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Design and Fabrication of Ultracompact 3-dB MMI Coupler in Silicon-on-Insulator*

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Abstract: An ultracompact 3-dB coupler is designed and fabricated in silicon-on-insulator, based on 1×2 line tapered multimode interference (MMI) coupler. Comparing with the conventional straight MMI coupler, the device is ~ 40% shorter in length. The device exhibits uniformity of 1.3dB and excess loss of 2.5dB.

Key words: multimode interference coupler; line tapered waveguide; silicon-on-insulator

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1 Introduction

Recently, silicon-on-insulator (SOI) attracts much attention in guided wave optics due to its excellent waveguide characteristics. Benefit from the large refractive index difference between silicon and silicon oxide, guided modes propagated in the silicon guiding layer are strongly confined in vertical direction while horizontal confinement to the guided modes can be also realized by using rib waveguide structure. As a result, SOI-based optical waveguide devices possess low loss.

As an important element in integrated optics, 3-dB couplers are widely used as optical splitter and optical combiner in Mach-Zehnder interferometer optical modulators or switches. Multimode interference (MMI) couplers, based on self-image effects in multimode waveguides, are gaining more and more popularity in the design of integrated optical circuits due to the advantages such as compactness, large fabrication tolerance, insensitivity to polarization, and large bandwidth[1,2]. In this paper, we report an ultracompact 3-dB MMI coupler in silicon-on-insulator, which possesses a shorter length as well as a large cross-section that matches singlemode (SM) fiber.

2 Principle of device

The schematic diagram of the 1×2 line tapered MMI coupler is shown in Fig. 1, where W_0 represents the minimum width of the multimode waveguide section and W_1 represents the maximum width of the multimode waveguide section. The input waveguide is located at $W_0/2$ and the two output waveguides are located at $W_1/4$ and $3W_1/4$, respectively. The width of the line-tapered multimode waveguide is

$$W(z) = W_0 + (W_1 - W_0)z/L_{MMI} \quad (1)$$

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where z represents the light propagation direction and L_{MMI} represents the length of line-tapered multimode waveguide. When the line tapered multimode waveguide keeps slowly varying, i. e. the taper slope is very small, the self-imaging properties remain[3].

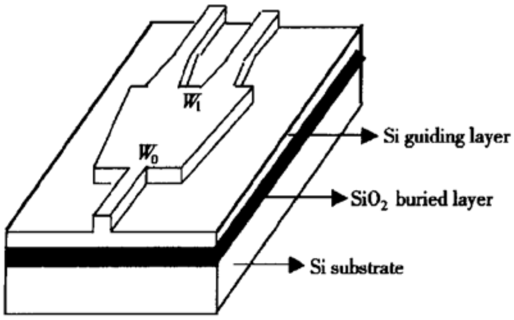

Fig. 1 Schematic diagram of SOI 1×2 line tapered MMI 3-dB coupler

SOI 3-D rib waveguide can be simplified to be 2-D waveguide structure by means of effective refractive index method. Assuming the multimode waveguide supports m lateral modes with mode numbers $v = 0, 1, 2, \cdots, (m-1)$ at a free space wavelength λ, the effective index of the multimode waveguide section and the lateral confinement section is n_r and n_c, respectively. According to the dispersion equation, the lateral wave number k_{vx} and the propagation constant β_v are related as follows[4]:

$$k_{vx}^2 + \beta_v^2 = k_0^2 n_r^2 \tag{2}$$

with

$$k_0 = 2\pi/\lambda \tag{3}$$

$$k_{vx} = (v+1)\pi/W_e(z) \tag{4}$$

where $W_e(z)$ takes into account the Goos-Hähnchen penetration depth and can be obtained from

$$W_e(z) = W(z) + W_g = W(z) + \left(\frac{\lambda}{\pi}\right)\left(\frac{n_c}{n_r}\right)^{2\sigma}(n_r^2 - n_c^2)^{-1/2} \tag{5}$$

where $\sigma = 0$ for TE and $\sigma = 1$ for TM. From Eqs. (2)~(4) we can deduce that

$$\beta_v = k_0 n_r\left[1 - \left(\frac{\lambda(v+1)}{2n_r W_e(z)}\right)^2\right]^{\frac{1}{2}} \approx k_0 n_r - \frac{(v+1)^2\pi\lambda}{4n_r W_e^2(z)} \tag{6}$$

