Design of Optical Circuit Devices Based on Topology Optimization

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***Abstract*—We apply a design method based on topology optimization technique to optical waveguide devices. In our approach, after a refractive index profile in a design region is automatically generated using a topology optimization method, the obtained structure is redefined using primitive geometries with some design parameters and those parameters are optimized by a sequential linear programming. As numerical examples, we demonstrate how the method can be used for 90° bends and T-branching waveguides with arbitrary splitting ratio.**

***Index Terms*—Finite-element method, optical circuit, sequential linear programming (SLP), topology optimization.**

I. Introduction

IN THE recent progress of optical communication systems, many kinds of high-performance optical waveguide devices have been developed. However, in order to realize all-optical communication systems, further improvement of device performances and miniaturization of optical devices are desired.

In order to search for structures which have a desired device operation, various optimization methods have been developed, such as a genetic algorithm [1], [2], a sequential linear programming (SLP), and so on. Topology optimization method [3]–[7] is one of the useful optimization methods. The topology optimization method was originally developed for structural optimization problems, but has recently been extended to some other design problems. This method is based on iterative finite-element analysis and at each iteration step, material parameters, such as density parameters, are modified to improve device operation. The topology optimization method is a class of optimization methods that can simultaneously deal not only with geometric form but also with topological configuration, so we can find out optimized structures without predefining any geometry.

In this letter, we apply a design method based on a topology optimization to optical waveguide devices. In our approach, first, we will apply the topology optimization method to design regions. In general, refractive index profiles obtained by topology optimization have some gray-scale area and complicated patterns of refractive index and those profiles also depend on initially generated finite element discretization. So, in order to obtain more practical structures, we extract characteristic structures from the obtained refractive index profiles and optimize the structural parameters of the simplified structures using SLP.

As numerical examples, we demonstrate how the method can be used for 90° bends and T-branching waveguides with arbitrary splitting ratio.

II. Topology Optimization-Based Design Method

We use the frequency domain finite-element method with a perfectly matched layer for the analysis of waveguide discontinuity problems [8]. This approach does not need a mode expansion technique at input and output waveguides and can suppress spurious reflections from artificial boundaries.

The topology optimization method is based on iterative finite-element analysis and at each iteration step, material parameters, such as density parameters, are modified to improve device operation. The permittivity in each element within the design region is expressed as follows:

$$\varepsilon_i = \varepsilon_{\min} + (\varepsilon_{\max} - \varepsilon_{\min})\rho_i^p \tag{1}$$

where i denotes element number, $\varepsilon_{\min}$ and $\varepsilon_{\max}$ are the minimum and maximum permittivity, respectively, ρ_i is the density parameter in the ith element, p is the penalization parameter that promotes convergence away from gray-scale results. In the following numerical examples, we assume $\varepsilon_{\min} = 1.0$, $\varepsilon_{\max} = 1.45$, $0 \leq \rho_i \leq 1$, and $p = 2$. As a penalization parameter p, larger values can be also used, but in our examples we could not see any dramatical improvement in the results for several values of p. This is because topology optimization was used only for extracting the characteristic structure.

After finite-element analysis, we estimate the sensitivity at each element, which is related to the output power variation depending on the small variation of density parameters. Then, based on these results, the density parameters are optimized to improve device operation. In order to effectively obtain sensitivities, we employ the adjoint variable method [3], and in order to optimize density parameters, we employ the SLP technique with the package DSPLP in the SLATEC library [9]. When SLP is used for some complicated devices, a result may fall into a local optimal value depending on problems and initial conditions. However, trying with different initial conditions, we can reduce the risk of reaching a local minimum with a poor performance.

The structures obtained by topology optimization usually have complicated refractive index patterns. In order to simplify the structures, we redefine structures using some primitive geometries with some design parameters and those parameters

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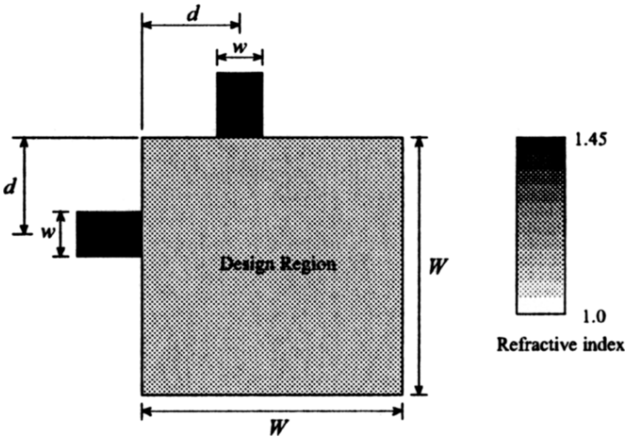

Fig. 1. Design structure for 90° bend.

