High Efficiency, High Gain and High Saturation Output Power Quantum Dot SOAs Grown on Si and applications

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Abstract: A high-performance quantum dot semiconductor optical amplifier directly grown on a CMOS compatible Si substrate is demonstrated to improve the receiver sensitivity in a filterless 60-Gbit/s NRZ transmission system over temperatures from 20°C to 60°C.

OCIS codes: (230.5590) Quantum-well, -wire and -dot devices; (250.5980) Semiconductor optical amplifiers; (250.5300) Photonic integrated circuits.

1. Introduction

Silicon photonics, benefiting from its unique material property and mature CMOS fabrication technology, has found diverse applications such as data communications, network switching, lidar, biomolecule sensing, quantum information processing and integrated gas sensors. As the silicon photonic integrated circuits become more sophisticated, integrating thousands of integrated components including the inputs/outputs (IO) couplers, passive optical devices and electro-optical modulators, the accumulated insertion loss in the optical path would be a limiting factor on further scalability. Introducing on-chip semiconductor optical amplifiers (SOA) into the photonic integrated circuit could be a natural way to address this issue. For instance, the minimum sensitivity of an optical receiver in a communication link can be dramatically improved by using the SOA as a pre-amplifier before the integrated photoreceiver [1]. Recent SOA on silicon all employ the wafer bonding technique, with decent performances achieved [2] [3].

In this work, we employ direct epitaxial growth technique to realize on-chip quantum dot (QD) SOAs directly on CMOS compatible silicon substrates [4]. Benefiting from QD's zero-dimensional carrier localization property, the devices fabricated on this platform are largely immune to dislocations introduced by the lattice constant mismatch between III/V and Si. The devices have high wall-plug efficiency (WPE), high gain and high saturation output power (SOP), comparable to that of SOAs grown on native substrates. We further leverage this high performance QD-SOA as a preamplifier in a filterless 60-Gbit/s NRZ transmission system to help enhance the receiver sensitivity over a wide wavelength range from 1280 nm to 1340 nm and temperature range from 20 °C to 60 °C. At least 15 dB photoreceiver sensitivity improvement with a minimum sensitivity of -25 dBm is demonstrated at 20 °C.

2. Device design

The InAs QD-SOA was grown directly on an on-axis (001) silicon substrate by molecular beam epitaxy (MBE) [4]. Fig. 1(a) shows the photograph of the fabricated devices. The total device length is designed to be 5000 μm to obtain a high on-chip gain, as the gain per unit length for QD is usually small due to a relatively small optical confinement factor. A tapered gain section from 5 μm to 11 μm is also adopted in order to achieve a high saturation output power. The device is 8° degree tilted with respect to the facet normal to minimize the facet reflection. A dual-layer

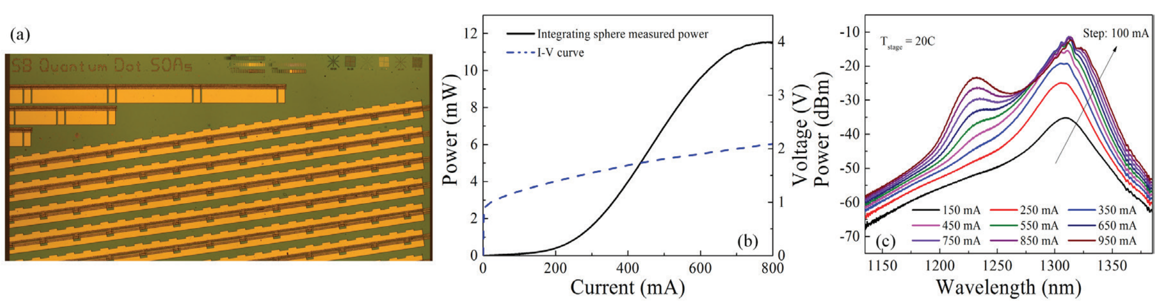

Fig. 1. (a) A photograph of the fabricated parallel Si-based QD-SOAs, 8° tilted waveguide with tapered gain section, (b) light-current-voltage curves of the reported device (light was collected from the 11 μm output port), (c) amplified spontaneous emission spectra of the device under different current injection.

