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Design of a Wavelength Demultiplexer Based on a Bent Waveguide Coupler Using the Three-Dimensional Beam-Propagation Method

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SUMMARY A bent-waveguide-based multimode interference (MMI) demultiplexer is designed for the operation at 0.85- and 1.55-μm wavelengths using the three-dimensional semi-vectorial beam-propagation method. First, it is shown that the use of a straight MMI waveguide results in a long coupler length of more than 1000 μm for wavelength demulitplexing. To reduce the coupler length, we next introduce a bent MMI waveguide. Bending with a radius of 1500 μm leads to a coupler length of less than 200 μm. After designing two output waveguides connected to the MMI section, we finally choose a coupler length to be 175 μm for efficient demultiplexing properties. Consequently, an output power of more than 90% can be obtained, leading to a low insertion loss of 0.34 dB at both 0.85- and 1.55-μm wavelengths. The demultiplexer achieves small polarization dependence, i.e., less than 2 dB difference in contrast and 0.02 dB difference in insertion loss.

key words: *multimode interference (MMI) coupler, bent waveguide, wavelength demultiplexer, beam-propagation method*

1. Introduction

There is increasing interest in the application of a multimode interference (MMI) coupler to optical integrated circuits, because of low loss, relaxed fabrication tolerance and large optical bandwidth. Soldano and Pennings [1] showed the principles and applications of the MMI devices. Ferreras et al. [2] designed and fabricated the $1\times N$ power splitter on InP, in which a good agreement was obtained between the theoretical and experimental results. Bachmann et al. [3] derived the self-imaging properties of generalized $N \times N$ MMI coupler. Several groups reported wavelength demultiplexers for the operation at 1.3- and 1.55-μm wavelengths [4], [5], and 0.98- and 1.55-μm wavelengths [6].

It should be noted that all the applications mentioned above are based on straight MMI couplers. Recently, Kumar et al. [7] have demonstrated that bending a multimode waveguide changes its mode properties. Bending the waveguide leads to the shift of the mode power distribution, which causes the effective index of the fundamental mode to increase and that of the first-order mode to decrease, at a large normalized frequency V. This effective index change can be used to reduce the beat length in the MMI coupler.

Janz et al. [8] have utilized this property to reduce the device length of a wavelength demultiplexer for the operation at 0.85- and 1.55-μm wavelengths. They designed the bent MMI demultiplexer using the effectively one-dimensional (1-D) local guided mode analysis. Although the 1-D analysis is effective in calculating the beat length of a propagating wave in the MMI coupler, it cannot treat the interaction between the two output waveguides connected to the MMI coupler. In fact, the 1-D analysis does not fully predict the experimental results [8]. In contrast, the 3-D beam-propagation method (BPM) can reveal optical wave propagation in the MMI coupler and evaluate the interaction between the output waveguides [9]. The use of the 3-D BPM reasonably explains the experimental results, as discussed in Appendix.

The conventional bent MMI demultiplexer described in Ref. [8] has been based on a strongly-guiding rib waveguide. Note that a relatively high insertion loss is experimentally observed, i.e., 3 dB at $\lambda = 0.85\,\mu$m. The cause of the high insertion loss seems to be a large (seven-degree) angular offset of the output waveguide. In addition, our preliminary calculations show that the demultiplexer exhibits polarization dependence particularly at $\lambda = 1.55\,\mu$m (See Appendix).

Janz et al. have also pointed out the presence of the polarization dependence in a straight MMI demultiplexer consisting of a strongly-guiding rib waveguide [10]. To reduce the dependence, they introduce an MMI waveguide composed of a SiO_2 upper cladding and a partially-etched 1.2-μm-thick SiON core on a SiO_2 substrate [10]. Although the effectiveness of this structure is demonstrated only for the straight MMI demultiplexer, reduced polarization dependence is expected for a bent MMI demultiplexer.

