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We present a photonic integrated circuit chip with two mode-locked lasers that was designed for gas sensing application using of Fourier transform spectroscopy. The monolithic indium phosphide PIC was fabricated in a multi-project wafer run using active-passive integration technology. Two quantum well, symmetrical ring cavity mode-locked lasers operate at wavelengths around 1550 nm with 2.5 GHz repetition rates. Each laser has intracavity electro-refractive phase modulators for tuning the spectral position of the lasing modes. In this work we present results on the RF locking range and timing jitter values in hybrid mode-locked operation of one of the lasers.

1. Introduction

Dual frequency comb spectroscopy is a form of Fourier transform spectroscopy that allows for fast recording of high quality absorption spectra. It does require however two frequency combs that have a small difference in repetition rate and the wavelengths of the comb lines from the two lasers are stabilised with respect to each other. The resolution of the spectra is determined by the repetition rate of the lasers. Photonic integration allows for the realisation of two mode-locked lasers on the same optical chip and this can make this spectroscopic technique much more accessible. However the repetition rates of the two lasers and the wavelengths need to be stabilised. In this paper, we demonstrate that two 2.5 GHz repetition rate ring lasers can be realised on a single chip and that the repetition rate of the laser can be stabilised over a sufficiently wide range using hybrid mode-locking.

2. Ring mode-locked laser structure

The optical spectrum of a periodic pulse train generated by a mode-locked laser (MLL) consists of a frequency comb with each mode correlated with each other and with an exact mode spacing between them, which is equal to the pulse repetition frequency.

Fig. 1 (a) shows the configuration of the ring mode-locked laser presented in this paper with 2.5 GHz repetition rate and operating in the telecommunication wavelength range of 1.55 µm. Each ring mode-locked laser cavity contains: two 450 µm long amplifier sections (SOA); one 50 µm long saturable absorber (SA) which is located between the both amplifiers and separated from them by two 50 µm long electrical isolation (ISO) sections; two 810 µm long electro-reflective phase modulators (ERM) sections to tune the spectral position of the lasing modes. The ring cavity is closed by deeply etched passive waveguides with a typical loss of 5 dB/cm. A 2x2 MMI is used for coupling out the optical signals in both directions (50 % output coupling). The laser cavity length is 33 mm and the laser design is completely symmetric with respect to the SA [2]. Fig. 1 (c) shows a microscope photograph of this dual mode-locked laser and its area is 16 mm^2.

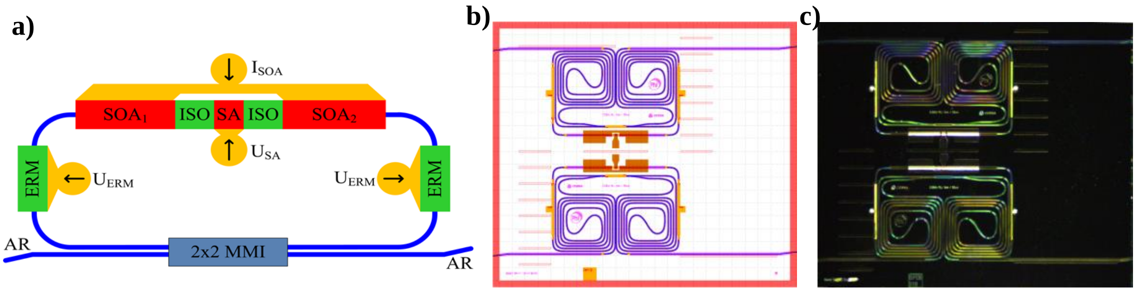

Fig. 1. (a) Schematic diagram of the photonic integrated circuit based ring mode-locked laser: semiconductor optical amplifier (SOA), saturable absorber (SA), electrical isolation (ISO), electro refractive modulator (ERM) and multi-mode interference coupler (2x2 MMI) sections and passive waveguides in blue. **(b)** Mask view of a dual mode-locked laser chip design. **(c)** Microscope photograph of a fabricated photonic integrated circuit chip with size of 16 mm^2.

3. Characterisation of a mode-locked laser

When stabilising the laser it is important to make sure that it is locked in the best conditions. Therefore first a characterisation in passive mode-locking (PML) regime for both lasers was presented in previous works [1]. Then, the RF locking range for one of these lasers under hybrid mode-locking regime conditions was studied in order to find the best locking point. Fig. 2 shows the experimental set-up used for studying the hybrid mode-locking regime.

