Design of an Electro-Optic Directional Coupler with Four Sections Poled in Four perpendicular Directions

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Abstract

Directional couplers with four sections poled in four perpendicular directions are proposed for the first time as a new electro-optic switch configuration in which complete conversion of both TE and TM light from one waveguide to the other can be achieved simultaneously by a low driving voltage adjustment. The perpendicularly poled sections of the switch make the device completely polarization-independent, and the inversely poled sections offer an extremely relaxed fabrication tolerance for the device. This configuration of each section poled in a different direction also makes it possible to drive the electro-optic coupler with a uniform electrode, which ensures high-speed operation of the device. Both the switching characteristics and the fabrication tolerance are simulated.

1. Introduction

High-speed electro-optic (EO) switches based on waveguide directional couplers are expected to play an important role in the fields of optical communication, optical interconnection, and optical neural networks. There are two main problems that limit the applications of conventional EO switches, one is strict fabrication tolerance, i.e., a switch must be fabricated exactly at the designed length to ensure a high extinction ratio; another is polarization-dependency, namely, the two polarization states of the signal light cannot be switched simultaneously with a high extinction ratio[1-9]. Switches with multiple sections of alternating Δβ have shown a completely relaxed fabrication tolerance, but are still polarization dependent[10]. By applying different driving voltages to each section, TE and TM modes have been switched simultaneously with -20dB crosstalk[11-13], but the multiple driving sources prevent the switch from having precise phase matching of the microwave and the optical signals, and hence prevent the device from operating at very high speeds. And besides the fabrication complexity of the multiple electrodes, the crosstalk is still not small enough to meet the special military-applications requirement of -40dB or bellow.

In this paper, we propose a innovative configuration of an EO directional coupler. The configuration has four sections which are reversely poled along horizontal and vertical directions. This poling technique can be achieved by applying external electrical fields in corresponding directions on an EO polymeric waveguide under certain conditions[14-17]. Since the four sections of the coupler are perpendicularly poled, TE and TM modes of the optical signal will experience the same net EO effect . This offers the device an important property of being completely polarization independent. And since two sections are reversely poled along the horizontal direction and the other two sections are reversely poled along the vertical direction, the reversal of Δβ effect also provides for the device to have an extremely relaxed fabrication

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tolerance. And in addition, this configuration of multiple sections poled in different directions makes it possible that only a uniform driving electrode need be used and hence ensures the device will have high-speed operation.

Following the description of a conventional directional coupler in section II, we will see that directional couplers with reversed Δβ domains (section III) have a significantly relaxed fabrication tolerance, but are polarization dependent. While directional couplers with rotated Δβ domains (section IV) are polarization independent, they have no fabrication tolerance. The proposed four-section directional coupler with both rotated and reversed domains (section V) is not only polarization-independent but also has a significantly relaxed fabrication tolerance.

2. The conventional Directional Coupler

A conventional waveguide directional coupler is shown in Fig. 1. Waveguide core material of refractive index n_1 is surrounded by cladding material of refractive index n_2. Application of a driving voltage V to the uniform traveling-wave electrode will induce a phase mismatch between the propagation constants of the two waveguides, $\Delta\beta(V)=\beta_1-\beta_2$. With a proper coupling length, a certain driving voltage adjustment can switch the light from a cross state to a bar state, i.e., from completely cross over from one channel to another, to completely straight through along one channel. We describe the light along the two guides by complex amplitudes R(z) and S(z), which vary slowly along the propagation direction, or z axis in Fig. 1. The energy exchange between the two channels is governed by the coupled-wave equations[18,19]:

