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Highly compact 2 × 2 multimode interference coupler in silicon photonic nanowires for array waveguide grating demodulation integration microsystem

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ABSTRACT

A highly compact 2 × 2 multimode interference (MMI) coupler based on silicon-on-insulator that can be used in an array waveguide grating demodulation integration microsystem is designed. The coupler is simulated using the beam propagation method. Taper waveguides are used as input/output waveguides. The footprint of the MMI region is only 6 μm × 57 μm. The excess loss is 0.46 dB, and the uniformity is 0.06 dB with transverse electric polarization when the center wavelength is 1.55 μm. The maximum excess loss is 1.55 dB in the range of 1.49 μm–1.59 μm. The simulation results show that a small 2 × 2 MMI coupler exhibits low excess loss, wide bandwidth, and good uniformity suitable for the requirements of the system on chip.

1. Introduction

The constant development of fabrication technology has given rise to the wide application of fiber Bragg grating (FBG) sensing technology [1]. In recent years, researchers have worked on FBG wavelength demodulation using a variety of signal processing schemes and algorithms to improve the signal-to-noise ratio and measurement accuracy of single-point, multi-point, or multiplexed fiber grating sensor systems. The array waveguide grating (AWG) demodulation system is a new kind of optical fiber grating demodulation scheme that is suitable for optoelectronic integration. The system diagram is shown in Fig. 1. The system consists of a light source, a coupler, an FBG array, an array waveguide grating (AWG), a photonics detector, and a signal-processing unit. The integrated microsystem has the advantages of compact form, high integration, low cost, stability, and easy implementation. Producing a silicon nanowire coupler for the FBG demodulation system is particularly important because the traditional coupler for FBG demodulation systems is large and expensive.

The system requires a four-port coupler. An X coupler, a two-mode-interference (TMI) coupler, and a 2 × 2 multimode interference (MMI) coupler can meet the system's requirements. The X coupler depends greatly on the wavelength and has a large size. The TMI coupler has a small size and can be used as an alternative to the X coupler, but it also depends greatly on the wavelength and is sensitive to polarization. MMI couplers having advantages such as compact construction, small size, simple fabrication techniques, large fabrication tolerance, low loss, and polarization insensitivity are widely used in planar lightwave circuits [2,3]. With the rapid development of integrated optics, MMI couplers have been applied in M–Z interferometer, optical switches, modulator, optical multiplexer–demultiplexer device, ring oscillators, and filters, among others [4,5]. In recent years, researchers have worked on an MMI coupler with different materials to produce a small coupler with low excess loss [6,7]. In 2006, Solehmainen designed a 2 × 2 MMI coupler based on silicon-on-insulator (SOI) with a multimode section footprint of 30.5 μm × 1394 μm and an excess loss of 0.5 dB [8]. In the same year, Dan-Xia Xu designed a 2 × 2 MMI coupler based on SOI with a multimode section footprint of 5 μm × 54 μm [9]. In 2007, Tseng designed a 2 × 2 MMI coupler with a multimode section of 24 μm × 1080 μm and a wavelength response of 1.5 μm–1.6 μm [10]. In 2009, Klamkin designed a 2 × 2 MMI coupler based on InP/InGaAsP with a multimode section footprint of 8 μm × 350 μm and an excess loss of 1.1 dB [11]. Takeda designed a 2 × 2 MMI coupler based on InP/InGaAsP with a multimode section footprint of 12 μm × 650 μm and a wavelength response of 1.53 μm–1.578 μm [12]. Singh designed a 2 × 2 MMI coupler based on SiO_2 with a multimode section footprint of 3 μm × 600 μm and an excess loss of 0.16 dB [13]. In 2011, Zhou designed and fabricated 1 × 2 MMI couplers based on SOI with splitting ratios of 85:15 and 72:28 [14].

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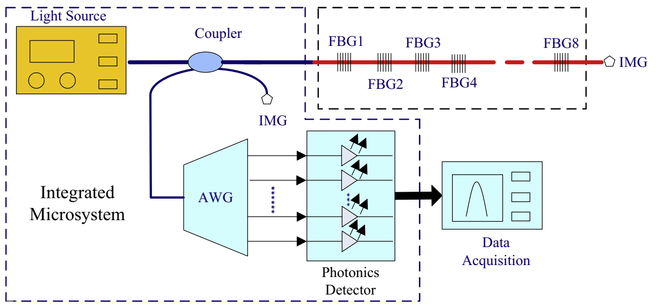

Fig. 1. Fiber grating demodulation system based on AWG.

The 2 × 2 MMI couplers mentioned above were applied in different optical devices. In this study, a 2 × 2 MMI coupler based on SOI is designed for an AWG demodulation integration microsystem. The coupler is used in the C band because the light source for the FBG demodulation system is usually in the C band. To obtain the maximum power for AWG, the splitting ratio of the coupler should be 50:50. The coupler is simulated using the beam propagation method (BPM). This study analyzes how the width of the multimode waveguide affects the properties of the coupler [15], optimizes the input/output waveguide to reduce loss, and analyzes the bandwidth of the coupler [16]. Compared with previously designed MMI, the 2 × 2 MMI coupler designed in the present study is highly compact and exhibits low loss and wide bandwidth.

