Reduced number of control variables for fast control and zero-mean voltages for DC drift suppression in distributed $LiNbO_3$-based PMD compensators

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Abstract: Cascaded mode converters on a birefringent X-cut, Y-propagation $LiNbO_3$ chip are ideal "distributed" PMD compensators. Here we show how the number of needed control variables can be significantly reduced, and how DC drift can be suppressed.

Keywords: PMD compensator, $LiNbO_3$, differential group delay profile, DC drift

Introduction

Polarization mode dispersion (PMD) [1] is a big obstacle for high-capacity, long-haul optical communication systems, but can in principle be fully removed by an optical PMD compensator (PMDC) [2]. A "distributed" PMDC with cascaded in-phase and quadrature mode converters in X-cut, Y-propagation $LiNbO_3$ is best suited for this task because of its ability to correct also higher orders of PMD [3, 4]. Waveguide nonuniformity can significantly decrease the conversion efficiency of long mode converters. Apart from improved fabrication the only way to combat it is to subdivide the mode converters into fairly short sections. However, it has been argued that a large number of electrode voltages can not be controlled sufficiently fast. Here we show that this is not true, that waveguide nonuniformity, highest mode conversion efficiency and fastest control speed do not exclude each other. Another potential problem is DC drift: Charges generated by the pyroelectric effect are separated under the influence of a static external electric field, thereby weakening this field inside and near the waveguide. Ion migration in the buffer layer and/or conductivity disturbances of the crystal cause a similar effect. DC drift limits are not specified for commercial $LiNbO_3$ polarization transformers, for good reasons. We show that distributed PMDCs can be driven by DC-free voltages, which avoids drift altogether.

Reduced number of control parameters tolerates waveguide-nonuniformity

An in-phase and quadrature mode converter may be called a Soleil-Babinet analogon $\mathrm{SBA}(j, y)$ [2] because of the analogy to a Soleil-Babinet compensator. It is described by a Jones matrix or a 3×3 rotation matrix

$$\begin{bmatrix} \cos j/2 & je^{jy}\sin j/2 \\ je^{-jy}\sin j/2 & \cos j/2 \end{bmatrix}, \quad \begin{bmatrix} \cos j & -\sin y \sin j & \cos y \sin j \\ \sin y \sin j & \cos^2 y + \sin^2 y \cos j & \cos y \sin y\,(1-\cos j) \\ -\cos y \sin j & \cos y \sin y\,(1-\cos j) & \sin^2 y + \cos^2 y \cos j \end{bmatrix},$$

respectively. A DGD t is represented by a phase shifter $\mathrm{PS}(-wt)$ with Jones and rotation matrices

$$\begin{bmatrix} 1 & 0 \\ 0 & e^{jwt} \end{bmatrix}, \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos wt & \sin wt \\ 0 & -\sin wt & \cos wt \end{bmatrix},$$

respectively, where w is the optical angular frequency. The whole distributed PMDC is approximately described by the Jones or rotation matrix product

$$\mathrm{PMDC} = \prod_{i=n}^{1}\left(\mathrm{PS}(-wt_i)\,\mathrm{SBA}(j_i, y_i)\right). \qquad (1)$$

The product must be executed from left to right with descending index i while the light passes the SBAs and PSs in ascending order i. A longitudinally variable pattern of in-phase voltages $V_{1,i}$ and quadrature voltages $V_{2,i}$ couples TE and TM modes. Using a constant G we can write

$$j_i e^{j y_i} = G\left(V_{1,i} + jV_{2,i}\right). \quad (2)$$

A pigtailed PMDC similar to that in [3, 4] was electrooptically investigated. It had n = 69 pairs of in-phase and quadrature electrodes, each segment $i = 1...n$ being ~1.27mm long. The total PMD was ~23ps, which is good for 40Gbit/s PMD compensation. The PMDC was operated with a horizontal input polarization in the waveguide. A polarimeter was connected to the PMDC output. Consider the case when all voltages except those of segment i are zero. With PMDC expressed by its Jones or its rotation matrix the output polarization state is given by the Jones or normalized Stokes vector

