Integrated Laser With Optical Feedback Shows Suppressed Relaxation-Oscillation Dynamics

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***Abstract*— We experimentally demonstrate a monolithically integrated laser with built-in weak optical feedback, which shows broad regions of operation without relaxation-oscillation-induced instabilities. The side mode suppression is >40 dB for all values of the feedback phase. The measured linewidth varied from 740 KHz to 14 MHz, depending on the feedback phase value.**

***Index Terms*— Delay systems, laser theory, optical feedback, relaxation oscillation, semiconductor lasers.**

I. Introduction

A SINGLE-MODE semiconductor laser with weak external optical feedback (EOF) has a stability limit, as for feedback strengths above a critical value, the laser may exhibit sustained relaxation oscillations (ROs) [1]. These are strongly depending on the, hardly controllable, external feedback phase [2]. Such instability leads to side peaks in the optical spectrum and largely restricts the applicability of weak EOF for single mode selection in feedback based integrated lasers [3]. Recently the existence of injection current intervals was predicted [4], where the ROs stay damped for all feedback phase values. These intervals occur when the RO-frequency f_{RO} is resonant with the external roundtrip time τ, e.g. $f_{RO}\ \tau \cong 1, 2, 3, \ldots$.

Enhanced stability around this RO-resonance condition was reported in [2], whereas [5] and [6] predicted enhanced stability for phase-conjugate feedback for anti-resonant rather than resonant conditions. The explanation for enhanced stability in case of conventional EOF was given in [4], where it was recognized as a counter-intuitive feature. Indeed, one would intuitively expect enhanced tendency for RO excitation under resonant feedback conditions, but it was shown that the dominant force driving the RO is proportional to the external-roundtrip phase difference and this quantity vanishes under resonant feedback condition. This will not happen in case of phase-conjugate feedback, since the very nature of phase-conjugate reflection implies that the external-roundtrip phase difference vanishes anyway.

As part of the feasibility study of damping ROs, we report here on a single-mode tunable Distributed Bragg Reflector (DBR) laser, monolithically integrated with EOF and fabricated in a low-cost generic foundry process [7]. The measurements show that the laser system behaves in good agreement with the predictions, as the first two stability intervals of laser injection current have been observed. Taking 40 dB Side-Mode Suppression Ratio (SMSR) as a criterion for stability, these intervals extend up to 10 mA wide. Typical optical and electrical spectra are presented as well as diagrams that explicitly prove the feedback-phase robustness of the laser. Concluding, linewidth measurements for different values of the feedback phase are presented.

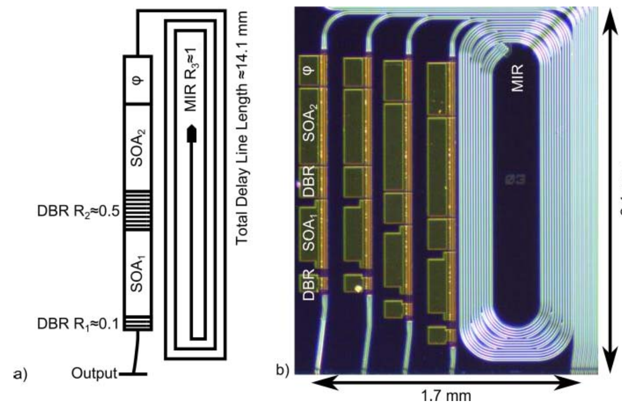

Fig. 1. (a) Schematic of one integrated DBR laser with feedback delay line. (b) Microscope photograph of realized laser arrays.

II. Circuit Layout

The device is schematically depicted in Fig. 1(a). A Semiconductor Optical Amplifier (SOA) of 400 μm length is placed in between two DBRs. The front grating R_1, has a power reflection of 0.1 and the grating R_2 at the backside, a value of 0.5. The output of the chip is formed by an angled cleaved waveguide termination, with anti-reflection coating. At the backside of the grating, a second 510 μm long amplifier SOA_2 and a 230 μm long phase section φ are placed. These allow the manipulation of feedback phase and amplitude respectively. The external delay line is chosen according to [4] and has in the present case a geometrical length of approximately 14.1 mm in total, including SOA_2 and φ. The delay line is terminated with a Multimode Interference Reflector R_3 (MIR) [8].