Therefore, the phase change between the v order mode and the fundamental mode over the line-tapered waveguide is

$$\Delta\Phi_v = (\beta_0 - \beta_v)L_{MMI} = \int_0^{L_{MMI}}(\beta_0 - \beta_v)\,dz = v(v+2)\frac{\pi\lambda}{4n_r}\int_0^{L_{MMI}}\frac{dz}{W_e^2(z)} \tag{7}$$

Substitute Eqs. (1) and (5) into Eq. (7), we obtained

$$\beta_0 - \beta_v = \frac{v(v+2)\pi\lambda}{4n_r(W_0 + W_g)(W_1 + W_g)} \tag{8}$$

By defining L_π as the beat length of the two lowest-order modes

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} = \frac{4n_r(W_0 + W_g)(W_1 + W_g)}{3\lambda} \tag{9}$$

According to the principle of symmetric interference MMI coupler, for 1×2 3-dB line-tapered MMI coupler, the length of the line tapered MMI section L_{MMI} is determined by

$$L_{MMI} = \frac{3L_\pi}{8} = \frac{n_r(W_0 + W_g)(W_1 + W_g)}{2\lambda} \tag{10}$$

Comparing with the conventional straight 1×2 3-dB MMI coupler, the reduction of the multimode waveguide length is $1-(W_0+W_g)/(W_1+W_g)$.

3 Design and fabrication

For SOI access waveguides to load only the fundamental mode, the rib structure should meet certain conditions[5]. In our design, the free space wavelength was 1.55μm, the width of the access waveguides was 4μm, the maximum and minimum width of line tapered multimode waveguide were 50μm and 30μm, respectively. The guiding layer thickness was 5μm and the etching depth of the SOI rib waveguide was 1.75μm. The length of the tapered multimode waveguide was 2020μm. To reduce coupling loss between output waveguides and multimode waveguide section, two tapered joint waveguides were used, as shown in Fig. 1. Comparing with the conventional straight 1×2 3-dB MMI coupler, the length of the multimode waveguide reduces about 40%, assuming the width of the straight multimode waveguide was 50μm. By using

2-D BPM, the optical intensity distribution inside the 1×2 line tapered MMI coupler was obtained and shown in Fig. 2. The simulated output power of the 1×2 line tapered MMI coupler was show in Fig. 3. It can be seen that the output images exhibit a uniform distribution.

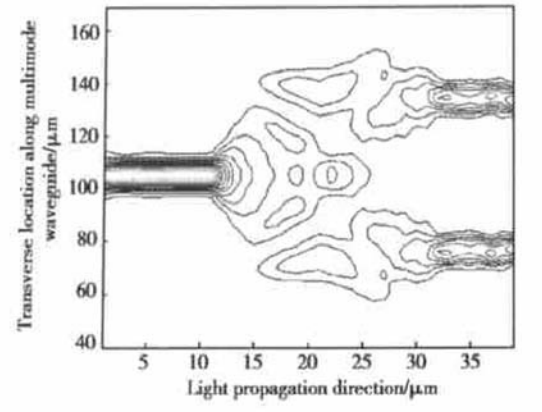

Fig. 2 Simulated optical intensity distribution inside 1×2 line tapered MMI coupler

