Vertical Coupling of Polymeric Double-Layered Waveguides Using a Stepped MMI Coupler

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We designed a multimode interference (MMI) coupler to use in vertical coupling of double layered polymeric waveguides and analyzed the coupling characteristics by comparing our experimental and simulation results. We found that our proposed new structure, a stepped MMI coupler, is effective in vertical coupling between waveguide layers with a short length of MMI and has a high tolerance for the variation in the structure of an MMI coupler that can be induced as errors in the fabrication process.

I. INTRODUCTION

As more communication capacity is demanded, more electronic components are being exchanged for optical components, and many research efforts are going into integrating optical components into planar waveguide devices or photonic integrated circuits (PICs). A PIC is comparable to a printed circuit board (PCB) in its role and shape. A PCB provides electric circuits on a board connecting various electrical components, such as resistors, diodes, and transistors, while a PIC provides optical circuits connecting optical components, such as optical filters, optical switches, and optical amplifiers. One of the differences between a PCB and a PIC is that most present PCBs have a multilayered structure that is composed of many (even up to several tens of) layers of electrical circuits for more dense integration, while very few PIC devices are multilayered.

In the future, demand for applications for PICs will surely increase and at the same time, there will be an increased need for reducing the size of PICs. A multilayered PIC presents an interesting solution for creating a highly dense integration. However, realizing a multilayered PIC comparable to that in the PCB faces difficult challenges. Each layer in a PCB can be simply connected to another by a metal filled hole, usually called a via. Connecting multiple layers of optical circuits, however, is not so simple, because critical loss occurs when a waveguide is severely bent.

One way to connect the neighboring layers of a PIC is to use directional coupling between layers located very close to each other [1], [2]. The problem with this solution is that when the distance between layers is too close, the optical signals can severely interfere with each other. Thus, for this method, the

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optical circuits, even on different layers, must be arranged so as not to overlap at all. This restriction on overlapping is an obstacle limiting the density of integration. To enhance the density of integration in a multilayered PIC, it is desirable to exchange the optical signal at some specific spot similar to the via in the PCB, while maintaining a proper distance between each layer in order to minimize the interference between the waveguides on the different layers.

M. Hikita et al. presented a way to vertically connect two layers far enough apart to be independent, by combining a directional coupler composed of the bottom layer waveguide and a closely located waveguide on it with a couple of corner-bent waveguides to guide the coupled beam to the top layer [3]. That method, however, is difficult to fabricate because of its complex structure and the long length of the coupling region, which is as long as several millimeters.

Here, we propose a multimode interference (MMI) coupler, which vertically couples multilayered waveguides whose layers are considerably far apart from one another, and double layered polymeric waveguides vertically coupled by the MMI coupler. In addition, we present a new structure, a stepped MMI especially modified for vertical coupling. The advantages of the stepped MMI are its short length and high tolerance to variation in the dimensions of the structure, which can induce errors during the fabrication process.

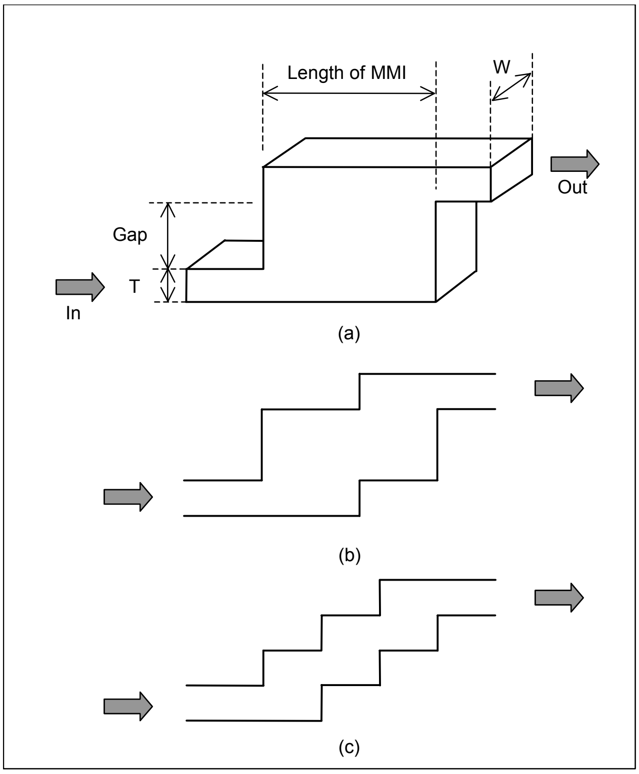

Fig.1. MMI structure for inversed self imaging: (a) simple MMI structure, (b) stepped MMI structure, and (c) double stepped MMI structure.

