A Novel Vertical $\Delta\kappa$ Directional Coupler Switch Using Liquid Crystals

Wei Yu Lee, Jin Shin Lin, and Sung Yuen Wang

***Abstract*—To decrease the switching length of the directional coupler switch and to use the advantages of the electro-optic properties of (LC's), we propose a novel vertical $\Delta\kappa$ directional coupler switch using LC's and present the calculated results relevant to the design considerations. Because of the large birefringence of LC's, a very short switching length less than 60 μm is possible. Besides, a $N \times N$ switch is also proposed for practical applications.**

I. Introduction

THE FUNCTIONAL integrated optical device has attracted considerable attention from practical points of view such as data processing and communication. One of the fundamentally necessary components is an electro-optic directional coupler, which is able to selectively switch the waveguide path of the light. In conventional directional couplers, power switching is achieved by introducing a phase mismatch ($\Delta\beta$) between the optical fields in two waveguides [1]. Most ones are made of inorganic materials such as GaAs and $LiNbO_3$. Utilization of the electro-optic effect in these switches poses difficulties because of the small electro-optic coefficient in these materials and high-power consumption, along with rather long interaction lengths, all of these conditions are undesirable in a practical system [2]. Either of these constraints results in high switching energy. Instead, the switching operation may be achieved by changing the coupling strength between the coupled waveguides. Recently, a $\Delta\kappa$ vertical directional couplers based on the multiple quantum well (MQW) have been demonstrated in semiconductor structures [3]–[4]. Since the separation between the waveguides can be much better controlled in the vertical direction, the coupling coefficient will be designed more accurately. In particular, a much larger κ can be obtained, with a corresponding reduction in the coupling lengths from several mm to 150 μm [5]. However, MQW devices must be fabricated by molecular-beam epitaxy or metalorganic chemical vapor deposition (MOCVD) [4]. Therefore, a long-time period of fabrication and expensive processes are required. Liquid crystals (LC's) are highly birefringent and thus coupling effect is much stronger than that of inorganic materials. So, some devices using electro-optic switching in polymer waveguides with LC's clad has been proposed recently [6]–[8]. However, their switching length are several mm and the long-term reliability is still in question since all the polymer waveguides of these device are partially exposed in the air [4].

Manuscript received April 4, 1994; revised September 13, 1994.
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IEEE Log Number 9407209.

In this paper, a novel vertical $\Delta\kappa$ directional coupler switch using liquid crystal is proposed. The F fact based on the beam propagation method, which is proved to be available for different distribution of refractive index in the switch, is used to estimate the coupling length and some design considerations such as switching length, switching time, integration have been calculated and discussed. It is important that a very short switching length about 60 μm or less can be achieved by the large birefringence of LC's in coupling region. Because of the advantages of pixel electrodes, small size, easy integration, and simple fabrication of the novel switches, it is expected to be easily produced by the highly developed fabrication techniques of liquid crystal displays (LCD's) and to be integrated on a small chip to work as a $N \times N$ switch for applications in a multi-channel syetem.

II. Proposed Directional Coupler Switch

Generally, a directional coupler transfers power from one guide to another in a coupling length $L_d = \pi/2\kappa$, where κ is the coupling coefficient. Being unbiased, the bar state operation is established and the device length (L_d) is

$$L_d = \frac{m\pi}{\kappa} \qquad m = 1, 2, 3 \ldots \tag{1}$$

As some biased voltage is applied, the coupling coefficient (κ) increases to κ' and the crossover state is operated. So, L_d must also satisfy that

$$L_d = \left(m + \frac{1}{2}\right)\frac{\pi}{\kappa'} \qquad m = 0, 1, 2 \ldots \tag{2}$$

Combining the criteria for bar and crossover states, a minimum device length relating to the change of coupling coefficient can be derived as

$$L_d = \frac{\pi}{2(\kappa' - \kappa)} \tag{3}$$

From the above expression, it is clear that the minimum device length can be achieved by designing a structure that maximizes the change of coupling coefficient. So the optimization of the design focuses on increasing κ' and decreasing κ, which must rely on the large refractive index change of LC's.

