Guided-Mode and Leaky-Mode Analysis by Imaginary Distance Beam Propagation Method Based on Finite Element Scheme

Yasuhide Tsuji, *Member, IEEE* and Masanori Koshiba, *Senior Member, IEEE*

***Abstract*—As a simple analysis method to solve eigenmodes of optical waveguides, we present an imaginary distance beam propagation method (BPM) based on finite element scheme. The matrices used in the beam propagation analysis are essentially complex, so lossy optical waveguides can be easily treated. Moreover, employing the transparent boundary condition or perfectly matched layer boundary condition, the validity of which has been already confirmed in the real distance BPM, we can easily treat not only guided modes but leaky ones. To show the validity and usefulness of this approach, eigenmodes of two- and three-dimensional leaky waveguides, and optical fibers are calculated.**

***Index Terms*—Beam propagation method (BPM), finite element method (FEM), guided-mode analysis, imaginary distance propagation method, leaky optical waveguide.**

I. Introduction

AN ANALYSIS of eigenmodes in longitudinally invariant optical waveguides is indispensable for designing optical waveguide devices and many kinds of analysis methods have been reported [1], [2]. On the other hand, in order to analyze the light propagation behavior of longitudinally varying optical waveguides, the beam propagation method (BPM) is at present widely used and there are great number of versions of the BPM [3], [4]; BPM based on the fast Fourier transform (FFT-BPM), BPM based on the finite difference method (FD-BPM), and BPM based on the finite element method (FE-BPM). Especially, FE-BPM is superior to FFT-BPM in the sense that the former can be applied to strongly guiding waveguides and strongly polarization dependent waveguides. In addition, FE-BPM can arbitrarily select the order and the number of elements, depending on the required computational accuracy. It is, of course, possible to use nonuniform finite element meshes. Furthermore, these meshes can be adaptively updated along the propagation direction so that computational efficiency can be improved without degrading numerical accuracy [5]–[8]. These features are not available in FFT-BPM and FD-BPM.

Recently, the so-called imaginary distance beam propagation method (ID-BPM) has been reported as an analysis method of eigenmodes [9]–[15]. In the ID-BPM, the propagation direction is selected along the imaginary axis and selecting the appropriate propagation step size, we can extract the specific eigenmode from the initial inputted field expressed by arbitrarily superposing the eigenmodes. The main advantages of the ID-BPM as an eigenmode solver are as follows: 1) high-efficient calculation algorithms developed for the BPM analysis can be directly utilized, 2) matrices derived from the BPM formulation are essentially complex, so lossy optical waveguides can be easily treated with no additional effort, 3) eigenmodes can be obtained successively from the fundamental to higher order modes, and 4) employing the appropriate boundary conditions, not only guided modes but leaky modes in such as ARROW optical waveguides may be treated [14] because radiation fields are automatically included in the BPM calculation. The ID-BPM developed so far is mainly based on the FDM (FD-ID-BPM). FEM has some advantages mentioned above, so if FE-BPM can be applied to the imaginary distance propagation method including the leaky mode analysis, its usefulness will be enhanced.

In this paper, we present the finite element ID-BPM (FE-ID-BPM). Here, in order to treat leaky modes, the transparent boundary condition (TBC) [16] or the perfectly matched layer (PML) boundary condition [17]–[19], the validity of which has been already confirmed in the real distance beam propagation method, are employed as boundary conditions for artificial boundaries. To show the validity and usefulness of this approach, eigenmodes of two-dimensional (2-D) and three-dimensional (3-D) leaky waveguides, and optical fibers are calculated.

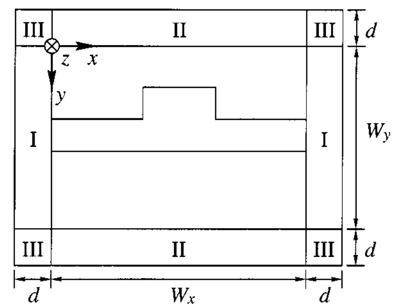

Fig. 1. Optical waveguide surrounded by PML.

II. Perfectly Matched Layer Boundary Condition

We consider a 3-D optical waveguide surrounded by PML regions I, II, and III with thickness d as shown in Fig. 1, where x and y are the transverse directions, z is the propagation direction, PML regions I and II are faced with the x and y directions, respectively, region III corresponds to the four corners, and W_x

Manuscript received June 22, 1999; revised November 29, 1999.

The authors are with the Division of Electronics and Information Engineering, Hokkaido University, Sapporo 060-8628, Japan.

