Proposal and Analysis of an Ultrashort Directional-Coupler Polarization Splitter with an NLC Coupling Layer

Kuen-Cherng Lin, Wei-Ching Chuang, and Wei-Yu Lee

Abstract— **We propose a novel and high-performance directional-coupler polarization splitter using nematic liquid crystal (NLC) as the coupling layer. The beam propagation method is used to investigate the propagation characteristics of the device under various conditions. Results of the numerical calculation relevant to the design conditions are presented. Because of the large birefringence of NLC, a very short device length of 140 μm is achievable at a high extinction ratio of 28 dB.**

I. INTRODUCTION

IN the optical fiber communication, TE/TM polarization splitters are essential components of the polarization diversity receiver in the coherent detection system [1]. Various types of optical polarization splitters have been reported in literature [2]–[14]. As for the guided-wave version, these devices can be classified into two categories: the Y-branched waveguide type [2]-[7], which relies on the mode sorting effect, and the directional-coupler type [8]–[14], which utilizes the polarization-dependent coupling effect to separate the TE and TM waves. Essentially, the former has both a large scattering loss at the branching point and a long device length. On the other hand, the latter has received particular attention in recent times [10]–[14] due to its high extinction ratio and low insertion loss. A disadvantage of such a kind of polarization splitter, however, is that a long coupler length (>3 mm, typically) is required. It can be overcome by introducing a material with a large polarization-dependent refractive index. For this reason, most of the polarization splitting devices were made with highly birefringent materials such as $LiNbO_3$ and III–V semiconductor compounds [2], [4], [7], [10]–[12], [14]. However, the technologies for fabricating polarization splitters in such materials are complex. Consequently, there still exists no compact polarization splitter that is simultaneously characterized by a high extinction ratio (>25 dB), a short device length (<0.5 mm), and an easy fabrication technology.

Recently, liquid crystal materials have been used successfully in the application of optical guided-wave devices [15]–[20], including optical switches [17], [20], stabilizers [18] and modulators [15], due to the large birefringence and electro-optic coefficients inherent in various kinds of liquid crystals. In this paper, we propose a novel directional-coupler polarization splitter which consists of two identical glass waveguides separated by a nematic liquid crystal (NLC) layer. It is expected to be easily produced by the well developed fabrication technologies for the ion-exchanged glass waveguide and the liquid crystal display (LCD). The beam propagation method (BPM) is used to investigate characteristics of the device including coupler length, extinction ratio, and throughput loss. The simulation results show that a device length as short as 140 μm is achievable at a high extinction ratio of 28 dB.

This paper is organized as follows. In Section II, we discuss the operating principle of the directional-coupler polarization splitter in terms of the normal modes of the structure and describe the characteristics of the NLC for application in the device. The finite-difference BPM is outlined in Section III. The numerical results for various device parameters are also presented and discussed in the same section. Finally, we conclude the results of this study in Section IV.

II. DEVICE CONCEPT

Fig. 1(a) shows schematically the proposed directional coupler structure with polarization splitting characteristics. The device consists of two slab waveguides which are deposited upon two glass plates by ion exchange. An intermediate NLC layer separates the upper guide from the lower one. In this configuration, only the TE polarization experiences power transfer between the two waveguides, while the TM polarization passes straight through the original waveguide. The splitting operation is achieved by virtue of a large polarization-dependent refractive index of the NLC layer.

For compatibility with single-mode fiber systems, the waveguides are assumed to be mono-mode and the wavelength $\lambda = 1.55\,\mu$m. The directional coupler supports two normal modes for each polarization, namely, two even and two odd TE and TM modes. These modes, with different phase velocities, interfere with each other as they propagate along the waveguide, causing the energy to transfer back and forth between the two waveguides. A directional coupler transfers power from one guide to the other in a coupling length $L_c = \pi/\Delta\beta$, where $\Delta\beta = \beta_{\rm even} - \beta_{\rm odd}$ is the difference

Manuscript received April 11, 1996; revised July 30, 1996. This work was supported by the National Science Council of the Republic of China under the Contracts NSC85-2615-E036-002 and NSC85-2612-E150-002.

K.-C. Lin and W.-Y. Lee are with the Department of Electrical Engineering, Tatung Institute of Technology, Taipei, Taiwan, R.O.C.

W.-C. Chuang is with the Department of Electro-Optic, National Yunlin Polytechnic Institution, Taiwan, R.O.C.

Publisher Item Identifier S 0733-8724(96)08730-0.

