SIMULATION OF ELECTROOPTIC MACH-ZEHNDER WAVEGUIDE MODULATOR USING FFT BASED BEAM PROPAGATION METHOD

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ABSTRACT

Optical intensity distribution is simulated in electrooptic lithium niobate Mach-Zehnder waveguide modulator using FFT based beam propagation method. This method reduces the runtime considerably, typically by a factor of several hundred. The simulation makes it possible to predict accurately the dynamic behavior of the modulator and several functional waveguide devices, which are used for broadband communication systems. The calculated output power, with and without half-wave applied voltage is in good agreement with theory. Also, the method can be applied to optimize the geometrical layout of the waveguide for high extinction ratio and low insertion loss with respect to loss and length.

INTRODUCTION

Integrated optics is a field of increasing interests. There has been considerable progress in design and development of high performance devices based on optical guiding structures, particularly those built by diffusion of titanium strips in lithium niobate ($LiNbO_3$) substrates. Increasing research is being done in the area of electrooptic $LiNbO_3$ Mach-Zehnder (MZ) modulators due to their potential use in time division multiplexers as well as in digital switches for high bit rate optical communications [1]. The light transmission is controlled by the electric field externally applied through metallic electrodes, which induces a refractive index change due to the electrooptic properties of the material used to build the devices. One example is Mach-Zehnder (MZ) optical modulator [2], which could be formed by diffusing of a layer of titanium strip with the MZ pattern, into a Z-cut $LiNbO_3$ substrate and is one of the most important components due to its application in optical communication systems. The configuration of an electrooptic MZ modulator is shown in Fig. 1.

The accurate analysis of a diffused waveguide modulator is rather complicated because the index profile is not only a function of the surface coordinates, but also a function of the distance from the surface and it forms a three-dimensional problem. Fast Fourier transform (FFT) based beam propagation method (BPM) is based on propagation through a waveguide consisting of a lens and a homogeneous medium of constant refractive index [3]. The BPM is very useful because firstly, it handles both the guided and the radiation modes within the same simple formalism, secondly, it can analyze devices with structural variations along the propagation direction, and thirdly, it provides detailed information about the optical field. However, a three-dimensional (3-D) BPM analysis for optimizing of a typical device usually requires a lot of computation time. Employing of two-dimensional (2-D) BPM is a good way to approach this problem, which has been applied successfully in analyzing of optical fibers. But to perform the 2-D BPM analysis of a channel waveguide device, one must transform its 2-D transverse refractive index profile into a 1-D effective index profile by effective index method (EIM). The CPU time can be reduced drastically, typically by a factor of several hundred. The usefulness of BPM has been analyzed as well as demonstrated [4].

EFFECTIVE INDEX METHOD

Effective index method (EIM) is first applied to reduce the refractive profile index from 2-D to 1-D [5]. The refractive index $n(x,y)$ for metal in-diffusion strip waveguide is defined as follows [6, 7]:

$$n(x,y) \cong n_b + (n_f - n_b) f(y/D) g(2x/W)\,, \tag{1}$$

where

$$f(y/D) = \exp[-(y/D)^2]\,, \tag{2}$$

and

$$g(2x/W) = \frac{1}{2}\left[erf(\frac{W/2+x}{D}) + erf(\frac{W/2-x}{D}) \right]. \tag{3}$$

n_b is the bulk refractive index for z-cut $LiNbO_3$, and n_f is the maximum refractive index at the surface due to the titanium (Ti) in-diffusion. *D* is the diffusion length and *W* is the width of titanium strip prior to diffusion.

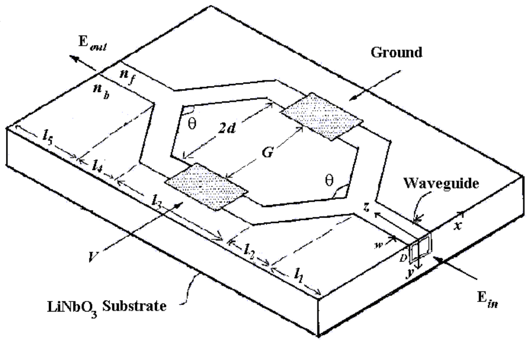


Fig. 1. Simple configuration of a waveguide MZ modulator

For the Ti:$LiNbO_3$ channel waveguide modulators, the normalized dispersion equations can be used to transform the 2-D transverse refractive index profile to its 1-D effective index profile. Using the normalized frequency $V(x) = kD\sqrt{(n_f^2 - n_b^2)\, g(2x/W)}$, the basic requirement for existence of TM mode is [4]

