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Hongqiang Li
Tianjin Polytechnic University

Yu Liu
Tianjin Polytechnic University, yl751@uowmail.edu.au

Chunjiao Miao
Beijing Jiaotong University

Meiling Zhang
Tianjin Polytechnic University

Wenqian Zhou
Tianjin Polytechnic University

See next page for additional authors

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Abstract

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Authors

Hongqiang Li, Yu Liu, Chunjiao Miao, Meiling Zhang, Wenqian Zhou, Chunxiao Tang, and Enbang Li

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High-performance binary blazed grating coupler used in silicon-based hybrid photodetector integration

Hongqiang Li,^{a,*} Yu Liu,^a Chunjiao Miao,^b Meiling Zhang,^a Wenqian Zhou,^a Chunxiao Tang,^a and Enbang Li^{a,c}

^aTianjin Polytechnic University, School of Electronics and Information Engineering, Tianjin 300387, China

^bBeijing Jiaotong University, School of Electronics and Information Engineering, Beijing 100044, China

^cUniversity of Wollongong, School of Physics, Faculty of Engineering and Information Sciences, Wollongong, NSW 2522, Australia

Abstract. An efficient and high-performance binary blazed grating coupler was designed based on silicon-on-insulator (SOI) used for silicon-based hybrid photodetector integration in an arrayed waveguide grating demodulation integrated microsystem. A relatively high coupling efficiency was obtained to optimize mode matching by the finite-difference time-domain method by choosing appropriate grating parameters, including period, etching depth, and fill factor. Coupling efficiency output at 1550 nm for the TE mode reached 68%. This value was >60% in the wavelength range of 1450 to 1600 nm, specifically 71.4% around 1478 nm. An InP/InGaAs photodetector and SOI wafer were integrated by using benzocyclobutene (BCB) bonding. When the thickness of the BCB bonding layer was 440 nm, power absorption efficiency at 1550 nm for the TE mode reached 78.5%, whereas efficiency reached ~81.8% around 1475 nm. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.53.9.097106]

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1 Introduction

Photonic integrated circuits allow the implementation of multiple optical functions on a single substrate, thereby reducing the cost and size of photonic systems. These features have attracted much attention in the last decades, facilitating the development of photonic integrated circuits for telecommunication applications. Si-based optoelectronic circuits¹ have attracted increasing attention because of their compact volumes and because of the high refractive index contrast of these waveguides. The large footprint and high price of the fiber Bragg grating (FBG) demodulation systems limit the promotion and application of optical FBG sensing technology. The results of our previous works on the array waveguide grating (AWG) demodulation system, which is a new kind of optical fiber grating demodulation scheme, show its suitability for optoelectronic integration.² The system consists of an on-chip light source, multimode interface coupler,³ FBG array, 1×8 AWG,⁴ output grating couplers (GCs), and InP/InGaAs photodetector array as shown in Fig. 1(a). Among AWG output waveguides, GC has been used to diffract light from the silicon-on-insulator (SOI) waveguide into the photodetector with a spin-coated benzocyclobutene (BCB) layer in the middle. Figure 1(b) shows the schematic of a cross-section of the silicon-based hybrid photodetector.

Different material systems are integrated by using either wafer bonding or epitaxial growth. Due to the difficulty of epitaxial growth caused by the lattice constant difference between III-V semiconductors and silicon, wafer bonding, especially polymer bonding, appears easier. Polymer bonding photodetector on SOI wafer was realized by using a GC. Roelkens et al.⁵ introduced the technology for traditional GC

and InP/InGaAsP photodetector integration. The absorbed power fraction in the detector was ~70% at a wavelength of 1500 nm. Shao et al.⁶ designed a T-shaped GC used in a silicon-based hybrid photodetector integration. Power absorption efficiencies are higher, but a complex craft technique is needed. A simple process efficiently couples light in and out of the planar optical system. The binary blazed grating coupler (BBGC)^{7,8} is a promising choice because of its novel characteristics, such as high diffraction efficiency in a specified order in an integrated optical system. However, most BBGCs reported are designed for coupling between optical fibers and SOI. As is well known, for practical application, BBGCs designed for coupling between an SOI and photodetector would be more favorable. High diffractive efficiency and easy integration of an approximately vertical out coupling structure compatible with the current fabrication facilities for CMOS technology also need to be considered.

In this study, we propose an efficient and high-performance BBGC that can be used for bonding an InP/InGaAs photodetector onto an SOI wafer. This novel coupler includes four subperiods with different widths and fill factors, but with identical etching heights. Simulation results are obtained by using the finite-difference time-domain (FDTD) method.⁹ The influence of design parameters on the coupling efficiency is also discussed in detail. In silicon-based hybrid photodetector integration, high-power absorption efficiency reached 78.5% at 1550 nm and is ~81.8% around 1475 nm for the TE mode and in a broad band.