Publisher Item Identifier S 0733-8724(00)03037-1.

and W_y are the computational window sizes along the x and y directions, respectively. Using the transversely scaled version of PML [18], Maxwell's equations can be written as

$$\nabla' \times \boldsymbol{H} = j\omega\varepsilon_0 n^2 s\boldsymbol{E} \tag{1}$$

$$\nabla' \times \boldsymbol{E} = -j\omega\mu_0 s\boldsymbol{H} \tag{2}$$

with

$$s = 1 - j\frac{\sigma_e}{\omega\varepsilon_0 n^2} = 1 - j\frac{\sigma_m}{\omega\mu_0} \tag{3}$$

where

$\boldsymbol{E}$ and $\boldsymbol{H}$	electric and magnetic field vectors, respectively;
ω	angular frequency;
ε_0 and μ_0	permittivity and permeability of free space, respectively;
n	refractive index;
σ_e and σ_m	electric and magnetic conductivities of PML, respectively.

The relation (3) is required to satisfy the PML impedance matching condition

$$\frac{\sigma_e}{\varepsilon_0 n^2} = \frac{\sigma_m}{\mu_0} \tag{4}$$

which means that the wave impedance of a PML medium exactly equals that of the adjacent medium with refractive index n in the computational window, $\sqrt{\mu_0/(\varepsilon_0 n^2)}$, regardless of the angle of propagation or frequency. In the PML medium, we assume an m-power profile of the electric conductivity as

$$\sigma_e = \sigma_{\max}\left(\frac{\rho}{d}\right)^m \tag{5}$$

where ρ is the distance from the beginning of PML. Using the theoretical reflection coefficient R [18] at the interface between the computational window and the PML medium

$$R = \exp\left[-2\frac{\sigma_{\max}}{\varepsilon_0 cn}\int_0^d \left(\frac{\rho}{d}\right)^m d\rho\right] \tag{6}$$

the maximum conductivity $\sigma_{\max}$ may be determined as

$$\sigma_{\max} = \frac{m+1}{2}\,\frac{\varepsilon_0 cn}{d}\,\ln\frac{1}{R} \tag{7}$$

where c is the light velocity of free space. Usually, a parabolic profile is assumed for the conductivity, $m = 2$, and thus, s in (1) and (2) is finally written as

$$s = \begin{cases} 1 - j\dfrac{3\lambda}{4\pi n\, d}\left(\dfrac{\rho}{d}\right)^2 \ln\dfrac{1}{R}, & \text{in PML region} \\ 1, & \text{in non-PML region} \end{cases} \tag{8}$$

where $\lambda = 2\pi c/\omega$ is the free-space wavelength.

The modified differential operator ∇' used in (1) and (2) is defined as

$$\nabla' = \boldsymbol{i}_x s_x\frac{\partial}{\partial x} + \boldsymbol{i}_y s_y\frac{\partial}{\partial y} + \boldsymbol{i}_z s\frac{\partial}{\partial z} \tag{9}$$

TABLE I
THE DEFINITION OF s_x, s_y

Region	s_x	s_y
I	1	s
II	s	1
III	1	1

where $\boldsymbol{i}_x$, $\boldsymbol{i}_y$, and $\boldsymbol{i}_z$ are the unit vectors in the x, y, and z directions, respectively, and the values of s_x and s_y are summarized in Table I.

III. BEAM PROPAGATION METHOD

A. Basic Equation

Under the scalar approximation, from (1) and (2) we get the following basic equation:

$$s_x\frac{\partial}{\partial x}\left(p\frac{s_x}{s}\frac{\partial\Phi}{\partial x}\right) + s_y\frac{\partial}{\partial y}\left(p\frac{s_y}{s}\frac{\partial\Phi}{\partial y}\right) + s\frac{\partial}{\partial z}\left(p\frac{\partial\Phi}{\partial z}\right) + k_0^2 qs\Phi = 0 \tag{10}$$

where k_0 is the free space wavenumber, and Φ, p, and q are given by

$$\Phi = E_x, \quad p = 1, \quad q = n^2 \tag{11}$$

for E^x (quasi-TE) modes and

$$\Phi = H_x, \quad p = 1/n^2, \quad q = 1 \tag{12}$$

for E^y (quasi-TM) modes.