II. MULTIMODE INTERFERENCE COUPLER

MMI couplers have been applied in various optical waveguide devices, such as 3-dB couplers, symmetric power splitters, and optical switches, based on their self-imaging characteristics [4], [5]. The behavior of MMI in a normal structure such as that in Fig. 1(a) was explained well with a modal propagation analysis [4]. In a multimode waveguide, there are many guided modes, such as the MMI region in Fig. 1(a), and each mode has its own propagation constant, β_m, where m = 0,1,2,3···. The self-image of the input field appears at the length of MMI,

$$L = p(3L_\pi), \quad \text{with } p = 0,1,2,\cdots, \tag{1}$$

where L_π is defined as

$$L_\pi \equiv \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_g W_\varepsilon^{\,2}}{3\lambda}, \tag{2}$$

where n_g is the effective refractive index of the core, W_ε is the effective width of the mode of the multimode wave guide, and λ is the wavelength of the guided light. The direct image appears when p is even and the inverse image appears when p is odd. Thus, the input beam is transformed into an output beam in Fig. 1(a) when p is odd, and the coupling ratio of the input to the output at the optimized length can be estimated by calculating the overlap integral of the input field to the multimode in the MMI region. It is expected from (2) that the length of MMI should be increased in proportion to the square of the width of MMI. This can be an obstacle in using MMI for vertical coupling of multilayers with enough separation, since even slight errors in fabrication can severely influence the property of MMI as the length of MMI is increased. In addition, the arrangement of waveguides becomes more flexible when the length of MMI is as short as possible.

Considering these factors, we tried to modify the structure of MMI to achieve a short length of MMI. A stepped MMI (Fig 1(b)) and a double stepped MMI (Fig.1(c)) constitute the modification we devised for this purpose. We designed the structures so that the stepped boundary can guide the lights more efficiently to the output ports and as a result increase the coupling ratio at a shorter length.

Figure 2 shows the calculated variation of the coupling ratio for each case: the simple structure (Fig. 1(a)), the stepped structure (Fig. 1(b)), and the double stepped structure (Fig. 1(c)). We made the estimation through simulation with the beam propagation method with parameters as follows: the width

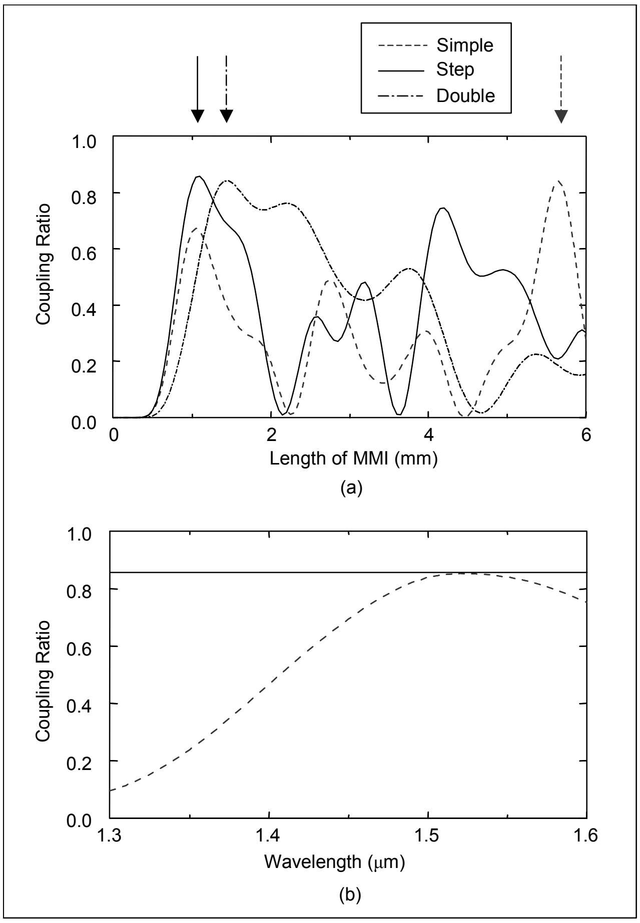

Fig. 2. Variation of coupling ratio by calculation: (a) with the length of MMI, (b) with the wavelength with a gap width of 20 μm.

