Novel Optical Waveguide Design Based on Wavefront Matching Method

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Abstract

The wavefront matching method provides a new way to create the optimum shape for waveguides used in planar lightwave circuit devices. The waveguide core pattern is deterministically determined by the electrical fields of the input light and the desired output light, so the calculation speed is higher than for cut-and-try numerical optimizations such as genetic algorithms and convergence is excellent. This paper describes the principle behind the method and shows its usefulness through some experimental results.

1. Introduction

Planar lightwave circuit devices including arrayed waveguide gratings, Mach-Zehnder switches, and splitters play important roles in various kinds of optical communication systems such as wavelength division multiplexing transmission, optical crossconnect, and fiber-to-the-home systems [1], [2]. They are usually composed of well-known waveguide elements such as Y-branches, delay lines, and couplers made of silica glass. This means that the function, performance, and size of the devices are limited by these elements. To overcome this limitation, we recently proposed a new method that creates waveguide shapes beyond our ability to imagine and optimizes the circuit elements [3]. We call this approach the wavefront matching (WFM) method. In this technique, the refractive index distribution in the design area is deterministically obtained under the condition that the coupling coefficient between the input and desired output optical fields should be made to approach unity by matching the forward and backward propagating wavefronts. The design calculation process determines the index distribution (i.e., the waveguide shape) that gives the waveguide a particular function. This process does not take a long time to complete, unlike cut-and-try methods such as genetic algorithms [4]. We believe this needs-oriented WFM constitutes a revolutionary design method. This paper explains the principle of WFM and describes some devices including a 1.3/1.5-µm wavelength filter, a pair of waveguide lenses, a low-loss Y-branch, and a low-loss X-crossing.

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2. Principle of wavefront matching method

Since we have no clear shape in mind before beginning the waveguide design process, we consider a rectangular design area that will include the optimum waveguide, as shown in **Fig. 1**. Our final goal is to decide the refractive index distribution in the area, which provides us with the function we require. The area is divided into small rectangles (pixels) with steps of Δz and Δx in the z and x directions, respectively. Δz and Δx are the parameters defined in the fast-Fourier-transform-based beam propagation method (FFT-BPM) that we use in WFM. The input light electrical field at $z = 0$ is expressed by $\phi_0(x)$ and the desired output field at $z = M \cdot \Delta z$ is $\psi_M(x)$, where the subscripts 0 and M denote the calculation step number in the z direction. Transmittance, which is equal to the coupling coefficient between the input

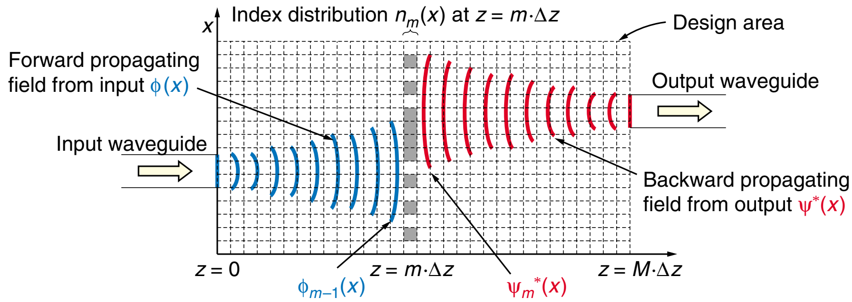

Fig. 1. Waveguide design model for wavefront matching method.

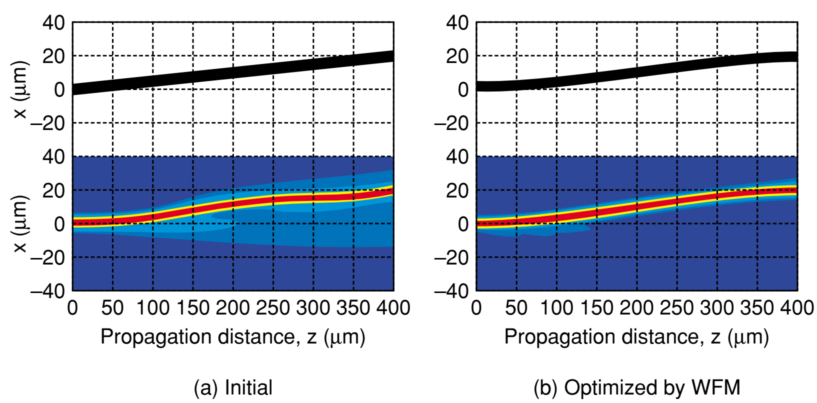

Fig. 2. S-bend optimization by WFM (top: index, bottom: electrical field).