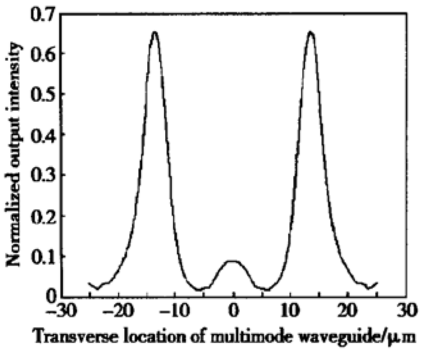

Fig. 3 Simulated output power of 1×2 line tapered MMI coupler

An SOI wafer with 1μm buried SiO_2 and 5μm top Si layer obtained by bonding and back-etching technique, was used to fabricate the device. The wafer was deposited with 0.2μm Cr. Then patterns were defined with lithography, followed by magnetic enhanced reactive ion etching (MERIE) with SF_6 to construct the rib waveguide structure. After the MERIE, a layer of 0.7μm SiO_2 was deposited on the wafer as the cladding layer by PECVD. The device was then thinned and cleaved for the purpose of test. For the MMI coupler, the performances are sensitive to the width of the MMI section. So, on the mask, the width of the MMI section was 0.5μm wider than the design value to compensate the lateral corrosion during MERIE process. However, the width of the waveguide in the fabricated device was still 0.5μm narrower than the design value. Figure 4 shows the SEM graph of input and output ports of the 1×2 line tapered MMI coupler.

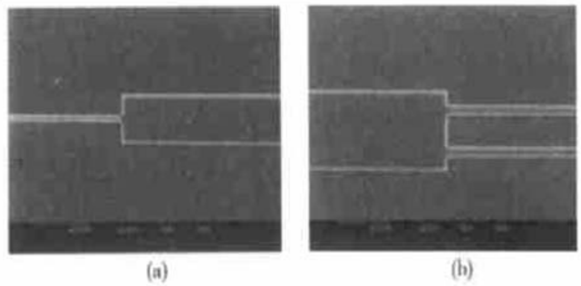

Fig. 4 SEM graph of the 1×2 line tapered MMI coupler (a) Input port; (b) Output ports

4 Results of measurement

Light from the singlemode fiber at a wavelength of 1.55μm was coupled into coupler through the cleaved facet of the input waveguide. The light emerging from the output ports was projected onto the microviewer (infrared viewing TV camera with model 7290) using a microscope (objective 20×). The near field pattern of one of the fabricated devices is shown in Fig. 5. The uniformity was 1.3dB. It is believed that the output uniformity of the 1×2 line tapered MMI coupler can be improved

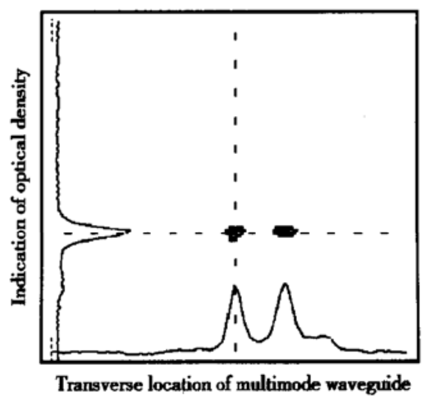

Fig. 5 Near field output of 1×2 line tapered MMI coupler

further by improving etching uniformity. The measured excess loss was 2.5dB. The loss was caused primely by the facet reflection due to refractive index mismatch between waveguide core and fibre core, input and output coupling due to model profile dismatch between rib waveguide and circle fibre mode, as well as the side wall roughness of the SOI rib waveguide. Among the loss mechanism, the facet reflection and coupling loss is estimated to be the dominant factors. Some measures such as polishing the waveguide facets and depositing an antireflection coating layer on the facets may contribute to the reduction of excess loss.

5 Conclusion

In summary, we have proposed, designed, and fabricated an ultracompact 3-dB MMI coupler in silicon-on-insulator. The device fabricated with a width slightly deviated from designed value shows a uniformity of 1.3dB and an excess loss of 2.5dB. The test results show that the fabricated device has approximate uniform output optical power. Moreover, the output power uniformity and excess loss of the 1×2 line tapered MMI couple can be improved by improving the process such as etching uniformity. The length of the device is only 2020μm, about 40% shorter than that of corresponding straight MMI coupler with an uniform multimode waveguide width of 50μm. The highly reduction of device length, together with the large cross-section (5μm×4μm) that matches the single-mode fiber, makes it more feasible in integrated optical circuits.

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一种紧缩型的SOI 3-dB多模干涉耦合器*

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摘要: 采用线锥形结构, 在silicon-on-insulator (SOI)材料上设计并实现了一种新的紧缩型3-dB多模干涉耦合器(MMI). 与普通的矩形结构3-dB MMI耦合器相比, 该器件长度减少了40%. 耦合器输出均衡度为1.3dB, 过剩损耗为2.5dB.

关键词: 多模干涉耦合器; 线锥形波导; SOI
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