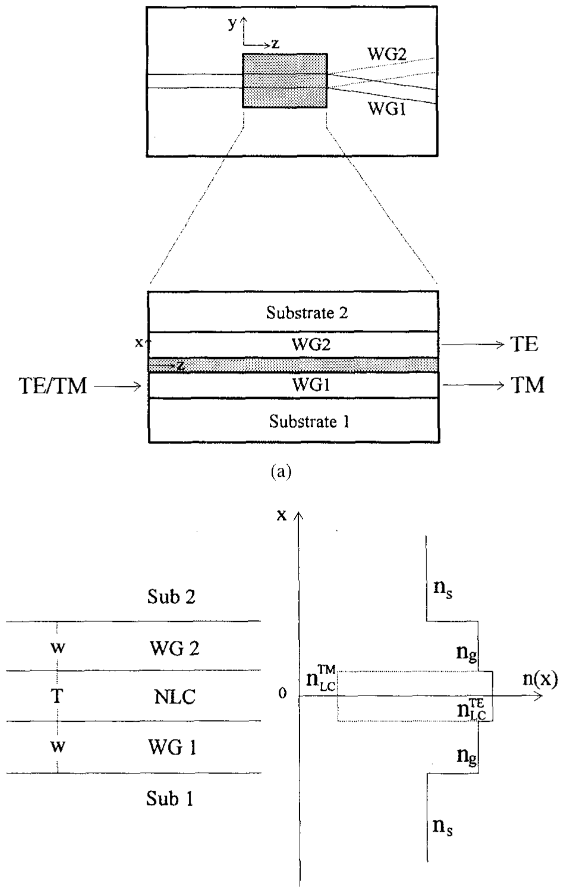


Fig. 1. (a) The schematic diagram ofthe proposed directional-coupler polarization splitter, which is composed of a pair of glass waveguides with an intermediate layer of nematic liquid crystal: the upper plot shows the top view of the whole device, while the lower one is the cross-section view in the coupling region. (b) The corresponding refractive index profile in the coupling region.

between the propagation constants of the two normal modes. The expression is well known in the coupled-mode theory [21]. For the crossover state operation, the device length L_d is an odd multiple of L_c; but for the straight-through state operation, L_d is an even multiple of L_c. In the polarization splitting directional coupler, it is supposed that the TE mode operates in the crossover state and the TM mode in the straight-through state; hence,

$$L_d^{\mathrm{TE}} = (2m-1)\pi/\Delta\beta_{\mathrm{TE}} \tag{1}$$

and

$$L_d^{\mathrm{TM}} = 2n\pi/\Delta\beta_{\mathrm{TM}} \tag{2}$$

where $\Delta\beta_{\mathrm{TE}}$ and $\Delta\beta_{\mathrm{TM}}$ are propagation-constant differences between the even and odd normal modes for TE and TM polarizations, respectively, and both m and n positive numbers.

For the design of a polarization splitter, it is required that, by launching both TE and TM polarizations at the same input port, the device is capable of separating the two polarizations at different output ports. Combining the criteria (1) and (2) for the two polarizations, a minimum device length can be derived as

$$L_d = \pi/(\Delta\beta_{\mathrm{TE}} - \Delta\beta_{\mathrm{TM}}). \tag{3}$$

From the above equation, in order to achieve a minimum device length, we can design a structure that maximizes the difference between $\Delta\beta_{\mathrm{TE}}$ and $\Delta\beta_{\mathrm{TM}}$.

The device behaviors are significantly affected by the ordering state of the liquid crystal molecules, which can be controlled by rubbing the waveguide surface or applying an electric field. In the case of positive dielectric anisotropy NLC ($\Delta\varepsilon > 0$), if the molecular axis is aligned along the direction parallel to the waveguide surface and has a pretilted angle θ to the light propagation, as shown in Fig. 2(a), then the TE and TM modes experience the indexes [22]

$$n_{\mathrm{LC}}^{\mathrm{TE}} = \frac{n_o \cdot n_e}{\sqrt{n_e^2 \sin^2\theta + n_o^2 \cos^2\theta}} \tag{4a}$$

and

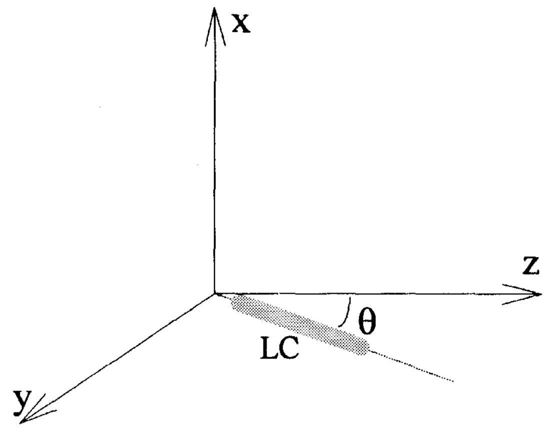
$$n_{\mathrm{LC}}^{\mathrm{TM}} = n_o, \tag{4b}$$

respectively, where n_o and n_e are the ordinary and extraordinary refractive indexes of the NLC, respectively. Fig. 2(b) illustrates the $n_{\mathrm{LC}}^{\mathrm{TE}}$ and $n_{\mathrm{LC}}^{\mathrm{TM}}$ as a function of the pretilted angle θ. Around $\theta = 90°$ the difference between $n_{\mathrm{LC}}^{\mathrm{TE}}$ and $n_{\mathrm{LC}}^{\mathrm{TM}}$ reaches the maximum and $n_{\mathrm{LC}}^{\mathrm{TE}}$ is almost independent of the values of θ. This range is more preferable in the process of rubbing, because small variations of $n_{\mathrm{LC}}^{\mathrm{TE}}$ have little influence on the device performance.