and desired output electrical fields, is given by

$$\eta = |\int \psi^*_M(x)\phi_M(x)dx|^2. \quad (1)$$

According to FFT-BPM theory, the output field $\phi_M(x)$ at $z = M \cdot \Delta z$ is expressed by

$$\phi_M = (\mathbf{AB}_M\mathbf{A})(\mathbf{AB}_{M-1}\mathbf{A})\cdots(\mathbf{AB}_1\mathbf{A})\phi_0, \quad (2)$$

where $\mathbf{A}$ and $\mathbf{B}_m$ are the operators for free-space propagation and the phase shift induced by the refractive index distribution $n_m(x)$, respectively. From Eqs. (1) and (2), the transmittance is given by

$$\eta = |\int \psi^*_M(x)(\mathbf{AB}_M\mathbf{A})(\mathbf{AB}_{M-1}\mathbf{A}) \cdots\cdots(\mathbf{AB}_1\mathbf{A})(\mathbf{AB}_0\mathbf{A})\phi_0(x)dx|^2$$
$$= |\int \psi^*_m(x)\mathbf{AB}_m\mathbf{A}\phi_{m-1}(x)dx|^2, \quad (3)$$

where

$$\phi_{m-1}(x) = (\mathbf{AB}_{m-1}\mathbf{A})(\mathbf{AB}_{m-2}\mathbf{A})\cdots\cdots(\mathbf{AB}_0\mathbf{A})\phi_0(x) \quad (4)$$
$$\psi^*_m(x) = (\mathbf{AB}_{m+1}\mathbf{A})(\mathbf{AB}_{m+2}\mathbf{A})\cdots\cdots(\mathbf{AB}_M\mathbf{A})\psi^*_M(x). \quad (5)$$

Here, $\phi_{m-1}(x)$ denotes the electrical field of input light arriving at $z = (m-1)\Delta z$ and $\psi^*_m(x)$ denotes the virtual electrical field backward-propagating from $z = M \cdot \Delta z$ to $z = m \cdot \Delta z$. Equation (3) means that the transmittance depends on the coupling between the forward and backward propagating waves and that we can improve it by giving an appropriate value to $\mathbf{B}_m$ somewhere in the range from $\phi_{m-1}(x)$ to $\psi_m(x)$. Since $\mathbf{B}_m$ is given by

$$\mathbf{B}_m(x) = e^{-jk(n_m(x)-n_{ref})\Delta z}, \quad (6)$$

if we choose $n_m(x)$ to satisfy:

$$-\arg[\psi_m(x)] + \arg[\phi_{m-1}(x)] - k(n_m(x) - n_{ref})\Delta z$$
$$= \text{constant along the } x \text{ axis}, \quad (7)$$

where k is the wave number and n_{ref} is the average refractive index, then the transmittance is improved. This choice means that the index distribution is decided so that the wavefront of the forward propagating wave matches that of the backward propagating wave. This is why we called this method the "wavefront matching" method. Although the improvement

