Bidirectional grating coupler based optical modulator for low-loss Integration and low-cost fiber packaging

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Abstract: We proposed and demonstrated a novel optical modulator based on a bidirectional grating coupler designed for perfectly vertical fiber coupling. The grating functions as the fiber coupler and 3-dB splitter. To observe the interference, an arm difference of 30μm is introduced. As a result of the high coupling efficiency and near perfect split ratio of the grating coupler, this device exhibits a low on-chip insertion loss of 5.4dB (coupling loss included) and high on-off extinction ratio more than 20dB. The modulation efficiency is estimated to be within 3-3.84V•cm. In order to investigate the fiber misalignment tolerance of this modulator, misalignment influence of the static characteristics is analyzed. 10Gb/s Data transmission experiments of this device are performed with different fiber launch positions. The energy efficiency is estimated to be 8.1pJ/bit.

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OCIS codes: (250.7360) Waveguide modulators; (050.0050) Diffraction and gratings; (220.0220) Optical design and fabrication; (230.1360) Beam splitters; (250.5300) Photonics integrated circuits.

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6dB) caused by process sensitive optical splitting/combining or heavy doping of millimeter-
yield commercial application. First, many of them suffer from heavy optical loss (more than

two main bottlenecks that hinder silicon modulators from high density integration and high
operating speed approaching Gigabit per second. This aroused great passion of research in
this field.

Present silicon optical modulators are mostly based on ring/disk resonator [3, 4] or Mach-
Zehnder interferometer (MZI) with a modulation mechanism of free carrier dispersion effect
[5]. Resonant-structure-based modulators can be much more compact and power efficient but
suffer from its limited optical bandwidth (around 100pm [1]). MZI based modulators, which
exhibit a broader working wavelength range, is so far more widely studied. With a fast carrier
depletion mechanism and travelling wave electrode design, several devices [6–9] can achieve
a transmission rate over 40Gb/s. In order to improve their performance further, a lot of works
have been done to optimize the diode configuration [10, 11], doping profile [12, 13] and
coplanar waveguide electrode design [14, 15].

Although the dynamic performance has been promoted a lot in recent years, there are still
two main bottlenecks that hinder silicon modulators from high density integration and high
yield commercial application. First, many of them suffer from heavy optical loss (more than
6dB) caused by process sensitive optical splitting/combining or heavy doping of millimeter-

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scale phase shifter. A large insertion loss will aggravate the link budget and limit the scalability of a wavelength division multiplex (WDM) system. Therefore, such devices are not suitable to be integrated in an on-chip photonics interconnect. Another problem is the high fiber packaging cost of present modulators. Because present on-chip light sources are highly process demanding [16–18], fiber couplers are still of great significance as an optical interface for off-chip lasers. Nano-taper spot-size converters [19, 20] are ultra-low-loss fiber couplers for on-chip optical modulator, however, they have only submicron misalignment tolerance and need additional processes such as edge polishing. Additionally, in order to increase the coupling efficiency, very expensive lensed fibers are usually required. This potentially makes the alignment quite time-consuming and increases the overall packaging cost. Grating couplers [21–23], which exhibit micron-size alignment tolerance, are another kind of widely used fiber couplers. Unfortunately, conventional grating couplers are usually designed for tilted fiber coupling in order to avoid the second order reflection. This will bring two main disadvantages. First, Boring angle-tuning makes the measurement quite time-consuming. Furthermore, costly angle-polishing [24, 25] is unavoidable in fiber packaging. Therefore, such optical interface is not optimal for rapid wafer-scale test and low-cost fiber packaging.

In this paper, we proposed and demonstrated a silicon optical modulator based on a perfectly vertical grating coupler. Unlike conventional optical modulators, this device combines the functions of coupler and modulator by using a bidirectional grating coupler, which can pull double duty as a 3-dB splitter at the input interface. Due to the high coupling efficiency and near perfect splitting behavior of the grating, this modulator exhibits good performance like low-loss and high on-off extinction ratio. Furthermore, the perfectly vertical fiber coupling interface of the device enables rapid wafer-scale test and low-cost fiber packaging. Therefore, this modulator can be a good candidate for low-loss integration and low-cost fiber packaging.

