Phase-Shifting VOA With Polymer Dispersed Liquid Crystal

P. Chanclou, B. Vinouze, M. Roy, C. Cornu, and H. Ramanitra

***Abstract*—A polymer containing fine droplets of liquid crystal (LC) is investigated for obtaining an optical phase-shifting attenuator at 1550-nm wavelength. Two mixtures of liquid crystals and monomers are compared for a cell thickness of 15 μm. The first method uses nanosized LC droplets to achieve 2.29-rad phase shifting for an applied voltage of 230 Vrms. The second method uses microsized LC droplets to achieve 2.35-rad phase shifting for an applied voltage of 15 Vrms. Theoretical analysis of the phase shifting is developed. This optical property is used to achieve a variable optical attenuator (VOA) between two single-mode fibers. An optical architecture using graded index rod lenses and a pattern of photoresist polymer is presented. Typical characteristics of such VOA are: 12-dB range of attenuation, a maximum polarization dependence loss of 0.5 dB, 1.1-dB insertion loss, and a saturation voltage of 20 Vrms.**

***Index Terms*—Liquid crystal, polymer dispersed liquid crystal, variable optical attenuator.**

I. Introduction

LIQUID crystal microdroplets dispersed in a matrix of polymer is an interesting material for a variety of light control and electrooptic applications. In this material, the fabrication problems inherent to either twisted and super-twisted nematic or ferroelectric LC, such as surface alignment, cell filling and precise thickness are not encountered. This simplifies design, reduces cost, and can increase device lifetime in high-temperature high-humidity conditions where drastic geometrical cells are not maintained.

Polymer dispersed liquid crystal (PDLC) is for this reason particularly convenient in optical telecommunication domain. The PDLC is used to achieve variable optical attenuator [1], [2]. The operation of theses polymers is based on the molecules' mobility when an electrical field is applied, and the birefringent of the LC droplets, which leads to either scattered or transmitted incident light. This optical phenomenon is achieved with a droplet's size in the range of the wavelength.

Other telecommunication applications could be achieved with smaller LC droplets. Nanosized droplets of LC cannot scatter the light in the infrared wavelength wavelength. But a phase variation of the incident light can be achieved. Another important property of the nano-PDLC material is its fast response time compared to PDLC. The aim of this paper is to achieve small-sized PDLC droplets [3]–[6] in order to use the phase variation for performing an optical attenuator or another optical functions.

In this paper, we describe the material and fabrication process of two types of cell:

1) specific nano-PDLC mixture for phase phenomena with droplets smaller than 100 nm;
2) standard PDLC mixture usually used for scattering phenomena that we have optimized in order to limit the scattering phenomena and improve the phase variation.

We present a theoretical modeling of phase variation. Then the optical properties (residual scattering and phase variation) of these cells are measured as a function of the driving voltage. Experimental results are compared with theoretical results. An optical application is proposed on the domain of the optical telecommunication: a variable optical attenuator. In this paper, we report an optical arrangement that uses the phase shifting to disturb the coupling between two single-mode fibers.

II. Material and Fabrication Method

In this paper, we use a combination of LC (Merck Industrial Chemicals), polymers, oligomer, and ultraviolet (UV) photoinitiators. We describe the principal and fabrication process of two types of cell with a mixture of:

Process 1) 50% of liquid crystal BL009 ($\Delta n = 0.281$ at 589 nm, 20 °C) and 50% of UV-curable prepolymer NOA 81 with a UV irradiation of 12 $\mathrm{mW/cm^2}$;

Process 2) 80% of liquid crystal TL 205 ($\Delta n = 0.217$ at 589 nm, 20 °C) and 20% of monomer PN 393 with a strong UV irradiation of 350 $\mathrm{mW/cm^2}$.

These mixtures are filled in glass cells with transparent electrode in indium-tin-oxide (ITO). The thickness of cells is calibrated at 11, 13, and 15 μm using spherical polymer spacers to achieved the LC droplets. We use the UV photopolymerization-induced phase separation [7], [8]. The adjustment of the LC droplets' size is performed by adjusting the UV power, and the UV light is filtered at 356 nm. Process 1) gives nano-PDLC. Process 2), with a maximum power of 350 $\mathrm{mW/cm^2}$, gives a PDLC with microsized droplets structure called micro-PDLC. After UV curing, the cells are sealed with UV epoxy glue.

