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Integrated Optical Beam Splitters Employing Symmetric Mode Mixing in SiO_2/SiON/SiO_2 Multimode Interference (MMI) Waveguides

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INTRODUCTION

Achieving multi-direction optical beam splitting with high accuracy and low loss in short propagation length has always been one of important research issues in integrated optics. Guided-wave devices based on multimode interference (MMI) effects fulfill the above requirements. They are based on the principle of self-imaging, first proposed by Bryngdahl *et al* [1] and elucidated in more detail by Ulrich *et al* [2]. The principle of operation of MMI devices is the phenomenon of interference between modal fields in multimode waveguide. The effect of multimode interference is connected with aforementioned self-imaging principle of input field exciting the multimode section. As a result of it the input field is reproduced in single or multiple images at periodic intervals along the propagation direction of the multimode waveguide. For all of these MMI-based devices, their multimode waveguide sections can be asymmetrically- or center-fed [3]. For asymmetrical input, both symmetric and anti-symmetric modes are excited. However, for applications such as 1-to-*N* optical beam splitters, the multimode waveguide can be center-fed, which excites only the symmetric modes [3], potentially making the device shorter, and less sensitive to fabrication errors than the corresponding asymmetrically-fed devices.

In this work, we describe the fabrication and testing of center-fed SiON/SiO_2 1-to-*N* optical beam splitters. Silicon oxynitride (SiON) is chosen as a waveguide material simply because of its large refractive index range, from 1.45 for silicon oxide (SiO_2) and up to 2.0 for silicon nitride (Si_3N_4), enabling the design of a large variety of waveguiding structures [4]. The other advantages of using these materials to fabricate optical devices also include, better index match to the optical fiber, thereby reducing the propagation losses to the minimum and compatible fabrication process to the existing silicon VLSI and ULSI technologies, enabling an ultimate integration of active and passive components on the silicon substrate, via either monolithic or hybrid means.

EXPERIMENTS

Both center-fed input and MMI multimode waveguides are based on the symmetric waveguide structure (SiO_2/SiON/SiO_2). All of the layers were deposited sequentially on the silicon substrate via plasma-enhanced chemical vapor deposition (PECVD). Initially, 3μm-thick SiO_2 and 2μm-thick SiON layers were deposited first on silicon. Next, input/output and multimode waveguides were lithographically patterned and dry etched down to the SiO_2 bottom cladding layer. Finally, the etched waveguide patterns were capped by a 3μm-thick SiO_2 upper cladding layer. Figure 1 shows the cross-section of SiO_2/SiON/SiO_2 waveguide structure. The refractive index contrast Δ*n* of ~0.01 between core and cladding regions were chosen by judiciously control the oxygen-to-nitrogen ratio of SiON, since this ratio would ultimately dictate the final refractive index value of SiON layer.

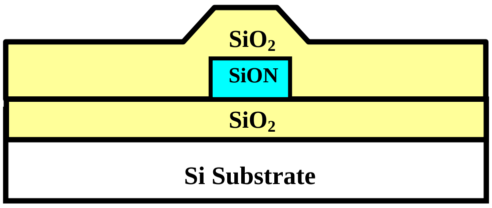

FIG. 1. The cross-section of SiO_2/SiON/SiO_2 center-fed input and MMI multimode waveguides (not drawn to scale).

As mentioned previously, the operating principle of MMI couplers/splitters is based on the self-imaging effect in a multimode section. We employed the theoretical description of MMI splitters in [5]. Figure 2 is a top view of 1 × *N* (in this particular example, *N* = 8) MMI coupler/splitter showing the positions of the input and output waveguides. W_{eq} is the equivalent width of the multimode waveguide section. Its length is given by

$$L_{MMI} = \frac{3L_\pi}{4N} = \frac{n_c W_{eq}^2}{N\lambda}; \qquad L_\pi = \frac{4n_c W_{eq}^2}{3\lambda}$$

where L_π is the coupling or beat length between the two lowest order modes, n_c is the effective refractive index of the guiding film, and λ is the operating wavelength. Since

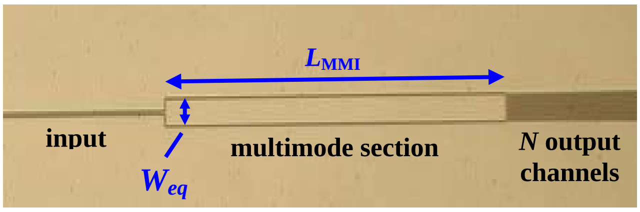

FIG. 2. The optical micrograph of 1 × *N* MMI waveguide devices (here, *N* = 8).

the length of an MMI splitter is proportional to W_{eq}^2, short devices are obtained for narrow widths. They also yield large optical bandwidth and fabrication tolerances [4]. However, a narrow W_{eq} would require waveguides at the output sides to be closely spaced. Thus, in order to avoid the coupling between output waveguides, we purposely used ICP dry etch technique to etch waveguides down to the SiO_2 bottom cladding layer to minimize the waveguide coupling from influencing the split light output generated under self-imaging principle.