Substituting a solution of the form

$$\Phi(x, y, z) = \phi(x, y, z)\exp(-jk_0 n_0 z) \tag{13}$$

into (10), and assuming Fresnel approximation, we obtain the following beam propagation equation for the slowing varying complex amplitude ϕ:

$$-2jk_0 n_0 ps\frac{\partial\phi}{\partial z} + s_x\frac{\partial}{\partial x}\left(p\frac{s_x}{s}\frac{\partial\phi}{\partial x}\right) + s_y\frac{\partial}{\partial y}\left(p\frac{s_y}{s}\frac{\partial\phi}{\partial y}\right) + k_0^2 s(q - n_0^2 p)\phi = 0 \tag{14}$$

where n_0 is the reference refractive index.

B. Finite Element Discretization

Dividing the waveguide cross section into quadratic (second-order) triangular or line elements for 3-D or 2-D waveguide structures, and applying the standard FEM to (14), we obtain

$$-2jk_0 n_0[M]\frac{d\{\phi\}}{dz} + \left([\tilde{K}] + k_0^2 n_0^2[M]\right)\{\phi\} = \{0\} \tag{15}$$

where $\{\phi\}$ is the global electric or magnetic field vector, $\{0\}$ is a null vector. The matrix $[\tilde{K}]$ is given by

$$[\tilde{K}] = [K] + [K]_\Gamma \tag{16}$$

and the finite element matrices $[K]$ and $[M]$ are given by

$$[K] = \sum_e \iint_e \left[k_0^2\, qs\{N\}\{N\}^T - p\frac{s_x^2}{s} \frac{\partial\{N\}}{\partial x} \frac{\partial\{N\}^T}{\partial x} - p\frac{s_y^2}{s} \frac{\partial\{N\}}{\partial y} \frac{\partial\{N\}^T}{\partial y} \right] dx\, dy \tag{17}$$

$$[M] = \sum_e \iint_e ps\{N\}\{N\}^T\, dx\, dy. \tag{18}$$

Here, $\{N\}$ is the shape function vector, T denotes a transpose, and Σ_e extends over all different elements. The term $[K]_\Gamma$ in (16) is related to TBC and is given by

$$[K]_\Gamma = {\sum_e}' \int_\Gamma -jk_n\{N\}_\Gamma\{N\}_\Gamma^T\, ds \tag{19}$$

where $\{N\}_\Gamma$ is the shape function vector on the TBC-imposed boundary, Γ, $\Sigma_e{}'$ extends over all boundary elements, and the integration is performed on the boundary Γ. The way of determination of k_n corresponding to the outside wavenumber is described in [7]. In this formulation, we employ the isoparametric triangular elements and matrices $[K]$, $[M]$ are calculated by using the numerical integration formula derived by Hammer *et al.* [20].

In the case of 2-D slab waveguide, $\partial/\partial x = 0$ and $[K]$, $[M]$, and $[K]_\Gamma$ are given by

$$[K] = \sum_e \int_e \left[k_0^2 qs\{N\}\{N\}^T - \frac{p}{s}\frac{\partial\{N\}}{\partial y}\frac{\partial\{N\}^T}{\partial y} \right] dy \tag{20}$$

$$[M] = \sum_e \int_e ps\{N\}\{N\}^T\, dy \tag{21}$$

$$[K]_\Gamma = \begin{bmatrix} -jpk_1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ & & & \\ 0 & 0 & \cdots & -jpk_M \end{bmatrix}. \tag{22}$$

C. Crank–Nicholson Method

Applying the Crank–Nicholson algorithm for the propagation direction z to (15) yields

$$[A]_i\{\phi\}_{i+1} = [B]_i\{\phi\}_i \tag{23}$$

with

$$[A]_i = -2jk_0n_0[M]_i + 0.5\Delta z\left([\tilde{K}]_i - k_0^2n_0^2[M]_i\right) \tag{24}$$

$$[B]_i = -2jk_0n_0[M]_i - 0.5\Delta z\left([\tilde{K}]_i - k_0^2n_0^2[M]_i\right). \tag{25}$$

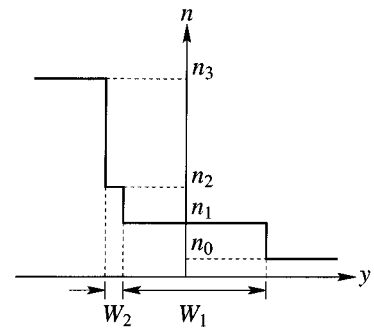

Fig. 2. Two-dimensional leaky waveguide.