III. Theoretical Background

Our PDLC is composed of nematic LC droplets with a positive dielectric anisotropy $\Delta\varepsilon$, n_{o} and n_{e} are the ordinary and extraordinary refractive indexes of the droplets, respectively, and n_{p} is the refractive index of the polymer. The optical anisotropy

Manuscript received January 29, 2003; revised September 9, 2003.

P. Chanclou, B. Vinouze, and H. Ramanitra are with GET–ENST Bretagne Département d'Optique, Technopole Brest-Iroise, F 29238 Brest, France (e-mail: philippe.chanclou@enst-bretagne.fr).

M. Roy and C. Cornu are with Optogone, 29280 Plouzane, France.

Digital Object Identifier 10.1109/JLT.2003.821719

TABLE I
TOTAL PHASE VARIATION BETWEEN THE ON- AND OFF-STATE IN FUNCTION OF THE CELL THICKNESS FOR TWO PDLC PROCESSES

Phase variation $\Delta\Phi_T$	e = 11 µm	e = 13 µm	e = 15 µm
Nano-PDLC (Process 1)	1.67 rad	1.97 rad	2.28 rad
Micro-PDLC (Process 2)	2.06 rad	2.44 rad	2.81 rad

corresponds to $\Delta n = n_e - n_o$ and the refractive index of the polymer n_p is chosen to be closed to the ordinary LC refractive index n_o. The size of the droplets is much smaller than the wavelength of the light used in telecommunication systems. So a medium containing such droplets apparently becomes optically isotropic to these wavelengths.

Without voltage, LC molecule alignment is uniform inside the droplets but randomly oriented from one droplet to others in the polymer host, so the effective refractive index is equal in all directions at the average of the refractive index of three axes of the ellipsoid. Inside the droplets, the effective refractive index for an operating light in this OFF-state is estimated to

$$\bar{n}_{\mathrm{OFF}} = \frac{n_e + 2.n_o}{3} \quad (1)$$

for a low value of the optical anisotropy ($\Delta n \ll 1$). When an electric field is applied, the LC molecules in the droplets align themselves parallel to the electric field due to the positive dialectical anisotropy. If the electrical field is parallel to the light propagation, the index for an incident light in this ON-state is estimated to be

$$\bar{n}_{\mathrm{ON}} = n_o. \quad (2)$$

Therefore, different light processing can be achieved by applying an electric field. The variation of the effective refractive index between the ON- and OFF-state is given by

$$\Delta\bar{n} = \bar{n}_{\mathrm{OFF}} - \bar{n}_{\mathrm{ON}}$$
$$\Delta\bar{n} = \frac{n_e - n_o}{3} = \frac{\Delta n}{3}. \quad (3)$$

The phase of the output light shifts with the applied electric field because the effective refractive index decreases. The optical path of incident light in the LC/polymer medium can be expressed, in the ON- and OFF-state, by

$$L_{\mathrm{OFF}} = \bar{n}_{\mathrm{OFF}} \cdot \chi \cdot e + n_p \cdot (1-\chi) \cdot e$$
$$L_{\mathrm{ON}} = \bar{n}_{\mathrm{ON}} \cdot \chi \cdot e + n_p \cdot (1-\chi) \cdot e$$
$$\Delta L = L_{\mathrm{OFF}} - L_{\mathrm{ON}} = \chi \cdot e \cdot \frac{\Delta n}{3} \quad (4)$$

for χ is the mass proportion (%) of LC in the mixture. We suppose that the optical path in the PDLC is the sum of the fixed optical path in the polymer plus the optical path in LC with a variation of effective refractive index between $\bar{n}_{\mathrm{OFF}}$ and $\bar{n}_{\mathrm{ON}}$ versus the electric field. Here, we also consider that the phase separation of LC and polymer by UV photopolymerization is complete. The total phase variation between the ON- and OFF-state for the incident infrared light is described by

$$\Delta\Phi_T = \Delta L \cdot \frac{2\pi}{\lambda} = \frac{2\pi \cdot \chi \cdot e}{3 \cdot \lambda} \cdot \Delta n \quad (5)$$

where λ is the wavelength of the transmitted light (1550 nm) and e is the thickness of the PDLC. We consider a variation of LC refractive indexes of −20% between the wavelength of 589 and 1550 nm at 20 °C [9]. Calculated total phase variations for two LCs (BL009 and TL205) are reported Table I. These results are compared in the next section with optical measurements and discussed in relation to the topic of complete phase separation of LC and polymer.

