Single Mode Rib Optical Waveguide Modeling Techniques

Norazan Mohd Kassim, Abu Bakar Mohammad, Abu Sahmah Mohd Supa'at, Mohd Haniff Ibrahim and Shee Yu Gang

Photonic Research Group,
Faculty of Electrical Engineering,
University Technology Malaysia,
81310 Skudai, Johor.

Abstract - In this paper, a single mode rib optical waveguide is modeled using three distinct methods which include the finite difference method (FD), effective index method (EI) and two dimensional beam propagation method (2D-BPM). Starting from the fundamental equations of Maxwell's, the functionalities of the said methods in solving the wave equation are discussed. Using a standard rib optical waveguide structure, comparisons between the methods are made in terms of normalized propagation constant values and the obtained results are shown to have a good agreement.

Keywords: Optical waveguide, finite difference method, effective index method, beam propagation method

1. Introduction

The transmission and processing of signals carried by optical beams has been a topic of great interest since the early 1960s, when the development of the laser first provided a stable source of coherent light for such application. Thus, the concept of integrated optics emerged in which the conventional electric integrated circuits are replaced by the miniaturized optical or photonic integrated circuits. Most useful configurations of photonic integrated circuits utilize the channel waveguides as a fundamental component. The waveguides can be in various transverse structures which include the rib, strip, embedded, strip loaded and buried type. These structures can be further manipulated to produce passive and active waveguides. These two are classified based on the ability to control the direction or intensity of the light based on the applied external field. Such waveguides are straight, curved, Y-junction, directional coupler and modulator. To further realizing this type of waveguides for the commercial use, many critical steps may involved. Undoubtedly, the most basic and important step lies in the modeling process. The importance of the modeling phase can be regarded as it plays several significant roles in the advancement of optical components, including optimization of current designs, shortening of the design cycle for new designs and performance evaluation of new design concepts. For this reasons, numbers of modeling techniques have been developed for years, ranging from the analytical methods which normally requires less computation time up to the numerical methods which may take longer simulation period.

In this paper, three techniques are adopted in the modeling process of single mode rib optical waveguide structure. Those techniques are scalar finite difference method, effective index method and two-dimensional beam propagation method. The first method is a numerical technique while the second method is based on analytical studies. The latter is a combination of an analytical and numerical technique. Further elaborations of the methods are provided in this paper.

The paper is arranged as follows. Section 2 is focusing on the theoretical reviews of fundamental wave equation and working concepts of the modeling methods. Methods of analyzing the waveguide structure are presented in section 3. Simulation results of structural modeling and comparison between methods are presented in section 4, followed by discussions and conclusion remarks.

2. Theoretical Reviews

To compare the validity of the modeling techniques discussed in this paper, a rib optical

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waveguide structure is utilized as the test structure as shown in figure 1.

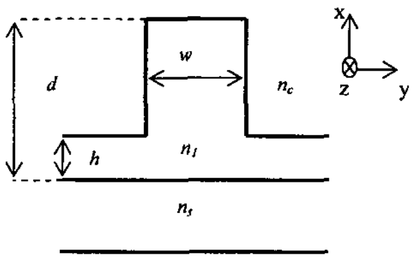

Figure 1: Rib structure

where:

n_s = substrate refractive index;
n_c = cladding refractive index;
n_l = core refractive index;
w = rib width.