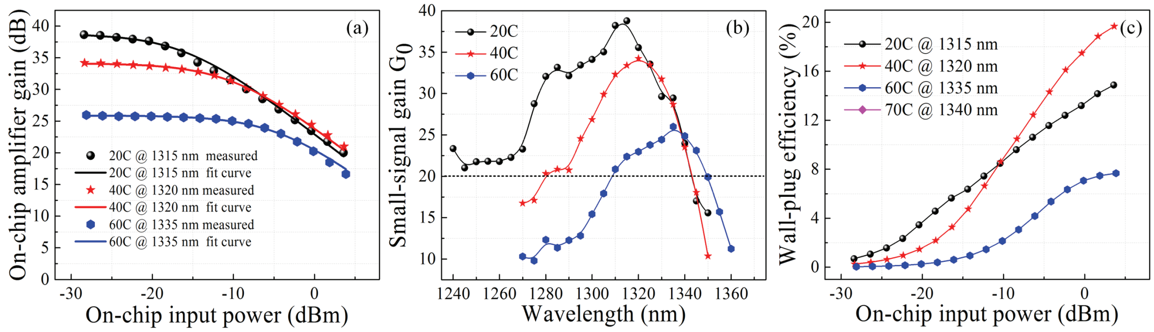

Fig. 2 Si-based QD-SOA performance comparison under different stage temperatures: (a) on-chip amplifier gain and fit curve as a function of on-chip input power, (b) on-chip small signal gain as a function of wavelength, (c) wall-plug efficiency as a function of on-chip input power (I_{gain} = 750 mA, T_{stage} = 20, 40, and 60°C, respectively).

antireflection (AR) coating (Ta_2O_5 and SiO_2) is also applied to the cleaved facet using ion beam deposition to further reduce facet reflectivity.

3. Device static measurements

The fabricated QD-SOA was tested on a stage with initial temperature of 20 °C to investigate its static performance. Fig. 1(b) shows the light-current-voltage (L-I-V) curve of the device (light was collected from the output port). No clear turn on point is observed on the L−I curves, indicating the device is operating as an SOA. The I-V curve indicates the device has a <1 Ω series resistance. Fig. 1(c) shows the amplified spontaneous emission spectra (ASE) of the device from 150 to 950 mA with a step of 100 mA. It is found that the ground state (GS) approaches saturation around 750 mA, while the excited state continues to grow, with no saturation phenomenon observed in the investigated range. The GS peak wavelength is also red-shifted due to heating. The ripple of the ASE spectra is smaller than 0.05 dB, indicating the effectiveness of the combination of tilted waveguide design and high-quality AR coating to decrease the facet reflectivity. By comparing the light intensity collected by the integrating sphere and the single mode fiber, we conservatively determine the coupling loss to be 4 dB for the input port and 8.1 dB for the output port, respectively, which will be used to calculate the on-chip gain and the other corresponding parameter.

The on-chip gain (TE polarization) measurement has been carried out by comparing the spectral peak intensity with and without the QD-SOA inserted in the test link (fiber-to-fiber gain plus the coupling losses). Fig. 2(a) shows the on-chip amplifier gain with corresponding fit curves as a function of on-chip input power at different GS gain peaks under different stage temperatures. The obtained small signal gain G_0 values for 20, 40, and 60 °C are 39, 34.1, and 25.8 dB, respectively. The corresponding SOP fitting values are 23, 24.1, and 23.1 dBm, respectively. Fig. 2(b) presents the G_0 as a function of wavelength. The achievable wavelength range, where the SOA can offer >20 dB on-chip gain, shrinks from >100 nm at 20°C to >40nm at 60°C as the temperature increases. Fig. 2(c) shows the corresponding WPE values as a function of on-chip input power, which is determined by the amplified signal power over the electrical power consumption. The values of the WPE increase monotonically with the input power at all conditions, with a maximum of 19.7% demonstrated for a 2.3 mW input power at 40 °C. Compared to the published SOA reports, the demonstrated performance of the QD-SOA on Si is among the best in terms of all critical parameters.

4. System transmission results

The experimental setup and digital signal processing (DSP) of the receiver sensitivity measurement under a range of temperatures is depicted in Fig. 3. A 60-Gbit/s optical signal is generated by an arbitrary-waveform generator (AWG)

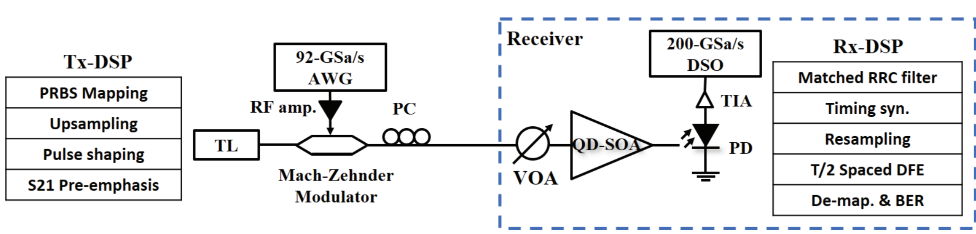

Fig. 3. 60-Git/s NRZ transmission setup. DSP, digital signal processing; PRBS, pseudo-random bit sequence; TL, tunable laser; BER, bit error ratio; DFE, decision-feedback equalizer; DSO, digital storage oscilloscope; PC, polarization controller; AWG, arbitrary waveform generator; VOA, variable optical attenuator; QDSOA: Quantum dot semiconductor optical amplifier; PD: photodiode; TIA: transimpedance amplifier.