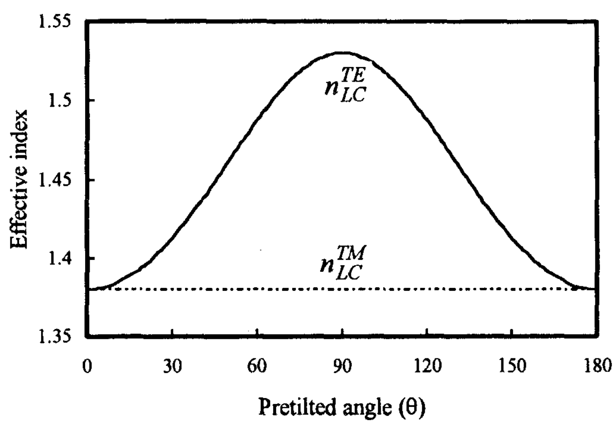
The corresponding refractive index profiles of the proposed directional coupler are shown in Fig. 1(b). Because $n_{\mathrm{LC}}^{\mathrm{TE}}$ is larger than the refractive index of the waveguides n_g ($n_{\mathrm{LC}}^{\mathrm{TE}} > n_g > n_s$), the TE mode is expected to experience strong coupling between two waveguides. However, the coupling effect can be neglected for the TM mode since $n_{\mathrm{LC}}^{\mathrm{TE}}$ is much smaller than n_g ($n_g > n_s \gg n_{\mathrm{LC}}^{\mathrm{TM}}$). Thus, the presence of the NLC layer brings about a very large difference in the $\Delta\beta$'s of both polarizations, i.e., $\Delta\beta_{\mathrm{TE}} \gg \Delta\beta_{\mathrm{TM}}$. Now if the coupler length is chosen to be the coupling length of the TE mode, we would have the TM mode in the original waveguide and the TE mode in the other waveguide.

Fabrication of the proposed device can be implemented by following the procedure as described in [17], [19], [23]. The process includes ion-exchanging glass substrates (to form the waveguides), rubbing the substrate surface (to perform the LC molecular alignment), spacing and sealing the two substrates (to build the LC cell), and injecting the LC into the cell. The thickness w and refractive index n_g of the two waveguides can be well controlled by timing the ion-exchange process [24], while the NLC layer thickness is controlled by the spacer (diameters of 2, 3, 4, 6, and 8 μm are commercially available). The particular fabrication method used to fabricate LC integrated-optics devices makes the vertically multilayered structure and, thus, high-density integration possible.

The performance of the polarization splitter is characterized by the extinction ratio, which is defined as the ratio of the optical power of the unwanted polarization state to the total



(a)



(b)

Fig. 2. (a) The oriention state of NLC, assuming that the molecular axis is aligned along the direction parallel to the waveguide surface and with a pretilted angle θ to the light propagation. (b) The effective indexes seen by the TM and TE modes as a function of the pretilted angle θ: the solid and dotted lines correspond to the $n_{\rm LC}^{\rm TE}$ and $n_{\rm LC}^{\rm TM}$, respectively.

optical power in the output waveguides

$$\mathrm{ER_{TE}} = -10 \cdot \log\left(\frac{P_1^{\rm TE}}{P_1^{\rm TE} + P_1^{\rm TM}}\right) \tag{5a}$$

$$\mathrm{ER_{TM}} = -10 \cdot \log\left(\frac{P_2^{\rm TE}}{P_2^{\rm TE} + P_2^{\rm TM}}\right) \tag{5b}$$

where $P_1^{\rm TE}$ denotes the fractional power of the TE polarization in waveguide 1 at $z = L_d$, and similar definitions are also applicable to the $P_2^{\rm TE}, P_1^{\rm TM}$, and $P_2^{\rm TM}$. Moreover, the excess loss of the device can be defined as

$$\mathrm{EL_{TE}} = -10 \cdot \log\left(\frac{P_2^{\rm TE}}{P_i^{\rm TE}}\right) \tag{5c}$$

$$\mathrm{EL_{TM}} = -10 \cdot \log\left(\frac{P_1^{\rm TM}}{P_i^{\rm TM}}\right) \tag{5d}$$

where $P_i^{\rm TE}$ and $P_i^{\rm TM}$ are the input power of the TE and TM modes, respectively.

III. Analysis

A. Numerical Method

In the proposed structure as shown in Fig. 1, the large refractive index of the intermediate layer ($n_{\rm LC}^{\rm TE} > n_g > n_s$) is predicted to build up a strong coupling effect. However, the conventional coupled mode theory fails to work for such a structure. In order to solve the problem, we use the beam propagation method (BPM) to calculate the propagation characteristics of the polarization splitting directional coupler. The BPM has been studied extensively and has proven to be a powerful tool in analyzing optical guided-wave components. For the sake of simplicity, weekly guiding and weakly polarization-coupling conditions are assumed in our case; thus, the vectorial wave equation can be reduced to the scalar equation without loss of its generality. The FD-BPM, as proposed by Chung and Dagli [25], is employed in our calculations and outlined as follows. Assuming that the waves propagate in the z-direction and under the paraxial limit, we get the paraxial wave equation

$$2jkn_0\frac{\partial\psi}{\partial z} = \frac{\partial^2\psi}{\partial x^2} + k^2\{n^2(x,z) - n_0^2\}\psi \tag{6}$$

where ψ denotes E_y for the TE wave and H_y for the TM wave. The optical field ψ is characterized by the free-apace wave number $k = 2\pi/\lambda$ in a medium with a refractive index distribution $n(x,z)$. In FD–BPM, the finite difference approximation yields

$$\begin{aligned} &-a\cdot\psi_{i-1}(z+\delta z) + b\cdot\psi_i(z+\delta z) - a\cdot\psi_{i+1}(z+\delta z) \\ &\quad = a\cdot\psi_{i-1}(z) + b\cdot\psi_i(z) - a\cdot\psi_{i+1}(z) \end{aligned} \tag{7}$$

where

$$a = \frac{\delta z}{2\delta x^2} \tag{8a}$$

$$b = \frac{\delta z}{\delta x^2} - \frac{\delta z}{2}k^2\left[n_i^2(z+\delta z) - n_0^2\right] + 2jkn_0 \tag{8b}$$

$$c = -\frac{\delta z}{\delta x^2} + \frac{\delta z}{2}k^2\left[n_i^2(z) - n_0^2\right] + 2jkn_0 \tag{8c}$$

δx denotes the spacing between sampling points transverse to the propagation direction, and δz denotes the size of each propagation step. This tridiagonal system of linear equations can be solved by the simple matrix operations.

