Demonstration of Self-Pulsating InP-on-Si DFB Laser Diodes

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***Abstract*— Self-pulsating InP-on-Si two-section DFB laser diodes are demonstrated. The lasers have stable controllable pulsation frequencies at 12.5, 25 and 40 GHz, RF spectral widths of around 40 MHz and 15 dB extinction ratio.**

***Index Terms*— Integrated Optics Devices, Distributed Feedback Lasers, Semiconductor Lasers, Optical Devices, Silicon Photonics.**

I. Introduction

As a result of the CMOS compatible fabrication technology and the low material cost, Silicon-on-Insulator (SOI) is emerging as the platform of choice for the implementation of photonic integrated circuits (PICs). However, as silicon is an indirect bandgap material, it cannot be used to make lasers. This motivates the integration of III-V materials on silicon to create laser diodes.

InP-on-SOI distributed feedback (DFB) laser diodes have already been used for various applications e.g. for high-speed direct modulation [1] and as tunable lasers [2]. The stable single mode operation, relatively simple structure and small footprint make DFB lasers attractive for many applications. In this paper, we discuss the implementation of self-pulsating III-V-on-SOI heterogeneously integrated DFB laser diodes. Such self-pulsating laser diodes can be used for the generation of optical microwave carriers or for the generation and/or extraction of optical clock signals. There are two mechanisms responsible for the self-pulsations. The first one is referred to as dispersive self-Q-switching [3], and it was first reported in [4]. This mechanism can result in self-pulsations at very high frequencies e.g. 64, 80 and 100 GHz [5-6]. The second mechanism is caused by Longitudinal Spatial Hole Burning (LSHB) [7-9].

In this paper, different self-pulsating InP-on-SOI two-section DFB laser diodes are demonstrated, with pulsation frequencies of 12.5, 25 and 40 GHz, RF spectral widths of 40 MHz and 15 dB extinction ratio.

II. Theory

The theory behind both self-pulsation mechanisms of two-section DFB lasers is comprehensively explained in [6-11]. In the first mechanism, dispersive self-Q-switching, each laser section could be thought of as a stand-alone laser, with a different stop-band due to a different effective index n_e in each section. The self-pulsation frequency is determined by the difference between the stopband width and the detuning of the Bragg wavelengths in both DFB sections [10]. If the stop-bands of both sections overlap, the lasing peak of one section coincides with the negative slope in the reflection spectrum of the other section, causing instability. This instability is manifesting itself in a variation of carrier and photon densities, which changes the effective indices, and shifts the stop-bands. The resulting power variation creates a periodic short-pulse train in the time domain. Intuitively this phenomenon results from the locking of the beating between two laser lines.

The second mechanism is caused by LSHB [7-9]. The introduction of carrier perturbation mechanisms throughout the laser, e.g. an asymmetrically-located $\lambda/4$ phase shift in the case of DFB laser, causes asymmetry in the carrier distribution, which causes different effective indices and Bragg wavelengths across the laser. This perturbation is encouraged by biasing the sections at high and different currents. Multi-mode operation is a noticeable result of this phenomenon.

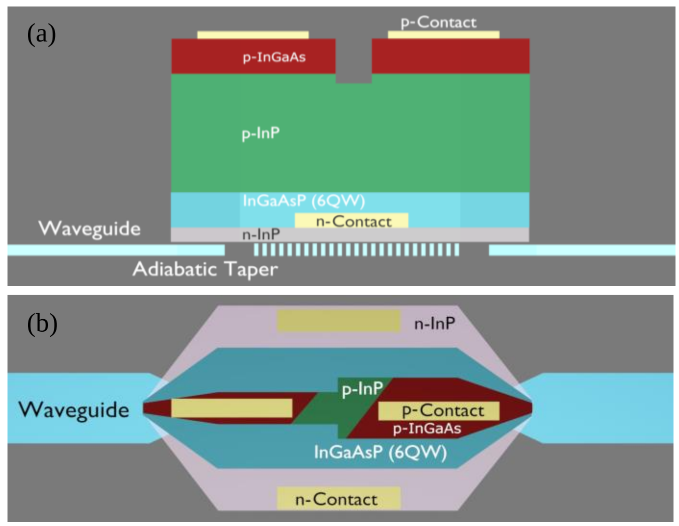

Fig. 1. a) Side-view of the demonstrated laser, with two electrically isolated sections having different widths, and b) top-view.

