Time Domain Optical Response of Electro-optic Modulator using FDTD

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***Abstract* — We perform a time domain analysis of a $LiNbO_3$ electro-optic modulator using the Finite Difference Time Domain (FDTD) technique. This allows us to obtain the optical modulation and the time domain optical response of an electro-optic modulator. The electromagnetic fields computed by FDTD are coupled to standard electro-optic relations that characterize electo-optic interactions inside the embedded Ti diffused $LiNbO_3$ optical waveguides. The change in index of refraction inside these optical waveguides is determined in time, allowing for the simulation of optical intensity modulation. This novel approach to $LiNbO_3$ electro-optic modulators using a coupled FDTD technique allows for previously unattainable investigations into device operating bandwidth and data transmission speed.**

I. Introduction

As the technological trend towards faster data transmission speeds continues, optical devices and communications systems can only grow in importance. This is due to the large bandwidth afforded to communications systems with optical devices. The next generation of electro-optic devices will require powerful simulation tools that will be both accurate and capable of simulating all aspects of device operation. Without such a simulation tool, device performance will not reach maximum physical potential. Finite Difference Time Domain (FDTD) is a powerful and flexible technique that can be expected to play a central role in future developments in the simulation of electro-optic devices.

Published numerical work on the $LiNbO_3$ electro-optic modulator has concentrated on using static methods to optimize device geometry to meet various design constraints. Work has been done using Finite Elements Method to find optimum electrode thickness and wall angle to achieve a good traveling wave-optical velocity match [1]. Other work has included more exotic techniques like modified-step-segment method (MSSM) to analyze the optical waveguide region of this device [2]. No previous work, however, has proposed an intuitive approach to simulate complete device performance.

A radically new approach that utilizes a fully dynamic physical simulation of this device is proposed. The power of this approach is that it provides a complete simulation tool capable of being used to optimize device geometry to meet certain microwave design specifications as well as to optimize device optical performance by simulating the physical electro-optic interaction.

In section II, a brief description of the device structure is presented. Section III presents the time domain analysis of device performance and the procedure for coupling FDTD results to electro-optic effects to generate optical response. Finally, results are presented and discussed in section IV.

II. Electro-optic Modulator Device Structure

Briefly, this electro-optic modulator is a coplanar waveguide (CPW) structure with an anisotropic $LiNbO_3$ substrate that exhibits a Pockels electro-optic effect [3]. Electric fields applied to this substrate cause a change in its index of refraction that is proportional to the applied electric field. Inside this substrate are Ti diffused optical waveguides supporting optical signal propagation. This waveguide is split and comes in the close vicinity of a CPW structure to allow for electro-optic interaction. Electric signals traveling along the CPW structure induce electric fields in the substrate that change the phase of light traveling in the two embedded optical waveguides. After some interaction region, the optical waveguides combine allowing the optical signals to interfere. Upon interference, the induced changes in phase translate into intensity modulation. For the modulation to be optimal (i.e. to maximize bandwidth), the velocity of electric signals traveling along the CPW structure and the optical signals traveling inside the embedded optical waveguides must be matched. This is one of the most important considerations for designing the electrodes from a microwave point of view. Possible strategies to achieve such an electro-optic phase velocity match include the use of thick electrodes and SiO_2 buffer layers between the electrodes and the $LiNbO_3$ substrate. Figure 1 demonstrates the increase in phase velocity possible for a CPW line with a gap width and central conductor width of

10 μm each and a SiO_2 buffer layer of 1 μm when the electrode thickness increases from 5 μm to 10 μm.

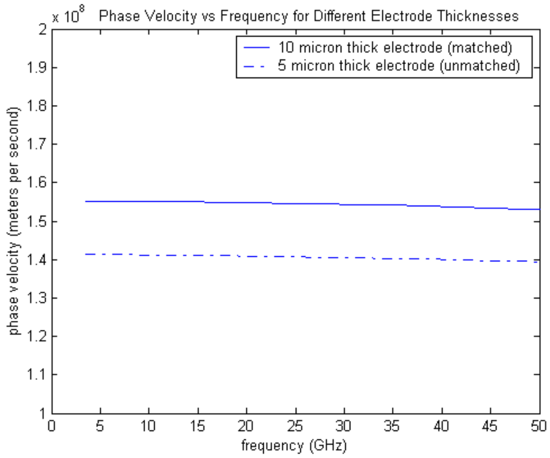

Fig. 1. Phase velocity increase for a CPW line with increase in electrode thickness.

Furthermore, the interaction length should be properly optimized. An interaction region that is too short will result in a shallow optical response (given a fixed driving voltage), while an interaction region that is too long may suffer from phase reversal.

Figure 2 provides a brief schematic of the general structure of the device.

