Pushing distributed PMD compensator performance toward highest bit rates by Lithium Niobate–Tantalate or Lithium Tantalate crystals

S.Bhandare and R. Noé
Dept. of Optical Communication and High-Frequency Engineering,
University of Paderborn, Warburger Str. 100, 33098 Paderborn, Germany
suhas@ont.upb.de, noe@upb.de

Abstract: Simulations show that cascaded integrated optical TE-TM mode converters with endlessly adjustable coupling phase permit distributed PMD compensation at 160 Gbit/s and 640 Gbit/s if they are implemented in $LiNb_{1-y}Ta_yO_3$ or $LiTaO_3$ crystals, respectively.

Keywords: Polarization mode dispersion, Lithium Niobate, Lithium Tantalate, guided-wave optics

Introduction

Polarization mode dispersion (PMD) is caused by noncircular fiber cores and limits the capacity of optical trunk lines. It can be compensated if appropriately oriented birefringence is added at the receiver side in reverse order. Particularly suited is *X*-cut, *Y*-propagation $LiNbO_3$ (LN). Its natural birefringence (0.24 ps/mm) can be oriented by electro-optical mode converters in order to cancel the differential group delay (DGD). The principle is based on the spatially weighted coupling between two waves with different propagation constants [1]. The phase difference between one mode and the coupled mode therefore depends on the position where coupling occurs and is periodic with the beat length $\Lambda = \lambda/\Delta n$ of ~22µm. Interdigital electrodes are needed for phase matching. The widths W of fingers and gaps G are ~Λ/4. The coupling factor is $\kappa \cong \hat{\Gamma}(\pi/2)n^3 r_{51}(V/G)\lambda^{-1}$, where $\hat{\Gamma}$ is a weighted field overlap integral factor and n is the average refraction index of the waveguide. r_{51} is the relevant electrooptic coefficient in pm/V and V is the inter-electrode voltage.

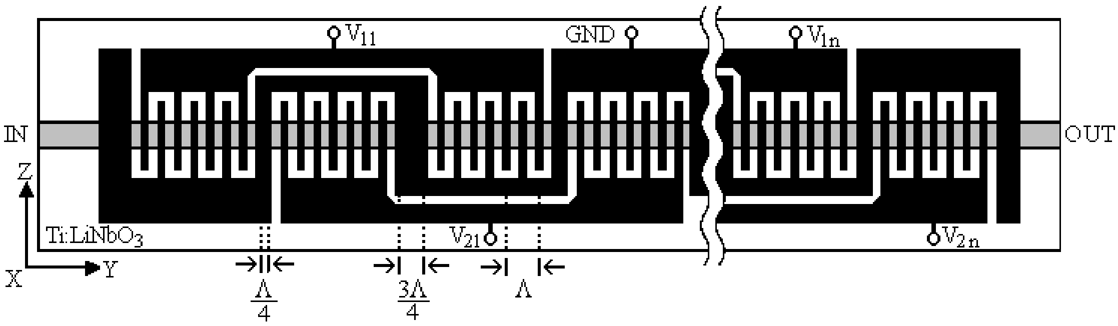

Figure 1: Structure of 2-phase mode converters on *X*-cut, *Y*-propagation $LiNbO_3$

Figure 1 shows the electrode structure of a chip used in [2, 3] where successful PMD compensation was demonstrated. Voltage $V_{1,i}$ $(i = 1...n)$ acts on one set of comb electrodes and performs mode conversion in phase. Voltage $V_{2,i}$ acts on another set of comb electrodes which are translated, with respect to the first, by $\Lambda/4$, and performs mode conversion in quadrature. The resulting local complex coupling factor is proportional to $V_{1,i} + jV_{2,i}$ [4]. This type of LN-based PMD compensator (PMDC) should work up to at least 40 Gbit/s. At 160 Gbit/s a poor performance is to be expected because the experimentally needed length for one full mode conversion is on the order of 5 mm. This means that the corresponding DGD of about 1.2 ps is only partly orientable. However, PMD compensation at 160Gbit/s or beyond seems to be mandatory to maximize dispersion-shifted fiber capacity, in particular in all Japan. We show that $LiTaO_3$ (LT) and a mixture $LiNb_{1-y}Ta_yO_3$ (LNT), also known as lithium niobate–tantalate, are suitable for PMD compensation at highest bit rates.

