The use of 2d and 3d WA-BPM models to analyze total-internal-reflection based integrated optical switches

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ABSTRACT

The well known beam propagation method (BPM) has become one of the most useful, robust and effective numerical simulation tools for the investigation of guided-wave optics, for example integrated optical waveguides and fiber optic devices. In this paper we examine the use of the 2D and 3D wide angle-beam propagation method (WA-BPM) combined with the well known perfectly matched layer (PML) boundary conditions as a tool to analyze TIR based optical switches, in particular the relationship between light propagation and the geometrical parameters of a TIR based optical switch. To analyze the influence of the length and the width of the region in which the refractive index can be externally controlled, the 3D structure of a 2×2 TIR optical switch is firstly considered in 2D using the effective index method (EIM). Then the influence of the etching depth and the tilt angle of the reflection facet on the switch performance are investigated with a 3D model.

Keyword*:* Optical switch, total internal reflection, beam propagation method, reflection loss

1. INTRODUCTION

Optical switches are an important element in many optical communication systems for a variety of operations-such as signal routing, protection switching and as components in multiplexing systems [1,2]. Integrated waveguide optical switches are attractive since they are compact and can be integrated with other components. One approach to the design and fabrication of integrated waveguide based optical switches is the use of the total internal reflection (TIR) [3-9]. In a TIR based optical switch there is a light propagation region which has a controllable refractive index. By controlling the refractive index, it is possible to switch TIR on or off, resulting in switching of the input light between the output ports of the switch.

The well known beam propagation method (BPM) [11] has become one of the most useful, robust and effective numerical simulation tools for the investigation of guided-wave optics, for example integrated optical waveguides and fiber optic devices. In this paper we examine the use of the 2D and 3D wide angle-beam propagation method (WA-BPM) combined with the well known perfectly matched layer (PML) boundary conditions as a tool to analyze TIR based optical switches, in particular the relationship between light propagation and the geometrical parameters of a TIR based optical switch. To analyze the influence of the length and the width of the region in which the refractive index can be externally controlled, the 3D structure of a 2x2 TIR optical switch is firstly considered in 2D using the effective index method (EIM). Then the influence of the etching depth and the tilt angle of the reflection facet on the switch performance is investigated with a 3D model.

2. STRUCTURE OF THE TIR OPTICAL SWITCH

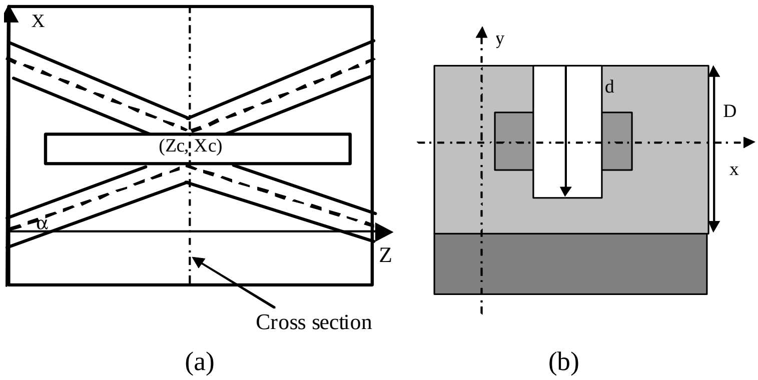


Fig. 1. Schematic structure of an integrated optical waveguide switch using the total internal reflection effect: (a) Top view and (b) Cross-section (marked by a dash dot line) view of the optical waveguide based switch in X-Z plane.

Fig. 1 illustrates top and cross-sectional views of an optical integrated waveguide 2×2 switch using the TIR effect. In the configuration shown, two optical channel waveguides intersect at a certain angle. At the point of intersection shown in the Fig. 1(a), a rectangular groove is etched into the substrate which can be filled with a tunable refractive index medium, such as a liquid crystal or a thermo-optic polymer. One face of the etched groove serves to controllably reflect or pass a light beam propagating in an input waveguide, to allow switching to take place. Depending on the nature of the medium, the refractive index of the medium in the groove can be adjusted through an external electric field or an electrode heater.

