Wideband chaos in hybrid III-V/silicon distributed feedback semiconductor lasers under optical feedback

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ABSTRACT

The dynamics of hybrid III-V/silicon Distributed Feedback (DFB) semiconductor lasers were studied under a combination of long and short feedback conditions. The allure of silicon photonics lies in the potential for production of low-cost, compact circuits that integrate photonics and microelectronics on a single Photonic Integrated Circuit (PIC)[1,2]. It has been recently demonstrated that such tight integration of optical components increases the risk of short-cavity reflections within a PIC that can destabilize the laser[3]. Using novel III-V/Si DFB lasers, we simulated such reflections by coupling the laser using a cleaved fiber, thus creating a free-space cavity between the laser and the fiber tip. The sensitivity of such devices to this short feedback and its phase was then studied by comparing measurements performed with either a cleaved or a lensed anti-reflection-coated fiber, and revealed the modal and temporal dynamics created by the short-cavity feedback. A long fibered feedback cavity was then created within the experimental setup to study the route to chaos of the devices under long feedback, as well as the impact of the short feedback's phase on this route. Due to a relatively high relaxation oscillation frequency of 15 GHz and the destabilization of the laser by both the short cavity and the long one; very wide chaos can be achieved when combining both types of feedbacks. This study thus reveals the impact parasitic reflections can have on a DFB laser's characteristics in a PIC, as well as how these reflections can affect the dynamics of the laser in a well-known optical feedback scheme.

Keywords: Photonics Integrated Circuits, III-V materials, Silicon-on insulator, optical feedback,

1. INTRODUCTION

Integrated components of a PIC can experiment unintentional reflections from various possible interfaces such as active and passive transitions, waveguide crossings, regrowth interfaces, or process imperfections. Unwanted reflections can travel back into the laser cavity resulting in a variety of nonlinear dynamics arising under five distinct regimes, depending on feedback strength and cavity length[4]. In most cases, the feedback levels corresponding to such reflections can cause deleterious effects such as linewidth broadening, mode hopping, and/or increased amplitude noise which is detrimental to most data communication systems[4]. Lasers integrated with a silicon photonic chip are particularly susceptible to these deleterious effects, as the low loss waveguides and high index contrast inherent to the platform are particularly conducive to the creation of strong unintentional feedback. Although silicon based on-chip isolators have been recently demonstrated with maximum isolation ratios up to 32 dB[5], the integration of an isolator significantly increases cost, process complexity, overall chip/system size, and total loss within the system.

This paper aims at analyzing the non-linear dynamics of a hybrid III-V DFB semiconductor laser when subject to a variation of optical feedbacks conditions. With the recent developments of PIC, these lasers have attracted large attention because of their vast potential in increased performance advantageous to a wide range of applications. Various domains such as optical communication, optical signal processing, sensing and the exponentially increasing demand for higher data communication rates will benefit of the drastic reduction of the size of integrated photonics, electronic circuits and embedded systems[3]. Complex dynamical behavior in the emission intensity, induced even by weak optical feedback can alter the performance of communication systems by reducing the signal to noise ratio. At the same time, these complex phenomena can be utilized for chaos communication encryption and random number generation[6], two fundamental features necessary to achieve secured communication. Therefore, this nonlinear, unstable and aperiodic

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characteristic of chaotic communication has numerous features that makes it attractive for communication use[7,8] and potentially for other unknown applications that will most likely be identified as experimental achievements of future research in this area develop.

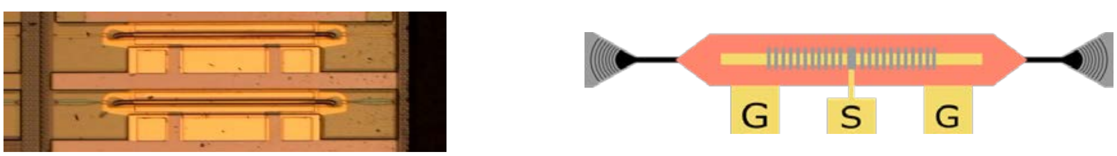
In interband semiconductor lasers, the route to chaos usually occurs via the undamping of the relaxation oscillations. However, the bandwidth of the chaotic waveform is inherently limited by the relaxation oscillation frequency (ROF) of several GHz[7]. The bandwidth can be enhanced by using strong optical injection from another semiconductor laser[9,10] or by designing a laser structure with a larger ROF, which is the case presented in this paper. In order to determine the prospective and increased capability that can be offered by PICs, the chaotic dynamical properties and sources of parasitic reflections inside the laser cavity must be fully understood.