of the waveguide W, 6 μm; the thickness of the waveguide T, 6 μm; the refractive index of the core, 1.505; the refractive index of the cladding, 1.5; and the width of the gap between the layers, 20 μm, that is, the distance between the waveguides was 26 μm. Figure 2(a) shows the variation of the coupling ratio with the length of MMI at a wavelength of 1.55 μm. The best coupling of about 84% is shown at a length of MMI of 5.65 mm for the simple structure, at 1.1 mm for the stepped one, and at 1.45 mm for the double stepped one. The length of MMI for the peak value for the simple MMI structure is almost in accord with p=1 in (1).

It is interesting that the length of MMI for the best coupling peak is much shorter for the stepped MMI structure than for the simple one. The position of the peak point of the stepped structure is almost in accord with the position of the peak point of the first peak of the simple MMI, while the value of the peak point of the stepped structure is much higher than the first peak of the simple MMI.

We explain our simulation results on the basis of ray optics. The propagation of light can be considered to be free propagation rather than guided propagation when it enters into a broad waveguide or an MMI region from a narrow input waveguide. If the width of MMI is wide enough and the input waveguide is attached at its middle point rather than at an edge, the light will propagate quite a long distance without interference by the side boundary of the MMI region. When the narrow waveguide is attached at an edge of MMI as in our example, about half of the beam is regarded to freely propagate and the other half to propagate after reflection off the side boundary, and the reflected beam interferes with the original beam during propagation. The reflection accompanies a phase shift and the phase shift varies from 0 for the critical angle of incidence to π for the incidence angle of 90 degrees [6], where the incidence angle is defined as the angle of the beam to the vertical plane to the reflecting boundary surface. Therefore, there should be a negative interference for the beam near the reflecting boundary since there is a phase shift of π between the original beam and the reflected beam. The negative interference effect decreases as the reflection angle approaches the critical angle since the phase difference comes up to 0 at the critical angle. The peak of the propagation beam profile will be along the angle located between the reflecting boundary and the critical angle since the original free propagating beam has an intensity profile with its peak along the reflecting boundary.

The first peak of the simple MMI can be regarded as just that point where the peak angle of propagation meets the output waveguide. The first peak of the stepped waveguide is higher than that of the simple waveguide since the reflection from the stepped upper boundary and the stepped lower boundary causes more of the beam to gather around the angle of propagation along the peak.

Figure 2(b) shows the variation of the coupling ratio with the wavelength at the optimized length of MMI for the simple MMI and the stepped MMI. The coupling ratio at the peak is almost flat in the stepped MMI while it depends considerably on the wavelength in the simple one. This shows that the stepped MMI has merit in flexibility for the wavelength.

Figure 3 shows the calculated variation of the coupling ratio as in Fig. 2 but with a gap width of 30 μm. The best coupling ratio of 84% is shown at a length of 8.95 mm for the simple structure, which is also approximately in accord with p=1 in (1), and a coupling ratio of 92.4% is shown at an MMI length of 1.9 mm for the double stepped structure while the first peak at an MMI length of 1.3 mm for the stepped one is not so high as that of Fig. 2. This shows that the first peak of the coupling ratio is not highly improved as the gap becomes wider compared with the output waveguide as expected. However, we can see the first peak of the coupling ratio is highly improved even beyond the highest peak for the simple

