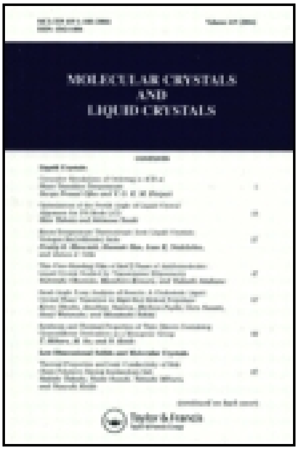

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Investigation of Long Period Fiber Gratings Sensitivity to Liquid Crystal External Medium

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In this work, we study the response of Long Period Fiber Gratings (LPG) to an external Nematic Liquid Crystal medium. By a coupling between the fundamental mode of the core and the cladding modes of the fiber, losses occure at different wavelengths. The spectral position and the intensity of those losses depending on the index of the external medium, one can expect that different orientations of the NLC will induce a modification of the response of LPG. To check this assumption, we have realised two types of experiments: In a first time, we have studied the response of LPG to different treatments of the fiber. In particular, we present for the first time a method to obtain a planar alignment directly on the fiber. It will then be demonstrated that the response of LPG can be modified by Fredericksz reorientation of NLC, creating new opportunities in telecommunications networks.

Keywords: Optical fiber grating, liquid crystal cladding, coupled modes.

INTRODUCTION

Since the birth of the laser, optical fibers are a key element of optical signal processing. By their unique capacity to drive high rate datas over long distances, they have conditioned the conception of numerous integrated elements as light sources, polarizers, filters or interferometers. Now, fibers networks are arriving on age and the growing of channels is supported by new optical couplers like Wavelength Division Multiplexers (WDM). In those networks, the amplification of the different wavelengths simultaneously is realised by Erbium Doped Fiber Amplifiers (EDFA). Unfortunately, the response of those amplifiers is not flat enough to obtain a uniform amplification over all the channels. To overcome this problem, new pass-band optical filters have been studied, which allow by there association the rectification of the response of the EDFA over the near infrared spectral range. More precisely, Long Period Fiber Gratings (LPG) have been chosen since they induce selective wavelengths losses over a few nanometers without changing the transmission of the fiber over the spectrum[1]. Furthermore, their response can be modulated by changing the external medium without modifying the shape of the fiber, opening new applications for NLC. After a few theoretical considerations about LPG, we will examine how NLC can be anchored on a fiber and how this new external cladding can influence the shape of the transmission spectrum when it is excited by an electric field. In particular, we will show that hypothesis concerning the LPG polarisation can be verified from the analysis of the transmission spectrum modification.

THEORY

Polarization properties of light in a monomode fiber

It is wellknown that the light guided in a fiber is mainly confined in the core, where it establishes itself in a fundamental mode modelized as a Gaussian-like beam, weakly evanescent in the cladding. The polarisation state of this mode can be defined as hybrid, i.e. non transverse.

Usually, the difference of indices between the core and the cladding is smaller than 10^{-2} and the components of the electric field along the fiber axis can be neglected. The mode can be considered as transversally polarised with a linear polarisation. In fact, local anisotropic stresses applied to the fiber (for example a bend) or some anisotropy of the core transform the linear polarisation in a weakly elliptical one[2]. We will consider that the wave at the beginning of a LPG exhibits this state of polarisation.

The long period grating

When a periodical modification of the index of the core is applied along the fiber axis (usually induced by UV irradiation), the guided wave suffers Bragg diffraction and the wavevector along the fiber axis is modified. Two cases can be examined. First one, if the spatial period of the perturbation is small - around one micron - the direction of propagation is inverted and a coupling occurs between counterpropagating fundamental modes[3]. We obtain a reflection in the fiber for a wavelength λ_0 depending on the period of the perturbation. Second one, and this is the subject of this work, if now the spatial period of the perturbation is about a few hundred microns, the guided wave spreads out in the cladding until it reaches the cladding limit. This diffracted light organizes itself in a guided mode of the overall fiber (core and cladding). This mode exhibits the same symmetry as the fundamental mode. The wavelength for which the coupling and then the decrease of the fundamental mode transmission coefficient occurs, verifies the so-called *phase matching condition*, expressed in 1:

$$n_{eff}^{co} - n_{eff}^{cl} = \lambda_0/\Lambda \qquad (1)$$

were n_{eff}^{co} and n_{eff}^{cl} are respectively the effective indices of the core and of the cladding and Λ the spatial period of the perturbation. The coefficient of efficiency of the coupling k, which determines the value of the attenuation for the fundamental mode, is given in 2,

$$k = \eta \, \pi \, \Delta n^{U.V} / \lambda_0 \qquad (2)$$

where $\eta = \omega \int_0^\infty \Delta\varepsilon \; E_1.E_2 \; r \; dr$ is the recovery integral of the electric field distribution between the fundamental (E_1) and one cladding mode (E_2) on the total section of the fiber, Δn^{UV} the variation of index induced in the core of the fiber by a UV irradiation and $\Delta\varepsilon$ the variation of permittivity associated to Δn^{UV}.

