Domain inversion in phase-velocity matched $LiNbO_3$ electro-optic modulators for large bandwidth and low driving voltage

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Abstract - An appropriate sign reversal of the electro-optic interaction is proposed in velocity matched modulators to significantly increase the bandwidth to driving voltage ratio (BW/V_π). The concept is applied to domain inverted $LiNbO_3$ and may lead to >30% increase for BW/V_π.

Keywords: Optoelectronic devices, modulators, guided-wave optics

Introduction

In electro-optic (EO) phase and intensity modulations there are two main limiting factors for the bandwidth (BW): phase-velocity mismatch between the optical waves and microwaves and frequency-dependent microwave loss [1]. The former is due to dispersion, i.e. different effective refractive indices (Δn_{eff}) at optical and microwave frequencies, and produces an increasing phase-shift between the optical wave and microwave along the modulator length, which eventually leads to a reversal of the sign of the EO interaction. This phase-shift, which increases with the microwave frequency, would limit the effective interaction length (i.e. the modulation efficiency): the higher the microwave frequency the lower the modulation efficiency, which is equivalent to say that the longer the modulator the lower the bandwidth. To overcome this limitation, phase velocity matching (i.e. $\Delta n_{eff} = 0$) can be achieved by an appropriate design of the transverse modulator geometry, for example through the use of buffer layers and thick electrodes. However even in the case of phase velocity matching (PVM) the BW would be limited by the frequency dependent microwave loss, which increases with microwave frequency, thus the higher the microwave frequency the lower the effective interaction length. On the other hand the driving voltage V_π, i.e. the voltage that produces a π phase shift of the optical wave, decreases for increasing modulator length, thus a trade-off exists between large BW and low V_π. Therefore one can assume the ratio BW/V_π as figure of merit for an EO phase or intensity modulator.

In this paper we present a simple method that allows to overcome the limitation due to frequency dependent microwave loss of conventional PVM modulators, which can lead to a significant improvement of the BW/V_π ratio.

Summary

The idea at the basis of our work is to provide a two-section modulator, such that the phase modulation of the optical wave in the second section, located near the end of the device, has opposite sign to that of the first section. Since the phase-shift is proportional to the product of the electro-optic coefficient (r) and the applied electric field (E_{app}), one could change the sign of either r or E_{app} in order to change the sign of the phase modulation contribution. The sign of r is related to tensorial properties and can be usually changed by reversing the crystal orientation (e.g. in $LiNbO_3$ through domain inversion [2]) or poling orientation (e.g. in poled polymers and poled glass). The sign of E_{app} can instead be changed by an appropriate electrode design, e.g. interdigitated electrodes.

It is worth noting that while interdigitated electrodes [3] and domain inversion [4] have already been proposed with the aim of compensating for the phase-velocity mismatch between

optical and micro waves, in our application these techniques are instead used in structures which are already PVM (or at least nearly PVM).

From now on we will refer to a $LiNbO_3$ based Mach Zehnder modulator which is domain inverted to change the sign of *r* along the direction of propagation of the optical and microwave signals (see fig.1). However it is clear that the idea can be applied to other materials, e.g. poled polymers or glasses, as well as to other modulator designs, e.g. interdigitated electrodes.

Due to the frequency dependence of the microwave loss, at high frequency the electric field becomes rapidly attenuated, so that only the first section is significant in inducing the optical phase shift. On the other hand, at low frequency the microwave attenuation is lower and almost the whole modulator length is effective in inducing the phase shift. The result of the discontinuity in *r* (in combination with phase velocity matching) is that the device operates in three successive zones along the modulator length: in the upstream zone, desirable phase modulation of the optical wave is induced for all frequencies in the bandwidth of the device; in the middle zone, desirable phase modulation is induced for frequencies in the upper part of the bandwidth, but phase modulation in the lower frequencies becomes excessive; while in the downstream zone, there is no significant phase modulation at higher frequencies but the excess modulation at lower frequencies is reduced by the fact that phase modulation has opposite sign with respect to the upstream and middle zones.

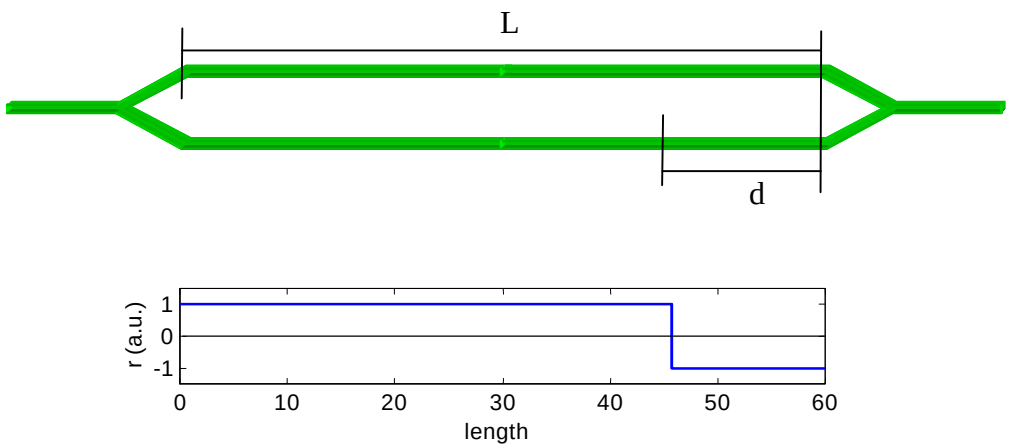

Fig. 1 Mach-Zehnder intensity modulator with double-domain inverted structure.
L is the modulator length and *d* the last section with opposite domain orientation.

