Optica Applicata, Vol. XLI, No. 3, 2011

Improving the self-imaging in multimode interference (MMI) couplers

RUI YIN

College of Information Science and Engineering, Shandong University,
Jinan, Shandong, China 250100;
e-mail: yinrui@sdu.edu.cn

A new structure is firstly proposed to be used as the multimode interference (MMI) region in this paper. For comparison with conventional MMI region, two extra layers with thin thickness and lower index beside the core layer are introduced to increase the difference of propagation constant between the first two modes. Meanwhile, high order modes are not affected so much. Thus the propagation constant errors of the guided modes are decreased and better self-imaging is realized. The designing process is also given in this paper. This new structure can be applied to any kind of $M \times N$ MMI couplers. By incorporating this new structure, an MMI based power splitter is 1/6 shorter and contrast of MMI optical switch is 10 dB higher according to the results of exact mode analysis.

Keywords: integrated optics, multimode interference (MMI), self-imaging.

1. Introduction

Multimode interference (MMI) coupler has attracted much interest in the past decades, owing to its compact structure, low loss, easy fabrication and large fabrication tolerances. Many functions can be realized using MMI couplers, such as power splitting [1], optical switching [2], wavelength division multiplexing (WDM) [3], *etc*. Thus the MMI coupler has been used more and more widely as a building block in integrated optics and optical network.

The basic principle of MMI coupler is self-imaging in the MMI region. In conventional structures, a 2-step index waveguide is usually used as the MMI region. The self-imaging in such a waveguide is not so good since extra loss and degradation in uniformity/contrast occur. A lot of effort has been made to improve the self-imaging effect in the past. For example, a tapered waveguide was used to reduce the loss of $1 \times N$ type MMI couplers [4]. In References [5] and [6], self-imaging was improved by tuning the refractive index contrast and good uniformity under large route number was realized. The price is that the device is large in size due to the weak-confined waveguide structure, and it is only suitable for MMI splitters. A graded-index MMI region can give the best self-imaging quality while keeping the device compact and suitable for any kind of MMI couplers [7]. However, MMI region with exponential index distribution is difficult to be realized in current semiconductor processes. In this paper, we add 2 waveguides in the MMI region. With this new structure, performances of MMI splitters remain at the same level as in the previous researches and device size is only 1/6. The contrast of MMI switch is also improved by 10 dB. This new structure is simpler and relatively realizable compared to the graded-index waveguide.

2. Theory and design

The basic self-imaging effect in conventional MMI coupler can be expressed as:

$$\beta_0 - \beta_m = \frac{m(m+2)\pi}{3L_\pi} \tag{1}$$

where β_m represents the propagation constant of the m-th mode and $L_\pi = \pi/(\beta_0 - \beta_1)$ is the beat length of the first two modes. Self-imaging in conventional MMI coupler is not perfect. For example, in a waveguide with core/cladding indices of 3.5/1.0, core width of 64 μm and application wavelength of 1.55 μm, the calculated effective indices of the guided TE modes are listed in Tab. 1 (TM modes are similar). For comparison purposes, results of ideal self-imaging are also given. In this ideal self-imaging, β_0 and β_1 in the waveguide are used as standards, β of higher order modes are calculated by

Table 1. Effective indices of the guided modes in real waveguide and the requirement of ideal self--imaging (TE modes).

Mode number	0	1	2		100		270	
Effective index in real waveguide	3.4999791	3.4999165	3.4998123	…	3.2804221	…	1.2445619	…
Ideal self-imaging	3.4999791	3.4999165	3.4998310		3.2871391		1.9675311	

Eq. (1). Table 1 clearly shows the difference between ideal self-imaging and self--imaging in real waveguide. If β_0, β_1, …, β_m are the propagation constants of guided modes in real waveguide, we have:

$$p_m(\beta_0 - \beta_m) = \frac{m(m+2)\pi}{3L_\pi} \tag{2}$$

where p_m is a factor of the m-th mode and is smaller than 1.0 for $m > 1$ according to Tab. 1. Considering β_0 and β_1 are standards, $p_1 = 1.0$.

Then we have:

$$\beta_0 - \beta_m = \frac{\pi}{L_\pi} \tag{3}$$

From Equations (2) and (3):

$$p_m \frac{(\beta_0 - \beta_m)}{(\beta_0 - \beta_1)} = \frac{m(m+2)}{3} \tag{4}$$

We define Δ_m as the propagation constant error of the m-th mode:

$$\Delta_m = \frac{(\beta_0 - \beta_m)}{(\beta_0 - \beta_1)} - \frac{m(m+2)}{3} \tag{5}$$

In the case of $\Delta_m \equiv 0$, we have $p_m \equiv 1$. Phase differences between guided modes are strictly $2m(m+2)\pi$ (this means no phase differences) after a propagation distance of $6L_\pi$. The input field is perfectly "imaged" at this MMI length. This is ideal self--imaging. If $|\Delta_m|$s are not equal to zero, modes have phase differences at the propagation distance of $6L_\pi$. This causes degradation in the final image. Phase differences will be closer to $2m(m+2)\pi$ when $|\Delta_m|$s are nearer to 0 and the image quality will be better.