The effects of LPG on the transmission spectrum of the fiber

As shown on the Figure 1, each coupling to a cladding mode results in a hole in the transmission spectrum of the fiber, occurring for a particular value of λ_0.

FIGURE 1 Transmission spectrum of a monomode fiber with a LPG.

The normalized depth S(L) of the holes is given by $S(L) = \sin^2(k\,L)$ where L is the length of the grating. The power square of the sinus in S(L) indicates that the transfer of energy from the core to the overall fiber can be reversed when the variation of index is too high for a given value of L. As a result, during the writing of the grating, the depth of the holes grows then decreases when the energy is coupled again in the core. For others wavelengths than λ_0 (resonance), it appears in the calculation of S(L) that the more L increases, the more the width of the holes decreases.

Polarization considerations

To model the influence of an anisotropic medium like nematic liquid crystal around a fiber, we needed to estimate as precisely as possible, how the cladding modes are polarized when the fiber is surrounded by air and how this state is modified by the presence of the liquid crystal. Up to now, this problem has never been solved due to the high difference of indices between the fiber and the air (≈0.5). In this case, the so-called *weak guidance approximation* is not fulfilled for cladding modes. Their polarization state is called Hybrid Electric (HE) and a straightforward analysis in the transverse plan of the fiber is not possible.

Let us consider now, as shown on Figure 2, the three basic orientations a semi-infinite liquid crystal external cladding can take around the fiber.

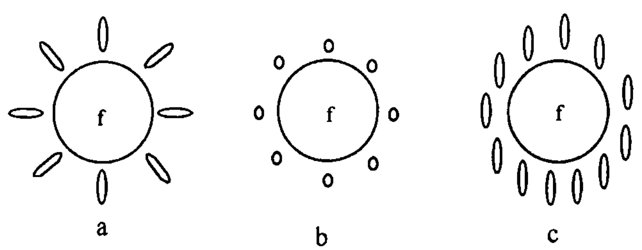


FIGURE 2 The three basic orientations a nematic liquid crystal can take round a fiber f: a) radial, b) planar, c)unidirectional.

For those configurations, the difference Δ between the index of the fiber

(n_{silica}=1.444) and the ordinary index of the nematic which insures the guidance (in our case ZLI 1083, by Merck, n_o=1.440) is small and the hybrid polarization of cladding modes can be approximated to a transverse one.

By a uniform orientation of the liquid crystal along all the length of the grating, the effective index of the cladding modes n_{eff}^{cl} changes and the wavelength λ_0 for which the coupling occurs is shifted. Any local tilt of LC with respect to the desired uniform orientation will result in a broadening and a decrease of depth for the holes (Figure 3), the phase matching condition being now fulfilled for a smaller effective length of the grating.

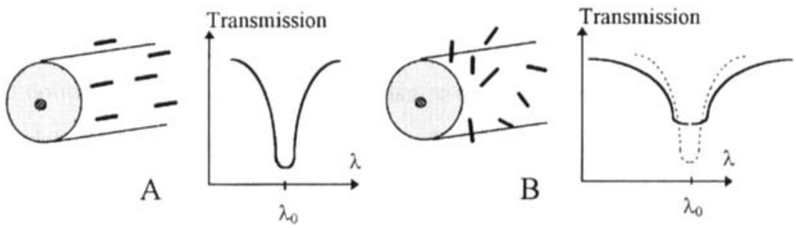


FIGURE 3 Comparison of a hole shape in the transmission spectrum with a well-defined alignment (A) and a bad alignment (B) of LC around the fiber.