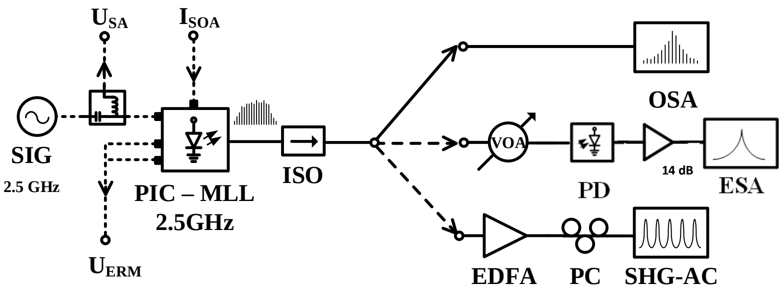

Fig. 2. Experimental set-up when laser operates in hybrid mode-locking (HML) regime.

In the passive mode-locking regime, the laser was dc biased with forward current injection (I_{SOA}) into the SOA sections and a reverse bias (U_{SA}) was applied to the saturable absorber. Left optical output of the laser allocated on the bottom of the chip ($RMLL_1$) was recorded using a high resolution (20 MHz) optical spectrum analyzer (OSA), the RF beat tone produced on a fast (50 GHz) photodiode (PD) was connected to an electrical spectrum analyzer (ESA) and an autocorrelator (SHG-AC) was used to monitor optical pulses. The passive operating regime for both lasers was investigated by mapping of the optical bandwidth, the signal to noise ratio (SNR) and the linewidth of the fundamental RF beat tone produced on the photodiode as a function of injected currents to the SOA sections and reverse bias voltages applied to the SA section.
After studying all mappings and taking into account wider optical bandwidth, narrower RF beat linewidth and larger SNR, a working point of 130 mA of total injection current into the SOAs and -6.5 V reverse bias on the SA was selected. The optical bandwidth measured at -3 dB of the optical frequency comb for the $RMLL_1$ is 0.5 nm and the RF beat linewidth measured for this laser at -3 dB is 13.8 kHz. At this point both lasers were operated under the same conditions and the autocorrelation width measured for the $RMLL_1$ operating in PML regime is 25 ps [1]. Fig. 3 (a) shows optical spectra and

Fig. 3 (c) shows the RF beat tone around the fundamental frequency for $RMLL_1$ at the selected operating point when both lasers are operating at the same time and under the same conditions.

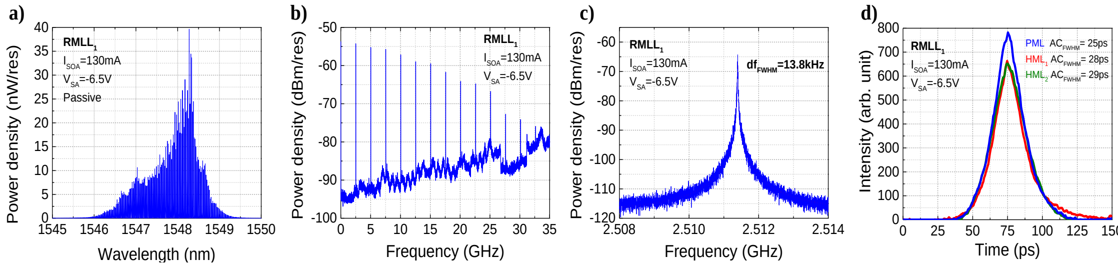

Fig. 3. $RMLL_1$ in passive mode-locking regime (PML) **(a)** High resolution (20 MHz) optical spectra **(b)** wide span RF spectra recorded with resolution bandwidth (RBW) of 330 kHz and video bandwidth (VBW) of 33 kHz **(c)** RF spectra recorded around the fundamental frequency (RBW: 1 kHz, VBW: 100Hz), the Lorentzian fitting function is represented by the red line **(d)** autocorrelation trace when laser is operating in PML (blue line) and when it is operating in HML at different RF frequencies at around +/- 1 MHz from the PML frequency (red and green lines).

For HML operation, a RF signal was added to the reverse voltage applied to the saturable absorber (SA) via bias-tee. Two phase modulators (ERM) were connected to ground (U_{ERM} = 0 V). The optical output went to the 50 GHz photodiode (PD), the signal of which was amplified by 14 dB and then led to the ESA. Timing jitter and phase noise were calculated in the frequency range of 10 KHz to 25 MHz from the single side band spectrum. When the laser operates in HML, the amount of phase noise of the output signal is reduced due the external RF signal. Smaller values of phase noise can be achieved when increasing the RF power applied to the absorber section.

