Xin Fu

The normalized transmission spectra of the 5-channel multiplexer before and after the heterogeneous integration of EAMs are shown in Fig. 6. The curves are normalized to a reference waveguide with grating couplers showing 12dB fiber-to-fiber insertion loss~~. By comparing the spectra shown in Fig. 6(a) and 6(b), one finds that the central wavelength of each AWG channel shifts a little after the hybrid integr ation, and the side lobes of the AWG are slightly broadened. This is attributed to the different top cladding of the AWG after the III-V processing. Therefore, the phase relation will be affected and finally the spectrum will change. The channel spacing of the AWG is 1.6 nm and the device has an insertion loss less than 3 dB. However,~~ after EAM integration the insertion loss varies from between − 9.3 dB to − 3.4 dB (measured after passing through the EAMs and AWG), which is mainly attributed to non-uniform insertion losses of the fabricated EAMs, although each EAM is designed to be identical. The III-V processing is expected to have no influence on the passive silicon waveguide circuit, as the etching is selective and the silicon layer is well protected beneath the oxide layer. The minimum insertion loss of the EAM at 0V bias is measured to be 1.2 dB. Figure 7 illustrates the measured static extinction ratio of the 100µm-long EAMs under different reverse biases. More than 12 dB extinction ratio can be achieved when the bias is changed from 0 V to − 2.5 V.

For the large signal modulation measurements, a tunable continuous wave (CW) laser was aligned to each channel of the AWG. A SHF pattern generator followed by a driving amplifier and a bias tee produced a PRBS signal with 2.3 to 2.6 Vpp with a DC offset of −1.5 V to −2 V to drive the EAMs. The modulated light was boosted by an erbium-doped fiber amplifier (EDFA). A narrow optical filter was inserted to remove the amplified spontaneous emission (ASE) noise generated by the EDFA. Finally, eye diagrams were obtained with a Tektronix 8300A digital series analyzer. The 20 Gb/s and 28 Gb/s eye di agram of the EAM on channel 2 are displayed in Figs. 9(a) and 9(b), respectively. Figures 10(a)-10(e) shows the eye diagrams after the AWG multiplexer at 20 Gbps for the five different channels. All EAMs exhibit clean and open eyes. The dynamic extinction ratios vary between 4.9 dB and 6.9 dB, limited by the large insertion loss of the chip in the experiment.

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We initially characterized the modulator’s static transmis-sion performance as a function of the reverse bias at 20◦C.The measured data for input wavelengths from 1285 nm to 1315 nm are shown in Fig. 2. The data is normalized by the insertion loss of the reference blank silicon waveguides. We can see that this modulator can support a wavelength window of 30 nm with an extinction ratio larger than 10 dB for a 2 V bias change although the insertion loss is increased from ˜ 9 dB to 11.5 dB towards a shorter wavelength due to the increased residual absorption. This insertion loss is higher an expected. Misalignment between the MQW layer and the silicon waveguide (an offset of ˜160 nm is found from the cross-section), the rough sidewall of the intrinsic region due to the nonuniform undercut rate for different compositions and unexpected residues attached to the tapers might be the primary reasons behind this. We then fixed the input wavelength at 1300 nm and measured the static transmission under different temperatures. As shown in Fig. 3, a high temperature leads to a similar curve as the case in Fig. 2 for a shorter wavelength. This is due to the temperature-induced red shift of the absorption spectrum. Up to 50 ◦ C, the penalty of the insertion loss is less than 2 dB. Based on the comparison of Fig. 2 and Fig. 3, we estimate that the red shift rate is slightly larger than 0.5 nm/◦C, which matches the typical shift rate of the gain peak for a semiconductor optical amplifier [11].

Large signal measurements were carried out at 40 Gb/s. The 2ˆ31-1 PRBS signal was amplified and then went through a 23 dB RF attenuator and a bias tee to get an appropriate drive voltage. The electric eye diagram captured by a DCA with a 50Ωinput impedance shows an eye amplitude of 494 mV.

Since a lumped HSEAM can be treated as an open terminator where the reflection is constructively added to the forward voltage at the end, this configuration gives a total drive voltageswing of around 1 V applied to the modulator.

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Figure 4 shows the measured transmission curves as a function of the bias at different input wavelengths. The data is normalized by the insertion loss of a reference silicon waveguide. The insertion loss of the modulator is around 4.9 dB for a wavelength larger than 1300 nm. Moving to a shorter wavelength, the insertion loss will be increased but the extinction ratio will be enhanced. For the demonstrated 30 nm wavelength window, this hybrid silicon modulator can give a static extinction ratio from 10 dB to 20 dB with a 2 V bias change.

We characterize the device loss by using a set of cascaded EAMs as shown in the inset of Fig. 2. The input optical powers reaching the two modulators are labeled as P1 and P2, respectivley. They are proportional to the photocurrents extracted from the modulators. Supposing that the two EAMs are identical, the device loss of one EAM can be approximately obtained by:

where I1 and I2 are the photocurrents simultaneously extracted from the two modulators under the same bias. Note that the loss from two tapers and the connecting silicon waveguide is included. Based on this method, we measured the bias-dependent device loss for a hybrid silicon TW-EAM with an active length of 100 μm. During the measurement, the polarization of the input light is optimized by using a polarization controller to have a maximal photocurrent. It corresponds to the TE polarization, which is verified by checking the output optical spot through a crystal polarization beam splitter.

