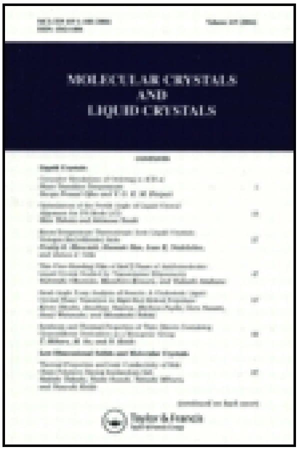

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Controlled Leakage of a Tapered Optical Fiber with Liquid Crystal Cladding

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CONTROLLED LEAKAGE OF A TAPERED OPTICAL FIBER WITH LIQUID CRYSTAL CLADDING

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Abstract We present the feasibility of a directional coupler composed of a tapered monomode fiber surrounded by a Liquid Crystal (LC) external cladding. After a short review of the different losses induced by bending or tapering of a fiber, we describe a method to couple light out of a tapered fiber, opening perspectives in the field of integrated optical couplers and we show how to control the direction of the losses, by electrically induced reorientation of LC.

INTRODUCTION

In the field of optical waveguides, during the development of optical fibers networks, more and more laboratories have studied, since 20 years, new configurations of waveguides, based on numerous materials like liquid crystals (LC), polymers and dyes. Three ways are mainly investigated. The first is developed around the planar geometry of liquid crystals waveguides. In such a structure, selection of modes,[1] beam splitting,[2] modulation of guided light intensity,[3] controlled losses[4] have been investigated. The second way concerns the cylindrical geometry of LC confined volumes, in connection with the future applications in optical fibers components. Although some groups have showed the possibility of transitions between LC phases[5] or the formation of patterns in LC cylindrical waveguides[6], most of the studies are performed in the theoretical domain, in particular to simulate the coupling of modes[7] or the stability of the LC configuration[8]. The third way, in which the experiences described in this paper can take place, is the control of the propagation in optical fibers by a LC outer cladding. The intensity or the polarization of the guided light is controlled by an appropriate nematic liquid crystal layer, which locally takes the place of the fiber cladding. By this means, it is possible to adjust the power coupled from a fiber to another[9] or to affect the state of polarization of the wave propagating in the core of the fiber.[10]

Conventionally, the coupling is obtained by affecting the evanescent field located in the cladding close to the core.[11] One of the main method used to reach this part of the fiber, the thickness of which is typically about 1 μm, consists in polishing the fiber with appropriate abrasives. Although this method do not affect the propagation in the core and is therefore compatible with guiding over a long distance, the precision required to guarantee a constant coupling efficiency makes it long and expensive.

We have explored a new approach to couple the light out of the core. It consists in mixing the well-known pertubation that induces losses with an electrooptical material as a cladding. After reminding a few results concerning the monomode propagation in the fibers, we focus on the main causes that induce losses, namely tapering and bending the fiber.

In a second part, we present some preliminary experimental results on losses of fibers, both tapered and bent, controlled by an external electric field through a liquid crystal cladding. It is shown that not only the amount of losses is controlled but also the direction: the using of such a device for coupling purpose is considered.

THEORY

In this part, we just remind the theoretical results on guided propagation that are required to understand the origin of the losses. In a waveguide, the energy is confined mainly in the core with a small amount travelling in the cladding. There will be losses as soon as the energy is spreading up to the external part of the cladding. The distribution of the electric field and in turn that of the energy, can be estimated in the gaussian model associated with the monomode propagation. As the difference between the core index (n_{co}) and the cladding index (n_{cl}) is small, the transverse electric field E(r) of the guided wave is solution of the differential equation:

$$\left[\frac{d^2}{dr^2}+\frac{1}{r}\frac{d}{dr}+k^2n_{(r)}^2-\beta^2\right]E(r)=0 \tag{1}$$

where r is the transverse distance from the axis of the fiber, k the usual wave vector, n(r) the index profile of the fiber and β the longitudinal constant of propagation. Then the electric field E(r) can be approximated with:

