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Topology optimal design for optical waveguides using time domain beam propagation method

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Abstract: New topology optimal design approach for optical waveguide devices using a time domain beam propagation method (TD–BPM) is presented. A sensitivity analysis method for topology optimization using TD–BPM is formulated based on an adjoint variable method (AVM). A density method is used as a way to represent refractive index distribution. As design examples, a loss–reduced bending waveguide and a reflector are designed. It is confirmed that our design approach can surely enhance the performance of optical waveguide devices.

Keywords: optical waveguide, topology optimization, time domain beam propagation method

Classification: Integrated optoelectronics

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1 Introduction

Recently, topology optimal design has attracted attention in the field of photonics, and it has already been employed so as to obtain compact optical waveguide devices with high performance [1, 2, 3, 4]. Since material distribution itself can be optimized, it can be expected to get optical devices with smaller foot-print and higher performance using topology optimization than using sizing or shape optimization.

In conventional topology optimization, as a numerical analysis method, a finite element method (FEM) or a finite difference time domain (FDTD) method is mainly used to analyze wave propagation behavior. On the other hand, in optical waveguide analysis, a beam propagation method (BPM) [5, 6] is also widely employed. The BPM is quite useful technique for analysis of optical waveguides whose refractive index distribution vary slowly in the longitudinal direction. In our previous study, we developed topology optimization utilizing the BPM [7, 8]. Since the standard BPM can not evaluate backward reflected waves, this approach is useful for the design of long-length devices like planner lightwave circuit (PLC) devices with low-contrast refractive index distribution. The time domain BPM (TD–BPM) [9] can take into account backward reflection, and it is reported that the computational time can be higher than the FDTD in a two dimensional problem [10]. Since the TD–BPM is an implicit scheme, the time step is not restricted by Courant condition. Transmission spectrum can be evaluated by single TD-BPM analysis using the Gaussian pulse, thus the TD–BPM can be more useful than the FEM for the design taking into account wavelength dependency.

In this paper, we propose topology optimal design utilizing the TD–BPM for optical waveguide devices. Our optimal approach is based on sensitivity analysis, thus we develop a method to calculate the sensitivity with respect to the design parameter in the case of using the TD–BPM. By designing a bending waveguide and a reflector as design examples, it is confirmed that sensitivity analysis method that we formulated works correctly and our approach can surely enhance the device performance.

2 Topology optimization using TD–BPM

We start with the formulation of the TD–BPM based on a finite difference scheme. For simplicity, using the standard narrow band TD–BPM formula where the effect

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of material dispersion is neglected, we consider a two dimensional problem for TE wave. The two dimensional time dependent wave equation is given by

$$\frac{n^2(x,z)}{c^2}\frac{\partial^2 E_y(x,z,t)}{\partial t^2} = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right)E_y(x,z,t), \tag{1}$$

where E_y is the y component of the electric field, n is the refractive index, c is speed of light in free space, and t is time. The electric filed can be represented by its envelope and the time-dependent phase factor as follows:

$$E_y(x,z,t) = \mathrm{Re}\{\phi(x,z,t)\exp(j\omega_0 t)\}, \tag{2}$$

where ω_0 is the angular frequency of the carrier wave. Substituting (2) to (1), and employing the slowly varying envelope approximation (SVEA), we get

$$\frac{\partial\phi(x,z,t)}{\partial t} = \left\{\frac{c^2}{j2\omega_0 n^2(x,z)}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right) + \frac{\omega_0}{j2}\right\}\phi(x,z,t). \tag{3}$$

Applying the Crank-Nicolson method and the alternative direction implicit method (ADIM) to (3), the equation can be represented by the following form [10].

$$1^{\text{st}}\text{ step:}\quad [\Gamma_2]_k\{\phi\}_{k+\frac{1}{2}} = [\Gamma_1]_k\{\phi\}_k, \tag{4}$$

$$2^{\text{nd}}\text{ step:}\quad [\Gamma_4]_k\{\phi\}_{k+1} = [\Gamma_3]_k\{\phi\}_{k+\frac{1}{2}}, \tag{5}$$

where $\{\phi\}_k$ denotes a vector form of $\phi(x,z,k\Delta t)$.

Next, we derive the sensitivity analysis method based on an adjoint variable method (AVM) in the case of using the TD-BPM. By the density method, material distribution in the design region is represented as follows:

$$n_{ij}^2 = n_2^2 + (n_1^2 - n_2^2)H(\rho_{ij}, m), \tag{6}$$

where n_{ij} denotes $n(i\Delta x, j\Delta z)$, n_1 and n_2 are core and cladding index, respectively, and ρ_{ij} is the normalized density parameter. $H(\rho, m)$ is a modified step function whose range is $0 \le H \le 1$, and $H(\rho, \infty)$ means a standard step function [7, 8]. In sensitivity analysis, the derivative of n_{ij}^2 with respect to the design parameter ρ_{ij} is necessary. This modified step function which is differentiable is employed gradually increasing the value of m in the optimization process. Eventually, binarized refractive index distribution can be obtained by $m \to \infty$.

