Crosstalk in Ti:$LiNbO_3$ Directional Coupler Switches Caused by Ti Concentration Fluctuations

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Abstract—**We have observed random fluctuations in the local Ti concentration profiles of Ti-diffused $LiNbO_3$ waveguides. Calculations show that these variations explain the degraded switch extinction ratio (i.e., crosstalk) and other nonideal characteristics observed in $LiNbO_3$ optical switches. We also demonstrate by calculation a new device configuration for eliminating this source of crosstalk.**

INTRODUCTION

ELECTRICALLY activated optical switches with high switching speeds and low optical insertion loss have been demonstrated in $LiNbO_3$ using Ti-diffused waveguides [1]–[3]. Reasonable levels of integration have been achieved [3]–[6], with as many as 16 switches on one substrate [6]. As a greater number of devices come between the light source and detector, optical crosstalk becomes more important. Unlike other performance factors, the extinction ratio of these optical switches has not improved, remaining $\gtrsim -30$ dB [1]–[8]. This is further illustrated by a set of 16 nominally identical directional coupler switches recently fabricated on a single substrate [6]. An approximately random distribution of extinction ratios was measured ranging from -11.6 to < -35 dB (Table I).

TABLE I
EXTENSION RATIOS (dB) FOR THE BAR STATES OF 4 × 4 Ti:$LiNbO_3$ SWITCH

	INPUT			
OUTPUT	1	2	3	4
1	-18.3	-22.2	<-35.0	-16.4
2	-27.2	-22.5	-17.8	-11.6
3	-35.7	-30.0	-21.6	-12.5
4	-19.8	-11.6	-34.0	-20.7
	RANGE	-11.6 dB to <-35 dB		
	MEAN	-22 dB		
	STD. DEV.	- 8 dB		

Recently, it has been shown [9] using a one-dimensional model calculation that unequal power coupling between the fundamental mode of an isolated waveguide and the normal modes of the directional coupler waveguide pair would produce crosstalk. As was pointed out [9], the proposed mechanism might also account for the crosstalk present in the two voltage-controlled states (the crossed and bar states) of the Ti:$LiNbO_3$ switch. If so, the crosstalk should decrease as the interwaveguide separation increases. It is the experience of ourselves and others, however, that the ~ -30 dB bar state (uncrossed) extinction ratio is independent of interwaveguide gap. It has also been put forth that weighted coupling will eliminate this mode mismatch [10]. Polarization-independent switches using weighted coupling, however, do not show improved extinction ratios [3], [5], [11], [12].

Other electrooptical anomalies are observed, but unexplained. The fraction of light energy exchanged between the waveguide pair as a function of voltage should be symmetric about $V = 0$ V. The crossed state maximum is observed to be shifted slightly away from $V = 0$. The magnitudes of the nulls (bar state maxima) and the sidelobe maxima are different in the positive and negative voltage half planes. We hypothesize and demonstrate that there is a common explanation for all of these nonideal characteristics: random fluctuations in the effective index along the length of the diffused waveguide pair. Local random variations in the Ti concentration of the diffused waveguides could produce random fluctuations in their effective index. As we will show, although the fluctuations are small, random, and average to zero, their effect is nonzero.

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EXPERIMENT

To test this hypothesis, the Ti concentration profiles of diffused Ti:$LiNbO_3$ channel waveguides were examined with an electron microprobe. Ti strips of individual waveguides and directional coupler waveguide pairs were made by photolithographic patterning and the liftoff technique on $\hat{z}$-cut y-propagating $LiNbO_3$ (see Fig. 1). The Ti was deposited by sputtering. The strip dimensions were 5 μm wide by 670 Å thick. The pattern was diffused at 1050°C for 6 h under flowing oxygen and water vapor.

An ARL SEMQ electron microprobe using an LiF wavelength dispersive analyzer was used. Electron energy was 10 keV, implying ~ 0.7 μm penetration depth into the $LiNbO_3$ substrate. The beam diameter was estimated to be 2 μm, realizing a 2.2 μm^3 excitation volume. The waveguide patterns were scanned by the microprobe on a grid of 1 μm intervals perpendicular to the direction of light propagation and 2 μm intervals parallel to this direction (Fig. 1). Fractional Ti concentrations are reported relative to a thick film deposited by electron beam evaporation.

