Modeling Ultra Short Optical Pulse Propagation In Integrated Optical Waveguides Using A New Time Domain Technique

Husain M. Masoudi
Visiting Research Professor
Emerging Communications Technology Institute, Electrical and Computer Engineering Department
10 King's College Rd. M5S 3G4, University of Toronto, Ontario, Canada

The author is with the Department of Electrical Engineering
King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

***Abstract*- A novel non-paraxial Time-Domain technique based on Pade approximant for modeling ultra short optical pulses has been formulated and tested. The new method is an extension to the parabolic Time-Domain Beam Propagation Method (TD-BPM) that solves the time domain wave equation along one direction that allows the time window to follow the evolution of the pulse. In this work the technique was applied efficiently and effectively to model ultra short pulses in dielectric optical waveguides.**

I. INTRODUCTION

There is an increasing demand to develop efficient techniques that can model short pulse propagation in long dielectric optical structures. In principle, the well known Finite-Difference Time-Domain (FDTD) is suited to simulate both Time-Domain (TD) and continuous wave problems, but it requires huge computer resources and more importantly it is not suited for long optical pulse interaction [1]. In the literature there are a few TD techniques which are very similar in their approach to the original FDTD. However, most of these techniques proved to be inferior to FDTD in terms of computer resources consumption [2]. Earlier, we proposed two paraxial TD-Beam Propagation Methods (TD-BPM) techniques to model optical pulse propagation in waveguide structures [3]. The techniques proved to be very efficient in modeling optical pulse propagation in long device interaction. However, the parabolic TD-BPM showed limitation in modeling ultra short pulses due to the paraxial approximation involved. In this work we propose a new non-paraxial Time-Domain BPM using the same principle approach of the paraxial TD-BPM. The new TD-BPM involves writing the time-domain wave equation as a one-way equation for the propagation along the axial direction *z* while keeping all time variations intact by treating them as another transverse variable in addition to the other spatial dimensions. One major advantage of this approach is to allow the numerical time window to follow the evolution of the pulse and hence minimize computer resources. The new non-paraxial operator uses the rational complex coefficient approximation of the well known Pade approximant to overcome the paraxial limitation. The square root propagation operator can be approximated as

$$\sqrt{1+X} \approx \prod_{i=1}^{m} \frac{1+a_i^m X}{1+b_i^m X} \tag{1}$$

where *a* and *b* are called Pade coefficients and *m* being the Pade order. The new operator showed very robust and stable behavior in the propagation of short optical pulses in optical structures. In this work we use the operator to model ultra short pulse propagation in dispersive dielectric waveguide structures and test the convergence of important numerical parameters. We also make comparisons with the paraxial TD-BPM technique.

II. THEORY

The full time domain wave equation after extracting a carrier frequency ω and a propagation coefficient $k = k_o n_o$ in the direction of propagation can be written as

$$q\frac{\partial^2\Psi}{\partial z^2} - 2j\left\{qk\frac{\partial\Psi}{\partial z}\Psi + uk_o\left(\frac{1}{c_o}-\frac{1}{v_g}\right)\frac{\partial\Psi}{\partial\tau}\right\} - \frac{u}{c_o^2}\frac{\partial^2\Psi}{\partial\tau^2}\Psi + \frac{\partial}{\partial x}\left(q\frac{\partial\Psi}{\partial x}\right) + (uk_o^2 - qk^2)\Psi = 0 \tag{2}$$

where a moving time coordinate $\tau = t - v_g^{-1} z$ with arbitrary v_g has been used to adjust for the velocity of the pulse envelope. For TE fields $q = 1$, $u = n^2$ and $\Psi = E_y$ representing the electric field, for TM fields $q = 1/n^2$, $u = 1$ and $\Psi = H_y$ representing the magnetic field, c_o is the wave velocity in free space. The solution of Eq. (2) can be written in a product form as forward propagation operator and a backward propagation operator [4]. For one-way propagation the solution can be formulated as

$$\Psi(z) = exp\{jk(1-L)z\}\Psi(0) = exp\left\{jk\left(1-\sqrt{1+X}\right)z\right\}\Psi(0) \tag{3}$$

where $\Psi(0)$ is the initial field and L is a pseudo-differential square root operator that has all time and transverse derivatives defined in (2) [5-6].