LNT crystals

Mixed ferroelectrics have been the focus of intensive fundamental and applied research for many years. Interest in the study of these materials arises from the fact that the physical properties of crystalline materials are governed to a large extent by the composition of the crystals, thus can be tuned by varying the composition. One of the simplest ferroelectric mixed crystal systems is lithium niobate–tantalate (LNT), as both end members exhibit the same crystal structure (space group *R3c*) with only slight differences in the lattice and positional parameters. The physical properties can be very easily tuned by varying the parameter y in the composition of LNT crystals. To a certain degree, the mixed system yields a simple crystal modelling that may lead to well functional materials and devices, which has direct implication for PMD compensation in optical communication.

Lithium niobate is a slightly nonstoichiometric, typically Li-deficient, preferably grown at the congruently melting composition with 48.5 Mol% of Li_2O. A large variety of dopants ranging from +1 valent state H^+ to the +3 valent state such as rare earth cations can be introduced into the crystal structure frame of lithium niobate. Most are known to occupy Li-sites. In contrast to these Li-site dopants, tantalum is isomorphic to niobium and replaces niobium when introduced into the crystal structure frame of LN. Tantalum can substitute niobium up to 100%. Any changes in the crystal composition will finally affect all physical properties of the crystal such as the linear dielectric response, i.e. refractive index, electro-optic coefficients and so on. It has been shown in [4] that refractive index and electro-optic coefficients depend linearly on the Ta content y in LNT crystals. Therefore one can tailor the birefringence of this mixed crystal especially for PMD compensation at higher bit rates.

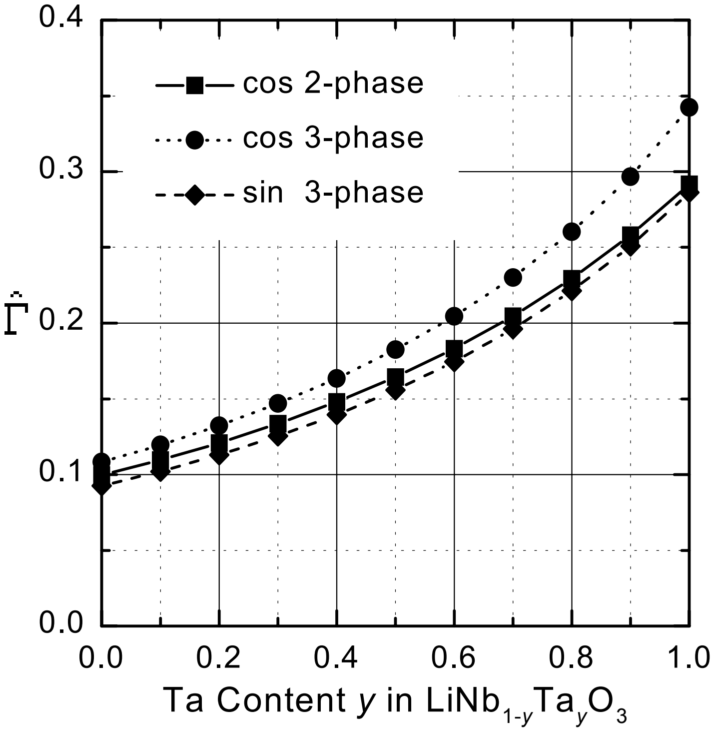

Figure 2: Weighted field overlap integral factor $\hat{\Gamma}$ as a function of Ta content y for TE-TM mode converters in lithium niobate tantalate crystals

X-cut, Y-propagation LNT

As has been mentioned in [5], the 2-phase implementation is not the only possible choice. If isolated electrodes crossings are available then 3-phase electrodes can be used with electrode widths and gaps equal to $\Lambda/6$. For further details of 3-phase electrode design the reader is referred to [6]. The ordinary refractive index n_o and the relevant electro-optic coefficient r_{51} depend linearly on the Ta content y in LNT crystals: n_o=2.2125-0.07y, and r_{51}=28-8y. Figure 2 shows the calculated optimum weighted field overlap integral factor $\hat{\Gamma}$, as defined in [7], for 2-phase as well as two representative cases of 3-phase TE-TM mode converters with interdigital electrodes. The numbers can be directly compared

