InP-on-Si DFB Laser Diode with Distributed Reflector for Improved Power Efficiency

(Student paper)

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ABSTRACT

A heterogeneously integrated InP-on-Si DFB laser diode with an active distributed reflector is demonstrated. The goal is to improve the power efficiency of the laser, by reducing the threshold current, and obtaining similar 3-dB modulation bandwidth with similar optical output power levels to previously demonstrated lasers, at lower injected current values. The device was first fabricated as a standard single-section DFB laser, then electrically isolated in two sections with unequal lengths. The shorter section is pumped and acts as an active laser section, while the other section is not pumped and acts as an absorbing distributed reflector. The threshold current was reduced from 17 mA to 9 mA, and the bias current required to achieve similar 3-dB modulation bandwidth to previously demonstrated lasers was reduced from 100 mA to 45 mA. Transmission of a 28 Gbps NRZ-OOK signal for both a back-to-back configuration and over 2 km of NZ-DS fiber is demonstrated, with bit-error-rate below the hard-decision forward-error-correction threshold.

Keywords: InP-on-Si, distributed feedback lasers, silicon photonics.

1. INTRODUCTION

Silicon photonics is given a lot of attention in recent years, due to the possibility of dense integration and its potential for large volume production at low cost. However, the main drawback that is always associated with silicon photonics is the lack of light sources, due to the indirect bandgap of silicon. One method to realize light sources on silicon is to heterogeneously integrate III-V layer stacks on Si [1]. One could use adhesive die-to-wafer bonding for this [2], in which a III-V die is bonded on top of the silicon waveguide circuit, by means of an adhesive bonding agent such as divinylsiloxane-bis-benzocyclobutene (DVS-BCB).

The distributed-feedback (DFB) laser diode is considered the preferred light source for optical data-communication applications, due to its stable single mode behaviour, accompanied with large side mode suppression ratio. In [3], a standard single-section III-V-on-Si DFB laser was demonstrated, with threshold current of 17 mA, and 3-dB modulation bandwidth of 15 GHz at 100 mA. Obviously, power efficiency is of key importance to these devices. In [4], an InP-based DFB laser with an active distributed reflector on one end (ADR-DFB), was demonstrated. It was shown that, in comparison to a standard DFB with AR-coated facets (AR-AR), an ADR-DFB could reduce the threshold current, and produce equally high optical output power levels at lower injected current values. The reported threshold current was 10 mA for the ADR-DFB, compared to 15 mA for the AR-AR laser, which is around 34% improvement.

In this paper, we report on the performance of an integrated InP-on-Si DFB laser with an active distributed reflector on one end. We aim to reduce the threshold current values, and consequently obtain similar 3-dB modulation bandwidth and data transmission with smaller injected current values. The structure of the paper is as follows. First, we discuss the design and fabrication of such a laser. Then, we report on the static characteristics, and compare the threshold current values to the case of a standard single-section DFB laser. After that, we show the dynamic characteristics, starting from small signal modulation and ending with large signal modulation experiments, and compare the bias current values to these of [3].

2. DESIGN AND FABRICATION

The 3D- and top-view of the laser structure are shown in Fig. 1 (a, b). The light is coupled from the III-V waveguide to the silicon waveguide using an adiabatic taper on both ends. The device is initially fabricated as a standard single-section DFB laser. Later, by the end of the fabrication process, an isolation etch takes place, by wet-etching the top p-InGaAs contact layer, and dry-etching 200 nm of the p-InP layer. The laser is 500 μm long (excluding the tapers) and is cut in two sections with unequal length. The lengths of the left and the right section are around 340 μm and 140 μm, respectively. To maximize the achieved relaxation oscillation frequency f_r, it is desired to design a narrow and short laser. Therefore, the short (right) laser section of 140 μm is chosen to be pumped and modulated, compared to the 340 µm long laser in [3]. Moreover, the laser is 1.5 µm wide, as opposed to the 3.4 µm wide laser in [3]. However, as shown in Fig.1 (c), due to the V-shaped mesa structure, the width of the bottom of the p-InP is less than 1.5 µm. The tapers are electrically connected to the laser sections, each of them being 230 µm long. This suggests that the threshold current associated with the active section is less than the threshold current measured for both the active section and the taper. To measure the exact threshold current of the active section, the tapers should be electrically isolated, and only the active section should be pumped. The quantum wells are patterned 9 µm wide to avoid surface recombination. The silicon DFB grating has a period of 246 nm, with a duty cycle of 50%. The detailed fabrication process is reported in [5], and the InP layer stack parameters are the same as the ones reported in [6].

