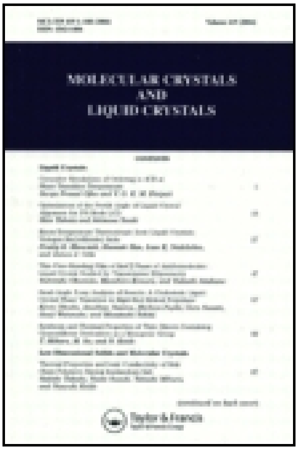

Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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Version of record first published: 18 Oct 2010

Mol. Cryst. Liq. Cryst., Vol. 421, pp. 175–186, 2004

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400490501770

POLARIZATION MODE DISPERSION IN AN ELLIPTICAL LIQUID CRYSTAL-CORE FIBER

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Polarization phenomena in an elliptical liquid crystal-core fiber at third optical window, i.e., close to 1550 nm have been investigated. This includes direct measurement of polarization mode dispersion and the beat-length parameter. The elliptical liquid crystal-core fiber contained a nematic mixture characterized by extremely low values of refractive indices.

Keywords: liquid crystal fiber; polarization; polarization mode dispersion

INTRODUCTION

Polarization properties of highly birefringent (HB) polarization-maintaining (PM) fibers have been extensively investigated for over the last two decades [1] and significant progress in optical fiber technologies has been achieved. This includes also an elliptical liquid crystal-core fiber (ELCF) that reveals particular propagation and polarization properties [2]. It has been recently demonstrated that the ELCF with a nematic liquid crystal (LC) mixture characterized by extremely low values of refractive indices can exhibits single-polarization behavior at certain temperature range [3].

The paper presents for the first time (to our best knowledge) results of polarization measurements of an ELCF at the wavelength around 1550 nm. This includes direct measurement of polarization mode dispersion (PMD) that is one of the crucial parameters influencing badly performance of light-wave systems at high bit-rates well above 10 Gbit/s and measurement of

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the beat length. It is anticipated that due to reorientation possibilities of nematic molecules within the fiber core, the value of PMD could be easily modified.

The long-term aim of these studies is to propose an efficient system with dynamically controlled birefringence to compensate for PMD effect in optical telecommunication as well as in fiber-optic sensing systems.

POLARIZATION MODE DISPERSION IN HB FIBERS

Polarization mode dispersion is regarded as a major limitation in optical transmission systems in general and an ultimate limitation for ultra-high speed single channel systems based on standard single mode fibers.

Real single-mode fibers as used in telecommunication possess nonzero intrinsic birefringence due to either asymmetry of the fiber optic cross section or anisotropic stresses acting on the core of the fiber [4]. And two orthogonally polarized modes have randomly different phase velocities, inducing fluctuations of the polarization state of the light guided in the fiber. Moreover, they experience also bends, twists, stresses, inhomogeneities, and imperfections that induce additional birefringence and simultaneously affect the two polarization states of the light guided in the fiber differently. These effects produce a nonzero level of internal birefringence varying randomly along the fiber and it is exactly the origin of PMD.

If the input pulse excites both polarization components, it becomes broader as the two components disperse along the fiber due to their different group velocities (Fig. 1). Since optical fibers allow very large propagation distances even very small birefringence effects can cumulate along fiber and their random distribution over the large lengths causes polarization properties of guided light generally difficult to determine. It concerns both the state and the degree of polarization, and consequently PMD is a stochastic process.

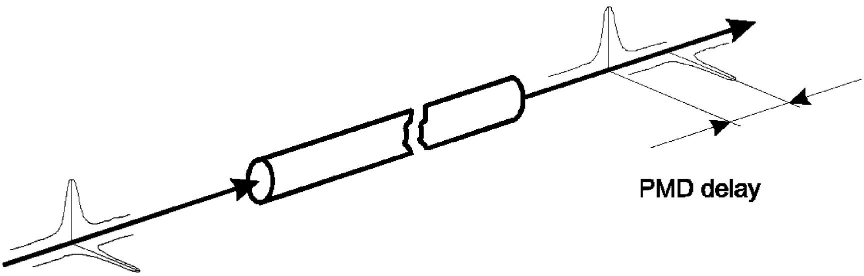


FIGURE 1 Definition of a PMD delay in a birefringent fiber.

