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Optimal design of a multi-mode interference splitter based on SOI*

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In this paper, the multimode waveguide lengths and the output port locations of a SOI (silicon on insulator) material-based 1x4 MMI (multimode interference) optical splitter are optimized by means of FD-BPM (finite difference – beam propagation method). An improved 1x4 MMI optical splitter is designed. Compared with an usual optical splitter, a smaller loss 0.12dB and a better output port power uniformity 0.11dB are achieved for the optical signal transmission.

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Optical waveguide splitter is an important device in integrated optical interconnect systems based on planar lightwave circuits (PLCs). An optical waveguide with silicon on insulator (SOI) structure has a large refractive index difference. Therefore, the optical beam can be well confined in a silicon waveguide. Besides, SOI devices are also suitable for optical integrated circuits with large density because of the small bending radius of the optical waveguide. Compared with an usual Y-optical splitter, a SOI-based multimode interference (MMI) optical splitter has a series of advantages including low loss, good uniformity, insensitive to operation wavelength, polarization, temperature and other environmental factors, large bandwidth, simpler fabrication technique, larger tolerance allowed and minimized structure. These attract a significant research work on SOI-based MMI optical waveguides used in optical integrated circuits.

Research and design of $N \times N$ MMI optical waveguides are an important work for the practical application of waveguides. Regarding the research on SOI waveguides, previous reports have been mainly about the calculation and analysis, design and loss investigation of the waveguide with a single mode transmission while the cross-section area of the waveguide is large [1-3]. The calculation formula of the waveguide length of usual MMI multimode waveguides is an approximation under an assumption of large refractive index differences. In order to enhance the performance of the waveguide devices, an optimization is required to re-calculate the waveguide parameters with small index differences during design of SOI-based MMI waveguides [4]. In this paper, a finite difference – beam propagation method (FD - BPM) is used to calculate and optimize accurately the MMI waveguide length and the output port location of a SOI based 1 × 4 MMI optical splitter. Apart from this, the input and output waveguide structure of the 1 × 4 MMI optical splitter is improved. The results show that a low loss and a better output uniformity can be obtained for the improved MMI optical splitter compared with the ones before improving.

FD-BPM is a type of numerical algorithm, which is usually used to simulate and analyse the lightwave transmission in optical fibers or other optical waveguides. In this part of the paper, the optical transmission characteristics and the MMI waveguide structure are studied by using FD-BPM method, and the uniformity of the MMI waveguide output power is calculated.

MMI constructed waveguide devices consist of input and output waveguides with single mode characteristics at both sides and a multiple mode waveguide in the middle, as shown in Fig.1 which illustrates a 1x4 MMI optical splitter, where W_{mmi} is the width of the multimode waveguide and L_{mmi} is the length of the multimode waveguide.

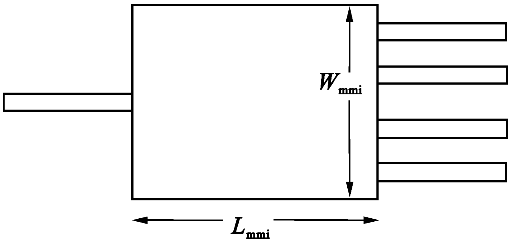

Fig.1 Illustration of a 1 × 4 MMI splitter.

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The operation principle of the MMI optical splitter is based on the self-imaging effect of the multimode waveguide found by Ulrich [4]. The self-imaging effect results from a constructive interference between the modes excited in the waveguide. With the effect, optical field generates one or several images of the input field periodically in the direction of transmission. By defining an effective waveguide width W_e, the beat length L_π of the two lowest order modes can be written as:

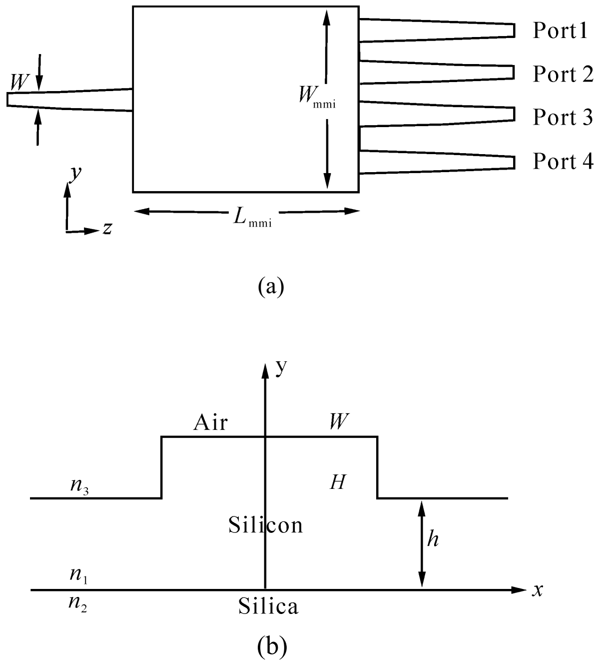
$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \cong \frac{4 n_r W_e^2}{3\lambda_0} \qquad (1)$$

