(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, $l = L \leq L_f$, where $L$ is the length of the coupler and $L_f$ is the coupling length. However, $L$ should not be less than $L_0$. Hence, the minimum possible length will be $L = l + e$, where $e$ 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 $\Delta \alpha$ 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 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, $\Delta \alpha$ modulation is not generally considered because it calls for large values of $\Delta \alpha$ and thus an impractical voltage requirement. The idea is that it can be conveniently used to tune for the cross state because the $\Delta \alpha$ required is small. Theoretically any length can be tuned, but the voltage requirements limit the range of tuning. Unlike the alternating $\Delta \beta$ switch, the length on designing can be $L \geq L_0$, since $\Delta \alpha$ can be 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 $e$-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 two modes of operation](image)

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

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Indexing terms: Directional couplers, Optical couplers, Photonic switching

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 but 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 $|V|$ will be costly and each of these signals has to be interfaced to the integrated-optic chip through coaxial cables. Moreover the rise in the number of signal drivers will reduce reliability.

![Fig. 2 Variation of coupling length against voltage for various titanium film thicknesses](image)
Method 2: In this method, two electrodes are grounded and hence
the pin out per switch in a switch array can be reduced. The sig-
nals for $\Delta g$ and $\Delta k$ modulations are applied to the same set of elec-
trodes. Either one of $V_1$ or $V_2$ can be a DC voltage and the other
is the signal $V_2$, so that $V_1 - V_2 = V_t$. Thus for switching, $V_2$
switches between $V_t$ and $(V_1 + V_2)$. This is disadvantageous if $V_2$
is high, of the order of 10V, because $(V_1 + V_2)$ will be high,
increasing the cost of the driver. Otherwise the high frequency sig-
nal $V_2$ will have to be biased externally over $V_t$. In this case the
first method is preferable.

Analysis: The voltage requirement for various tolerances can be
calculated theoretically. The calculations were based on the model
suggested by Hawkins et al. [4]. Fig. 2 gives the variation of $I_i$
with titanium film thickness. The values of other parameters are:
- Width of the titanium film = 8µm
- Coupler gap = 2µm
- Gap between inner and outer electrodes of one side = 2µm
- Temperature of diffusion = 1050°C
- Duration of diffusion = 5h

The voltage requirement is less if the film thickness is less; this is because,
when the film thickness is less, the refractive index change $\Delta n$
of the waveguide will be smaller and then the coupling length will be
more sensitive to small changes in $\Delta n$. The Figure indicates that
voltages of the order of $\pm 10$V will be sufficient for tuning with
length tolerances of the order of $\pm 100$µm and for titanium thick-
ness of 650Å and lower. From Fig. 3 (titanium film thickness =
550Å) it can be seen that $\partial I / \partial V$ increases as the guide width
decreases. This is because, when the width is smaller, mode con-
finement is poorer and hence the variation of mode size with index
changes is greater.

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

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