Long cavity hybrid mode-locked laser with improved modulation efficiency

(Student paper)

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In this work, we highlight the enhancement of the performances of our hybrid InP/Si_3N_4 mode-locked laser under active and harmonic mode locking. To this end, we use a two-section R-SOA with a dedicated section for modulation. This configuration provides 3 times the modulation efficiency, which not only improves the overall performances of active mode locking but also allows for harmonic mode locking up to the 10th harmonic.
Keywords: *Mode-locked lasers, R-SOA modulation, Silicon nitride extended cavity, Active mode locking*

INTRODUCTION

Optical frequency combs (OFC) provide an effective solution for many applications that requires accuracy and precision such as metrology, spectroscopy and frequency banks generation in the microwave domain for RADAR and LIDAR systems [1-2]. OFC is a coherent source made of a train of equidistant lines in the frequency domain and can be generated using different methods such as ring resonators [3] or mode-locked Fabry-Perot laser oscillators. In this work, we present active and harmonic mode locked laser on the InP/Si_3N_4 hybrid platform based on low FSR and high quality factor extended cavity. The Si_3N_4 (silicon nitride) chips provides low propagation losses (< 10 dB/m) and low bend losses allowing for compact waveguides and very long cavities which is suitable for very low FSR (Free Spectral Range) mode-locked lasers. Our laser cavity is made of an R-SOA (Reflective Semiconductor Optical Amplifier) on InP which provides the gain source (>20 dB) and the back mirror of the cavity, butt-coupled to an Si_3N_4 chip that contains a delay line (~28 cm) and a Bragg grating used as the filter and the second cavity mirror. The cavity FSR is of 364 MHz. The passive Si_3N_4 chips are using a 90 nm thick, 2.9 µm wide stoichiometric Si_3N_4 buried in silica [4].

R-SOA RF MODULATION

The R-SOA chip provides a compact optical gain source with a large modulation bandwidth. For our application, the gain from the R-SOA allows to compensate the losses in the extended Si_3N_4 cavity. The R-SOA chips are also used for their electro-optical modulation ability [5] that allowed us to achieve active mode locking via electrical modulation.

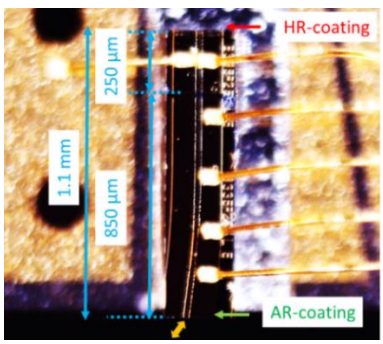

Figure 1 Two-section R-SOA with 250 µm section for modulation access and a 850 µm section for DC current access

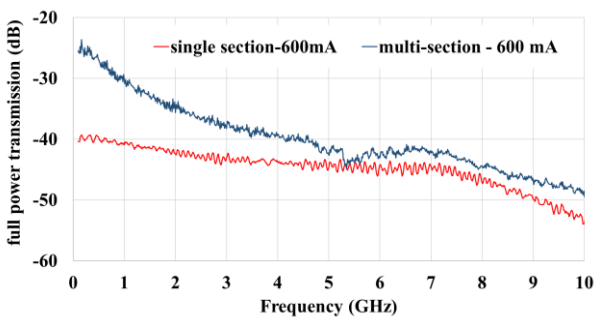

Figure 2 : Comparison of the RF power transmission with a two-section R-SOA (dark blue) and a mono-section R-SOA (red)

In this work, we used a two-section R-SOA. The 1.1mm waveguide is divided into two sections: the first section has a length of 250 µm, it has an RF access that allows for modulation, while the second section has a length of 850 µm and is only DC biased (*Figure **1***). Using a dedicated section for electrical modulation allows for a higher modulation efficiency [6]. We investigated this hypothesis by measuring the RF power transmission of the two section R-SOA and compare it with a 1100 µm long single section R-SOA from the same fabrication run used in our previous work [4]. The power transmission is measured using a VNA (Vector Network Analyser) and measurement results can be found in *Figure **2***. The modulation section was biased at 50mA and the second section at 600 mA. The single section R-SOA was biased at 600 mA. We can see that the power transmission achieved using two-section R-SOA is more than 14 dB higher than that of a single-section R-SOA at 364 MHz and more than 4 dB higher at 3.64 GHz, the mode-locked laser's 10th harmonic. We concluded that using a two-section R-SOA could improve active and harmonic mode locking efficiency.

ACTIVE AND HARMONIC MODE LOCKING RESULTS

We used a dynamic alignment setup to align the two-section R-SOA to the Si_3N_4 passive chip. For active mode-locking, we used an RF source which provides up to 30 dBm RF power to the R-SOA via the modulation section. The butt-coupling setup is illustrated in *Figure **3***.

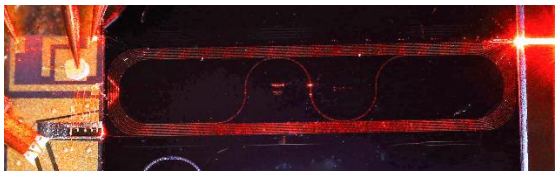

Figure 3: Photograph of R-SOA butt-coupled to the Si3N4 chip. The waveguide illuminated with a red laser to make it visible

Figure **4** and Figure **5** show the optical and the electrical spectrum of the mode-locked laser (MLL) in active mode-locking configuration at 364 MHz. The results are similar to those obtained in our last work [4], but we've applied significantly less RF power to achieve it (14 dBm instead of 23 dBm), this shows that the modulation efficiency is indeed higher when using a two-section R-SOA. We can see that the electrical spectrum measurement shows that the mode at 364 MHz is 20 dB higher than the higher frequency tones (above 2 GHz).