2. Device structure and principle

The 3-D schematic of the device is shown in Fig. 1. The proposed device is designed on SOI substrate. Compared to common optical modulators, the optical configuration of our device is quite different. It is based on a bidirectional uniform grating designed for vertical fiber coupling (The design details will be discussed in section3). Our device is comprised by several basic elements such as grating, mode converter, phase shifter, coplanar waveguide (CPW) travelling wave electrode and optical combiner. The operation principle can be explained as follows. When the fiber is placed perfectly vertical on the top of the grating region, the light beam launched from it is coupled in and split into two parts with opposite directions. And due to the symmetry of the grating, the split ratio will be a perfect 50:50 when the vertical fiber is placed right in the grating center. In this condition, the grating cannot only
function as a coupler but also a 3-dB splitter at the input interface. The light beam diffracted by the gratings is split equally into two waves and then compressed adiabatically to the mode sizes of single mode waveguides by two mode converters. By embedding a PN phase shifter in both single mode waveguide arms and building a CPW electrode connect, the phase of the light wave in two arms can be changed individually or simultaneously with the external electrical signal. Also, the transmission loss of the two arms can be balanced, which will help to maintain the perfect split ratio. At this point, when a $\pi$ phase shift is introduced between the light waves in two arms, a strong interference beating can be obtained at the optical combiner output end. Therefore, the output light intensity can be modulated between the state of “ON” and “OFF” with a properly driven RF signal.

3. Design and realization

![Figure 2](image.png)

Fig. 2. Characteristics of the grating. (a) Cross-sectional view of the grating coupler. (b) Simulated electric field intensity distribution of the grating cross-section. (c) Split ratio of the bidirectional grating with different fiber launch positions. (d) Comparison between the simulated and measured coupling efficiency at different fiber launch positions.

This device is designed and realized in a 220-nm-thick silicon waveguide layer on a 2-μm-thick buried oxide. As a key component of the optical configuration, the grating plays a role of both the fiber coupler and the 3-dB splitter as depicted in Fig. 2(a). Similar functions of the bidirectional chirped grating are also demonstrated in the prior work [26]. In our device, it is designed to be a uniform grating for perfectly vertical coupling, the grating period $\Lambda$ of which should fit Bragg condition:

$$\Lambda = \frac{\lambda}{N_{eff}}$$

Where, $\lambda$ is the light wavelength in vacuum and $N_{eff}$ is the effective index of the grating region. According to this basic principle, we can estimate the grating period fit for vertical
coupling. Then a series of calculations were carried out to find the optimal grating period (\( \Lambda \)), etch depth (d), filling factor (FF = \( W/\Lambda \), where W is the un-etched top silicon segment length in a period) and grating coupler length (number of periods) respectively using the two-dimensional (2-D) FDTD method. Finally, we obtained the optimal design with a grating period of 580nm, etch depth of 70nm, filling factor of 47% and 22 periods. As a design reference [27], the grating coupler width is 12\( \mu \)m. Finally, we simulated the optimal design structure using the three dimensional (3-D) FDTD calculation method. In this simulation, a Gaussian source with 1/e full width of 10.4\( \mu \)m was employed to represent the fiber mode source and the background index was set to be 1.44 to simulate the silicon dioxide cladding layer. Figure 2(b) shows the simulated electric field intensity of the fiber incidence coupling. It is clear that both the coupling and the splitting work well.

The splitting behavior of this bidirectional grating is of great significance to this modulator performance. In order to investigate the influence of fiber misalignment, we calculated the split ratio of the + x direction with different fiber launch positions (LP). As shown in Fig. 2(c), when the fiber is placed at the grating center, the split ratio is 0.5 which agrees well with our predictions. When the fiber moves towards the + x direction, the split ratio will increase drastically except at the wavelength range around 1547nm. We noted that the split ratio at 1547nm is quite close to 0.5 and remain unchanged even if the fiber has a displacement of 3\( \mu \)m. This phenomenon is caused by the strong second order reflection at the resonant wavelength. At the wavelength regions which are far from resonance, the second order reflection is relatively weak. Therefore, the split ratio there is quite stable and increase progressively with the fiber LP increasing. To explain this, it is more convenient to discuss this problem in the perspective of output coupling. Under a one-dimensional approximation, the diffracted field for each port and the fiber mode profile can be expressed as follows [28]:

\[
E_{d1}(x) = \left( \frac{D}{L_d} \right) \exp\left( -\frac{(x + L/2)^2}{2L_d} \right)
\]