The DFB laser under study is first presented in section 2, and in particular the achievable values of ROF. In section 3, the dynamics of the device under a short delay feedback are studied, revealing how relaxation oscillations are affected in terms of amplitude and frequency. The route to chaos under long delay feedback is then studied in section 4, with and without the effect of short feedback on the ROF, to reveal not only how wide the chaotic spectrum is but also how it can be affected by the short feedback.

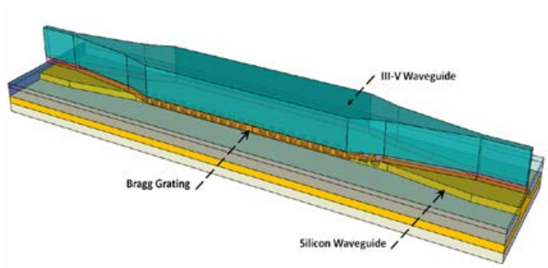
2. DESCRIPTION OF THE LASER DEVICE

2.1 Structure and Design

The device studied is a 1 mm-long hybrid III-V DFB laser. Fig. 1 shows the schematics of the DFB structure. As described in[2], the hybrid III-V Silicon-on Insulator (SOI) DFB laser is fabricated using a III-V structure bonded to processed silicon waveguide. To ensure single-mode operation, a 50 nm-deep and 600 µm-long Bragg grating with a quarter-wavelength phase shift in the center is etched on the silicon waveguide, below the III-V material. The strength of the grating is chosen such that the product $K \times L_{bragg}$ is of a few units, and the period of the grating is 240 nm. The light is coupled from silicon to the III-V material with adiabatic tapers, and outcoupled using Vertical Bragg Gratings (VBG) on both side of the device. The VBG couples the light out of the laser with an angle of 80° from the waveguide, and light must thus be coupled vertically using a fiber positioned above the laser, with a 10° angle from the normal to the laser's surface.



(a)



(b)

Figure 1. a) Top view and b) cross-sectional schematics of the hybrid laser.

2.2 Characterizations

Fig. 2 presents the experimental set-up used to characterize the device. In this case, the laser was isolated from the set-up and the light from the DFB laser was coupled using an anti-reflection (AR) coated lens-ended fiber. 10 % of the light was used to monitor the coupled optical power with a power-meter (PM). The remaining 90% was amplified using an Erbium-doped fiber amplifier (EDFA) with a fixed output power of 10 dBm, and equally split between optical and electrical spectrum analyzers. The EDFA was only required to increase the accuracy of the ROF measurements.

Fig. 3(a) presents the light-current characteristic of the free-running device measured at 20 °C, where the threshold of the laser is of 45 mA. The optical spectrum in Fig. 3(b) was obtained using an OSA with a resolution of 20 pm. It can be noted that the dominant side modes of the DFB laser are well rejected, with a side-mode suppression ratio close to 50 dB and visible relaxation oscillations. Fig. 3(c) unveils large ROFs in this device with respect to the bias current, with a value close to 14 GHz measured above 3 times the threshold.

Overall, this device offers much more stable operation than the multi and single-mode devices studied in[3] since no temporal or modal instability were observed in the free-running laser. In both these devices as well as the one under study, the optical cavity was created using Bragg reflectors in the optical waveguide. However, in our previous study the Bragg reflectors were located in regions of the Si waveguide, which was not covered with active material. Also, the tapered region where light was coupled between Si and III-V waveguides was believed to act as an optical interface creating reflections within the optical cavity. For the DFB lasers, while the Bragg grating is still in the Si waveguide, the optical cavity is confined to the region where Si and III-V overlap, and the taper regions are thus outside the cavity.