Polarization mode dispersion is usually expressed by differential group delay (DGD) over the length of the fiber $\Delta\tau/L$ Both values: PMD and modal birefringence $\Delta\beta$ are the most important parameters characterizing birefringent fibers interrelated according to the formula [4]:

$$\frac{\Delta\tau}{L} = \frac{d(\Delta\beta)}{d\omega} = \frac{1}{c}\left(\Delta n_{eff} + \omega\frac{d\Delta n_{eff}}{d\omega}\right) \tag{1}$$

where $\Delta\tau/L$ is usually expressed in units of picoseconds per kilometer of fiber length, Δn_{eff} is the differential effective index of refraction for the slow and fast polarization modes, and $\omega = 2\pi c/\lambda$ is the angular frequency of light.

In HB fibers with stress-induced birefringence (e.g., HB bow-tie fibers [1]) in which birefringence is caused by stress applying parts introduced in cladding close to the core region of the fiber, Δn_{eff} is nearly wavelength independent and the chromatic dispersion of the modal birefringence is negligible. Hence for this type of fibers measurements of birefringence and PMD are equivalent.

$$\frac{\Delta\tau}{L} \cong \frac{1}{c}\Delta n_{eff} = \frac{\lambda}{L_B c} \tag{2}$$

where L_B is beat length expressed as:

$$L_B = 2\pi/|\beta_y - \beta_x| \tag{3}$$

and responsible for phase difference changes along the HB fiber. The spatial period L_B of these changes reflects the modulation in the polarization states along the fiber. Linearly polarized light coupled into the HB fiber with plane of polarization directed at the angle of 45 degrees between both axes of birefringence excites both field components $HE_{11}{}^x$ and $HE_{11}{}^y$ of the fundamental HE_{11} fiber mode and as these two orthogonal mode components are characterized by different propagation constants β_x and β_y, they run into and out of phase at a rate determined by the birefringence of the HB fiber producing at the same time a periodic variation in the transmitted polarization state from linear through elliptic to circular and back again.

The magnitude of polarization mode dispersion in the HB fibers is close to 1000 ps/km, that is four orders of magnitude higher in comparison to 0.1 ps/km a typical PMD value of today's telecommunication fibers [5].

LOW-BIREFRINGENCE NEMATIC MIXTURES FOR ELLIPTICAL LC-CORE FIBERS

It has been demonstrated [2] that circular liquid crystal-core fiber either in planar, or axial/radial geometries of the core do not reveal any birefringence. Contrary, elliptical liquid crystal-core fibers (ELCFs) are characterized always by non-zero value of birefringence due to non-symmetrical geometry of the core (Fig. 2). This originally geometrical birefringence could be significantly enhanced by replacing silica core with an anisotropic liquid crystal with transverse orientation of its molecules. Hence, the obtained ELCF can reveal particular polarization properties [2,3].

Since a nematic core within the ELCF is surrounded by a glass capillary of elliptical cross section, its molecular orientation strongly depends on capillary dimensions, boundary conditions, and on physical fields influencing the LC medium. Any external factor acting on the nematic core is in the position to change the effective refractive indices. The extraordinary index of refraction n_e depends on α, the angle between direction of propagation and the optical axis and is described by:

$$n_e(\alpha) = \frac{n_o n_e}{\sqrt{n_o^2 \cos^2 \alpha + n_e^2 \sin^2 \alpha}} \tag{4}$$

where: n_o, n_e are ordinary and extraordinary refractive indices, respectively. In the waveguide configuration, the formula (4) sets the upper limit of the effective refractive index of the fiber mode that could propagate within the ELCF. Possible alignments of the LC in the elliptical core and their influence on the mode structure have been discussed elsewhere [6].

