Wide-bandwidth, low-waveguide-width-sensitivity InP-based multimode interference coupler designed by wavefront matching method

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Abstract: A wavefront matching design method is successfully applied to a high-index-contrast InP waveguide for the first time. Fabricated 2×2 MMI coupler exhibits a 1.6 times wider operation wavelength range than a conventional MMI coupler. This coupler has less waveguide-width sensitivity and is suitable for InP-based large-scale photonic integrated circuits.

Keywords: photonic integrated circuit, MMI coupler, wavefront matching method

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Due to the recent demand for huge transmission capacity resulting from the data traffic increase on the Internet, high-speed optical transmitters and receivers are strongly desired. However, the speed of discrete modulators and photodiodes is not increasing fast enough. Therefore, an integrated device which includes a laser diode/photodiode array is indispensable for increasing total transmission speed of the transmitters/receivers, and large-scale photonic integrated circuit (PIC) technology is being intensively studied [1, 2]. In these PICs, in addition to active components, passive waveguide components are also integrated for multiplexing/demultiplexing, polarization control, and so on. Since integrated transceivers are based on wavelength division multiplexing in many cases, passive components with large fabrication tolerance are highly desired. Their most basic building block is a 2×2 multimode interference (MMI) coupler, which, for example, is used in Mach-Zehnder interferometer (MZI)-based filters and modulators. However, the excess-loss spectrum of a MMI coupler has its minimum at the center wavelength and increases for other wavelengths, which limits the operation bandwidth. Moreover, the center wavelength is sensitive to the width of the MMI. Therefore, the wavelength and waveguide width dependence of the MMI coupler should be reduced further.

In this paper, we propose a novel 2×2 MMI coupler with a wider operation bandwidth and smaller waveguide width dependence than conventional MMI couplers for InP-based large-scale photonic integrated circuits. The MMI is designed to have an irregular waveguide outline by the wavefront matching method (WFM) [3], which generates the optimized waveguide shape and has been successfully applied to reduce the excess loss of Y-branch and X-crossing waveguides made of silica. To the best of our knowledge, this is the first time that the WFM has been applied to high-index-contrast waveguide systems. The operation bandwidth can be improved significantly and is 1.6 times larger with large fabrication tolerance than that of the conventional structure, which is beyond the limit of conventional MMI design rules.

2 Device design and fabrication

Fig. 1 shows a schematic of the 2×2 MMI coupler considered here. As shown in the upper-right inset, the waveguides have $0.3\text{-}\mu\text{m}$ -thick core layer, which is lattice-matched to InGaAsP grown on InP substrate with the band-gap wavelength of $1.3\text{ }\mu\text{m}$. Input and output waveguides are deep ridge waveguides with the width of $2\text{ }\mu\text{m}$. The two input (output) waveguides are labelled as i1 and i2 (o1 and o2). The width and length of the MMI region are $W_{\text{MMI}} = 12\text{ }\mu\text{m}$ and $L_{\text{MMI}} = 205\text{ }\mu\text{m}$. Linear tapers with the length of $50\text{ }\mu\text{m}$ are used to connect the MMI region to the input/output waveguides. The waveguide width is $2.5\text{ }\mu\text{m}$ at the MMI junction. The waveguide pitch between input (output) waveguides is $4\text{ }\mu\text{m}$. WFM-optimization was performed for this conventional MMI coupler (hereafter, called the normal structure).

In the WFM-optimization calculation, we used the finite-difference beam

Fig. 1. Schematics of WFM-designed 2×2 MMI coupler. Magnifications illustrate irregular outlines designed with WFM. Conventional MMI used in this paper for comparison is composed of straight lines.

propagation method (FD-BPM). In BPM, we used the second-order Pade approximation to treat wide-angle beam propagation. The basic algorithm for the optimization is similar to that for low-index-contrast waveguides [3]. The effective index method was applied to suppress the dimensions (three dimensions to two) to simplify the calculation.

Since one of our aims is to reduce the wavelength dependency of the MMI, we have to take into account the wavelength dependence of the refractive index of the material. We used the following equation of the refractive index as a function of wavelength λ :

$$n(\lambda) = a\lambda^2 + b\lambda + c \quad (1)$$

where $a = 0.12774$, $b = -0.49566$, and $c = 3.62969$ for InP, and $a = 0.6118$, $b = -2.1732$, and $c = 5.3017$ for the $1.3\text{-}\mu\text{m}$ InGaAsP core layer. The coefficients had been fitted from a prior experiment.

Fig. 1 shows the waveguide outlines after WFM optimization. Enlarged views of i1, o1, and both waveguide edges of the MMI region are also shown. Due to the symmetry of the structure, the structures of i2 and o2 are omitted since they have the same structures as i1 and o1. The waveguide edge has an irregular (not smooth) outline as a result of the WFM design. During the WFM design process, the waveguide widths at the edges of the input/output waveguides and the MMI junction are kept constant (2 and $2.5\text{ }\mu\text{m}$).