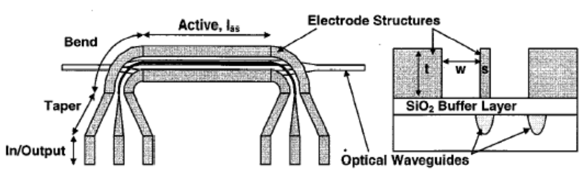

Fig. 2. Schematic showing top (left) and cross sectional (right) views of basic device structure for a z-cut electro-optic modulator. The active or interaction region is essentially a CPW structure with optical waveguides in the electro-optically active $LiNbO_3$ substrate. Electric fields propagating along CPW structure change the phase of light traveling in each optical waveguide which, upon interference, yields optical intensity modulation.

III. TIME DOMAIN ANALYSIS OF ELECTRO-OPTIC MODULATOR

The flexibility and power of the FDTD method make it ideal for the unique numerical challenges posed by this problem, which include anisotropy and non-linearity. Simulating the full optical response of the device is simply not possible using the static techniques so far applied to this problem.

The power of FDTD lies in its full calculation of electric and magnetic fields. This is exploited by launching an electric gaussian pulse along the CPW part of this device. The FDTD scheme calculates at each time step the electric field everywhere inside the device, including inside the embedded Ti diffused $LiNbO_3$ optical waveguide regions. This electric field information can then be coupled to the linear electro-optic effect using the electro-optic relations:

$$\begin{aligned} \Delta n_1 &= -\alpha n^3(r_{22}E_2 + r_{13}E_3) \\ \Delta n_2 &= -\alpha n^3(r_{22}E_2 + r_{13}E_3) \\ \Delta n_3 &= -\alpha n^3 r_{33}E_3 \end{aligned} \quad (1)$$

where α, r_{22}, r_{13} and r_{33} are constants, Δn_i is the change in index of refraction for optical fields polarized in the crystallographic *i* axis, and *n* is either the ordinary or extraordinary index of refraction [3]. If there is an electro-optically induced difference in index between the two waveguides, then light traveling in the optical waveguides will no longer be in phase and upon interference will become intensity-modulated. Because r_{33} is the largest of the above electro-optic coefficients, the design of electro-optic modulator electrodes typically try to maximize the electric field in that crystallographic direction. The design under investigation here is an x-cut design.

Designs are currently typically based on simplified equations like

$$\Delta n = \frac{-n^3}{2} r \frac{V}{d} \Gamma \quad (2)$$

where *r* is the appropriate electro-optic coefficient, V/d is an ideal approximation to the electric field in between the CPW central conductor and the ground plane and Γ is an empirically determined ratio used to improve the result since the V/d electric field approximation is crude. This equation is manipulated with the following equation which relates the phase shift imparted to an optical signal that has traveled over a length *L* with a change in index Δ*n*

$$\Delta\phi = \frac{2\pi}{\lambda} \Delta n L \quad (3)$$

The FDTD calculation of the E-field throughout the device represents a profound improvement over the V/d approximation represented in (2). We exploit FDTD by coupling these calculated electric field data to physical electro-optic effect. From equation (2) and (3), one may derive an expression that describes the minute changes in phase induced in light signals interacting with electric fields as a function in time for optic signals traveling with

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a velocity c_n. We use a linear model to describe this electro-optic interaction:

$$\delta_{phase} = \xi E \quad (4)$$

where ξ lumps together all the coefficients in (2) and (3). Since the spatial resolution (in the direction of both optical and electrical signal propagation) of the E-field data calculated using FDTD is not high enough compared to the resolution needed for the δ_{phase}, a standard interpolation scheme is used to generate a high-resolution electric field. These calculations are done in the time marching scheme to allow for time domain optical response.

An optical signal propagating in an embedded optical waveguide interacting with electric fields is represented as:

$$\sin(\omega t - \beta \cdot \mathbf{z} - \delta_{phase1}) \quad (5)$$

where ω and β are chosen appropriately for optical signals. Another optical waveguide carries an optical signal that is affected by the electric field in its vicinity. This optical signal is represented simply as

$$\sin(\omega t - \beta \cdot \mathbf{z} - \delta_{phase2}) \quad (6)$$

The electric field is given some distance to propagate and interact with the optical signal, representing the interaction region of the physical device. After this distance the two sine waves are added, and their phases interact to constructively or destructively interfere. The intensity of this optical field is calculated to complete the optical response calculation.

IV. Results

To demonstrate the power of this approach two CPW structures have been simulated with different phase velocities resulting from different electrode thicknesses. These different electric signal phase velocities will numerically demonstrate how the phase velocity mismatch can effect the performance of electro-optic modulators.

Figure 3 shows a direct comparison of two time domain electro-optic responses for the matched and mismatched cases.

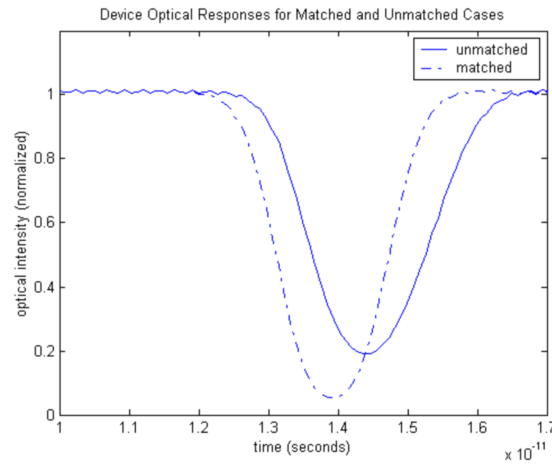

Fig. 3. Electro-optic modulator time domain optical responses to a gaussian electric pulse for two electrode designs representing an electro-optic phase velocity match and mismatch for the same interaction length.