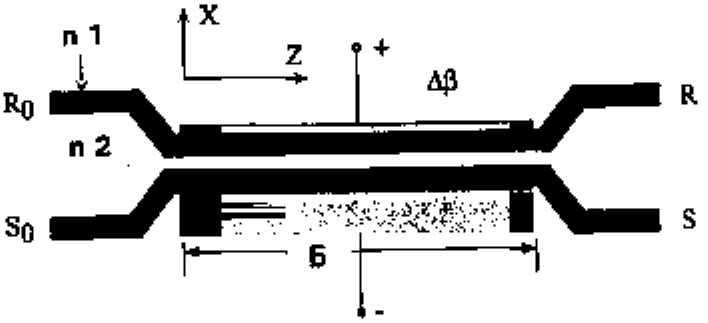

Fig. 1. The conventional directional coupler composed of two strip wave guides with an interaction length L. The electrodes are shown in the COBRA configuration.

$$\begin{cases}\dfrac{\partial R}{\partial z} = +j\delta R - j\kappa S \\ \dfrac{\partial S}{\partial z} = -j\delta S - j\kappa R\end{cases}, \qquad (1)$$

where $\delta=\Delta\beta/2$, and κ is the coupling coefficient determined by the waveguide material, waveguide structures, and waveguides relative position

$$\kappa = \frac{2k^2_{x1}k_{x2}e^{-k_{x2}S}}{\beta\omega(k^2_{x1}+k^2_{x2})}. \quad (2)$$

where ω is the channel width, S is the separation of the two channels. The quantities β and K_{x1} are the propagation constants in the z and x directions respectively, and K_{x2} is the evanescent coefficient in the x direction. All of them are given by

$$\begin{cases} \beta = k_0 n_{eff} \\ k_{x1} = (n_1^2 k_0^2 - \beta^2)^{\frac{1}{2}}, \\ k_{x2} = (\beta^2 - n_2^2 k_0^2)^{\frac{1}{2}} \end{cases} \quad (3)$$

where n_{eff} is the effective index of the mode supported by the waveguides, which can be calculated using Mactilli's method, the effective index method, or the beam propagation method[2,20-22]. The propagation constant mismatch Δβ is related to the applied driving voltage and the polarization of the light signal. In the configuration of Fig. 1, for TM modes, we have

$$\Delta\beta_{tm} = \frac{1}{2} k_0 n_1^3 \gamma_{33} \frac{V}{d}, \quad (4)$$

and for TE modes we have

$$\Delta\beta_{te} = \frac{1}{2} k_0 n_1^3 \gamma_{13} \frac{V}{d}, \quad (5).$$

where γ_{13} and γ_{33} are electro-optic coefficients, V is the applied voltage, and d is the separation of the electrodes.

For arbitrary input amplitudes R_0 and S_0, the solution of the coupled-wave Eqs. (1) can be written in matrix form as

$$\begin{pmatrix} R \\ S \end{pmatrix} = M^+ \begin{pmatrix} R_0 \\ S_0 \end{pmatrix}, \quad (6)$$

where

$$M^+ = \begin{pmatrix} A_1 & -jB_1 \\ -jB_1^* & A_1^* \end{pmatrix} \quad (7)$$

is the transfer matrix of the directional coupler with uniform +Δβ, and asterisks represent a complex conjugation. The matrix coefficients are

$$\begin{cases} A_1 = \cos(z\sqrt{\kappa^2+\delta^2}) + j\dfrac{\delta}{\sqrt{\kappa^2+\delta^2}}\sin(z\sqrt{\kappa^2+\delta^2}) \\ B_1 = \dfrac{\kappa}{\sqrt{\kappa^2+\delta^2}}\sin(z\sqrt{\kappa^2+\delta^2}) \end{cases}, \qquad (8)$$

where **z=L** is the device length.

The coupler is in the cross state when $\mathbf{A_1=0}$. As is well known, this requires that $\Delta\beta=0$, and **L/l=2n+1**, where $l=\pi/2\kappa$ is called conversion length, **n=0, 1, 2...** The coupler is in the bar state when $\mathbf{B_1=0}$, which occurs if

$$\left(\frac{L}{l}\right)^2 + \left(\frac{\Delta\beta L}{\pi}\right)^2 = (2n)^2. \qquad (9)$$

The conditions for the cross and bar states can be depicted in a switching diagram that uses the value of **L/l** and $\Delta\beta L/\pi$ as coordinates, as shown in Fig. 2.

