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Method for cross-state tuning in a directional coupler with uniform $\Delta\beta$ switching

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A new electrode structure for a directional coupler based photonic switch is proposed for achieving cross-state tuning in uniform $\Delta\beta$ operation. **Two** different ways of using this structure are discussed. The voltage requirement for tuning and the advantages and disadvantages of the proposed structure **in** relation to the alternating $\Delta\beta$ coupler are discussed.

Directional couplers based on $LiNbO_3$ have been found to be promising candidates for photonic switch arrays of smaller dimensions, with very high transmission bandwidth. If the length of the coupler is not exactly an odd multiple of coupling length, it is not possible to achieve a perfect cross state in the case of a uniform $\Delta\beta$ directional coupler switch [1]. **An** alternating $\Delta\beta$ electrode structure is the popular solution **[2].** The alternating $\Delta\beta$ structure has the following drawbacks:

(i) Two signals per switch are required for switching. The two signals will be of different types, one bipolar and the other unipolar, if alternating $\Delta\beta$ operation is used for cross-state and uniform $\Delta\beta$ operation for the bar state. If alternating $\Delta\beta$ operation is used for both states, the two signals will be similar hut of opposite polarities and the voltage required to switch to bar state will be high. **In** any case, when switching is carried out at high frequencies, signal drivers with voltages of the order of 10 V will be costly and each of these signals has to he interfaced to the integrated-optic chip through coaxial cables. Moreover the rise in the number of signal drivers will reduce reliability.

(ii) The length of the coupler should be within certain allowed limits, to achieve a perfect cross state with the alternating $\Delta\beta$ structure. For example, L can he such that $l_c \leq L \leq 3l_c$, where L is the length of the coupler and l_c is the coupling length. However, L should not be less than l_c. Hence, the minimum possible length will be $L = l_c + e$, where $\pm e$ is the fabrication tolerance.

In this Letter, we propose a new electrode structure that has the advantages of the uniform $\Delta\beta$ switch and the capability of cross-state tuning. **In** the proposed switch, $\Delta\beta$ modulation is used for switching between the cross state and bar state, and $\Delta\kappa$ modulation [3] is used for tuning the coupler to achieve a perfect cross state. $\Delta\beta$ modulation results when the electrodes are placed in such a way that the electrical field along the c-axis of the crystal is in opposite directions in the two waveguides, causing a mismatch in the propagation constants β_1 and β_2 of the two waveguides. For $\Delta\kappa$ modulation, the electrodes are placed in such a way that the field is in the same direction in both the waveguides, thus changing the refractive index of the two waveguides equally, causing a change in coupling coefficient. For switching between the cross state and bar state, $\Delta\kappa$ modulation **is** not generally considered because it calls for large values of $\Delta\kappa$ and thus an impractical voltage requirement. The idea is that it can be conveniently used to tune for the cross state because the $\Delta\kappa$ required is small. Theoretically any length can be tuned, but the voltage requirement limits the range of tuning. Unlike the alternating $\Delta\beta$ switch, the length on designing can be $L = l_c$, since $\pm e$ can he tuned. In the proposed switch, only one signal is required per switch for $\Delta\beta$ modulation, as in the uniform $\Delta\beta$ switch. Cross-state tuning is performed using a DC voltage. The proposed electrode structure for the directional coupler switch in c-cut $LiNbO_3$ crystal, in its two possible modes ***of*** operation, is shown in Fig. 1. The two modes, which are the same in principle, are explained below.

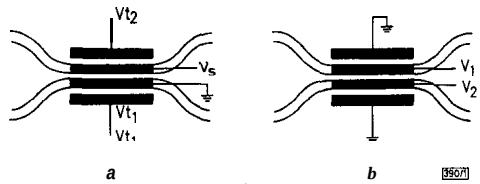

Fig. 1 ***Proposed electrode structure in its two modes of operation***

Method 1: Vt_1 and Vt_2 are the DC voltages used for tuning and v_s is the switching signal. While tuning to obtain a perfect cross state, v_s is kept at zero. Equal voltages Vt_1 and Vt_2 are applied. The fields in both the waveguides will be equal in magnitude and direction, because v_s is now at ground potential. Hence $\Delta\kappa$ modulation results. By choosing the right polarity for Vt_1 and Vt_2, both $\pm\Delta\kappa$ changes can be achieved. If there is any $\Delta\beta$ mismatch due to fabrication errors, it can be corrected by slightly differing Vt_1 and Vt_2.