IV. Imaginary Distance Propagation Method

Assuming that the effective refractive index of the jth eigenmode is $n_{\text{eff},\,j}$ and that the corresponding field is $\{f_j\}$, the eigenvalue equation can be written as follows:

$$[\tilde{K}]\{f_j\} = k_0^2 n_{\text{eff},\,j}^2[M]\{f_j\}. \tag{26}$$

After Δz propagation, from (23)–(26) the field distribution of the jth eigenmode yields

$$\{f_j\}_{i+1} = \frac{-2jk_0n_0 - 0.5\Delta z k_0^2(n_{\text{eff},\,j}^2 - n_0^2)}{-2jk_0n_0 + 0.5\Delta z k_0^2(n_{\text{eff},\,j}^2 - n_0^2)}\{f_j\}_i. \tag{27}$$

When m eigenmodes including radiation modes exist in the waveguide, the field $\{\phi\}_i$ at the ith propagation step can be expressed by

$$\{\phi\}_i = \sum_{j=1}^m A_{j,\,i}\{f_j\} \tag{28}$$

where $A_{j,\,i}$ is the complex amplitude of the jth eigenmode. Selecting the propagation step size along z-direction, Δz, as

$$\Delta z \simeq j\frac{4n_0}{\left(n_{\text{eff},\,j}^2 - n_0^2\right)k_0} \tag{29}$$

for a sufficiently large number of i, $\{\phi\}$ converges to the jth eigenvector $\{f_j\}$ [13]. The effective index of this eigenmode, $n_{\text{eff},\,j}$, is obtained by

$$n_{\text{eff},\,ji}^2 = \frac{\{\phi\}_i^\dagger[K]_i\{\phi\}_i}{k_0^2\{\phi\}_i^\dagger[M]_i\{\phi\}_i} \tag{30}$$

at the ith propagation step with † denoting complex conjugate and transpose.

In the actual case, the effective index of the desired mode is unknown at the beginning of calculation, so we use the largest refractive index of the waveguiding region to determine Δz. After a few iterative calculations using this Δz are performed, and the effective index difference from the previous propagation step is converged to 10^{-3}, we use $n_{\text{eff},\,ji}$ to determine Δz, and then the field distribution and effective index of the fundamental mode are obtained. The value of reference refractive index, n_0, may be arbitrarily chosen. Here, we use the smallest value among the refractive indexes so as to make the imaginary distance of Δz positive.

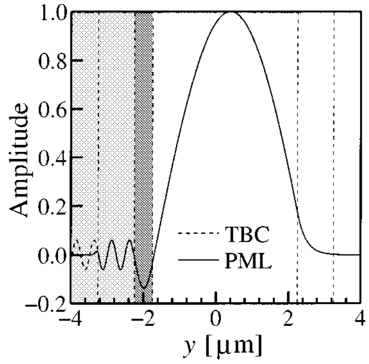

Fig. 3. Electric field distribution.

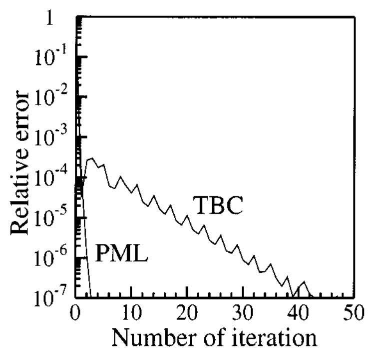

Fig. 4. Relative error of the effective index.

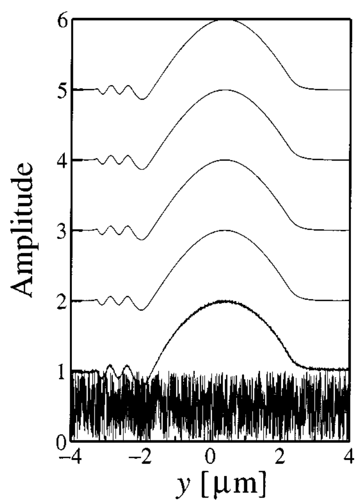

Fig. 5. Electric field evolution.

When calculating the higher order mode, for example, the kth higher order mode, the lower order field components are eliminated from the initial inputted field as

$$\{\tilde{\phi}\}_1 = \{\phi\}_1 - \sum_{j=1}^{k-1} \frac{\iint \{f_j\}^\dagger [M] \{\phi\}_1 \, dx \, dy}{\iint \{f_j\}^\dagger [M] \{f_j\} \, dx \, dy} \{f_j\}. \quad (31)$$

Using (31) as a new inputted field, $\{\phi\}$ will converge to the desired higher order mode without converging to the lower order modes.