In real waveguide, we have $\Delta_m > 0$ because $p_m < 1$. There are two means to decrease $|\Delta_m|$: decrease $\beta_0 - \beta_m$, or increase $\beta_0 - \beta_1$. It is not easy to decrease $\beta_0 - \beta_m$ because we need to increase β_m a lot: 1.24 to 1.97 for β_{270} in Tab. 1. So, a more practical method is to increase $\beta_0 - \beta_1$. We use two additional layers for this purpose.

Figure 1**a** shows the top-view index model of conventional MMI coupler and Fig. 1**b** is the cross-section index distribution of its MMI region with the width of $W + 2d$ and index contrast of n_1/n_3. Figure 1**c** shows our structure designed. In this new structure, core layer of the original waveguide is divided into three parts: one new core layer with the width W and index n_1, two additional layers with the width d and

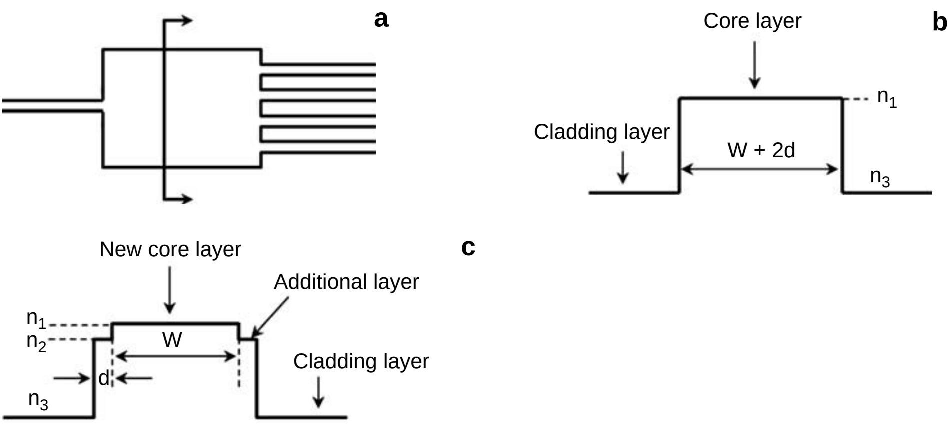

Fig. 1. Index model of conventional and the new designed MMI coupler. Top-view index model of MMI coupler (**a**). Cross-section index distribution of conventional MMI region (**b**). Cross-section index distribution of the new designed structure (**c**).

index n_2. The function of additional layer is tuning the propagation constants of low order modes while not affecting high order mode much. So, d should be very small compared with W. The n_2 should be close to n_1, and smaller than the effective indices of the first two modes. This will decrease the values of β_0 and β_1 slightly. β_1 is affected more because β_1/k is closer to n_2 compared to β_0/k. Thus, $\beta_0 - \beta_1$ in the new structure is increased. Here is an example: in a 3-layer planar waveguide with core/cladding index of 3.5/3.0, core width of 21 µm and wavelength of 1.55 µm, $(\beta_0 - \beta_1)/k = 0.0005689$ and $(\beta_0 - \beta_{46})/k = 0.4433928$. In the structure shown in Fig. 1**c** with $W = 20$ µm, $d = 0.5$ µm, $n_1 = 3.5$, $n_2 = 3.4$ and $n_3 = 3.0$, we have $(\beta_0 - \beta_1)/k = 0.0006078$ and $(\beta_0 - \beta_{46})/k = 0.4487593$. In this example $\beta_0 - \beta_1$ is increased by 6.8% while $\beta_0 - \beta_{46}$ is only increased by 1.2% in the new structure. An more detailed numerical analysis is carried out in the following part to show the effect of the additional layer.

Figure 2 shows the simulation result of modes' behavior in this new structure. The parameters we used are: $\lambda_0 = 1.55$ µm, $W = 20$ µm, $n_1 = 3.5$, $n_2 = 3.4$ and $n_3 = 3.0$. Square symbol ($d = 0$ µm) is actually conventional structure, where $\Delta_m > 0$. $\beta_0 - \beta_1$ becomes larger with an increase of d and Δ_m is decreased effectively when $d = 0.5$ µm (circle symbol). However, if the thickness of the additional layer keeps increasing, *e.g.*, $d = 1.0$ µm, we have $\Delta_m < 0$. This means $\beta_0 - \beta_1$ is too large and $(\beta_0 - \beta_m)/(\beta_0 - \beta_1)$ is smaller than $m(m + 2)/3$. The result shows that properly designed additional layers can decrease propagation constant errors and improve the self-imaging quality. The design process can be done by optimizing the thickness d for a chosen n_2 and then optimizing n_2 for the optimized d. Such step can be repeated 2–3 times for a satisfactory result.