Fig. 1 shows the device configuration we proposed here. It consists of two normal waveguides fabricated on two substrates respectively, a pair of electrode deposited on the two waveguides, and a thin LC's layer separating the two

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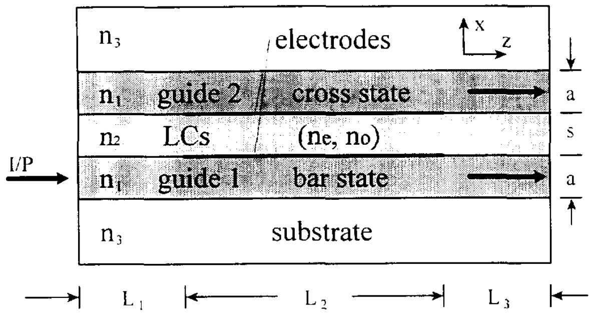

Fig. 1. The device configuration we proposed is shown here. It consists of two normal waveguides fabricated on two substrates respectively, a pair of electrode on the two waveguides, and a thin LC's layer separating the two guides.

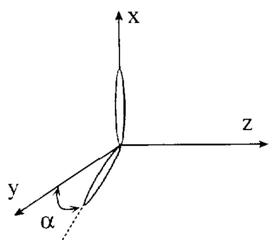

Fig. 2. Two states of NLC's are illustrated. One is molecular parallel to the guiding layer surface but with a pretilted angle α to the y axis; another is molecular normal to the surface and parallel to the x axis.

guides. Hence, the electric field can be applied entirely to the L_2 region in the LC's layer. In our design, L_1 and L_3, which are weakly coupling regions, work as a separator to degrade cross-talk and to increase extinction ratio and L_2, a active region, selects the bar state or crossover state.

In the case of no voltage applied, n_2 in the region becomes no and L_2 is also a weak coupling region (bar state); as a external voltage is applied, n_2 in L_2 region changes to ne and L_2 is switched to be a strong coupling region (crossover state).

The larger index of the coupling layer at bias is expected to yield strong coupling coefficient because of large κ'. The electro-optic effect of LC's is much effective because its refractive index change is orders of magnitude larger than that of the electro-optic solid material [10]. So a very small κ and a large κ' may achieved ($\kappa \ll \kappa'$). Consequently, a very small size directional coupler switch can be obtained.

III. Calculation and Analysis

Optical integrated circuits such as modulators or switches require that they would be embedded in laterally limited waveguides. Restriction in the lateral width of waveguides will introduce lateral modes, propagation loss, and dispersion. However, the slab waveguide approximation is simpler for calculation and analysis. As a consequence, the slab waveguide approximation has been generally used for an initial optimization of the dimensions and refractive indices. It remains to complete the evaluation of the laterally limited single mode waveguide coupling, but the qualitatively similar results are obtained. In analysis of most waveguides, modes is always propagating along the waveguide with the highest refractive index layer in the device [11]–[13]. In this analysis, we assume a step-index profile of the two coupled identical waveguides. Indices relations are chosen so that $n_0 < n_3 < n_1 < n_e$, where n_0 and n_e are the ordinary and extraordinary refractive index of the LC's coupling layer, respectively, as indicated in Fig 1. The larger index (n_e') of coupling layer at bias state is expected to yield strong coupling coefficient. However, no analytic theory exists to describe the power transition between waveguides in such a structure where the refractive index of coupling layer (n_e) is larger than that of waveguides (n_1).

To simulate and calculate the optical power couples between waveguides along the directional coupler switch, we use the beam propagating method (BPM) [13], [14], which is very useful in integrated optics, since the field can be simply obtained along any complicated geometric structure without modal formalism [15]. To prevent spurious reflections from the boundaries of the sampling window, an absorber is used in our calculation. We also make use of the conditions of applicability of BPM derived in [13]; moreover, we looked for the propagation conditions where the optical field along the coupler is not depending on the propagation step to simulate and calculate the optical power couples between waveguides along the directional coupler switch, we use the beam propagating method (BPM) [13], [14], which is very useful in integrated optics, since the field can be simply obtained along any complicated geometric structure without modal formalism [15]. To prevent spurious reflections from the boundaries of the sampling window, an absorber is used in our calculation. We also make use of the conditions of applicability of BPM derived in [13]; moreover, we looked for the propagation conditions where the optical field along the coupler is not depending on the propagation step Δz. A value of $\Delta z = 1$ μm is taken in our simulation.

