Improved optical switching extinction in three-electrode Ti:LiNbO$_3$ directional couplers

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Utilizing three electrodes and three independent voltages in Ti:LiNbO$_3$ directional coupler optical switches, we have achieved significant improvements in switching extinction over the standard uniform $\Delta\beta$ configuration. The reductions in optical crosstalk vary from 3 to 24 dB for both switching states of several fabricated devices. We have observed a bar state extinction of -47.8 dB, which is the largest extinction ratio reported to date. We find that switching measurements are limited by the largest contrast ratio which can be obtained in the optical waveguides.

The directional coupler switch is an important component of lithium niobate integrated optics. Actual devices exhibit electro-optical characteristics which deviate from the ideal directional coupler. The most undesirable property is optical crosstalk: the inability to completely extinguish the light in one of the two output waveguides. Crossed and bar (uncrossed) state crosstalks have been attributed to nonoptimum coupling length (uniform $\Delta\beta$ devices),[1] to unequal coupling of the input wave to the local modes of the directional coupler,[2] and to regions in the directional coupler where optical coupling between the waveguides occurs without the presence of electro-optic induced phase mismatch.[3] It has been demonstrated that the use of a two-electrode pair in the reverse $\Delta\beta$ configuration relaxes the fabrication tolerances, but the extinction ratio remains approximately -35 dB.[4] Tapered couplers have also been recommended to improve the coupling to the local modes of the directional coupler and thus eliminate crosstalk.[5]

Recently it has been shown that all of the nonideal characteristics of Ti:LiNbO$_3$ directional couplers including optical crosstalk can be explained by considering the effects of small random refractive index fluctuations detected along the diffused waveguides.[6] Inhomogeneities in the initial Ti film have been found to be the source of the index variations in the waveguides.[7] Model calculations of a directional coupler possessing random refractive index variations predict that three electrodes with three independent voltages can achieve perfect bar and cross states in directional coupler switches in spite of this fabrication deficiency.[6,8] Refractive index fluctuations are compensated by the three electrically driven degrees of freedom, which are sufficient to transform the light to any arbitrary output state.[9] In this letter we report the switching results of Ti:LiNbO$_3$ directional couplers with three electrodes fabricated for 1.3 μm wavelength.

Figure 1 illustrates the three-electrode optical switch. Directional couplers consisting of single-mode Ti-diffused waveguides were fabricated in z-cut LiNbO$_3$ in the conventional manner[7] with varying interaction lengths and waveguide separations. The titanium diffusion was accomplished under flowing oxygen and water vapor. An optical buffer layer of SiO$_2$ approximately 2000 Å thick was applied between the aluminum electrodes and the LiNbO$_3$ substrate. Light from a cooled laser diode operating at 1.28 μm was polarized (to better than -55 dB) and end fired into and coupled out of the waveguides using 20$\times$ objectives. Introducing a second polarizer after the output objective consistently resulted in a 2–5 dB improvement in switching extinction over unpolarized output measurements. (The combined birefringence of the input and output objectives and a Ti-diffused waveguide was measured to be $\leqslant -46$ dB.) To improve the signal-to-noise ratio the output light was also apertured so that only the central portion of the optical mode (approximately 10% of the guided light intensity) was imaged onto a germanium photodetector.

The switching characteristics for the TE (ordinary) mode of three devices are shown in Table I. The extinction ratio is defined as the ratio of light intensity in the "off" waveguide to that in the "on" waveguide in decibels. The

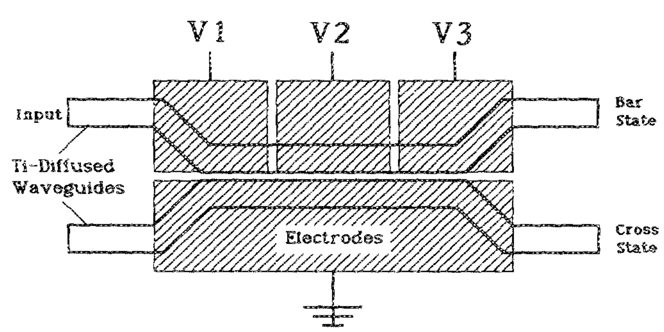

FIG. 1. Sketch of Ti:LiNbO$_3$ three-electrode directional coupler optical switch with S bends.

TABLE I. Three-electrode coupler switching extinction ratios for the TE mode at 1.3 μm.

	Device No. 1	Device No. 2	Device No. 3
Uniform $\Delta\beta$ bar state ($V1 = V2 = V3$)	-7.4 dB (55 V)	-30 dB (-110 V)	-26 dB (-33.8 V)
Three-electrode coupler bar state ($V1,V2,V3$)	-31.8 dB (0,49,14 V)	-42.0 dB (-14, -65, -33 V)	-47.8 dB (-20, -40, -38 V)
Uniform $\Delta\beta$ cross state ($V1 = V2 = V3$)		-23.8 dB (-10.6 V)	-7.6 dB (-5.3 V)
Three-electrode coupler cross state ($V1,V2,V3$)		-34.6 dB (-44,129, -60 V)	-10.3 dB (-3.8, -3.7, -3.6 V)
Optimum waveguide contrast ratio	35 dB	50 dB	50 dB

contrast ratio is taken to be the ratio of the largest light intensity in the waveguide to the residual background light in the substrate. The background radiation was measured at a point midway between the two output ports of the directional coupler. Utilizing a common voltage, the cross and bar states were measured for uniform $\Delta\beta$ switching. By varying all three voltages independently, various extinction nulls could be attained for both states, which was consistent with the computer simulations.[6] We list only the largest extinction ratios observed and the corresponding voltages in Table I.