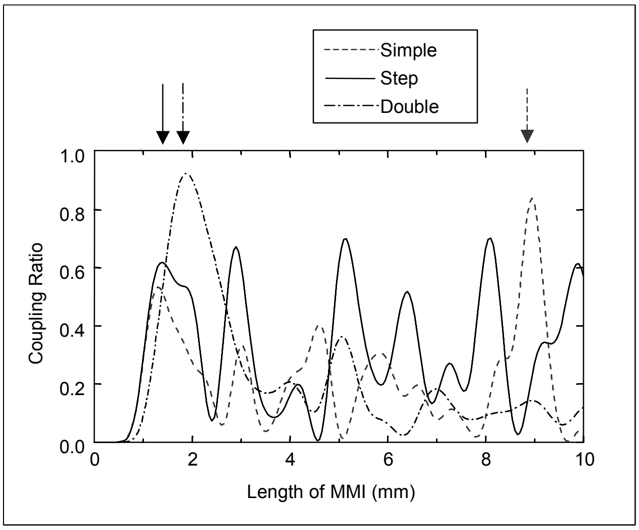

Fig. 3. Variation of coupling ratio by calculation with the length of MMI with a gap width of 30 μm.

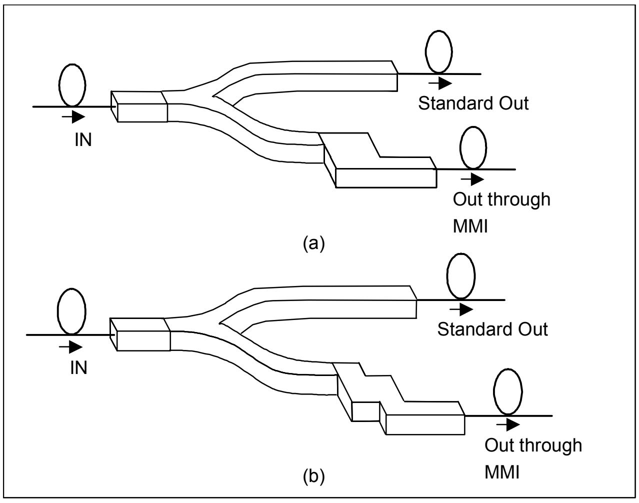

Fig. 4. Experimental scheme to measure the coupling ratio: (a) for the simple MMI, (b) for the stepped MMI on a plane.

structure by increasing the number of steps.

These results from simulation show that the stepped MMI structure has merits in the short length of MMI and in the broad spectral bandwidth.

III. EXPERIMENT AND RESULTS

Compared with silica [11], [12], polymeric material has lately attracted considerable attention for various waveguide devices, such as optical switches and variable optical attenuators, especially for its simple fabrication process [3], [7]-[10]. We applied polymeric materials in realizing and testing the vertically coupled multilayered waveguides.

At first, we tested the properties of MMI couplers by making experimental waveguides with polymeric materials, including MMI couplers on a plane. The polymeric materials used in this experiment were thermally curable fluorinated polyethers (FPEs; ZP1010, ZP2145) synthesized by Zen Photonics Co., Ltd. The refractive index of the core material (ZP1010) was 1.499 and that of the cladding material (ZP2145) was 1.484 at 1.55 μm. Figure 4 shows a schematic diagram of the experimental waveguide structure we used to test the properties of an MMI coupler. The Y-branch structure of the waveguide was used to compare the coupling ratio. Unpolarized light with a wavelength of 1550 nm was coupled to the input port through a single mode fiber which was butt coupled to the input waveguide. An output port of the Y-branch was used as the standard output, while the other port was composed of output through the MMI coupler. Each output port was butt coupled to a single mode fiber and the output from the single mode fiber was measured. We measured the coupling ratio by comparing the power from the output through the MMI coupler with the power from standard output. Figure 4(a) shows a schematic diagram of the Y-branch with the simple MMI coupler and Fig. 4(b) shows one with the stepped MMI coupler. Both the width and the height of the waveguide were about 4 μm and the thickness of the gap was 8 μm, that is, the distance between the waveguides was 12 μm. We considered a gap width of 8 μm a reasonable distance for a multilayer structure at a high refractive index difference of 1%. We expect to be able to enhance the integration density of double layered waveguides by avoiding parallel arrangement of the waveguides along an excessively long distance.

The fabrication process of the waveguide was as follows. The cladding material was spin coated on an Si wafer and thermally cured. The core layer was formed in the same way and dry etched selectively to form the waveguide. Then the upper cladding layer was coated on it.