The purpose of this paper is to present the detailed study of a bent-waveguide-based MMI demultiplexer with low loss and small polarization dependence, using the 3-D BPM. The MMI demultiplexer to be designed acts as a bar-coupler and as a cross-coupler at 0.85- and 1.55-μm wavelengths, respectively. We utilize an MMI waveguide composed of a partially-etched core

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with an upper cladding [10] to reduce the polarization dependence. We first show that the use of a straight MMI waveguide gives rise to a long coupler length of more than 1000 μm. To reduce the coupler length, we introduce a bent MMI waveguide that changes a beat length. A bending radius of $R = 1500\,\mu$m leads to a coupler length of less than 200 μm. Next, we carefully determine the configurations of two output waveguides, adjusting the coupler length of the MMI section. As a result, the following characteristics of the demultiplexer are obtained with a coupler length of 175 μm: the contrast (extinction ratio) and insertion loss at 0.85 μm are 13.65 dB and 0.34 dB, respectively, and those at 1.55 μm are 20.96 dB and 0.34 dB, respectively. The multiplexer achieves small polarization dependence, i.e., less than 2 dB difference in contrast and 0.02 dB difference in insertion loss.

2. Numerical Method

To analyze a bent MMI demultiplexer, we use the 3-D semi-vectorial BPM with the magnetic field H. The basic equation for the quasi-TE mode is expressed as

$$2jkn_0\frac{\partial H}{\partial z} = n^2\frac{\partial}{\partial x}\left(\frac{1}{n^2}\frac{\partial H}{\partial x}\right) + \frac{\partial^2 H}{\partial y^2} + k^2(n^2 - n_0^2)H \tag{1}$$

where k, n_0 and n are the free-space wavenumber, the reference refractive index and the refractive index of the waveguide, respectively. For the quasi-TM mode analysis, the derivatives with respect to the x and y directions are interchanged. We apply the alternating-direction implicit method [11] to (1), in which we use the modified finite-difference formula [12] to approximate the derivatives in space. The equation to be solved results in a tridiagonal matrix, so that the Thomas algorithm can be used. We impose the perfectly matched layer boundary condition [13] at the edge of the computational window.

To treat the bending waveguide, we transform the index profile $n(x, y)$ into the equivalent straight one $n_e(x, y)$ using [14], [15]

$$n_e(x, y) = n(x, y)\left(1 + \frac{y}{R}\right) \tag{2}$$

where R is the bending radius.

The accuracy of the present numerical method is verified in Appendix, through the analysis of the conventional bent MMI demultiplexer reported in Ref. [8].

3. Design of Bent MMI Demultiplexer

Figure 1 shows the configuration of an MMI demputiplexer. The refractive indices of SiO_2 and SiON are 1.465/1.459 and 1.568/1.562 (at 0.85/1.55-μm wavelengths), respectively. This configuration has been

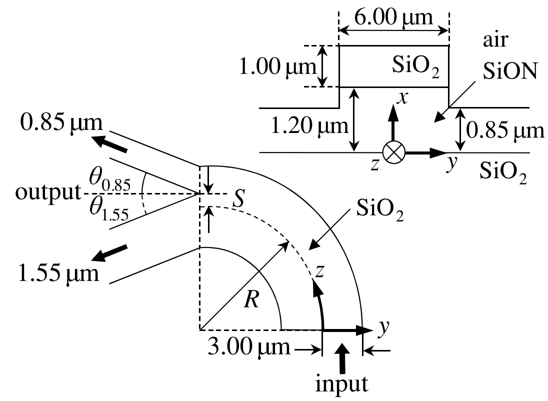

Fig. 1 Configuration of a demultiplexer.

used to reduce the polarization dependence only for the straight MMI demultiplexer in Ref. [10]. We introduce this structure into a bent MMI demultiplexer. A width of the MMI waveguide is chosen to be 6 μm. We treat the quasi-TE mode propagation, unless otherwise noted.

3.1 Straight MMI Waveguide

Before considering a bent MMI waveguide, we analyze a straight MMI waveguide ($R = \infty$ in Fig. 1), in order to know the length required for wavelength demultiplexing. We calculate the coupling efficiency between the propagating field in the MMI waveguide and the mode field of each output waveguide that is assumed to be straight ($\theta_{0.85} = \theta_{1.55} = 0°$) and 3-$\mu$m wide ($S = 0$). This calculation corresponds to the case where the interaction between the two output waveguides is neglected. It is seen in Fig. 2 that the coupling efficiency oscillates periodically. The beat lengths agree well with $L_{\pi,0.85} = 110\,\mu$m and $L_{\pi,1.55} = 65\,\mu$m obtained from

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \tag{3}$$

where β_0 and β_1 are the propagation constants of the fundamental and first-order modes, respectively (The propagation constants of the 3-D waveguide are calculated by the imaginary-distance procedure [16]). In Fig. 2, the peak position at $\lambda = 0.85\,\mu$m coincides with that at $\lambda = 1.55\,\mu$m around $z = 1100\,\mu$m, resulting in a long coupler length.