$$\begin{bmatrix} \cos j_i/2 \\ je^{-j(y_i+z_i)}\sin j_i/2 \end{bmatrix} = \mathrm{PMDC}\cdot\begin{bmatrix}1\\0\end{bmatrix}, \qquad \begin{bmatrix} \cos j_i \\ \sin(y_i+z_i)\sin j_i \\ -\cos(y_i+z_i)\sin j_i \end{bmatrix} = \mathrm{PMDC}\cdot\begin{bmatrix}1\\0\\0\end{bmatrix}, \quad (3)$$

respectively. Unequal phase shifts $z_i = -w\sum_{k=i}^{n} t_k$ (modulo $2p$) represent waveguide nonuniformity. Four voltage pairs $V_{1,i} + jV_{2,i} = 20\mathrm{V}\cdot\{1, j, -1, -j\}$ were applied sequentially to each of the electrodes in section i, and the output polarization state was measured. Eqns. (2), (3) allowed to determine j_i and z_i. Performance was best at l = 1540nm, where j_i varied somewhat as a function of i but not too much (Fig. 1). However, z_i varied a lot. If a number of adjacent in-phase electrodes were connected in parallel, and likewise for quadrature electrodes, then a low mode conversion efficiency would result, especially for i = 25...45 where adjacent z_i differ by about p.

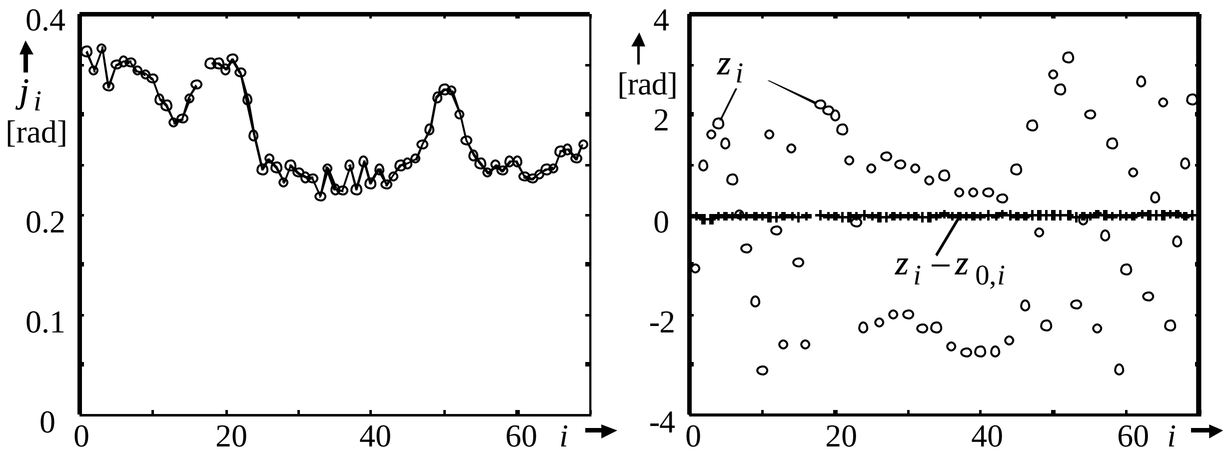

Fig. 1: Polarization change j_i (left), and its orientation z_i (o) and orientation error $z_i - z_{0,i}$ (+, solid line) for $V_{1,i} + jV_{2,i} = 20\mathrm{V}$ (right). Point i = 17 is omitted where both electrodes had internal shorts to ground.