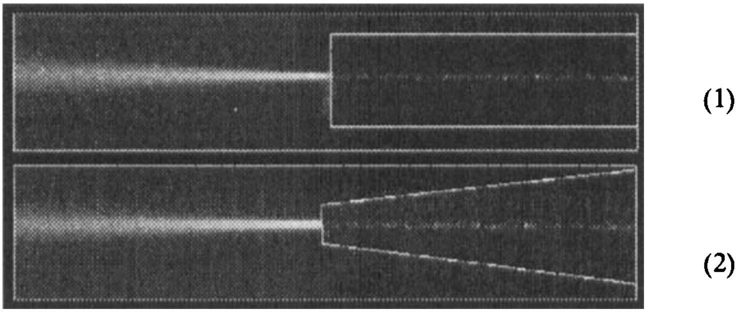
$$E(r)=E_0.e^{-\frac{r^2}{2w_0^2}} \tag{2}$$

where w_0 is the so called spot size which corresponds to the largest value of β and which is different from a, the core radius of the fiber. In the gaussian model, it is shown that the ratio w_0/a can be expanded as a polynomial function of the normalized frequency V, for values of V between 1.2 and 3. [12]

$$V=k.a.\sqrt{n_{co}^2-n_{cl}^2} \tag{3}$$

$$\frac{w_0}{a}=0.65+1.619\ V^{-\frac{3}{2}}+2.879\ V^{-6} \tag{4}$$

As it can be seen from the Equations 3 and 4, for a decreasing core radius, the normalized frequency decreases and the spot size increases, becoming larger than the core radius, increasing the fraction of power in the cladding. Such a behaviour can be seen on the Picture 1. Indeed on this picture, it is shown a beam emerging out of cleaved fibers, one (top) is a normal fiber whereas the second is tapered. Even if it is not obvious on such poor quality copy, the beam emerging out of the tapered fiber is wider and less diverging than the one emerging out of the normal fiber. It is worth noticing that by processing such an image, it is possible to measure quite accurately the width and the divergence of the outgoing beam and in turn to deduce the core radius in the tapered region.



PICTURE 1 Comparison of a beam emerging out of a cleaved normal fiber (1) and a tapered fiber (2) (fiber outlines artificially marked).

For a core radius small enough, the spot size can be as large as the cladding itself and the energy escapes the fiber. Experimentally, the core radius can be locally reduced by heating and pulling the fiber, such an handling is known as tapering. Such a tapering induces local losses and the energy radiates isotropically all around the fiber axis, providing that the external material is itself isotropic.

Directional losses can be induced by bending the fiber. Depending on how strong is the bending, the energy is partially or totally escaped out of the fiber.

a) Strong bend

The bend is said strong as the radius of curvature of the bend is small, about three or four times that of the diameter of the fiber. In this case, the phase fronts of the guided planar wave are rotating in the curved part of the fiber, as shown on Figure 1. The longitudinal phase velocity v_p increases linearly with the distance from the center of the bending.

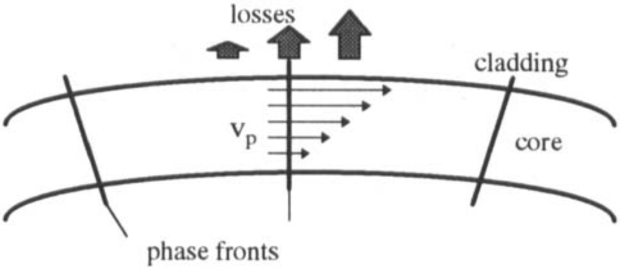


FIGURE 1 Losses from a strongly bent fiber.

The condition of guidance $c/n_{co} < c/n_{cl}$ (where c is the speed of light in vacuum) is no longer verified and the wave is no longer guided. All the power escapes into the cladding, leading to an efficient coupling out of the fiber.

b) Weak bend

As the radius of bend is rather large compared to its diameter, the Gaussian-shaped mode is weakly transversaly shifted from its axial position.[13]

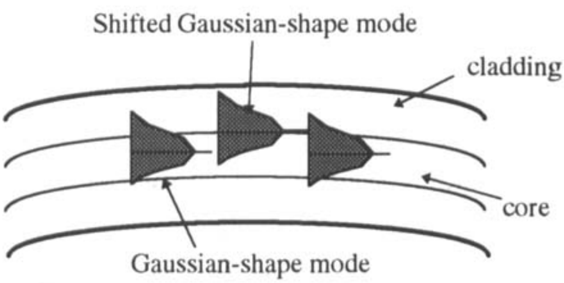


FIGURE 2 Shifted mode in a weakly bent fiber.