Figure 5 shows the measured coupling ratios for both the simple MMI (Fig. 5(a)) and the stepped MMI coupler (Fig. 5(b)) along with the calculated results for the same structures. The figure shows that the overall trend of the measured coupling ratio follows the calculated results while the optimal points shifted by around 50 μm for the stepped MMI and by about 200 μm for the simple MMI. The optimal length of MMI is out of the MMI lengths for the samples, even though our samples were based on the simulation results. The minimum coupling loss for the stepped MMI was measured as low as 1.2 dB while that for the simple one was 4.2 dB. The difference was due to the large shift of the optimal length for the simple MMI. The shift seemed to come from the waveguide structure that had a deformed shape compared with that assumed in the simulation. It is interesting that the shift of the optimal length of MMI was almost in proportion to the

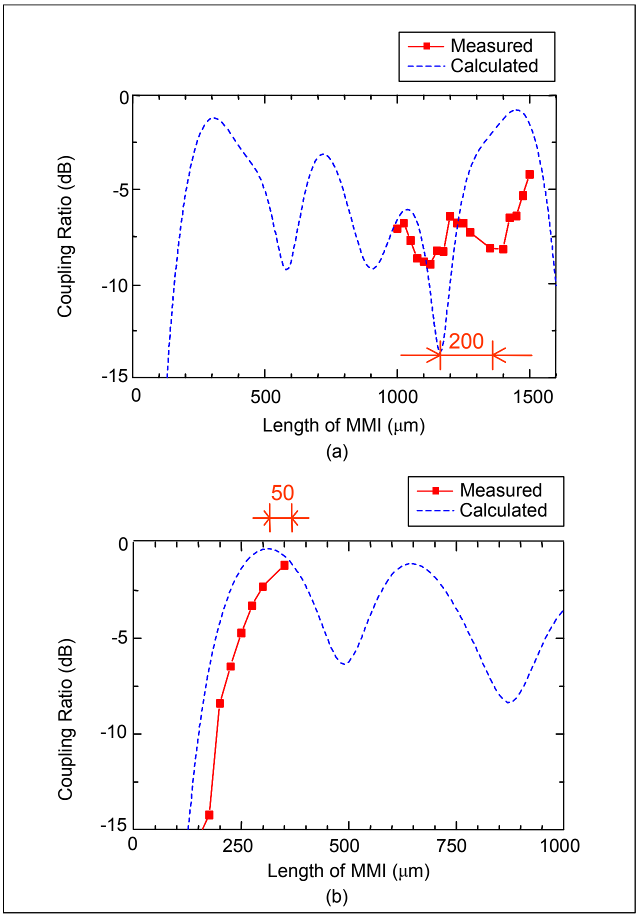

Fig. 5. Measured coupling ratio in comparison with the calculated values: (a) for the simple MMI, (b) for the stepped MMI.

length of MMI itself, so the shift was much less for the stepped MMI than for the simple one.

This result reveals that the stepped MMI coupler has merits in low coupling loss at a short length of MMI as we expected from the simulation results, and in addition, it has an excellent tolerance to fabrication errors in comparison to the simple MMI coupler. Tolerance to fabrication errors is a very important factor in real application fields.

Based on the results for the MMI coupler on a plane waveguide, we designed double-layered waveguide structures with the same polymeric materials. Figure 6 shows a schematic diagram of the experimental waveguide structures. The overall scheme using Y-branched waveguides was similar to that of Fig. 4, while the MMI coupler was formed as a vertical structure and the output port through the MMI coupler was located on the upper layer. The width of the waveguide was about 10 μm and the height about 3 μm. The thickness of the gap was 8 μm, that is, the distance between the waveguide was 11 μm. TE polarized light with a wavelength of 1550 nm was used for the measurement.