Figure 3 shows a wider unmatched optical response, which is intuitively understood since the peak electric signal applies phase shift over a larger region of the optical signal than in the matched case. Similarly, such an unmatched signal will result in a higher V_π for a given electro-optic interaction length. Figure 3 also numerically demonstrates how important electro-optic phase velocity match is to bandwidth of electro-optic modulators especially for digital applications where the wider time domain response can be clearly seen to limit the time domain proximity of two bits for data transmission.

Given a defined driving voltage and desired V_π, the interaction length of electro-optic modulators must be properly designed so as not to be too short so that the optical response is too shallow, nor too long so that the optical response will exhibit phase reversal. Figure 4 shows the optical response to an electric gaussian pulse for different lengths of electro-optic interaction regions for the matched case.

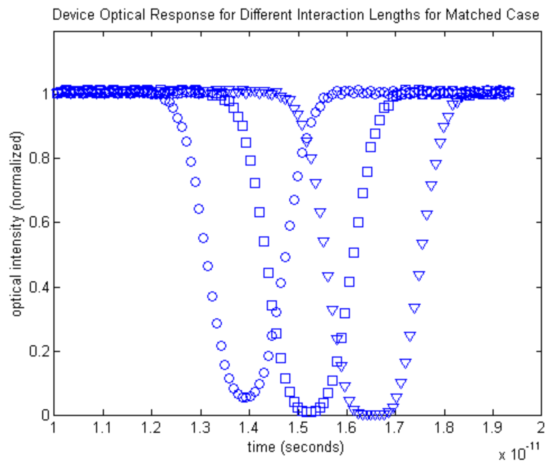

Fig. 4 Electro-optic modulator time domain optical response to a gaussian electric pulse for an electrode design respresenting an electro-optic phase velocity match for different electro-optic interaction lengths.

In figure 4, it is seen that the optical response is just beginning to exhibit phase reversal. If the interaction region is made just a bit longer, this matched electro-optic modulator will exhibit phase reversal for the given driving voltage. Such phase reversal is represented in Figure 5.

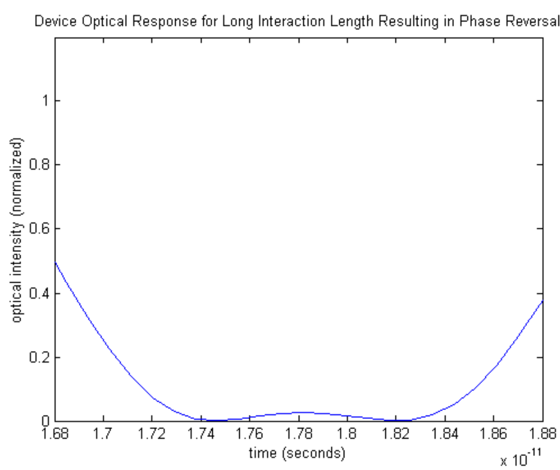

Fig. 5. Electro-optic modulator time domain optical response to a gaussian electric pulse for an electrode design respresenting an electro-optic phase velocity match for a long electro-optic interaction length that results in phase reversal.

Figure 6 displays results for the unmatched case. In this case, the pulses have become much wider, and V_π has significantly increased.

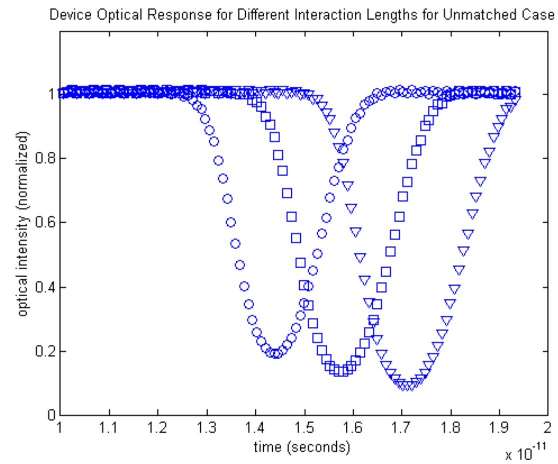

Fig. 6. Electro-optic modulator time domain optical response to a gaussian electric pulse for an electrode design respresenting an electro-optic phase velocity mis-match for different electro-optic interaction lengths.

V. Conclusion

FDTD provides for a fully intuitive approach to the simulation of electro-optic modulator optical response. Using the FDTD solution of the E-field in time coupled to electro-optic interactions, a fully physical simulation of electro-optic modulators is possible. Such advanced modeling of electro-optic modulators can be expected to contribute significantly to superior device performance in the future.

Acknowledgement

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