3. ANALYSIS OF THE BEAM BEHAVIOR BASED ON A 2D BPM MODEL

Using the effective index method, the 3D waveguide structure can be approximated by a 2D planar structure. In this approximation we assume that the groove is etched down to the substrate and the reflection facet's tilt angle is zero. Fig. 2 illustrates a basic structure of the proposed TIR switch in the X-Y plane. The two center lines of the waveguides cross at the point (Yc, Xc). The angle between the input waveguide and the reflecting facet α is chosen to be 10 degrees. The refractive indices for the cladding and the core are 1.5000 and 1.5152, respectively. The cross-section area of the waveguide is $4.8\times 3.7\mu m^2$. The input wavelength is 1550 nm. Following the Helmholtz Equation for a scalar electric (or magnetic) field $\Psi(x, y)$ in 2 dimensions, the equation for the TE mode can be written as follows:

$$\nabla_t^2 + k_0^2 n^2(x,z)\Psi = 0 \qquad (1)$$

where $\nabla_t^2 = \partial^2\Psi/\partial x^2 + \partial^2\Psi/\partial z^2$, $\Psi(x,z) = \exp(-jk_0\bar{n}z)\psi(x,z)$, k_0 is the wave number in free space and n is the refractive index distribution.

Multiplying both sides of Eq. (1) by the factor $-(j/2k)$ and then taking a partial derivative $(\partial\Psi/\partial z)$ of the equation (1) one can obtain:

$$-\frac{j}{2k}\cdot\frac{\partial^2\Psi}{\partial z^2}+\frac{\partial\Psi}{\partial z}=\frac{j\cdot(\nabla_t^2+k_0^2n^2)}{2k}\Psi+\frac{\partial\Psi}{\partial z} \qquad (2)$$

where $k = k_0 \cdot n_{ref}$, n_{ref} is the reference refractive index.

The Eq. (2) can be rewritten as follows:

$$\frac{\partial\Psi}{\partial z}=\frac{\frac{j\cdot(\nabla_t^2+k_0^2n^2)}{2k}+\frac{\partial}{\partial z}}{1-\frac{j}{2k}\frac{\partial}{\partial z}}\Psi \qquad (3)$$

And the Eq. (3) can be derived further as:

$$\frac{\partial}{\partial z}\Big|_{n+1}=\frac{\frac{j\cdot(\nabla_t^2+k_0^2n^2)}{2k}+\frac{\partial}{\partial z}\Big|_n}{1-\frac{j}{2k}\cdot\frac{\partial}{\partial z}\Big|_n} \qquad (4)$$

Using the initial value of $\frac{\partial}{\partial z}\big|_0 = 0$, the Padé (m,n) approximation based wide angle propagation formula can be given as follows:

$$\frac{\partial \Psi}{\partial z} \approx jk \frac{N(m)}{D(n)} \Psi \tag{5}$$

where *N(m)* and *D(n)* are polynomials in $X = ((\nabla_t^2 + k_0^2 n^2)/k^2)$.

Using the above WA-BPM model combined with the PML boundary conditions, the calculated results are presented as follows.

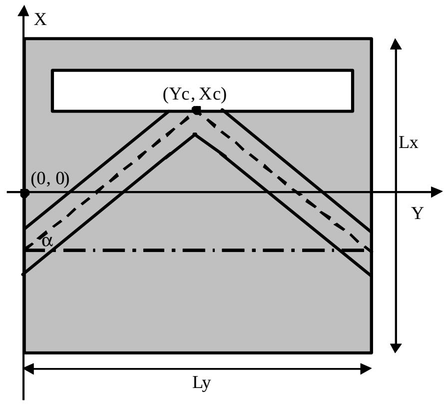
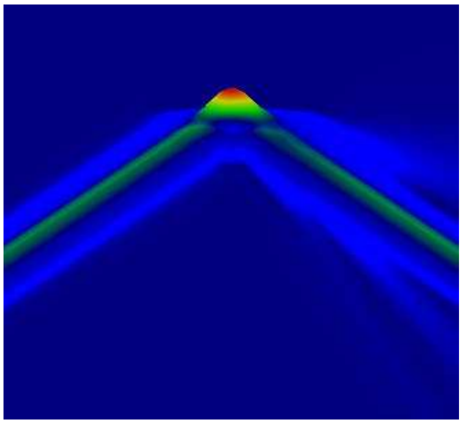