We can see from Fig. 2 that because the EO coefficients of the waveguide material are different for TE and TM modes, under the same driving voltage, $\Delta\beta$ is also different for TE and TM modes. Thus for a coupler with a certain length, although TE and TM modes can have a common cross state, they cannot be switched to one common bar state simultaneously. In other words, this kind of directional coupler is polarization dependent. We can also see from Fig. 2 that, for a directional coupler with any length, the bar states can always be addressed by adjusting the driving voltage, or $\Delta\beta$, while, the cross states of the device require one to fabricate the coupler at some exact lengths. This leads to a strict fabrication condition that is difficult to implement in practice.

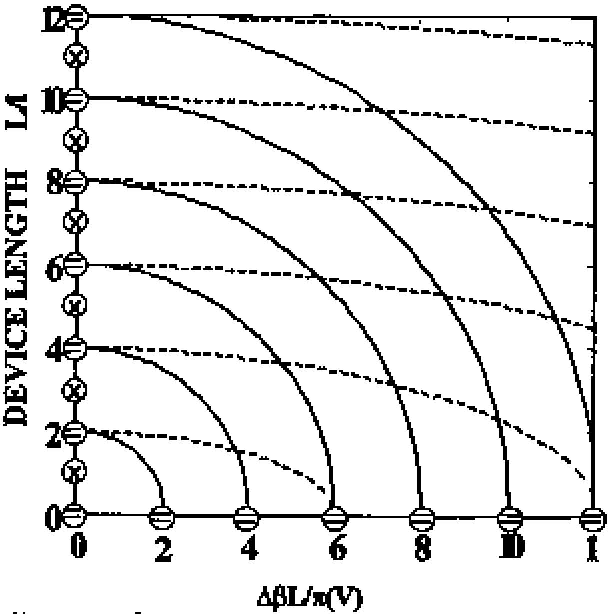

Fig. 2. Switch diagram of a conventional directional coupler. Solid and dashed lines are TM and TE modes respectively, where $\Delta\beta_{TE}/\Delta\beta_{TM}=1/3$ is assumed.

3. Two sections of reversal in Δβ

To alleviate the fabrication tolerance, a multi-section directional coupler with alternating Δβ has been proposed[10]. Fig. 3 shows such a coupler with two sections of reversal in Δβ. The two sections of reversal in Δβ can be achieved by reverse poling the waveguide material or by applying two opposite driving voltages.

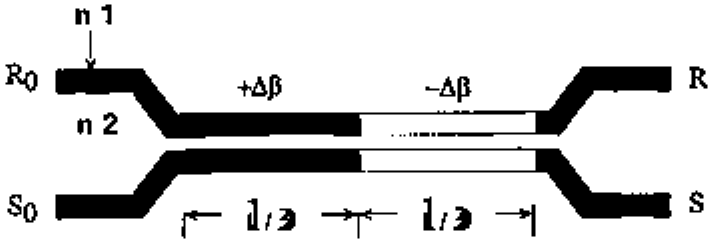

Fig.3. A directional coupler with two sections of reversal Δβ.

The transfer matrix of the first section with +Δβ is the same as Eq. (7) except that the parameter z in the matrix coefficients of Eq. (8) is half of the device length, (i.e., **z=L/2**). The transfer matrix of the second section with -Δβ has the form ,

$$M^{-}=\begin{pmatrix} A^{*}_{1} & -jB_{1} \\ -jB^{*}_{1} & A_{1} \end{pmatrix}, \qquad (10)$$

where **A1** and **B1** are expressed in Eq. (8) with **Z=L/2**. The transfer matrix of the coupler is

$$M=M^{-}M^{+}=\begin{pmatrix} A^{*} & -jB \\ -jB^{*} & A \end{pmatrix}, \qquad (11)$$

where the matrix coefficients are

$$\begin{cases} A=1-2B^{2}_{1} \\ B=2A^{*}_{1}B_{1} \end{cases} \qquad (12)$$

The switch is in cross state when **A=0**, which also implies

$$\frac{k^{2}}{k^{2}+\delta^{2}}\sin^{2}\frac{L}{2}\sqrt{k^{2}+\delta^{2}}=\frac{1}{2}=\sin^{2}\frac{\pi}{4}. \qquad (13)$$

This condition leads to a family of curves shown in Fig. 4. The curves intersect the vertical axis at the points **L/l=1, 3, 5, 7, ...** Near the vertical axis, these curves are very nearly sections of circles, and all curves are tangent to a 45° line through the origin.