Nevertheless, as shown in Figure 2, the shifted wave keeps propagating close to the fiber axis, inducing a weak variation in the monomode propagation after the bent region. Equation (5) gives the transverse shift r_d of the wave from the axis of the fiber.

$$r_c = \frac{V^2 w_0^4}{2\Delta R_c \mathbf{a}^2} \tag{5}$$

where R_c is the radius of curvature of the fiber and Δ is given by Equation (6).

$$\Delta = \frac{n_{co}^2 - n_{cl}^2}{2 n_{co}^2} \tag{6}$$

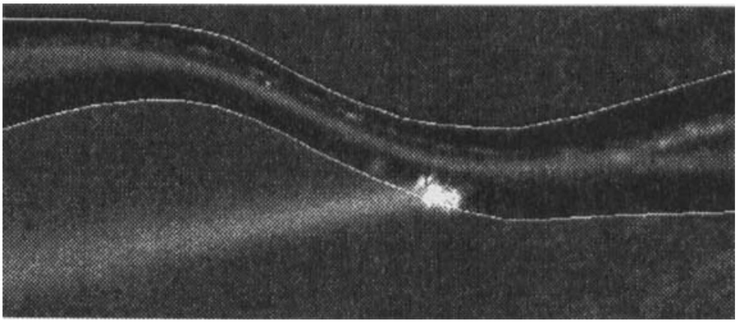
It is usually considered that for a shift r_d lower than the core radius a, the propagation keeps being monomode after the bend.

EXPERIMENTS

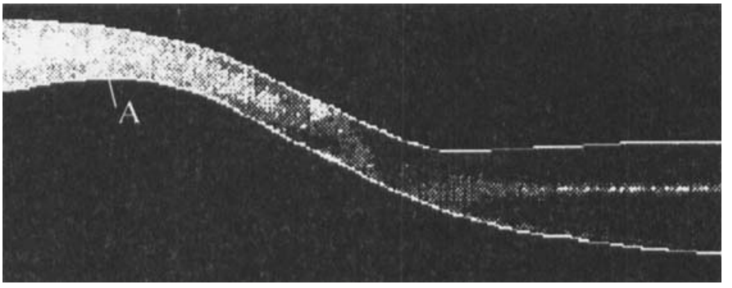
According to those theoretical results, we wondered whether associating tapering and bending can induce any controllable directional losses. Both transformations have been achieved using a splicing machine, controlled by a computer. To obtain a bend, a weak stress has been first applied to the bare fiber in the machine, before very accurately heating and pulling it. Let us examine two configurations, corresponding to the two types of losses studied before. All the presented experiments have been performed using a classical fiber monomode for the visible range of wavelength, the core and cladding diameter being respectively 3.1 μm and 125 μm. The lenght of the fiber on which the stress was applied is about 1.5 cm.

First configuration: strongly bent fiber

For a transversal shift which is about twice the diameter of the fiber and applied to the heated fiber, the final shape is shown on Picture 2. On this picture, to have the losses of the core viewable, we have fed the fiber with the green line of an Ar^+ laser (514 nm), and sunk the fiber within an index oil. According to the theory, we observed losses escaping from the curved part of the fiber, leading to a sharp beam in the oil.

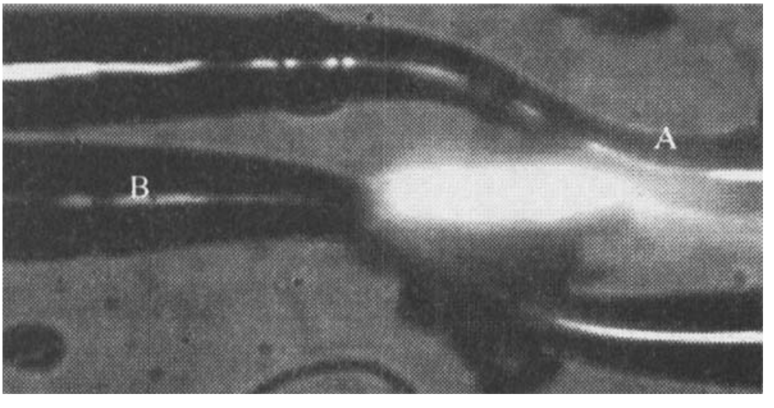


PICTURE 2 Directional losses from a strongly bent fiber immersed in oil. The light is propagating from the right to the left. The outlines of the fiber have been artificially marked.



PICTURE 3 Non monomode propagation in a strongly bent fiber. The fiber is in the air. The light is propagating from the right to the left. The outlines of the fiber have been artificially marked.