The laser is fabricated in an InP foundry (Oclaro) on a shared wafer, a so called Multi-Project Wafer (MPW) [7]. We made use of readily available building blocks provided by the foundry, to match the schematic of Fig. 1(a).

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A microscope image of the fabricated circuit is displayed in Fig. 1(b). We designed an array of four lasers with variable external delay length. The length of SOA_2 and φ have been varied and designed longer than necessary, to ensure sufficient amplitude and phase control in at least one of the devices. Nonetheless, the laser array has a compact footprint of 1.7 mm × 2.1 mm.

III. Experimental Results

For characterization the chip is placed on a copper carrier and maintained with a thermoelectric cooler (TEC) and water cooling at a temperature of 18 C. The light is collected using a lensed anti-reflection coated fiber placed at the angled output of the laser. An optical isolator connected to the fiber prevents back reflections into the laser, to avoid undesired optical feedback. A power meter and a 20 MHz optical spectrum analyzer are connected to the isolator. For the experiment, the electrical contacts of SOA_1, SOA_2 and φ are driven in forward bias using low-noise current sources. The tunable DBRs, R_2 and R_1, are not contacted.

The aim of this section is to identify the first two bands of operation in which the laser shows a reduced sensitivity to the value of the feedback phase. This is when the inverse RO frequency coincides with a multiple of the external roundtrip time $\tau \sim 0.3\ ns$. According to Lenstra [4] we predict SOA_1 currents of 1.8 and 4.2 times threshold and associated RO frequencies of 3.3 GHz and 6.6 GHz respectively. Values around −20 dB are estimated for the relative feedback strength, which is realized in the experiment with a SOA_2 bias varying from 4.0 to 4.3 mA. In fact, direct measurement of the feedback strength was not possible. We deduced the feedback rate from the experimental results in Fig. 5, using a theoretical linewidth formula by Agrawal [10]. This yields only an estimate since other parameters such as the photon lifetime and α parameter are not accurately known either. The threshold of the laser in the absence of feedback (SOA_2 bias = 0) is measured as 15.5 mA.

Optical characterization has been carried out by variation of the pump strength and manipulation of the phase φ. In Fig. 2(a), we show the typical behavior of the laser operated in an unstable region, at approximately 3 times threshold. Each spectrum corresponds to one specific phase shifter current I_φ varied from 0 mA to 1.5 mA in 0.1 mA steps. The spectra were manually shifted in wavelength to make them distinguishable. The spectra show side peaks, related to the external cavity length, with amplitudes depending on the precise value of the feedback phase. High SMSR is obtained for 108° and 468°, which indicates that 1 mA variation of I_φ is sufficient to introduce a 2π phase shift in the external delay. The feedback-phase dependence introduces a SMSR variation between 20 and 50 dB.

Different behavior is observed when operating the laser inside a predicted stability band, at approximately 4.2 times threshold. The spectra in Fig. 2 (b) show SMSR variation of only a few dB, maintained above 40 dB throughout the experiment.

The experiment has been repeated for a wide range of pump strengths, while changing I_φ from 0 to 1 mA.

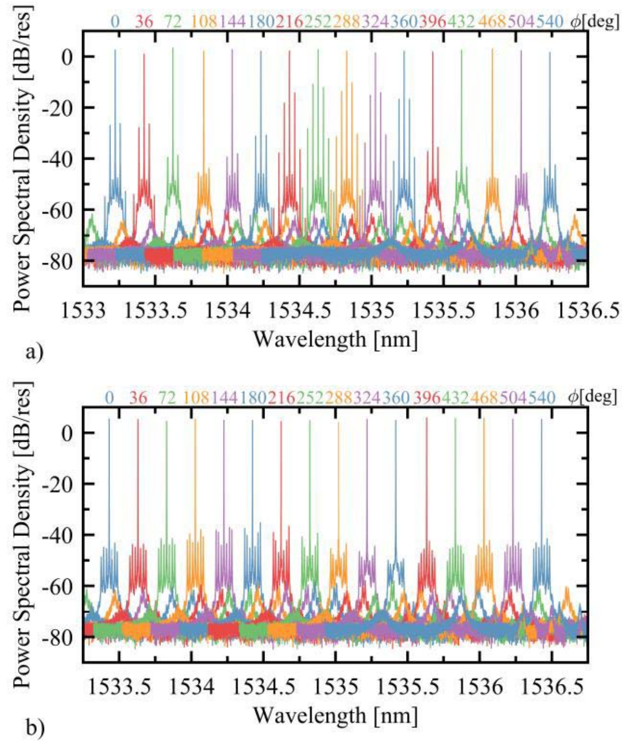

Fig. 2. Laser spectra for different values of the feedback phase, when operated (a) outside the stability band (SOA_1 = **45** mA, SOA_2 = 4.3 mA) and (b) inside the stability band (SOA_1 = **63** mA, SOA_2 = 4.3 mA). Spectra are manually red shifted to enhance the visualization.