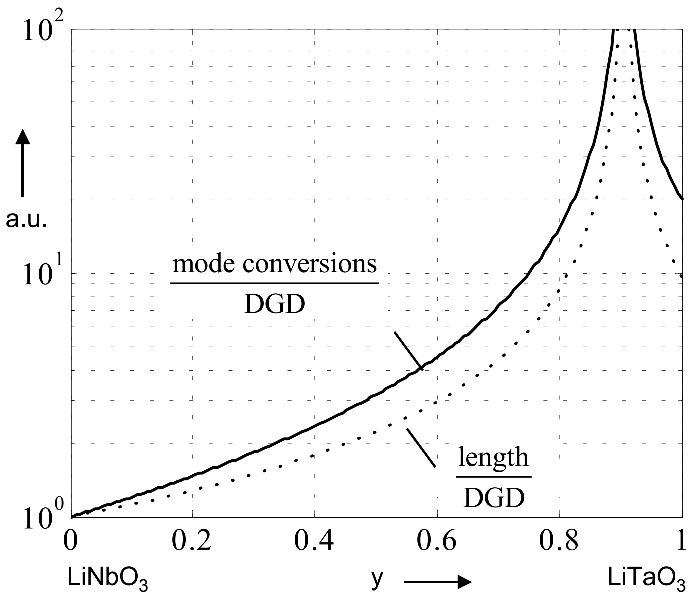

Figure 3: mode conversions/DGD and length/DGD for a TE-TM mode converter in LNT as a function of Ta content *y*.

because the 2-phase $\hat{\Gamma}$ has been halved due to the fact that the 2-phase design need at least twice the length of the 3-phase design.

Using this $\hat{\Gamma}$ and assuming 2-phase electrodes, the achievable number of full mode conversions per DGD at electric field strength near breakdown (10V/µm), and the required length per DGD have been calculated as a function of the Ta content *y* in the LNT crystals (Figure 3). Pure LN allows for ~8 full mode conversions / ps in theory if $\hat{\Gamma}=1$, and ~0.8/ps experimentally, in agreement with theory ($\hat{\Gamma}\approx 0.1$). Pure LT allows for ~20 time more mode conversions/DGD. The length/DGD is ~4.2mm/ps in LN, and ~42mm/ps in LT. But this should not be problematic since less PMD may be expected in links for highest bit rates. LT alone should work in principle up to at least 640 Gbit/s. Appreciable advantages over pure LN with the potential of reaching 160 Gbit/s can also be expected for low *y* which may be accessible either by incorporating Ta into LN during crystal growth or later by thermal in-diffusion. An interesting situation occurs near $y=0.9$ where the sign reversal of Δn promises Tbit/s PMD compensation. A major problem for large *y* in LNT and pure LT are the large beat lengths, which scale proportional to the length/DGD. High voltages are required to reach fields near breakdown, even for 3-phase electrodes where the gaps are smaller (~370 V in LT).

Z-cut LT

This problem is solved in *Z*-cut $LiTaO_3$. Figure 4 shows the needed electrode pattern. Several periods will form one in-phase and quadrature mode converter and several mode converters will form a distributed PMD compensator. The voltage requirements are independent of the beat length Λ because the electric field perpendicular to the waveguide, parallel to the chip surface is decisive. Small gaps of 6...10 µm gaps yield already large overlap factors but require modest voltages (110 V for 10 µm, conveniently accessibly by 300 V transistors). The gaps between neighbour electrodes may be slightly wider than those across the waveguide. This is not a problem since Λ is large. Multiphase electrodes are therefore most efficient. An advantageous example is a 4-phase design which only needs two independent voltages (Figure 4).