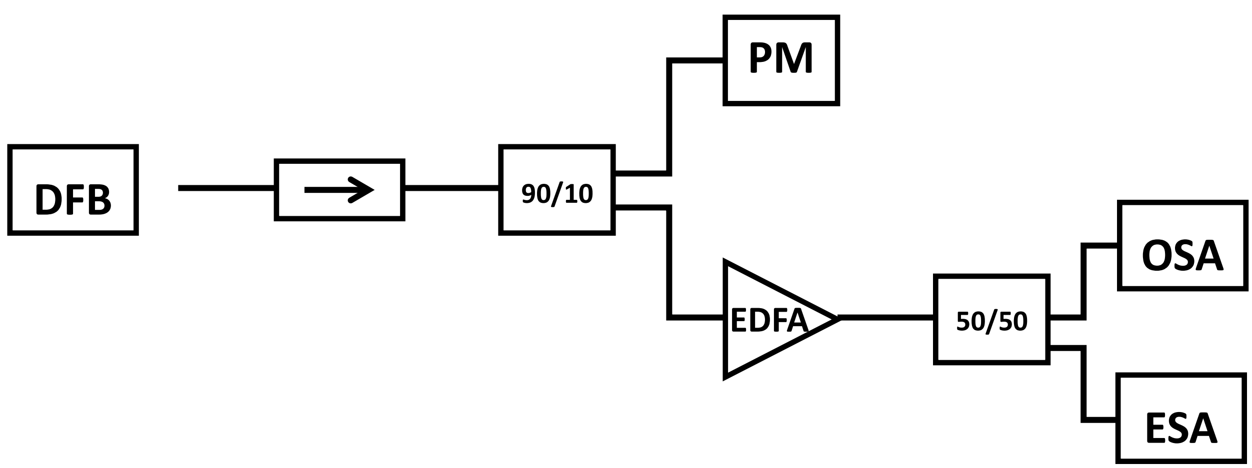


Figure 1. Experimental set-up; PM: power-meter, OSA: optical spectrum analyzer, ESA: electrical spectrum analyzer

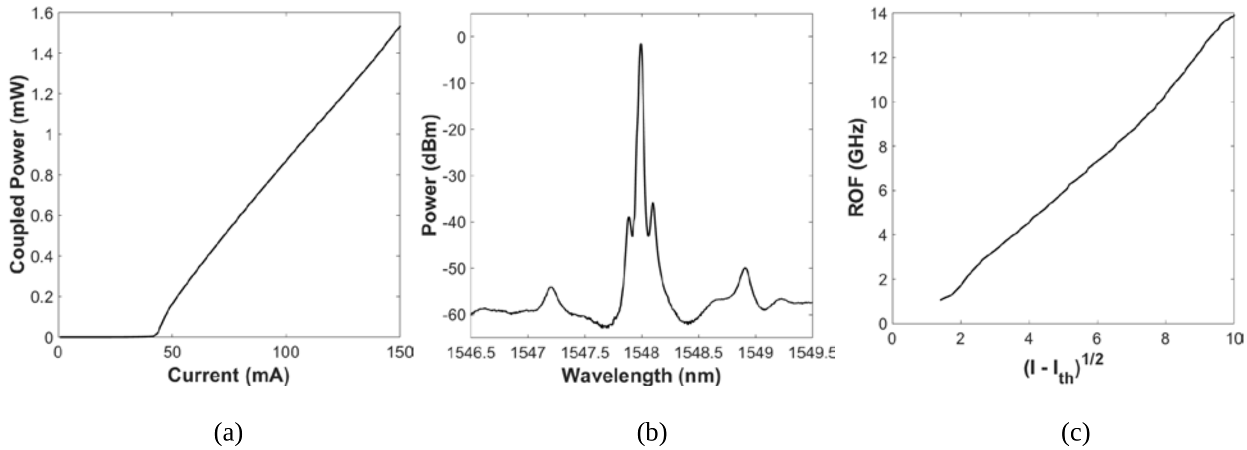


Figure 2. a) L-I curve of the laser. b) Optical spectrum of the laser for I = 140 mA. c) Evolution of the ROF as a function of the square root of the current overdrive above threshold.