In order to observe and make use of the property, we define a fact F based on the BPM method to describe the power distribution on waveguides according to z.

$$F(z) = \frac{\int_x |\overline{E}_2(x,z)|^2 dx}{\int_x |\overline{E}_1(x,0)|^2 dx} \tag{5}$$

where $\overline{E}_1$ and $\overline{E}_2$ are the electric field of propagating modes. A value of $\Delta z = 1$ μm is taken in our simulation. In order to observe and make use of the property, we define a fact F based on the BPM method to describe the power distribution on waveguides according to z.

IV. Design Considerations

A. Coupling Length

The difference between the values of the refractive indices of the guide (n_1) and the coupling layer (n_2) affects the power distribution in both guides. Fig. 5 illustrates this influence of n_2 on the coupling length (L_2) in the crossover state for different coupling layer thicknesses (s). In the case of the LC directional coupler switch, a little increase of n_2 will cause a exponentially decrease of L_2, e.g., from 5 mm ($n_2 = 1.4531$) to 52 μm ($n_2 = 1.487$) for $s = 2$ μm at $\lambda = 0.6328$ μm.

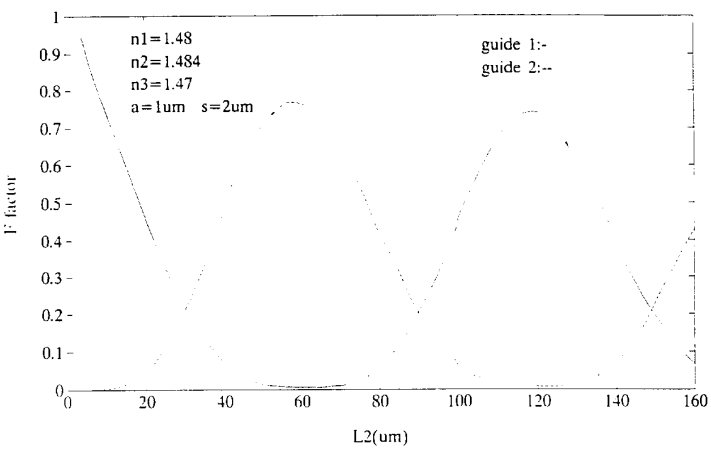

Fig. 3. At crossover state, the power exchange between waveguide 1 (solid line) and waveguide 2 (dash line) is shown as a function of propagation distance z along the coupler region L_2.

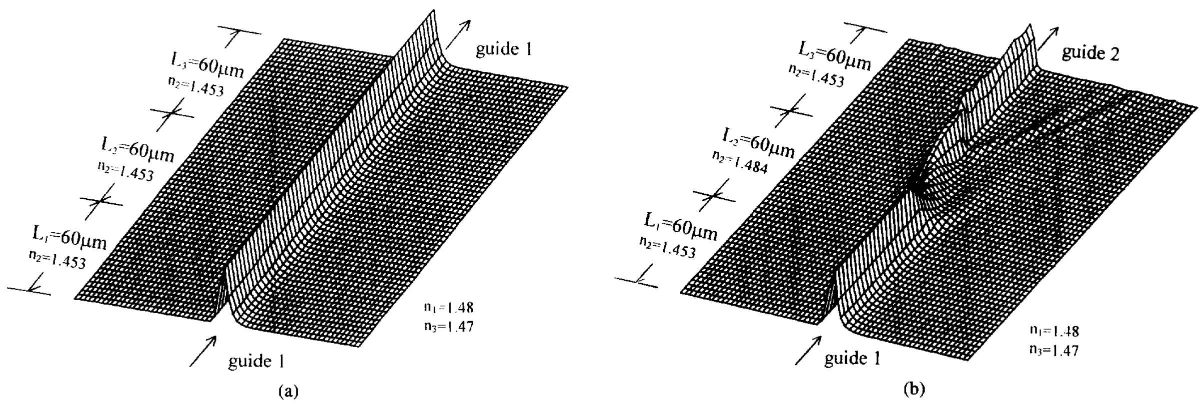

Fig. 4. (a) The bar state: power is confined in waveguide 1 and no coupling occurs; (b) The crossover state: power in waveguide 1 is coupled to another one, where $L_1 = L_2 = L_3 = 60$ μm.