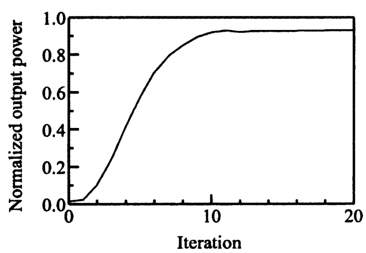

Fig. 2. Convergence behavior of normalized output power.

are again optimized by SLP. In order to create the simplified structure, some detailed structures are disregarded and boundaries of refractive indexes are roughly fitted by primitive geometries manually. In the following numerical examples, we use only circular arcs as a fitting geometry. However, in order to treat more complicated structures, using spline functions may be more suitable.

III. Numerical Examples

As numerical examples of the design method, first we consider a 90° bend, as shown in Fig. 1. The refractive indexes of core and cladding are 1.45 and 1.0, respectively. The waveguide width is $w = 0.7\ \mu$m, the design region size is $4 \times 4\ \mu\text{m}^2$, and $d = 1.5\ \mu$m. We assume that the fundamental TE mode with wavelength $\lambda = 1.55\ \mu$m is inputted and the objective function in the topology optimization is given as follows:

$$\text{Maximize } |S_{21}|^2 \qquad \text{at } \lambda = 1.55\ \mu\text{m} \tag{2}$$

where the scattering parameter S_{21} is the ratio of output amplitude to input one. Fig. 2 shows convergence behavior of the transmitted power during the iteration process. An initial value of ρ_i in the design region is assumed to be 0.5 in all the elements. Fig. 2 shows that less than 20 iteration steps are required in this problem and the normalized output power is 0.94 at the final iteration step. For comparison, in the case of a simple bend structure composed of circular arc, the normalized output power is 0.38. From these results, we can see that a relatively high transmission can be obtained by the topology optimization. Fig. 3 shows the optimized refractive index profile and propagating field intensity. In Fig. 3(a), the refractive index profile is expressed by gray level. It is shown that the optimized structure can be automatically generated in the design region though there is a homogeneous structure in the beginning. We can see that in the bend region of the optimized refractive index profile, the light propagating outside is accelerated due to the lower refractive index and the light propagating inside is decelerated due to the higher refractive index, so wave front is kept constant and outside grating structure works to suppress radiating wave.

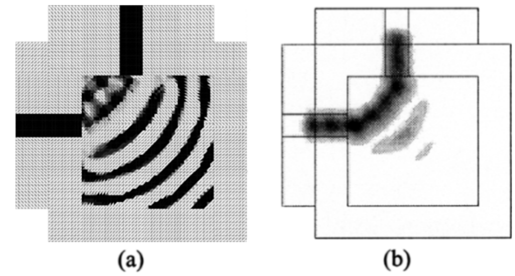

Fig. 3. 90° bend obtained by topology optimization. (a) Refractive index profile; (b) field intensity.

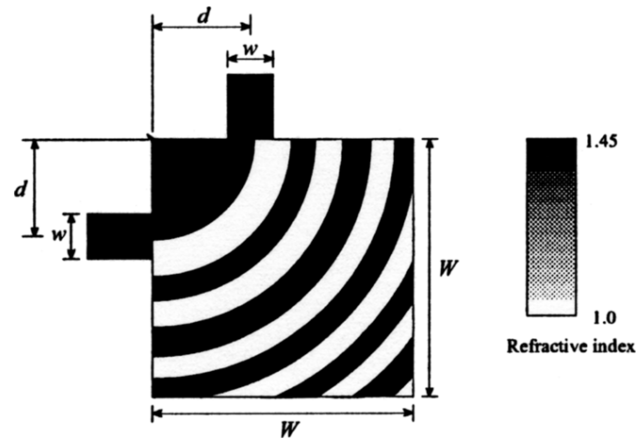

Fig. 4. Redefined structure using primitive geometries.

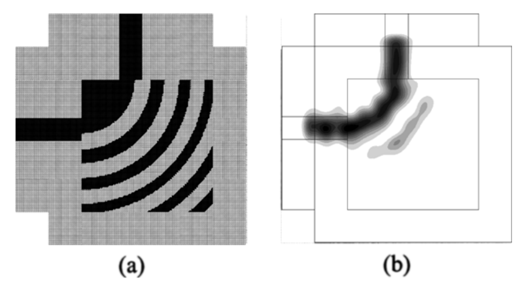

Fig. 5. Simplified 90° bend. (a) Refractive index profile; (b) field intensity.

Next, we consider a simplified structure based on the obtained structure, as shown in Fig. 4. The structure is expressed by some circular arcs and those radius are optimized simultaneously by SLP. The centers of the arcs are fixed at the upper-left corner of the design region. Fig. 5 shows the optimized refractive index profile and propagating field intensity. Fig. 6 shows the wavelength dependency of the normalized output power. In the case of the simplified structure, relatively high transmission through 90° bend can still be obtained, although the peak wavelength is shifted. We also tried to optimize the structure with three circular air holes in the inner part of the bend; then it was confirmed that the peak wavelength was shifted toward $\lambda = 1.55\ \mu$m.