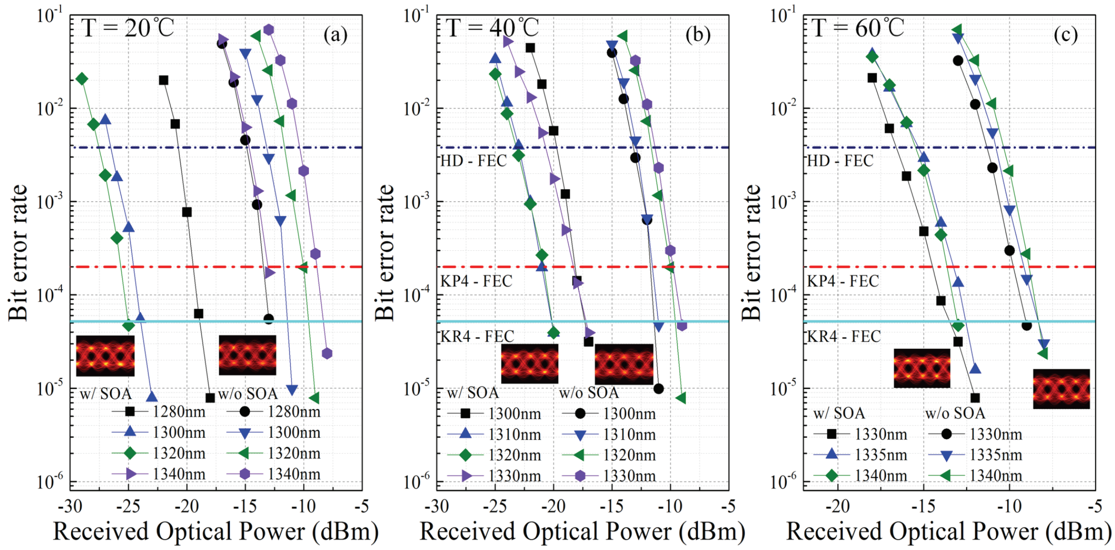

Fig. 4. Bit error rate (BER) against the received optical power for the optical receiver (PD+TIA) with and without QD-SOA under a range of temperatures including 20 °C, 40 °C and 60 °C. Eye diagrams of the receiver with and without QD-SOA are shown in the insets.

with a sampling rate of 92 GSa/s and a 30-GHz $LiNbO_3$ Mach-Zehnder modulator. A root-raised-cosine (RRC) filter with a roll-off factor of 0.12 is applied for the Nyquist pulse shaping. Pre-emphasis is implemented using an inverted linear filter. The highly sensitive receiver includes the QD-SOA, a p-i-n photodiode (PD) and a transimpedance amplifier (TIA). A polarization controller in used before the receiver for polarization alignment. DSP at the receiver side includes the matched RRC filtering, synchronization, resampling and a decision-feedback equalizer (DFE).

Fig. 4(a) shows the measured bit error rate (BER) curves with and without QD-SOA at 20 °C. The minimum receiver sensitivity with a BER of 5.2E-5 (the KR4 forward-error-correction (FEC) coding limit) is -25 dBm with a QD-SOA and -10 dBm without a QD-SOA. The receiver sensitivity is improved by at least 15 dB at 1320 nm without employing any optical filter, as we only take the input coupling loss of the QD-SOA into account. We omit the output coupling loss as well as the additional attenuation introduced into the link to protect the PD in this case. Benefiting from the wide gain spectrum of the QD, the sensitivity of PD is at least improved by 6 dB and 4 dB at the blue side of 1280 nm and the red side of 1340 nm, where the on-chip gain is already dropped by at least 10 dB from the peak. Receiver sensitivity enhancement is also observed for the QD-SOA under elevated temperatures at 40 and 60 °C as shown in Figs. 4(b) and 4(c). Minimum receiver sensitivities of -20 dBm and -13 dBm can still be obtained at higher temperatures of 40 and 60°C , respectively, at the KR4-FEC coding limit. 30 nm and 10 nm effective enhancement in operating bandwidths are observed respectively. Better receiver sensitivity is expected by improving the device-lensed fiber coupling interface to obtain a smaller coupling loss**.**

5. Conclusion

We have demonstrated an O-band QD-SOA that is directly grown on the CMOS compatible Si substrate. 19.7% wall plug efficiency, 39 dB on-chip gain, 24 dBm saturation output power, > 100 nm amplification bandwidth (gain > 20 dB) and high temperature operation are shown. By employing this QD-SOA as a pre-amplifier in a filterless 60-Gbit/s NRZ transmission system, at least 15 dB photodiode sensitivity improvement (-25 dBm minimum sensitivity) is obtained at 20 °C. Receiver sensitivity improvement over a wide wavelength range from 1280 nm to 1340 nm and temperature range from 20°C to 60°C is also reported.

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