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Splitting-on-demand optical power splitters using multimode interference (MMI) waveguide with programmed modulations

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Abstract

Reconfigurable multi-channel optical power splitter is proposed and its optical properties are calculated. The device can dynamically reconfigure the number of splitting channels by providing programmed refractive index modulations on a multimode interference (MMI) waveguide. A reconfigurable 3-channel optical power splitter is designed to work as 1×1, 1×2 or 1×3 optical power splitter depending on the state of the heat electrodes using thermo-optic modulation, and the input light can be distributed to three output channels with sequential orders. The device can work in the whole C-band (1530–1565 nm) with extinction ratio better than −29.0 dB, excess loss better than −0.45 dB, imbalance better than 0.08 dB and polarization dependent loss (PDL) better than 0.14 dB. The design conception is scalable to a multi-channel splitting-on-demand optical power splitter which can divide input light to 1, 2, ..., N output channels equally by using the 3-channel reconfigurable optical power splitter as a building block.

Keywords: Integrated optics; Optical power splitter; Multimode interference (MMI); Reconfigurable

1. Introduction

In recent years, there has been a growing interest in the application of multimode interference (MMI) effects in integrated optics [1]. Compared to single-mode waveguide devices, MMI devices have the advantages in compactness, loose fabrication tolerance, polarization and wavelength insensitivity [2]. At the beginning, passive MMI devices were investigated, such as optical power splitter [3,4] and (de)multiplexer [5,6]. Later on the works on MMI have been expanded to active devices, such as optical switches [7,8], tunable optical power splitter [9,10], and variable optical attenuator (VOA) [11]. The operation mechanism of these MMI-based devices is similar. They are controlled via phase shifters by modulating the refractive indices of self-image areas in the multimode waveguide.

MMI structure enables not only single-function activities [7–11] that can be also accomplished by single-mode waveguide configurations, but also multi-functional applications and is therefore more intelligent. Intentionally manipulating phase shifters on MMI can result in switching between different activities. Thus, MMI can be regarded as the optical analog of an electronic integrated circuit to achieve programmed specific functions. In this work, a reconfigurable 3-channel optical power splitter achieved on silicon-based planar lightwave circuits (PLCs) is proposed as a multi-functional device, and it has four functions: (a) 1×1 optical power splitter; (b) 1×2 optical power splitter; (c) 1×3 optical power splitter; (d) dynamic optical power splitter. The input light can be distributed to three output channels with sequential orders by using three heat electrodes as phase shifters to achieve 1×1, 1×2 and

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1×3 optical power splitting function. The dynamic optical power splitting function could be achieved with a 4th heat electrode. By combining all the four functions, a reconfigurable N-channel optical power splitter ($N = 2M + 1$) can be achieved by cascading M stages of the reconfigurable 3-channel optical power splitter. This reconfigurable N-channel optical power splitter can increase output channels with sequential orders and divide input light to 1, 2, ..., N output channels equally. The N-channel optical power splitter would be lossless if it is integrated with an erbium doped waveguide amplifier, and could be used in FTTH (fiber to the home) or cable TV network to avoid traffic disruption of existing premises. It may be used as next-generation optical splitter-on-demand [12].

In Section 2, the operation principle of the 3-channel reconfigurable optical power splitter is introduced. A general matrix method is used to predict the properties of the device, and a three-dimensional (3D) beam propagation method (BPM) numerical simulation is used to optimize the device properties. The numerical simulation results are shown and discussed in Section 3, and a conclusion is given in Section 4.