IV. OPTICAL PROPERTIES

A. Scattering Phenomena

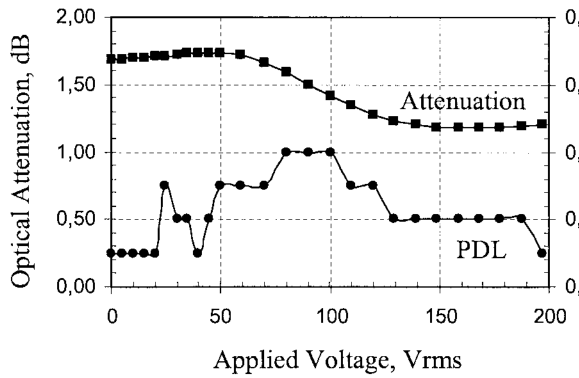
One goal of this paper consists of making high phase variation and low scattering cells. The scattering state is a parasitic phenomenon that increases the insertion loss. Our experiment consists of a free-space interconnection between two single-mode fibers (at 1550 nm) through collimators with 400-μm optical beam. The cell is inserted in the free space to achieve measurements. Fig. 1 shows the measurements of the optical attenuation and polarization dependence loss (PDL) in function of the applied voltage for 15-μm cells with a) nano-PDLC and b) micro-PDLC mixtures. The driving voltage is a square wave at the frequency of 3.5 KHz.

The nano-PDLC cell has a residual optical attenuation range of 0.6 dB with a saturation voltage of 150 Vrms and PDL below 0.04 dB. The micro-PDLC cell has a residual optical attenuation range of 2 dB with a saturation voltage of 10 Vrms and PDL below 0.1 dB.

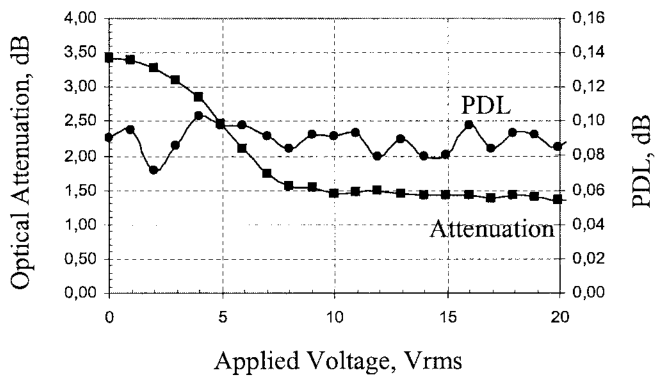
The nano-PDLC mixture allows limiting the residual scattering with a ratio of 4.10^{-3} dB/V, but high voltage is necessary. The micro-PDLC has low operating voltage but has more residual scattering with a ratio of 0.2 dB/V.

B. Phase Variation

This paragraph presents the phase variations of the cells. We use a free-space Mach–Zender interferometer to characterize the cells at 1550 nm. The cells are inserted in one of the interferometer arms and the movements of the fringes (Fig. 2) are measured versus voltage. The experimental curves in Fig. 3 correspond to optical phase shifts for a) nano-PDLC and b) micro-PDLC for 15-μm cells versus voltage. A total phase variation of 2.29 rad is measured with nano-PDLC at 230 Vrms. This voltage corresponds to our experimental limit; we cannot



(a)



(b)

Fig. 1. Optical attenuation and PDL for (a) nano-PDLC and (b) micro-PDLC, 15-μm cells.

apply higher voltage to reach higher phase shift. For micro-PDLC, a total phase variation of 2.35 rad is measured with a saturation voltage of 15 V (157 mrad/V). This material has no threshold voltage and a very low saturation voltage. So the micro-PDLC is a better compromise because it reaches almost the same phase shift with a lower voltage than the nano-PDLC. We focus only on the micro-PDLC cells [Process 2)].