The coupler length of the MMI section can be predicted by

$$L = p_1 \cdot L_{\pi,0.85} = (p_1 + p_2) \cdot L_{\pi,1.55} \tag{4}$$

where p_1 and p_2 are positive and odd integers, respectively. In the case of Fig. 2, a length of 1100 μm corresponds to $p_1 = 10$ and $p_2 = 7$. To obtain a short coupler length, we require $p_1 = 2$ and $p_2 = 1$, resulting in a beat length ratio of $L_{\pi,0.85}/L_{\pi,1.55}$=1.5 from (4). However, it is impossible to choose a ratio of 1.5 because of $L_{\pi,0.85} = 110\,\mu$m and $L_{\pi,1.55} = 65\,\mu$m, as long

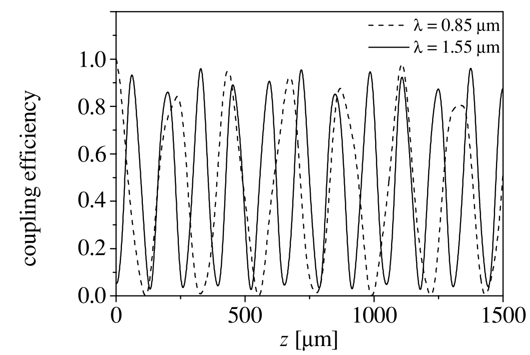

Fig. 2 Coupling efficiency as a function of z ($R = \infty$).

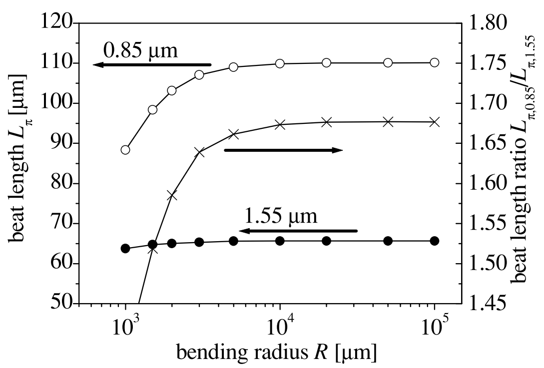

Fig. 3 Beat lengths and their ratio.

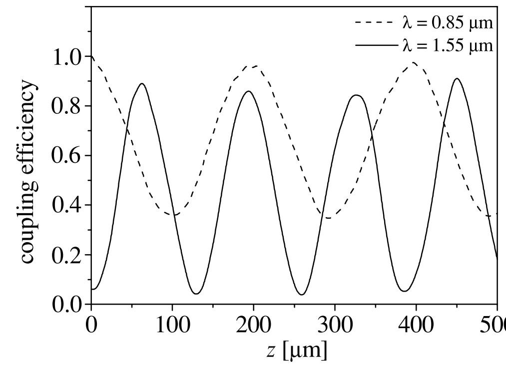

Fig. 4 Coupling efficiency as a function of z ($R = 1500\,\mu$m).

as a straight MMI coupler is used.

3.2 Bent MMI Waveguide

It should be noted that bending a multimode waveguide changes its mode properties [7]. At a large normalized frequency V, the propagation constant of the fundamental mode always increases with a reduction in a bending radius, while that of the first-order mode may decrease or not change. This leads to an increase in difference between the two propagation constants. Consequently, from (3), the beat length can be shortened.

We here introduce a bent waveguide into the MMI section. In the calculation of the bent MMI waveguide, the index profile is transformed by (2). Figure 3 shows the beat lengths $L_{\pi,0.85}$ and $L_{\pi,1.55}$ and their ratio $L_{\pi,0.85}/L_{\pi,1.55}$ as a function of bending radius R. It is seen that $L_{\pi,0.85}$ reduces as R is reduced, while $L_{\pi,1.55}$ is not sensitive to R. When selecting $R = 1500\,\mu$m in Fig. 3, we obtain a beat length ratio of 1.52, leading to almost the same peak position along the z-direction for the two wavelengths.

