Integrated electro-optic modulators in micro-structured $LiNbO_3$

D. Janner[1], D. Tulli[1], M. Belmonte[2], and V. Pruneri[1,3]

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

Abstract - *We review recent advances in micro-structuring $LiNbO_3$ crystals and demonstrate the achievement of large bandwidths and lower driving voltages using domain inversion. We will report on a domain engineered Mach-Zehnder modulator for 10Gb/s transmission with ∼2V switching voltage driven by inexpensive Si-Ge drivers.*

Introduction

Optical networks as main carriers of information are continuously growing in importance due to the ever increasing demand in bandwidth. External $LiNbO_3$ modulators are still extremely effective [1], in particular for long haul and metro applications. With respect to e.g. semiconductor based modulators, $LiNbO_3$ market share could even become larger if performance, integration and cost further improve. Indeed, even though the use of velocity matched (VM) traveling wave electrodes configurations [1, 2] greatly increase the modulation bandwidth (BW), the potential of $LiNbO_3$ in terms of modulation efficiency has been far from being exploited. The frequency dependent microwave loss limits the bandwidth (BW) making it inversely proportional to active length L, similarly to the switching voltage (V_π), so that a trade-off exists between V_π and BW and the ratio BW/V_π is used as a figure of merit. To obtain improved efficiency (increase in BW/V_π), improved interaction (overlap integral) between microwave and optical fields is required. To this end, different solutions have been proposed [3, 4, 5] which, although effective in some cases, rely on sophisticated techniques, not ideal for a large scale production environment.

Domain inversion (DI) in ferroelectrics, such as $LiNbO_3$, has been widely exploited in many all-optical processes, even though its use in electro-optics, has been mostly limited to quasi-velocity-matching for nonlinear processes or to achieve a desired chirp value for high-frequency and broadband modulators [6]. More recently, domain engineering of z-cut $LiNbO_3$ structures has been proposed to produce large bandwidth and very low voltage modulators in single drive configuration [7]. 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. As a demonstration of the impact of our approach, we report the design, fabrication and test of a DI modulator with 15 GHz bandwidth and ∼2 V switching voltage suited for the use with inexpensive Si-Ge drivers.

Improvements in micro-structured domain inverted modulators

Recently, we have demonstrated that by using DI in $LiNbO_3$, an efficient modulator can be designed and produced [7]. The cross section of the proposed modulator highlighting the working principle is shown in Fig. 1c. 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 traveling optical and microwave fields.

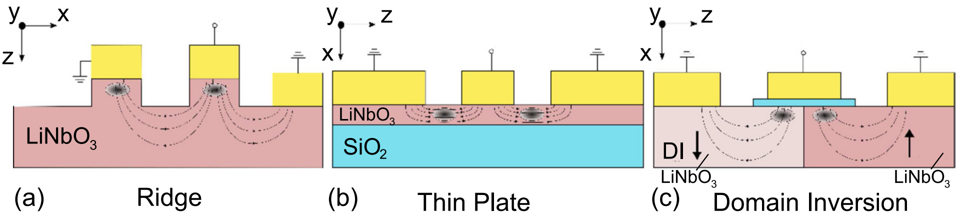

Figure 1: Comparison between different modulator schemes: a) ridge, b) thin plate, c) domain inverted push-pull

With respect to previous structures of coplanar waveguide (CPW) modulator [1, 6] the proposed layout offers several advantages, and with respect to the other approaches including ridge modulators [4, 5] or thin plate [3], it offers greater feasibility, even though the performance in some cases is slightly lower. The comparison between classical and more different schemes is summarized in table 1, where the characteristic parameters are considered: switching voltage ($V_\pi L$), microwave-optical overlap (Γ as defined in [2]), residual chirp factor (α) and RF drive configuration. 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 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.

Table 1: Comparison of the performances of different configurations

Structure	$V_\pi \cdot L$ (V· cm)	Γ	Chirp (α)	RF drive
$LiNbO_3$ physical limit	≈ 3.6	1	0	Single
Standard CPW [1]	≈ 12	0.3	$\neq 0$	Single
Dual drive CPW [1]	≈ 8	0.45	arbitrary(=0)	Dual
CPW with longitudinal DI [6]	≈ 12	0.3	≈ 0	Single
Domain inverted push-pull	≈ 9	0.4	0	Single
Ridge [4, 5]	≈ 6	0.6	≈ 0	Single
Thin plate [3]	≈ 9	0.4	≈ 0	Single

As an experimental demonstration of this type of modulator, we have fabricated a single-drive Mach-Zehnder with an active length of ~ 40 mm. To obtain the required inverted domain structure, high-voltage (>10 kV) pulsed poling is performed after Ti indiffused waveguide fabrication on the 0.5-mm thick crystal [8].