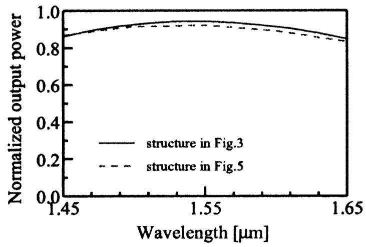

Fig. 6. Wavelength dependency of normalized output power.

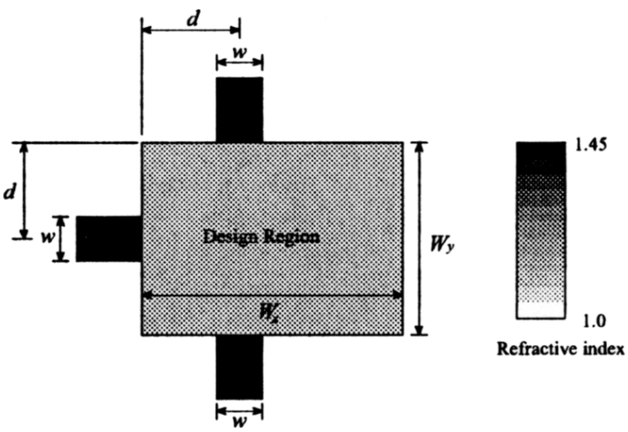

Fig. 7. Design structure for T-branching waveguide.

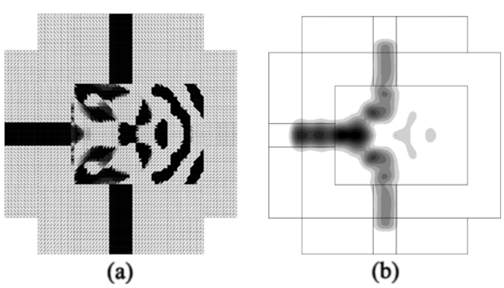

Fig. 8. T-branching waveguide with 1 : 1 power ratio. (a) Refractive index profile; (b) field intensity.

As another optimization example, we consider T-branching waveguides with arbitrary splitting ratio, as shown in Fig. 7. The design region size is $4 \times 3\ \mu\mathrm{m}^2$, and the other parameters are the same as in the case of 90° bend.

In this problem, an objective function is given by maximization of total transmission power and minimization of deviation from the desired splitting ratio. The objective function for $\alpha : \beta$ branching is given as follows:

$$\text{Minimize } \left| \frac{\beta |S_{21}|^2 - \alpha |S_{31}|^2}{|S_{21}|^2 + |S_{31}|^2} \right| \text{ at } \lambda = 1.55\ \mu\text{m} \qquad (3)$$

where the scattering parameter S_{n1} is the ratio of output amplitude at port n to input one. Figs. 8 and 9 show the optimized refractive index profile and propagating field intensity for 1 : 1 and 1 : 2 branching, respectively. The normalized output powers in the output waveguides are 0.46 and 0.46 for 1 : 1 branching and 0.30 and 0.62 for 1 : 2 branching, respectively.

Next, we simplify the obtained structure for 1 : 1 branching using some circular arcs, and optimize the structural parameters by SLP. This simplified structure is obtained by the superposition of the structures for the 90° bend. Fig. 10 shows the optimized refractive index profile and propagating field intensity. The normalized output powers are 0.39 and 0.39, respectively.

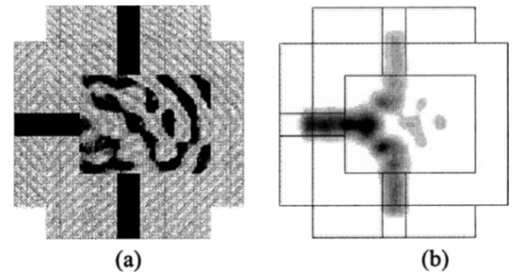

Fig. 9. T-branching waveguide with 1 : 2 power ratio. (a) Refractive index profile; (b) field intensity.

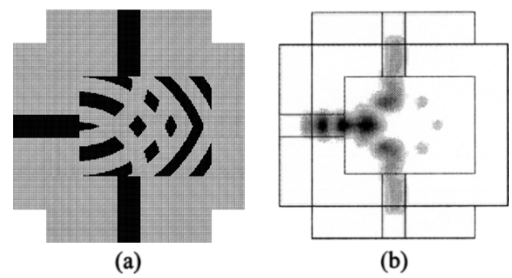

Fig. 10. Simplified T-branching waveguide with 1 : 1 power ratio. (a) Refractive index profile; (b) field intensity.

IV. Conclusion

We have applied a design method based on topology optimization method to optical waveguide devices. In order to confirm the effectiveness of the present method, we applied this method to a 90° bend and T-branching waveguides. This optimization method can be applied to various types of optical waveguide devices. To extend this method to three-dimensional structures is now under consideration.

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