2.1 Mathematical Formulation

For simplification in most optical waveguiding analysis, the scalar wave equation is adopted and this assumption is valid only for the case of weakly guiding problem in which the refractive index contrast between the waveguide and substrate region is often small, ($\Delta n \rightarrow 0$) [1]. Assuming a small index contrast, this research is thus fully concentrated on solving the scalar wave equation which is given as;

$$\frac{d^2E}{dx^2}+\frac{d^2E}{dy^2}+\frac{d^2E}{dz^2}+k_o^2n^2E=0 \qquad (1)$$

by taking into consideration that the propagation is along the +z axis.
where;

E = electric field intensity
k_o = free space wavenumber
n = material refractive index

Considering a y-polarized TE mode that propagates in the z direction and β as propagation constant in longitudinal direction will then yield the equation of:

$$\frac{d^2E_y}{dx^2}+\frac{d^2E_y}{dy^2}+(k_o^2n^2-\beta^2)E_y=0 \qquad (2)$$

Equation (2) is the eigenfunction that need to be solved for determining the eigenvalue of β and TE field distribution throughout the medium of interest. A variety of methods have been developed and applied for years [2]-[6]in solving (2) which include analytical and numerical methods. 3 methods are adopted which are finite difference method (FD), effective index method (EI) and two-dimensional beam propagation method (2D-BPM).

2.2 Finite Difference Method (FD)

For this method, the E field and the refractive index, n is considered to be a discrete value at respective x and y coordinate and bounded in a box, which represent the waveguide cross section. The box is divided into smaller rectangular area or mesh with a dimension of Δx and Δy in x and y directions respectively [7]. Applying finite difference formulation to (2) will then produce a discrete formulation of electric field represented by:

$$E(i,j)=\frac{E(i+1,j)+E(i-1,j)+\left(\frac{\Delta x^2}{\Delta y^2}\right)^2(E(i,j+1)+E(i,j-1))}{2\left(1+\left(\frac{\Delta x^2}{\Delta y^2}\right)^2\right)-\Delta x^2\left(k_o^2n^2(i,j)-\beta^2\right)} \qquad (3)$$

where i and j represent the mesh point corresponding to x and y direction respectively. Further manipulation of (3) together with numerical integration will then produce a numerical equation to calculate the propagation constant, β as given in [7].

2.3 Effective Index Method (EI)

The method was first developed by Marcatili [8] and further improved by Toulious and Knox [9], Itoh [10] and McLevidge et. al.[11]. To implement the effective index method, the basic idea is to solve for the eigenvalue equation of slab waveguide. In this method, the waveguide cross section is divided into two distinct steps. With regard to figure 1, the first step is to solve for two distinct asymmetric slab structures in x-direction which may then produce the effective index value for respective slab. Progressing further, the second step is to solve for a single asymmetric slab structure with effective refractive index value in y-direction. The obtained value is the effective refractive index or alternatively the propagation constant of the structure.

2.4 Two-Dimensional Beam Propagation Method (2D-BPM)

The method is first introduced by Feit and Fleck [12] in which the Fourier transformation is adopted in solving the paraxial wave equation of [13]

$$j\frac{dE}{dz}=\frac{1}{2k_on_o}\left[\frac{d^2E}{dx^2}+\frac{d^2E}{dy^2}+k_o^2\left(n^2-n_o^2\right)E\right] \quad (4)$$

For the matter of effective computation, the finite difference based BPM is introduced by Chung and Dagli [13] and Yevick [14] which demonstrated the wave propagation using both explicit and Crank-Nicholson implicit scheme. With refer to figure 1, by applying the effective index method in x-direction and further applying the Crank-Nicholson scheme to (4) will produce [15]:

$$\frac{E_{n+1}-E_n}{\Delta z}=\alpha GE_{n+1}+(1-\alpha)GE_n \qquad (5)$$

where:

$$G=\frac{1}{j2k_on_o}\left[\frac{d^2E}{dx^2}+k_o^2\left(n^2-n_o^2\right)E\right] \qquad (6)$$

α = ½ for Crank Nicholson implicit scheme
E_n = field at the nth step size
E_{n+1} = field at the $(n+1)$th step size

Solution of equation (5) characterize the behavior of light propagation in any two-dimensional optical waveguide structures, simplified from its three dimensional case by the use of the effective index method.

According to Scarmozzino [16], (5) can be used to obtain the structural propagation constant by eliminating the imaginary factor j, or by changing the propagation domain to imaginary axis.