The coupling efficiency for a bending radius of $R = 1500\,\mu$m is presented in Fig. 4 (The results for $R = \infty$ correspond to Fig. 2). It is seen that almost the same peak position is realized at $z = 190\,\mu$m, which is less than 20% of the length needed for the straight MMI waveguide shown in Fig. 2. To investigate the polarization dependence, we further calculate the coupling efficiency of the quasi-TM mode for the same bending radius. As a result, the beat length ratio is calculated to be 1.51 that is almost the same as that of the TE mode. This predicts small polarization dependence for demultiplexing properties. Accordingly, as an initial guess, we choose a junction position with output waveguides to be $z_j = 190\,\mu$m (We should recall that the initial guess has been made neglecting the mutual coupling between the output waveguides. An optimum z_j should be less than $190\,\mu$m, when the effect of the interaction of the output waveguides is taken into account, as will be discussed in Sect. 3.3).

3.3 Optimization of Configuration Parameters

Next, we determine the tilt angles ($\theta_{0.85}$ and $\theta_{1.55}$) of the output waveguides and the distance S defined in Fig. 1. If the tilt angles of the output waveguides match those of the phase planes of the propagating fields, the loss caused at the junction of the bent and output waveguides is substantially reduced. To find appropriate tilt angles of the output waveguides, we calculate the coupling efficiency for various values of θ as a function of S. As can be seen in Fig. 5, a coupling efficiency of about 90% is achieved for $S = 0.5\,\mu$m, $\theta_{0.85} = 0°$ and $\theta_{1.55} = 0.5°$ at each wavelength.

Note that the achieved coupling efficiency may not be equal to the output powers obtained when the two output waveguides are connected, because of the interaction between the waveguides. In fact, according to the BPM simulation, desirable demultiplexing properties are not observed for a combination of $\theta_{0.85} = 0°$ and $\theta_{1.55} = 0.5°$. The interaction must be reduced, when a larger tilt angle is employed. Here, we choose $\theta_{1.55} = 1.0°$ rather than $\theta_{1.55} = 0.5°$. A choice of $\theta_{1.55} = 1.0°$ leads to output powers of 89.5% and 83.6% at $\lambda = 0.85\,\mu$m and $\lambda = 1.55\,\mu$m, respectively.

We notice that the output power at $\lambda = 1.55\,\mu$m is small when compared to that at $\lambda = 0.85\,\mu$m. This is due to the fact that part of the field at $\lambda = 1.55\,\mu$m

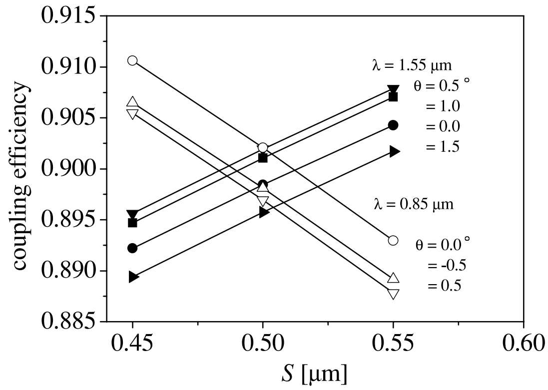

Fig. 5 Coupling efficiency as a function of S.

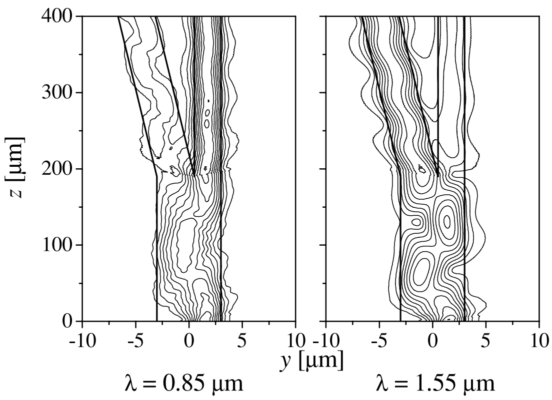

Fig. 6 Field distributions ($\theta_{0.85} = 0°$, $\theta_{1.55} = 1.0°$, and $z_j = 190\,\mu$m.