In the design of MMI couplers, another important parameter is the effective waveguide width of the MMI region, W_e. The length of the MMI region and the positions of access waveguides are all determined by W_e. In conventional MMI couplers the widely used estimation of effective width $W_e \approx W + \lambda / [\pi(n^2_{\text{core}} - n^2_{\text{cladding}})^{1/2}]$

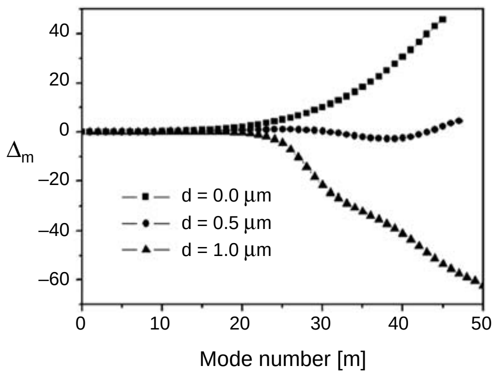

Fig. 2. Propagation constant error of guided modes in the new MMI region with difference d. The parameters are: $W = 20$ µm, $n_1 = 3.5$, $n_2 = 3.4$ and $n_3 = 3.0$, application wavelength is 1.55 µm.

cannot be applied to the new structure. Note that in conventional MMI region the effective width of the first mode W_{e0} can be accurately expressed as:

$$W_{e0} = \frac{\pi}{q_0} \tag{6}$$

where q_0 is the transverse wave number of the fundamental mode in the core layer. Considering the two additional layers in our new structure are quite thin, we still use Eq. (6) for the estimation of W_e. For a given waveguide, $q_0 = (k^2 n_1^2 - \beta_0^2)^{1/2}$ can be easily obtained by numerical analysis.

3. MMI based power splitter and optical switch

Two major applications for MMI couplers are power splitters, including uniform splitting and non-uniform splitting, and switch-type devices, including optical path switching and wavelength division multiplexing. In the following part, the two types of devices will be analyzed by exact mode analysis to show the improvements by incorporating the new structure. Exact mode analysis is a very effective numerical method for MMI couplers and is used by many researchers [6–8].

Table 2. Loss and uniformity of different 1×16 splitters.

Type	L [μm]	TE/TM loss [dB]	TE/TM uniformity [dB]
Conventional structure	578.5	0.122/0.197	0.151/0.194
Weak-confined structure [6]	3647.0	0.022 (only TE)	0.006 (only TE)
New structure	589.6	0.026/0.031	0.017/0.035

We first analyze the splitter type MMI couplers. Table 2 gives the calculated performance of a 1×16 MMI splitter with conventional structure, weak-confined structure [6] and the new structure as the MMI region, respectively. The parameters for the MMI region in the new structure are $\lambda_0 = 1.55$ μm, $W = 64$ μm, $d = 0.81$ μm, $n_1 = 3.5$, $n_2 = 3.44$, $n_3 = 3.0$. In conventional structure all the parameters are the same except $d = 0$ μm. The data for weak-confined MMI splitter are taken from [6]. The loss is defined as:

$$\mathrm{Loss} = -10\log\frac{\sum_{n=1}^{16} P_n}{P_{\mathrm{input}}} \tag{7}$$

where P_n is the power in the n-th output waveguide. And uniformity is:

$$\mathrm{Uniformity} = -10\log\frac{P_{\min}}{P_{\max}} \tag{8}$$

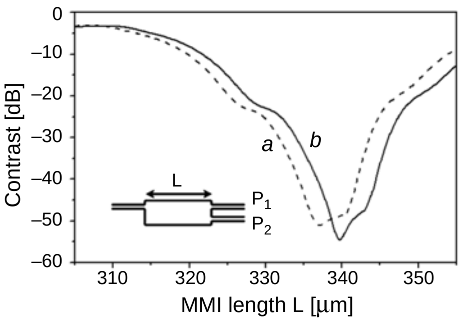

Fig. 3. Contrast of a 1×2 MMI coupler versus MMI length *L*. Curves *a* and *b* are for TM and TE modes of the new structure.

where $P_{\min}$ and $P_{\max}$ are the minimum and maximum powers of 16 outputs, respectively. As shown in Tab. 2, the TE/TM loss for the new MMI splitter is only 20% of that in conventional structure. The uniformity is improved by 9 and 5 times for TE and TM, respectively. The new MMI splitter has a similar TE loss and uniformity to that of the weak-confined MMI splitter, but the device length is 6 times shorter. This result means that the new structure can show high performance and compactness at the same time for splitter type MMI couplers.