There is a simple remedy: The voltage pairs $V_{1,i} + jV_{2,i}$ in (2) are not applied directly but are first multiplied by $e^{-jz_{0,i}}$. This replaces $y_i + z_i$ in (3) by $y_i + z_i - z_{0,i}$. The values $z_{0,i}$ should be equal to z_i and must be measured once in factory for all i. We took the measured z_i values as the calibration set $z_{0,i}$, and repeated the measurement to obtain new z_i values and test stability. Fig. 1

shows the resulting orientation error $z_i - z_{0,i}$. It ranged from –0.08 to +0.01 rad and may be partly due to multipath reflections at the straight chip endfaces. Now the effects of any set of segments can be combined because the quantity $j_i e^{j(y_i + z_i)} \approx j_i e^{j(y_i + z_{0,i})}$ has become user-accessible.

In PMD compensation algorithms it is common to dither various electrode voltages, one at a time, and to optimize them by a multidimensional gradient search using one or more control criteria. For a maximum voltage of 55V (= 10V/mm) a waveguide length of ~4...6mm will be needed for full mode conversion, and it is therefore possible to reduce the number of control variables below $2n$. A straightforward approach is to specify, say, 4 “discrete” polarization transformers at 0, $L/4$, $L/2$ and $3L/4$ where L is the chip length. This PMDC needs ≤48 voltages but just 8 control variables, and is 4 times more powerful than a PMDC featuring one commercial X-cut, Z-propagation $LiNbO_3$ device, which requires up to 16 control variables for its 8 waveplates.

An alternative approach, which may permit highest PMDC performance, employs a number of spatial Fourier coefficients $F_k = n^{-1} \sum j_i e^{j(y_i + z_{0,i})} e^{-j2p\, ik/n}$ as control variables. The required inverse Fourier transform and multiplication can be implemented in an FPGA for fast execution,

$$V_{1,i} + jV_{2,i} = G^{-1} e^{-jz_{0,i}} \sum F_k e^{j2p\, ik/n} .$$

The PMD vector W has a length equal to the differential group delay (DGD) and points in the direction of a principal state-of-polarization in the 3-dimensional normalized Stokes space. If n DGD sections are cascaded the overall PMD vector is given the sum $\mathrm{W} = \sum_{i=1}^{n} \mathrm{W}_i$ of individual PMD vectors $\mathrm{W}_i = \mathbf{R}_{<i}^{-1} \mathrm{W}_{local,i}$. The W_i are referred to the input of the whole cascade whereas $\mathrm{W}_{local,i}$ are the local individual PMD vectors. $\mathbf{R}_{<i}$ is the 3×3 rotation matrix representing all DGD sections (PSs) and SBAs which precede the DGD section i. Plotting the sequence of W_i in such a way that the tail of W_{i+1} starts from the head of W_i results in a DGD profile [5, 2]. Its endpoint is given by W. For a distributed PMD compensator the DGD profile is a straight rod as long as no voltages are applied. The Fourier coefficient F_0 causes a bend or loop, and F_k with $k \neq 0$ a spiral of the DGD profile. The coefficiencts permit a precise control of the DGD profile shape. Some 38 control variables or so (real and imaginary parts of F_k, $k = -9, -8, ..., 9$) may be sufficient for a 96mm long chip. To significantly improve PMD compensation speed the F_k with small $|k|$ may be optimized more often than those with large $|k|$. If the center of gravity of the coefficient spectrum, rms-averaged over extended times, is not near $k = 0$ there may be a static phase mismatch. To overcome it one may correct the chip temperature accordingly.