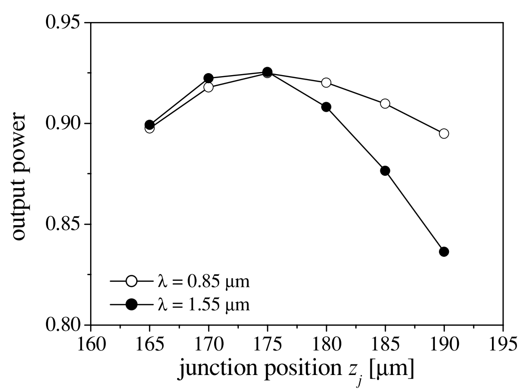

Fig. 7 Output power as a function of z_j.

is coupled to the output waveguide at $\lambda = 0.85\,\mu$m, as shown in Fig. 6 (The field distributions are observed at $x = 0.5\,\mu$m in the y-z plane, where their field intensities are nearly maximal). This coupling may stem from an equivalently long MMI length, since the output waveguide is close to the other one near the junction point. Therefore, we expect that the output power should be increased, when the bent MMI waveguide is slightly shortened. Figure 7 presents the output power as a function of junction position z_j. As expected, the output powers increase for slightly shorter z_j's, e.g., 92.5% at both $\lambda = 0.85\,\mu$m and $1.55\,\mu$m for $z_j = 175\,\mu$m.

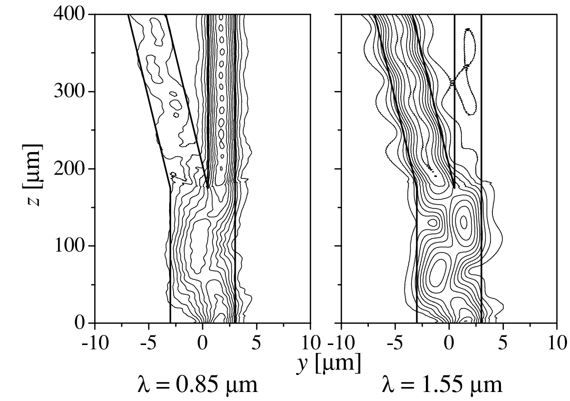

Fig. 8 Field distributions ($\theta_{0.85} = 0°$, $\theta_{1.55} = 1.0°$, and $z_j = 175\,\mu$m).

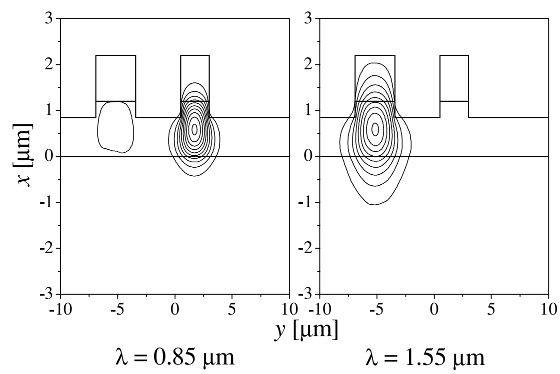

Fig. 9 Field distributions observed at $z = 400\,\mu$m.

As a result, we obtain the following parameters: $S = 0.5\,\mu$m, $\theta_{0.85} = 0°$, $\theta_{1.55} = 1.0°$ and $z_j = 175\,\mu$m. Figure 8 illustrates the propagating field in the x-z plane. Figure 9 shows the field distributions observed at $400\,\mu$m. The wavelength demultiplexing behavior is clearly observed, although slight crosstalk field is seen at $\lambda = 0.85\,\mu$m.

4. Performance of the Bent MMI Demultiplexer

The performance of the bent MMI demultiplexer is assessed by the contrast and insertion loss defined as

$$C = 10 \log_{10} (P_1/P_2)\,[\text{dB}]$$
$$L = -10 \log_{10} (P_1/P_i)\,[\text{dB}]$$

where P_1 and P_2 are the intensities in the bar and cross output waveguides at $\lambda = 0.85\,\mu$m, respectively, or are the intensities in the cross and bar output waveguides at $\lambda = 1.55\,\mu$m, respectively, while P_i is the intensity in the input waveguide. The contrast and insertion loss are shown in Table 1. It is noteworthy that the demultiplexer achieves the low loss characteristics. The contrast at $\lambda = 0.85\,\mu$m is less than that at $\lambda = 1.55\,\mu$m,

Table 1 Characteristics of the demultiplexer.

	quasi-TE mode		quasi-TM mode	
	C	L	C	L
$\lambda = 0.85\,\mu$m	13.65	0.34	15.59	0.32
$\lambda = 1.55\,\mu$m	20.96	0.34	21.23	0.35

because of the crosstalk field in the output waveguide, as shown in Figs. 8 and 9. This crosstalk field is due to the generation of the higher-order modes in the bent MMI coupler.

