# Design and fabrication of the star coupler based on SOI material

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Received March 17, 2003

A 1 × 25 star coupler is designed through calculation and beam propagation method (BPM) simulation. Improvement methods are focused on the design of the tapered waveguides in the device, improving the uniformity of the output light power of the star coupler. Utilizing the conventional Si process technology, the device is fabricated based on silicon-on-insulator (SOI) material. The test result shows that the star coupler has a perfect function of power splitting.

*OCIS codes:* 230.1360, 130.3120.

Many photonic and optoelectronic systems, such as WDM, optical switch array and OADM, require $1 \times N$ splitters for power or signal distribution. Various passive and active splitter designs have been proposed[1,2]. The star coupler is one type of passive splitters, which can spilt light power from the input waveguide into the output waveguides. Design and optimization of the star coupler is important for improving the function of power splitting. Improvement of the uniformity of the light power in the output waveguides of a star coupler is essential if the star coupler is used as a component in other photonic devices, such as the arrayed-waveguide grating (AWG) device[3]. We want to improve the uniformity of the light power in the output waveguides, which propagate through the slab waveguide region of the star coupler. Through calculation and BPM simulation, we give the design parameters of the star coupler.

Fabrication of the $1 \times 25$ star coupler is based on silicon-on-insulator (SOI) material. The SOI technology has shown to be a promising technology for guided wave photonic devices operating in the infrared ($\lambda > 1.2$ $\mu$m). Test result shows that the design and improvement of the star coupler has application prospect.

A star coupler consists of an input waveguide, a slab waveguide and output waveguides (Fig. 1). Only three output waveguides are shown in the figure, others are neglected. The star coupler can split the input light power into the output waveguides. The junction of the star coupler and each output waveguide is always a tapered waveguide. The width of a tapered waveguide is defined as the junction length of the tapered waveguide and the slab waveguide. In a conventional star coupler, the tapered waveguides have the same widths. So there is more light power in outer output waveguides than in inner output waveguides, because of the Gaussian-beam approximation of the light in the slab waveguide. If we decrease the widths of the inner tapered waveguides, the inner tapered waveguides will transport less light power into the relevant output waveguides, thus improving the uniformity of the light power in the output waveguides. Our design is different from the conventional star coupler due to the non-uniformity widths of the tapered waveguides.

The length of our designed $1 \times 25$ star coupler (denoted by $f$) is 5000 $\mu$m. The width of the input waveguide and each output waveguide is 5 $\mu$m. The distance between two adjacent output waveguides ($\Delta d$) is 16 $\mu$m. In a conventional star coupler, the width of each tapered waveguide is just 16 $\mu$m, which equals to the distance between two adjacent output waveguides. Using the Gaussian-beam approximation the intensity of the far field in the slab waveguide region is found from

$$I(\theta) = I_0 \mathrm{e}^{-2\theta^2/\theta_0^2}, \tag{1}$$

where $I_0$ is the intensity when $\theta = 0$ and $\theta_0$ is the width of the equivalent Gaussian far field

$$\theta_0 = \frac{\lambda}{N_{\mathrm{slab}}} \cdot \frac{1}{w_{\mathrm{e}}\sqrt{2\pi}}. \tag{2}$$

$N_{\mathrm{slab}}$ is the effective refractive index of the slab waveguide region. $\lambda$ is the wavelength in vacuum, which equals to 1.55 $\mu$m. $w_{\mathrm{e}}$ is the effective width of the modal field in the input waveguide

$$w_{\mathrm{e}} = \frac{\int_{-\infty}^{+\infty} E(y)^2 \mathrm{d}y}{E_{\max}^2}, \tag{3}$$

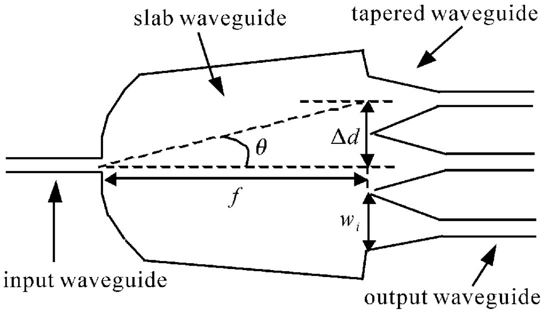

Fig. 1. Schematic diagram of the star coupler.