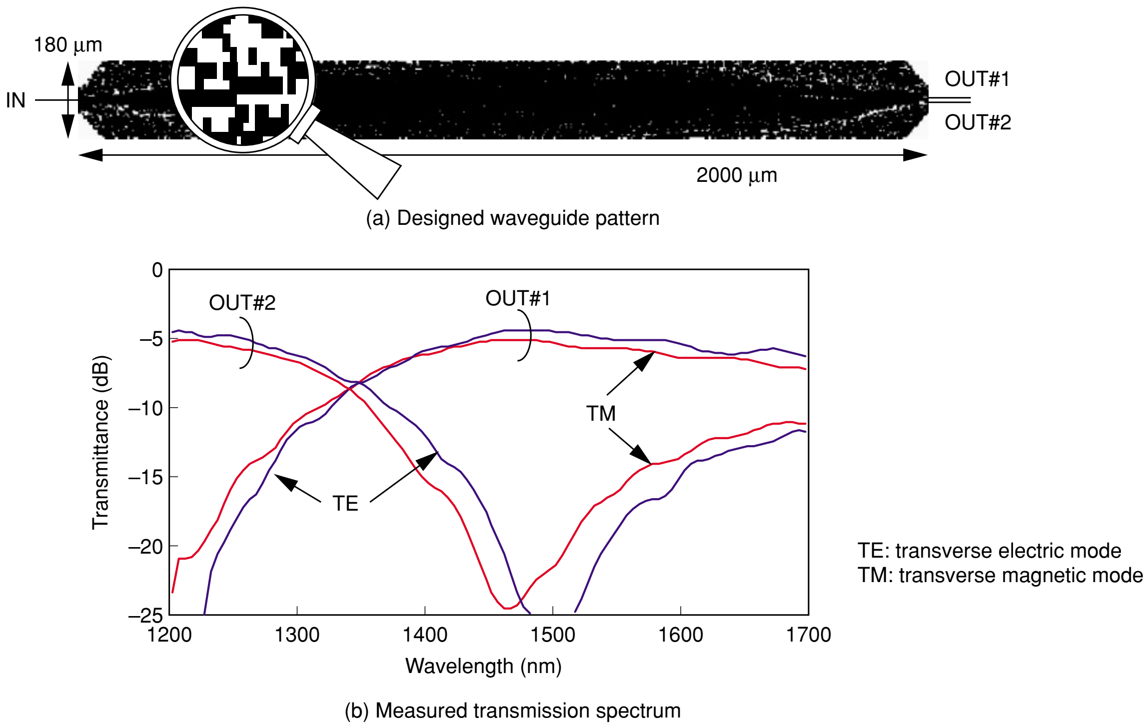

Fig. 3. Experimental results for wavelength filter.

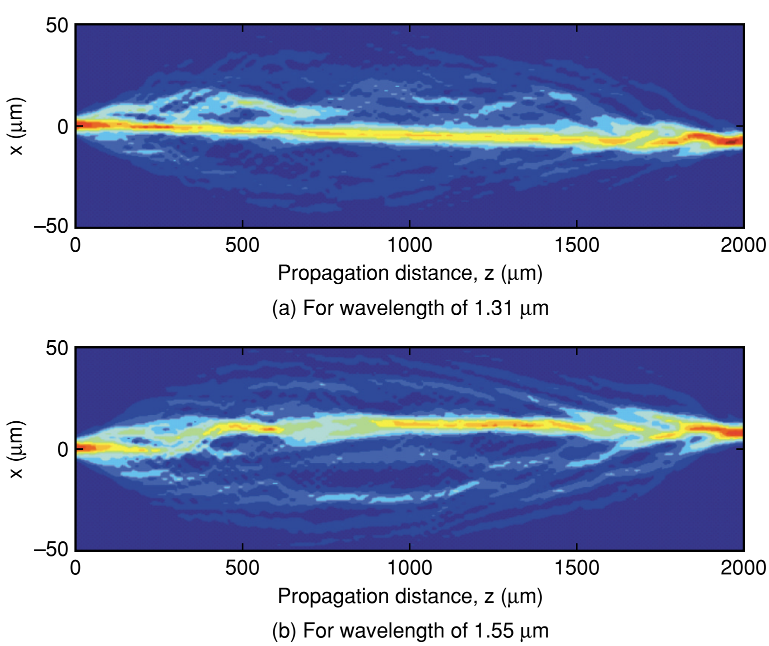

Fig. 4. Simulation results for wavelength filter.

in transmittance at $z = m \cdot \Delta z$ is small, we can finally obtain a high transmittance after performing the same operation for every m and thus obtaining the optimum total index distribution, that is, the optimum waveguide shape. Although the index ideally has an analog value as a result of the calculation based on Eq. 7, it is convenient to treat $n_m(x)$ as a digital value or to give it either of two values (existence or nonexistence