Tuning voltages for all the switches in the array can be derived from a common regulated DC supply with potentiometer tapping. Once tuning is carried out, the bar state can be obtained by making $v_s = V_b$, where V_b is the bar state voltage for uniform $\Delta\beta$ operation. Switching is obtained by applying a signal v_s that switches between 0 and V_b.

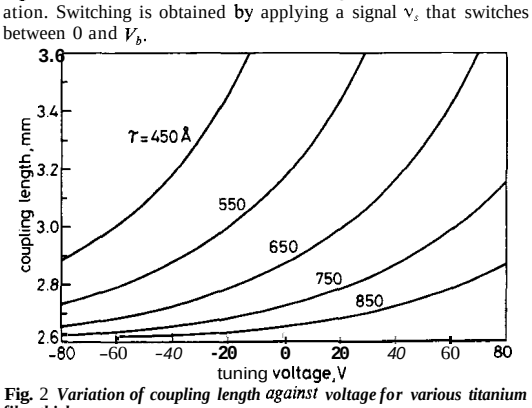

Fig. 2 ***Variation of coupling length against voltage for various titanium film thicknesses***

Method 2: In this method, two electrodes arc grounded and hence the pin out per switch in a switch array can be reduced. The signals for $\Delta\beta$ and $\Delta\kappa$ modulations are applied to the same set of electrodes. Either one of V_1 or V_2 can be a DC voltage and the other can be varied for switching. To tune for the cross state, equal voltages V_1 and V_2 (same as Vt_1 and Vt_2 of method 1) are applied. A difference between V_1 and V_2 **can** be used for correcting the $\Delta\beta$ mismatch as before. For switching, one of them, say V_2, can be changed to $Vt_2 + V_b$ ***so*** that $|V_1 - V_2| = V_b$. Thus for switching, V_2 switches between Vt_2 and $(Vt_2 + V_b)$. This is disadvantageous if Vt_2 **is** high, of the order of 10V, because $(Vt_2 + V_b)$ will be high, increasing the cost of the driver. Otherwise the high frequency signal V_b **V** will have to be biased externally over Vt_1. In ths case the first method **is** preferable.

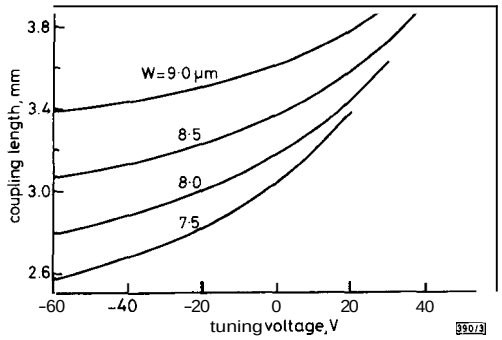

Fig. 3 ***Variation of coupling length against voltage for various widths of titanium film***

Analysis: The voltage requirement for various tolerances can be calculated theoretically. The calculations were based on the model suggested by Hawkins *ef a/.* [4]. Fig. 2 gives the variation of l_c with titanium film thickness. The values of other parameters arc, width of the titanium film = 8 μm, coupler gap = 2 μm, gap between inner and outer electrodes of one side = 2 μm, A = 1.3 μm, temperature of diffusion = 1050°C, duration of diffusion = 5 h. The voltage requirement **is** less if the film thickness is less; this is because, when the film thickness is less, the refractive index change ***An,*** of the waveguide will be smaller and then the coupling length will be more sensitive to small changes in ***An.*** The Figure indicates that voltages of the order of ±10V will be sufficient for tuning with length tolerances of the order of ±100 μm and for titanium thicknesses of 650 Å and lower. From Fig. **3** (titanium film thickness = 550 Å) it can be seen that dl_c/dV increases as the guide width decreases. This **is** because, when the width is smaller, mode confinement is poorer and hence the variation of mode size with index changes is greater.

Conclusion: We have suggested **a** new electrode structure to obtain cross-state tuning with uniform $\Delta\beta$ operation. If the fabrication tolerance is around ±100 μm, the tuning voltage required will be around ±10V (DC). With good quality fabrication (i.e. less error in length) the proposed method is advantageous compared to the popular alternating $\Delta\beta$ technique, because the number of signal drivers required is reduced by half.

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