in which $E(y)$ is the field distribution in the transverse direction in the waveguide and $E_{\max}$ is the maximum value of $E(y)$. From Eqs. (2) and (3), we can get that $\theta_0 = 0.0447$ (rad). So we can calculate the light power in the $i$th output waveguide

$$P_i = \int_{\theta_i-\Delta\theta_i/2}^{\theta_i+\Delta\theta_i/2} I(\theta)\mathrm{d}\theta \approx I(\theta_i)\Delta\theta_i, \qquad (4)$$

where $\theta_i$ equals to $i\Delta d/f$ and $\Delta\theta_i$ is the angle range of the $i$th tapered waveguide. In a conventional star coupler, $\Delta\theta_i$ is equivalent to the angle interval between adjacent output waveguides, which equals to $\Delta d/f = 16/5000 = 0.0032$ (rad). From Eq. (4), we get the light power distribution in the output waveguides of the conventional star coupler. The uniformity of the light power in the output waveguides is not good. For improvement, we use non-uniformity widths of tapered waveguides instead of the conventional straight waveguides in the junction of the star coupler and each output waveguides. The width of the middle tapered waveguide (denoted by $w_0$) is 5 $\mu$m, and the width of the $i$th tapered waveguide (denoted by $w_i$) is so set that the light power in the corresponding output waveguide is the same or close to that of the middle output waveguide

$$I(\theta_i) \cdot w_i/f = I(0) \cdot w_0/f \rightarrow$$

$$w_i = w_0 \cdot \frac{I(0)}{I(\theta_i)} = 5 \cdot \frac{1}{I(\theta_i)}\ (\mu\mathrm{m}). \qquad (5)$$

If the calculated value of $w_i$ is more than 16 $\mu$m, we set it to be 16 $\mu$m, because the width of each tapered waveguide in our designed star coupler is not more than 16 $\mu$m. So $w_i$ is not less than 5$\mu$m and not more than 16 $\mu$m. Through calculation, we get the light power distributions before and after improvement method is used, which are denoted by the white columns and the gray columns, respectively in Fig. 2. We can see that the uniformity of the light power in the output waveguides is improved. The insertion loss of the star coupler increases in the same time. This new design of the star coupler can improve the performance of the AWG device if it is used to the device.

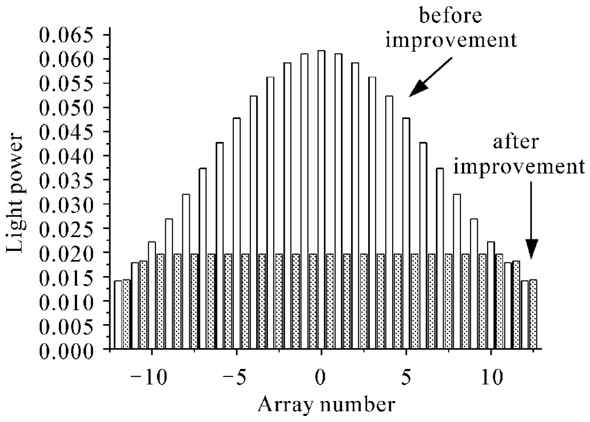

Fig. 2. Light power distribution comparison.

The length of each tapered waveguide is under consideration now. For simplicity, the length of each tapered waveguide is set to be the same value, which is denoted by $L$. And the width of the simulated tapered waveguide is 16 $\mu$m. The width of the junction of the tapered waveguide and the output waveguide is 5 $\mu$m. When $L$ increases, the loss of light propagating through the tapered waveguide decreases. But the size of the device will be large if $L$ is set to be a large value. So choosing the value of $L$ is a trade-off between the loss and the device size. Figure 3 is the light power propagating through a tapered waveguide as the function of $L$, which is gotten through BPM simulation. From the figure, we find that if $L$ is more than 500 $\mu$m, more than 98% light power can propagate through the tapered waveguide. So we set $L$ to be 500 $\mu$m, which is the trade-off result.