We have realized micro-PDLC cells with different thicknesses. The thickness of the cell plays an important role in the total phase variation. Fig. 4 shows the total phase variation for micro-PDLC mixture versus the cell thickness. We compare experiment and simulation; the theoretical curve is given by (5) and the parameters in Table I. There is a good correlation between model and experiments. When the PDLC thickness increases, the total phase variation and the saturation voltage also linearly increase. π and 2π total phase variations are obtained for around 17- and 32-μm cells, respectively. For a 32-μm micro-PDLC cell, the optical attenuation range due to scattering is 8 dB with a saturation of driving voltage of 70 Vrms. The π cell is investigated now for an optical telecommunication application.

V. An Optical Function: Variable Optical Attenuator

We apply the phase-shifted function with micro-PDLC to realize a variable optical attenuator (VOA) for the optical telecommunication at 1.55-μm wavelength. To achieve the optical attenuation, the micro-PDLC modifies the phase of only a part of the optical beam. We report in Fig. 5 the structure of the active

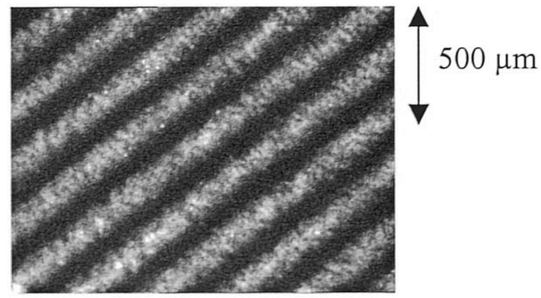


Fig. 2. The interference fringes for micro-PDLC at 1.55 μm, 15-μm cell.

area of our VOA. In order to apply a phase variation on only part of the optical beam, a photopolymer pattern is deposited on one substrate. A commercial photoresist is chosen to match the $\bar{n}_{\mathrm{On}}$ index of the micro-PDLC. The simplest pattern is composed of two pixels diagonally opposed. After patterning the photoresist, the ITO coated plates are laminated and the mixture is introduced. Then the polymerization of the mixture is performed with Process 2). No etching is needed for making electrodes because the substrates are completely covered with ITO.

The cell with this structure is inserted between two single-mode fibers, and the spot size of the beam is collimated by a graded index (GRIN) rod (SELFOC lens) of 400-μm diameter (Fig. 6). The optical beam is centered on this pattern, which divides the beam in four parts. The cross-section is composed of two micro-PDLC parts, which are electrooptically active, and two polymer areas, which are optically fixed. The control voltage is applied on the full cell and modifies only the effective refractive index (and the optical phase) of the micro-PDLC areas. The light passing through these micro-PDLC areas is phase-shifted by π relative to its phase without any voltage applied.

The Gaussian beam passing through this PDLC cell is therefore transformed such that it has a symmetric center field distribution, which prevents coupling to the symmetric fundamental mode LP_{00} of the single-mode fiber. The light is converted to a similar LP_{21} mode, which cannot propagate in the fiber. Moreover, this field cannot propagate in the GRIN rod with the adequate property to achieve the magnification of the symmetric fundamental mode of the single-mode fiber. The attenuator is then at its maximum attenuation state, ideally fully blocking the light (Fig. 7). For intermediate voltage, when the phase shift of the light passing through the micro-PDLC areas is less than π, only a part of the light is transformed to the similar LP_{21} mode so the light is partially attenuated. The level of optical attenuation is thus a function of the applied voltage. When a saturation voltage is applied to the electrodes, the micro-PDLC and photoresist $\bar{n}_{On}$ areas exhibit the same optical path so these areas are optically uniform and no more phase shift occurs, which leads to a minimum attenuation. Fig. 8 shows a polarizing microscopic photograph of the cell. The micro-PDLC uniformity is good enough to allow an optical function with a spot size of 400 μm at 1.55-μm wavelength.