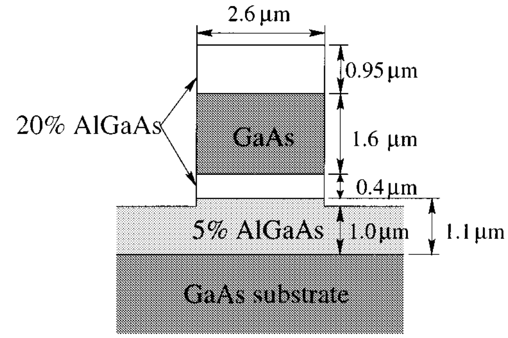

Fig. 6. Three-dimensional leaky waveguide.

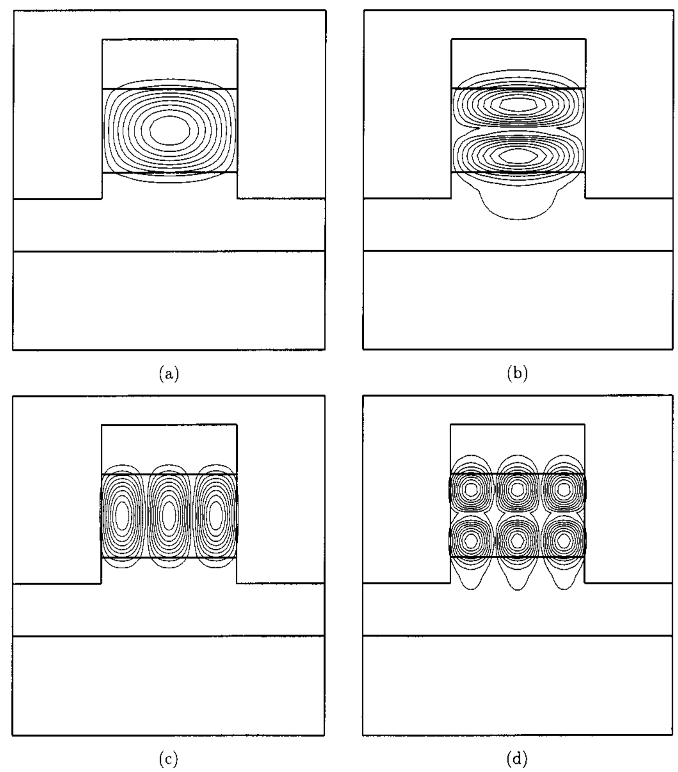

Fig. 7. Electric field distributions: (a) E^x_{11}, (b) E^x_{12}, (c) E^x_{31}, and (d) E^x_{32} modes.

V. Numerical Results

First, in order to confirm the validity of FE-ID-BPM with TBC or PML, we consider a 2-D leaky waveguide as shown in Fig. 2 [19]. The eigenmodes supported in this type of waveguide are essentially leaky modes and generally those complex effective indexes cannot be easily calculated. On the other had, in our FE-ID-BPM, TBC, or PML, the validity of which has been already confirmed in the real distance beam propagation method, has been incorporated and the complex effective indexes are easily calculated. The waveguide parameters are given by $n_0 = 1.0$, $n_1 = 1.458$, $n_2 = 2.01$, $n_3 = 3.5$, $W_1 = 4.0$, and $W_2 = 0.5$, and the operating wavelength is 1.55 μm, and the fundamental transverse electric (TE) mode is calculated. The complex effective index calculated with TBC or PML is $1.4462244 - j4.722 \times 10^{-4}$ and is in good agreement with the theoretical one, $1.4462245 - j4.721 \times 10^{-4}$ [19]. Fig. 3 shows the field distribution calculated with TBC and PML. In

TABLE II
COMPLEX EFFECTIVE INDEX

Mode	FE-ID-BPM	Vector-FEM [21]
E_{11}^x	$3.574131 - j1.6976^{-7}$	$3.574125 - j1.7649^{-7}$
E_{12}^x	$3.543530 - j5.4823^{-5}$	$3.543505 - j5.5352^{-5}$
E_{31}^x	$3.529949 - j1.6915^{-6}$	$3.529994 - j1.4923^{-6}$
E_{32}^x	$3.498591 - j1.2316^{-4}$	$3.498680 - j1.2273^{-4}$