Using the method described above, we can calculate the characteristics of waveguide devices with different refractive indexes, geometry, and polarization-dependence. Our aim is to determine the coupler length, extinction ratio, and throughput loss of the polarization splitter. In our calculation, δx is 0.2λ, δz is 0.3λ, and the initial field excited at the input port of waveguide 1 is assumed to be the fundamental mode of the waveguide structure: $n_{\rm LC} = n_s = 1.512, n_g = 1.526$, and $w = 3.52$ μm.

B. Simulation Results

To show the applicability of the concept of the polarization splitter, we carried out numerical calculations for the directional-coupler configuration (see Fig. 1), which was made

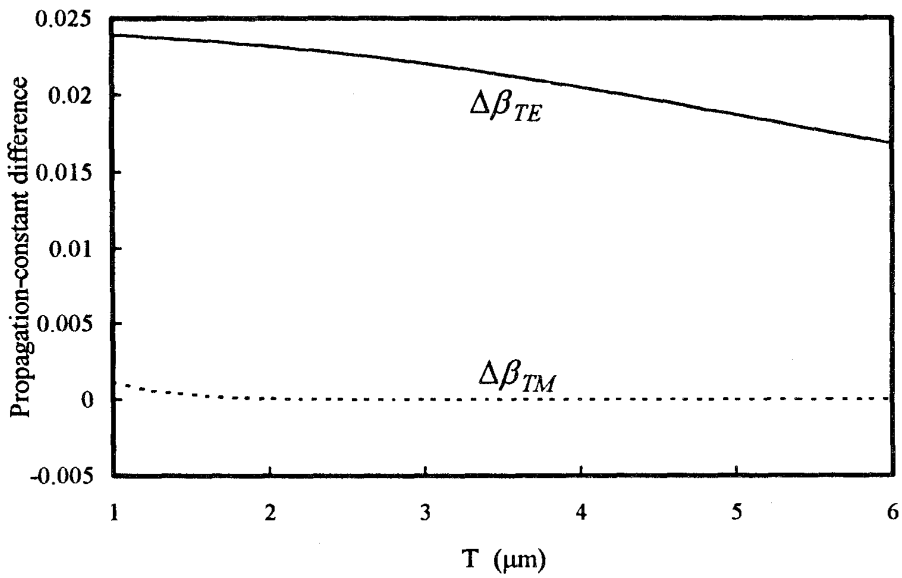


Fig. 3. The dependence of propagation-constant differences between the two normal modes on T: the solid and dotted linescorrespond to the $\Delta\beta_{\rm TE}$ and $\Delta\beta_{\rm TM}$, respectively. The waveguide parameters are $n_{\rm LC}^{\rm TE} = 1.530$, $n_{\rm LC}^{\rm TM} = 1.380$, $n_g = 1.526$, $n_s = 1.512$, and $w = 3.52$ μm.

of a pair of glass waveguides with an intermediate layer of nematic liquid crystal (NLC GR-3B, CHISSO, $n_o = 1.38$ and $n_e = 1.53$). Our purpose was to use these numerical results to design the device and optimize its performance. We computed the propagation constants of the even and odd normal modes of the structure for both the TE and TM polarizations as a function of the thickness T of the NLC layer. The dependence of propagation-constant differences, $\Delta\beta_{\rm TE}$ and $\Delta\beta_{\rm TM}$, between the two normal modes on T is shown in Fig. 3. The waveguide parameters are $n_{\rm LC}^{\rm TE} = 1.530, n_{\rm LC}^{\rm TM} = 1.380, n_g = 1.526, n_s = 1.512$, and $w = 3.52$ μm. As T increases, both $\Delta\beta_{\rm TE}$ and $\Delta\beta_{\rm TM}$ decrease, and thus the coupling strength wanes. It is observable that $\Delta\beta_{\rm TM}$ is smaller than $\Delta\beta_{\rm TE}$ by two orders of magnitude for $T > 1.6$ μm, yet by three orders for $T > 2.6$ μm. In the proposed configuration, the polarization splitting operation is based on the polarization-dependence of coupling length, which is one of the important considerations in designing a directional-coupler device. From (3), the device length of the polarization splitting directional coupler can thus be approximated by $L_d = \pi/\Delta\beta_{\rm TE}$ for $T \geq 2$ μm. As a consequence, L_d depends on the thickness T and the index $n_{\rm LC}^{\rm TE}$ of the NLC layer as well as the thickness w and the index n_g of the waveguide layer. Below we illustrate the dependence of L_d on the waveguide parameters by fixing the values of w and n_g.

The first factor which determines L_d is the index $n_{\rm LC}^{\rm TE}$ of the NLC layer. Fig. 4 shows the calculated device length as a function of $n_{\rm LC}^{\rm TE}$ for various NLC layer thickness, assuming that $n_g = 1.526$ and $w = 3.52$ μm. An increase of $n_{\rm LC}^{\rm TE}$ from 1.510 to 1.530 will reduce the required device length from 4700 to 170 μm for $T = 5$ μm and from 600 to 140 μm for $T = 2$ μm. L_d also depends on the NLC layer thickness T and the refractive index n_g of the waveguides. Assuming again that $w = 3.52$ μm and choosing $n_{\rm LC}^{\rm TE}$ to be 1.530, we illustrate the influence of T on the device length L_d calculated for $n_g = 1.524$ and 1.526 in Fig. 5. In contrast to the influence of $n_{\rm LC}^{\rm TE}$, the NLC layer thickness can reduce the device length by decreasing the value of T. Note that there are significant variations in L_d with the change in the value of $n_{\rm LC}^{\rm TE}$ and T. The reason for the above-mentioned phenomenon is that as a larger fraction of the modal field distribution is extended into the NLC coupling layer, a stronger coupling can be obtained.