In order to achieve a good attenuator, we have chosen a cell with more than π phase shifting. A 17-μm cell thickness is prepared. Preliminarily, this cell has been characterized

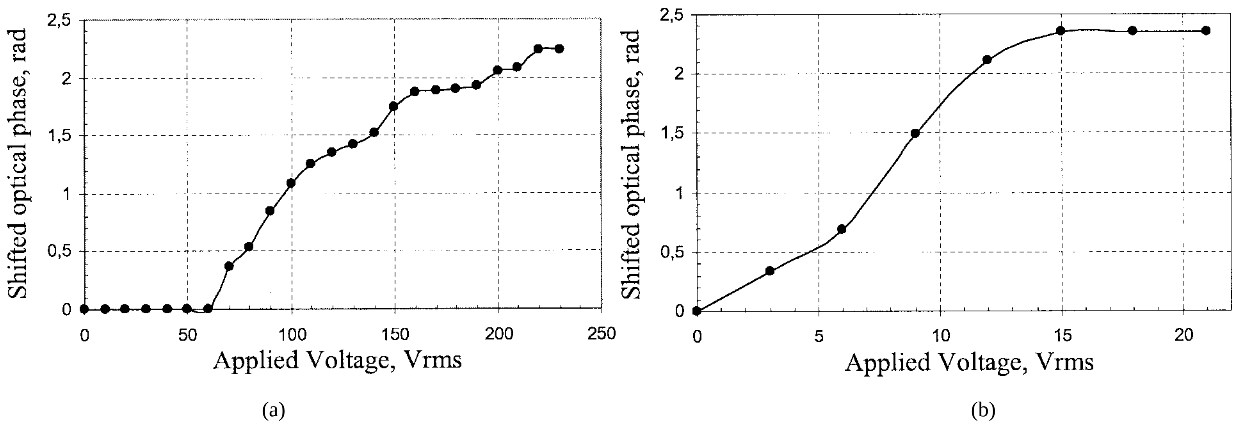


Fig. 3. Optical phase variation for (a) nano-PDLC and (b) micro-PDLC, 15-μm cells.

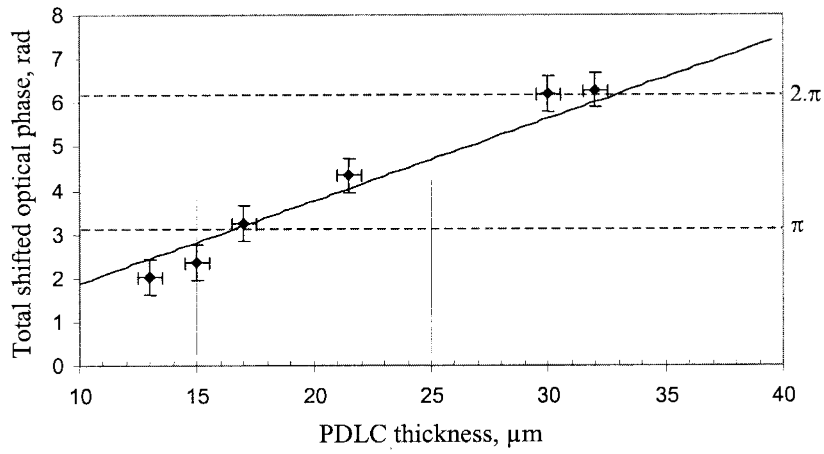


Fig. 4. Total optical phase variation for micro-PDLC versus cell thickness. Solid line and dots represent theoretical and measured results, respectively.

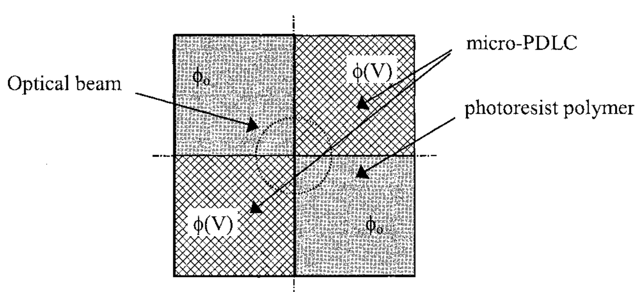


Fig. 5. Structure of the active optical area.