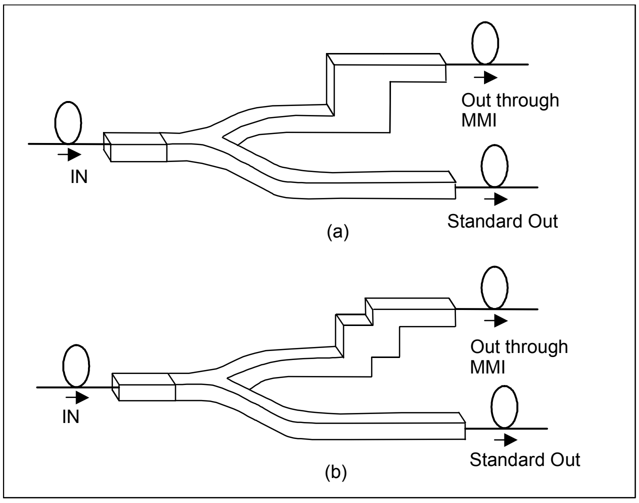

Fig. 6. Experimental scheme to measure the coupling ratio: (a) for the vertical simple MMI coupler, (b) for the vertical stepped MMI coupler.

Figure 7 briefly illustrates the fabrication process of the double-layered structure. The waveguide structure was basically fabricated the same way, consisting of spin coating, thermal curing, and dry etching. After creating the lower waveguide as in (a), the cladding material was coated as in (b) and etched down to the top surface of the lower-core layer as in (c). In the step in (b), the cladding material was coated thick enough to make the surface as flat as possible. On the surface of (c), the core material was coated and etched to form the MMI coupler layer as in (d). Steps (e) and (f) were the same as (b) and (c). On the surface of (f), the upper-core layer was formed as in (g) and the cladding material was coated on it as in (h).

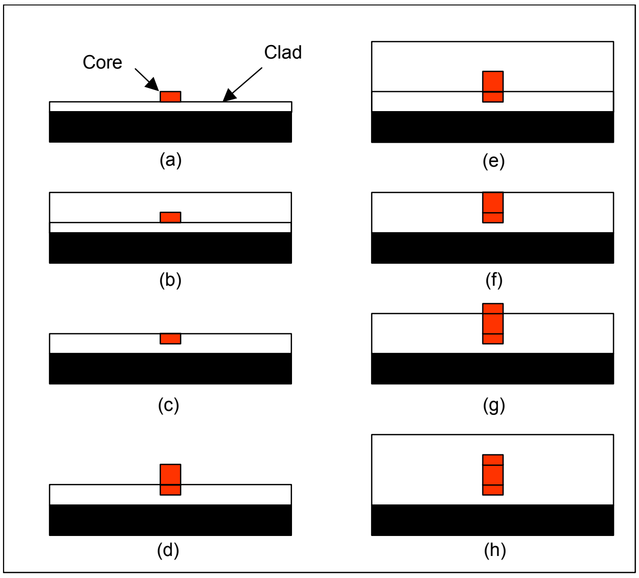

Fig. 7. Fabrication process of double-layered waveguide with MMI vertical coupler.

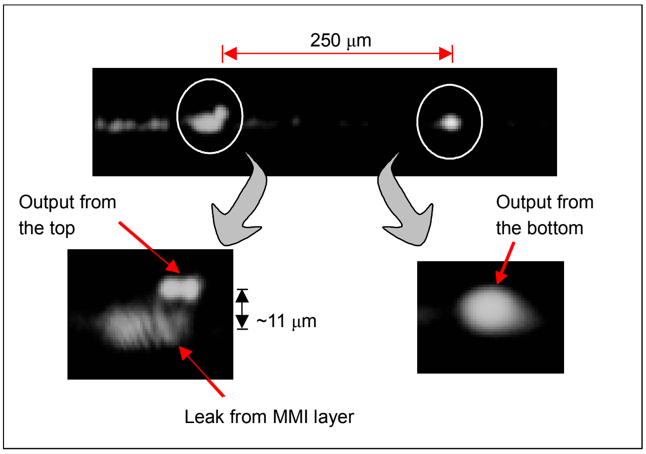

Fig. 8. The beam patterns from the standard output port and from the output through the vertical stepped MMI.

Figure 8 is a picture of the output beam pattern showing both the standard output from the bottom layer and the output from the top layer after the vertical MMI coupling. The picture shows that the output through the MMI is located on the upper layer distinguished from the leakage light from the bottom layer. The output from the upper layer is near to the TE_{10} mode as shown in the picture rather than the TE_{00} mode of the standard output also shown in the picture. The multimode seems to be induced for the output through the MMI coupler by misalignment of the layers.