3. SHORT DELAY FEEDBACK

In this section, the effects of a free-space cavity between the laser and the tip of a cleaved fiber are studied. Fig. 4 presents the experimental set-up used to carry out the short and long delay feedback measurements. A long feedback path was created using a Yenista back-reflector module, equivalent to a mirror with variable losses. 90% of the coupled light was used in this feedback path, consisting of the back-reflector preceded by a polarization controller. The remaining 10% of the light was used to perform measurements of the optical spectrum.

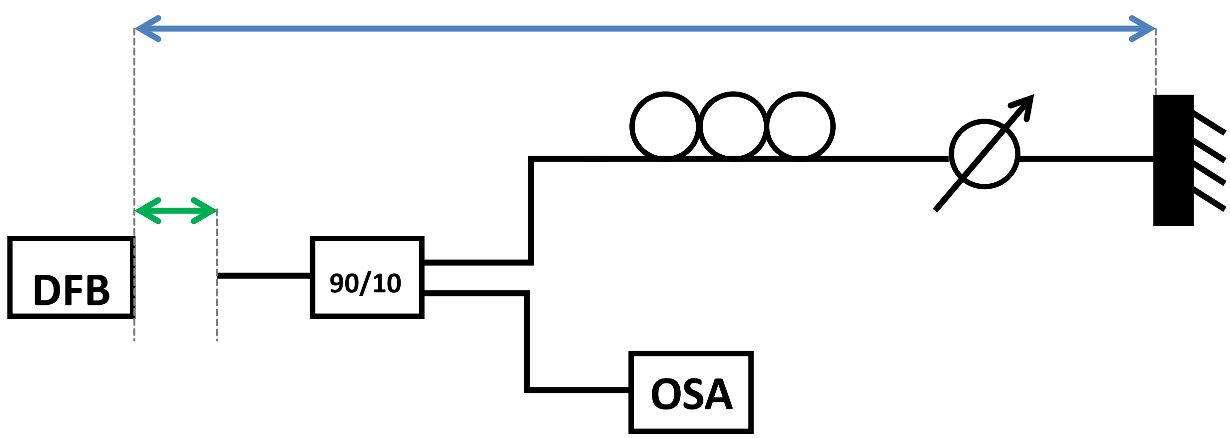


Figure 3. Experimental set-up for the short and long delay feedback. A lens-ended and a cleaved fiber were used in turn to either suppress or generate short-cavity feedback.

Using the lens-ended fiber to collect the light emitted by the laser and setting the long delay feedback path attenuation to its maximum (55 dB) allows measuring the laser in almost free-running configuration. For the short delay feedback study, the attenuation of the long feedback path was kept at its maximum and a short feedback cavity was created by coupling the light using a cleaved fiber without any coating, thus generating a reflection of about 4%.

To optimize the coupling, the fiber was positioned using a three-axis piezoelectric actuator. The actuator was also used to move the fiber along the vertical axis to change the distance between the fiber tip and the laser facet by minute steps.

This distance can thus be controlled by applying an additional voltage to the actuator, the displacement being roughly proportional to the voltage outside regions where the actuator exhibits mechanical hysteresis.

Fig. 5 presents the evolution of the optical spectrum with the fiber position when the light is coupled using a lens-ended and a cleaved fiber at a bias current of 146 mA. While the tip of the lens-ended fiber should not reflect any light to the laser due to its geometry and coating, reflections from the setup can have a slight impact on the laser. It can indeed be seen in Fig. 5(a) that the laser wavelength wiggles in a sinusoidal fashion as the fiber is moved, which indicates that the laser is experiencing feedback with a varying phase. At the same time, it can be observed that independently of the position of the lens-ended fiber, the laser operates in conditions close to free-running operation.