For switch-type devices, the most important characteristic is the output contrast. A 1×2 MMI coupler is shown in the inlet of Fig. 3 as an example. A 1×2 MMI optical switch can be gained by cascading 1×2 MMI couplers and a similar 2×2 MMI coupler. If the contrast of this 1×2 MMI coupler is higher, the contrast of optical switch can be improved to the same level. Contrast of the 1×2 MMI coupler is defined as:

$$\text{Contrast} = -10\log\frac{P_2}{P_1} \tag{9}$$

Curves *a* and *b* (see Fig. 3) are the TM and TE results of the new structure, respectively. The MMI region of the new structure has $W = 10$ μm, $d = 0.34$ μm, $n_1 = 3.5$, $n_2 = 3.43$, $n_3 = 3.0$. For convenience, d and n_2 are optimized for TE mode only. Access waveguides have the same structure with the MMI region except that the core width is 2 μm. The positions of the input and output waveguides are 1.77 μm and ±1.77 μm, respectively. The contrast is 49.5 dB at 338.6 μm for both polarizations. If we only consider TE mode, the MMI length of the new structure can be set at 339.7 μm and the contrast is 54.6 dB. For comparison, the TE result of graded-index structure in [7] is 44.2 dB at 365 μm. A 10 dB improvement is gained by the new structure. The graded-index MMI region cannot decrease β_1 that much as the new structure does because its index change is not so large near the edge of the core. This simulation shows that the new structure improves the contrast of MMI couplers much while device size remains compact.

4. Conclusions

A new structure has been proposed to improve the self-imaging in MMI couplers. Two additional layers are used to increase the propagation constant difference between the first two modes. Better self-imaging is realized due to smaller propagation constant errors of the guided modes compared to conventional MMI coupler. A complete design process for the new MMI coupler is given. By incorporating the new structure, loss of TE and TM modes in a 1×16 MMI splitter is 20% of that in the conventional MMI coupler and uniformity is 5–9 times better. Contrast of a 1×2 MMI coupler using the new structure can reach 49.5 dB for both TE and TM modes. If we only consider TE mode, this value can even reach 54.6 dB which is 10 dB higher than in the previous research. The new designed MMI coupler is as compact as the conventional MMI coupler and can be applied to any kind of $M\times N$ MMI couplers.

Acknowledgements – This work was supported by the Independent Innovation Foundation of Shandong University (IIFSDU) under grant No. 2009TB015 and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry.

References

[1] FARDAD M.A., FALLAHI M., *Sol–gel multimode interference power splitters*, IEEE Photonics Technology Letters **11**(6), 1999, pp. 697–699.
[2] LAI Q., HUNZIKER W., MELCHIOR H., *Low-power compact 2×2 thermooptic silica-on-silicon waveguide switch with fast response*, IEEE Photonics Technology Letters **10**(5), 1998, pp. 681–683.
[3] PAIAM M.R., MACDONALD R.I., *Polarisation-insensitive 980/1550 nm wavelength (de)multiplexer using MMI couplers*, Electronics Letters **33**(14), 1997, pp. 1219–1220.
[4] LORENZO R.M., LLORENTE C., ABRIL E.J., LOPEZ M., *Improved self-imaging characteristics in 1×N multimode couplers*, IEE Proceedings Optoelectronics **145**(1), 1998, pp. 65–69.
[5] HUANG J.Z., SCARMOZZINO R., OSGOOD R.M., *A new design approach to large input/output-number multimode interference couplers and its application to low-crosstalk WDM routers*, IEEE Photonics Technology Letters **10**(9), 1998, pp. 1292–1294.
[6] YIN R., YANG J., JIANG X., LI J., WANG M., *Improved approach to low-loss and high-uniformity MMI devices*, Optics Communications **181**(4–6), 2000, pp. 317–321.
[7] YIN R., JIANG X., YANG J., WANG M., *Structure with improved self-imaging in its graded-index multimode interference region*, Journal of the Optical Society of America B **19**(6), 2002, pp. 1301–1303.
[8] THOEN E.R., MOLTER L.A., DONNELLY J.P., *Exact modal analysis and optimization of N×N×1 casaded waveguide structures with multimode guiding sections*, IEEE Journal of Quantum Electronics **33**(8), 1997, pp. 1299–1307.

Received September 19, 2010
in revised form December 17, 2010