We have used ELCFs composed of new, extremely low-birefringence nematic mixtures introduced into a hollow elliptical-core fiber characterized by the dimensions of the ellipse either 4×10 or $4 \times 18\,\mu m$. The low-birefringence nematic LC compositions included 4 components esters

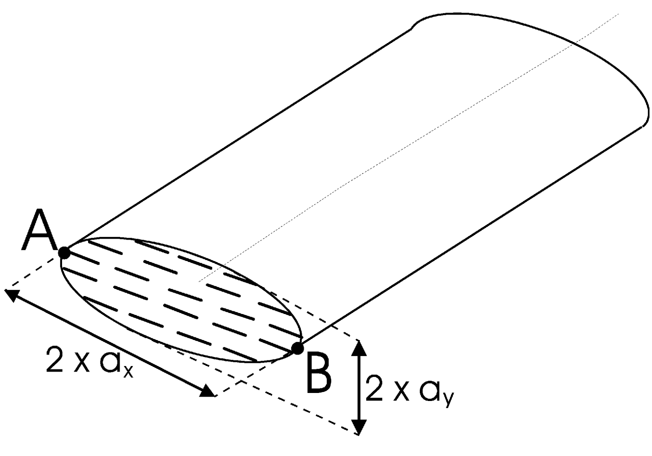
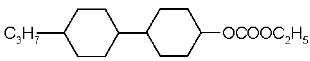
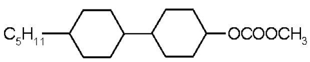
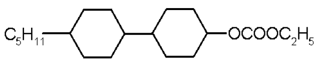
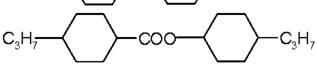


FIGURE 2 Elliptical-core liquid crystal fiber with homogeneous orientation of LC molecules.

mixtures (composed by Military Univ. of Technology, Poland and abbreviated as: P2 and P2-5% mixtures) were characterized by ordinary $n_o = 1.46-1.45$ and extraordinary $n_e = 1.478-1.505$ refractive indices at 20°C with phase transition order: S_B19.5N51.4I for the P2 mixture and S_B5N38.4I for the P2-2,5% mixture as presented in Table 1 and Figure 3. In certain region of nematic phase (above 22°C), its ordinary refractive index n_o is below the refractive index of fused silica $n_{cl} = 1.458$ ($\lambda = 589\,\mathrm{nm}$) while the extraordinary index is still a little bit higher ($n_e = 1{,}480$). Consequently, only single polarization could be guided within the fiber in this temperature region. The ELCF characterized by

TABLE 1 Composition and Phase Transition Temperatures of P2 (a) and P2-5% (b) Nematic Mixtures for ELCFs

Eutectic mixture of composition	Wt.%
	10,44%
	8,01%
	16,24%
	65,31%

Phase transitions during cooling: Iso 51,4°C N 19,5°C SmB

	Temperature $T - T_{N-I}$	
	−10°C	−20°C
n_o	1,4565	1,4567
n_e	1,5000	1,5002
Δn	0,0435	0,0435

Phase transition during cooling: Iso 38,4°C N 5°C SmB

	Temperature $T - T_{N-I}$	
	−10°C	−20°C
n_o	1,4560	1,4588
n_e	1,4927	1,5002
Δn	0,0367	0,0414

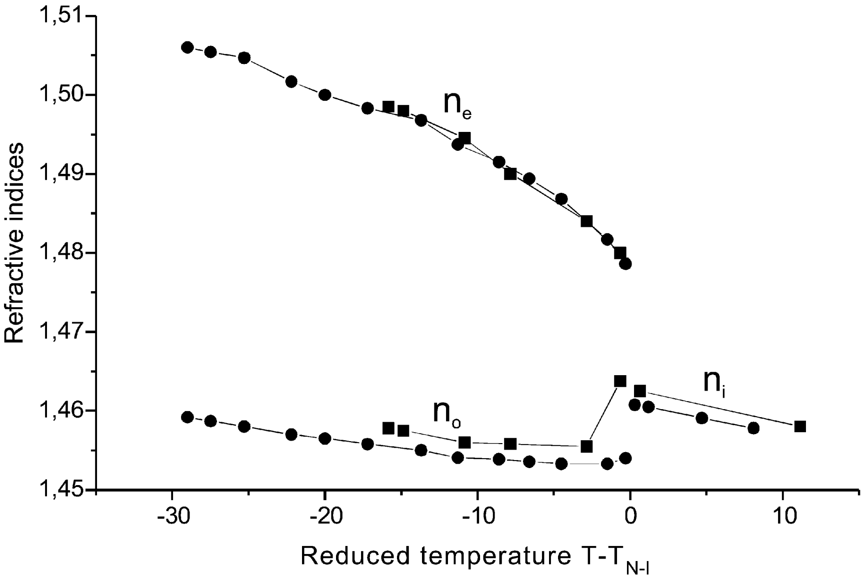


FIGURE 3 Temperature dependence of refractive indices of mixtures P2 and P2-5%.

homogeneous transverse orientation of LC molecules has a property of single-polarization multimode propagation. The whole manufacturing process of the ELCF was described in details elsewhere [2,3].