Figure 2 shows a group of loss curves obtained at different input wavelengths from 1535 nm to 1565 nm. We can see that the unbiased loss keeps reducing until the wavelength increased to 1550 nm, implying that the static material absorption is no longer an issue at a longer wavelength. The on-chip loss at 1550 nm is around 5 dB, larger than that of the previously reported lumped device (3dB in [15]). We believe that it mainly comes from the mode transition loss in the taper and the free carrier absorption due to the proton bombardment. Increasing the taper length and reducing the implantation area could help reduce the device loss. We can also see the steady-state extinction ratio from Fig. 2. For the wavelength of 1550 nm, more than 11 dB extinction ratio is achieved with a voltage change from 2 V to 4 V. Shorter wavelength gives a better extinction ratio and a reduced optimal bias but an increased on-chip loss.

In order to evaluate the large signal performance, a non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS) pattern with a word length of 231-1, generated by an SHF BERT and amplified to a level of 2 V swing, was applied to the TW-EAM sample under a bias of 3 V. The modulated optical signal was collected by a lensed fiber and amplified by an erbium doped fiber amplifier (EDFA) followed by a 200 GHz bandpass optical filter to suppress the amplified spontaneous emission (ASE) noise. The optical signal was detected by a 50 GHz photodetector mounted on an Agilent digital communication analyzer (DCA). As shown in Fig. 5, a clear eye opening was observed at 50 Gb/s with a dynamic extinction ratio of 9.8 dB, which is sufficient for practical applications. The asymmetry of the eye diagram is due to the nonlinearity of the transfer function of the EAM, depending on the bias.

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Fig. 12 shows the measured 40-Gb/s driver and optical eye diagram. Eye opening with an RF ER of 10.5 dB was successfully observed, even with a peak-to-peak voltage as low as 0.79 V with the device under −2.2-V bias and 50- Ω termi-nation conditions [Fig. 12(b)]. Since the ON-state side has not sufficiently reached the saturation region of the extinction characteristics for the 0.79-V-swing amplitude of driver volt-age, the upper band of the eye pattern signal is large. Somewhat enlarging the swing amplitude or moving a bias point to low voltage slightly makes the swing start from the saturation region and thereby improves the eye pattern. Fig. 12(c) shows the optical eye diagram of the device under −2.05-V bias condition as an example. The upper band is reduced, however, the ER becomes 8.3 dB. The dominant reason for the remaining excess jitter compared with that of the driver signal is thought to be the optical axis fluctuation arising from the on-chip measure-ment using lensed-fiber coupling with both input and output facets. The measured bit error rate for a 40-Gb/s nonreturn-to-zero (NRZ) pseudorandom-binary-sequence pulse pattern of 27− 1 signal with 0.79-V driving voltage under −2.2-V bias is shown in Fig. 13. Error-free operation is confirmed.

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We firstly measure the EAM’s static performance with different bias at 1.55 μm, shown in Fig. 4(a). The measurement’s results is normalized to a straight waveguide with same grating couplers. The insertion loss is around 5dB, larger than the simulation results. We think that it mainly comes from the width of the intrinsic region is larger than designed values 1.5 μm, shown in Fig. 1(c). In this case, the bi-level taper coupler will excite high order modes and cause unwanted reflection during mode transformation, especially in the first level. Fig. 4(a) shows that there are two absorption variation section when we changes bias voltage. The absorption variation in reverse bias is caused by continuum transitions absorption. The extinction ratio is around 4dB with voltage changing from -1V to -2V.The absorption variation in forward bias is caused by exiton transition absorption. The extinction ratio is more than 20dB with only 100mV bias variation. Furthermore, we measure the normalization absorption spectra with bias variation. The exiton absorption peak intensity and shifts are in good agreement with the simulation results shown in Fig. 3. In the forward bias, the exciton absorption peak shifts rate is around 50nm/V, without reduce absorption intensity. So in this way, we can achieve a low driven voltage EAM in the forward bias.

Then, we measure the high speed performance of the EAM at forward bias 0.6V at 1.55 μm. a non-return-to-zero 231-1 pseudorandom bit sequence pattern generated and attenuated to a level of 50 mV swing, is applied to EAM sample via a bias bee under a forward bias 0.6V. The modulated light is coupled into a fiber though a grating coupler and amplified by an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission caused by EDFA is filtered out by a narrow optical filter. After that, we can measure the eye diagrams from a Tektronix 8300A digital series analyzer. The 1.25 Gbps eye diagram of the EAM is shown in Fig. 5(a). The dynamic extinction ratios is 6.3 dB which is twice larger than the low voltage driven silicon modulator based on tuning resonant wavelength with same peak-to-peak voltage. The energy consumption for the EAM, we use the method presented in reference [1]. Due to the cross-section of our 80 μm long EAM is same to our pervious 100 μm long modulator,13 the junction capacitance is around 116fF. The transient energy consumption is 0.29fJ/ bit. The transient energy consumption can be further reduced by narrowing the intrinsic layer width to decrease the junction capacitance. The DC energy consumption at 1.25Gbps is 110fJ/bit. The DC consumption can be reduced by increasing the modulator speed.

Fig. 5(b) shows the high speed performance for the identical EAM at reverse bias. The speed of EAM with lump electrode worked at reverse bias is limited by the RC time constant. However, for the EAM worked at forward bias, the rise and fall time is limited by the carrier lifetime in MQW. Though using modulation-doped MQW, we can shift the work point to the reverse bias. In this way, we can reduce the carrier liftetime and increase the EAM speed.