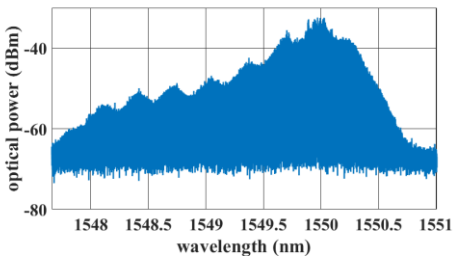

Figure 4: Active mode locking optical spectrum acquired using a high resolution optical spectrum analyzer

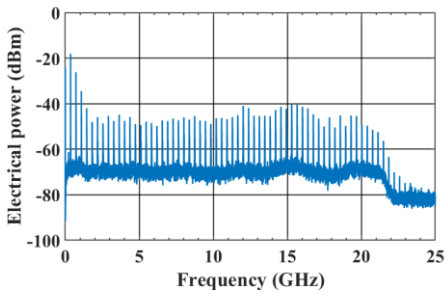

Figure 5: Active mode locking electrical spectrum

We operated the MLL in the harmonic mode-locking configuration. Figure **6** and *Figure 7*7 show the results obtained with a modulation frequency at the 10th harmonic (3.64 GHz) when applying 30 dBm of RF power.

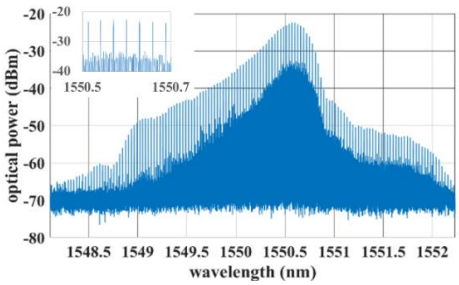

Figure 6 : harmonic mode-locking optical spectrum with $f_{RF} = 3.64$ GHz. Insert gives a zoom on the center of the spectrum

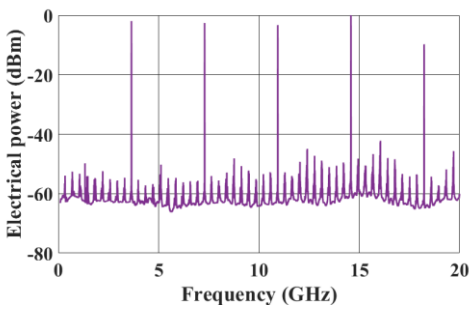

Figure 7: corresponding electrical spectrum detected with a 20GHz BW photodiode, showing a SMSR of more than 50 dB

We obtain an electrical SMSR (side mode rejection ratio) of more than 50 dB Figure 7. On the optical spectrum (Figure **6),** we can see the modes with a 3.64 GHz spacing, and an optical SMSR of more than 10 dB. In our previous work [4], we were able to achieve harmonic mode locking up to the 6th harmonic only and at very low R-SOA bias currents (around 120 mA). In this case, however, the current was set at 450 mA for the DC current supply section and at 16mA for the modulation section. We were hence able to achieve harmonic mode locking at a higher frequency while operating the MLL at almost twice the current used previously. Biasing the laser at a higher current, as far as possible from its threshold, allows to have a better rejection of spontaneous emission noise and leads to more gain in the cavity which means a higher output power.

To complete our study, we performed phase noise measurements on the MLL in the harmonic mode locking regime. Figure **8** ***6*** shows the MLL phase noise at 3.64 GHz. For this measurement, we used the phase noise measurement option of a Rohde&Schwarz FSU 67 electrical spectrum analyser. Figure **8** shows also the phase noise measurement of the synthesizer used for the electrical injection locking, the measurement floor here is mainly due to the electrical spectrum analyser limits. We obtain a phase noise level of the mode-locked laser below -120 dBc/Hz for an offset frequency above 1 kHz. We observe noise excess above 1MHz due to the laser large cut-off frequency (> 10's of MHz). This noise can be filtered with longer cavities. We observe also noise excess at harmonics of the laser FSR due to spontaneous emission located at non-lasing modes frequencies.

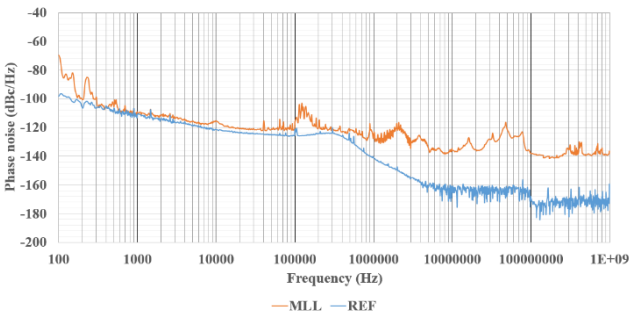

Figure 8 6 Phase noise measurement in harmonic mode locking configuration

DISCUSSION

We demonstrated that separating the modulation section from the current supply section in an R-SOA improves the modulation efficiency in our extended hybrid mode-locked laser cavity. Harmonic mode locking up to the tenth harmonic has been obtained with a good phase-noise level considering the dynamically butt-coupled laser cavity configuration. Packaging of this laser should lead to a better mechanical stability of the laser cavity and even better phase noise performances.

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