The switch is in bar state if **B=0**, which occurs for either $\mathbf{A_1=0}$ or $\mathbf{B_1=0}$. The first condition implies $\Delta\beta=0$ and **L/l=2(2n+1), n=0,1,2,...,** which represents the isolated points at **L/l=2,6,10, ...** as shown in Fig. 4. The second condition can be written as

$$\left(\frac{L}{l}\right)^2+\left(\frac{\Delta\beta L}{\pi}\right)^2=(4n)^2, \qquad n=0,1,2\ldots, \qquad (14)$$

This condition for the bar states corresponds to the concentric circles with radius 4, 8, 12, etc. in Fig. 4.

Fig. 4 indicates that, for TM or TE modes, the reversed-$\Delta\beta$-mismatch configuration makes available ranges of L/l values (e.g., the range from L/l=1 to 3) in which complete cross or bar states can be achieved by driving voltage adjustment alone, so that fabrication tolerance are remarkablly relaxed. However, since TE and the TM modes always experience different EO coefficients, they cannot be switched from a common cross state to a common bar state at the same time. Fig. 5 shows the energy distribution of TE and TM modes along one channel of the coupler shown in Fig. 3. One can see that the bar states of TE and TM modes are not overlapping. In other words, a directional coupler in this configuration is polarization dependent, no matter how many sections we use.

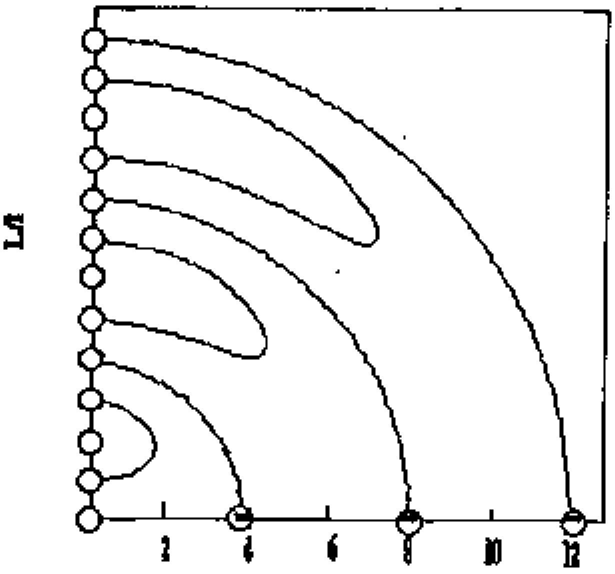

Fig.4 Switching diagram of TM mode for the switch with two sections of reversal $\Delta\beta$. The ⊗ sign marks cross states, and the ⊖ sign marks bar states.

4. Two sections of rotated $\Delta\beta$

In order to obtain a polarization-independent directional coupler, we pole the two sections of the coupler in two perpendicular directions, as shown in Fig. 6. This is feasible, especially with an EO polymer waveguide directional coupler. In this configuration, TE modes experiences γ_{13} in