TABLE I
THE TRANSMISSION CHARACTERISTICS OF THE DIRECTIONAL-COUPLER POLARIZATION SPLITTER FOR DIFFERENT NLC THICKNESS T. THE DATA ARE CALCULATED FOR THE WAVEGUIDE PARAMETERS: $n_{\rm LC}^{\rm TE} = 1.530, n_{\rm LC}^{\rm TM} = 1.38, n_s = 1.512, n_g = 1.526$, AND $w = 3.52\,\mu$m

Sample Number	$n_{\rm LC}^{\rm TE}$	Coupler length (μm)	Transmission (dB) TE (WG 1)	TE (WG 2)	TM (WG 1)	TM (WG2)
1	1.506	703.5	24.10	0.09	0.26	27.59
2	1.512	483.0	21.75	0.04	0.17	26.83
3	1.518	311.6	23.12	0.13	0.08	25.03
4	1.524	188.6	11.67	0.87	0.18	25.47
5	1.530	139.3	30.31	0.21	0.03	27.61

Propagation characteristics of the polarization splitter are calculated by the BPM, which gives a unified treatment of guided and radiation modes of a waveguide structure. The effects of radiation, which is present at the input and the geometrical variations, can degrade the extinction ratio significantly [26]. The BPM calculation includes the effects, which are not included in the coupled-mode analysis. In our characteristic analysis, the output power of the mode fields was evaluated by the fractional power confined in the WG1 and WG2 regions [see Fig. 1(b)]. It is reasonable due to the proportional relations of the field power in the characteristic parameters as defined in (5a)–(5d). Calculation results for different NLC thickness T are listed and compared in Table I. The data are calculated for the waveguide parameters: $n_{\rm LC}^{\rm TE} =$

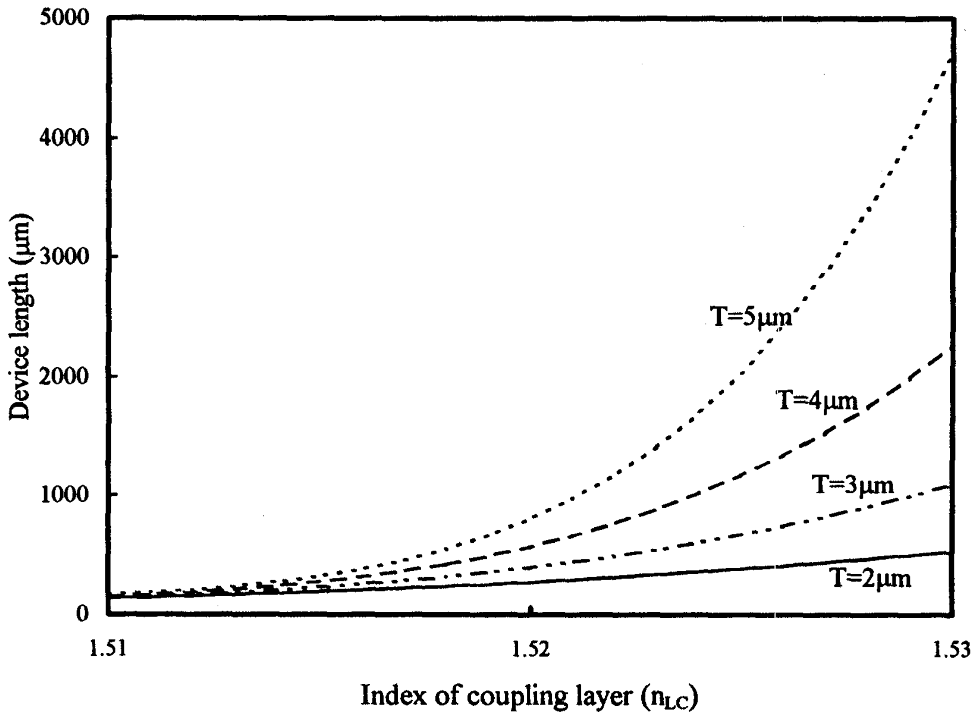


Fig. 4. The calculated device length as a function of $n_{\mathrm{LC}}^{\mathrm{TE}}$ for various NLC layer thickness T. Assume that $n_g = 1.526$ and $w = 3.52$ μm.