$$2V(x)\int_0^{\xi_t} \sqrt{f(\xi) - b(x)}\; d\xi \cong (2m + 1.48)\pi, \qquad m = 0,1,2,... \tag{4}$$

where $f(\xi_t) = b(x)$, $k = 2\pi/\lambda$ is the free-space propagation constant and λ is the light wavelength. The normalized mode index can be calculated numerically by solving (4) for fundamental TM mode. The effective index profile for waveguide modulator can be expressed as

$$n_{eff}(x) = n_b + (n_f - n_b)\, g(2x/W)\, b(x). \tag{5}$$

FFT BASED BEAM POPAGATION METHOD

Although there are numerical methods can simulate a propagating optical field within a waveguide, FFT based BPM is chosen due to its increased speed, comparable accuracy and suitability for optimization of devices [5]. This method can be applied to optical devices with small variations in refractive indices.

For z-cut $LiNbO_3$ devices, we can express the electric field as $\bar{E}(x,y,z) = \vec{E}(x,y,z)\exp(-ikn_b z)$ where n_b is the refractive index of the substrate. In such optical devices, waveguide modes satisfy the scalar Helmholtz equations. Assuming that $\vec{E}(x,y,z)$ varies slowly along the propagation direction, the paraxial-wave equation for TM mode is

$$2in_{eb}k\frac{\partial E_y}{\partial z} = \nabla_\perp^2 E_y + k^2(n^2(x,y) - n_{eb}^2)E_y, \tag{6}$$

where n_{eb} is the extraordinary refractive index of the substrate and $\nabla_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$. It is seen that the first term of the right-hand side of (6) represents free-space light propagation in the medium having refractive index n_{eb}. The second term of it represents the guiding function or influence of the region having the refractive index $n(x,y)$. Both terms of (6) affect the light propagation simultaneously. However, in this analysis, we assume that two terms can be separated and that each term affects the light propagation separately and alternately in the axially small distance Δz.

Two-dimensional FFT based BPM solves the scalar Helmholtz with Fresnel approximation and employing the FFT for computation of the terms containing the partial derivatives. In this analysis, The electric field $E(x,z)$ is first propagated in the free space over a distance of $\Delta z/2$. Then phase retardation of the entire length Δz, is taken into account at the center of propagation. This electric field is again propagated in the later free space with distance $\Delta z/2$ to obtain $E(x,z+\Delta z)$. The basic procedure of the FFT based BPM is formulated over the small distance Δz so as to relate the transmitted field $E(x,z+\Delta z)$ to the initial field $E(x,z)$. Light propagation in various kinds of waveguides can be analyzed by repeating this same procedure many times. The evolution of the electric field for a single polarization of a monochromatic optical wave in our lossy case is written as [4]:

$$E_y(x,z+\Delta z) = e^{-i k n_{eb} \Delta z}\, e^{\left(-\frac{i\Delta z}{4k n_{eb}}\frac{\partial^2}{\partial x^2}\right)} \cdot e^{\left\{-\alpha(x,z+\Delta z)-\left(\frac{i k n_{eb}}{2}\right)\left[\left(\frac{n(x,z+\Delta z)}{n_{eb}}\right)^2-1\right]\right\}\Delta z}\, e^{\left(-\frac{i\Delta z}{4k n_{eb}}\frac{\partial^2}{\partial x^2}\right)} E_y(x,z) + O(\Delta z^3), \tag{7}$$

where $O(\Delta z^3)$ is the error term and α is the waveguide absorption loss. The optical field that is input to the modulator is the fundamental TM mode with unit power, here called the eigenfunction $u_0(x,0)$. The power of the fundamental mode P_{out} guided by the modulator at any distance z of the output waveguide can be calculated using

$$P_{out}(z) = \int u_0^*(x,0) E_{out}(x,z)\, dx\,, \tag{8}$$

where $E_{out}(x,z)$ is the normalized optical field of the mode.