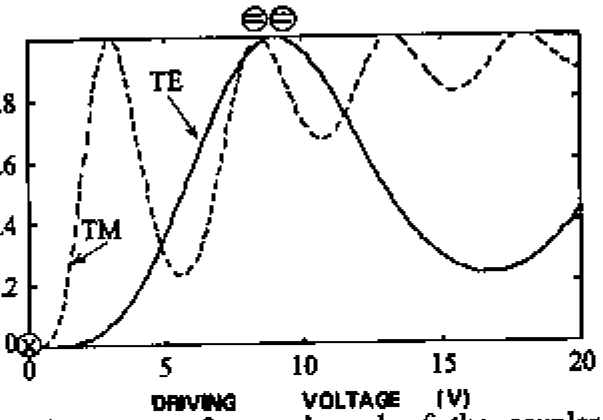

Fig.5 Normalized light output of one channel of the coupler with two reversal $\Delta\beta$ sections. Channel width is 10μm, thickness is 1.5μm, core material refractive index is $n1=1.5416$, and cladding material refractive index is $n2=1.5409$ with respect to wave length $\lambda=1.55\mu m$, $\gamma 33=10$ pv/m, $\gamma 13=\gamma 33/3$, $L/l=3$ are assumed.

the first section and $\gamma 33$ in the second section, while TM modes experiences $\gamma 33$ in the first section and $\gamma 13$ in the second section. Therefore, both TE and TM modes experience the same net EO effect. This compensates the phase difference of the two modes, and consequently the two modes can be switched simultaneously from a cross state to a bar state. As one can see in the following, directional couplers in this configuration are completely polarization independent.

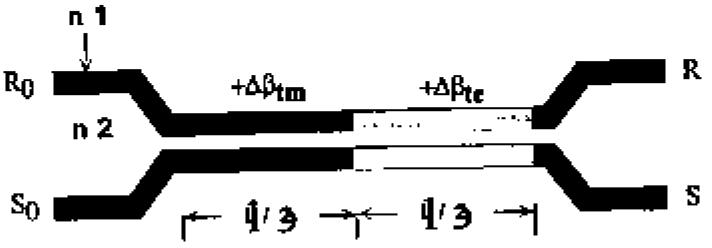

Fig.6. A directional coupler with two perpendicularly poled sections.

Take TM modes as an example, the transfer matrix $M^{+}{}_{tm}$ of the first section is given by Eq. (7) in conjunction with Eq. (4), and the transfer matrix $M^{+}{}_{te}$ of the second section is given by Eq. (7) in conjunction with Eq. (5), so the transfer matrix of the coupler is

$$M = M^{+}{}_{te}M^{+}{}_{tm} = \begin{pmatrix} A & -jB \\ -jB^{*} & A^{*} \end{pmatrix}, \tag{15}$$

where the matrix coefficients are

$$\begin{cases} A = A_{tm}A_{te} - B_{tm}B_{te} \\ B = A^{*}{}_{tm}B_{te} + A_{te}B_{tm} \end{cases}. \tag{16}$$

The coupler is in a cross state when A=0, this requires that $\boxed{\delta_{tm}}=\boxed{\delta_{te}}=0$, and **L/l=2m+1**, (**m=0, 1, 2...**), which represent some isolated points along **L/l** axis at **L/l=1, 3, 5, ...** as depicted in the switch diagram of Fig.7. The coupler is in a bar state, when **B=0**, which corresponds to either $\boxed{\delta_{tm}}=\boxed{\delta_{te}}=0$ and **L/l=2n (n=0, 1, 2...)** or

$$\left(\frac{L}{l}\right)^2+\left(\frac{\Delta\beta_{tm}L}{\pi}\right)^2=(4m)^2 \qquad m=0,\,1,\,2... \qquad (17)$$

and

$$\left(\frac{L}{l}\right)^2+\left(\frac{\Delta\beta_{te}L}{\pi}\right)^2=(4n)^2 \qquad n=0,\,1,\,2...\,. \qquad (18)$$

Both conditions above lead to some isolated points marked ⊖ in Fig. 7.

