual geometry of our experiment into account. First, the electrodes are slightly apart from the NLC surface boundaries (by the sleeve thickness of ~0.4 mm). Second, the NLC length ($L \sim 320\ \mu$m) is much smaller than the NLC lateral dimension, which is equal to the inner diameter of the sleeve ($D \sim 2.5$ mm). Therefore additional elastic forces induced by surface forces cause some resistance to NLC tilting by applied electric field. Thus in a rough approach the actual voltage must be increased by a factor of ratio D/L in order to yield the proper tilting angle θ in the presented geometry.

The above consideration just gives an idea of the possibility of a low-voltage-driven NLC-based in-line fiber-optic polarization controller. For its practical design it will be necessary to consider the complex interplay of the light-induced Fréedericksz effect, the thermal orientation effect and the Fréedericksz effect induced by electrostatic field. An optimal balance between them has to be found by adjusting the NLC length and applied voltage in order to prevent degradation of the optical coupling between the fibers.

4. Conclusions

We have demonstrated the feasibility of fiber-to-fiber nonlinear coupling in a simple coaxial arrangement of telecom single-mode fibers separated by a gap filled with NLC. The coupling efficiency depends on the input optical power. It can reach up to ~0.7 even between fibers spaced at a relatively large distance (300 ÷ 400 μm) equal to several diffraction lengths (defined for a beam with a core-sized waist). The underlying physics is mainly based on the light-induced reorientation of nematic molecules, which causes the self-confinement of a propagating beam. The stability of such light guiding is sustained by the highly nonlocal response of NLCs to applied fields.

The demonstrated results open up possibilities for the development of novel NLC-based in-line fiber-optic elements with different functionalities (laser frequency conversion, power limitation and polarization control). One important feature that was discovered is the possibility of producing a relatively long interaction length in such elements (nonlinear coupling can be sustained even in a 0.4 mm long NLC). Thus, a low-voltage-driven NLC-based in-line fiber-optic polarization controller was proposed and considered in this first approach.

Acknowledgments

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