2 Device Structure and Principle

The proposed silicon-based hybrid integrated photodetector structure is shown in Fig. 2(a), in which the core is the BBGC and is shallow-etched on the top silicon waveguide of an

*Address all correspondence to: Hongqiang Li, E-mail: lihongqiang@tjpu.edu.cn

Fig. 1 (a) Array waveguide grating demodulation integrated microsystem based on silicon-on-insulator (SOI). (b) Coupling scheme of the system of the silicon-based hybrid photodetector integration.

SOI wafer. To achieve high performance, some design parameters, such as incident wavelength λ , fill factor f , number of pills in one period M , grating height H , grating period T , grating length L , Si layer thickness d_{Si} , SiO₂ buffer layer thickness d_{SiO_2} , and BCB bonding layer thickness d_{BCB} , are considered.

As shown in Fig. 2, the incident power P_{in} is divided into four parts throughout the grating: P_{up} , P_{down} , P_{R} , and P_{T} . Coupling efficiency η is defined as $\eta = P_{\text{up}}/P_{\text{in}}$.

According to the phase match condition between the gratings and waveguide mode, grating period T should be as follows:

$$T \times (N_{\text{eff}} - n_1 \cdot \sin \theta) = m\lambda \quad (m = 0, \pm 1, \pm 2, \dots), \quad (1)$$

where n_1 is the refractive index of BCB ($n_1 = 1.54$) and N_{eff} is the effective refractive index of the waveguide for the propagation mode. Therefore, when we consider the TE mode horizontal incidence and vertical coupling, i.e., $\theta = 0$, $m = 1$, and $\lambda = 1550$ nm, the grating period T can also be acquired. When T becomes long or short, the coupling efficiency has an obvious decrease due to the mode mismatch. On the basis of this original value, T is further optimized by using the FDTD method. Thus, the optimum grating period is fixed at $0.7 \mu\text{m}$.

Another important parameter is the fill factor. Every period of the binary grating is equally divided into M subperiods with the width of $\Lambda = T/M$. The fill factor of each subperiod f_i ($i = 1, 2, 3, \dots, M$) is defined as the ratio of the pillar width to the grating subperiod. The width of each pillar can be controlled to obtain the desired refractive index distribution. The basic design procedure and discrete

processing are shown in Fig. 3. We apply rigorous diffraction analysis to the localized subwavelength features within the grating period and optimize it with the simulated annealing method.¹⁰

As shown in Fig. 3, H_1 is the height of the common blazed grating. h_i ($i = 1, 2, 3, 4$) is the height of each discrete multilevel grating. H denotes the height of the BBGC. Then, the following equation is drawn:

$$h_i = \frac{1}{2} \left[\frac{H_1}{M} \cdot i + \frac{H_1}{M} (i - 1) \right] = \frac{(2i - 1)H_1}{2M}. \quad (2)$$

Based on the form-birefringence theory,¹¹ the effective index of the TE mode $n_{\text{eff}(i)}^{\text{TE}}$ in the grating is determined by the following equation:

Fig. 3 Blazed grating coupler discretization process. (a) Common blazed grating. (b) Discrete multilevel grating. (c) Binary grating.

Fig. 2 Schematic structure of binary blazed grating coupler (BBGC).

Fig. 4 BBGC structure model for three-dimensional finite-difference time-domain simulation.

$$n_{\text{eff}(i)}^{\text{TE}} = \sqrt{f_i n_2^2 + (1 - f_i) n_1^2}. \quad (3)$$

Equations (2) and (3) show that fill factors can be computed as follows:

$$f_i = \frac{\left[\frac{2i-1}{2M} \frac{H_1}{H} (n_2 - n_1) + n_1 \right]^2 - n_1^2}{n_2^2 - n_1^2} \quad (4)$$

($i = 1, 2, 3, \dots, M$),

where n_2 is the refractive index of Si ($n_2 = 3.46$). The above-mentioned assumptions and calculations facilitate the computation of all data required for constructing a ridge-width-modulated grating with localized subwavelength

features by using straightforward quantization of the conventional grating. Consequently, fill factors can be given when $M = 4$. In our structure, considering coupling efficiency and fabrication constraint, f_4 is set to 1, therefore, $H_1/H = 8/7$ can be obtained. The remaining fill factors can be fixed ($f_1 = 0.096, f_2 = 0.335, f_3 = 0.636$), and the width of each pillar can be acquired by $w_i = f_i \cdot \Lambda$. $f_4 = 1$, w_4 is obviously linked with w_1 in the next subperiod. Therefore, w_2 instead of w_1 is the narrowest pillar during one period, with a width of ~ 58 nm. w_2 is not difficult to fabricate using state-of-the-art lithography technology.¹²