(2)

\[
E_{d2}(x) = \left( \frac{D}{L_d} \right) \exp\left( \frac{(x - L/2)^2}{2L_d} \right)
\]

(3)

\[
E_f(x) = \frac{1}{w_0} \exp\left( -\frac{(x - \mu)^2}{w_0^2} \right)
\]

(4)

Where, \( D \) is the directionality of the grating structure, \( L_d \) is the grating coupling length, \( L \) is the lateral length of the grating, \( w_0 \) is the waist radius of the fiber mode, \( \mu \) is the launch center position of the fiber. Given the input-output equivalence of this bidirectional coupler, the power coupling efficiency of two arms can be given by the overlap integral of the diffracted field profile with respect to both ports and the fiber mode profile respectively. The coupling efficiency of two ports can be expressed by [27]:

\[
\eta_1 = \int \frac{\mu^{+d/2}}{\mu^{-d/2}} E_{d1}(x) A \exp\left( -\frac{(x - \mu)^2}{w_0^2} \right) dx
\]

(5)

\[
\eta_2 = \int \frac{\mu^{+d/2}}{\mu^{-d/2}} E_{d2}(x) A \exp\left( -\frac{(x - \mu)^2}{w_0^2} \right) dx
\]

(6)

In which, \( A \) represents the normalization of the Gaussian beam and \( d \) represents the one-dimensional diameter of the fiber facet. After a series of calculations, we found that Eqs. (5) and (6) can be further simplified to:
The expressions imply the dependent relationship between the coupling efficiency of two ports and the fiber launch positions. If we define $R(\mu)$ as the ratio between the power splitting to $+x$ direction and the power splitting to $-x$ direction, then it can be expressed as follows:

$$R(\mu) = \frac{S}{1-S} = \frac{\eta_2}{\eta_1} = \exp\left(\frac{2\mu}{L_d}\right)$$  \hspace{1cm} (9)

This means the function values at the fiber position of 0, 1\(\mu\)m, 2\(\mu\)m, 3\(\mu\)m will be a geometric series with a common ratio of $\exp(2/L_d)$. By curve fitting the simulated diffracted electric field, we obtained that the grating coupling length $L_d$ is about 8.46\(\mu\)m giving a common ratio of 1.267. However, according to the simulated results in Fig. 2(c), the function values of $R(\mu)$ at LP = 0, 1, 2, 3\(\mu\)m are 1, 1.597, 2.012, 2.508, which gives a ratio of 1.597, 1.259, 1.246 respectively. These results show a little disagreement with the common ratio predicted by Eq. (9). This can be possibly attributed to the position dependent second order reflection which is not taken into account in our discussions. Although such a relationship isn’t quite accurate, it still implies that a larger grating coupling length can make the grating more misalignment tolerant as a 3-dB splitter. On the other hand, a larger coupling length means a decrease of the total coupling efficiency.

In order to demonstrate our predictions, a series of calculations were carried out. As the coupling strength $\alpha$ (inversely proportional to the coupling length $L_d$) can be varied by changing the filling factor (FF) of the grating [23, 27], we simulated the coupling efficiency and splitting ratio of the grating with different FF to study the effect of the coupling length change. The grating period is also adapted to fit for Eq. (1) and ensure the maximum coupling at 1550nm for different FF. As a comparison, the FF is varied from 0.2 to 0.5. According to our simulations, when FF<0.4, the grating coupling length decreases with the increasing FF, which also coincides with the discussions in [23]. Figure 3(a) shows the dependent relationship of the total coupling efficiency on the grating filling factor. We can see that both the 3-dB bandwidth and the coupling efficiency suffer a lot as the FF decreases. When FF = 0.5, the coupling curve exhibits a flat-top filtering characteristic with a 3-dB bandwidth as large as 85nm. Such a broadband grating allows a broad working wavelength range for the
modulator based on it. Figure 3(b) gives the wavelength dependent curve of the split ratio of the grating (split ratio of the + x direction) with different FF when the fiber has a 1µm misalignment. It is worth noting that the wavelength dependent curve of the split ratio is symmetric around the resonant wavelength of 1543nm when FF = 0.5. This can be explained that both the coupling and the reflection are symmetrical respect to the resonant wavelength in this condition. As the FF changes from 0.5, the wavelength dependent relationship begins to run out of symmetry. Thus, there is some disagreement between what this simulation shows and our discussion predicts at some period of wavelength. However, for a grating coupler, the splitting performance at the wavelength range of strongest coupling is what we are most concerned about, which is shown in the inset picture of Fig. 3(b). It is clear that the curves at this wavelength range is more flat, which means a stable value of split ratio. As the FF increases from 0.2 to 0.4, the split ratio increases significantly due to the decreasing coupling length. Because the grating coupling length remains unchanged when FF increases from 0.4 to 0.5, the split ratio of FF = 0.5 almost overlapped with that of FF = 0.4. From the above discussions, we know there is a compromise between the coupling efficiency and the misalignment tolerance of the splitting behavior for this bidirectional grating. A possible method to reach a trade-off is tailoring the coupling length by chirping the gratings while not breaking the symmetry of this device. Such a work is left for future discussion.