To optimize the device performance, an overlap integral associated with port 1 and port n is defined by

$$\eta_{n1}(t) = \iint_{\Omega} \psi_n^*(x,z)\phi(x,z,t)dxdz, \tag{7}$$

where Ω means the computational domain, ψ_n is an ideal output pulse in port n, and * denotes complex conjugate. Here, we define the peak value of $|\eta_{n1}(t)|$ as $|\eta_{n1}(\tau\Delta t)|$, that is,

$$\max_t\{|\eta_{n1}(t)|\} = |\eta_{n1}(\tau\Delta t)| \equiv |\eta_{n1}^{\tau}|. \tag{8}$$

It is used for performance evaluation. Using the rectangular approximation, (7) is represented by the vector form.

$$\eta_{n1}^{\tau} = \{\lambda_n\}^T\{\phi\}_{\tau}, \tag{9}$$

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where $\{\lambda_n\} = \Delta x \Delta z \{\psi_n\}^*$, and ^{T} denotes transpose. If the input and output port are not in the design region, the sensitivity with respect to ρ_{ij} is given by

$$\frac{\partial \eta_{n1}^{\tau}}{\rho_{ij}} = \{\lambda_n\}^T \frac{\partial \{\phi\}_{\tau}}{\rho_{ij}}. \tag{10}$$

Applying (4) and (5) to (10), the derivative can be rewritten as

$$\frac{\partial \eta_{n1}^{\tau}}{\partial \rho_{ij}} = \{\lambda_n\}^T \frac{\partial}{\rho_{ij}} \prod_{k=0}^{\tau-1} ([\Gamma_4]^{-1}[\Gamma_3][\Gamma_2]^{-1}[\Gamma_1])_k \{\phi\}_0, \tag{11}$$

where $\{\phi\}_0$ is an input field. Finally, we get the form

$$\begin{aligned}\frac{\partial \eta_{n1}^{\tau}}{\partial \rho_{ij}} = \sum_{k=1}^{\tau} \Bigg[&-\{\lambda_{n,k-1/2}\}^T \frac{\partial [\Gamma_4]_k}{\partial \rho_{ij}} \{\phi\}_k + \{\lambda_{n,k-1/2}\}^T \frac{\partial [\Gamma_3]_k}{\partial \rho_{ij}} \{\phi\}_{k-1+\frac{1}{2}} \\ &- \{\lambda_{n,k-1}\}^T \frac{\partial [\Gamma_2]_k}{\partial \rho_{ij}} \{\phi\}_{k-1+\frac{1}{2}} + \{\lambda_{n,k-1}\}^T \frac{\partial [\Gamma_1]_k}{\partial \rho_{ij}} \{\phi\}_{k-1} \Bigg].\end{aligned} \tag{12}$$

The adjoint equations are given by

$$[\Gamma_4]_k^T \{\lambda_{n,k+1/2}\} = [\Gamma_1]_{k+1}^T \cdots ([\Gamma_2]_{\tau-1}^{-1})^T [\Gamma_3]_{\tau-1}^T ([\Gamma_4]_{\tau-1}^{-1})^T \{\lambda_n\}, \tag{13}$$

$$[\Gamma_2]_k^T \{\lambda_{n,k}\} = [\Gamma_3]_k^T \{\lambda_{n,k+1/2}\}. \tag{14}$$

Since refractive index distribution is given by analytical representation (6), the derivative of $[\Gamma_n](n = 1, 2, 3, 4)$ can be obtained without numerical differentiation. Thus, the additional cost for the sensitivity analysis is mainly to solve (13) and (14) for all $k = 1, 2, \cdots, \tau$ which can be calculated efficiently by backward propagation analysis of an ideal output pulse. The design parameters are updated using a steepest descent method in this study. By iterating the update process based on the sensitivity, the device performance, e.g. output power, can be maximized.