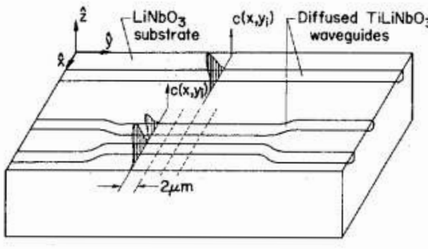

Fig. 1. Schematic diagram of Ti-diffused $LiNbO_3$ waveguide structures: straight waveguide and a directional coupler. Coordinate system is consistent with the crystallographic structure.

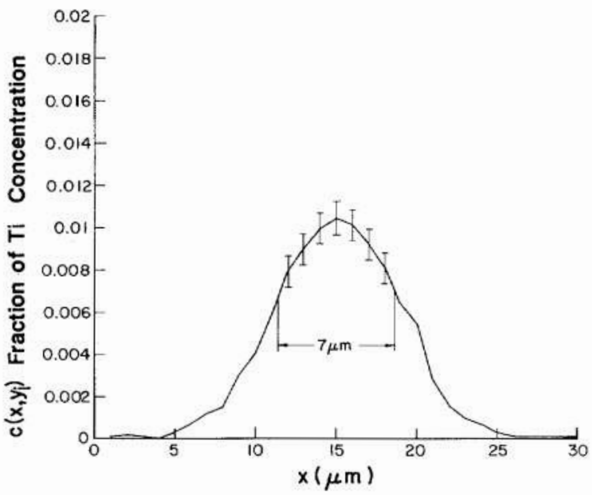

Fig. 2. Surface concentration profile measured by electron microprobe across a $Ti:LiNbO_3$ isolated waveguide. Initial Ti strip dimensions were 5 μm wide by 0.065 μm thick. Concentration is relative to a thick evaporated (but undiffused) Ti film. Counting time was 20 s/data point.

Fig. 2 is a plot of the surface titanium profile $c(x, y_i)$ of an isolated waveguide parallel to the surface and perpendicular to the direction of light propagation (cf. Fig. 1). The statistical errors are 3–5 percent at the concentration profile peak. Assuming isotropic diffusion, the diffusion length is calculated [13] from this curve to be $D \cong 4$ μm, which is slightly larger than previous measurements [14], [15]. The optical mode width (i.e., parallel to the $LiNbO_3$ surface) of these waveguides has been measured to be $w \sim 7$ μm FWHM of the intensity. Refractive index fluctuations will have the strongest effect in this region. Each concentration profile was therefore averaged over the center 7 μm of the waveguide $\bar{c}(y_i) = \int_w c(x, y_i)\, dx$, and plotted in Fig. 3 as a function of position along the guide. The average fractional concentration has a mean value of 9.4×10^{-4} and a standard deviation of $\sigma_c = 1.5 \times 10^{-4}$. The latter value corresponds to an envelope of index fluctuation of $2\sigma_n = 1.9 \times 10^{-4}$ for the extraordinary polarization ($dn_e/dc = 0.625$) [16] and is nearly twice the size of the error bars. A running analysis [17] of the fluctuations above and below the average concentration is consistent with a set of random fluctuations.

The surface concentrations of the waveguides of a $Ti:LiNbO_3$ directional coupler were measured in a similar manner. Before diffusion, the Ti strips were 5 μm in width and separated by 6 μm (edge to edge). Profiles (Fig. 4) were recorded at 2 μm intervals along the directional

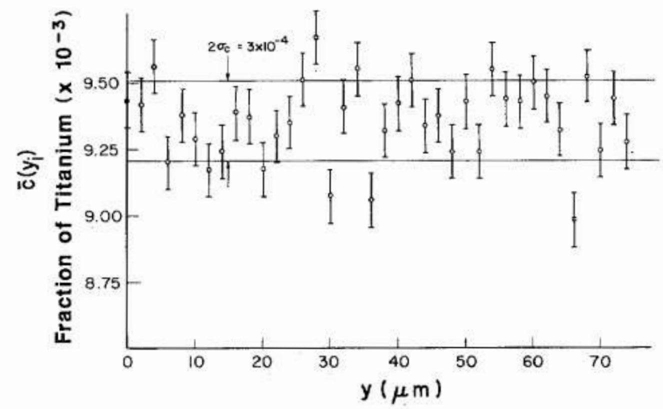

Fig. 3. Plot of the fractional Ti surface concentration versus position along an isolated waveguide. The Ti concentration was averaged over the 7 μm FWHM of the mode width intensity.