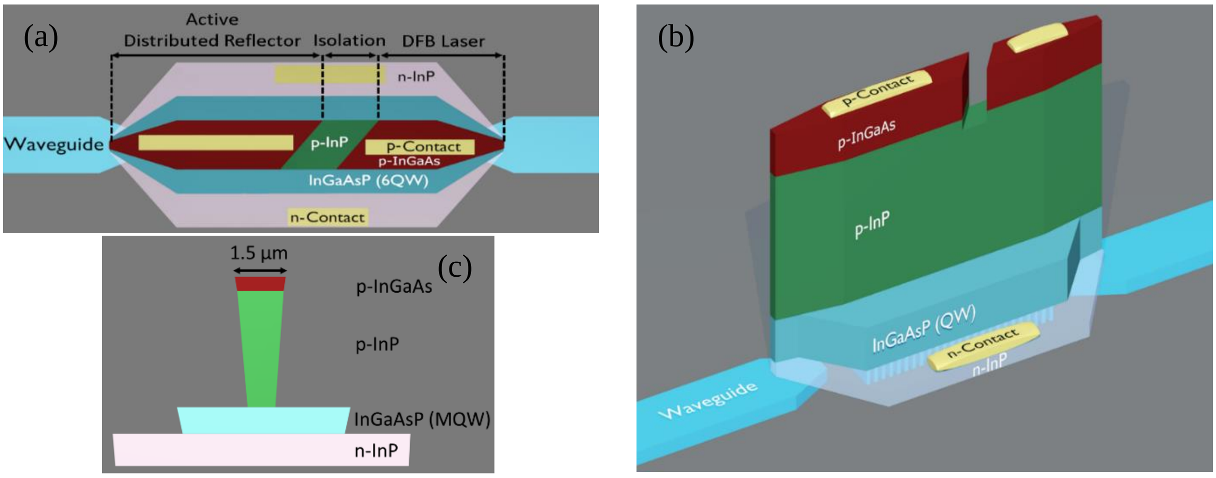

Figure 1. (a) Top- and (b) 3D-view of the fabricated laser showing two electrically isolated sections. The short (right) section is pumped and acts as a laser diode, while the long (left) section is not pumped and acts as an active distributed reflector. (c) The V-shape mesa structure

3. CHARACTERIZATION

3.1 Static characteristics

Grating couplers are used to couple the light out of the chip. The coupling efficiency of the grating couplers is -6 dB. In Fig. 2 (a), we show a comparison between the output power in the waveguide as a function of injected current. This is done in the case of: (1) injected current I_R in the right section (while I_L=0), (2) injected current while short-circuiting both sections and pumping them with a single current I_{Single} (i.e. identical to a standard single-section DFB laser). The threshold currents for each case are: (1) $I_{th, R}$= 9 mA and (2) $I_{th, Single}$ = 17 mA. As shown, $I_{th, R}$ is less than I_{Single} by 47%. $I_{th, R}$ is also 47% less than the 17 mA reported in [3]. Since the taper is also pumped, it is predicted that the actual threshold current for the right active section is around half of the measured threshold current value. The maximum output power in the waveguide was 3.55 mW for the case (1), higher than the value reported in [3] and 6 times higher than for the case (2) as shown in Fig. 2(a), measured at the same bias current. Fig. 3 (b) shows the single mode behaviour of the laser operating at 1540.5 nm with I_R = 45 mA.

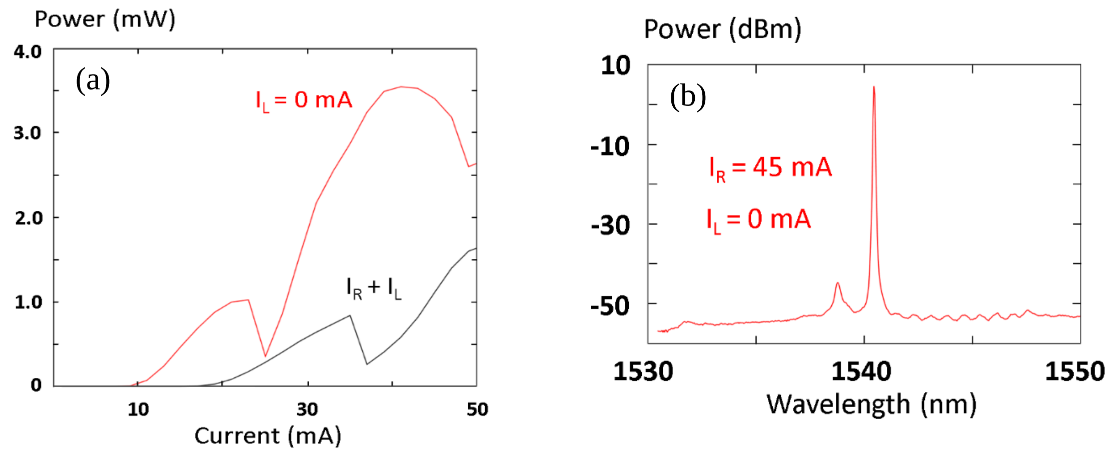

Figure 2. (a) Optical output power P_{opt} in the waveguide as a function of the current in the right section (I_R for I_L=0 mA), and as a function of the current injected in the complete laser length by short-circuiting both sections I_{Single}. (b) The spectrum of the laser showing single mode operation at 1540.5 nm for I_R = 45 mA and I_L = 0 mA