When the cleaved fiber is used, a short cavity of the order of 50 µm is created, and the impact on the laser is clearly visible in Fig. 5(b). The wiggling of the laser wavelength becomes a strong periodic variation that is no longer sinusoidal, which is expected from medium feedback in a cavity where the feedback phase has a significant impact[11] in the operation of the laser. The impact on the relaxation oscillations is significantly noticeable in the optical spectra. Two regions can be distinguished in each of the periods: regions of stable operation where the relaxation oscillations can be seen as small side-bands on either side of the emission peak, and regions of periodic oscillation of the laser where the relaxation oscillations are strongly excited.

In the stable regions, the ROF varies greatly as it can be seen that the two side-bands merge as they move closer to the lasing peak. The RF spectrum measurements of the laser showed that the ROF varies from a maximum value of about 15 GHz (larger than the free-running value of 14 GHz at 146 mA) to a minimum value of 10.5 GHz. In the unstable region, the laser is in fact showing the beginning of a period-doubling route to chaos as the relaxation oscillations grow into strong periodic oscillations at the ROF and its harmonics and before becoming an oscillation at half of the ROF with harmonics. Using a cleaved fiber with a high-reflection coating and increasing the feedback intensity of the short feedback might thus allow observing a full route to chaos using this feedback alone.

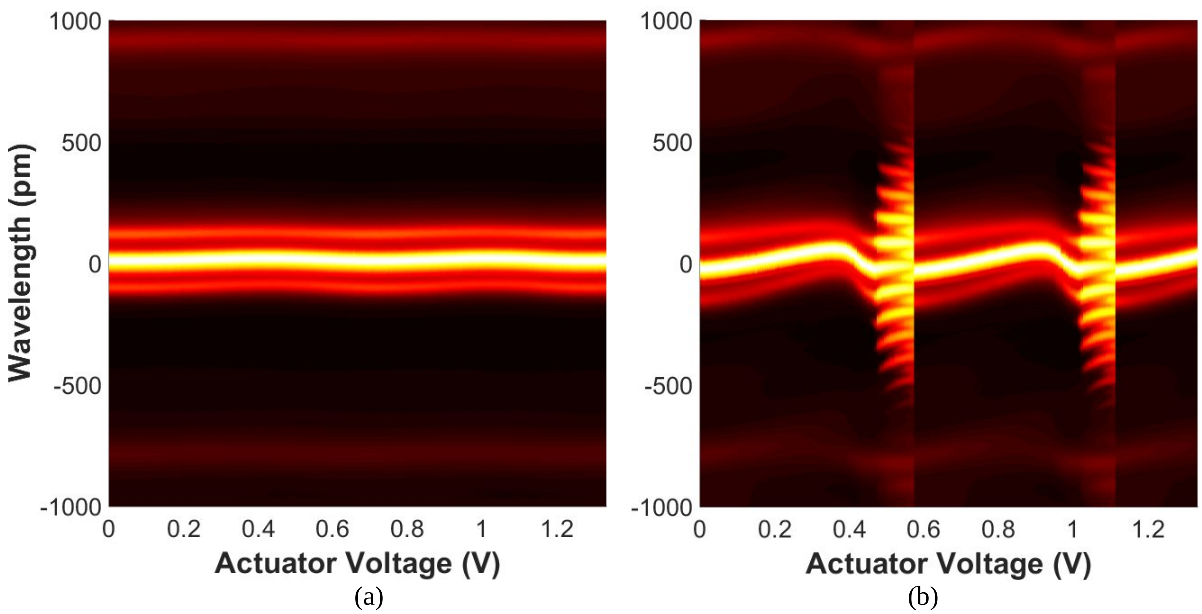


Figure 4. Evolution of the optical spectrum with the piezoelectric actuator voltage, using a) a lens-ended fiber and b) a cleaved fiber. Both measurements are performed at a bias current of 146 mA.