2. Simulations

2.1. MMI theory

The MMI principle has been discussed in detail in [1]. In a two-dimensional step-index multimode waveguide, the propagation constant β_m of the mth lateral mode is expressed approximately as:

$$\beta_m \approx k_0 n_r - \frac{(m+1)^2 \pi \lambda_0}{4 n_r W_e^2}, \tag{1}$$

$$W_e \approx W_M + \left(\frac{\lambda_0}{\pi}\right)\left(\frac{n_r}{n_c}\right)^{2\sigma}\left(n_r^2 - n_c^2\right)^{-\frac{1}{2}}, \tag{2}$$

where $k_0 = 2\pi/\lambda_0$, n_r is the effective refractive index of the multimode waveguide, n_c is the effective refractive index for the lateral cladding region, W_M is the width of the MMI waveguide region, and λ_0 is the vacuum wavelength. The effective width W_e takes into account the lateral penetration depth of each mode field associated with the Goos–Hähnchen shifts at the ridge boundaries, and $\sigma = 0$ for TE modes, $\sigma = 1$ for TM modes. The beating length of the two lowest order modes L_π is defined as:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_r W_e^2}{3\lambda_0}. \tag{3}$$

A general matrix theory has been introduced in [13] to predict the properties of an $N \times N$ MMI device with single-mode input and output waveguides. For a 5×5 MMI, input light to a MMI with a length of $L_5 = \left(\frac{1}{N+1} \cdot \frac{3L_\pi}{2}\right)_{N=5} = \frac{L_\pi}{4}$ propagates to the output following the equation [13]:

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{pmatrix}_{\text{out}} = M_5 \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{pmatrix}_{\text{in}} = \frac{1}{\sqrt{12}} \begin{pmatrix} \eta^7 & \sqrt{3}\eta^4 & 2\eta^{-1} & \sqrt{3}\eta^{-8} & \eta^7 \\ \sqrt{3}\eta^4 & \sqrt{3}\eta & 0 & \sqrt{3}\eta & \sqrt{3}\eta^{-8} \\ 2\eta^{-1} & 0 & 2\eta^3 & 0 & 2\eta^{-1} \\ \sqrt{3}\eta^{-8} & \sqrt{3}\eta & 0 & \sqrt{3}\eta & \sqrt{3}\eta^4 \\ \eta^7 & \sqrt{3}\eta^{-8} & 2\eta^{-1} & \sqrt{3}\eta^4 & \eta^7 \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{pmatrix}_{\text{in}}, \tag{4}$$

where $\eta = \exp(j\pi/12)$ and $j = \sqrt{-1}$. The column vectors $(E_i)_{\text{in}}$ and $(E_i)_{\text{out}}$ represent five field amplitudes in the input and output, respectively.

Fig. 1 is the proposed device. The width of single-mode input and output waveguides is 2.5 μm, the width of the multimode waveguide is 40 μm. The length of each heat electrode is 150 μm, and the length of the multimode waveguide is 2860 μm. In order to reduce the crosstalk between different channels, input waveguide 1, 2, 4, 5, and output waveguides B, D are removed without affecting the functions of the device. Four electrodes are placed at $z = L_5$ and $z = 3L_5$, the refractive index beneath the electrodes can be modulated by either thermal optic effect or electro-optical effect. In theoretical simulation, the device is chopped to five sections and the performance of each section (with length L_5) can be predicted by Eq. (4) [13]. Certain controllable functions can be achieved by putting phase shifters between sections. If the ith shifted phase is

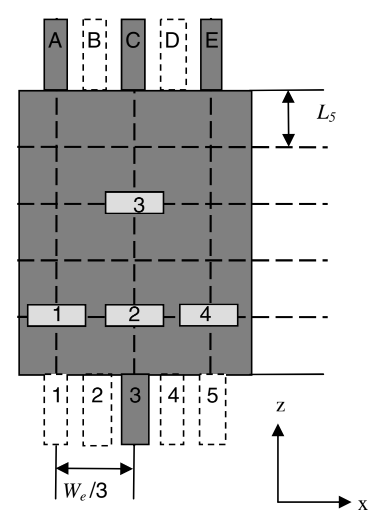

Fig. 1. Layout of the 3-channel optical power splitter including one input and three output single-mode waveguides. Values of width and length of the MMI are given in the text.