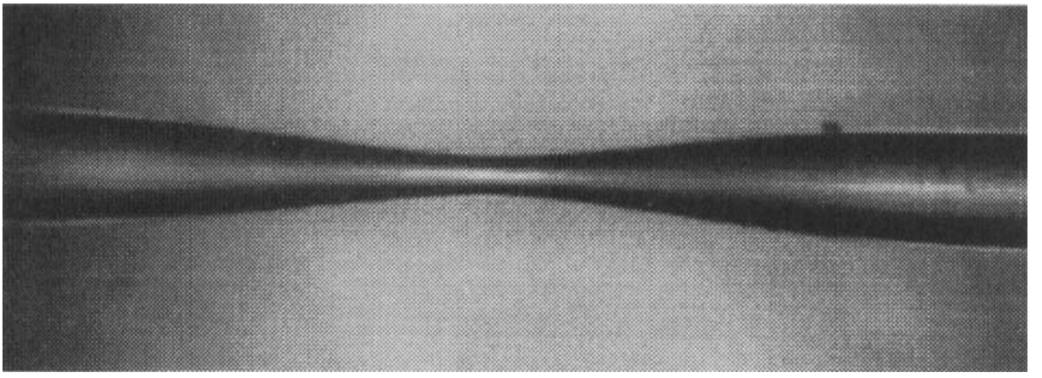
Nevertheless, as shown on the Picture 4, it is possible to use such a large loss to couple light from this fiber to another one. This preliminary experiment has been performed without extra adjustement of the relative position of both fibers, leading to a quite low coupling efficiency (around 5%), nevertheless it has been possible to estimate the precision required to optimize such a kind of coupler.



PICTURE 4 Coupling of light between two strongly bent fibers via index oil.

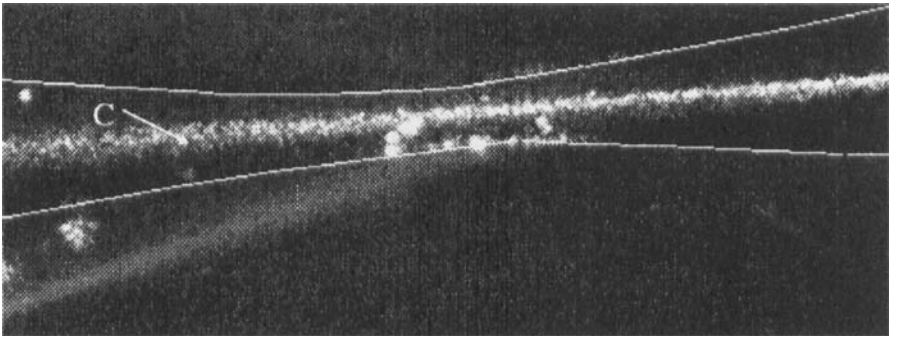
Second configuration: weakly bent fiber

As the shift applied to the fiber is about half of the diameter, the fiber is weakly bent, as shown on Picture 5.



PICTURE 5 Weakly bent and tapered fiber.

The losses of the fiber, inserted in oil, appear to be weaker (Picture 6) than for the previous case but the light is still guided in the fiber after the bend (C, Picture 6), allowing us to device a coupler, without interrupting totally the propagation in the fiber.



PICTURE 6 Losses escaping from a weakly bent fiber. The light is propagating from the right to the left. The outlines of the fiber have been artificially marked.

These preliminary experiments on losses show that it is extremely important to control very accurately the final geometry of the taper together with the bending: both the final core and cladding radius determine the amount of losses, also a cut-off in the guide has to be avoided. That is the reason why we have developped a testing bench to monitor the power still guided in the fiber during the process of tapering and bending.

Control of the process

During the process, the fiber is fed with a laser line and the emerging power is continuously measured. As the fiber is slowly heated and pulled in the splicing machine, the power is decreasing: the greatest value of the power lost before cut-off was measured to be about 20 % of the total guided power. Thus, by controlling the decreasing of the power, it was possible to adjust precisely the geometry of the fiber.

Reorientation of the losses

To improve the coupling efficiency between two fibers as shown on the Picture 4, one of the parameters to be considered is the direction of the emerging beam. We have addressed this question by using a liquid crystal material as cladding. Both the uniaxial character of such a material and the bending breaking the symmetry of the cladding, it should yield to some directional losses. The used NLC is the commercially available E7 (Merck).

As shown on Figure 3, the tapered part of the fiber was inserted between two glass plates, separated by mylar spacers (125 μm, the diameter of the bare fiber). The inner sides of the plates were metallized, to allow NLC reorientation by application of an electric field. The plates were unidirectionally rubbed with diamond paste to achieve planar alignment of the NLC molecules without electric field, parallel to the fiber axis. The NLC E7 exhibits a positive dielectric anisotropy, leading to homeotropic alignment under electric field.