The ELCF under investigation was introduced to a large hollow-core capillary (diameter 127 μm) along with both input and output single-mode (SM) fibers. The ELCF and SM fibers were coupled "face to face"

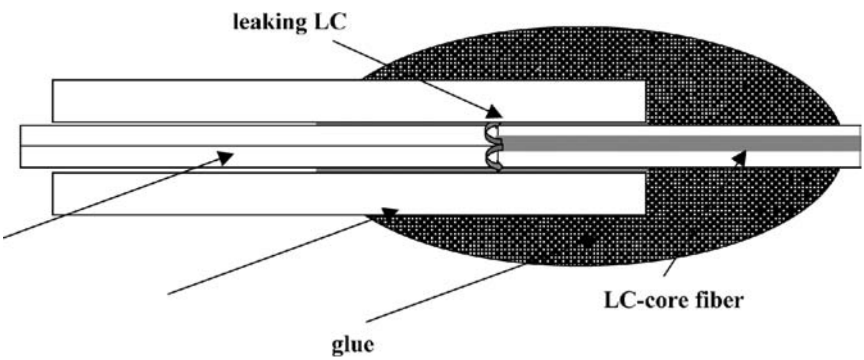


FIGURE 4 Connection of the ELCF with input (output) fiber and its packaging.

(Fig. 4) enabling leaking of an extra nematic mixture. The ends of the 127 µm-diameter-housing capillary were epoxy glued with the ELCF.

METHODS OF BEAT LENGTH AND PMD MEASUREMENTS

For HB fibers, there have been numerous measuring methods developed to determine the beat length parameter. Most of them are direct measurements e.g., based on the Rayleigh scattering and cannot be straightforwardly used in infrared and in particular in the case of small beat lengths as is the case of the ECLCF. Consequently we applied an indirect method for the beat length measurement [7,8], that resambles the idea of our earlier beat-length measurements [9]. The difference in phase between the modes after a length of fiber L is:

$$\varphi = \delta\beta L = \frac{2\pi L}{L_B} \tag{5}$$

where L_B is a beat length of the fiber. Hence, we receive the following relation for the signal measured at the detector:

$$I(\lambda) = I_o \sin^2\left(\frac{2\pi\lambda}{(\Delta\lambda)} + \varphi\right) \tag{6}$$

where $\Delta\lambda$ is the spectral beat period, φ and $\Delta\lambda$ result from the fitting of the experimental data to the function described by the nonlinear curve fitting. Hence, we could determinate the beat-length parameter as follows:

$$L_B = \frac{(\Delta\lambda)L}{\lambda + (\Delta\lambda)\varphi} \tag{7}$$

Any change in φ is not as important as $\Delta\lambda$ in determination of L_B. Notice, that the method cannot be precisely applied to the fibers with non-zero value of chromatic dispersion as it relies on wavelenth sweeping. Since chromatic dispersion at infrared (close to 1550 nm) of the LC mixtures is not well established yet, the results of the mesurement should be verified by alternative measurements.

EXPERIMENTAL RESULTS

The measurement apparatus included a tunable laser source (*Tunics Plus CL*) operating at third optical window (around 1550 nm) and a modular system for polarization analysis PAT 9000B (*Profile-Tektronix*), Figure 5. We have measured both: the beat length parameter and the PMD effect of

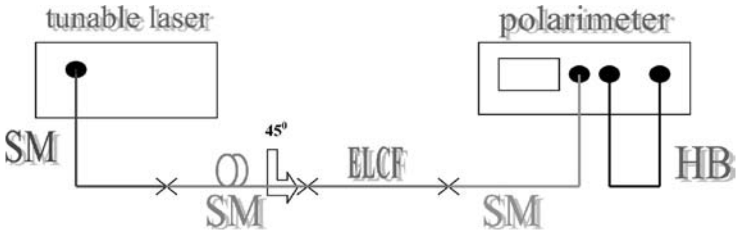


FIGURE 5 Experimental setup for polarization measurement in an ELCF by using the PAT 9000B Polarimeter and a tunable laser source.

