Very low voltage single drive domain inverted $LiNbO_3$ integrated electro-optic modulator

F. Lucchi[1]**, D. Janner**[2*]**, M. Belmonte**[1]**, S. Balsamo**[1]**, M. Villa**[1]**, S. Giurgola**[1]**, P. Vergani**[1]**, V. Pruneri**[2,3]

[1]*R&D, Avanex Corporation Sede Secondaria, via Fellini 4, 20097, San Donato Milanese (MI), Italy*
[2]*ICFO - Institut de Ciencies Fotoniques, 08860, Castelldefels (Barcelona), Spain*
[3]*ICREA - Institució Catalana de Recerca i Estudis Avançats, 08010, Barcelona, Spain*
**Corresponding author:*

davide.janner@icfo.es

Abstract: Domain inversion is used in a simple fashion to improve significantly the performance of a waveguide electro-optic modulator in z-cut $LiNbO_3$. The waveguide arms of the Mach-Zehnder interferometer are placed in opposite domain-oriented regions under the same, narrower and more efficient electrode, so that opposite phase shifts (push-pull effect) can still be achieved despite the arms being subjected to the same electric field. Switching voltages close to 2 V are obtained, which allow 10Gb/s modulation with inexpensive drivers, such as those used for electro-absorption modulators, which deliver driving voltages well below 3V.

OCIS codes: (230.4110) Modulators; (130.3730) Lithium niobate

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1. Introduction

Over the last year the demand of integrated electro-optic $LiNbO_3$ modulators has been steadily increasing. Current driving voltages for 10 Gb/s are in the 4 to 5 V range in the telecom window centered at 1.55 μm [1]. Transponder makers would benefit from lower driving voltage modulators ($<$2.7 V) because these would allow the use of the cheaper drivers, designed for electro-absorption modulators (e.g. SiGe based), with a cost savings in the range of $ 100 per transmitter. Higher modulation efficiency (i.e. lower driving voltage-length product) would also allow producing more compact transmitters to be used with standard drivers. In this paper we show how domain inversion (DI) can be exploited to drastically reduce the driving voltage of integrated $LiNbO_3$ based modulators, down to values well below 3 V, while still keeping bandwidth in excess of 10 GHz. The corresponding switching voltage (measured at low frequency, typically 1 kHz) is close to 2 V.

DI in ferroelectrics, such as $LiNbO_3$, has been widely exploited in all-optical processes, e.g. quasi-phase-matched second harmonic generation, optical parametric oscillation and WDM frequency conversion [2, 3, 4, 5]. So far its use in electro-optics, where one of the interacting fields is at low or microwave frequency, has been mostly limited to quasi-velocity-matching devices using periodic structures [6, 7]. It has also been exploited to achieve a desired chirp value for the electro-optic modulated output wave from high-frequency and broadband integrated Mach-Zehnder modulators [8]. More recently, domain engineering of z-cut $LiNbO_3$ structures has been proposed to produce large bandwidth and very low voltage modulators where the push-pull effect in the Mach-Zehnder interferometric structure has been obtained by placing the waveguides in opposite-sign electro-optic coefficient regions (i.e. opposite-oriented domains) and under the same electric field [9]. Hence the optical fields in the two waveguides experience an opposite phase shift despite being subjected to the same electric field. As it was proposed in ref. [9], the hot travelling wave electrode can either be of Mach-Zehnder type (i.e. it follows the shape of the optical layout) [10] or a single straight electrode as in this work. This is in contrast with previous high frequency modulating structures in single domain crystals where the two waveguides are placed under two different electrodes having different (usually opposite sign) voltages [1]. With respect to previous modulating structures in single domain crystal, the proposed DI symmetric scheme allows to achieve at the same time maximum-efficiency, chirp-free and single-drive operation all at once.

2. Device concept and comparison with previous approaches

The cross section of the proposed modulator highlighting the working principle is shown in Fig. 1. Note that there is a silica based buffer layer between the hot electrode and lithium niobate crystal. This layer ensures at the same time low optical loss by keeping the evanescent optical field low in the lossy metal electrodes and velocity matching between the travelling optical and microwave fields.