III. Design and Fabrication

The III-V epitaxial stack for the self-pulsating DFB laser is adhesively-bonded [12] on the SOI using DVS-BCB (divinylsiloxane-bis-benzocyclobutene). The stack is patterned to resemble the structure in Fig.1. An adiabatic taper is used to couple the light from the III-V mesa to the silicon waveguide. In the center of the mesa, all the p-InGaAs and a small part of the p-InP is dry etched, to create two electrically isolated laser sections. This raises the resistance between the two p-contacts to more than 3000 Ω. The cut has an angle of 45° to reduce reflections caused by the discontinuity in the top layer. The quantum well layer is wider than the mesa to reduce surface recombination. The fabrication process is comprehensively explained in [13-14].

We investigate two 500-µm-long lasers, with different mesa width in each section. The different width creates different effective index (n_e). This introduces a wavelength shift ($\Delta\lambda_B$) of the stop-band of one section with respect to the other. Typical stop-band widths of similar lasers were shown to be around 4 nm [1]. Therefore, a $\Delta\lambda_B$ of around 4 nm is desired to overlap the edges of the stop-bands. This requires a Δn_e of around 0.01. With the mesa width of one section being 4 µm, we estimated the required mesa width in the other section for such Δn_e to be between 2 and 2.5 µm. We therefore investigated two two-section DFB lasers (referred to as L_1 and L_2, respectively) with mesa widths being 2.5 - 4 and 2 - 4 µm respectively. There is also an asymmetrically-located λ/4 phase-shift section in the left hand section of L_2 to demonstrate LSHB-type self-pulsation.

IV. Characterization

The lasers under study have a threshold current of around 2x12 mA. To search for the self-pulsation peaks, a 2-dimentional current scan with 1 mA increment for both laser sections was performed. This unveiled stable peaks (moving in around 200 MHz range due to temperature variations) with RF spectral widths of around 40 MHz, at 15 °C. Controlling the current, and/or the temperature, shifts the peak over a few GHz, before it vanishes. Fig.2. shows the self-pulsation at around 12.5, 25 and 40 GHz measured using a Keysight N9010A EXA Electrical-Spectrum-Analyzer. The extinction ratio of the pulsations is around 15 dB. The required current combinations (which are sensitive to fabrication variations) and the used laser are summarized in Table.1.

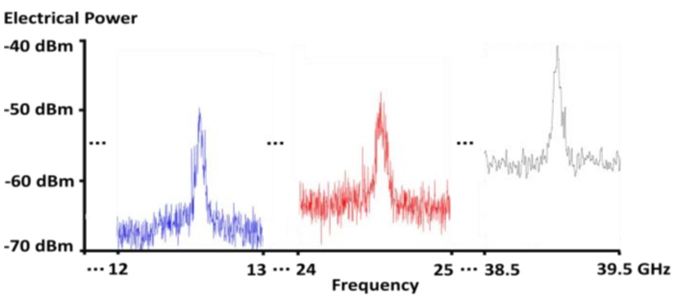

Fig. 2. RF spectra of the self-pulsations at around 12.5, 25 or 40 GHz, with spectral widths of around 40 MHz. The noise-floor level of the ESA increases for higher frequencies.