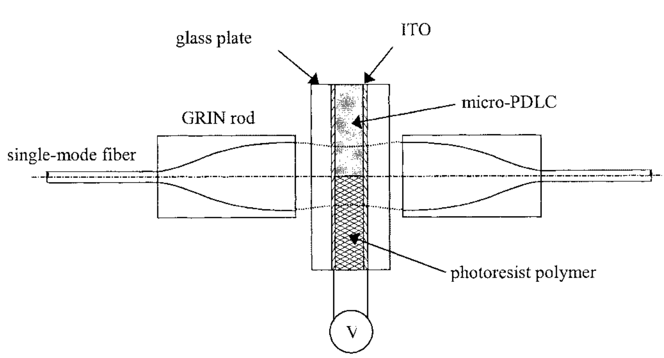


Fig. 6. The VOA component between Selfocs.

by measuring the electrooptical characteristics in a uniform micro-PDLC area. We have obtained a scattering attenuation range of 3.2 dB, a 0.04-dB maximum PDL, and 3.25-rad phase shifting at 18 Vrms.

Then, we have characterized the VOA by aligning the optical beam in the phase shift area. Experimental optical attenuation, PDL, and insertion loss of the VOA is reported in detail in Fig. 8. The alignment of the optical beam in the center of the pattern and the adjusting voltage during alignment must be chosen to optimize these optical characteristics. Fig. 9(a) shows a device with a 400-μm collimated beam diameter with a 15.8-dB range of attenuation, a maximum of 0.8-dB PDL, and a 1.5-dB insertion loss. This same device with an appropriate alignment has 12- dB range of attenuation, a maximum of 0.5-dB PDL, and a 1.1-dB insertion loss [see Fig. 9(b)]. This result shows that the intensity repartition in the four areas of phase shifting is critical on the angular and lateral alignments between the optical beam and the cell. The level of attenuation and PDL is a function of the quality of the phase repartition. Another device has been done with a 2-mm collimated beam diameter. Fig. 9(c) shows the experimental results: 10.5-dB range of attenuation, a maximum of 0.3-dB PDL, and a 1.8-dB insertion loss. The saturation voltage of these devices is around 18 Vrms, equivalent to the saturation voltage of the phase phenomena. The larger beam size decreases

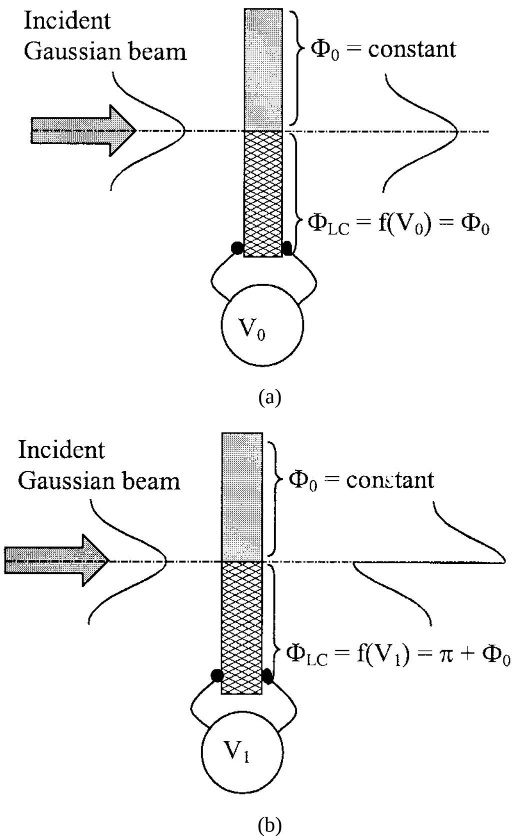


Fig. 7. Schematic view of the attenuation function. (a) Transparent state and (b) attenuation state.