where β_0 and β_1 are the propagation constants of the fundamental mode and the first order mode of the multimode waveguide respectively, λ_0 is the wavelength in free space, and n_r is the effective refractive index of the core layer of the planar waveguide. It is noted that the effective width of the multimode waveguide W_e is a little larger than the geometrical width W_{mmi} of the waveguide. Since different waveguide modes (TE mode and TM mode) have different values of the effective refractive index and the effective width of the waveguide, it can be known from formula (1) that the beat lengths for the TE modes and TM modes are not equal. For a 1 × N MMI splitter, the multimode waveguide length M_{mmi} can be written as:

$$L_{\mathrm{mmi}} = \frac{3L_\pi}{4N} = \frac{n_r\left[W_{\mathrm{mmi}} + \left(\frac{n_c}{n_r}\right)^{2\sigma} \times \frac{\lambda_0}{\pi(n_r^2 - n_c^2)^{1/2}}\right]^2}{N\lambda_0} \qquad (2)$$

where n_c is the effective refractive index of the cladding material. When the transmission mode is TE wave, $\sigma = 0$, and when TM wave, $\sigma = 1$. N is the number of the output ports.

In order to reduce the influence of high order modes to the optical power splitting ratio, the input/output waveguides are usually in the form of ridge shaped uniform single mode waveguide. By gradually increasing the width of the input/output waveguides, a narrow diffraction pattern can be obtained for a wide input waveguide at the end of self-imaging.[3] Consequently, the overall performances of the optical waveguide transmission can be enhanced. Also, it is important for optical signal transmission that the length L_{mmi} of the multimode waveguide is determined accurately and so the output ports are located. For that, the main points in this design include to improve the performance of the 1 × 4 MMI splitter as shown in Fig.2 and to optimize the parameters of the waveguides.



(a)

(b)

Fig.2 (a). Illustration of an improved 1 × 4 MMI splitter (b).Illustration of the input cross-section of the improved optical splitter waveguide.

The 1 × 4 MMI splitter shown in Fig.2(a) has tapered waveguides as its input/output waveguides. W is the width of the input/output waveguides (varying from 4 μm to 8 μm). The width of the multimode waveguide is 60 μm. The ridge height (H) is 5 μm, the planar waveguide thickness (h) is 3 μm and the operation wavelength λ_0 is 1.55 μm. After effective refractive index equalizing, $n_r = 3.4517$ and $n_c = 3.4462$. By replacing the parameters in formula (2) with these values, it is obtained that the MMI waveguide length $L_{mmi} = 2004$ μm (TE wave). As mentioned before, this result came with a large error since the calculation was based on the assumption of a large refractive index difference while the index difference is small in our case. It means that an optimization for an accurate L_{mmi} value is needed. Fig.3 shows the transmission curves of a TE wave in the MMI waveguide simulated by FD-BPM, with the upper curve representing for the output ports 1 and 4, and the lower curve for ports 2 and 3, as seen from the middle part of the figure. Every time the length value is read out from the simulation output, it is input in the simulation again for a more accurate length value. After several iterative processing, the obtained accurate MMI waveguide length is $L_{mmi} = 2227$ μm. At this length, the maximum output power can be observed at each output port of the 1 × 4 MMI splitter. The difference of the waveguide lengths calculated from formula (2) and from the simulation is 230 μm.

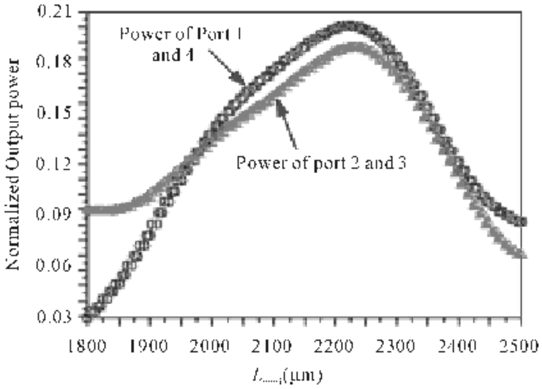


Fig.3 Output power variation versus multimode waveguide length in the 1 × 4 splitter.