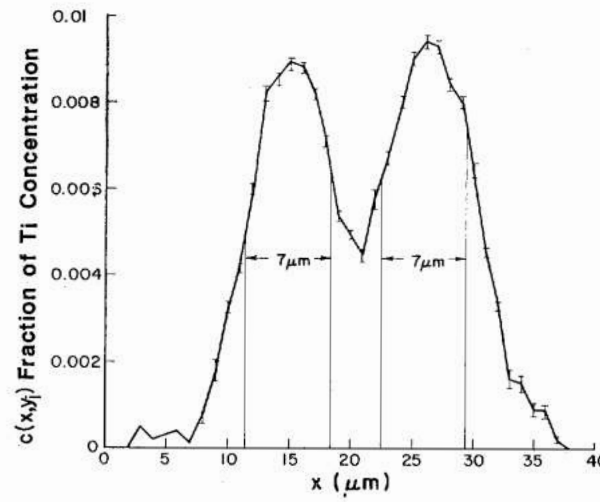

Fig. 4. Surface Ti concentration profile measured by electron microprobe across a pair of directional coupler waveguides. Refractive index is related to Ti concentration by $dn/dc = 0.625$ (extraordinary index). Counting time was 80 s/data point.

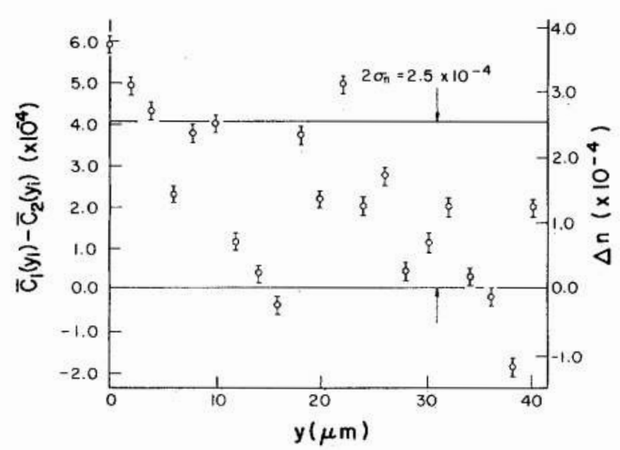

Fig. 5. Electron microprobe measurements of Ti surface concentration difference between the directional coupler waveguide pair. Ti surface concentration profiles were averaged over the mode width (~ 7 μm) of each waveguide, subtracted, and plotted as a function of position along the guide pair.

coupler. The concentration values were averaged as before (over the 7 μm regions centered around the peak values). The difference between these values is plotted in Fig. 5 as a function of position along the waveguide pair.

The average fractional concentration difference between the two waveguides is 2×10^{-4} (with respect to bulk Ti). We attribute this nonzero difference to a small (< 2 percent) difference in the Ti strip dimensions. If the concentration fluctuations of the waveguide pair are uncorrelated, the envelope of concentration differences should be $\sqrt{2} \times 1.5 \times 10^{-4} = 2.1 \times 10^{-4}$. This agrees well with the excursion of concentration differences $\sigma_c = 2 \times 10^{-4}$ (Fig. 5). The corresponding envelope of refractive index variations in the directional coupler interaction region is $2\sigma_n = 2.5 \times 10^{-4}$. The standard deviations and the average concentrations of the individual waveguides of the directional coupler were nearly the same as in the isolated waveguide.

