Multimode-Waveguide-Based Optical Power Splitters in Glass *

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Low-loss glass-based buried multimode waveguides are fabricated by using the field-assisted Ag^+–Na^+ ion-exchange technique, and multimode optical power splitters are investigated. The measured loss of the multimode waveguides is lower than 0.1 dB/cm, and the additional loss of the multimode optical power splitters is lower than 1.3 dB under the uniform splitting condition.

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Although multimode fibres (MMFs) have not been dominant since the 1980s, they can still find wide applications in short distance networking, optical interconnect, automobile systems, audio systems, etc.[1−3] because of their low cost and low precision requirement in fabrication and usage as compared to the single mode fibres. The multimode optical power splitter is one of key components for MMF application systems. Now commercially available multimode power splitters are mainly produced by the fibre-fusing technology. The fibre-fusing technology is simple and mature for the fabrication of single-mode-fibre-based optical components. However, it is difficult to mass-produce multimode-fibre-based components, which are all required to be with balanced characteristics and insensitive to the input conditions. The integrated optic approach is another choice to develop multimode optical waveguide components. Nowadays, there are several kinds of materials for fabricating multimode waveguides using integrated optic approach, including polymeric materials,[3,4] silica-on-silicon,[5] and ion-exchanged glass.[6−8] Ion-exchanged-glass-based waveguide components are expected to be of low cost and high reliability. Therefore, in this study, the ion exchange technique is applied to fabricate multimode-waveguide-based optical power splitters (MW-OPS) in glass substrates.

Glass-based multimode waveguides were fabricated first by using the Ag^+–Na^+ ion exchange technique.[9] Self-designed glass substrates were used. Ion exchange was run at 400°C for 5 h. In order to obtain a waveguide with low loss, low polarization dependence, and an MMF-matched core, the electric-field-assisted ion exchange method[10] was applied to bury the core into the glass substrate. The applied electrical field is about 350 V/mm at the temperature of 350°C for 4 h. Figure 1 illustrates the cross-section

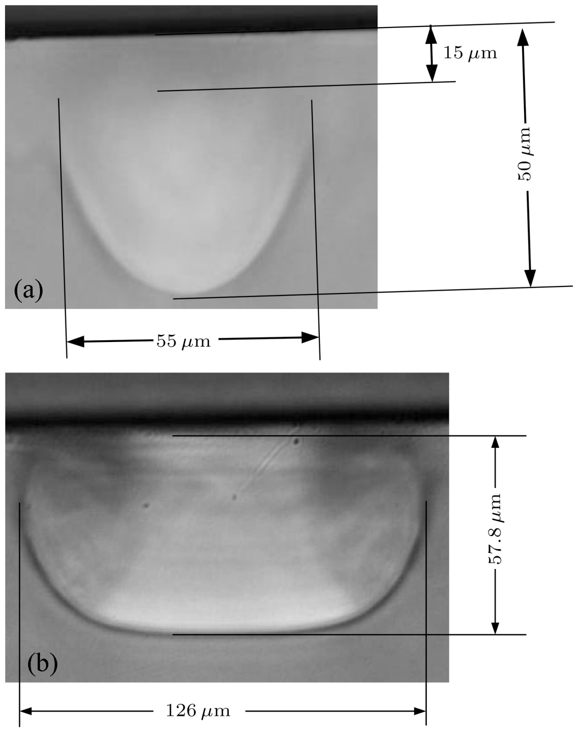

Fig. 1. Cross-section view of the multimode waveguides when the width of the open patterns is taken to be (a) 25 μm and (b) 100 μm in the photomask.

view of the multimode waveguides when the width of the open patterns in the photomask is 25 μm and 100 μm, respectively. It can be found that the observed

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sizes of the multimode waveguides are larger than the designed values. It is caused by lateral diffusion. The experimental results also show that the buried depth of the waveguide varies with the width of the open pattern. The larger the open width is, the deeper the waveguide core is. As shown in Fig. 1, the depth is about $50\,\mu$m for the 25-μm open width, and $57.8\,\mu$m for the 100-μm open width. Experiment shows that the buried depth becomes a constant value when the open width larger than $75\,\mu$m.