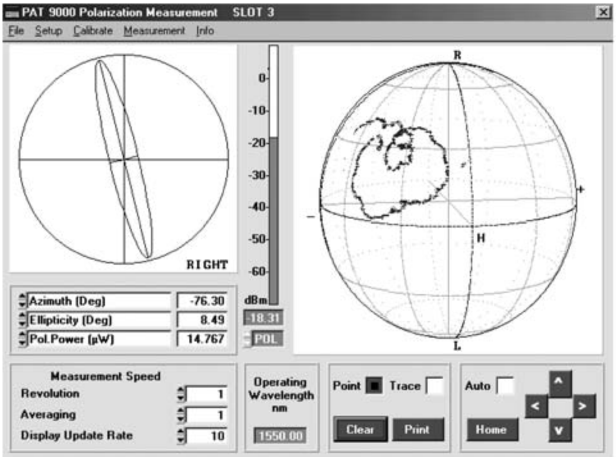
the elliptical liquid crystal-core fibers and the results obtained were discussed in terms of polarization properties of birefringent fibers.

The effect of PMD was directly measured by the fixed analyzer technique. The fixed analyzer technique (Fig. 6) enables measurement of the angular characteristics of the fiber and localization of its principal birefringence axes. The value of differential group delay (DGD) will be maximal if the input linear polarization is injected at 45 degrees to both birefringence axes.

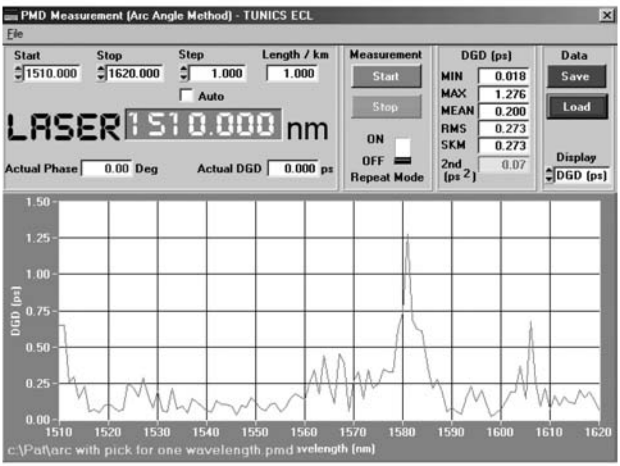
For birefringence measurement, a novel experimental method of indirect beat length determination was adapted [7,8]. The method was initially tested for HB fibers: PANDA SM15-PS-U25 (produced by Fujikura, Japan) and bow-tie HB 1500 (produced by Fibercore, UK), and then applied to the ELCFs. In our experiment we launched the linearly polarized light at 45° to the principal axes. Using the tunable laser a change of the output signal in function of wavelength for around 1550 nm was investigated. The results of the measurements were visualized on the Poincaré sphere. Results of of beat length and PMD measurements are presented in Tables 2 and 4 for different ELCFs: with new P2, P2-5% mixtures, but also with formerly investigated 7VOL and 1451 nematic mixtures. Table 3 presents calculated "beat length" $L_{B(\mathrm{cal})}$ values of nematic mixtures used for ELCFs. The total material birefringence gives rise to this value according to the formulae

$$L_{B(\mathrm{cal})} = \lambda/\Delta n \qquad (8)$$

and represents the lower limit of the measured beat lengths. This approach could also serve for a rough estimation and an alternative method of birefringence and refractive index dispersion at infrared in comparison to the methods presented elsewhere [9,10]. Generally, both values: PMD and beat length are about one order of magnitude higher and respectively lower than the values characterizing "solid-core" HB both: bow-tie and PANDA fibers.



(a)



(b)

FIGURE 6 Beat-length measurement visualized on the Poincaré sphere (a) and PMD measurement by PAT 9000B system a tunable laser source (b) in a 5.2 cm long ELCF (nematic mixture: P2-5%, core: $4 \times 18\,\mu$m).