The result is displayed in Fig. 3 for four currents of SOA_2. White regions indicate that the SMSR is 40 dB or better, while black regions indicate that it is 20 dB or worse. Apart from a few gray regions, which were identified as mode-hop instabilities, all the figures indicate two wide regions of stability. The pictures show good agreement with predictions by Lenstra [9], reproduced in Fig. 4.

The origin of the tilted stratified structure in Figs. 3 and 4 is that the mode frequency of the laser is subject to an injection current induced red shift (∼−0.85 GHz/mA in Fig. 3). This implies a feedback phase shift of ∼−2 rad/mA, which explains the tilt angle in Figs. 3. It goes without saying that due to this effect, control over the feedback phase is hard, if not impossible, in practice. The present finding demonstrates the existence of sizeable (∼10 mA) injection-current intervals where control of the feedback phase is not necessary to achieve RO-free operation in the presence of EOF.

However, dependence on the feedback phase is present in the linewidth. Using a standard self-heterodyning method, with an acousto-optic modulator, a fiber delay line of 25 km and polarization controllers, the autocorrelation function was measured in the center of the first stability band, i.e. current $SOA_1 \sim 30$ mA. This produced the linewidth data indicated in Fig. 5 assuming Lorentzian shapes. The lowest value observed is 740 KHz and the highest 14 MHz. The lowest value occurs for the same phase where the SMSR is maximized and the solitary laser linewidth for this case was 1.9 MHz.

Finally, in Fig. 6 we show recorded electrical spectra taken below the first stability band (20mA), within the first

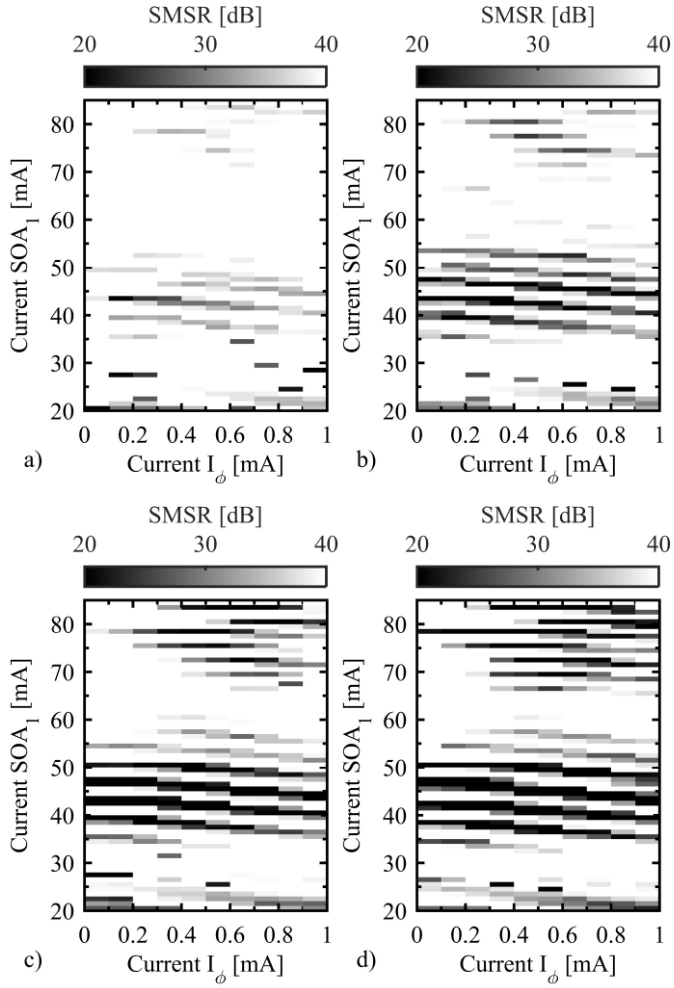

Fig. 3. Measured stability map for (a) 4.0 mA, (b) 4.1 mA, (c) 4.2 mA and (d) 4.3 mA bias of SOA_2. White regions imply a SMSR of 40 dB or better, black regions 20 dB or worse. The grey scale is valid for all the figures.