For the high detector efficiency consideration of the system of silicon-based hybrid photodetector integration, the thickness of the SiO₂ buffer and BCB bonding layers as a cavity is formed by the reflection at the BCB/InP and SiO₂/Si substrate interfaces. The thickness of silicon

Fig. 5 (a) Relationships between output coupling efficiency and etching depth. (b) Relationships between output coupling efficiency and grating length. Inset: optical field of the output grating. (The grating length is 25 μm and coupling efficiency is $\sim 68\%$ at ~ 1550 nm). (c) The simulation of BBGC's far-field projection. (d) Output angle at 1550 nm wavelength. (e) Relationships between output coupling efficiency and wavelength.

dioxide of the SOI should obey the reflection condition as follows:¹³

$$d_{\text{SiO}_2} \approx (2b + 1) \frac{\lambda}{4n_{\text{SiO}_2}}, \quad (5)$$

where n_{SiO_2} is the refractive index of SiO_2 ($n_{\text{SiO}_2} = 1.45$), and b is an integer. The thickness of the BCB layer should act as an antireflection film to help light pass into the detector as follows:¹³

$$d_{\text{BCB}} \approx \frac{c\lambda}{2n_{\text{BCB}}}. \quad (6)$$

3 Analysis and Discussion

The FDTD method is selected to simulate and design the BBGC because it is a powerful and accurate method for a finite size structure. In the simulation, a commercial FDTD software, EastFDTD (from DONGJUN TECHNOLOGY Co., Ltd., Shanghai, China)¹⁴ was used. Figure 4 illustrates the three-dimensional (3-D) model of the BBGC at TE mode light around 1550 nm in a BCB environment without a detector on top. The BBGC is modeled with boundaries that have perfectly matched layers. The total coupling efficiency obtained by 3-D FDTD simulation.

The relationship between coupling efficiency and etching depth is given in Fig. 5(a). This structure has tolerances of 110 nm in etched depth because the coupling efficiency is > 50% when the etching depth changes from 50 to 160 nm. Fortunately, this range is convenient for manufacturing, and due to fabrication limitation, we choose 70 nm as the etch depth. To improve the integration density in optical circuits, the feature sizes of the BBGC must be shrunk step by

step. Overcoupling or undercoupling occurs when the grating is too long or too short, which reduces coupling efficiency accordingly. Thus, an optimum grating length must be chosen. The relationships between the grating length and efficiency are shown in Fig. 5(b). As shown in Fig. 5(b), the coupling efficiency first increases monotonously with the grating length and then only slightly changes with the grating length. Moreover, the photosensitive area of the photoelectric detector used in this study is a circle with a diameter of 55 μm . Thus, a grating length of 25 μm is chosen. The optical field of the output grating calculated by the FDTD method is shown in the inset of Fig. 5(b). At a wavelength of 1500 to 1600 nm, the peak angle is between 11.4 and 20.5 deg as shown in Fig. 5(c), which is obtained from the monitor's far-field projection. Far-field projection shows ~15.6 deg emission at 1550 nm, as depicted in Fig. 5(d). The output coupling efficiency at 1550 nm for the TE mode reached 68%, which is >60% in the wavelength range of 1450 to 1600 nm, and is 71.4% around 1478 nm, as shown in Fig. 5(e). All important parameters used in the simulation are given in Table 1.

The tapered part of the BBGC was simulated with the beam propagation method (BPM). The length of the taper required to create a transition with a negligible loss between the 450-nm-wide silicon wire waveguide and grating ($W = 10.8 \mu\text{m}$) was 300 μm , determined through linear tapering. Figure 6 shows the input waveguide with the tapered part in the BPM simulation region. Figure 6(a) displays the height-coded graph that shows the distribution of the electric field intensity along the propagation direction in the tapered part and input waveguide. The input mode is smoothly distributed across the cross-section. Figure 6(b) shows the contour map (x - z plane), 85% of which is from the input optical power. The optical field from BPM

Table 1 Design parameters of binary blazed grating coupler (BBGC).

Grating period	Etching depth	Si layer thickness	Grating length	Pillars in one period	Fill factors
$T = 0.7 \mu\text{m}$	$H = 0.07 \mu\text{m}$	$d_{\text{Si}} = 0.22 \mu\text{m}$	$L = 25 \mu\text{m}$	$M = 4$	$f_1 = 0.096$, $f_2 = 0.335$, $f_3 = 0.636$, $f_4 = 1$

Fig. 6 Input waveguide and tapered part of BBGC in beam propagation method simulation region. (a) Height-coded intensity of electrical field. (b) Contour map (x - z plane) with optical power along propagation direction.