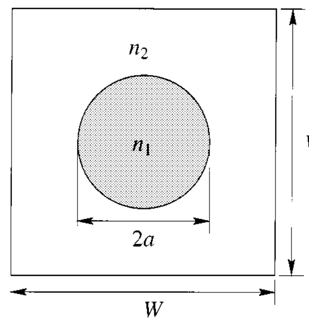

Fig. 8. Optical fiber.

the case of PML, PML layer with 1 μm width is uniformly divided into 40 elements and $R = 10^{-8}$. The results agree well with each other within the analysis region. Fig. 4 shows the convergence behavior of the effective index. We can see that the PML boundary condition can converge the effective index faster than TBC. This is because that TBC is required to simultaneously converge the effective index and the TBC parameter k_n in (19) related to the outside wavenumber at the boundary. On the other hand, the PML parameter needs not be changed in this calculation. Fig. 5 shows the field evolution in this calculation with PML. We select the random field as an initial inputted field and it is quickly modified to the fundamental eigenmode.

Next, we consider a 3-D leaky waveguide as shown in Fig. 6. The refractive indexes are 3.452 for 20% AlGaAs, 3.555 for 5% AlGaAs, and 3.590 for GaAs, and the operating wavelength is $1.064\,\mu$m. The PML boundary condition is imposed at the outer boundaries and the first four symmetric quasi-TE modes are calculated. PML layer with 1 μm width is uniformly divided by 6 and $R = 10^{-8}$. In this calculation, to accelerate the convergence behavior, we use the modal field profile and effective index for the same structure in which GaAs substrate is replaced by 5% AlGaAs. Fig. 7 shows the field distributions and Table II shows the effective indexes for each mode. Our results agree well with those of the full-wave conventional eigenmode analysis [21].

Finally, we consider an optical fiber as shown in Fig. 8. The refractive indexes are $n_1 = 1.515$ and $n_2 = 1.5$, core radius $a = 2.0\,\mu$m, and the normalized frequency $v = 2$. The PML or TBC boundary condition is imposed and the fundamental quasi-TE mode is calculated. PML layer with 1 μm width is uniformly divided by 4 and $R = 10^{-8}$. Fig. 9 shows the effective index as a function of the computational window size. For comparison, the results obtained by using the standard Neumann and Dirichlet boundary conditions are also shown. We can see that the PML boundary condition and TBC can drastically reduce the computational window size. Fig. 10 shows the electric field distributions in the optical fiber. Fig. 10(a) is the results calculated for a sufficiently large computational window ($W = 20$ μm) and Fig. 10(b)–(e) are those calculated for a smaller computational window ($W = 8\,\mu$m) with PML, TBC, Neumann, and Dirichlet boundary conditions, respectively. The results of Fig. 10(a)–(c) are in good agreement and the effectiveness of PML and TBC boundary condition is confirmed.

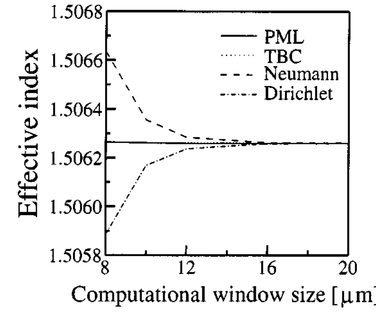

Fig. 9. Effective index as a function of the computational window size.

