

An Efficient Wide-Angle Beam Propagation Method Using Denman–Beavers Iterative Scheme for Tilted Optical Waveguides

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Abstract—An efficient wide-angle beam propagation method based on Denman–Beavers iterative scheme for tilted optical waveguides is proposed, where the beam is shifting along the propagation. By shifting the beam opposite to the variation of the waveguide geometry in every step, the propagation in a longitudinally varying waveguide is realized through an equivalent straight waveguide. Significant improvement in efficiency with almost no influence on the accuracy is achieved.

I. INTRODUCTION

The finite-difference beam propagation method (FD-BPM) is now one of the most widely used numerical techniques for modeling optical and photonics devices, mostly owing to its calculational speed and numerical simplicity [1]-[3]. These attractive properties result chiefly from the use of the paraxial approximation. However, for longitudinally varying waveguides, the wide-angle BPM (WA-BPM) often needs a large size of simulation window for ensuring the desired accuracy [4], [5], which may lower the efficiency of the algorithm. Moreover, the variation of the longitudinal refractive index profiles usually results in plenty of evanescent waves to be dealt with and a number of transverse characteristic matrixes to be calculated, which also decreases stability and efficiency of the WA-BPM. The recently developed WA-BPM based on the Denman–Beavers iterative (DBI) scheme [5], has the advantages of excellent convergence, and high accuracy and stability, superior to the classical WA-BPM, but less efficient at most cases. Here, we present a shifting-beam scheme for the DBI based WA-BPM for efficiently analyzing tilted optical waveguides. The proposed scheme can greatly improve the efficiency of the WA-BPM with almost no influence on the accuracy.

II. CALCULATION MODELS AND PROCEDURE

A governing equation for WA-BPM is expressed as [4], [5]

$$\frac{\partial \phi}{\partial z} = i(\sqrt{P+k^2} - k)\phi = ik(\sqrt{A} - I)\phi \quad (1)$$

where $k = k_0 n_{\text{ref}}$ with k_0 being the wavenumber in vacuum and n_{ref} being the reference refractive index, and P is the transverse characteristic matrix [1]-[5], and I is the identity matrix with the same size as P . Then, by applying the DBI scheme [5], [6] to (2) along with the stable and robust Crank–Nicholson scheme, a WA-BPM is constructed.

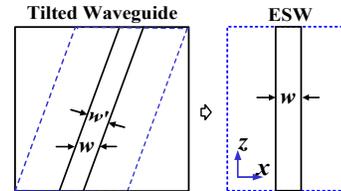


Fig. 1. Transformation schematic for the tilted waveguides.

The variation of the longitudinal refractive index profiles results in a number of transverse characteristic matrix (P , as defined in eq. (1)) to be calculated, which greatly increases the computational load of the WA-BPM. Moreover, for higher-order approximation, we may need to perform more matrix inversions corresponding to each P [5], which further decreases the efficiency. To alleviate this issue for those waveguides with unchanging geometry in cross-section, we first simplify the tilted waveguide structures into an equivalent straight waveguide (ESW) as shown in Fig. 1, and such transformation can be readily extended to three dimensional (3-D) cases. Then, by numerically shifting the input beam opposite to the variation of the waveguide geometry in every step, the propagation in a longitudinally varying waveguide can be realized through an ESW. This can be performed by generating cells with zero field values at the specific edge(s) of the input beam and dropping the same number of cells at the opposite edge(s). After the propagation is finished, we can obtain the results by rearranging the output field pattern.

The main advantage of the present method comes from that we only need to calculate the transverse characteristic matrix for a single ESW, while classical WA-BPM should recalculate the transverse characteristic matrix every few steps since the refractive index profile is changed. Consequently, the computational time and necessary memory are greatly reduced. Moreover, the size of the simulation window may also influence the computational efficiency. Generally, a smaller simulation window is preferred if the accuracy and stability can be guaranteed. Fortunately, the shifting-beam scheme makes it possible for us to perform the calculation using a small simulation (blue line dashed as shown in Fig. 1) since main part of the guided field power is concentrated in the core.

III. NUMERICAL RESULTS AND DISCUSSION

Now, we first assess the ability of DBI based WA-BPM to accurately deal with the evanescent waves correctly as

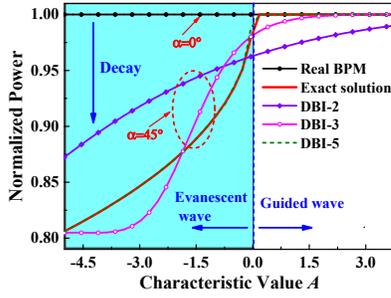


Fig. 2. Normalized power with respect to the characteristic value A .