Model Calculations

The exchange of light as it propagates down a pair of closely spaced waveguides is given by the coupled-wave equations whose solution can be expressed by the matrix equation [18]

$$\begin{vmatrix} R(z + \Delta z) \\ S(z + \Delta z) \end{vmatrix} = \begin{vmatrix} A & -iB \\ -iB^* & A^* \end{vmatrix} \cdot \begin{vmatrix} R(z) \\ S(z) \end{vmatrix} \tag{1}$$

where

$$A \equiv \cos \Psi + i\delta(V)\Delta z \sin \Psi/\Psi,$$

$$B \equiv \kappa \Delta z \sin \Psi/\Psi,$$

and

$$\Psi \equiv \sqrt{\kappa^2 + \delta^2(V)}\, \Delta z.$$

A voltage applied to electrodes patterned above the waveguides produces a uniform phase mismatch in each of the two guides over a distance Δz by an amount

$$2\delta(V)\Delta z = 2\pi \Delta N(V) \Delta z/\lambda$$
$$= 2\pi\alpha n^3 r V \Delta z / g\lambda$$

where $\Delta N(V)$ is the effective index difference between the two guides produced by the electric-optic effect, α is the electrical/optical field overlap, n is the substrate index, r is the electrooptic coefficient, g is the interelectrode gap, V is the applied voltage, and λ is the free-space wavelength. For a waveguide pair of length $L_c = \pi/2\kappa$ (one coupling length long), light entering one waveguide at $z = 0$, $[R(0), S(0)] = [1, 0]$ will exit in the adjacent guide $[R(L_c), S(L_c)] = [0, 1]$. A uniform phase mismatch $\delta(V)L_c = \sqrt{3}\,\pi/2$ applied to the coupler via the surface electrodes causes the light to exit the same guide it entered, i.e., $[R(L_c), S(L_c)] = [1, 0]$.

Now consider the nonideal case of a pair of waveguides with small random fluctuations in their effective index $\Delta N_1(z)$ and $\Delta N_2(z)$ distributed over the length of the guides. Corresponding to the experimental data (Fig. 3), the magnitudes of these fluctuations are uniformly distributed between $\pm \Delta N_{\max}$ ($\Delta N_{\max} = \sqrt{3}\,\sigma_n$ for a uniform random distribution) and are of length Δz. The redistribution of the light entering the waveguide pair must be calculated by operating successively over Δz with the 2×2 matrix in (1) where now the phase mismatch is $2\pi[\Delta N(V) + \Delta N_1(z) - \Delta N_2(z)]\Delta z/\lambda$. The coupling constant κ of waveguides far from cutoff of the fundamental mode (i.e., well confined) is approximately constant for small changes in the effective index as experimental measurements have shown. The model calculations therefore ignore the effect of a change in the coupling constant with the small change in the effective indexes of the waveguides $\Delta N_1(z)$ and $\Delta N_2(z)$. A small constant index difference ($\sim 1.2 \times 10^{-4}$), as seen in Fig. 5, is a constant bias and does not affect the results.

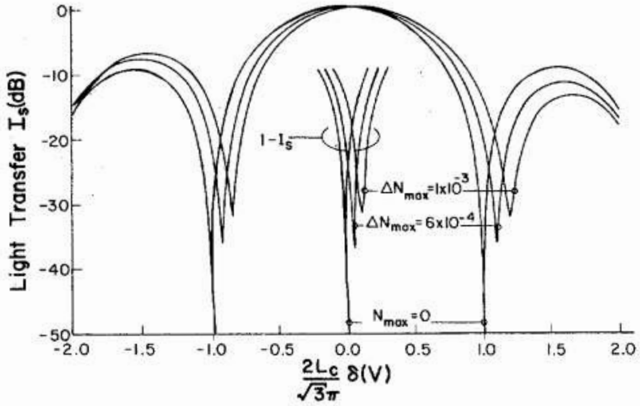

Fig. 6. Calculated light fraction (in decibels) exchanged between a directional coupler waveguide pair of length L_c (one coupling length long) versus mismatch $\delta(V)L_c$. Calculated results are plotted for several random index fluctuation ranges $\pm \Delta N_{\max}$.

The fraction of light intensity $S(L_c)^2$ exchanged between a pair of waveguides with one coupling length (10 mm) is plotted in Fig. 6 as a function of the applied electrooptic phase mismatch $\delta(V)L_c$. Plots are shown for several values of $\Delta N_{\max}$, using one particular pseudorandom distribution function. The step length is $\Delta z = 2\ \mu$m. For the ideal case $\Delta N_{\max} = 0$, a perfect uncrossed state occurs at $\delta(V)L_c = \sqrt{3}\,\pi/2$ and a perfect crossed state is achieved at $\delta(V)L_c = 0$. The response curve is symmetric about $\delta(V)L_c = 0$. As seen in Fig. 6, the presence of fluctuations in the effective index degrades the quality of both the crossed and uncrossed state extinction ratios. Their positions are also shifted along the abscissa. The height of the sidelobes, and to a lesser extent the node minima, are no longer equal.