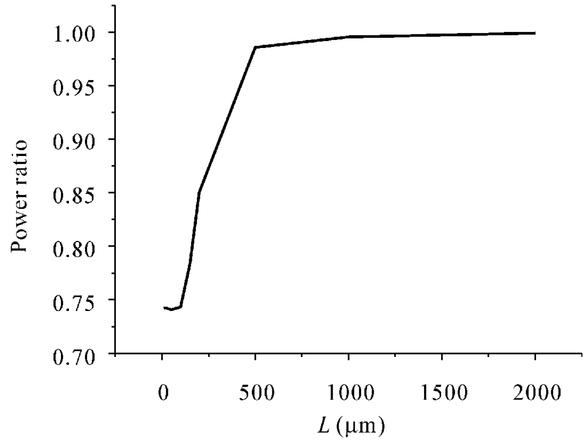

Fig. 3. Light power through a tapered waveguide versus $L$.

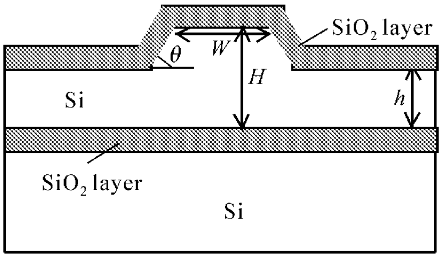

Fig. 4. Schematic diagram of the SOI waveguide.

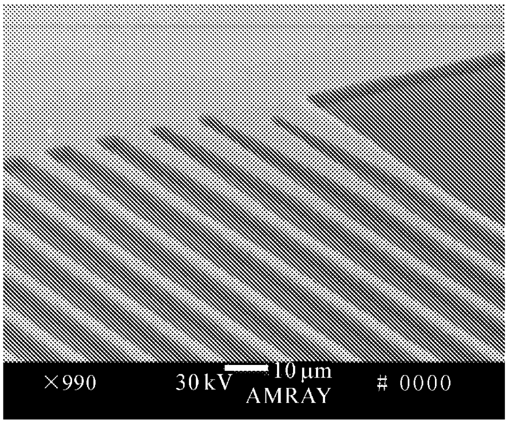

Fig. 5. SEM picture of the star coupler.

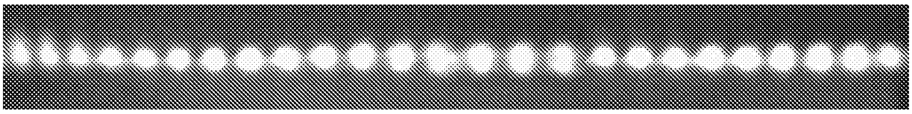

Fig. 6. The near-field images of the light emerging from the output waveguides.

Fabrication of the star coupler is based on SOI material. The conventional Si process technology is used to fabricate the device. Figure 4 shows the cross-section of the SOI waveguide, which satisfies the single-mode condition by the large cross-section theory[4,5]

$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}}, r = h/H > 0.5. \qquad (6)$$

The geometrical parameters of the waveguide are as follows: $W = 5$ μm, $H = 5$ μm, $h = 3$ μm. $\theta$ equals to 54.74°, which is due to the wet etching technology on silicon. Figure 5 is the SEM picture of the star coupler. The waveguides are fabricated after the SOI chip is dipped in 50% KOH liquor for 20 minutes. The cleaved facet of the input waveguide is polished to facilitate light coupling between the optical fiber and the input waveguide.

The light from the optical fiber at wavelength $\lambda = 1.55$ μm is coupled into the star coupler through the cleaved facet of the input waveguide. The images on TV show the light emerging from the output waveguides. Figure 6 is the near-field images of the light of the 25 output waveguides.

From the figure, we can see that the star coupler has a perfect function of power splitting.

A 1 × 25 star coupler is fabricated based on SOI material, which is improved through calculation and BPM simulation. Setting the widths of the tapered waveguides to be different values, we can improve the uniformity of the light power in the output waveguides of the star coupler. The clear and uniform images of the light emerging from the 25 output waveguides are observed.

This work was supported by the Major State Basic Research Development Program (Grant No. G1999033104) and the National Natural Science Foundation of China (Grant No. 60177012). X. Jiang's e-mail address is iseejxq@zju.edu.cn.

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