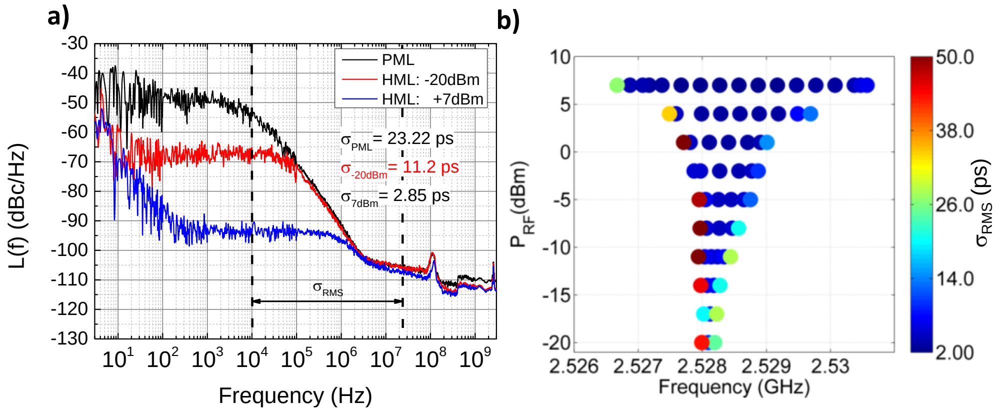

Fig. 4. (a) Phase noise of the MLL; black line when the laser operates in the PML regime, red line when the laser operates in the HML regime with an RF signal of –20 dBm power at 2.52824 GHz frequency and blue line with an RF signal of 7 dBm power at 2.52824 GHz frequency. **(b)** Timing jitter of the MLL as a function of RF power and RF frequency.

As Fig. 4 (a) shows for PML operation 23.22 ps integrated timing jitter is obtained. In the HML regime and applying an RF signal with -20 dBm power at 2.52824 GHz frequency, the integrated timing jitter is 11.2 ps. Increasing the RF power to 7 dBm power reduces the jitter to 2.85 ps. Fig. 4 (b) shows the RF locking range for the laser as a function of RF power and RF frequency. RF power ranges from 7 dBm to -20 dBm and is modified in steps of 3 dBm. RF frequency range is centralised at 2.52824 GHz and is scanned with a step size down to 100 kHz. The results show a locking range of

3 MHz is achieved in case of applying 7 dBm RF power. The lowest jitter of 2.85 ps is at 7 dBm power and at 2.52824 GHz.

Fig. 5 (a) shows the timing jitter as a function of the RF power in more detail. Considering reasonable values of RF power, i.e. not the higher power values, a RF signal with 1 dBm power at 2.52824 GHz frequency is selected as a RF signal to lock the laser and to get a timing jitter around 3.65 ps.

As last current result Fig. 5 (b) shows the RF beat frequency change as a function of voltage applied to the phase modulators (ERM). The repetition rate of the laser operating in hybrid mode-locking regime remains fixed when the amount of voltage applied to the phase modulators (ERM) is modified as can be seen from the red data points. This was tested for two current settings.

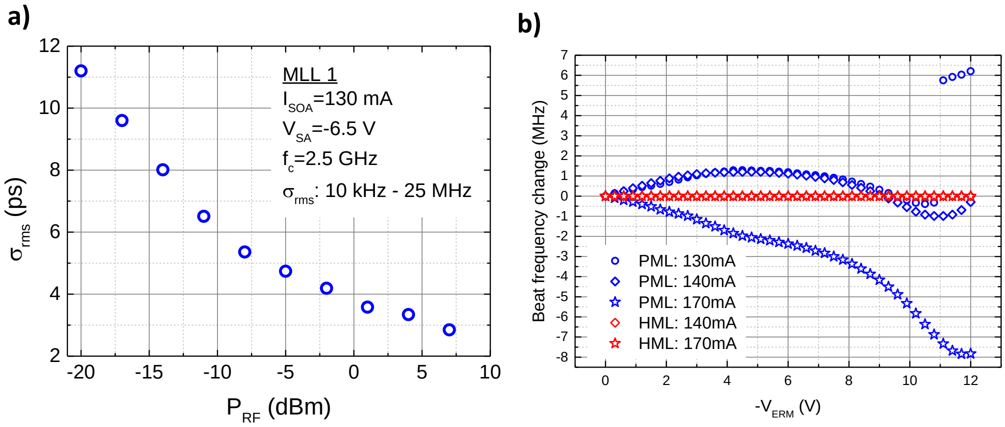

Fig. 5. (a) Timing jitter as a function of RF power and the RF signal centralized at 2.52824 GHz. **(b)** RF beat frequency change as a function of voltage applied to the phase modulators (ERM).

4. Conclusions

In this paper we presented the characterisation of one of two ring mode-locked lasers integrated together on a monolithic indium phosphide PIC and its operation in hybrid mode-locking. Using hybrid mode-locking a tuning range of the repetition rate of the laser just over 3 MHz was achieved. This range is sufficient for the dual comb spectroscopy application which requires 2 to 3 MHz difference between the two lasers since the repetition rate difference of the two ring lasers in PML was just under 500 kHz [1]. A good operating point was selected for using both lasers. Further steps to do in order to improve the ring-MLL would be to stabilise the offset frequency of the optical frequency comb under the previous mentioned conditions.

References

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