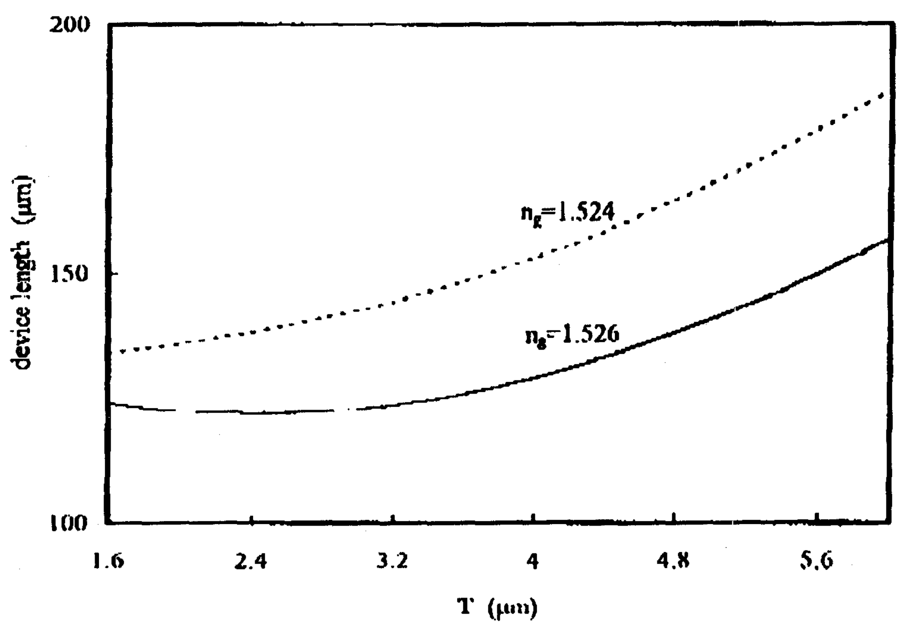


Fig. 5. The influence of T on the device length L_d, calculated for $n_g = 1.524$ (dotted line) and 1.526 (solid line) with $w = 3.52\,\mu$m and $n_{\mathrm{LC}}^{\mathrm{TE}} = 1.530$.

$1.530, n_{\mathrm{LC}}^{\mathrm{TM}} = 1.38, n_s = 1.512, n_g = 1.526$, and $w = 3.52$ μm. An unpolarized light is launched into waveguide 1. Note that although the L_d is minimum in the case of $T = 1$ μm, the extinction ratios are lower than 20 dB. From the point of view of the device application, a high extinction ratio is necessary for a polarization splitter to be utilized in the optical coherent communication. Therefore, the case of $T = 2$ μm is preferable. Furthermore, Table II tabulates the transmission characteristics of the coupler for different $n_{\mathrm{LC}}^{\mathrm{TE}}$. As indicated in the table, the maximum extinction ratios $\mathrm{ER}_{\mathrm{TE}} = 29$ dB and $\mathrm{ER}_{\mathrm{TM}} = 28$ dB, and the shortest device length, $L_d = 140$ μm, can be obtained simultaneously in the case of $n_{\mathrm{LC}}^{\mathrm{TE}} = 1.530$. Under the circumstances, the excess losses for TE and TM modes are 0.2 and 0.06 dB, respectively.

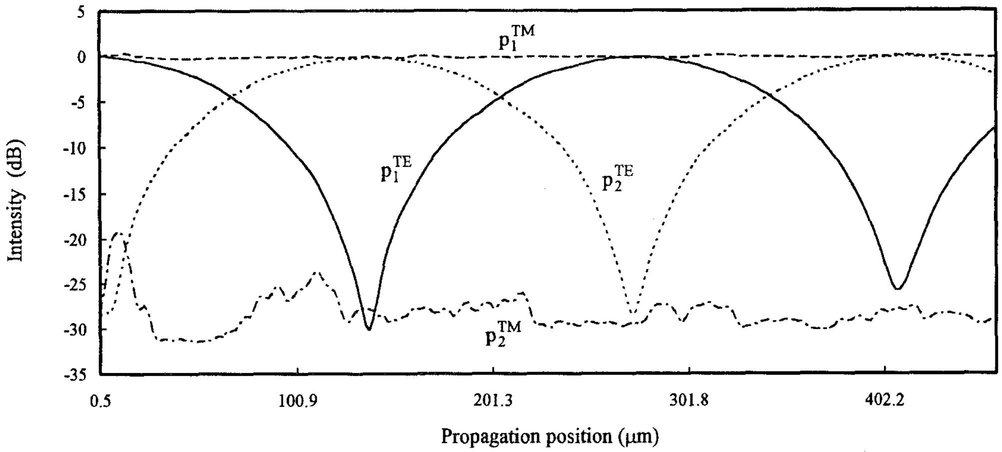


Fig. 6. Propagating behaviors of this polarization-splitting coupler. The solid, dotted, dot-dashed, dashed lines, respectively, correspond to power evolution of the P_1^{TE}, P_2^{TE}, P_1^{TM}, and P_2^{TM} along the directional coupler.

TABLE II
THE TRANSMISSION CHARACTERISTICS OF THE DEVICE FOR DIFFERENT $n_{\mathrm{LC}}^{\mathrm{TE}}$. THE DATA ARE CALCULATED FOR THE SAME WAVEGUIDE PARAMETERS AS USED IN TABLE I

Sample Number	T (μm)	Coupler length (μm)	Transmission (dB)			
			TE (WG 1)	TE (WG 2)	TM (WG 1)	TM (WG2)
1	1	129.7	14.67	0.40	0.35	16.74
2	2	139.5	29.39	0.21	0.06	28.02
3	3	150.2	21.86	0.37	0.56	28.50
4	4	159.0	20.13	0.40	0.26	29.02
5	5	168.8	23.11	0.38	0.26	35.51

From the above calculations, the case of $T = 2$ μm and $n_{\mathrm{LC}}^{\mathrm{TE}} = 1.530$ appears to be the optimum parameters for the polarization splitting directional coupler with the other waveguide parameters $n_g = 1.526, n_s = 1.512$, and $w = 3.52$ μm. Propagating behavior of this polarization-splitting device was simulated and is shown in Fig. 6. The solid, dotted, dot-dashed, dashed lines represent the power evolution of the $P_1^{\mathrm{TE}}, P_2^{\mathrm{TE}}, P_1^{\mathrm{TM}}$, and P_2^{TM} along the directional coupler, respectively. The TE mode moves back and forth between the two waveguides, while the TM one passes straight in the original waveguide. It is observable that a device length as short as 140 μm is possible. To our knowledge, this is the shortest device length among all kinds of polarization splitters reported so far. Furthermore, the field evolution along the directional coupler is illustrated in Fig. 7. The incident TM mode emerges from waveguide 1, while the TE mode from waveguide 2. The small perturbation in the field evolution as shown in Fig. 7(b) is inferred from the abrupt change of boundary conditions at the interface between the input access waveguide region and the coupler region. Accordingly, the expected operation of a polarization splitter is achieved with high extinction (>28 dB). Although the overall device may be bulky due to the use of the NLC layer, the vertically multi-layer structure still offers the possibility of high-density integration.