The waveguide geometry was patterned by photolithography, and the deep-ridge waveguides were formed by dry etching. The total ridge height is $3\text{ }\mu\text{m}$ and the lateral cladding is air.

Fig. 2 shows scanning electron microscopy (SEM) images of normal (top) and WFM-optimized (bottom) MMI couplers. The images were taken around the input of the MMI region (enclosed in red circle in the geometry shown

Fig. 2. SEM pictures of normal (top) and WFM-optimized (bottom) 2×2 MMI couplers. Red circle in lower geometry shows that which part of MMI coupler is taken for pictures.

in the lower part of Fig. 2). It is clear that a corrugated waveguide edge is formed at the MMI region of the WFM-optimized structure, whereas the waveguide edge in the normal structure is straight.

3 Performance

Green lines in the left part of Fig. 3 show calculated transmission losses of normal (upper part) and WFM-optimized (lower part) MMI couplers. For the normal structure, the transmission loss is minimum around $\lambda_c = 1.53 \mu\text{m}$,

Fig. 3. (Left) calculated and (right) measured transmission spectra of normal (upper part) and WFM-optimized (lower part) 2×2 MMI couplers.

where λ_c is the wavelength with minimum loss, and monotonically increases for other wavelengths. For the optimized structure, the transmission loss is significantly reduced and the transmission bandwidth becomes wider, showing the effectiveness of the WFM design. It should be noted that although the transmission bandwidth of the MMI strongly depends on the input/output waveguide width at the MMI junction, the waveguide geometry obtained by the WFM has the same input/output waveguide width as the original geometry, which means that the wider bandwidth does not come from a change in waveguide width.

Green lines in the right part of Fig. 3 show measured normalized transmission spectra of the normal (upper part) and WFM-optimized (lower part) MMI couplers. The transmission bandwidth for the optimized structure is clearly wider than that for the conventional one. For example, the 0.25-dB transmission bandwidth is about 50 nm for the normal MMI coupler, and it is 80 nm (1.6 times larger) for the optimized one. The differences between experiments and calculations in absolute values of loss and spectral position arise from, for example, the imperfect fabrication. As can be seen from Figs. 1 and 2, the fine pattern designed by the WFM is not fully reproduced in the fabricated device. Use of effective index model is another reason for the differences, because the out-of-plane loss can not be considered. For the normal structure, the out-of-plane loss calculated by three-dimensional BPM is 0.2 dB.

To investigate the waveguide width tolerance, we performed simulations and experiments with W_{MMI} purposely changed from $12 \mu\text{m}$. The blue and red lines in the upper part of Figs. 3 show the calculated and measured transmission spectra of a normal MMI coupler for MMI widths of 11.95, and $12.05 \mu\text{m}$ (The differences δW_{MMI} in W_{MMI} are -50 and 50 nm). Other parameters are the same as that of MMI coupler with $W_{MMI} = 12 \mu\text{m}$. The spectra are blue- and red-shifted for different MMI widths, and the experimental results show the same behavior. The position of bottom wavelength

λ_c for the measured results varies from 1530 nm ($W_{MMI} = 11.95 \mu\text{m}$) to 1550 nm ($W_{MMI} = 12.05 \mu\text{m}$). The variation of λ_c , $\delta\lambda$, with the variation of MMI width, δW_{MMI} , is theoretically given by following equation [4]:

$$|\delta\lambda| = 2\lambda_c \frac{|\delta W_{MMI}|}{W_{MMI}} \quad (2)$$

The typical fabrication error for waveguide width is less than 100 nm when an i-line stepper is used for photolithography. For $\lambda_c = 1.53 \mu\text{m}$, $W_{MMI} = 12 \mu\text{m}$, and $\delta W_{MMI} = 100 \text{ nm}$, $\delta\lambda$ is 25.5 nm, which agrees well with the experiment. The blue and red lines in the lower part of Figs. 3 show the calculated and measured transmission spectra of the WFM-optimized MMI coupler. For comparison with normal structures, $\pm 50 \text{ nm}$ was intentionally added to the position-dependent W_{MMI} of the optimized geometry, meaning that W_{MMI} is simply offset by $\pm 50 \text{ nm}$ without changing the edge geometries obtained by WFM design shown in Fig. 1. The spectral shift is very small for both calculated and measured spectra. Therefore, the WFM-optimised structure has large fabrication tolerance, i.e., it is insensitive to MMI-waveguide width, which is beyond the limit of a conventional MMI coupler [Eq. (2)].

4 Conclusion

A WFM-designed broadband 2×2 MMI coupler with reduced sensitivity to waveguide width was developed for InP-based large-scale PICs. The transmission bandwidth of the optimized coupler is 1.6 times larger and the spectral shift due to fabrication error to waveguide width is very small, exceeding the limitation of conventional MMI design rules. The results indicate the WFM design method is applicable to high-index-difference waveguides such as InP. These WFM-optimized, high-index-contrast passive components will play a key role in future large-scale PICs.