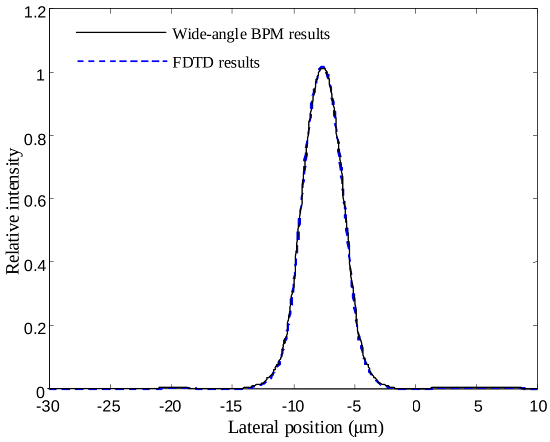
Fig. 2 Basic 2D structure of the TIR switch.

For the effective index method, the effective refractive index for the core in the 2D model is 1.5099. For the proposed structure the size and the position of the etched groove affects the value of the reflection loss. Firstly, the 2D WA-BPM is employed to calculate the distribution of the optical field intensity in the TIR switch. Fig. 3(a) shows the modeled results obtained by the 2D WA-BPM based model in the X-Y plane. In the simulation L_x=60 μm and L_y=250 μm. The length and the width of the groove is 100 μm and 10 μm, respectively. The reflection facet is located at the point of intersection of the two center lines of the waveguides as shown in the Fig. 2. The reflection loss is defined as $L = -10\lg(P_o/P_i)$, where P_i is the input waveguide power at the position z = 0 and P_o is the transmitted power in the output waveguide at the position $z = L$. The corresponding inherent reflection loss when TIR occurs is 0.064 dB. Customized source codes utilizing Compaq Visual Fortran 6.6 have been developed for the analysis of the theoretical models in the paper. For the case presented in Figure 3, the computation time of the 3D WA-BPM model is circa 40% of the computation time required for an equivalent FDTD model for the same sets of input parameters.

In Fig. 3(b), the optical field intensity distribution at the output is calculated by using the 2D WA-BPM based on the Padé (3, 3) approximation. For comparison, a simulation based on the 2D finite-difference time domain (FDTD) method [13] is also employed to simulate the output optical field intensity distribution. The corresponding calculated results are shown by the blue dashed line in Fig. 3 (b). In the FDTD model there is no approximation used in the model, resulting in an exact solution. From this figure one can see that for the presented switch structure, the WA-BPM results are in a good agreement with the results obtained by 2D FDTD. However WA-BPM is significantly more computationally efficient compared to FDTD. A WA-BPM based on the approximation of Padé (3, 3) is employed in the following numerical analysis.



(a)



(b)

Fig. 3 Simulated beam propagation behaviors for the TIR optical switch; a) optical field distribution in the X-Y plane simulated by 2D WA-BPM; b) output optical field intensity along the X-coordinate, simulated by both WA-BPM and FDTD.

3.1. Analysis of the effect of the length and width of the etched groove

The influence of the length of the etched groove is firstly discussed. In these calculations, we choose the same width and position of the etched groove as shown in Fig.2. Fig. 4 shows the relationship between the reflection loss and the length of the groove. The simulation result shows that for this structure, the length of the groove should be large enough to achieve the minimum possible reflection loss, which is for the parameters used in this simulation, the length should be larger than 100 µm.

In considering the effect of the width of the etched groove, it is known that the corresponding effective depth of the penetration of the evanescent wave at the reflection facet in the presence of TIR is about 0.2 µm. A groove with a width larger than this value will allow the minimum reflection loss to be achieved. This is confirmed by the simulation results shown in Fig. 5 which show the relationship between the reflection loss and the width of the etched groove.