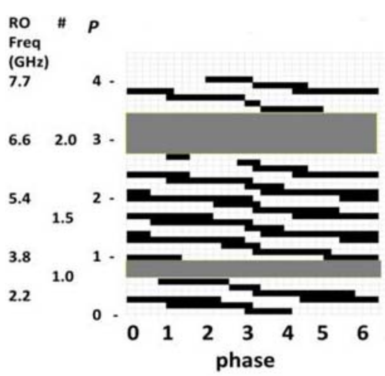

Fig. 4. Theoretical stability map with the effect of the pump-current induced frequency shift (−0.6 GHz/mA) included. The tilting is due to this red-shift effect, with the slope of the (in) stability bands approximately equal to $\frac{\Delta p}{\Delta \varphi} \approx -0.05$ per radian. The stability gaps are indicated in grey. P is the pump strength, $P = (I - I_{th})/I_{th}$. Picture taken from [9].

stability band (28mA), in between the two stability bands (45mA), in the second stability band (65mA) and above the second stability band (74mA). These spectra were selected to represent the worst case scenario within the respective

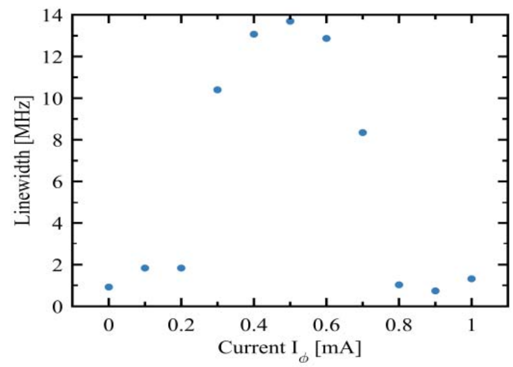

Fig. 5. Measured linewidth obtained from autocorrelation measurements in the center of the first stability band, i.e. ∼ twice threshold. Assuming Lorentzian lineshape, the FWHM values are displayed versus the phase shifter current I_φ. SOA2 bias 4.1 mA.

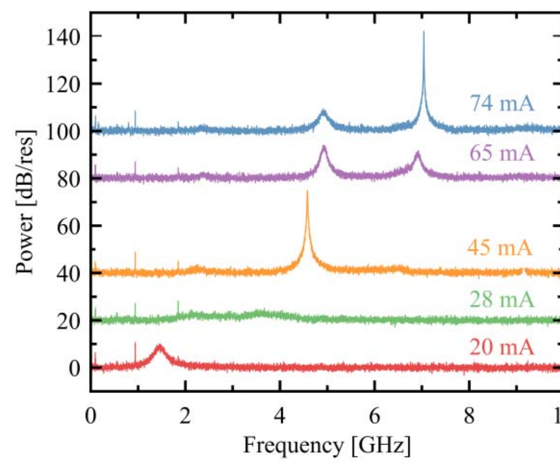

Fig. 6. Observed electrical spectrum for 5 different settings of the injection current as indicated. Self-sustained relaxation oscillations occur for 45 mA (∼4.5 GHz) and 74 mA (∼7 GHz). Note the almost flat curve at 28 mA, which is near the center of the first stability band.

operation regime. In case of 45 and 74 mA, the RO is visible as narrow peaks indicating their sustained oscillating nature, whereas in the other cases broad peaks demonstrate the RO as damped oscillations. It is also seen that the RO frequencies tend to split up. This may indicate a signature of RO-bistability, already anticipated in [9] on the basis of numerical simulations, where it was interpreted as RO-avoiding behavior in the presence of moderate to strong feedback.

IV. Conclusions

We experimentally demonstrate an integrated single-mode laser with built-in weak to moderate optical feedback, which shows two broad regions of operation where reduced relaxation-oscillation dynamics is observed. In these regions, we recognize no instabilities related to the relaxation oscillation. As a result, the side mode suppression is almost insensitive to the feedback phase and maintained above 40 dB. This concept forms the basis for RO-instability-free lasers whose operation employs weak to moderate EOF. The linewidth shows significant feedback-phase dependence.

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