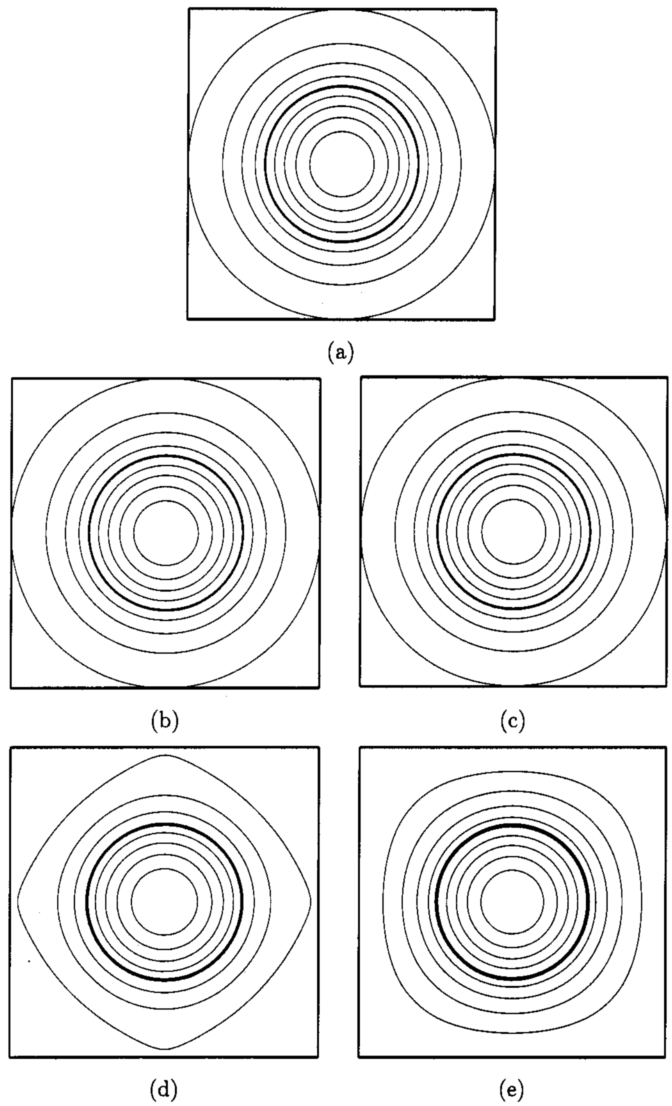

Fig. 10. Electric field distributions: (a) $W = 20\,\mu$m with Neumann boundary condition, (b) $W = 8\,\mu$m with PML boundary condition, (c) $W = 8\,\mu$m with TBC boundary condition, (d) $W = 8\,\mu$m with Neumann boundary condition, and (e) $W = 8\,\mu$m with Dirichlet boundary condition.

VI. Conclusion

As a simple and efficient eigenmode analysis method for 3-D optical waveguides, an imaginary distance BPM based on finite element scheme was newly described. In order to treat not only guided modes but leaky modes, the TBC and PML boundary conditions were introduced as boundary conditions for artificial boundaries. To show the validity and usefulness of this approach, numerical results for 2-D and 3-D leaky waveguides, and optical fibers were presented. A full-wave FE-ID-BPM using edge/nodal hybrid elements is now under consideration.

References

[1] S. M. Saad, "Review of numerical methods for the analysis of arbitrarily-shaped microwave and optical dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 894–899, Oct. 1985.

[2] K. S. Chiang, "Review of numerical and approximate methods for the modal analysis of general optical dielectric waveguides," *Opt. Quantum Electron.*, vol. 26, pp. 5113–5134, 1994.

[3] M. D. Feit and J. A. Fleck Jr., "Light propagation in graded-index optical fibers," *Appl. Opt.*, vol. 17, pp. 3990–3998, Dec. 1978.

[4] H.-P. Nolting and R. März, "Results of benchmark tests for different numerical BPM algorithm," *J. Lightwave Technol.*, vol. 13, pp. 216–224, Feb. 1995.

[5] Y. Tsuji and M. Koshiba, "A finite element beam propagation method for strongly guiding and longitudinally varying optical waveguides," *J. Lightwave Technol.*, vol. 14, pp. 217–222, Feb. 1996.

[6] M. Koshiba and Y. Tsuji, "A wide-angle finite-element beam propagation method," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1208–1210, Sept. 1996.

[7] Y. Tsuji, M. Koshiba, and T. Shiraishi, "Finite element beam propagation method for three-dimensional optical waveguide structures," *J. Lightwave Technol.*, vol. 15, pp. 1728–1734, Sept. 1997.

[8] Y. Tsuji and M. Koshiba, "Simple and efficient adaptive mesh generation for guided-mode and beam-propagation solutions," *IEICE Trans. Electron.*, vol. E81-C, pp. 1814–1820, Dec. 1998.

[9] D. Yevick and B. Hermansson, "New approach to lossy optical waveguide," *Electron. Lett.*, vol. 21, pp. 1029–1030, Oct. 1985.

[10] D. Yevick and W. Bardyszewskky, "Correspondence of variational finite difference (relaxation) and imaginary-distance propagatoin methods for modal analysis," *Opt. Lett.*, vol. 17, pp. 329–330, Mar. 1992.

[11] C. L. Xu, W. P. Huang, and S. K. Chaudhuri, "Efficient and accurate vector mode calculations by beam propagation method," *J. Lightwave Technol.*, vol. 11, pp. 1209–1215, July 1993.

[12] J. C. Chen and S. Jüngling, "Computation of high-order waveguide modes by imaginary-distance beam propagation method," *Opt. Quantum Electron.*, vol. 26, pp. S199–S205, 1994.