Before we set out to fabricate the MMI devices, we employed the beam propagation method (BPM) to design and simulate 1 × 8 and 1 × 16 optical beam splitters in order to extract proper geometrical dimensions of devices. After simulating 1 × 8 splitter, the optimal device dimensions were determined as follows: 3μm wide and 2μm deep for the input waveguide to ensure single-mode operation, and the multimode section would have to be 64μm wide and 1246μm long in order to render 8 individual outputs with optimal field distribution. The corresponding result is shown in Figure 3. As the result would demonstrate, 8 light spots were successfully produced at the end of multimode section and the corresponding light signals were subsequently channeled out using the S-bend waveguides for ease of measuring the intensity of individual output.

RESULTS AND DISCUSSION

The operation of the MMI device was first demonstrated by employing 0.6328μm continuous-wave (cw) He-Ne laser as a light source, and a silicon photodiode as a detector. The laser beam was focused into the single-mode input waveguide via the aspheric lens in order to excite modes in the multimode section. The output spots were then collected and magnified by an objective lens so that the resultant output image could then be properly displayed on the screen. The typical near-field output spots of 1 × 8 MMI optical beam splitter is demonstrated in Figure 4.

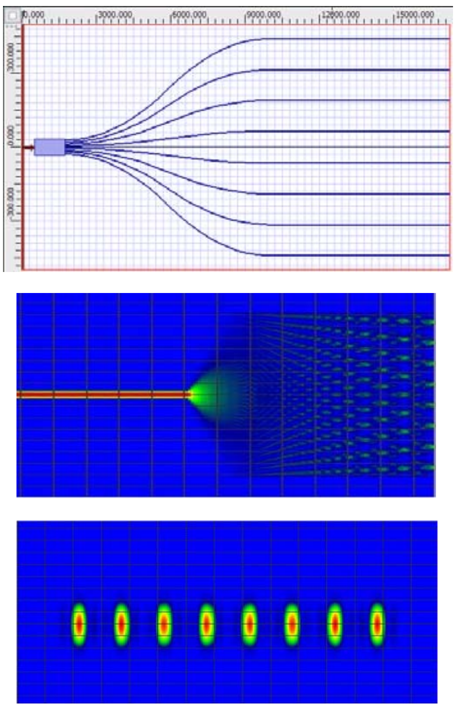

FIG. 3. The BPM simulation of 1 × 8 MMI optical beam splitter.

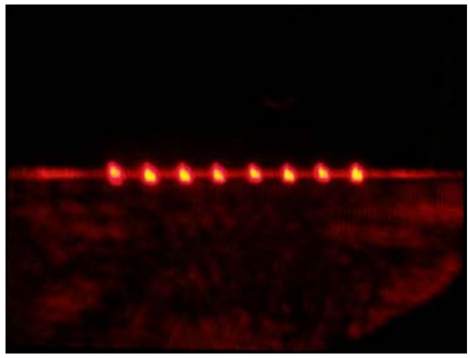

FIG. 4. Near-field output spots of 1 × 8 MMI optical beam splitter.

The output powers of the eight outputs at wavelength of 0.6328μm normalized against the highest output intensity from one of the ports were 0.63, 0.63, 0.68, 0.59, 0.66, 0.56, 0.75, and 1.00. The corresponding maximal power imbalance of 1 × 8 MMI splitter was 2.53dB.

CONCLUSIONS

In summary, we have successfully demonstrated 1 × 8 SiO_2/SiON/SiO_2 multimode interference (MMI) optical beam splitters based on the self-imaging principle for the operating wavelength of 0.6328μm. The normalized output powers of 1 × 8 MMI device at wavelength of 0.6328μm were 0.63, 0.63, 0.68, 0.59, 0.66, 0.56, 0.75, and 1.00. The corresponding maximal power imbalance of 1 × 8 MMI splitter was 2.53dB. Furthermore, works involving the design, simulation, fabrication and characterizations of 1 × 8 splitter to be operated at λ = 1.55 μm and 1 × 16 splitter to be operated at λ = 0.6328μm and 1.55μm are currently underway. The results will be reported during the upcoming SSDM 2006 conference.

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