3 Design example

3.1 Bending waveguide

To assess our design approach, first, we apply it to the design problem of a bending waveguide. The design model of the bending waveguide is shown in Fig. 1. The parameters are taken to be as follows: $n_1 = 2.2$, $n_2 = 1.445$, $w = 0.5\,\mu\text{m}$, $l_i = 5\,\mu\text{m}$, $l_{r1} = 10\,\mu\text{m}$, $l_d = 10\,\mu\text{m}$, $l_{r2} = 35.525\,\mu\text{m}$, $W_z = 45\,\mu\text{m}$, $L_z = L_x = 5\,\mu\text{m}$, $d = 1.5\mu\text{m}$, $D = 4\,\mu\text{m}$, $w_p = 1.05\,\mu\text{m}$. The step sizes are $\Delta x = \Delta z = 0.035\,\mu\text{m}$, and $\Delta t = 1\,\text{fs}$. The input and output pulse are observed in reference plane 1 and 2 respectively. The Gaussian pulse is put in port 1 as an initial pulse at $t = 0$.

$$\phi(x, z, t = 0) = \phi_1(x) g(z - l_i) \exp[-j\beta_1(z - l_i)], \tag{15}$$

$$g(z) = \exp[-(z/a)^2], \tag{16}$$

where $a = 2\,\mu\text{m}$, ϕ_n and β_n are the eigenmode field in port n and the phase constant at a wavelength of $1.55\,\mu\text{m}$. To maximize output power in port 2, the objective function is taken to be as follows:

$$\text{Minimize } C = \left(1 - \frac{|\eta_{21}^{\tau}|^2}{|\eta_{21}^{\text{ideal}}|^2}\right)^2, \tag{17}$$

where η_{21}^{ideal} is defined by the ideal output pulse ψ_n in (7), here $n = 2$.

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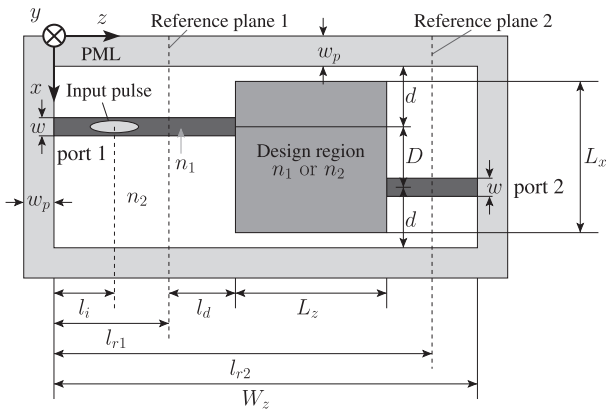


Fig. 1. Design model for bending waveguide.

$$\eta_{21}^{\text{ideal}} = \iint_{\Omega} |\psi_2(x,z)|^2 dxdz, \tag{18}$$

$$\psi_2(x,z) = \phi_2(x) g(z - l_{r2}) \exp[-j\beta_2(z - l_{r2})]. \tag{19}$$

Fig. 2 shows the objective function as a function of iteration number. We can see that the value of the objective function decreases in the iterating process. Some small peaks appear, which is not failure of the sensitivity analysis, because the value of m in (6) is changed in order to remove gray region when the variation of the objective function becomes smaller. Fig. 3 indicates the optimized structure after 103 iterations of the optimization process and the normalized output power spectrum over the C+L band. For comparison, topology optimal results obtained from the conventional approach [2] and the analysis results of an offsets-added bending waveguide (the optimized offset value is ±0.1225 μm) are shown. As a conventional approach, topology optimization using the FEM [2] is employed, where the objective function is determined so as to maximize the output power in port 2 at a wavelength of 1.55 μm. As shown in Fig. 3(a), the normalized output power in the optimized bending waveguides is higher than that in the offsets-added bending waveguide. The output power spectrum of the optimized structure with the conventional approach has a peak at a center wavelength of 1.55 μm. We can see that the spectrum in the optimized structure with our approach is relatively flat, although it is not significant in this design example. Figs. 3(b) and (c) are topology optimal structures with our approach and with the conventional approach, respectively. Waveguide offsets for reduction of the bending loss emerge in the both

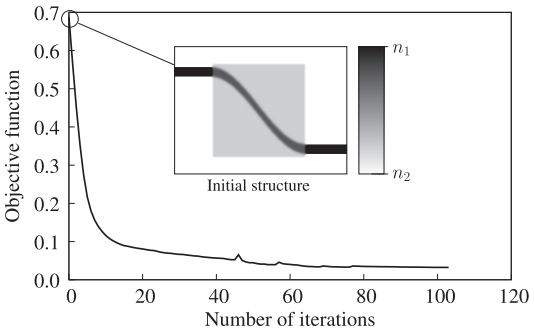
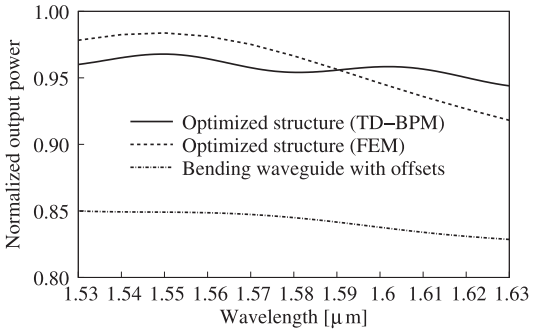


Fig. 2. Objective function as a function of iterating number.