SIMULATION

The aim of this numerical simulation is to design a MZ modulator with high extinction ratio and low insertion loss. The view of the modulator is shown in Fig. 1, which its waveguide parts consist of five sections. Sections with lengths l_2 and l_4 consist of two tapers and branches. The waveguides are assumed to be diffused in a z-cut $LiNbO_3$, which the waveguides of section with length l_3 covered, by electrode causing vertical electric fields of opposite directions. The refractive index of the section three is given by

$$n(x) = n_{eff}\left(|x| - d - W/2\right) - \frac{1}{2}\frac{x}{|x|} n_{eb}{}^3\, r_{33}\, \frac{U}{G}\Gamma\,, \tag{9}$$

where $d+W/2$ is the half distance between the centers of the parallel waveguides, $r_{33} = 30.8\times10^{-12}$ m/V is the electrooptic coefficient, U is the applied voltage, G is the inter-electrode gap, and Γ is the overlap integral between the applied electric field and the optical field and is given by [6]

$$\Gamma = \frac{G}{U}\iint E_e(x,y)\,|E_o(x,y)|^2\, dx\, dy\,, \tag{10}$$

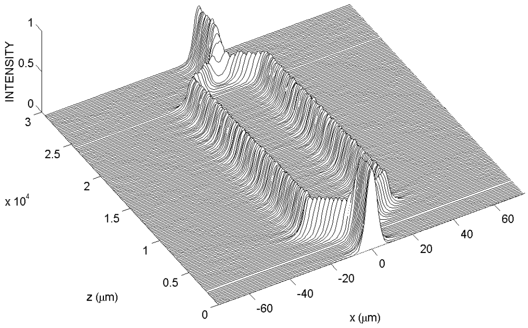
where E_e and E_o are the electrical and optical fields, respectively.

In (10) the electric field may be assumed uniform across the waveguide. A more realistic calculation of the optical field would require a calculation of the overlap integral between the electrodes using a numerical method. These fields can be used to determine the overlap integral, which subsequently used in computing of the effective index for applying in the FFT based BPM.

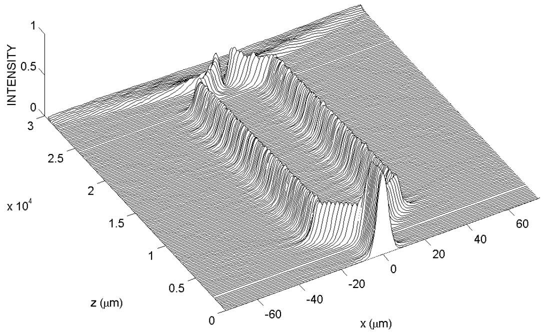
RESULTS

The calculation will be performed at a wavelength of λ=1.55 μm and we set n_f-n_{eb}=0.02. The design parameters of the modulator are d=15 μm, l_2= l_4 $\approx$ 2.4 mm and l_3=20 mm and we assume waveguide absorption loss as α=0.3 dB/cm. Computations show that when the branch angles are less than one degree, the loss due to leakage from each of them is about 0.2 dB, which is less than the assumed absorption loss per centimeter. Results show that for a waveguide with prediffusion width of 6 μm and depth of about 2 μm, the waveguide can support only the fundamental mode.

Fig. 2(a) depicts the optical intensity distribution for TM mode in the single-mode waveguide modulator (MZ) in a 150-μm wide window, which an absorber may be placed near the either sides of the window edges to dampen probable weak fields. The normalized output power without applied voltage is about 0.8. Fig. 2(b) shows the optical intensity distribution for TM mode at value of applied voltage V_π, where V_π is the half-wave voltage and its resultant electric field, is the field giving nearly zero transmitted optical power [6]. P_{out} in this case is 10^{-4}. The extinction ratio and insertion loss, which are two important parameters in digital modulation, are about 39 and –1 dB, respectively.



(a)



(b)

Fig. 2. Light intensity distribution through a MZ waveguide modulator excited by its fundamental mode, (a) without applied voltage (ON state) and (b) with half-wave applied voltage (OFF state)

CONCLUSION

The optical intensity distribution was shown in a Ti:$LiNbO_3$ waveguide MZ modulator using the FFT based beam propagation method, which reduced the runtime significantly. The time reduction has been attained by applying the effective index method and fast Fourier transform, which predicts well the propagation of the fundamental mode. The method can be applied to simulate and optimize the geometrical layout of the other functional waveguides with respect to loss and length.

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