We finally analyze the optimized structure discussed above using the quasi-TM mode. The numerical results are included in Table 1. It is seen that the differences in performances between two polarizations are small, as predicted in Sect. 3.2. The structure of Fig. 1 is effective in reducing the polarization dependence for a bent MMI demultiplexer.

5. Conclusion

Using the 3-D BPM, we have designed a bent-waveguide-based MMI demultiplexer for the operation at 0.85- and 1.55-μm wavelengths. Introducing a bent waveguide leads to a short MMI section of 175-μm long which is 16% of that of the straight MMI waveguide. An output power of more than 90% can be obtained at both 0.85- and 1.55-μm wavelengths, maintaining nearly the same contrasts for the quasi-TE and quasi-TM modes.

Throughout this paper, we have employed the semi-vectorial BPM, which ignores mixed derivatives in coupled wave equations. The full-vectorial analysis of the multiplexer is the remaining issue.

References

[1] L.B. Soldano and E.C.M. Pennings, "Optical multi-mode interference devices based on self-imaging: Principles and applications," J. Lightwave Technol., vol.13, no.4, pp.615–627, April 1995.
[2] A. Ferreras, F. Rodríguez, E. Gómez-Salas, J.L. de Miguel, and F. Hernández-Gil, "Useful formulas for multimode interference power splitter/combiner design," IEEE Photonics Technol. Lett., vol.5, no.10, pp.1224–1227, Oct. 1993.
[3] M. Bachmann, P.A. Besse, and H. Melchior, "General self-imaging properties in $N \times N$ multimode interference couplers including phase relations," Appl. Opt., vol.33, no.18, pp.3905–3911, June 1994.
[4] K.-C. Lin and W.-Y. Lee, "Guided-wave 1.3/1.55 μm wavelength division multiplexer based on multimode interference," Electron. Lett., vol.32, no.14, pp.1259–1261, July 1996.
[5] B. Li, G. Li, E. Liu, Z. Jiang, J. Qin, and X. Wang, "Low-loss 1×2 multimode interference wavelength demultiplexer in silicon-germanium alloy," IEEE Photonics Technol. Lett., vol.11, no.5, pp.575–577, May 1999.
[6] M.R. Paiam, C.F. Janz, R.I. MacDonald, and J.N. Broughton, "Compact planar 980/1550-nm wavelength multi/demultiplexer based on multimode interference," IEEE Photonics Technol. Lett., vol.7, no.10, pp.1180–1182, Oct. 1995.
[7] A. Kumar, R.L. Gallawa, and I.C. Goyal, "Modal characteristics of bent dual mode planar optical waveguides," J. Lightwave Technol., vol.12, no.4, pp.621–624, April 1994.
[8] C.F. Janz, M.R. Paiam, B.P. Keyworth, and J.N. Broughton, "Bent waveguide couplers for (de)multiplexing of arbitrary broadly-separated wavelengths using two-mode interference," IEEE Photonics Technol. Lett., vol.7, no.9, pp.1037–1039, Sept. 1995.
[9] J. Shibayama, K. Sadano, J. Yamauchi, and H. Nakano, "Design of a bent waveguide coupler for wavelength demultiplexing by the three-dimensional beam-propagation method," Optoelectron. Comm. Conf. (OECC), 10P-86, pp.358–359, Yokohama, Japan, July 2002.
[10] M.R. Paiam, C.F. Janz, R.I. MacDonald, B.P. Keyworth, and J.N. Broughton, "Compact planar waveguide couplers for broadband dual-channel wavelength (de)multiplexing," in Appl. Photon. Technol. 2, ed. G.A. Lampropoulos and R.A. Lessard, pp.445–450, Plenum Press, New York, 1997.
[11] J. Yamauchi, J. Shibayama, O. Saito, O. Uchiyama, and H. Nakano, "Improved finite-difference beam-propagation method based on the generalized Douglas scheme and its application to semvectorial analysis," J. Lightwave Technol., vol.14, no.10, pp.2401–2406, Oct. 1996.
[12] J. Yamauchi, G. Takahashi, and H. Nakano, "Modified finite-difference formula for semivectorial H-field solutions of optical waveguides," IEEE Photonics Technol. Lett., vol.10, no.8, pp.1127–1129, Aug. 1998.
[13] C.M. Rappaport, "Perfectly matched absorbing boundary conditions based on anisotropic lossy mapping of space," IEEE Microw. Guid. Wave Lett., vol.5, no.3, pp.90–92, March 1995.
[14] M. Heiblum and J.H. Harris, "Analysis of curved optical waveguides by conformal transformation," IEEE J. Quantum Electron., vol.11, no.2, pp.75–83, Feb. 1975.
[15] J. Yamauchi, M. Ikegaya, and H. Nakano, "Analysis of bent step-index optical fibers by the beam propagation method," IEE Proc. J, vol.139, no.3, pp.201–207, June 1992.
[16] J. Shibayama, M. Sekiguchi, J. Yamauchi, and H. Nakano, "Eigenmode analysis of optical waveguides by an improved finite-difference imaginary-distance beam propagation method," IEICE Trans. Electron. (Japanese Edition), vol.J81-C-I, no.1, pp.9–16, Jan. 1998.