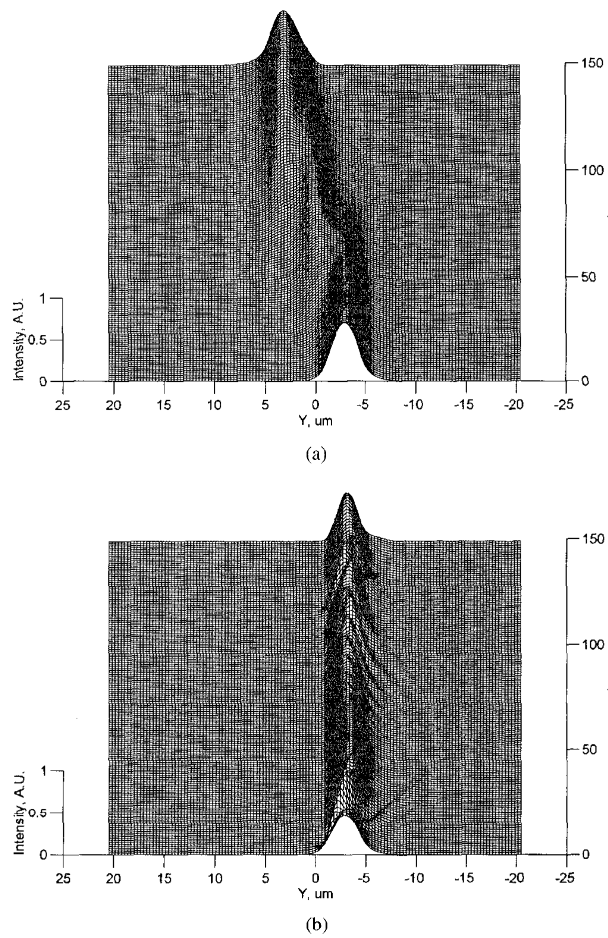


Fig. 7. The BPM simulated field evolution along the directional coupler of (a) TE mode and (b) TM mode.

IV. CONCLUSION

We have proposed a novel and high-performance polarization splitter by virtue of the large birefringence of the nematic liquid crystal. By using the beam propagation method, characteristics of the polarization splitter were analyzed. Results of numerical calculation predicted polarization splitting behaviors with a device length as short as 140 μm and extinction ratios of 29 dB and 28 dB for the TE and TM modes, respectively.

Due to the well-developed fabrication technologies of the ion-exchanged glass waveguide and the liquid crystal display (LCD), our proposed directional-coupler polarization splitter can be implemented in the near future.

ACKNOWLEDGMENT

The authors would like to thank H. H. Lin for his valuable editorial assistance.

REFERENCES

[1] F. Ghirardi, A. Bruno, B. Mersali, L. Giraudet, A. Scavennec, and A. Carenco, "Monolithic integration of and InP based polarization diversity heterodyne photoreceiver with electrooptic adjustability," *IEEE J. Lightwave Technol.*, vol. 13, pp. 1536–1549, 1995.

[2] N. Goto and G. L. Yip, "A TE-TM mode splitter in $LiNbO_3$ by proton exchange and Ti diffusion," *J. Lightwave Technol.*, vol. 7, pp. 1567-1573, Oct. 1989.

[3] Y. Shani, C. H. Henry, R. C. Kistler, R. F. Kazarinov, and K. J. Orlowsky, "Integrated optic adiabatic polarization splitter on silicon," *Appl. Phys. Lett.*, vol. 56, no. 2, pp. 120–121, 1990.

[4] J. J. M. van der Tol and J. H. Laarhuis, "A polarization splitter on $LiNbO_3$ using only Titanium diffusion," *J. Lightwave Technol.*, vol. 9, pp. 879–886, July 1991.

[5] T. Mizumoto, N. Iwakiri, T. Kaneko, and Y. Naito, "Analytical and experimental study of waveguide optical polarization splitter with Langmuir-Blodgett cladding layer," *J. Lightwave Technol.*, vol. 10, pp. 1807–1813, Dec. 1992.

[6] R. M. de Ridder, A. F. M. Sander, A. Driessen, and J. H. J. Fiuitman, "An integrated optical adiabatic TE/TM mode splitter on silicon," *J. Lightwave Technol.*, vol. 11, pp. 1806–1810, Nov. 1993.

[7] P. K. Wei and W. S. Wang, "A TE-TM mode splitter on lithium niobate using Ti, Ni, and MgO diffusion," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 245–248, Feb. 1994.

[8] M. Kobayashi, H. Terui, and K. Egashira, "A optical waveguide TE-TM mode splitter," *Appl. Phys. Lett.*, vol. 32, no. 5, pp. 300–302, 1978.