The total coupling efficiency obtained by both 3-D FDTD simulation and measurement with fiber position of 0 and 1µm is depicted in Fig. 2(d). The measured results were obtained by normalizing the transmission of a balanced device and eliminating the insertion loss of the combiner. As can be seen from the picture, the simulation and measurement results show good agreement in curve trend. Due to the strong reflection between the grating and fiber, the measurement coupling curves show some ripples. Because of the bidirectional performance of this grating, the total coupling efficiency curves at LP = 0 and LP = 1µm almost overlapped. Compared with the simulation results, the measured coupling efficiency shows more decrease due to fiber tuning. This is because the effect of interference is not taken into account in combining the simulated coupling efficiency of the two arms. The simulation shows that the peak coupling efficiency as high as 54% can be obtained at 1570nm when the fiber is perfectly aligned. The measured peak coupling efficiency is 46%, which is a bit lower. This can be attributed to the scattering loss, Fresnel reflection loss and the polarization dependent loss.

For the other components of the optical configuration, the mode converter is designed to be a linear taper with a length of 200µm. The single mode ridge waveguide is 500nm in width and 60nm in slab thickness. In order to watch the interference and align the fiber easier, a 30µm built-in arm length difference is introduced. A Y-branch with a designed insertion loss of 0.3dB is utilized to combine the optical power in two arms.

For modulators, the phase shifters design is critical to the performance. Figure 4(a) shows the phase shifter design of our device. In order to make the device more compact, we designed a symmetrical phase shifter in which two PN junctions are parallel. The two parallel PN junctions are embedded in the upper and under waveguide of one folded waveguide arm respectively. Compared with conventional configurations, we can shorten the electrode length by half without affecting the effective phase shifter length. For our device, the phase shifter length is 800µm, which means that the effective phase shifter length is 1600µm. In order to balance the transmission loss, both arms are doped with the same length. The P-type doping concentration is $7 \times 10^{17}$ cm$^{-3}$, and the N-type doping concentration is about $5 \times 10^{17}$ cm$^{-3}$. In order to achieve an efficient overlap between P doped region and the strongest optical mode, the PN junction is designed to be located 50nm right off waveguide center which means the P doped region is 300nm wide in waveguide. The P + and N + regions are doped to a concentration of $10^{20}$ cm$^{-3}$ to minimize the contact resistivity. To avoid the optical loss caused by heavy doping, the P + and N + doped regions are located 1µm away from the ridge side.
This device was fabricated on a 200mm in diameter SOI wafer, using standard CMOS technology. Figure 4(b) shows us the microscope photo of the fabricated device. We use a nano-taper tip coupler at the device output end, which can be interfaced with a lensed fiber. The fabrication procedure is as the followings. Firstly, the ridge waveguides, gratings and channel waveguides were patterned sequentially using 193nm deep UV lithograph and dry etching. Then the P⁺, P, N, N⁺ implants for the modulators were performed, after which 1.1μm silicon dioxide cladding layer was deposited. Thirdly, the metal contact holes were patterned and aluminum electrode layer was deposited. As the last step, the CPW electrode was patterned. In order to make the alignment of fiber easier, we also designed a ring alignment mark using the electrode layer. The metal ring centered in the middle of the grating region has an inner diameter of 125μm, the same as the uncoated single mode fiber.