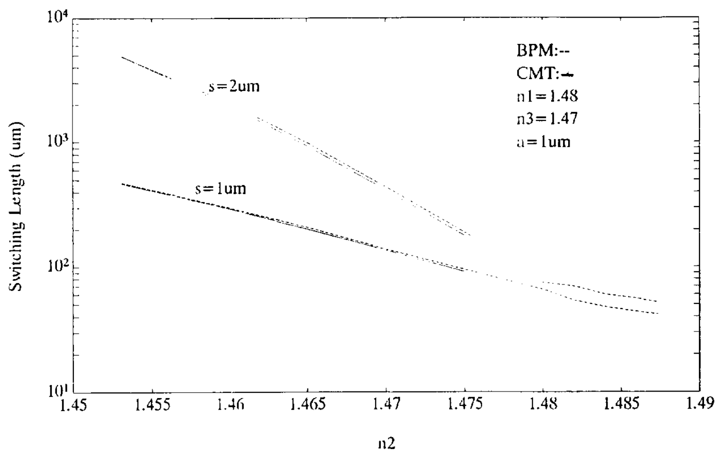

Fig. 5. The switching length as function of coupling layer thicknesses (s) for two widely used wavelength (0.6328 μm and 1.32 μm) is compared in the case of $n_1 = 1.48$, $n_2 = 1.484$, and $a = 2$ μm.

The coupling layer thicknesses (s) also enter the figures of merit by determining the length of the device. Narrowing the coupling layer thickness can either lower bias voltage or shorten the device length, as desired. However, it is worthy of noting that the influence of the coupling thickness (s) to the coupling length (L_2) depends on the difference between n_1 and

TABLE I
THE REFRACTIVE INDEX n_2 SEEN BY TE OR TM WAVE IN L_2 REGION AND THE STATES OF THE SWITCH FOR DIFFERENT CONDITIONS

	$\Delta\epsilon > 0$				$\Delta\epsilon < 0$			
	V=0	STATE	V=V′	STATE	V=0	STATE	V=V′	STATE
TE	$n_e{}'$	CROSS	n_0	BAR	n_0	BAR	$n_e{}'$	CROSS
TM	n_0	BAR	n_e	CROSS	n_e	CROSS	n_0	BAR

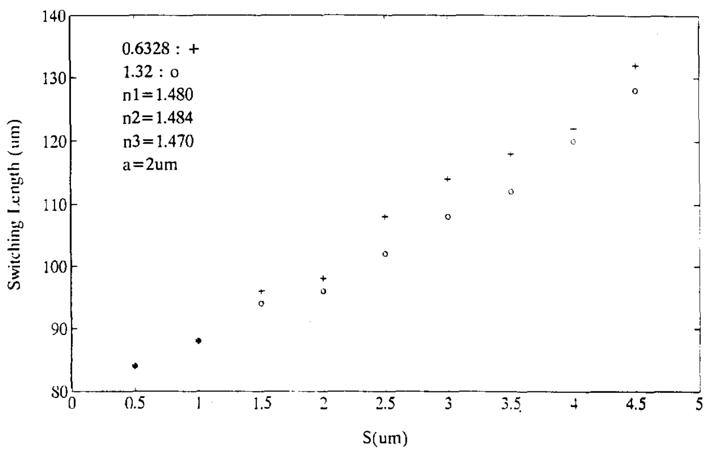

Fig. 6. Capacitance of the switch as function of the coupling layer thicknesses (s) is calculated for the two states.

n_2. For larger difference, the coupling length of $s = 2$ μm is found to exceed by two order of magnitude that of $s = 1$ μm; while, there is little difference of L_2 when n_2 is closer to n_1, shown in Fig. 4.