Figure 9 shows the measured vertical coupling ratios for both the simple MMI coupler (Fig. 9(a)) and the stepped MMI coupler (Fig. 9(b)) along with the simulation results for the same structures. The variation of measured coupling ratios was similar to the simulation results, while the peak value was about half the expected value and the position of the peak was shifted slightly for the stepped MMI structure and considerably for the simple one. The shift of the peak position was much more critical for the simple MMI structure for the severe variation of the coupling ratio than for the stepped structure as in the previous case of the MMI on the same plane. The measured minimum coupling loss of the stepped MMI coupler was 3.5 dB while that of the simple one was 5.5 dB. This shows the coupling ratio of the stepped one was higher than the simple one as expected from the simulation results, even though each value was about half the value of the estimated one. The difference between the measured data and the calculated values was probably caused by multimode excitation for the output through the MMI coupler, misalignment of the layers, and higher scattering losses for the upper layer by incomplete fabrication.

This experimental result shows that it is possible to realize multilayered PIC devices with polymeric materials, even though the coupling efficiency is still below the estimation. We expect that the coupling ratio can be increased by optimizing the waveguide structure and the fabrication process.

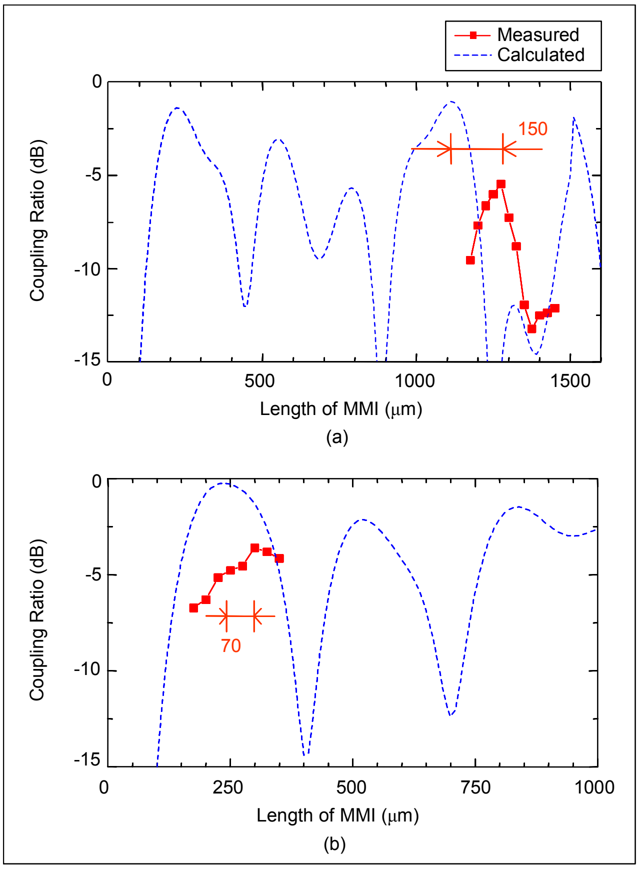

Fig. 9. Measured coupling ratio in comparison with the calculated values: (a) for the simple MMI, (b) for the stepped MMI.

VI. CONCLUSION

We used an MMI structure as a way of vertical coupling for polymeric multilayer waveguides and investigated the characteristics of vertical coupling using the MMI structure by comparing the measured data with beam propagation method simulation results. We found that a new structure of stepped MMI is effective in vertical coupling between waveguide layers with a relatively short length of MMI and exhibits better tolerance for variation of the structure, which can induce errors during the fabrication process. The measured minimum coupling loss of the stepped MMI coupler was 1.2 dB for the coupler on a plane and 3.5 dB for the vertical coupler. We attribute the difference between the vertical coupler and the plane coupler to incomplete fabrication and we expect that the coupling ratio of the vertical coupler can be enhanced by optimizing the fabrication process. We are confident that with further appropriate investigations, vertical coupling with the stepped MMI structure can be applied to creating highly dense multilayered waveguide devices in the near future.

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