2.5 GHz Extended Ring Cavity Mode-locked Laser with an Integrated Phase Modulator for Dual Comb Fourier Transform Spectroscopy

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A 2.5 GHz mode-locked ring laser emitting at 1.58 μm developed for gas sensing application is presented. The device is realized as an InP based photonic integrated circuit with a quantum-well amplifiers. The 33mm long ring cavity contains gain, saturable absorption and passive waveguide sections as well as electro refractive modulators integrated to enable tuning of the spectral position of the lasing modes. Passive and hybrid mode-locked operation of the laser and an impact of the intra-cavity phase shifters on its performance are experimentally investigated.

Introduction

Semiconductor photonic integration technology is a convenient solution to develop mode-locked (ML) lasers for dual frequency comb gas spectroscopy [1]. With such technology two mode-locked lasers can be realized in the form of a photonic integrated circuit (PIC) on a single semiconductor chip enabling a wider application of this gas sensing scheme. There are several constrains in terms of the optical bandwidth, spectral width of individual modes and mutual relative position of the combs from both sources in order to be suitable for such application.

Ring mode-locked laser design

Targeting such application a 2.5 GHz ring cavity mode-locked laser (RMLL) with accurately tunable spectral position of the comb lines has been designed and fabricated as a photonic integrated circuit using active-passive photonics integration technology [2]. The laser cavity has a symmetrical arrangement with respect to the saturable absorber (SA) and output coupler as presented in Fig. 1(a) and a total length of 33 mm. In such a configuration the laser operates in a colliding pulse mode and provides a wide range of operating conditions resulting in a stable mode-locking regime [3].

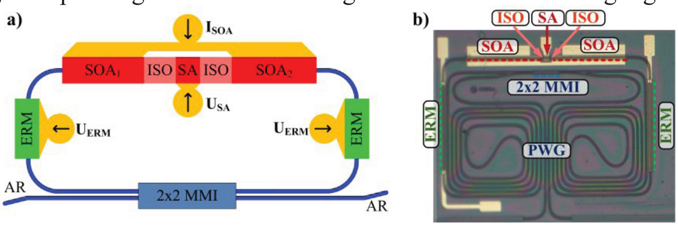

Fig. 1. a) Schematic diagram of the photonic integrated circuit based ring mode-locked laser: semiconductor optical amplifier (SOA), saturable absorber (SA), electrical isolation (ISO), electro refractive modulator (ERM) and multi-mode interference coupler (2x2 MMI) sections and passive waveguides in blue b) A microscope image of the fabricated device.

A 50 µm long saturable SA is surrounded by two semiconductor optical amplifiers (SOA) each being 725 µm long and separated from these by two 25 µm long electrical isolation sections (ISO). The SOA, SA and ISO sections share a shallow etch ridge waveguide with a multiple quantum well (MQW) active core underneath. Two 810 µm long electro refractive modulators (ERM) are used to allow for a spectral tuning of the optical comb lines and a 2x2 multimode interference coupler (MMI) provides 50% out-coupling in both directions. The ring is closed using deeply etched passive waveguides which with a typical value of optical loss of 5 dB/cm. The output signals are guided with shallow waveguides to angled output ports at the edges of the PIC chip. A microscope image of the photonic IC fabricated SMART Photonics within multi project wafer run is presented in Fig. 1(b).

Experimental setup and results

The chip was mounted on an aluminium sub-carrier and electrical contacts were wire-bonded to a distribution printed circuit board (PCB) providing with several DC and RF feed lines as presented in Fig. 2(a). The metal sub-carrier allows for water cooling and was temperature stabilized at 23 ºC. A lensed single mode fiber (SMF) with an optical isolator was used to collect the output signal from the chip and deliver it to the measurement setups as shown in Fig. 2(b). The voltage across the gain sections and collected light power against the injected current characteristics are presented in Fig. 2(c). Out of a range of stable mode-locking conditions, a point close to laser threshold with current injected into the SOAs I_{SOA} = 73 mA and the SA reverse bias U_{SA} = -6.3 V was selected and is used for all results presented in this paper. For hybrid mode-locking (HML) an additional RF signal at frequency of 2.5260 GHz and -5 dBm of power was added to the U_{SA} via a bias tee.

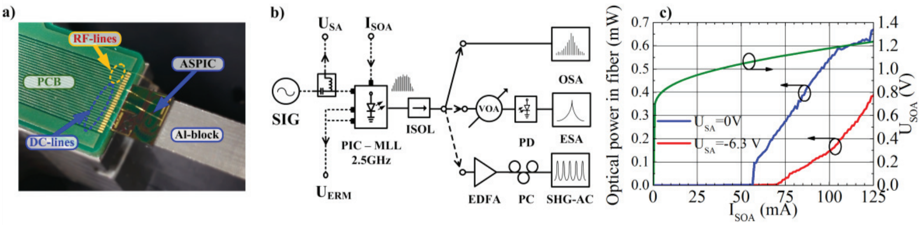

Fig. 2. a) Photonic IC evaluation platform: application specific photonic integrated circuit chip (ASPIC); water cooled aluminum sub-mount (Al-block); PCB with wire-bonding pads, 4 RF (RF-lines) and 16 DC (DC-lines) feed lines. b) Experimental setup: optical isolator (ISOL), in-line variable optical attenuator and power monitor (VOA), 50 GHz photodiode (PD), electrical spectrum analyzer (ESA), high resolution optical spectrum analyzer (OSA); erbium doped fiber amplifier (EDFA), polarization controller (PC), second harmonic generation based intensity autocorrelator (SHG-AC); ultra-low noise signal generator (SIG) c) Optical power and amplifier voltage against injected current characteristics.