To demonstrate the stop-bands overlap, the optical spectrum at two bias current combinations in L_1 is shown in Fig.3.a. One section is biased at the self-pulsation current (Table.1), while the other section is biased close to threshold. The stop-bands of both sections overlap. When biasing both sections at the correct combination, self-pulsation happens (Fig.3.b). Two peaks spaced by 0.31 nm are produced, which correspond to a self-pulsation at 38.75 GHz.

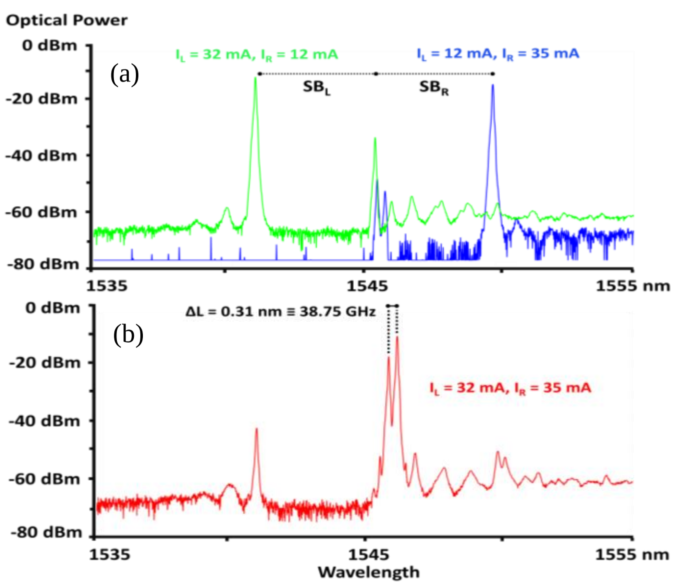

Fig. 3. a) An overlap of the stop-bands (SB_L and SB_R) is clear for each laser section when the other section is biased close to threshold, b) two peaks spaced by 0.31 nm are produced, which corresponds to 38.75 GHz.

Table.1: Summary of the current combinations to produce the self-pulsation

Laser	Pulsation Frequency (GHz)	I_L (mA)	I_R (mA)
L_2	12.5	45	19
L_2	24.5	43	23
L_1	38.75	32	35

In the same way, the optical spectrum corresponding to the 12.5 GHz pulsation is shown for L_2 in Fig.4. We notice that the stop-bands of the laser sections don't overlap. However, the self-pulsation is seen in the lasing-peak split of 0.096 nm, which corresponds to 12.5 GHz. This is due to the carrier perturbation caused by the asymmetrically-located phase-shift, which creates different Bragg wavelengths across the laser. This instability and the observed multi-mode operation agrees with the explanation in [9].

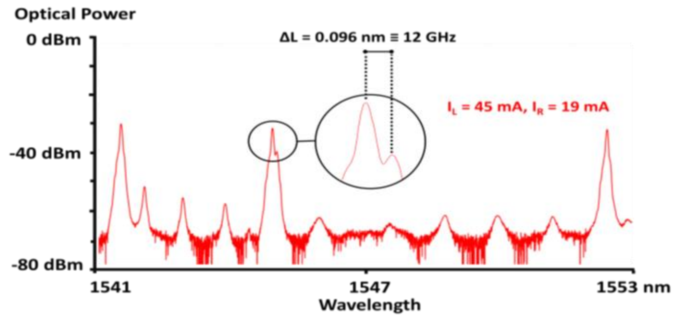

Fig. 4. Self-pulsation happens due to spatial hole burning, resulting in the split of two peaks spaced by 0.096 nm, which corresponds to 12.5 GHz.

V. Conclusion

Self-pulsating InP-on-Si two-section DFB laser diodes, with a wide range of pulsation frequencies were demonstrated. The RF spectra have widths of 40 MHz, and an extinction ratio of 15 dB. Choosing the pulsation frequency can be done by choosing the correct current values and/or controlling the temperature. Locking the pulsation frequency to a specific frequency by applying a small RF-voltage is being investigated now.

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