4. Measurement and discussion

To obtain the static characteristics of the device, we use an amplified spontaneous emission (ASE) broadband source as the light source. The optical power is fed into the chip by a polarization maintained (PM) single mode vertical fiber with cleaved facet of one end and then focused into a lensed fiber at the output end, which is connected to an optical spectrum analyzer (OSA). Figure 5(a) shows the measured fiber to fiber normalized optical transmission spectrums of the device with different fiber launch positions (LP) in the lateral direction. In this measurement, we assume the fiber position where we get the deepest notch depth as the grating center (LP = 0). Because of the flat-top filtering response of the grating coupler, the transmission curves are quite flat at the top. The fiber-to-fiber insertion loss is as low as 8dB, which includes 3.3dB grating coupling loss, 2.6dB tip coupler loss, 1dB loss of Y branch combiner and 1.1dB doping loss of phase shifter. Considering the grating is part of the modulator, the on-chip insertion loss (IL) is 5.4dB. Due to the built-in arm length difference of 30μm, the strong interference beating is clearly observed. When the fiber is placed at the right middle of the grating region (LP = 0), the extinction ratio (ER) of the interference pattern exceeds 20dB, which indicates the grating is nearly perfect as a 3-dB splitter. However, when the fiber has a displacement along the grating lateral direction, the spectrum shifts occur and the notch depth of the spectrum begins to suffer. This can be explained using the similar principle of a MZI configuration. For this quasi-MZI, the output intensity can be expressed by:

\[ I_{\text{out}} = I_{\text{in}} \left( \frac{1}{2} + \sqrt{S(1-S)} \cos \Delta\Phi \right) \]  

(10)

\[ \Delta\Phi = \frac{2\pi N_{\text{eff}}}{\lambda} \cdot \Delta L \pm \frac{2\pi N_{\text{eff}}}{\lambda} \cdot 2\Delta \nu \]  

(11)
Where, $S$ is the split ratio of the $+x$ direction, $\Delta \Phi$ is the phase difference between two arms, the first part in Eq. (11) represents the phase difference caused by the waveguide arm length difference, and the second part is due to fiber misalignment. $N_{\text{effw}}$ and $N_{\text{effg}}$ are the effective index of the single mode waveguide arm and the grating respectively, $\Delta L$ is the length difference between two single mode waveguide arms. $\Delta x$ is the fiber displacement along the $x$ direction. At the dip wavelengths, $\Delta \Phi$ should fit:

$$\Delta \Phi = (2n + 1)\pi \quad (12)$$

Therefore, the dip wavelengths can be expressed by:

$$\lambda_d = \frac{2N_{\text{effw}} \cdot \Delta L \pm 2N_{\text{effg}} \cdot 2\Delta x}{2n + 1} \quad (13)$$

When the fiber is launched at the grating center ($LP = 0$), the grating functions as a 3-dB splitter, which means $S = 0.5$. According to Eq. (10), the output intensity should reach a maximum value of $I_{\text{m}}$ and a minimum value of 0 at the constructive point and destructive point respectively. Therefore, when the fiber shifts away from grating center, the IL has a small increase and the notch depth decreases. If the fiber moves towards the $+x$ direction (more close to the longer arms as shown in the inset of Fig. 5(a)), the second part of $\Delta \Phi$ should be negative. According to Eq. (13), the dip wavelengths will shift to the smaller wavelengths, which means a blue shift of the spectrum will occur. On the contrary, a fiber move towards the $-x$ direction will cause a spectrum red shift. With the calculated waveguide group index of 3.9, the designed free spectral range (FSR) can be obtained by the following equation:

$$\text{FSR} = \frac{\lambda_1 \cdot \lambda_2}{N_{\text{gw}} \cdot \Delta L} = \frac{\lambda_0^2}{N_{\text{gw}} \cdot \Delta L} \quad (14)$$

However, if taking into account the influence of the fiber displacement, Eq. (14) should be modified to:

$$\text{FSR} = \frac{\lambda_1 \cdot \lambda_2}{N_{\text{gw}} \cdot \Delta L \pm N_{\text{gg}} \cdot 2\Delta x} = \frac{\lambda_0^2}{N_{\text{gw}} \cdot \Delta L \pm N_{\text{gg}} \cdot 2\Delta x} \quad (15)$$