Appendix: Analysis of the Conventional Bent MMI Demultiplexer

To verify the accuracy of the present 3-D BPM, we analyze the bent MMI demultiplexer discussed in [8]: a 1-μm-thick SiON guiding layer with 6 μm in wide, and a SiO_2 lower cladding. First, we calculate the beat lengths and their ratio. Although not illustrated, the results close to Fig. 1 in Ref. [8], estimated from the 1-D analysis, are reproduced by the 3-D BPM, in which a ratio of 1.51 is obtained for a bending radius of $R = 925\,\mu$m. In Fig. A· 1, we evaluate the coupling efficiency for $R = 925\,\mu$m as a function of z. It can be seen that the optimum device length z_j lies around 150 μm.

Next, we calculate the contrast and the insertion loss, for a coupler length ranging from $z_j = 141$ to 155 μm. As a result, we obtain an optimum length z_j of 147 μm. In Table A· 1, the performance calculated from the present BPM is compared with the theoretical

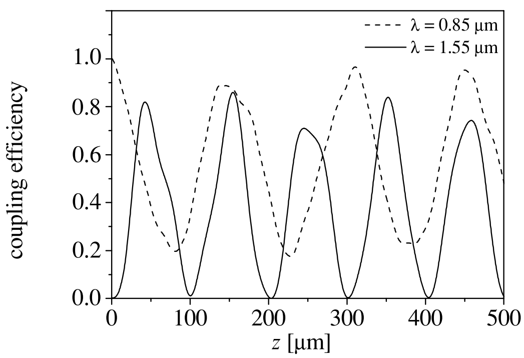

Fig. A· 1 Coupling efficiency as a function of z ($R = 925\,\mu$m).

Table A· 1 Characteristics of the conventional demultiplexer.

	1-D analysis [8]		experiment [8]		present	
	C	L	C	L	C	L
$0.85\,\mu$m	25	$\simeq 1$	14	3.0	11	3.7
$1.55\,\mu$m	30	$\simeq 3$	20	1.4	16	0.8
optimum z_j	$155\,\mu$m		$145\,\mu$m		$147\,\mu$m	

and experimental results reported in Ref. [8]. It is seen that the results of the present method reasonably agree with the experimental results. In particular, the BPM accurately predicts the optimum length z_j and the insertion loss. In contrast, the 1-D analysis does not fully predict the performance of the demultiplexer, although it effectively provides the beat length comparable to the 3-D BPM as discussed above.

We further investigate the polarization dependence of the conventional demultiplexer. The BPM analysis for the quasi-TM mode shows that the beat lengths are $L_{\pi,0.85} = 78.1\,\mu$m and $L_{\pi,1.55} = 55.4\,\mu$m, resulting in a ratio of 1.41. This predicts the degradation of the demultiplexing performance. For a coupler length of $147\,\mu$m, we obtain about 6.4 dB difference in contrast and 1.3 dB difference in insertion loss at $\lambda = 1.55\,\mu$m, while we observe less than 0.2 dB difference both in contrast and insertion loss at $\lambda = 0.85\,\mu$m. To reduce the polarization dependence at $\lambda = 1.55\,\mu$m, we primarily focus our attention on the configuration of Fig. 1 in this paper.

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