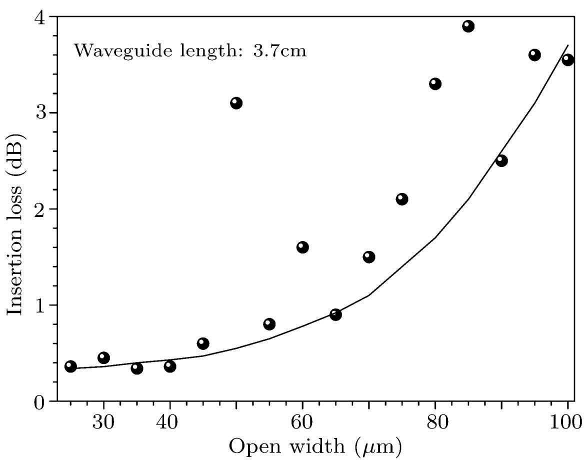

Fig. 2. Measured insertion loss of the multimode waveguides with various open width.

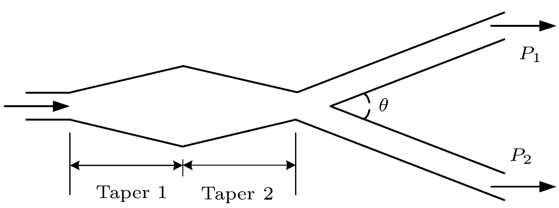

Fig. 3. Schematic diagram of the 1×2 MW-OPS with a double-taper mode scrambler.

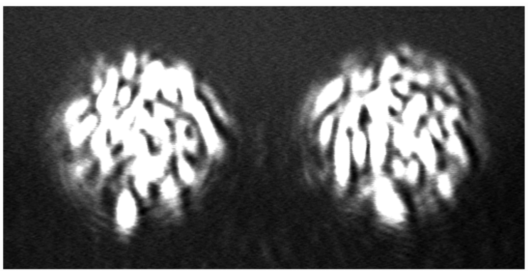

Fig. 4. Near field of the two outputs of the MW-OPS.

To characterize the multimode waveguides, a 1.55-μm LD was used as the light source, and multimode fibres with the core diameter of $62.5\,\mu$m were used as the input/output coupling fibres. Figure 2 shows the measured insertion loss of multimode waveguides with a length of 3.7 cm when the width of the open pattern in the photomask varies from $25\,\mu$m to $100\,\mu$m. It can be found that the insertion loss depends on the open width. When the open width is less than $55\,\mu$m, the loss of the multimode waveguide is rather small. If the width is greater than $55\,\mu$m, the insertion loss increases obviously. It may attribute to the increase of coupling loss arising from a mismatched waveguide dimension. The lowest insertion loss of the multimode waveguides is 0.34 dB, so the propagation loss is lower than 0.1 dB/cm.

To fabricate an MW-OPS, we selected $50\,\mu$m as the width of the open pattern in the photomask. Figure 3 shows the Y-branch-based MW-OPS. In order to improve the splitting uniformity of the MW-OPS, a structure formed by two tapers were employed as a mode scrambler.[11] We analysed the effect of the mode scrambler. The MW-OPS based on the tapered-Y-branch were also analysed for comparison. The taper could be a linear, parabolic, or exponential shape. Analysis shows that this mode scrambler can effectively enhance mode coupling and can improve the splitting property.[12] The structural parameters of the mode scrambler designed for the photomask were optimized by using the beam-propagation method. The length of the taper is $3650\,\mu$m and the width of the wide side of the taper is $100\,\mu$m. The branching angle of the Y-branch is 2°. The final separation of the two output ports is $250\,\mu$m, and the whole length of the MW-OPS is 24.5 mm. After fabricated by the field-assisted ion-exchange method, the MW-OPS was characterized by using a 1.55-μm light source. Figure 4 shows the near field of its two outputs.

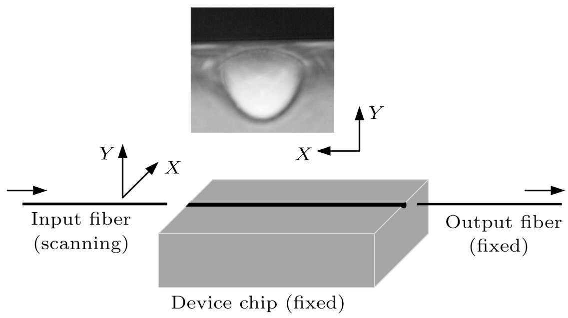

Fig. 5. System to measure the influence of the incident position of the input light.