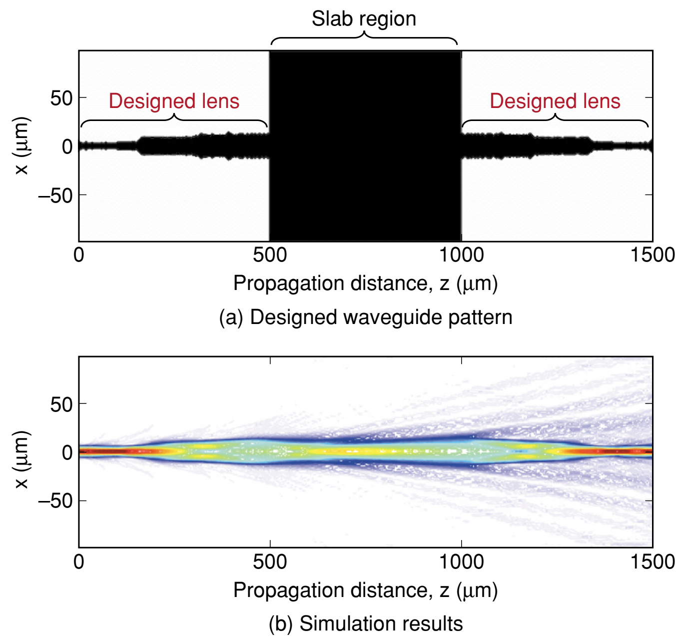

Fig. 5. Design of lens pair over slab region.

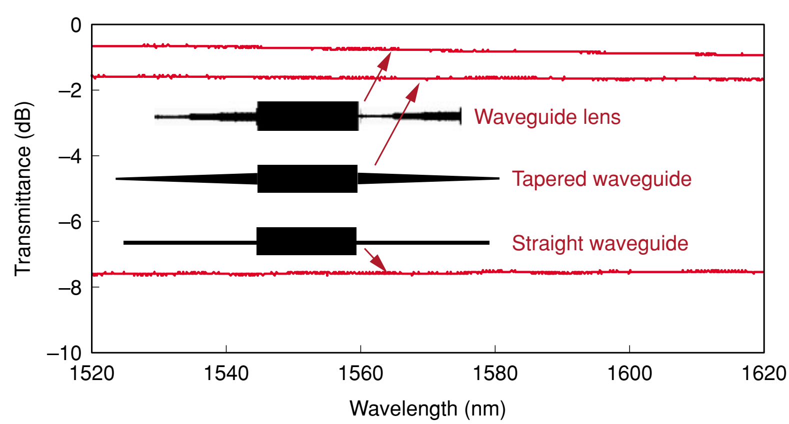

Fig. 6. Measured transmission spectra of lens pair.

of high index material). The index value of $n_m(x)$ is a digital value in all the designs in this paper.

One of the simplest, most recognizable examples of WFM is to make an optimum S-shaped waveguide bend. The refractive index distribution and light propagation are shown in **Fig. 2**. The initial value and the value optimized by WFM are shown in Figs. 2(a) and (b), respectively. The assumed input and output fields are the fundamental modes of the waveguide located at $x = 0$ μm and $x = 20$ μm, respectively. We set the straight waveguide as the initial index distribution where light leaks and the transmittance is –4.5 dB. Meanwhile, the transmittance is as high as –0.34 dB in the optimized S-bend.

3. Application to waveguide elements

We designed and fabricated several waveguide elements to confirm the principle of WFM experimentally. All the samples were fabricated using silica-based planar lightwave circuit technology including flame hydrolysis deposition, photolithography, and reactive ion etching. The core layer was 6 μm thick and the refractive index difference between the core

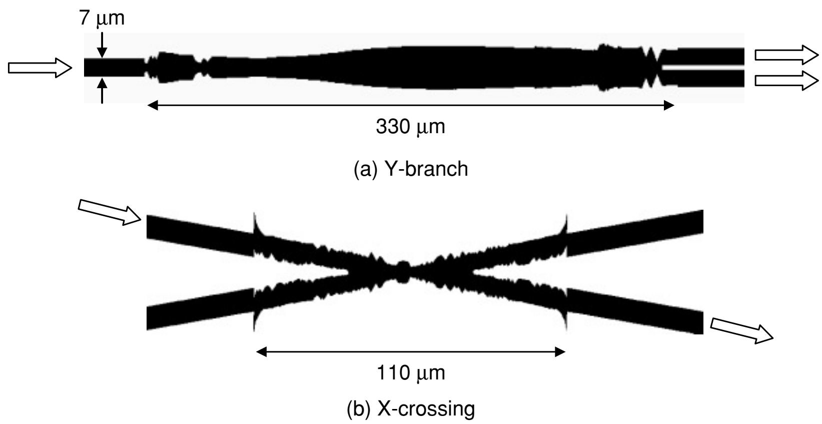

Fig. 7. Designed low-loss Y-branch and X-crossing.