Fig. 7 Relationships between the output coupling efficiency and the thickness of SiO₂ buffer layer.

Fig. 8 Relationships between the power absorption efficiency and the thickness of benzocyclobutene bonding layer.

Fig. 9 Relationships between power absorption efficiency and wavelength. Inset: simulation of light diffraction from the SOI waveguide toward the InP/InGaAs photodetector at 1550 nm.

simulation at the end of taper was used as the input field of the BBGC of the FDTD simulation tool.

An InP/InGaAs photodetector is bonded onto this BBGC with a spin-coated BCB layer in the middle to achieve Si-based hybrid photodetector integration. First, the SiO₂ buffer layer thickness is optimized in a BCB environment without a detector on top. Relationships between the thickness of the SiO₂ buffer layer and the output coupling efficiency for the TE mode are shown in Fig. 7. Specifically, the buffer layer and coupling efficiency oscillate because of reflection and antireflection effects. The thickness of the SiO₂ buffer layer is chosen as 2 μm, which accords with the whole arrayed waveguide grating demodulation system with a standard SOI chip.

Then, the thickness of the BCB layer is optimized to determine how much influence the thickness has on the power absorption efficiency of the InP/InGaAs photodetector. The thicknesses of the top InP layer and the lower InP layer are assumed to be 1 μm, and the thickness of the InGaAs absorbing layer is 2 μm. Relationships between the thickness of the BCB bonding layer and power absorption efficiency for the TE mode are shown in Fig. 8.

The bonding layer and power absorption efficiency also oscillate because of reflection and antireflection effects. The thickness of the BCB bonding layer is 440 nm. Relationships between wavelength and power absorption efficiency for the TE mode are shown in Fig. 9. Simulation results of light diffraction at 1550 nm for the TE mode are shown in the inset of Fig. 8; these results indicate high power absorption efficiencies. A power absorption efficiency of 78.5% is achieved at 1550 nm and is ~81.8% around 1475 nm. Power absorption efficiencies >75% are realized in a wide wavelength range of 1450 to 1600 nm. Table 2 shows a comparison of grating couplers designed in recent years.

4 Conclusion

This study proposes an efficient and high-performance BBGC used for silicon-based hybrid photodetector integration in an AWG demodulation integrated microsystem. The grating region was 10.8 μm wide and 25 μm long. High power absorption efficiency of the InP/InGaAs photodetector for the TE mode is acquired in a broad band. Power absorption efficiency at 1550 nm for the TE mode reached 78.5% and was >75% in a wide wavelength range of 1450 to 1600 nm. Notably, an 81.8% power absorption efficiency was achieved around 1475 nm. Simulation results and theoretical analysis show that the BBGC is useful for integrated optical circuits. Furthermore, it is not difficult to fabricate

Table 2 Comparison of grating couplers.

Reference (year)	Grating coupler types	Coupling application	Efficiency
15 (2009)	Fully etched grating coupler	Fiber to waveguide	49%-1.55 μm
16 (2010)	Apodized grating coupler	Fiber to chip	43%-1.53 μm
17 (2011)	Multilevel grating coupler	Waveguide to waveguide	67.5%-1.45 μm
18 (2013)	Vertical grating coupler	Fiber to waveguide	37%-1.55 μm
Present paper (2014)	BBGC	Waveguide to photodetector	78.5%-1.55 μm

this grating with conventional CMOS technology, which will be useful for integrated optical circuits. The designed BBGC is a promising material for the silicon-based hybrid integration of photodetectors because of its high efficiency and compact structure.

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Hongqiang Li received his BE, MSc, and PhD degrees from Tianjin Polytechnic University. He is a professor in the School of Electronics and Information Engineering, Tianjin Polytechnic University. His research interests lie in the area of optical fiber grating sensor demodulation and optoelectronics integration.

Yu Liu is working on her master's degree in the School of Electronics and Information Engineering, Tianjin Polytechnic University.

Chunjiao Miao is working on her doctor's degree in the School of Electronics and Information Engineering, Beijing Jiaotong University.

Meiling Zhang is a vice professor in the School of Textile Division, Tianjin Polytechnic University.

Wenqian Zhou is working on his master's degree in the School of Electronics and Information Engineering, Tianjin Polytechnic University.

Chunxiao Tang is a lecturer in the School of Electronics and Information Engineering, Tianjin Polytechnic University.

Enbang Li is a professor in the School of Physics, Faculty of Engineering and Information Sciences, University of Wollongong.