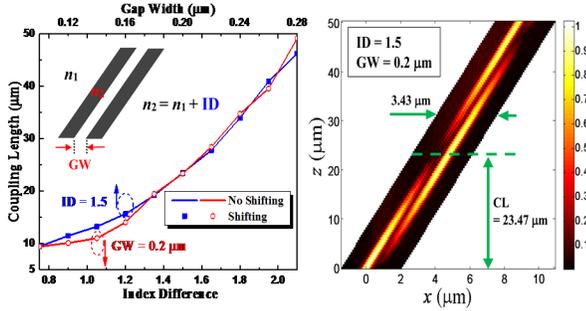


Fig. 3. Coupling length versus the index difference and the gap width (a) and field distribution (b) for a typical tilted directional coupler.

mentioned above. For simplicity, we consider a single plane-wave component propagating in a homogeneous medium as is previously used in [5], [6]. Fig. 2 shows the normalized power with respect to the characteristic value A at the step size $\Delta z = 0.1\mu\text{m}$. It is noted that DBI- n ($n=1, 2, \dots$) and α respectively corresponding to the number of iteration and the rotation angle in [5]. As is seen, the real BPM incorrectly treats the evanescent waves as the guided waves, while the DBI with $\alpha = 45^\circ$ presents the evanescent waves properly decay toward to the exact solution with the iteration number increases. Therefore, the proposed propagator can attenuate unstable evanescent waves generated at the longitudinal discontinuities, not appreciably affecting guided modes as expected.

Then, we validate the accuracy and utility of the present shifting-beam scheme by applying it to a typical tilted directional coupler as shown in the inset of Fig. 3(a). The waveguide has a tilt angle of 10° and the width of the core is $w = 0.5\mu\text{m}$. The refractive index of the cladding is $n_1 = 1.5$ and that of the core (n_2) is the sum of n_1 and the index difference (ID). The operation wavelength is set to be $1.55\mu\text{m}$ and the WA-BPM based on DBI-2 operator is utilized in the following analysis. Fig. 3(a) shows the coupling length (CL) in term of the ID and the gap width (GW). As is seen, results from the shifting-beam scheme agree well with those from the classical no shifting-beam scheme. Fig. 3(b) illustrates the electric field distribution of the fundamental TE mode propagating in the tilted directional coupler computed using the shifting-beam scheme at $\text{ID} = 1.5$ and $\text{GW} = 0.2\mu\text{m}$. Similar field distribution is also obtained by the classical WA-BPM without using the shifting-beam scheme [4]. It is noted here that a very small simulation window ($3.43\mu\text{m}$) is used for the simulation while a $12.36\mu\text{m}$ simulation window is needed using the classical

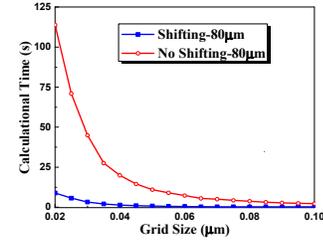


Fig. 4. Computational time with respect to the grid size.

WA-BPM, and the difference will be larger as the length of the waveguide increases. Moreover, the present method can also be directly applied to the S-bend waveguide, and can partially applied to waveguides which contain such kinds of components, for instance, the Y-branch waveguide.

Finally, to further illustrate the advantage of the proposed method, we plot the computational time with respect to the grid size for an $80\mu\text{m}$ simulation window in Fig. 4. Comparison has also been made between the shifting and the no shifting scheme. Obviously, the WA-BPM based on shifting-beam scheme takes less computational time than the classical WA-BPM even the same size of simulation window is used, and the difference is more evident for smaller grid size. This advantage may be very useful for the analysis of 3-D waveguides since the size of the characteristic matrix is N^2 (N is grid number in one dimension) times larger, especially for full-vectorial Analysis ($4N^2$ times larger).

IV. CONCLUSION

Using a shifting-beam scheme, an efficient finite-difference WA-BPM based on the DBI scheme for tilted optical waveguides is developed. Numerical results show that the present approach can improve the efficiency of the classical WA-BPM with almost no influence on the accuracy. This advantage may be very useful for efficient analysis of 3-D waveguides.

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REFERENCES

- [1] R. Scarmozzino, A. Gopinath, R. Pregla, and S. Helfert, "Numerical techniques for modeling guided-wave photonic devices," *IEEE J. Sel. Top. Quant. Electron.*, vol. 6, no. 1, pp. 150-162, Feb. 2000.
- [2] D. Yevick and B. Hermansson, "Efficient beam propagation techniques," *IEEE J. Quantum Electron.*, vol. 26, pp. 109-112, Jan. 1990.
- [3] J. Xiao and X. Sun, "A modified full-vectorial finite-difference beam propagation method based on H -fields for optical waveguides with step-index profiles," *Opt. Commun.*, vol. 266, pp. 505-511, Feb. 2006.
- [4] G. R. Hadley, "Wide-Angle Beam Propagation Using Pade Approximant Operators," *Opt. Lett.*, vol. 17, pp. 1426-1428, Oct. 1992.
- [5] S. Wu and J. Xiao, "A Wide-Angle Beam Propagation Method Using Denman-Beavers Iterative Scheme," *IEEE Photon. Technol. Lett.*, vol. 27, pp. 2512-2515, Dec. 1 2015.
- [6] S. Wu and J. Xiao, "An Efficient Semivectorial Bidirectional Beam Propagation Method for 3-D Optical Waveguide Structures," *J. Lightw. Technol.*, vol. 34, pp. 1313-1321, 2016.