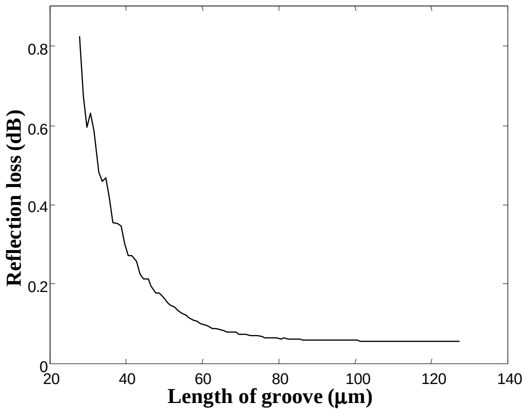


Fig. 4 Relationship between the reflection loss and the length of the groove.

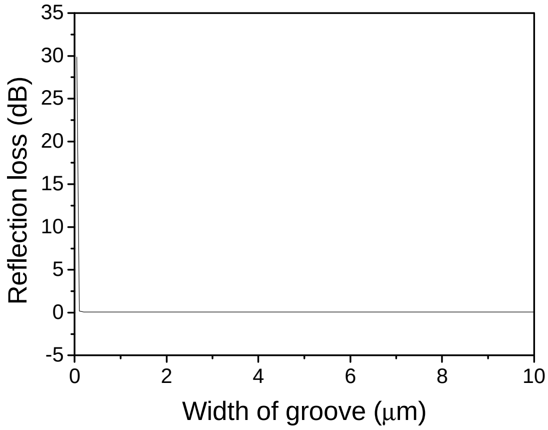


Fig. 5 Relationship between the reflection loss and the width of the groove.

3.2. Using the model to examine the effect of manufacturing tolerance

The 2D WA-BPM model can also be used to examine the effect of manufacturing tolerances. As an example of this we consider the effect of the tilt angle of the groove, that is, when the etched groove reflection facet is not ideally parallel with the Y axis. The simulated result is presented in Fig. 6. It shows that for this structure, when the tilt angle is within $\pm 1^{\circ}$, the corresponding reflection loss is less than 1 dB. When the tilt angle is larger than $\pm 1^{\circ}$, the reflection loss increases significantly with the increase of the tilt angle.

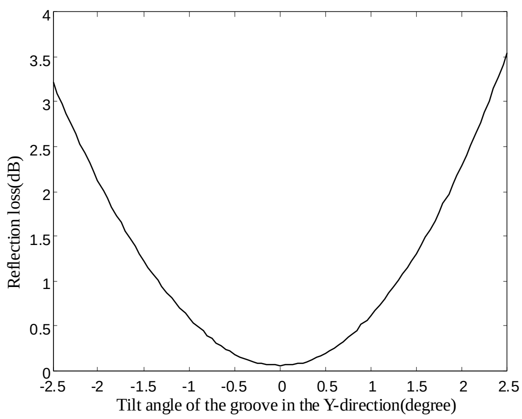


Fig.6 Relationship between the reflection loss and the tilt angle of the etched groove.

4. 4. BEAM BEHAVIOR ANALYSIS BASED ON A 3D WA-BPM MODEL

To further examine the applicability and the accuracy of the theoretical analysis using the 2D WA-BPM, a theoretical model based on a quasi-vector 3D WA-BPM is employed for a 3D analysis. For the 3D case, we consider the guided mode propagation along the Y-coordinate and the influence of the etched depth and tilt angle of the reflection facet on the performance of the switch.

4.1. Effect of etching depth of the groove

A cross-section view of the waveguide switch in the X-Z plane is shown in Fig. 7. The thickness of the waveguide (including the buffer layer, core layer and the cladding layer) is D=40 μm. When the etched depth is 40 μm, i.e., the groove is etched down to the base-wafer, the reflection loss is about 0.067dB, the minimum possible (assuming the position of the reflection facet is at x = Xc).