Another important parameter considered is the operating wavelength (λ). Two widely used wavelength (0.6328 μm and 1.32 μm) in fiber communication is compared in the case of $n_1 = 1.48$, $n_2 = 1.484$, and $a = 2$ μm, shown in Fig. 5. The influence of the operation wavelength on L_2 is also not obvious when s is smaller than 1 μm. Smaller wavelength (0.6328 μm) results in larger L_2 because it supports smaller propagation constants in the same waveguide structure.

In Table I, the calculated figures of merit for the conventional directional coupler switches are listed. Comparing with other type directional couplers [2], [4], [21], the switching length of the novel device we proposed is shorter. Because the large birefringence of LC's in coupling layer yields better coupling effect than the other inorganic material do.

B. Switching Time

Generally, there will be three kinds of delay time of the LC directional coupler switch for design considerations. First one is the LC's response time. Since the orientation of LC's requires displacement or rotation of the organic molecules which have viscous forces, representing interactions with neighboring molecules, the response time is typically milliseconds [6], [22], [23]. Second one is the transfer time of light through the device. The transfer time of a single mode light is estimated to be about 29.6 ps in the case of $nl = 1.48$ and $L_2 = 60$ μm. Third one is the RC time constant. The device length could be minimized, leading to a decrease of the switch capacitance and an increase of the RC-limited operating frequency. The capacitance of the switch depends on the structure of LC cell. The electrodes in our design can be regarded as a pixel in a LCD panel. Recently, we have analyzed the capacitance of a pixel by the discrete Fourier transform (DFT) method [24], [25]. Capacitance of the switch as function of coupling layer thicknesses (s) is calculated for two states (cross and bar states), illustrated in Fig. 6. The square area of electrode is 60×60 μm^2 and an infinitely thin electrode is assumed. The capacitance of the crossover state is little larger than that of the bar state because the dielectric constant of LC in the former is larger than that in the latter. Thicker the coupling layer is, smaller the capacitance of both states will be. The capacitance exponentially decreases as the coupling layer thickness increases. The switch ($L_1 = L_2 = L_3 = 60$ μm, $s = 2$ μm) is estimated to have a capacitance of 190 pF and RC-limited switching time (with $R = 50$ ω) of 9.5 ns.

It is clear that the most serious delay time mainly arises from the inherently slow response of LC's, which is much larger than others listed in Table I. It limits the applications of LC's to the high-speed-modulators in integrated optics. However, the high extinction ratio (44 dB) of the switch we proposed could potentially satisfy the requirements of a low cross-talk device and operated as a path-selection switch, which not requires very high switching speed.

C. Integration

To guide and control optical signals in a plan, channel waveguides will be required from practical points of view. However, the coplanar structure utilizing only one layer to include optical devices is difficult and will not satisfy the requirements such as high density, small size, and low cost for optical integrated circuits. So, extending components vertically

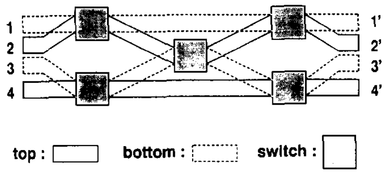

Fig. 7. Fig. 7 shows the top view of a 4 × 4 switch we proposed.

on a device has been studied to increase the density and achieve high performance of integrated optical devices in the future [4]–[6].

Fig. 7 shows the top view of a 4 × 4 switch we proposed. It is organized by five 2 × 2 switches consisting of two channel waveguides (bottom and top). The pattern defining the waveguides can be symmetrically fabricated on the top and bottom substrate at one time. It is worthy noting that the waveguide pattern on top or button substrates are the same so only one mask is required in the fabrication process. The coupling layer thickness of the LC directional coupler switch can be extremely well controlled by spacers, which have been widely used in LCD's. Since the fabrication process of LCD's has been highly developed, the concept can be easily extended to a $N \times N$ switching array. Besides, all the waveguides are bond in a cell so the vibration from the environments can be degraded largely.