[9] K. Thyagarajan, S. Diggavi, and A. K. Ghatak, "Design and analysis of a novel polarization splitting directional coupler," *Electron. Lett.*, vol. 24, no. 14, pp. 869–870, 1988.

[10] P. Albrecht, M. Hamacher, H. Heidrich, D. Hoffmann, H. P. Nolting, and C. M. Weinert, "TE/TM mode splitters on InGaAsP/InP," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 114–115, Feb. 1990.

[11] C. Edge, R. J. Duthie, and M. J. Wale, "Passive integrated optical polarization mode-splitter in lithium niobate employing a resonent metal-loaded structure," *Electron. Lett.*, vol. 26, no. 22, pp. 1855–1856, 1990.

[12] F. Ghirardi, J. Brandon, M. Carre, A. Bruno, L. Menigaux, and A. Carenco, "Polarization splitter based on modal birefringence in InP/InGaAsP optical waveguides," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1047–1049, 1993.

[13] A. N. Miliou, R. Srivastava, and R. V. Ramaswamy, "A 1.3 μm directional coupler polarization splitter by ion exchange," *J. Lightwave Technol.*, vol. 11, pp. 220–225, Feb. 1993.

[14] H. Maruyama, M. Haruna, and H. Nishihara, "TE-TM mode splitter using directional coupling between heterogeneous waveguides in $LiNbO_3$," *J. Lightwave Technol.*, vol. 13, pp. 1550–1554, July 1995.

[15] D. J. Channin, "Optical waveguide modulation using liquid crystal," *Appl. Phys. Lett.*, Vol. 22, pp. 365–366, 1973.

[16] J. R. Whinnery, C. Hu, and Y. S. Kwon, "Liquid crystal waveguides for integrated optics," *IEEE J. Quantum Electron.*, vol. 13, pp. 262–267, 1977.

[17] Y. Okamura, K. Kitatani, and S. Yamamoto, "Low-voltage driving in nematic liquid crystal overlayered waveguide," *J. Lightwave Technol.*, vol. 4, pp. 360–363, 1986.

[18] S. Muto, T. Nagata, K. Asai, H. Ashizawa, and K. Arii, "Optical stabilizer and directional coupler switch using polymer thin film waveguides with liquid crystal clad," *Japan. J. Appl. Phys.*, vol. 29, pp. 1724–1726, 1990.

[19] M. Ozaki, Y. Sadohara, Y. Uchiyama, M. Utsumi, and K. Yoshino, "Linear optical switching in a FLC/waveguide composite device," *Liquid Crystals*, vol. 14, pp. 381–387, 1993.

[20] W. Y. Lee, J. S. Lin, and S. Y. Wang, "A novel $\Delta\kappa$ directional coupler switch using liquid crystal," *J. Lightwave Technol.*, vol. 13, pp. 49–54, 1995.

[21] D. L. Lee, *Electromagnetic Principles of Integrated Optics*. New York: Wiley, 1986, pp. 209–243.

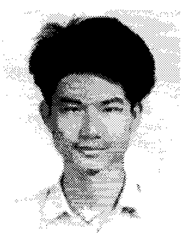
[22] A. Yariv and P. Yeh, *Optical Waves in Crystals*. New York: Wiley, 1984, pp. 266–270.

[23] J. S. Lin, "Investigation of the characteristics of liquid crystal integrated-optical devices," Ph.D. dissertation, Tatung Inst. Technol., Taipei, Taiwan, June 1995, ch. 3.

[24] R. V. Ramaswamy and R. Srivastava, "Ion-exchanged glass waveguides: A review," *J. Lightwave Technol.*, vol. 6, pp. 984–1002, 1988.

[25] Y. Chung and N. Dagli, "A assessment of finite difference beam propagation method," *IEEE J. Quantum Electron.*, vol. 26, pp. 1335–1339, 1990.

[26] J. P. Donnelly, H. A. Haus, and L. A. Molter, "Cross power and crosstalk in waveguide couplers," *J. Lightwave Technol.*, vol. 6, pp. 257–268, 1995.

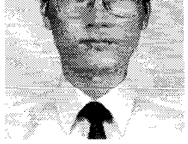


Kuen-Cherng Lin was born in Taipei, Taiwan, R.O.C., on July 28, 1970. He received the B.S. and M.S. degrees in electrical engineering from the Tatung Institute of Technology, Taipei in 1992 and 1994, respectively. He is currently pursuing the Ph.D. degree in electrical engineering at the same institute.

His current research interests include the guided-wave optics and the application of liquid crystals in optics.

Wei-Ching Chuang was born in Taipei, Taiwan, R.O.C., on February 25, 1963. He received the B.S. degree from the Tatung Institute of Technology, Taipei in 1987 and the M.S. and Ph.D. degrees in electrical engineering from the National Taiwan University in 1989 and 1992, respectively.

From 1992 to 1994, he served as a Communication Officer in the Chinese Army. Since 1994, he has been with the Department of Electro-Optic, National Yunlin Polytech Institution as an Associate Professor. His research interests include fiber optics and integrated optics.



Wei-Yu Lee was born in Taipei, Taiwan, R.O.C., on February 22, 1957. He received the B.S. degree in electrical engineering from the Tatung Institute of Technology, Taipei in 1979 and the M.S. and Ph.D. degrees in electrical engineering from the National Taiwan University in 1983 and 1988, respectively.

From 1983 to 1988, he served as a Teaching Assistant in the Department of Electrical Engineering, National Taiwan University. Since 1988, he has been with the Department of Electrical Engineering, Tatung Institute of Technology as a Professor. His research interests include semiconductor device and integrated optics.