Discussion

The finite extinction ratio of the uncrossed state, the slight offset in the crossed state maxima, and the unequal sidelobes and nulls observed in the response curves of $Ti:LiNbO_3$ switches are all explained by one phenomenon: small random variations in the effective index of the waveguides. We need only assume that the effective index of the waveguides has about the same magnitude of fluctuations as the surface refractive index fluctuations inferred from the observed Ti concentration variations. Refractive index fluctuations ($\pm \Delta N_{\max}$) inferred from the observed (Figs. 3 and 5) Ti concentration fluctuations would introduce a crosstalk of -35 to -40 dB in the bar, based on the model calculations treated here. This result, as well as the loss of symmetry in the calculated (Fig. 6) response curves, are consistent with the measured response of $Ti:LiNbO_3$ directional coupler switches.

The exact shape of the response curve (Fig. 6) depends on the particular random distributions $\Delta N_1(z)$ and $\Delta N_2(z)$ chosen for the model calculations. It is not possible to predict the extinction ratio of a particular device from a knowledge of ΔN_{max} alone. To illustrate, the calculations were repeated 100 times, using different random distributions with the same ΔN_{max} envelope for each iteration. Calculated extinction ratios ranged from -16 to -48 dB, with a mean value of -27 dB.

If our model is correct, a set of nominally identical switches on a single substrate would not be expected to have a common extinction ratio. The recently reported 4×4 array containing 16 switches [6] has an approximately random distribution of extinction ratios (Table I) ranging from -11.6 to < -35 dB. The mean value is -22 dB and the standard deviation is -8 dB.

Two likely sources for the index fluctuations are the local variations in the density or dimensions of the Ti strip (before diffusion) and local inhomogeneities in the diffusivity of the $LiNbO_3$ substrate. If it is the former, annealing the metal before diffusion may reduce the crosstalk.

It has been recently pointed out [19] that a three-section $\Delta\beta$ coupler device will transform any combination of input light $[R(0), S(0)]$ to any output combination $(R(L_c), S(L_c)]$. An extension of this idea is that three independent electrodes provide sufficient degrees of freedom to establish perfect crossed and bar states for a coupler switch with fixed effective index fluctuations. The 2×2 matrix in (1) represents two equations in three variables $\delta(V_1)$, $\delta(V_2)$, and $\delta(V_3)$ since κ and $\Delta N_1(z) - \Delta N_2(z)$ are fixed by the device. A directional coupler with three electrodes is therefore sufficiently overspecified to produce any desired solution (in this case, perfect extinction) [20].

To demonstrate, a three-electrode switch (1.1 coupling lengths) with random fluctuations was computer modeled. An optimal bar state extinction ratio of -38 dB was obtained with the electrodes at a common potential difference. Perfect extinction (< -100 dB) was obtained by independently adjusting the three electrode voltages. A -77 dB extinction ratio requires the three electrode voltages to be held to 0.1 percent of their ideal value.

Electrical compensation of the effective index fluctuations does not mean that a $Ti:LiNbO_3$ switch fabricated with three electrodes will have no measurable crosstalk. Rather, the extinction ratio will be improved to the point where other effects may dominate. For example, the problem of unequal mode coupling [9] could place a limit on the extinction ratio. Another limitation may involve the depolarization of light by the waveguide.

Summary

$Ti:LiNbO_3$ directional coupler switches have consistently shown a range of extinction ratios in the range -15 to -30 dB, rarely exceeding -30 dB. In addition, their response curves show nonideal behavior, such as unequal sidelobes and nonzero voltage values for the maxima of the crossed state. We hypothesize and demonstrate that there is a common explanation for all of these nonideal characteristics: random fluctuations in the effective index along the length of the diffused waveguide. Local random variations in the Ti concentration of the diffused waveguides are observed and are large enough to produce fluctuations in the mode effective indexes.

Finally, we have shown by model calculations that one effect of these fluctuations, crosstalk, can be electrically compensated by using three independent electrodes. The result should be extinction ratios which are significantly better than present ones.

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