In the ideal case in which phase-velocity matching is exact throughout the device, the optimum distance from the downstream end of the device to the discontinuity (*d*) can be determined by solving the equation

$$\sqrt{2}/2 \cdot (L-2d) = 1/\alpha \cdot (1 - 2e^{-\alpha (L-d)} - e^{-\alpha L})$$

where L is the total optical length of the device and α is the microwave loss at the upper limit of the intended microwave bandwidth of the device (at which the optical output is 3dB below its maximum).

The EO response is in this way flattened even with large modulator lengths *L* . This allows to combine low values for V_π (basically stemming from large length *L*) with large bandwidth (arising from flattened response). Figs. 2 and 3 show a comparison between conventional (single domain) modulators and our proposal (double domain structure). For this comparison we have

assumed the same transversal modulator structure. This is justified by the fact that domain inversion does not change the linear properties of the material, so that the optimization of transversal structure for conventional (single domain) and our modulators (double-domain) is basically identical. In fig. 2, the green (dotted) and red (dotted-dashed) lines show the EO response of conventional modulators with lengths L = 25.6 mm and L = 32 mm respectively, and corresponding V_π = 5.3 V and V_π = 4.3 V . The blue (continuous) line shows the EO response of a modulator with our design: with a modulator length of 60 mm we reach the same bandwidth as the conventional modulator with the larger V_π obtaining on the other hand a lower V_π. Fig. 3 shows V_π as a function of the modulation frequency. It can be clearly seen that with our design we ensure a bandwidth of 30 GHz with a V_π of 4.35 V, while, on the one hand, a conventional modulator with the same bandwidth would require V_π = 5.3 V and a conventional modulator with the same V_π as ours achieves a bandwidth of only 20 GHz.

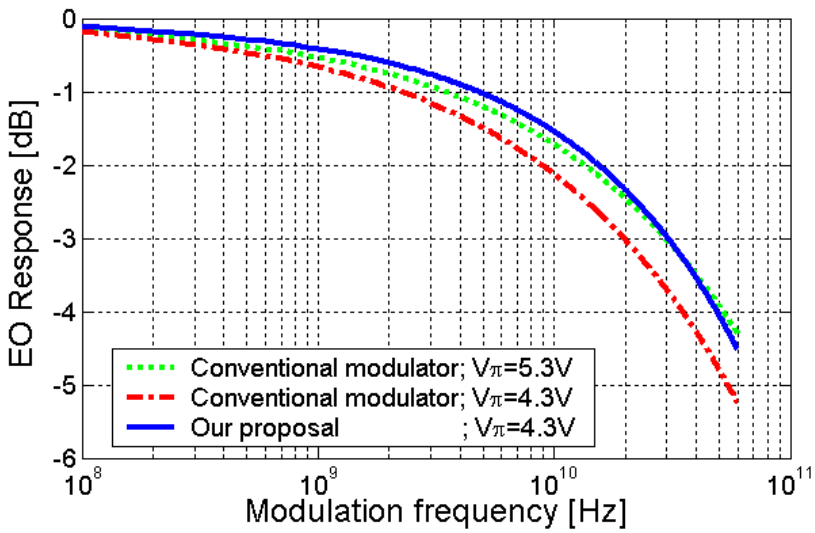

Fig. 2 Comparison between our proposal and conventional modulators in terms of EO response

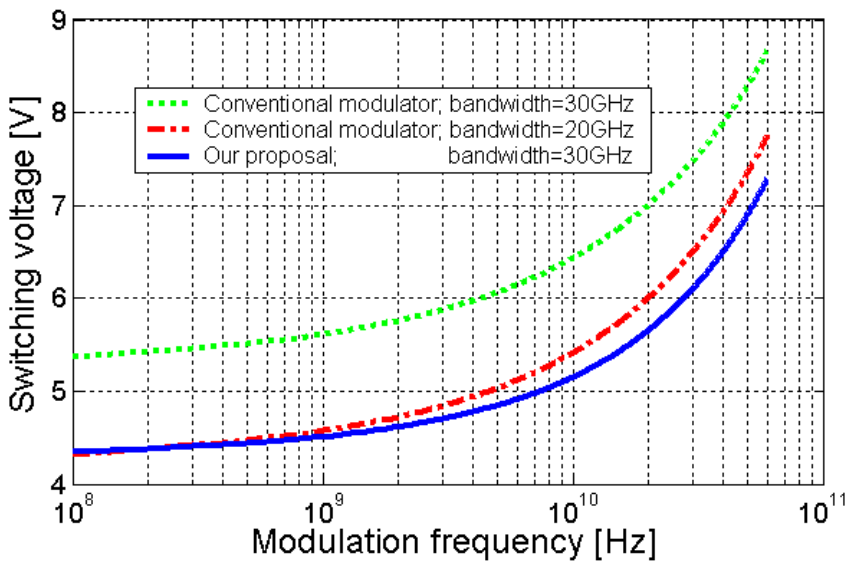

Fig. 3 Comparison between our proposal and conventional modulators in terms of V_p

Conclusions

We have presented a novel and simple method to increase the bandwidth to driving voltage ratio in phase-matched electro-otpic modulators. With respect to conventional modulators an improvement of up to 50% is expected and this could be crucial in applications, eg. at high bit rates (modulation frequencies) a decrease of driving voltage could be welcome to use cheaper electronic drivers. Experiments are underway to realise the proposed double domain inverted structure in a $LiNbO_3$ intensity modulator. However the concept can be applied to other materials (where the electro-optic coefficient can be modulated, e.g. semiconductors, poled polymers and glasses) and achieved by other means (e.g. intedigitated electrodes in a uniformly poled material).

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