EXPERIMENTS

Set-up used to write the LPG

The LPG have been realized by UV-beam exposition of a monomode fiber (FPG 2010, CNET, Lannion, cut-off = 1.2 μm), which polymer cladding have been removed on a length of about 10 centimeters. The UV beam, delivered by a frequency doubled Ar^+-laser, was focused on the fiber through an amplitude mask with a spatial period of 0.2 mm and 5 centimeters long. The diameter of the beam was ≈ 50 μm and the power density 5.10^3 Wt/cm^2. To write the grating, the laser beam was scanned along the fiber, the time irradiation being several seconds for one pitch. To obtain the necessary amplitude of the refractive index modulation, the scanning of the laser was repeated several times. The grating was written on about 3 centimeters of the fiber in order to optimize the spectral definition of the holes. As mentioned in the theoretical section, during the writing of the grating, the depth of the holes grows then decreases. In our study, we have stopped the inscription process just before this decrease.

Methods used to control the orientation of LC around the fiber

There was just a few descriptions of methods of anchoring of liquid crystals on a fiber before we started our study [4]. This field of research was practically not initiated compare to the usual methods applied to planar cells. As it has be said before, it is necessary to obtain an homogeneous orientation of the director in the transverse plan of the fiber and maintaining it so along all the grating, which is typically 3 centimeters long. Between all the anchoring methods developed for planar cells, we have chosen two of them, one to obtain the geometry labelled a) and one for b). The problem was to find a method compatible with the fragility of bare fibers and to insure an homogeneous treatment of the fiber all around its cladding. The geometry c) has required, as it will be explained later, the application of an electric field around the fiber.

Geometry « a » (radial)

We have obtained this orientation by immerging a bare fiber into a mixture of lecithin and chloroform (1g/l). After evaporation of the chloroform, the fiber was inserted into a capillary tube and the liquid crystal was filled in it. The transmission spectrum of the fiber over the spectral range comprised between 1300 and 1600 nm was recorded before and after the treatment of the fiber with the lecithin. For this purpose, the light supplied by a white lamp, emitting in the near infrared range, was injected at one end of the fiber. The light transmitted was analysed in a monochromator associated with a Ge detector. The spectrum recorded after the treatment didn't exhibit any modification compare to the previous one. This result indicates that the thickness of the film of lecithin around the fiber is not sufficient to modify the effective index of cladding modes.

Geometry « b » (planar)

This geometry is usually obtained by rubbing the glass surface with a diamond paste. More recently, a new technic have been developed to induce this alignment by softer means. It is based on the application of PTFE on the glass surface. We have adapt this technic to our study by rubbing a PTFE ribbon directly on the bare fiber. As the fiber was maintained straight right, two pieces of ribbon, maintained parallel to each other, were pressed against the fiber and moved slowly along the grating length. As for the previous case, the spectrum of the fiber was not affected by this treatment. Then, the fiber was introduced in a capillary tube and the LC was filled in it.

Geometry « c » (unidirectional)

We have tried to control the alignment of LC on the fiber as depicted in the geometry « c » by confining it between two plates treated with lecithin. Indeed, this asymmetric geometry cannot be obtained directly on the fiber. After this treatment, we have recorded the transmission spectrum of the fiber, which exhibited an important broadening of all the holes. We have see before that this broadening is correlated with a bad alignment and we have then leaven this technic. We choose then to create the geometry c) by applying a bipolar electric field in the transverse plane of the fiber. To estimate the efficiency of this operation in terms of homogeneity of the LC cladding, we needed a maximal efficiency of reorientation by the electrical torque whatever the place around the fiber. For this purpose, the fiber was first prepared in the geometry labelled b) (figure 4).

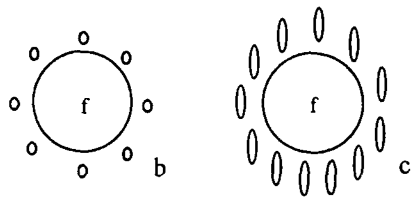


FIGURE 4 Reorientation of LC between b) and c).

After treatment as in the previous case, the fiber was inserted in a planar LC cell (Figure 5). The internal surfaces of the glass plates of the cell were metallized in order to apply a 200 Volts, 1 KHz AC voltage in the LC cladding. No treatment was applied to the plates to avoid a conflict with the treatment applied to the fiber. Then, the fiber was inserted in the cell and the LC was filled in it. As for the geometries described before, the treatment of the fiber didn't induce any modification of the spectrum.

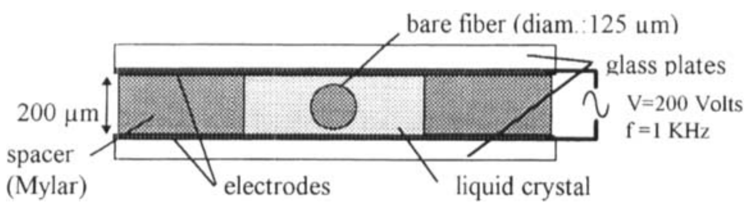


FIGURE 5 Planar cell used to create the geometry c).