[13] F. Wijnands, H. J. W. M. Hoekstra, G. J. M. Krijinen, and R. M. de Ridder, "Modal fields calculation using the finite difference beam propagation method," *J. Lightwave Technol.*, vol. 12, pp. 2066–2071, Dec. 1994.

[14] S. Jüngling and J. C. Chen, "Imaginary distance beam propagation for passive and active waveguide structures," *Progr. Electromagn. Res. Symp.*, July 24–28, 1995.

[15] J. Shibayama, M. Sekiguchi, J. Yamauchi, and H. Nakano, "Eigenmode analysis of optical waveguides by an improved finite-difference imaginary-distance beam propagation method" (in Japanese), *Trans. IEICE*, vol. J81-C-I, pp. 9–16, Jan. 1998.

[16] G. R. Hadley, "Transparent boundary condition for the beam propagation method," *Opt. Lett.*, vol. 16, pp. 624–626, May 1991.

[17] J.-P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves," *J. Comput. Phys.*, vol. 114, pp. 185–200, October 1994.

[18] Ü. Pekel and R. Mittra, "A finite-element method frequency-domain application of the perfectly matched layer (PML) concept," *Microwave Opt. Technol. Lett.*, vol. 9, pp. 117–122, June 1995.

[19] W. P. Huang, C. L. Xu, and K. Yokoyama, "The perfectly matched layer boundary condition for modal analysis of optical waveguides: Leaky mode calculations," *IEEE Photon. Technol. Lett.*, May 1996.

[20] M. Koshiba, *Optical Waveguide Theory by the Finite Element Method*. Tokyo, Japan/Dordrecht, Germany: KTK Scientific/Kluwer Academic, 1992.

[21] H. E. Hernández-Figueroa, F. A. Fernández, Y. Lu, and J. B. Davies, "Vectorial finite element modeling of 2D leaky waveguides," *IEEE Ttrans. Magnet.*, vol. 31, pp. 1710–1713, May 1995.

Yasuhide Tsuji (M'97) was born in Takikawa, Japan, on December 31, 1967. He received the B.S., M.S., and Ph.D. degrees in electronic engineering from Hokkaido University, Sapporo, Japan, in 1991, 1993, and 1996, respectively.

In 1996, he joined the Department of Applied Electronic Engineering, Hokkaido Institute of Technology, Sapporo, Japan. Since 1997, he has been an Associate Professor at Hokkaido University, Sapporo, Japan. He has been engaged in research on wave electronics.

Dr. Tsuji is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. In 1997 and 1999, he was awarded the Excellent Paper Award from the IEICE, and in 1999, he was awarded the Young Scientist Award from the IEICE.

Masanori Koshiba (SM'84) was born in Sapporo, Japan, on November 23, 1948. He received the B.S., M.S., and Ph.D. degrees in electronic engineering from Hokkaido University, Sapporo, Japan, in 1971, 1973, and 1976, respectively.

In 1976, he joined the Department of Electronic Engineering, Kitami Institute of Technology, Kitami, Japan. From 1979 to 1987, he was an Associate Professor of electronic engineering at Hokkaido University, and in 1987, he became Professor. He has been engaged in research on wave electronics, including microwaves, millimeter-waves, lightwaves, surface acoustic waves (SAW's), magnetostatic waves (MSW's), and electron waves, and computer-aided design and modeling of guided-wave devices using finite element method, boundary element method, beam propagation method, etc. He is the author or coauthor of more than 200 research papers in English and of more than 100 research papers in Japanese, both in refereed journals. He authored the books *Optical Waveguide Analysis* (New York: McGraw-Hill) and *Optical Waveguide Theory by the Finite Element Method* (Tokyo, Japan/Dordrecht, Germany: KTK Scientific /Kluwer Academic), and coauthored the books *Analysis Methods for Electromagnetic Wave Problems* (Norwood, MA: Artech House), *Ultrafast and Ultra-parallel Optoelectronics* (New York: Wiley), and *Finite Element Software for Microwave Engineering* (New York: Wiley).

Dr. Koshiba is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, the Institute of Electrical Engineers of Japan, the Institute of Image Information and Television Engineers of Japan, the Japan Society for Simulation Technology, the Japan Society for Computational Methods in Engineering, the Japan Society of Applied Electromagnetics and Mechanics, the Japan Society for Computational Engineering and Science, and the Applied Computational Electromagnetics Society. He was awarded the Excellent Paper Award from the IEICE in 1987, 1997, and 1999, respectively, and in 1998, he was awarded the Electronics-Society Award from the IEICE.