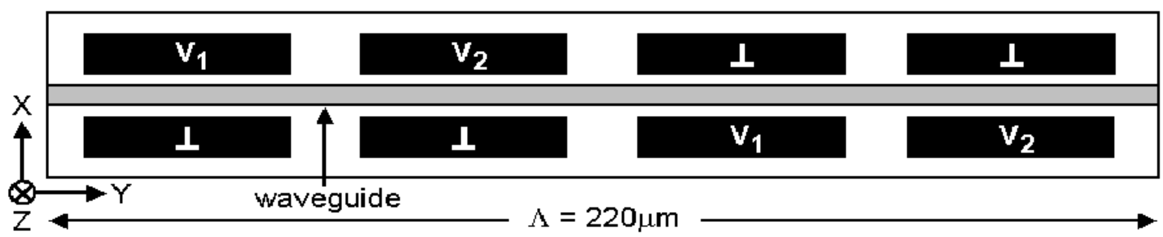

Figure 4: Electrode structure of a one period of a mode converter on Z-cut $LiTaO_3$

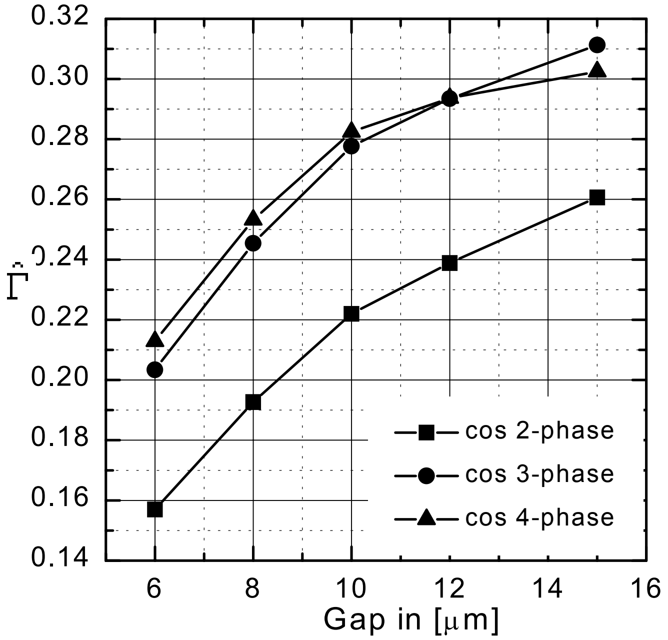

Figure 5: Weighted field overlap factor $\hat{\Gamma}$ as function of gap in μm

Figure 5 shows the weighted field overlap factor $\hat{\Gamma}$ for representative voltage patterns as function of the gap in μm. The other cases, shifted by Λ/12 for the 3-phase and by Λ/8 for the 4-phase case, behave roughly equivalent. The 4-phase outperforms the 3-phase case unless the lateral gap is so large that the compulsory longitudinal gaps consume too large a percentage of a period Λ. For a 10 μm gap, $\hat{\Gamma}$ is about the same (0.28) as for *X*-cut *Y*-propagation LT. So we may expect ~16 mode conversions/DGD, which is ~20 times more than in LN, and this should be fine for up to 640Gbit/s.

Conclusions

The birefringence Δn and the r_{51} electrooptic coefficient decrease linearly with increasing Ta content *y* in lithium niobate-tantalate crystals. A Ta content *y* of up to 0.5 is good to realize a PMD compensator for about 160 Gbit/s. *Z*-cut LT is suitable for PMD compensation up to 640 Gbit/s. In the *Z*-cut the voltage requirements are independent of the beat length, and 4-phase electrodes are attractive.

Acknowledgement

is made to Prof. W. Sohler, Prof. K. Buse, and Prof. K. Betzler for useful discussions.

References

[1] F. Heismann and R. Ulrich, *IEEE J. Quantum Electron.*, **QE-18**, 767-771, 1982.
[2] D. Sandel et al., *Proc. ECIO'99*. Turin, Italy, **PDP**, 17-19, April 14-16, 1999
[3] R. Noé et al., Electron. Lett. **35**, 652-654, 1999
[4] D. Sandel, R. Noé, *Proc. ECIO'99*. Turin, Italy, 237-240, April 14-16, 1999
[5] D. Xue, K. Betzler, H. Hesse, *Solid State Comm.*, **115**, 581-585, 2000.
[6] S. Bhandare and R. Noé, *Proc. ECIO'01*, Paderborn, Germany, 172-174, 2001
[7] S. Bhandare and R. Noé, *Appl. Phys. B*, **73**, 481-483, 2001.