RESULTS AND DISCUSSION

a) <u>Experiences with alignment of LC on the fiber (geometry a) and b))</u>

The transmission spectrum of the fiber has been recorded without and with the liquid crystal. The evolution of the spectrum before (1) and after (2) the application of the LC is shown on Figure 6 and Figure 7, corresponding to the geometries « a » and « b » respectively.

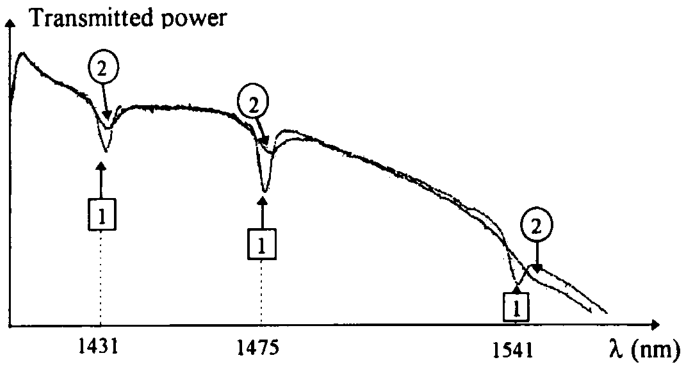


FIGURE 6 Transmission spectrum of the fiber 1) with lecithin, 2) with lecithin and liquid crystal.

For both records, the position of the holes for the three modes is shifted between curve 1 and curve 2, the value of this shift being comprised between 2 and 10 nanometers. As demonstrated in the theoretical section, this result is correlated to a change of the index of the external cladding, which is the air in the first situation. It indicates that the anchoring of the liquid crystal by the lecithin as by the Teflon is rather efficient on all the length of the grating. Nevertheless, the broadening of the holes as it can be seen on both figures, shows that the alignment is not perfect on all the grating.

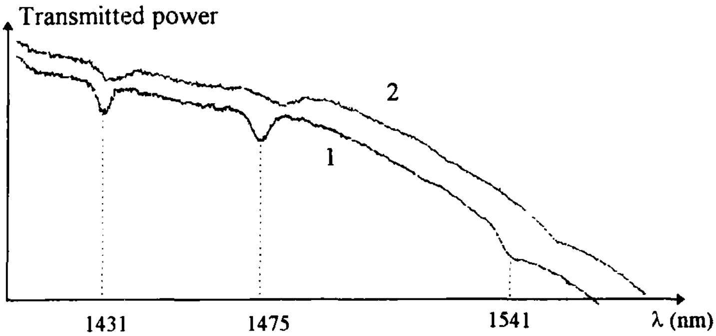


FIGURE 7 Transmission spectrum of the fiber 1) with Teflon and 2) with Teflon and liquid crystal.

One can also observe that the depth of the holes has decreased of about a factor two with the LC in geometry a). This effect can be explained by polarization and modes overlap considerations. Near cut-off and for a cylindrical symmetry of the medium surrounding the fiber, a cladding mode can be decomposed in two degenerated modes, the TE and the TM modes (Figure 8). For geometry « a » as for « b », the electrical field of the guided wave must see the ordinary index of the LC to establish itself in a cladding mode.

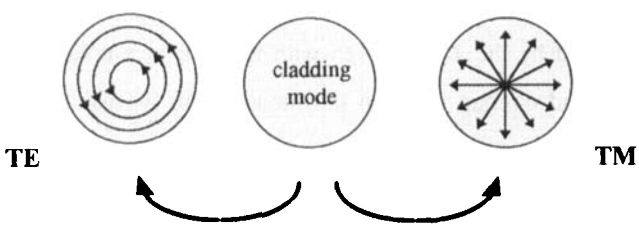


FIGURE 8 Degeneration of a cladding mode

Due to the orientation of the LC molecules at the surface of the fiber, the condition of guidance ($n_{CL}<n_{cladding}$) will be realized only in geometry « a » by a

TE mode, explaining partially the decrease observed. But another explanation, also valid for the decrease observed in geometry b) (10% of the holes), can be given: whatever the mode we consider, its electric field "sees" always the ordinary index of LC, which is very close to the index of silica. Under this condition, the cladding mode is near cut-off and spreaded out deeply in the cladding. Then, the overlapping between the fundamental and the cladding mode, as it is expressed in η, is weak and contributes to the attenuation of the coupling for both geometries.

b) Reorientation by electric field

In geometry c), the spectrum of transmission was recorded, as previously, before (1) and after the association with LC (2) (Figure 9). If we decompose the elliptical polarization of the fundamental mode on the frame of the cell, Ox and Oy (figure 10), the component E_x sees, when it is expanded by the grating to the external limit of the cladding, the extraordinary index of LC and doesn't contribute to the cladding mode whereas E_y sees the ordinary index, which insures the guidance of a linearly polarized cladding mode.