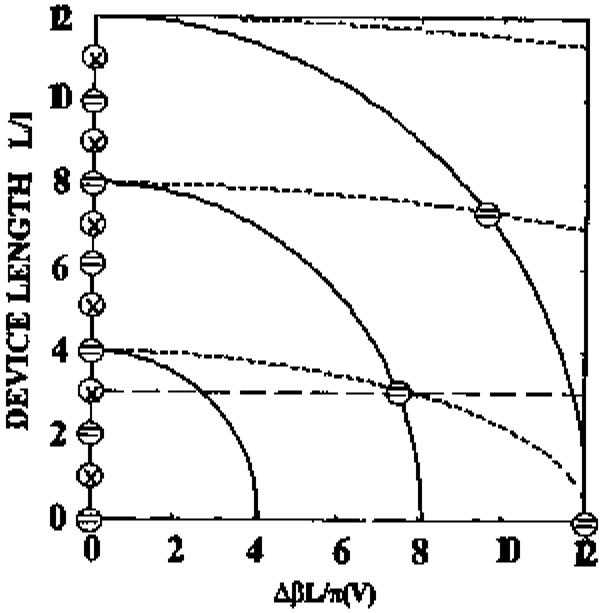

Fig. 7. The switch diagram of a directional coupler with two perpendicularly poled sections. $\gamma_{13}=\gamma_{33}/3$ is assumed.

As one can see from Fig. 7, although the coupler is completely polarization independent, the switch has only a few isolated solutions for complete cross and bar states. For example, when L/l=3, the light power distribution along one channel of the coupler is shown in Fig. 8, where TE and TM modes are completely overlapping. EO directional couplers in this configuration are polarization independent, but still have a strict fabrication tolerance.

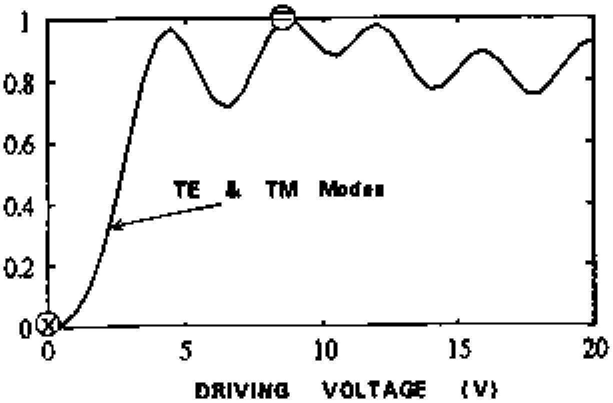

Fig. 8 Energy distribution along one channel of the directional coupler with two perpendicularly poled sections. All the conditions are the same as that in Fig. 5.

5. Four combined poled sections

As we discussed above, directional couplers with reversed $\Delta\beta$ sections have the merit of large fabrication tolerance, while they are polarization dependent; directional couplers with perpendicularly poled sections are completely polarization independent, while their fabrication tolerance are strict. To design a directional coupler that is not only polarization independent, but also has a large fabrication tolerance, a four-section configuration is proposed as shown in Fig. 9.

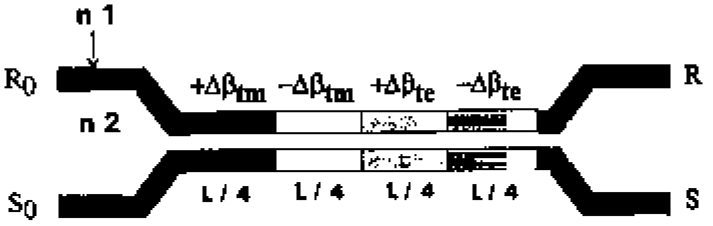

Fig. 9 A directional coupler with four combined poling sections.

The four sections are poled in four perpendicular directions, the first two sections are reversely poled in the vertical direction, i.e., +Y and -Y directions; and the other two sections are reversely poled in the horizontal direction, i.e., +X and -X directions. For TM mode, the transfer matrix of the coupler is

$$M_{tm} = M^{-}_{te} M^{+}_{te} M^{-}_{tm} M^{+}_{tm} \qquad (19)$$

while for TE mode, the transfer matrix of the coupler is

$$M_{te} = M^{-}_{tm} M^{+}_{tm} M^{-}_{te} M^{+}_{te} \qquad (20)$$

where $\mathbf{M^{+}_{tm}}$ is given by Eqs. (7) and (4), $\mathbf{M^{-}_{tm}}$ is given by Eqs. (10) and (4), $\mathbf{M^{+}_{te}}$ is given by Eqs. (7) and (5), and $\mathbf{M^{-}_{te}}$ is given by Eqs. (10) and (5), with all the parameter **Z** changed to a quarter of the device length, $Z=L/4$. Obviously, $M_{tm}=M_{te}$. The numerical solution of Eqs. (19) and (20) can be obtained with a computer as depicted in Fig. 10.