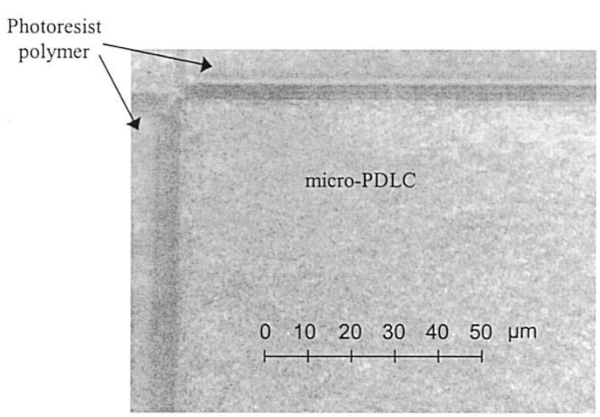


Fig. 8. Polarizing microscopic photograph of the cell.

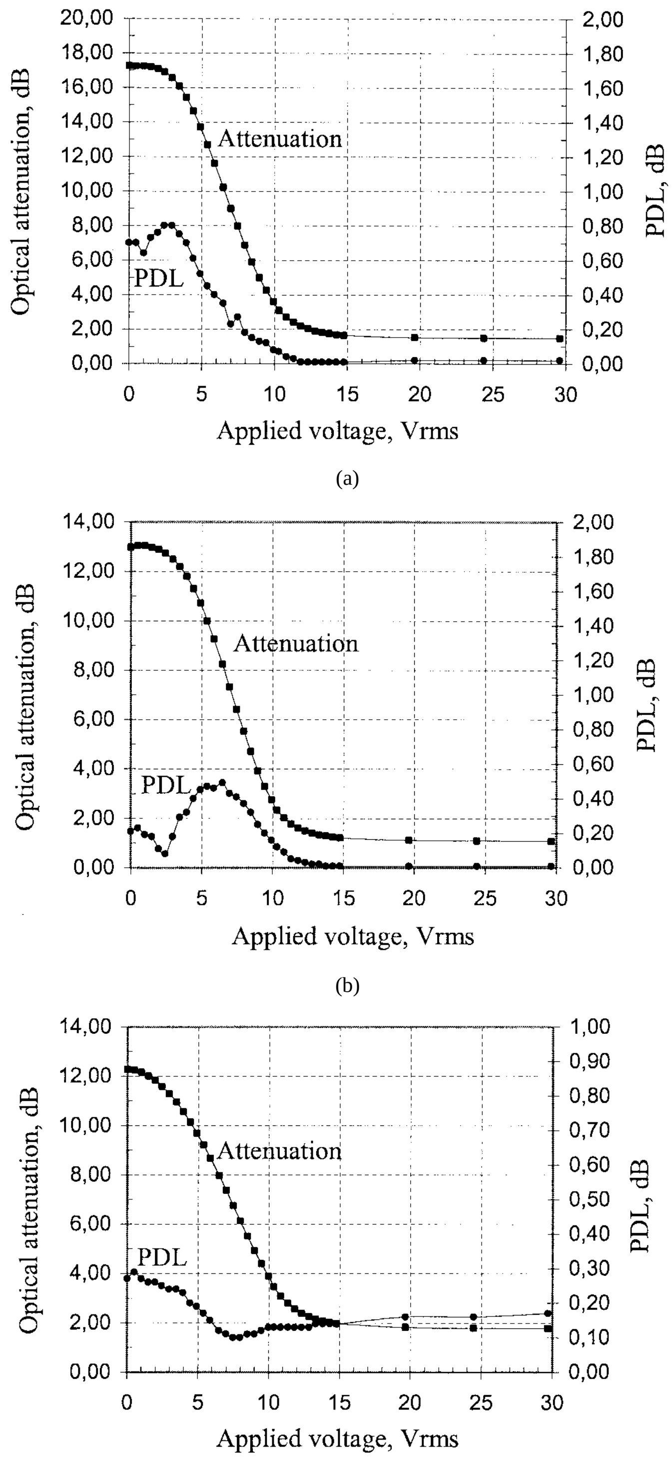


Fig. 9. Experimental optical attenuation and PDL versus voltage for collimated spot size diameter of (a) and (b) 400 μm and (c) 2 mm.

the PDL because more droplets are crossed by the beam, so the average PDL decreases.