The increase of the depth of the peaks indicates that the quality of the alignment achieved by the electric field is better along the LPG than the alignment induced by the Teflon, even with the lack of x-polarized cladding mode and the bad overlap between the modes. For a weakly elliptical LP mode (for low stresses of the fiber, as it was in our study), this effect doesn't depend on the azimuthal orientation of the fiber compare to the cell.

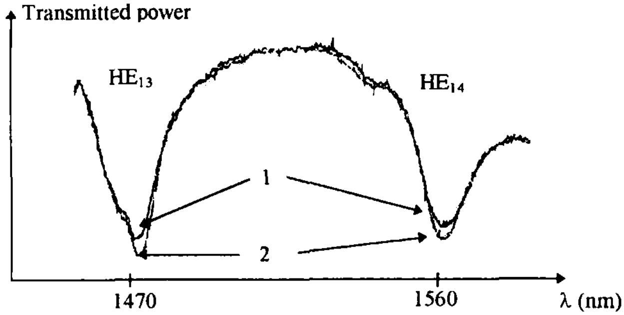


FIGURE 9 Transmission spectrum of the fiber without (1) and with voltage applied on the cell (2).

The comparison between (1) and (2) shows also that there is no shift of the resonances, in the limit of resolution of our monochromator (about 4 nm).

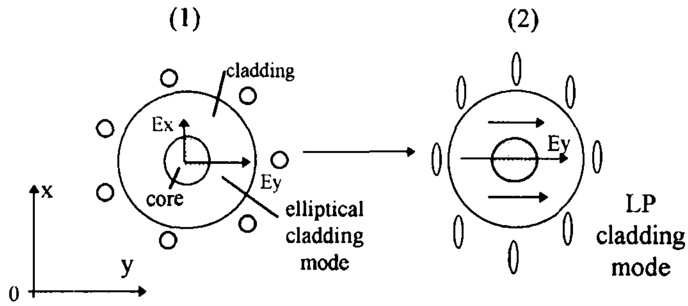
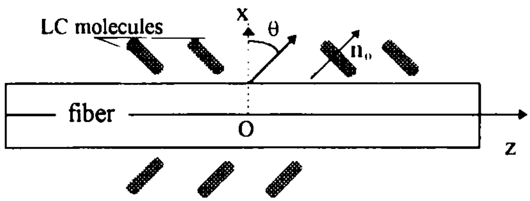


FIGURE 10 Polarization state of the cladding modes before (1) and after (2) the application of a 200 Volts 1 Khz AC voltage.

This result is in good agreement with the fact that the index of liquid crystal viewed by the cladding mode is always n_o and can be explained by the fact that a cladding mode can establish itself only if its electric field, confined in the transverse plan, "sees" the ordinary index of LC. Let us consider the angle θ between Ox and the average direction $\mathbf{n}_0$ of the LC molecules:



Intermediate value of θ between 0 and π/2 will not induce the formation of cladding modes, since in our case, the small value of Δ limits the orientation of the plan of polarization close to the xOy plan, just before the cut-off of the tranversaly polarized modes. Previous works have shown the possibility to modify the depth of the holes by modification of the cladding diameter, but this result was associated to a shift of the resonance wavelengths[6]. In our case, it is possible to decrease dramatically the shift by choosing a LC which ordinary index is as close as possible to the index of the cladding. This association could allow the conception of new totally fibered switches.

CONCLUSION

We have shown that it is possible to influence the response of a LPG by controlling the orientation of a liquid crystal external cladding. Classical technics of anchorage of LC, based on the treatment of glass surfaces by organic surfactants, have been successfully adapted to the cylindrical geometry of the fiber. The analysis of the transmission spectrum of the fiber have confirmed the different hypothesis concerning the polarization state of the cladding modes. Finally, as shown in the last part, reorientation of LC around a

LPG induces a modification of the intensity of the losses without changing their spectral assignment. The applications of LPG can then be extended to fibered switches. Nevertheless, this study requires further investigations about the influence of LC on the cladding modes polarization.

Acknowledgments

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