3.2 Small signal modulation

The small signal modulation response S_{21} was obtained using a vector network analyzer. The right section is modulated at two different bias currents, while the current in the left section $I_L = 0$ mA. The measured 3-dB modulation bandwidth is nearly 15 GHz, and is obtained at $I_R = 45$ mA, a 55% lower bias current than used in [3] to obtain about the same bandwidth. The drop in S_{21} at low frequencies was also observed in previous devices and is attributed to the extra modulation from the taper at low frequencies, acting as an external amplifier. The impact of this low frequency roll-off in data transmission can be minimized by reducing the word length.

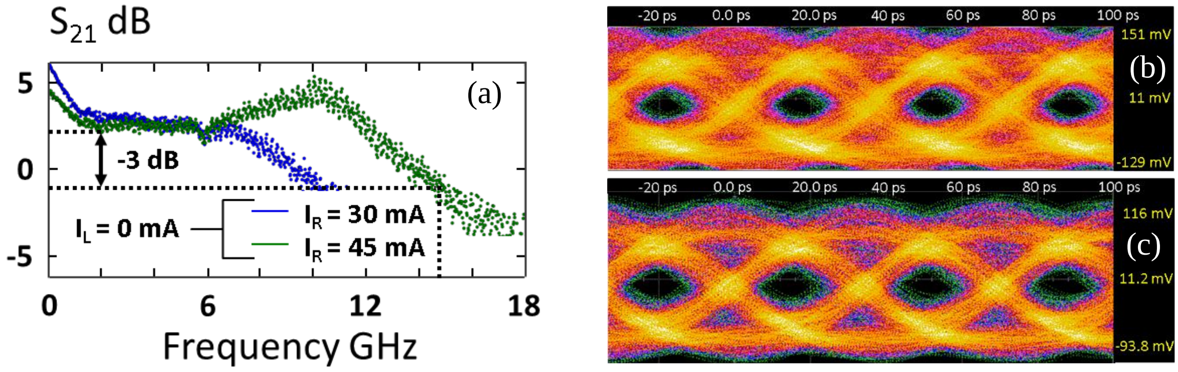

Figure 3. (a) Small signal modulation response S_{21} for two different injected currents into the right section I_R while $I_L = 0$ mA. The 3-dB modulation bandwidth is nearly 15 GHz for $I_R = 45$ mA. (b, c) Eye diagrams for transmission at 28 Gbps in the back-to-back configuration and with a 2 km NZ-DSF link for a pattern length of 2^7-1

3.3 Large signal modulation

A large signal modulation experiment was performed using an arbitrary waveform generator (AWG). After amplifying the signal using a 50 GHz RF electrical amplifier, the RF electrical signal generated by the AWG is applied to the right laser section. To boost the output optical signal, a C-band Erbium Doped Fiber Amplifier (EDFA) is used. The amplified spontaneous emission is filtered out using an optical tuneable filter. Finally, a photodetector converts the signal back to an electrical signal, which is fed to a real-time oscilloscope. Transmission of a 28 Gbps NRZ Pseudorandom-Binary-Sequence (PRBS) with a word length of 2^7-1 was verified. A voltage swing of 1.13 V_{pp} is applied to the device, at a bias current $I_R = 45$ mA. Fig. 3 (b, c) shows the eye diagrams for back-to-back configuration and after transmission over a 2 km long NZ-DSF link. The recorded BER with the 2 km long NZ-DSF is less than $1.0 \cdot 10^{-6}$.

4. CONCLUSIONS

An InP-on-Si DFB laser diode with active distributed reflector was demonstrated. In comparison to a standard single-section DFB laser, the threshold current is reduced by 47%, from 17 to 9 mA. The bias current required to obtain a 3-dB modulation bandwidth of 15 GHz was 45 mA, which is 55% less than the current required to obtain the same bandwidth in a single section DFB [3]. Finally, transmission of a 28 Gbps NRZ-OOK signal is shown for both a back-to-back configuration and for a 2 km long NZ-DSF link with BER below the 7% HD-FEC threshold.

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