3. Methods of Analysis

The simulation is based on the rib structure as shown in figure 1 above. The simulation is done on MATLAB® programming platform for all the above-mentioned methods. Two different configurations of figure 1 as listed in table 1 are used for comparison purposes.

Table 1: Parameters of rib waveguide for comparison

Guide	1	2
n_1	3.44	3.44
n_2	3.36	3.40
n_3	1.0	1.0
d(μm)	1.0	1.0
h(μm)	0.9	0.6-0.9
w(μm)	3	3

Analysis in this paper is based on the normalized propagation constant, in which a more sensitive comparison can be made [6]

$$b=\frac{n_{eff}^2-n_{substrate}^2}{n_{guide}^2-n_{substrate}^2} \qquad (7)$$

The results obtained from FD are labeled as P-FD, while results for EI are labeled as P-EI. The same goes for 2D-BPM in which P-2DBPM is used for labeling. For additional comparisons, a BPM_CAD simulation software from Optiwave® Corporation is employed. Two distinct packages namely Mode Solver 2D and Mode Solver 3D which are based on classical correlation method of FFT-BPM are simulated. The functionalities and reliabilities of these software packages have been tested by Nazib et. al. [17] and Sahbudin et. al. [18] which shows that their simulated results are within the acceptable range.

4. Results

The obtained results using the methods in this paper are compared with other analytical and numerical methods produced by several researchers as mentioned. For guide 1, the results are tabulated in table 2.

Table 2: Comparison of normalized propagation constant, b for guide 1.

Method	b (Guide 1)
Effective Index Method [2]	0.4404
Mode Matching [2]	0.4390
Function fitting [2]	0.4332
Finite Difference (FD1) [2]	0.4367
Finite Difference (FD2) [2]	0.4400
Finite Difference (FD3) [6]	0.4406

Beam Propagation Method [13]	0.4280
Variational Method [2]	0.4348
Scalar Finite Difference (P-FD)	0.4369
Effective Index Method (P-EIM)	0.4407
Mode Solver 2D	0.4408
Mode Solver 3D	0.4421
2D-Beam Propagation Method P-2DBPM	0.4317

Numerical values of b for simulation on guide 2 are given in table 3. The results are shown for four values of waveguide height.

Table 3: Comparison of normalized propagation constant, b for guide 2 of different guide thickness.

	h (μm)			
Method	0.6	0.7	0.8	0.9
Effective Index Method [3]	0.3583	0.3649	0.3749	0.3908
Variational Method [2]	0.3257	0.3374	0.3548	0.3819
Vector Finite Element [3]	0.3382	0.3522	0.3684	0.3905
Scalar Finite Element [3]	0.3369	0.3497	0.3656	0.3869
Semivectorial Finite Difference [6]	0.3382	0.3525	0.3696	0.3905
Scalar Finite Difference (P-FD)	0.3612	0.3711	0.3815	0.3916
Effective Index Method (P-EIM)	0.3586	0.3652	0.3751	0.3909
Mode Solver 2D	0.3587	0.3661	0.3761	0.3911
Mode Solver 3D	0.3462	0.3562	0.3711	0.3911
2D-Beam Propagation Method (P-2DBPM)	0.3511	0.3568	0.3654	0.3783

From table 2 and table 3, it clearly shows a strong agreement between the simulated methods in this paper with other simulated methods produced previously by other researchers. A strong agreement is also observed with the Optiwave® software packages. Although the results exhibit a bit difference in the normalized propagation constant, the value of β may almost be the same, as the normalized value is far more sensitive [13].

5. Conclusions

In this paper, three distinct optical waveguide modeling techniques have been adopted and simulated on rib structure. From the simulated results, a great agreement with other existing methods and commercial software packages are observed and presented in this paper. Thus, this promising and important output will grant the authors for the next step of modeling the actual waveguide or device structure.

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