With respect to previous structures of coplanar waveguide (CPW) modulator [1, 8] the proposed layout offers several advantages as summarised in table 1. Driving voltages (for similar device length) are close to those offered by dual drive structures (two waveguides under two hot electrodes driven by opposite sign voltages), with the advantage of being single drive, hence in the absence of any synchronization issue between two microwave lines. On the other hand the typical single-drive structure in single-domain z-cut has one of the two waveguides under the

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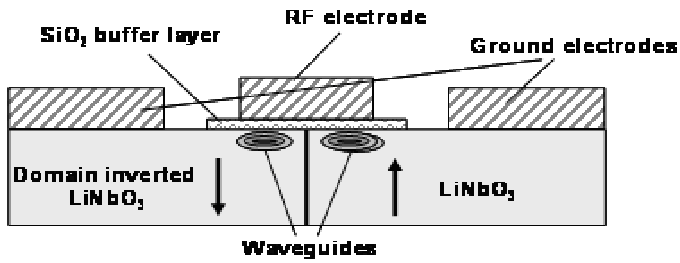

Figure 1. Cross section of proposed domain-inverted $LiNbO_3$ modulator.

ground electrode, which induces a lower electro-optic effect due to field spreading compared to the other waveguide under the narrower hot electrode. The result is that the typical driving voltage is about 1.5 times that of a dual-drive structure and 1.4 times that of the proposed geometry. Another complication of single-drive structure in single-domain z-cut is the residual chirp in the phase of the output modulated optical field, which makes it usable only for specific applications. Longitudinal domain inversion can be used to appropriately induce the targeted chirp in single-drive asymmetric structure [8]. Instead in our structure chirp-free operation is a consequence of the symmetry of electrodes with respect to waveguides, so that optical fields travelling in the two Mach-Zehnder arms experience same-amplitude (though opposite in sign) phase shifts.

Table 1. Comparison between previous configurations and our proposal.

Type	Structure	$V_\pi \cdot L$	Chirp	RF drive
#1	Standard CPW [1]	≈ 12 V· cm	$\neq 0$ (-0.7)	Single
#2	Dual drive CPW [1]	≈ 8 V· cm	0 (or any value)	Dual (opposite)
#3	CPW with longitudinal DI [8]	≈ 12 V· cm	Variable ($\approx$0)	Single
#4	Our proposal	≈ 9 V· cm	0	Single

Moreover, pyroelectric effects which are detrimental for thermal stability are reduced by the simultaneous presence of a domain inversion boundary and a symmetric structure (both optically and electrically) [9]. In fact, under temperature variations domain inversion (opposite crystal orientations) causes opposite-sign charges to develop at the interfaces and to produce opposite sign electric fields in the waveguides which tend to cancel each other out, thus reducing thermal drifts.

3. Design, fabrication and testing

The modulator we have fabricated is a single-drive Mach-Zehnder modulator with an active length of 43 mm. The device is designed according to the previous considerations–see Fig. 1–where the RF hot electrode is 20 μm thick and 18 μm wide, the gap between it and the ground electrodes is 11 μm, while the thickness of the SiO_2 buffer layer is about 1 μm. According to this geometry, the microwave index and the RF losses are estimated to be n_m=2.29 (with a mismatch δ=0.08 between microwave and optical indices) and $\alpha \simeq$1.3 dB/cm (@10 GHz) respectively. These values were also confirmed by experimental measurements. The optical waveguides were realized through Ti indiffusion (channel-width of 5 μm and inter-axes distance of 12 μm) so that for the fabricated modulator, the optical insertion loss is kept low,

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typically in the 3 to 4 dB range. High-voltage (>10 kV) pulsed poling is performed after Ti indiffusion on the 0.5-mm thick crystal. Figure 2 shows the top (z-) of the $LiNbO_3$ structure revealed by etching. The domain-inverted boundary is clearly in the middle of the two Ti indiffused waveguides which are in opposite-domain regions. In fact the process is now developed for a 4" wafer with a thickness of 0.5 mm. The uniformity of poling and waveguides over the full wafer size ensures a high yield (currently 95%) for the overall chip fabrication. Compared