In device No. 1 poor photolithographic delineation of the Ti precursor for the waveguides produced an extreme case of Ti concentration fluctuations which degraded the uniform $\Delta\beta$ extinction ratio.[6] The three-electrode configuration yields a 24-dB bar state extinction improvement. The coupler of device No. 2 was Hamming weighted[10] with multisection electrodes over the interaction region. The particular three electrodes used for switching on this device were chosen such that they were asymmetrically positioned, different lengths, and did not cover the entire interaction region. Nevertheless, the three-electrode configuration improved the crosstalk by 10 dB for both the bar and cross state over the results of a single voltage applied over the entire tapered interaction region. Time varying leakage currents were detected between the electrodes which gave rise to rapid voltage drift limiting the resolution of the extinction measurements.

For device No. 3 the SiO_2 buffer layer was etched away between the electrode gaps. No rapid drift with time of the extinction nulls was observed, similar to the findings of Ref. 11. As shown in Fig. 2, this device could be maintained in the bar state at greater than -40 dB switching extinction for several minutes without any voltage adjustments. The long-term switching drift apparent in Fig. 2 is presumably due to stray electric fields in the substrate; such fields might arise due to pyroelectric[12] or photorefractive effects.[13] Additionally it was determined that a bar state extinction greater than -40 dB could be maintained even with voltage variations of a few volts on any one of the three electrodes. The greatest bar state extinction ratio measured was -47.8 dB. Device No. 3 exhibited a poor cross state which resisted three-electrode improvements. The length of this device is estimated to be less than one coupling length, and computer simulations indicate that is is not possible to electrically compensate undercoupled directional couplers.

For all devices tested the waveguide contrast ratio for the TM (extraordinary) mode was approximately 35 dB, never exceeding 40 dB. We attribute the brighter (as compared to the TE polarization) background to a small degree of planar surface guiding arising from the surface outdiffusion of Li_2O.[14] Switching data for the TM polarization were also taken, and greater extinction ratios were again found

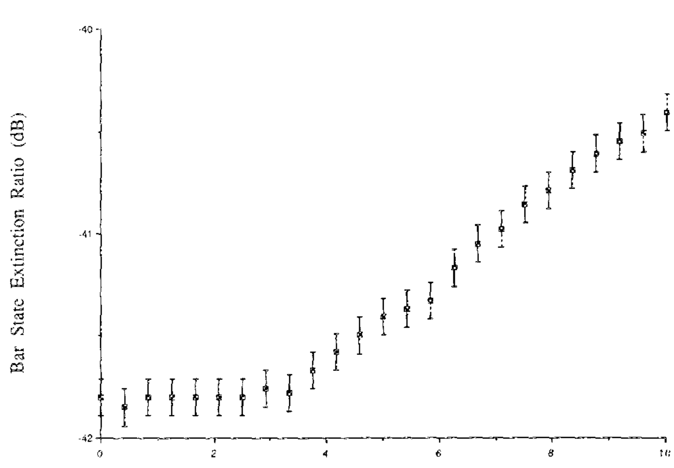

FIG. 2. Drift in the bar state extinction null vs time for device No. 3: $V1 = 32$, $V2 = 35$, $V3 = 22$ V.

using the three-electrode configuration; however, the optimum TM extinction nulls were never greater than 39 dB.

As was proposed in Ref. 6 we have found that the optical crosstalk can be improved to the point where other effects dominate. We observe that the measured switching extinction ratios for the three-electrode couplers are essentially limited by the optimum contrast ratio of the waveguides (see Table I): the greatest extinction state can be no darker than the surrounding substrate radiation intensity. A likely source of background radiation is imperfect coupling of the input laser light to the waveguide (300 μW was typically launched into the waveguides). Other possible sources of background light are Rayleigh scattering from index fluctuations in the waveguides and radiative loss at the waveguide bends (see Fig. 1). Device No. 3 exhibited the best extinction ratio due to its large waveguide contrast ratio and lack of SiO_2 between the electrodes. To accomplish even greater switching extinction will require increasing the contrast ratio of the system, either by decreasing the background (e.g., reduce waveguide bending losses), or by more efficient coupling into the waveguides (e.g., mode matching at input). The contrast ratio of the TM mode was always less than for the TE mode probably due to surface guiding effects. In order to exploit the larger electro-optic coefficient governing the TM polarization, reduction of surface guiding will be necessary.

In summary, we have fabricated and characterized three-electrode Ti:$LiNbO_3$ directional coupler switches. Using three independent voltages we have achieved significant improvements over uniform $\Delta\beta$ switching crosstalk for both the cross and bar state for the TE (ordinary) mode at 1.3 μm. The three degrees of freedom provided by the three electrodes over the directional coupler counteract the effects of *random* refractive index inhomogeneities in the waveguides. Therefore, there are no rigid restrictions on the position or lengths of the electrodes, as demonstrated by the switching results of device No. 2. The removal of SiO_2 between the electrodes gave rise to temporally stable (on the order of minutes) switching nulls and bar state extinction ratios in excess of -40 dB could be maintained even with voltage variations of a few volts. The optimum switching extinction is limited by the brightness of the background substrate radiation, which was found to be consistently darker for TE polarized light. For integrated optical applications requiring very low crosstalk, such as cascaded switching arrays, the employment of three-electrode directional couplers will be worthwhile, if not necessary.

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