2. Design of 2 × 2 MMI coupler

2.1. Self-imaging principle

The MMI coupler based on the self-imaging principle [17] has three kinds of interference mechanism: general, paired, and symmetrical. The self-imaging principle of the MMI coupler is shown in Fig. 2.

Paired interference is selected for the present paper. Input waveguides are set in the position $\pm w_e/6$ of the multimode waveguide:

$$w_e = w + \frac{\lambda_0}{\pi}\left(\frac{n_c}{n_r}\right)^{2\sigma}\left(n_r^2 - n_c^2\right)^{-\frac{1}{2}} \quad (1)$$

where w is the width of the multimode waveguide, λ_0 represents the center wavelength, $\sigma=0$ is set for TE mode, $\sigma=1$ is set for TM mode, n_c is the effective refractive index of cladding, and n_r denotes the effective refractive index of core.

According to the waveguide dispersion equation, we can obtain

$$k_{yv}^2 + \beta_v^2 = k_0^2 n_r^2 \quad (2)$$

where k_{yv} represents the lateral wave numbers of the mode $v(v=0,1,2\ldots m-1)$ in the multimode waveguide, k_{yv} can be expressed as

$$k_{yv} = \frac{(v+1)\pi}{w_e} \quad (3)$$

k_0, the wave vector in the vacuum, can be expressed as

$$k_0 = \frac{2\pi}{\lambda_0} \quad (4)$$

Considering that

$$k_{yv}^2 \ll k_0^2 n_r^2 \quad (5)$$

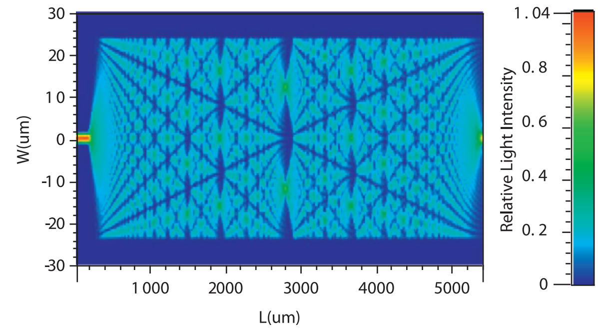

Fig. 2. Self-imaging principle of the MMI coupler.

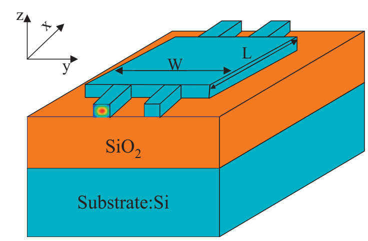

Fig. 3. Schematic illustration of 2 × 2 MMI coupler based on SOI.

From Eqs.(2)–(4), we can obtain

$$\beta_v = \left(k_0^2 n_r^2 - k_{yv}^2\right)^{1/2} \approx k_0 n_r - \frac{k_{yv}^2}{2k_0 n_r} = k_0 n_r - \frac{(v+1)^2 \pi \lambda_0}{4 n_r w_e^2} \quad (6)$$

where β_v represents the propagation constants of the lateral mode v. The first position of N mirror is in L_π/N. L_π, the coupling length of the two lowest-order modes, can be expressed as

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_r w_e^2}{3\lambda_0} \quad (7)$$

Thus, the length of the multimode waveguide can be expressed as follows:

$$L_{MMI} = \frac{L_\pi}{2} \approx \frac{2 n_r {w_e}^2}{3\lambda_0} \quad (8)$$

2.2. Design and optimization

In the present study, SOI is selected as the material during simulation. The schematic illustration of 2 × 2 MMI coupler based on SOI is shown in Fig. 3.

SOI is a prominent platform for monolithical integration with electronic circuits. Extremely small devices can be fabricated on SOI substrates because of the ultrahigh refractive index contrast between Si and SiO_2. The refractive index contrast can be expressed as

$$\Delta = \frac{n_1 - n_2}{n_1} \times 100\% = 58.1\% \quad (9)$$

where n_1 is the refractive index of Si, $n_1=3.46$, and n_2 is the refractive index of SiO_2, $n_2=1.45$.

In this paper, the coupler is simulated via BPM. The multimode waveguide width is expressed as w. The optical field and output power of MMI coupler when $w=48$, 24, 15, 12, and 6 μm are shown in Fig. 4. A greater value of w results in more model numbers that can be stimulated, clearer image points, and less excess loss. However, this also produces a larger device. Therefore, the width of the multimode waveguide is gradually reduced from $w=48$ μm to achieve a smaller 2 × 2 MMI coupler with good properties.