4. LONG DELAY FEEDBACK

The behavior exhibited by the laser studied under short feedback appears to be consistent with the response of DFB lasers [7,8]; however, the stability of the device is observed for the first time in a III-V DFB laser with an optical cavity in a silicon waveguide. Therefore, the changes in the laser operation under short feedback are mostly interesting in the context of applications of the laser using a long feedback loop. As it was shown that short feedback dynamics act as a seed for the oscillations obtained under long feedback[3]. Using the set-up in Fig. 4 with the lens-ended fiber allows studying the route to chaos of the device under long feedback only, thus suppressing short-cavity feedback, which will then serve as reference for the measurements performed with short and long feedbacks together. Fig. 6 presents the route to chaos observed when the attenuation of the long feedback is decreased towards its minimum value (2.2 dB). The route matches what is generally observed in DFB semiconductor lasers[7]. Hence, as the RF oscillations stem from the laser's relaxation oscillations, the chaotic spectra observed here appears wider than what is generally observed due to the large ROF[7,8].

Two figures of merit in the route are the feedback levels corresponding to the appearance of periodic and aperiodic dynamics. In this case, periodic oscillations appear for feedback attenuation above 20 dB, although they only appear to be stable over attenuations of 17 dB. Chaotic dynamics are also observed for attenuations below 6 dB.

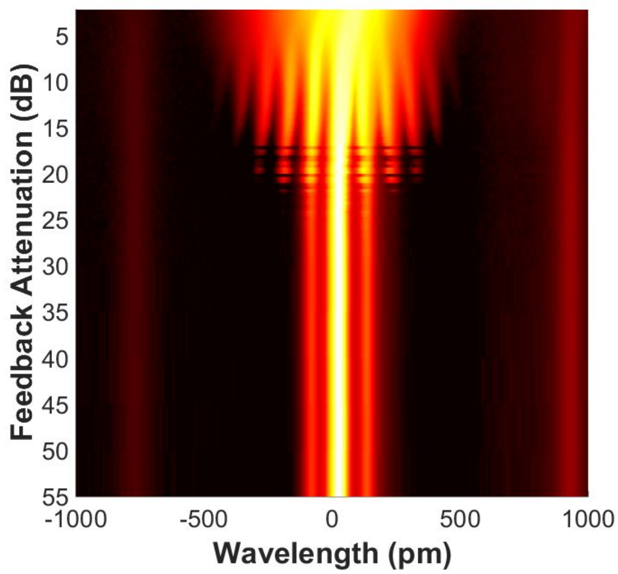


Figure 5. Evolution of the optical spectrum following the route to chaos under long feedback

Then, combining long and short feedback together allows generating chaotic dynamics with various "seeds" to the chaos. When using short feedback at the maximum ROF and the fiber position where the laser already exhibits strong periodic oscillations before long feedback is added to the short delay, the spectra (not shown here) can appear wider than the reference spectra that is indeed consistent with the fact that chaotic oscillations under long feedback lead to the laser's ROF. This observation is of paramount importance for applications in nonlinear integrated photonics where the realization of high bandwidth chaotic lasers can be used for developing on-chip secured communication channels.

5. CONCLUSIONS

This work aims at exploring the nonlinear dynamics of a hybrid III-V DFB lasers grown on silicon substrate. From an application point of view, the sensitivity to external feedback can be detrimental; however, from a fundamental physics point of view, this characteristic of the laser offers an ideal vehicle to investigate nonlinear dynamics and related phenomena. The variety of chaotic dynamics in the laser is an attractive attribute that can be used to investigate its practical application in secured communication and random number generation. This area has gained a great amount of interest from different communities and remarkable progress has already been made. The study and design of novel III-V/Si DFB lasers will continue to remain a fertile area for future research and development to exploit their vast potential in optical communications and address existing challenges such as PICs. Further studies will investigate more quantitatively the bandwidth of hybrid III-V semiconductor DFB lasers operating under a combination of both short and long delays of optical feedback. Hybrid quantum dot lasers with larger damping rate will be also considered.

6. ACKNOWLEDGMENTS

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