The corresponding optical field intensity profile in the X-Y plane is shown in Fig. 8. From these simulation results one can see that the calculated results using the 2D model presented in the Fig. 3(a) agree well with results from the 3D model. Therefore, our 2D model can achieve an acceptable accuracy compared with 3D model but with the advantage of a faster execution speed.

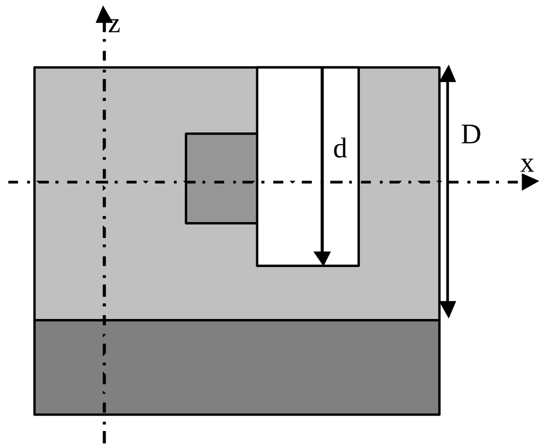


Fig.7 Cross-section view of the waveguide switch in the X-Z plane.

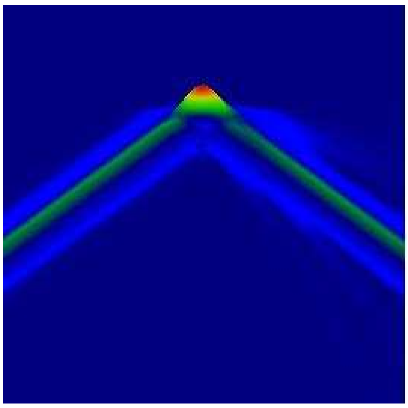


Fig. 8 Simulated field intensity profile in the X-Y plane by using a 3D WA-BPM.

4.2. Effect of the tilted angle of the reflection facet

Fig. 9 shows a cross-sectional view of the optical switch with a tilted reflection facet. If the tilt angle is equal to zero, the reflection loss obtained by both 2D and 3D models is circa 0.067dB as expected. Because of the limitations of the fabrication process, the tilt angle may not be zero. Based on the 3D model, Table 1 lists the reflection losses for different tilt angles. In the calculations, the position of the reflection facet was assumed to be (Xc, $-h_0/2$).

From these results, one can see that minimizing the tilt angle is important to reduce the reflection loss to a minimum.

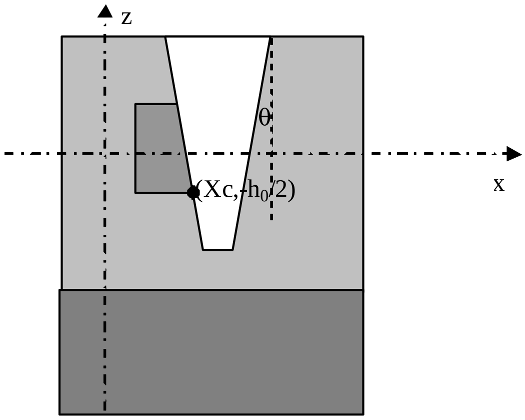


Fig. 9 Cross-section view of the waveguide switch with a tilted refection facet.

Table 1 Reflection losses for different tilt angles.

Tilt angle (degree)	**Reflection loss (dB)**
5	0.4
10	1.26
15	2.45
20	4.1
25	5.91

5. CONCLUSIONS

In this paper, the beam propagation method has been presented as an effective method for analyzing a TIR based optical switch. The effects of different geometrical parameters have been investigated using 2D WA-BPM and 3D WA-BPM models. We have shown that the 2D model can provide an accurate insight into the effect of several geometrical parameters, with the advantage of computational efficiency by a factor of 3-4 times compared to the 3D model. The 3D model allows for the analysis of parameters such as groove depth and the shape of the input and output waveguides. As an example the results indicate that by carefully selecting geometrical parameters, very low reflection loss can be achieved. The models also confirm that, apart from the material and scattering losses, the major factors contributing to the reflection losses are the length of the groove and reflection facet tilt angle and that these factors are the most critical for the overall performances of the optical switch.

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