The F-fact based on BPM As an example, we have simulated a vertical directional coupler switch of dimensions $s = 2$ μm and $a = 1$ μm, and of index profile $n_1 = 1.48$ and $n_3 = 1.47$ at $\lambda = 0.6328$ μm. Consider the nematic liquid crystals (NLC's, 14627 BDH Ltd., $n_e = 1.4874$ and $n_0 = 1.4531$), which is allowed the construction of active overlayer devices on common waveguides [16], is chosen as the coupling layer and the propagation loss in the layer is assumed to be −28 dB/cm [17], [18]. Since the NLC's possess a negative anisotropy of susceptibility, the molecules tend to align themselves perpendicular to the electric field. The normal alignment of NLC's to the substrate is assumed. If the pretilted angle is the effective refractive index n_e' seen by the TE wave can be estimated by [19]. We give only the analysis for TE modes because a similar analysis can be adopted for TM mode. The lowest mode corresponding to the waveguide boundary conditions, is launched into waveguide 1. Here $n_e' = 1.484$ and infinitely thin electrodes are assumed. At crossover state, the power exchanges between waveguide 1 (solid line) and waveguide 2 (dash line) as a function of propagation distance z along the coupler region L_2, as shown in Fig. 2. We note that a switching length as short as 60 μm is possible. To our knowledge, it is the shortest switching length in all kinds of optical directional couplers [2], [4]. Furthermore, the power exchanges in the novel directional coupler switch with $L_1 = L_2 = L_3 = 60$ μm is simulated, shown in Fig. 3(a) and Fig. 3(b) respectively. At zero bias, power is confined in waveguide 1 and no coupling occurs through the whole device (the bar state); while some bias applied, power in waveguide 1 is coupled to another one (the crossover state). In the example, the extinction ratios of waveguides at the output is as high as 44.14 dB (the crossover state) and 56.77 dB (the bar state). The smaller value of ratio at the crossover state is due to the radiation loss increasing when the mode in waveguide 1 crosses the coupling layer to waveguide 2 at L_2 region.

D. Comparing Conventionally

The coupling phenomena between waveguides is analyzed by the couple-mode theory [1], [20], which is based on the perturbation of the refractive index in an electro-optical waveguide by an applied voltage. Recently, some vertical directional couplers, which is based on the change of refractive index in coupling layer, has been proposed. A theoretical analysis of distributive coupling along dielectric waveguides is presented and often resolved by finding elementary solutions to Maxwell's equations specified by the geometry of the system. The result is an eigen-equation from which the propagation constants can be numerically computed as roots of this equation [2]–[5]. However, the root of eigen-equation fails to be extracted if the index of coupling layer is close to or larger than that of adjacent waveguides. There have been very few reports referring to solve the problem, although the coupling phenomena still occurs in the structure. The F-fact based on the BPM method is useful to solve the problem. It is that the coupling coefficient and length can be solved by finding the z position where the local maximum of the F fact along waveguide 2 appears. Comparing with the mode method [3], our method is suitable for various refractive index distribution of a device, although numerical integration of F using a step-by-step propagation through a model device requires a larger computation. Besides, the power exchange between waveguides is observable and scattering or radiation loss are also included for every step in our simulation. It is helpful for us to realize the device practical performance in detail. Fig. 5 illustrates the switching length (L_2) as function of refractive index of coupling layer (n_2) calculated for different guide separation ($s = 1$ and $s = 2$ μm) by the two method. The numerical results are very similar. But the mode method is out of use when n_2 is near or larger than n_1 (continues).

V. Conclusion

To improve the long switching length of conventional directional coupler switch and to use the advantages of the electro-optic properties of LC's, we propose a novel vertical $\Delta\kappa$ directional coupler switch using LC's and presented the calculated results relevant to the design considerations. A integration F fact based on the BPM method is used to analyzed the power coupling between waveguides for various conditions. Some characteristics of the switch such as switching length, switching time, capacitance, and integration are discussed in detail and compared with that of other switches. Because of the large birefringence of LC's, a very short switching length less than 60 μm is possible. To our knowledge, it is the shortest switching length in all kinds of optical directional couplers. Besides, the switching region defined by the electrode pair of the switch is designed as the pixel of a LCD panel, which is easy to be produced by the highly developed techniques in LCD's. For the present level of technical competence in integrated optics and LCD's, it is possible that a large number of these elements can be fabricated together to constitute a $N \times N$ high density switch for practical application.

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