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(a) output power spectrum in port 2



(b) optimized structure with our method

(c) optimized structure with FEM

(d) bending waveguide with offsets

Fig. 3. Optimization results of bending waveguide.

bending waveguides, and the optimized one with our approach contains an irregular grating structure. In a grating waveguide, the side lobe of the reflectance spectrum can be reduced modulating the grating period. The grating structure may appear so that transmitted spectrum is flatter in relatively wide band sacrificing the transmittance in the region far from the center wavelength.

3.2 Reflector

For further verification of our approach, we design a reflector. The design model is shown in Fig. 4. We aim to design a reflector where the fundamental TE wave is launched into port 1, then the wave is reflected and output to port 2. The parameters in the design model are taken to be as follows: $n_1 = 2.2$, $n_2 = 1.445$, $w = 0.5\,\mu\text{m}$, $l_i = l_{r2} = 5\,\mu\text{m}$, $l_{r1} = 10\,\mu\text{m}$, $l_d = 10\,\mu\text{m}$, $W_z = 25.9\,\mu\text{m}$, $L_z = L_x = 5\,\mu\text{m}$, $d = 2.5\,\mu\text{m}$, $D = 2\,\mu\text{m}$, $w_p = 1.05\,\mu\text{m}$. The step sizes, the center wavelength, and a in (16) are the same as the previous design example. The representation of the input pulse, the objective function, and the ideal output pulse are also the same as (15),

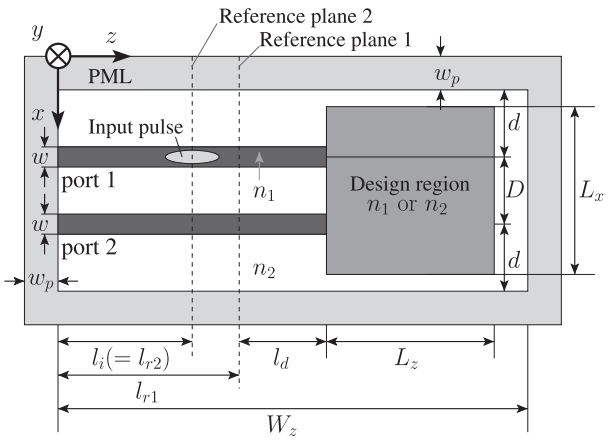
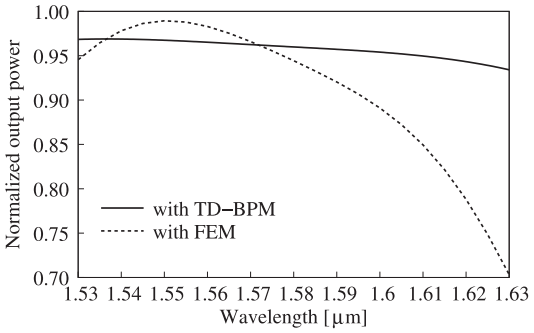


Fig. 4. Design model for reflector.

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(a) output power spectrum in port 2



(b) optimized structure with our method



(c) optimized structure with FEM

Fig. 5. Optimization results of reflector.

(17), and (19), respectively. The initial structure in the design region is a uniform medium with the normalized density parameter of 0.498.

Fig. 5 shows the optimized structure and the normalized output power spectrum in port 2 over the C+L band. Topology optimal results obtained from the conventional approach are shown for comparison. Fig. 5(a) indicates the wavelength dependence of normalized output power in port 2. We can see that the dependence on wavelength is strong in the optimized structure with the conventional approach, although the output power is high in the vicinity of the wavelength of 1.55 μm. The output power spectrum is much flatter in the optimized structure with our approach than in that with the conventional one, whereas the both optimized structures shown in Figs. 5(b) and (c) achieve a reflector using a waveguide grating. In the conventional topology optimization using a frequency domain method like the FEM, it is necessary to use the objective function taking into account multi-wavelengths, thus it costs additional numerical analysis. Since the TD–BPM can take into account wider frequency band at one time, our design approach is more efficient for a design of a wavelength-independent device than topology optimization using a frequency domain method.

4 Conclusion

Topology optimization for optical waveguide devices utilizing the TD–BPM is proposed. To realize this approach, sensitivity analysis method in the case of using the TD–BPM is formulated. The validity of the design approach is confirmed by the design examples of a bending waveguide and a reflector. Our approach will be applied to the case using an improved TD–BPM which can take into account material dispersion and wider band in future studies.

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