Where, $\lambda_0$ is the vacuum wavelength of 1.55$\mu$m, $\lambda_1$ and $\lambda_2$ are the two dip wavelengths closest to $\lambda_0$, $N_{\text{gw}}$ is the group index of the single mode waveguide, $N_{\text{gg}}$ is the group index of the grating region. The calculated result from Eq. (14) is about 20nm. The measured results show that the FSR is 19.2nm, 19.7nm and 20.1nm at fiber launch positions of $-1\mu$m, 0, 1$\mu$m respectively. This changing trend coincides well with what Eq. (15) implies. Figure 5(b) shows how the fiber position affects the IL and notch depth of the transmission spectrum. The IL increase is no more than 1dB within the $\pm 3\mu$m range off center. Although the misalignment of fiber in the $x$ direction will deteriorate the extinction ratio, a notch depth decrease of no more than 4dB within the $\pm 1\mu$m is still acceptable for the modulator application.
By applying the static voltage through a bias tee, we obtained the transmission spectra response of the device under different driving voltages. In our experiment, the longer arm of the modulator was driven. Figure 6 shows the response spectra around the dip wavelength near 1554nm with applied voltages of 0V, 3V and 6V at different fiber launch positions of 0, −1 and 1μm respectively. Comparing the spectra response at different LP, we found one thing in common is that the IL will decrease slightly with the increasing reverse bias. This can be explained by the reduced free carrier absorption with the enlarging depletion region. On the other hand, the notch depth change with the increasing voltage is quite different for different LP conditions. When LP = 0, the unequal transmission loss of two arms caused by the reverse bias will hurt the perfect split ratio at the combiner input and then deteriorate the notch depth at the output end. When LP = −1μm, the power split ratio of the longer arm is lower than 0.5, then the reduced transmission loss in the longer arm will help to balance the optical power in two arms and thus increasing the extinction ratio of the interference pattern. On the contrary, when the fiber is placed at + 1μm, the reduced carrier absorption in the longer arm will intensify the power unbalancing of two arms, which results in a decrease of notch depth. As shown by the figures, certain misalignment will deteriorate the loss and static ER characteristic when the working wavelength is at the destructive point. The spectrum shifts about 1.5nm with a reverse bias of 3V, while shifts about 2.4nm when the reverse bias was increased to 6V. Actually it is hard to achieve a π phase shift between two arms by increasing the voltage alone. Therefore, we can only estimate the modulation efficiency of the device. The modulation efficiency is estimated to be about 3V•cm and 3.84V•cm at a reverse bias of 3V and 6V respectively. This relatively low modulation efficiency is mainly attributed to the low doping concentration of the depletion PN diode. Considering the low doping loss of only 1.1dB, this figure of merit is still acceptable.
Figure 7 shows the wavelength dependent relationship of the static ER at different fiber positions with the applied voltage varying from 0 to 6V. For unbalanced devices which are not fully anti-phased, a high extinction ratio generally means an expense of introducing an excess loss (defined as the difference between the high level intensity of the modulated optical signal and the maximum output of the transmission spectrum). When the working wavelength is approaching the dip wavelength point, the extinction ratio is increasing. However, the excess loss is getting larger too. At the wavelength range between the two destructive interference points, the extinction ratio decreases rapidly and the excess loss is at its maximum value. Therefore, even if the fiber is perfectly aligned and packaged, the wavelength range $\Delta \lambda_1$ is considered to be not suitable for working. However, when considering the possible misalignment of fiber, the unsuitable wavelength range will be enlarged. We noted that the wavelength dependent curves for different fiber LPs differ from each other significantly in the wavelength range $\Delta \lambda_2$. This means the modulator performance at this wavelength range could be very sensitive to the fiber perturbation in testing or the fiber misalignment in packaging. It is also worth noting the dependent curves at LP = 0 and LP = $-1\mu$m and the dependent curves at LP = 0 and LP = $1\mu$m almost overlapped at the two side bands out of the range $\Delta \lambda_2$ respectively. This implies this modulator performance can be maintained for at least one side band within a $\pm 1\mu$m misalignment range. Furthermore, this wavelength dependent relationship could be eliminated by using a balance-armed modulator.