Zero-mean voltages for suppression of DC drift effects

Fig. 2 shows DGD profiles of two distributed PMD compensators. When bending radii are short enough these DGD profiles are equivalent. In one of the PMDCs (static case) DC drift may cause the joints to straighten out instead of staying bent, thereby distorting the DGD profile or requiring higher and higher voltages. In the other PMDC, an SBA performing a full mode conversion (U turn) under a suitable, slowly and linearly time-variable orientation angle is added at the input. It shifts the TE-TM phase difference by $y_0 = 2pft$. The frequency f may be in the µHz ... Hz range. As a consequence all following SBAs must rotate their orientations by y_0 to approximately maintain the overall DGD profile shape. Mathematically speaking, the expression (1) is identical with

$$\mathrm{PMDC} = \mathrm{SBA}(p, y_0/2)\mathrm{SBA}(p, p + y_0)\cdot\prod_{i=n}^{2}\left(\mathrm{PS}(-wt_i)\mathrm{SBA}(j_i, y_i + y_0)\right) \cdot \mathrm{PS}(-wt_1)\mathrm{SBA}(p - j_1, y_1 + p + y_0)\mathrm{SBA}(p, y_1 + y_0/2). \quad (4)$$

The $\mathrm{SBA}(p, y_0/2)\mathrm{SBA}(p, p + y_0)$ at the end of the PMDC may be left out if, as usual, a constant output polarization is not needed. That case, where a full mode conversion SBA is added only at the PMDC input, is illustrated in Fig. 2 for three different y_0. All driving voltages are pure AC voltages. DC drift is thereby avoided, at the cost of losing direct control over 1...1.5ps of DGD in a small input portion of the PMDC. Errors which may occur due to imperfect PMDC characterization can be corrected by the control algorithm which simultaneously optimizes all j_i, y_i in (4) or all F_k, while $y_0 = 2pft$ is being incremented automatically at a sufficiently low speed.

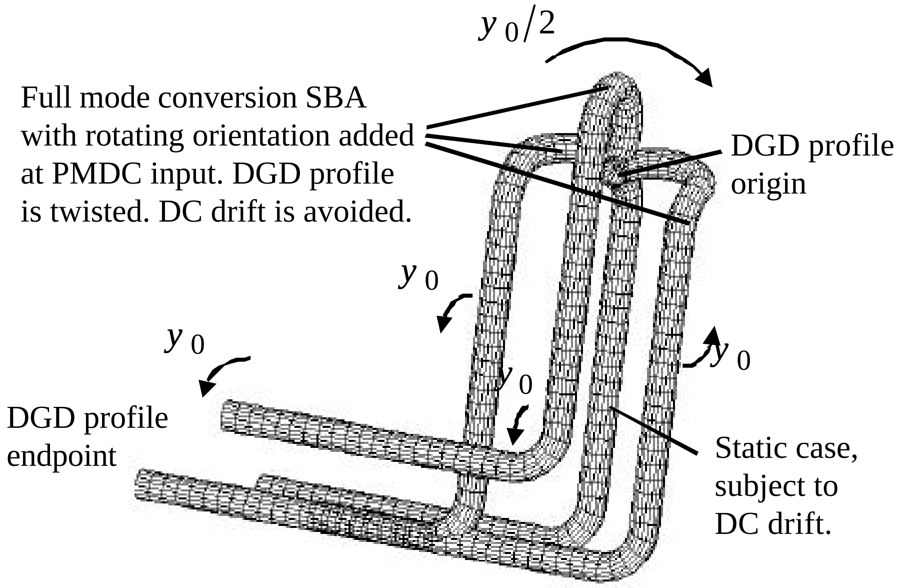

Fig. 2: Mechanical analogon with flexible but torsion-stiff rod: DGD profiles of two similar PMDCs

Summary

Solutions for the most challenging practical problems of distributed PMD compensators in X-cut, Y-propagation $LiNbO_3$ have been pointed out: Waveguide nonuniformity effects can be calibrated out, and a limited number control variables, possibly Fourier coefficients, provides an efficient control even though there may be many electrodes. DC drift, which is a severe limiting factor in X-cut, Z-propagation $LiNbO_3$ polarization transformers, can be avoided altogether in distributed PMDCs because they can be driven by pure AC voltages.

Acknowledgement

is made to R. Ricken, H. Herrmann and W. Sohler (Univ. Paderborn) for device fabrication, and to Siemens ICN for funding part of this work.

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