and cladding layers was 0.75%.

a) 1.3/1.5-µm wavelength filter

We can design wavelength filters by simultaneously performing WFM for multiple wavelengths. Whether the core or cladding should be selected for each pixel is decided by a “majority vote” among wavelengths. As a two-wavelength design example, a 1.3/1.5-µm wavelength filter is shown in **Fig. 3(a)** [5]. The mosaic-like core pattern functions like a Mach-Zehnder interferometer and lights with wavelengths of 1.3 and 1.5 µm are output to ports #2 and #1, respectively. The pixels are 3 µm × 3 µm in size. The widths of the input/output waveguides and the separation of the output waveguides were set to 7 and 15 µm, respectively. The measured spectrum (**Fig. 3(b)**) shows that the input light was successfully filtered into two outputs depending on its wavelength although the extinction wavelength was shifted from the designed value. The insertion loss including the fiber-to-fiber coupling loss was around 5 dB as a result of scattering at a number of core pixels. Some BPM simulation results that show how the filter works are presented in **Fig. 4**. The input light was scattered by the mosaic-like pattern and aggregated at the lower and upper ports for the 1.3- and 1.5-µm lights, respectively.

b) Waveguide lens

When we do not need a wavelength-dependent function, the mosaic-like core pattern should be filled in to reduce the undesired scattering loss. One such example is a waveguide lens [6]. For this purpose, we impose the condition that a cladding-pixel surrounded by core-pixels is changed to a core-pixel in the calculation. As a result, two waveguide lenses with irregular contours facing each other over the slab region are created as shown in **Fig. 5(a)**. The irregular contours excite the second-order propagation mode and inflect the wavefront at the lens exit so as to create a focal point in the middle of the slab, as shown in **Fig. 5(b)**. **Figure 6** shows the measured transmission spectra for this lens pair over the slab region, together with those for 2000-µm-long linear tapers and straight waveguides. The excess loss for the 500-µm-long slab region was dramatically reduced to 0.9 dB by means of the lens pair compared with that of the straight waveguide or the linear taper. This confirms that WFM can be used to create a wavelength-independent waveguide element.

c) Loss reduction in Y-branch and X-crossing

WFM with a solid pattern can be used to optimize existing waveguide elements such as Y-branches [7] and X-crossings [8], as shown in **Fig. 7**. The constricted pattern created by WFM excites higher and leaky modes and recouples them with the fundamental mode, resulting in a low-loss function. Excess loss is reduced to 0.15 dB for the Y-branch and to 0.1 dB for the 20° X-crossing. Moreover, the splitting ratio variation of the Y-branch and the crosstalk to the other output of the X-crossing were both successfully suppressed. These designs are very useful for constructing a high-port-count 1 × N splitter and a matrix switch that both include many Y-branches and X-crossings.

4. Conclusion

We have experimentally confirmed the principle and feasibility of a needs-oriented optical waveguide design method based on wavefront matching (WFM). This method provides new ways for creating functional waveguide elements and optimizing waveguide shapes such as S-bends, collimators, Y-branches, and X-crossings. It should be usefully in the design of a wide variety of planar lightwave circuit devices.

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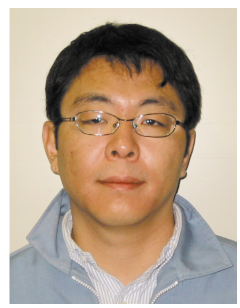

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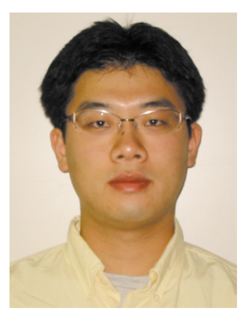

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