In order to investigate the dynamic performance of the device, the data transmission experiment is performed with the working wavelength of 1557nm (pointed out by a black arrow in Fig. 7). Figure 8 shows the experimental setup, which is described as follows. Monochromatic light from a tunable laser is coupled to a single mode fiber. Because of the polarization dependence of the one dimensional grating coupler, a polarization controller (PC) is added to the link to ensure a TE polarization coupling. Then after amplification by a
erbium-doped fiber amplifier (EDFA) with a maximum output power of 17dBm, the light is coupled to the chip by a PM vertical fiber. A signal quality analyzer (Anritsu MP1800A) is used to provide a high speed pseudorandom binary sequence (PRBS) data stream with a pattern length of $2^{31}-1$. The output RF signal with peak to peak value (VPP) of 1.6V is mixed with a DC reverse bias of 0.8V. In order to get an enough high driving voltage swing, the mixed signal is amplified by a microwave amplifier with a typical gain of 12dB and then coupled in to the device through a microwave probe. Then the amplitude of the amplified RF signal is about 6V. In order to lower down the microwave reflection, a standard 50Ω terminal resistance was used to terminate this device. The optical output from the lensed fiber is directly fed to a digital series analyzer (Tektronix DSA 8300) with a 14GHz optical head for eye diagram test. Figure 9 shows the eye diagram measurement results. The eye diagrams with different fiber positions (LP = −1, 0, 1μm) are all given as a comparison. The dynamic extinction ratios are 3.6dB, 5.4dB and 6.1dB respectively. Comparing with the static ERs of 4.8dB, 8dB and 9dB, the dynamic ERs are a bit lower. This can be attributed to the reflection of the electrical wave caused by impedance mismatch, the transmission loss of the CPW electrode and the velocity mismatch between the optical mode and the microwave mode. Although improving the absolute speed is not the focus of this work, the device speed is still a bit lower than we expected. A possible reason is that the symmetrical phase shifter in our device may make the travelling wave electrode ineffective though it cuts the electrode length by half.

Energy consumption is one of the most important figures of merit for an optical modulator. In order to justify the adoption of optical interconnects, the energy efficiency for an optical output device should meet the demanding target of 10fJ/bit [29]. Generally the power consumption of the modulator includes the dynamic consumption and static consumption. However, the static energy consumption can be eliminated by a DC block. Therefore, we only calculate the dynamic consumption here, which can be expressed by the equation below:

$$E = C \cdot V_{pp}^2 / 4$$  \hspace{1cm} (16)

The capacitance of the device was measured with a reverse bias of 3V at 10MHz, giving a result of 900fF. Then the power consumption of our device is estimated to be 8.1pJ/bit. Generally this is too high for the on-chip optical interconnection application. An optimized CPW electrode with perfectly matched terminator and higher doping concentration are expected to be the keys to reduce the power consumption drastically [15]. Additionally, a push-pull differentially driven method will be also helpful to achieve low-power operation [30].

5. Conclusion

To summarize, we proposed and demonstrated an optical modulator based on a bidirectional perfectly vertical grating coupler. When the input vertical fiber is placed in the right middle of the grating region, the device can function much like a Mach-Zehnder interferometer based optical modulator. The device is designed to be unbalanced with an arm difference of 30μm.

Fig. 9. 10Gb/s Eye diagrams test with fiber launch positions of (a) −1μm (b) 0μm (c) 1μm.

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The 800μm phase shifters with two parallel embedded-in PN junctions give the effective phase shifter length of 1.6mm. This device exhibits a low insertion loss of 5.4dB and high on-off extinction ratio of 21dB. The modulation efficiency is within the range of 3-3.84V•cm. To demonstrate the high speed operation capability, 10 Gb/s data transmission experiment was carried out with different fiber launch positions. The energy efficiency of this modulator is estimated to be 8.1pJ/bit. Although the dynamic performance of this modulator is inferior to the state-of-the-art, the low IL of only 5.4dB (including the input fiber coupling loss) are still comparable or even better than most of the MZI based modulators. In addition, the perfectly vertical grating interface allows low-cost packaging with micron-size misalignment tolerance. Further performance improvement including both the modulation depth and operation speed need to be studied and completed in future work by optimizing the doping profile and CPW electrode design.

Acknowledgments

The authors would like to thank Anritsu and Tektronix for their instrument support and A*STAR Singapore for their expertise in device fabrication. This work is supported by the National Basic Research Program of China (Grant Nos. 2011CBA 00608, 2009CB320300, 2010CB934104, 2011CB933203), the Nation Natural Science foundation of China (Grant Nos. 61036002, 61178051, 61021003, 61036009, 61076023 and 61178081), the National High Technology Research and Development Program (“863”Program) of China (Grant Nos. 2013AA013602, 2013AA031903, 2012AA030608).