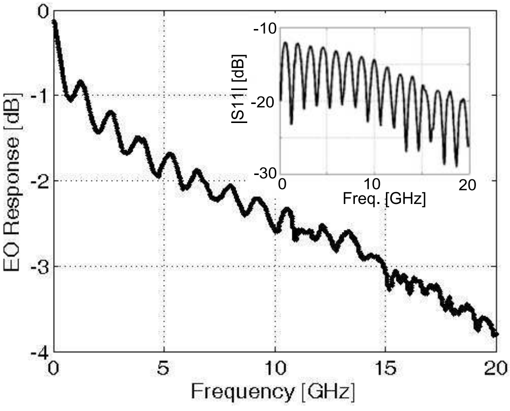

Figure 2: Domain engineered modulator electro-optic response (|S21|) and electrical reflection parameter (|S11| in the inset). The power reflected is below 10 dB over all the frequency range.

After DI, the modulator chip undergoes standard fabrication, e.g. silica buffer layer deposition, electroplated thick electrode, etc. In Fig. 2 we show the microwave reflection coefficient (|S11|) and the corresponding electrical frequency response (|S21|). From the figure one can see that the electrical reflection is always below -10 dB and the -6 dB electrical bandwidth is 15 GHz, which also is the expected value for the -3 dB electro-optic bandwidth.
The corresponding switching voltage is $\sim$ 2 V (measured at 1 kHz). The modulator could 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, thus allowing to use inexpensive Si-Ge electro-absorption drivers to modulate. We carried out system measurements for a typical low-voltage modulator driven by a Inphi 1015EA driver. The eye opening showed a performance suitable for standard optical communication at 10 Gb/s, with a dynamic extinction ratio >13 dB.

Conclusions

We have reported on micro-structured electro-optic waveguide $LiNbO_3$ modulators which are based on the use of domain inversion in order to enhance the BW/V_π figure of merit. We have experimentally demonstrated the feasibility of a modulator with a switching voltage of $\sim$2 V and a bandwidth of 15 GHz, suitable for inexpensive ultra low-voltage Si-Ge drivers. Besides, system measurements demonstrate the good performance in term of extinction ratio (>13 dB) and eye opening that make the device suited for 10 Gb/s transmission.

Acknowledgments

We acknowledge support from the Spanish national programs Plan Nacional no. TEC 2007-60185 and Juan de la Cierva.

References

[1] L. Wooten, K.M. Kissa, A. Yi-Yan, E.J. Murphy, D.A. Lafaw, P.F. Hallemeir, D. Maack, D.V. Attanasio, D.J. Fritz, G.J. McBrien, D.E. Bossi, *IEEE J. Sel. Top. Quantum* Electron. **6**, 69–82 (2000).

[2] R. C. Alferness, *IEEE Trans. Microwave Theory Tech.*, **30**, 1121–1137 (1982).

[3] K. Aoki, J. Kondo, A. Kondo, T. Ejiri, T. Mori, Y. Mizuno, M. Imaeda, O. Mitomi, M. Minakat, *J. Lightwave Technol.*, **24**, 2233–2237 (1982).

[4] N. Anwar, S. S. A. Obayya, S. Haxha, C. Themistos, B. M. A. Rahman, and K. T. V. Grattan, *J. Lightwave Tech.*, **20**, 826–833 (2002).

[5] M. Garcia Granda, H. Hu, *OptoEL*, MOI-13, (2007).

[6] N. Courjal, H. Porte, J. Hauden, P. Mollier and N. Grossard, *J. Lightwave Technol.* **22**, 1338–1343 (2004).

[7] F. Lucchi, D. Janner, M. Belmonte, S. Balsamo, M. Villa, S. Giurgola, P. Vergani, V. Pruneri, *Opt. Exp.*, **15**, 10739–10743 (2007).

[8] D. Janner, D. Tulli, F. Lucchi, P. Vergani, S. Giurgola and V. Pruneri, Appl. Phys. A, **91**, 319-321 (2008).