III. RESULTS

To demonstrate the features of the new formulation, we implemented the technique to model ultra short optical pulse propagation in a symmetric slab waveguide with a core a cladding refractive indices of 1.2 and 1.0 respectively. The input field excited at $z = 0$ was a Gaussian time pulsed beam that has a spatial profile of the first guided mode of the waveguide with a carrier wavelength of 1.0 µm. The pulsed beam was propagated using the non-paraxial method to a distance of 60 µm. Fig. 1 shows the evolution of the evolution of the pulsed optical beam inside the slab waveguide structure at several distances along the longitudinal direction. It is to be noticed that a moving time window was used to follow the propagation of the pulse. This moving window mechanism is a fundamental efficiency feature in modeling long pulse propagation using the proposed method. Apparently that computer resources of memory and execution time are reduced considerably compared to a similar simulation using the classical FDTD. The figure shows that the field does not change along the spatial dimension due to the guidance of the waveguide with the peak being in the center of the picture.

Fig. 2 shows a comparison between the new technique and the paraxial method percentage error for different initial pulse widths and different time step sizes. In general, the error of the new technique is far less than the parabolic technique for short pulses.

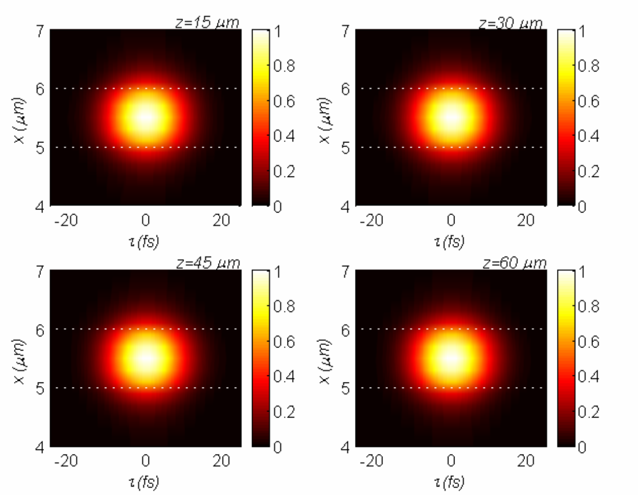

Fig. 1 The evolution of the pulsed optical beam with an initial pulse beam size of 10 fs inside the slab waveguide structure at several distances along the longitudinal direction. A moving time window was used to follow the propagation of the pulse. The two horizontal lines show the position of the core slab waveguide boundaries. The figure is a close up from the real simulation dimension to show detail of the pulse propagation.

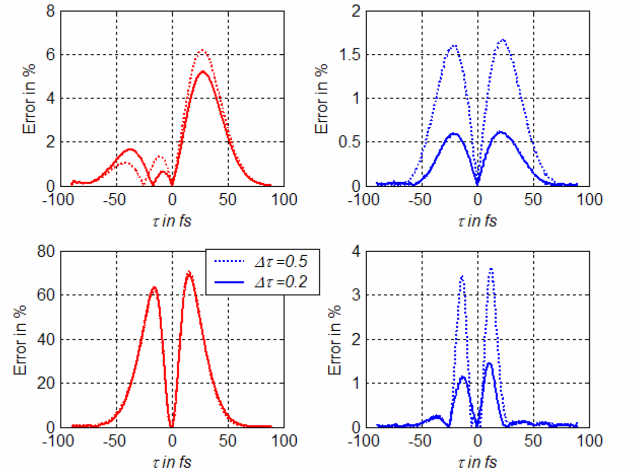

Fig. 2 Percentage error comparison between this technique and the parabolic TD-BPM for different initial short pulse widths and different time step sizes. The two left side figures (red) are for the parabolic method and the two right side figures (blue) are for the new technique. The two top figures are for initial 30 fs while the two bottom figures are for initial 10 fs.

It is also clear from the figure that as the initial pulse width decreases the error increases dramatically for the parabolic technique, but the error decreases rapidly by decreasing the initial time step size for the present work while remains almost the same for the parabolic case. This is to confirm that the error for the parabolic method is mainly associated with the paraxial approximation.

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