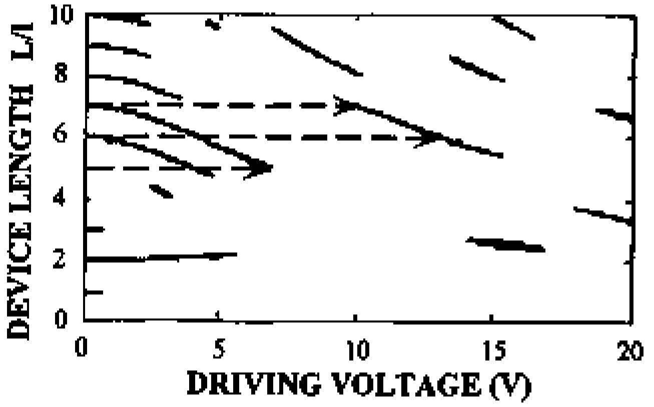

Fig. 10 Switch diagram of the directional coupler shown in Fig.9. Solid lines represent cross states and shaded lines represent bar states for both TM and TE modes.

In Fig. 10, all the settings are the same as that in Figs. 4, 5, and 7. The solid lines represent cross states and the shaded lines represent bar states for both TM and TE modes. Evidently, directional couplers in this configuration offer variability of the device length, $5<L/l<7$, within which both the cross state and bar state of TM and TE modes can be addressed simultaneously by only a driving-voltage adjustment. The strict fabrication tolerance is extremely alleviated. Fig. 11 gives out an example of the normalized output of one channel of the directional coupler. As one can see from Fig. 11, the TM and TE modes are totally overlapping, which means that the phase mismatch between TM and TE modes caused by different EO coefficients is compensated by this configuration. In other words, an EO directional couplers in this configuration is completely polarization insensitive. Fig. 10 also shows that the driving voltage for this EO switch is as low as about 5 volts, which is lower than most existing EO switches.

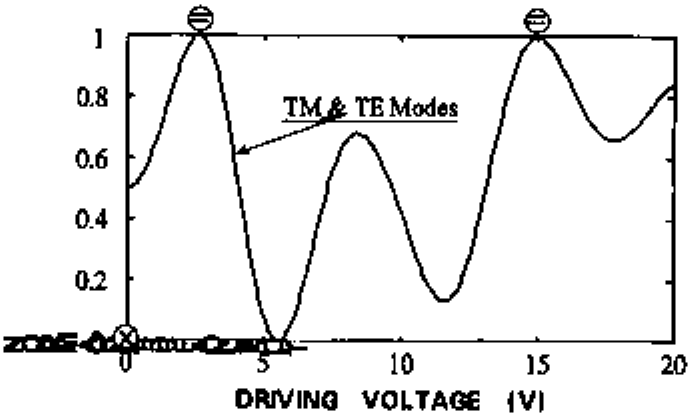

Fig.11 Normalized output of one channel of the coupler shown in Fig.9. $L/l=5.5$.

6. Conclusion

EO directional couplers with reversed $\Delta\beta$ sections relax the strict fabrication tolerance of conventional EO directional couplers, but they are polarization dependent. Directional couplers with two perpendicularly poled sections are completely polarization-independent, but their fabrication tolerance is as strict as conventional directional couplers. Directional couplers with four perpendicularly poled sections proposed in this paper is not only completely polarization independent, but also has a extrememly relaxed fabrication tolerance. In addition, since this configuration needs only a pair of simple uniform electrodes and a low drive voltage to drive, this further simplifies the fabrication of the traveling-wave electrode for the device and assures high-speed operation. All the simulations in this paper are based on the requirement for a practical design, and the experimental results will be reported in another paper.

7. Acknowledgment

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