The photoresist polymer index is chosen to be equal to the index of the micro-PDLC: $\bar{n}_{\mathrm{On}}$. In this condition, the scattering and phase-shifted phenomena can be associated to limit the insertion loss of the device and to improve the attenuation range. The originality of this VOA is that the phase-shift architecture allows reaching a low insertion loss ($\approx$1 dB) even though the level of the initial scattering attenuation is rather high ($\approx$ 2 dB). Moreover, the fabrication of the VOA is easy; there is no ITO ectching for the electrodes. With this architecture, we can perform an inverted VOA that is transparent without voltage. We just have to use a photopolymer exhibiting the same phase as the micro-PDL without voltage, for a 17-μm thickness. If there is no photopolymer layer to achieve a phase pattern in the micro-PDLC cell, the attenuation range and PDL are similar to those shown in Fig. 1(b). The design of the photopolymer and micro-PDLC phase pattern must be optimized to achieve high performance of attenuation.

VI. Conclusion

In conclusion, we have demonstrated the functionality of a VOA based on phased shift micro-PDLC. Simulation and experiments give similar results for phase shifting with micro-PDLC. A π phase shift is obtained for a 17-μm cell thickness and a low saturation voltage of 18 Vrms (≈ 1 V/μm). The residual scattering attenuation of this mixture is around 2 dB. The optical architecture of the proposed VOA prevents the drawback of the scattering on the insertion loss. The phase-shifting VOA uses a pattern of photoresist polymer to generate active area and static ones in order to modulate the phase shift. An attenuation range of 12 dB, 0.5-dB PDL, and 1.1-dB insertion loss with a saturation voltage of 20 Vrms are trends of the commercial VOA.

Acknowledgment

The authors wish to express their gratitude to L. Dupont from GET-ENST Bretagne, P. Gauthier from Optogone, and the CCLO team of GIS Photon (ENSSAT and GET-ENST Bretagne).

References

[1] K. Hirabayaschi, M. Wada, and C. Amano, "Compact optical-fiber variable attenuator arrays with polymer-network liquid crystals," *Appl. Opt.*, vol. 40, no. 21, pp. 3509–3517, July 2001.

[2] H. Ramanitra, P. Chanclou, B. Vinouze, and L. Dupont, "Compact optical variable optical attenuator using liquid christal dispersed in polylmer," *Electron. Lett.*, vol. 38, no. 19, pp. 1122–1123, 2002.

[3] S. Matsumoto, Y. Sugiyama, S. Sakata, and T. Hayashi, "Light processing and optical devices using nano-sized droplets of liquid crystal dispersed in polymer," *J. Intell. Mater. Syst. Struct.*, vol. 10, pp. 489–492, June 1999.

[4] S. Matsumoto, M. Houlbert, T. Hayashi, and K.-I. Kubodera, "Nano-sized fine droplets of liquid crystals for optical application," in *Materials Research Society Symp. Proc.*, vol. 457, 1997, pp. 89–92.

[5] S. Matsumoto, K. Hirabayashi, S. Sakata, and T. Hauyashgi, "Tunable wavelength filter using nano-sized droplets of liquid crystal," *IEEE Photon. Technol. Lett.*, vol. 11, no. 4, pp. 442–444, 1999.

[6] C. S. I. Wong, J.-Y. Liu, and K. M. Johnson, "Liquid crystal fiber phase modulator," in *OFC'92 Tech. Dig.*, WL12, pp. 173–174.

[7] P. J. Collings and M. Hird, *Introduction to Liquid Cristals*. New York: Taylor and Francis, 1997.

[8] D. Bosc, M. Guilbert, C. Trubert, and B. Vinouze, "Improvements in fabrication conditions of liquid crystal-polymer composite cells," *Molec. Cryst. Liq. Cryst.*, vol. 287, pp. 83–92, 1996.

[9] S.-T. Wu, U. Efron, and L. D. Hess, "Birefrengence measurement of liquid crystals," *Appl. Opt.*, vol. 23, no. 21, pp. 3911–3915, Nov. 1984.

P. Chanclou, photograph and biography not available at the time of publication.

B. Vinouze, photograph and biography not available at the time of publication.

M. Roy, photograph and biography not available at the time of publication.

C. Cornu, photograph and biography not available at the time of publication.

H. Ramanitra, photograph and biography not available at the time of publication.