The accuracy of output port locations influences the uniformity of the optical power transmission in a MMI splitter. First, it is calculated for the output waveguide location based on symmetry principle. Using the formula in Ref. [5], the output location can be expressed as:

$$y_i = \frac{[2i-(N+1)]}{2N} W_{\text{mmi}} \qquad i=1...N \tag{3}$$

Thus, y_i = ±7.5 μm for the two waveguides in the middle, and y_i = ±22.5 μm for the other two waveguides.

Fig.4 shows the MMI output waveguide locations and power variation along the transversal direction obtained from FD-BPM calculation. It can be seen that the maximum output powers occur at y_i = ±8 μm and y_i = ±23.5 μm.

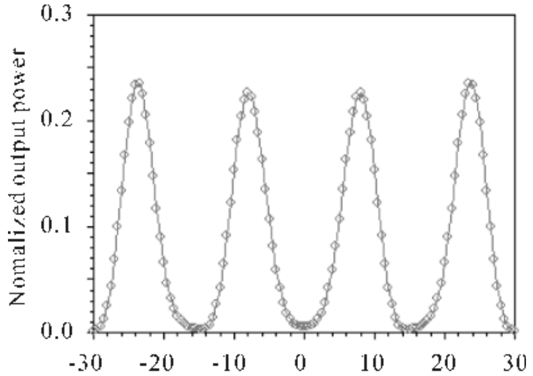


Fig.4 Output power variation versus the transversal po sition of the 1 × 4 splitter output waveguides

Fig.5 shows the optical field distribution pattern in the 1 ×4 splitter obtained from the simulation. It can be seen that an optical field exists outside the waveguides, which results in the optical power loss in transmission. This explains that the total power of the four output ports is less than 1.

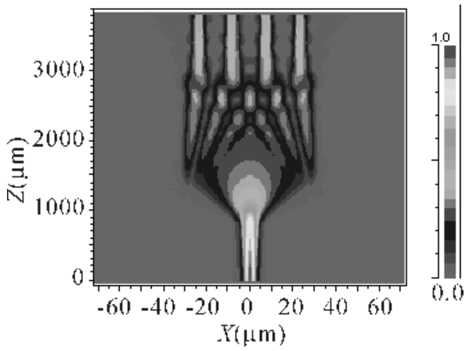


Fig.5 Optical field distribution pattern of the 1 × 4 MMI optical splitter.

$$\text{Propagation loss} = -10 \times \log_{10}\left(\frac{\sum P_{\text{iout}}}{P_{\text{in}}}\right) \tag{4}$$

$$\text{Power Uniformity} = -10 \times \log_{10}\left(\frac{\text{Min}(P_{\text{iout}})}{\text{Max}(P_{\text{iout}})}\right) \tag{5}$$

A normalized optical power levels versus the propagation distance of the output ports are obtained for the splitter and shown in Fig.6 for a comparison between the results before and after improving the device design.

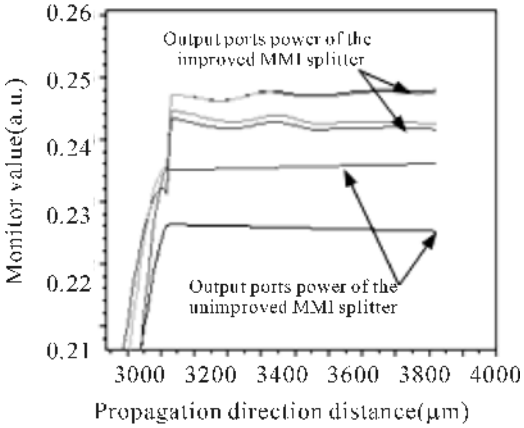


Fig.6 The output port power levels of the 1 × 4 MMI splitters with optimization and without optimization.

It can be seen that the output power distribution is in a range from 0.242 to 0.248 (a.u.) for the improved MMI splitter, while it is from 0.225 to 0.235 (a.u.) for the splitter without optimization. Also, calculated from formulae (4-5), the transmission loss and the power uniformity of the improved splitter are 0.12 dB and 0.11 dB respectively, while it is 0.34 dB and 0.20 dB respectively for the splitter without optimization. In other words, the transmission loss is reduced by 60 % and the output power uniformity is increased by 50 % for the splitter.

The multimode waveguide length and output waveguide locations of the SOI-based 1 × 4 MMI optical splitter have been calculated and optimized by means of FD-BPM. The usual 1 × 4 MMI optical splitter has been improved and a new form of splitter with the widths varying linearly for the input/output waveguides has been proposed. The results from simulation show that an improved optical splitter has the transmission loss of 0.12 dB, i.e. a reduction of 70 %, and the output power uniformity of 0.11 dB, i.e. a reduction of power fluctuation of 50 %. The results provide a guideline for a designer to enhance the performance of the MMI optical splitter.

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