CONCLUDING REMARKS

To conclude, we have discussed the phenomenon of PMD and presented for the first time (to our best knowledge) results of PMD measurements at the wavelength 1550 nm in ELCFs visualized on the Poincaré sphere and also

TABLE 2 Results of Beat Length Measurement in an ELCF at 1550 nm (at 20°C)

ELC fiber	$\Delta\lambda$ [nm]	L [mm]	L_B [mm]
1451 4*18	12	60	0.464
7 VOL 4*10	1.2	15	0.012
P2-5% 4*10	18	7	0.084
P2-5% 4*10	0.4	520	0.139
P2-5% 4*10	20	10	0.133
P2-5% 4*18	50	7	0.233
P2-5% 4*18	45	7	0.210
P2-5% 4*18	60	7	0.280
P2 4*10	84	11	0.616
P2 4*10	110	11	0.807
P2 4*18	47	36	1.128
P2 4*18	40	49	1.307

TABLE 3 Calculated Beat Lengths of Nematic Mixtures (at 20°C)

ELC fiber	n_o	n_e	L_B [mm]
P2-5%	1.458	1.496	0.038
P2	1.456	1.505	0.032
1451	1.466	1.518	0.030
7 VOL	1.459	1.515	0.028

TABLE 4 Results of PMD Measurements in an ELCF at 1550 nm (at 20°C)

LC mixture	L (mm)	PMD (ps/m)
1451 4*18	12	9
7 VOL 4*10	15	100
P2-5% 4*10	7	33
P2-5% 4*10	520	13
P2-5% 4*10	10	80
P2-5% 4*18	7	28
P2-5% 4*18	7	24
P2-5% 4*19	7	17
P2 4*10	11	9
P2 4*10	11	16
P2 4*18	36	12
P2 4*18	49	7

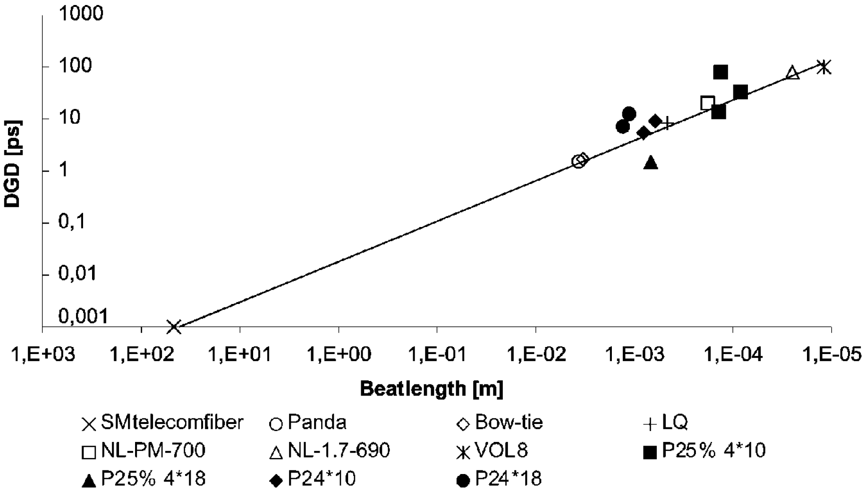


FIGURE 7 Relation between PMD and beat length in telecom, HB and liquid crystal-core fibers.

measured the beat-length parameter in the ELCFs by the wavelength sweeping technique in comparison to standard telecom and to single-mode HB fibers. These measurements enable rough estimation of refractive indices of extremely low-birefringence LC mixtures at C-band of telecoms.

Based on the experimental results obtained in this paper we are able to draw an approximate linear dependence between beat length and PMD (expressed in terms of differential group delay) for single-mode telecom, highly birefringent, photonic and elliptical liquid crystal-core fibers, see Figure 7. Any deviations from this linear dependence, as is the case of ELCFs, are either to non-zero chromatic dispersion of the liquid crystal-core fibers or non-perfect transverse alignment of nematic molecules along with long elliptical axis. This deserves further experimental work and additional studies.

The long-term aim of these studies is to propose an efficient system with dynamically controlled birefringence to compensate for PMD effect in optical telecommunication as well as in fiber-optic sensing systems.

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