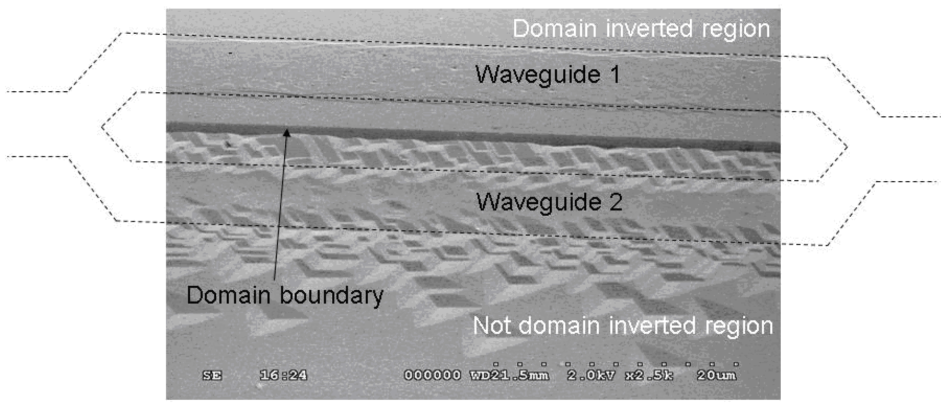

Figure 2. SEM image of etched $LiNbO_3$ structure. The domain boundary lies in between the two Mach-Zehnder waveguides.

to previous work on poled Ti indiffused substrates a breakthrough in our technological approach has been the possibility to induce domain inversion using high voltage pulses after Ti indiffusion without the need of any grinding of the z+ surface [11]. The grinding would otherwise lead to likely breakage of substrates, and is a time consuming process.

In Fig. 3 we show the microwave reflection coefficient (|S11|) and electro-optic response. From Fig. 3 one can see that the electrical reflection is always below -10 dB and the 3 dB electro-optic bandwidth is 10 GHz.

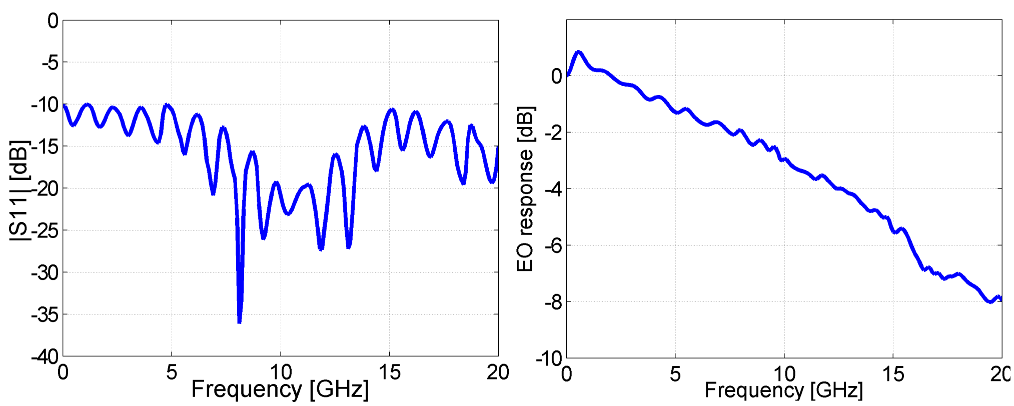

Figure 3. Typical modulator electrical reflection (S11) and electro-optic (EO) response .

The corresponding switching voltage is 2.1 V (measured at 1 kHz). The modulator could

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therefore easily be driven with significant extinction by a low-cost driver which typically provides less than 3 V for 10 Gb/s bit rate. When system measurements were carried out with an Inphi 1015EA driver (i.e. driver for electro-absorption modulators) and Agilent sampling oscilloscope (30 GHz optical head) a dynamic extinction of 13.5 dB (typical) was obtained, which is largely suitable for a 10Gb/s transmitter module.

4. Conclusions

In conclusion we have shown that domain inversion can be used to produce very low-voltage integrated $LiNbO_3$ modulators that can be driven by cheap electronics. It is also clear that the improvement associated with our structure is in the reduction of voltage length product (increase in efficiency); hence DI could also be used to shorten modulators for standard Mach-Zehnder modulator drivers, thus enabling greater integration. Besides driving voltage reduction the domain-inverted modulator offers several additional advantages with respect to a standard single-domain counterparts, including chirp-free operation and higher thermal stability. In the future more complex structures can be envisaged with the aim of tailoring the frequency response of the modulator (longitudinal DI) while still increasing the efficiency (transversal poling as in this work).

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