Since the incident position of the input light has serious impact on the property of the device, we measured the influence of the incident position. We first aligned the whole light path on the measurement setup, and then fixed the MW-OPS chip and the aligned output fibre. After that, the input fibre was moved along the X and Y axis of the input end, as shown in Fig. 5. The measured results are shown in Fig. 6. The incident light power was 6.8 dBm. Since it is difficult to clearly know the real position of the input fibre in the measurement, the position at which output port 1 has the maximum value is defined as the origin of the coordinate X-Y, as shown in Fig. 6(a). Meanwhile, limited by the accuracy of the measurement setup, we only scanned an area with the size of about $14 \times 17\,\mu\mathrm{m}^2$. We calculate the value of $|P_1 + P_2|$ and $|P_1 - P_2|$, the sum of and the difference between output powers of ports 1 and 2, respectively. The calculated results are illustrated in Fig. 7.

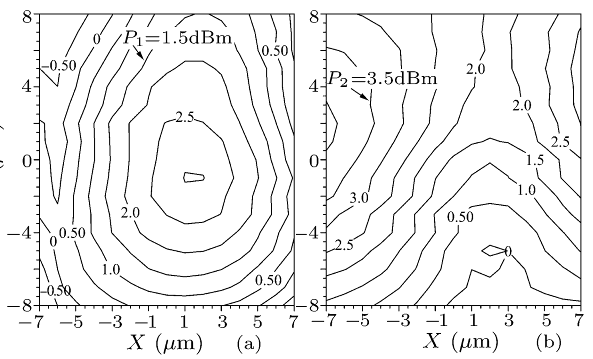

Fig. 6. Output of (a) port 1 and (b) port 2 when the incident position varies.

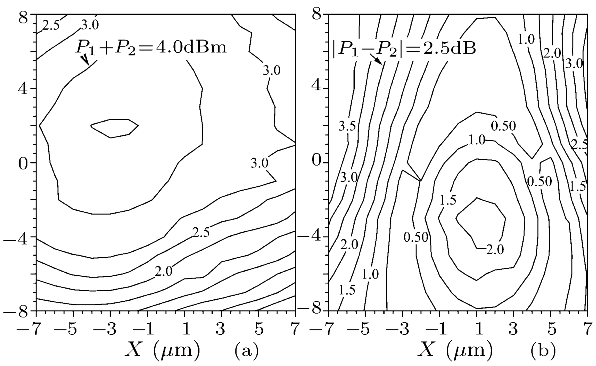

Fig. 7. (a) $|P_1 + P_2|$ and (b) $|P_1 - P_2|$ versus the incident position.

From Figs. 6 and 7, we can draw the following conclusions: (a) In the X direction, which is parallel to the surface of the glass substrate, P_1 and P_2 vary with an opposite trend and show complementary characteristic. (b) In Y direction, which is normal to the surface of the glass substrate, both P_1 and P_2 decrease when the incident light moves away from coordinate origin along the Y direction. (c) An incident region in which both P_1 and P_2 have about 2.5 dBm can be found. It means the insertion loss of each output port is about 4.3 dB at the uniform splitting condition, so the additional loss of the MW-OPS is about 1.3 dB. Taking into account the propagation loss of the multimode waveguide, it can be derived that the loss introduced by the splitter structure is less than 1 dB.

In conclusion, by using the electric-field-assisted Ag^+–Na^+ ion-exchange technique, glass-based buried multimode waveguides have been fabricated, and the measured loss of the multimode waveguides can be lower than 0.1 dB/cm. Based on the fabrication of multimode waveguides, MW-OPS is then designed and fabricated with a 50-μm-wide open pattern. A mode scrambler formed by two tapers is designed to improve the splitting property. The influence of the incident position on the property of the MW-OPS is measured and analysed in detail. The result shows that the additional loss of the MW-OPS is lower than 1.3 dB under the uniform splitting condition, in which less than 1 dB is introduced by the device structure.

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