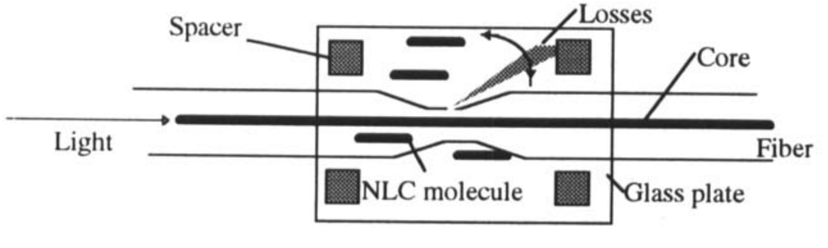
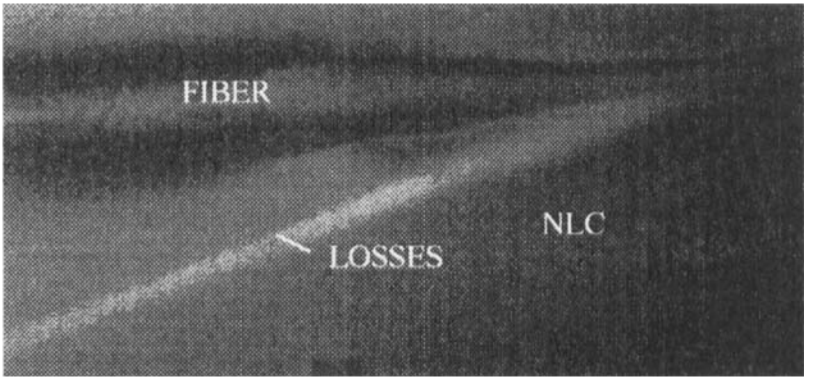


FIGURE 3 Top view of the experimental set-up designed to control the direction of the losses. This apparatus is inserted in the microscope.

After injection of light, directional losses appeared, in the form of a sharp beam, characterized by a low divergence (Picture 7), predicting an addressing of other optical components with good spatial resolution.



PICTURE 7 Losses in Nematic Liquid Crystal (E7), planarly aligned, parallel to fiber axis and without electric field.

According to the transverse mode model used to describe the monomode fiber propagation, the wave vector of the losses is parallel to the boundary between the cladding and NLC, as shown on Figure 4.[13]

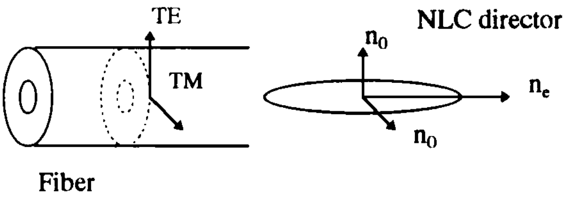


FIGURE 4 Interaction between both polarizations of guided light and the NLC director in planar alignment configuration.

The angle between the leaky beam and the fiber's axis is given by the Snell's law[14] and depends on the refractive index of the LC seen by the electric field of the light. In the planar alignment configuration (Figure 4, Picture 7), both TE and TM polarizations see the ordinary index n_o, leading to an angle between the fiber and the beam of 15°.

By applying a 20 volts, square-shaped signal, at a frequency of 1 KHz, to the plates, the reorientation of NLC from planar to homeotropic alignment occurs. In this case, as shown on Figure 5, TM polarization sees always the ordinary index while TE polarization sees the extraordinary index n_e, leading to two weaker beams, respectively characterized by the previous angle of 15° and a new angle of 33° (Picture 8, Figure 5).

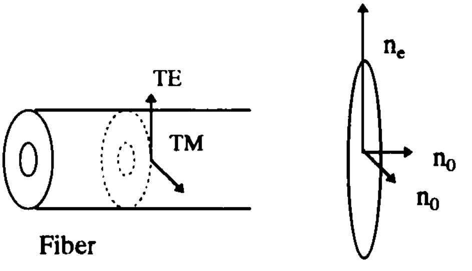


FIGURE 5 Interaction between both polarizations of guided light and the NLC director in homeotropic alignment configuration.

PICTURE 8 Same sample as on the Picture 7, under an electric field (20 V square shaped). Both ordinary and extraordinary beams are observable.

As the electric field is switched off, the emerging beam is relaxing back to its first position (Picture 7). It is worth noticing that the off-state geometry has a cylindrical symmetry whereas the on-state breaks such symmetry and in turn reduces the number of degrees of freedom of the emerging beam.

CONCLUSION

We have shown that directional coupling of light can be obtained from the cladding of a fiber without polishing it. Only a weak bend combined with tapering leads to cladding losses without pertubating the propagation in the fiber. The direction of the beam can be controlled by an «active» liquid crystal cladding. Those results open new perspectives in the field of integrated optical couplers.

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