The average output power coupled into the fiber is around 80 µW at this operating point. Corresponding optical spectra recorded using a high resolution optical spectrum analyzer (OSA) with a full width at half maximum (FWHM) of 3 nm centred at around 1582.5 nm are presented in Fig. 3(a) and Fig. 3(d) for the PML and HML regimes respectively.

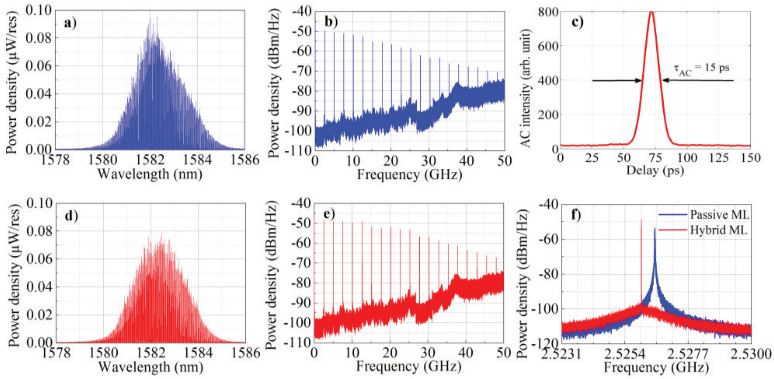

Fig. 3. Output characteristics of the laser operating in the passive and hybrid mode-locking regimes (PML and HML respectively). a) PML optical spectrum recorded with high resolution optical spectrum analyzer. b) Wide bandwidth spectrum of RF beat signals produced on a fast photodiode (PD) by the laser in PML regime c) A SHG autocorrelation trace from the laser in PML regime. d) Optical spectrum from the HML device. e) Wide electrical spectrum of the RF beat signals produced by the laser in HML regime. f) A detailed spectra of the PML and HML fundamental beat signals.

The optical spectra show the free spectral range (FSR) of 2.5 GHz which corresponds to the laser cavity length. Electrical beat signals produced on a fast (50 GHz) photodiode (PD) and recorded using an electrical spectrum analyzer (ESA) with a full bandwidth of 50 GHz (resolution bandwidth (RBW) of 330 kHz, video bandwidth (VBW) of 3.30 kHz and sweep time (ST) of 36 s.) show a strong fundamental beat tone and its higher order overtones spanning up to 45 GHz as depicted in Fig. 3(b) and Fig. 3(e) for PML and HML conditions respectively. These higher harmonics signals and the absence of low frequency components between DC and the fundamental beat signal prove that an optical pulse train proves pulsed output and mode-locked operation of the laser. This is also confirmed by a second harmonic generation based autocorrelation (SHG-AC) trace presented in Fig. 3(c) showing a clear optical pulse with a very low background noise. The fundamental beat tones for the PML and HML cases recorded with the ESA are presented in Fig. 3(d). In the PML regime (blue) the central frequency of this signal is at 2.5264 GHz. This corresponds to the ring cavity length and free spectral range (FSR) of the laser. It features a signal to noise ratio (SNR) in the excess of 50 dB and a full width at half maximum (FWHM) of 6.13 kHz (Δf_{-10dB}=18.9 kHz, Δf_{-20dB}=61.17 kHz). In the HML operation (red) the RF peak matches the frequency of the signal provided by the electronic signal generator. It has an SNR of more than 70 dB and the FWHM linewidth of less than 2 Hz (resolution limited). The effect of the integrated ERMs was investigated when the laser was operated in both PML and HML conditions. The optical output was recorded using the OSA with a resolution of 20 MHz. The mode frequency changes (Δf_{mode}) against reverse voltages U_{ERM} applied were analyzed and are shown in Fig. 4(a). In both PML and HML cases the changes follow a similar trend and the comb lines exhibit a red-shift of 1.01GHz (~0.4 FSR) over the full range of the applied bias voltage. The impact of the ERMs on the repetition rate frequency (f_{rep}) with respect to the applied U_{ERM} was also recorded and is presented as a variation Δf_{rep} in Fig. 4(b) in blue and red for PML and HML conditions respectively. In case of passive mode-locked operation the value of f_{rep} changes to lower frequencies by 1.6 MHz with a nonlinear trend while for the hybrid mode-locked case it remains stable and matches the one for the electronic signal generator to within the resolution of the measurement setup.

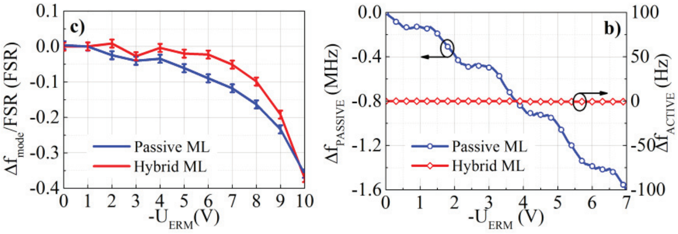

Fig. 4. a) The cavity mode frequency variation Δf_{mode} with respect to applied U_{ERM} for passive (blue) and hybrid (red) mode-locking regimes. b) repetition rate frequency change Δf_{rep} as a function of applied U_{ERM} for passive (blue) and hybrid (red) mode-locking regimes. For data in all sub figures biasing conditions were set at: I_{SOA}=73 mA, U_{SA}=-6.3 V and RF power set at -5 dBm for hybrid mode-locking.

Summary

A low repetition rate mode-locked laser with tunable optical comb lines and repetition rate was realized as an InP photonic integrated circuit. The device operates in a passive mode-locking regime at 2.5 GHz repetition rate and shows a good performance in comparison to state-of-the art passively mode-locked lasers of similar geometries [4, 5]. Furthermore the laser has been demonstrated to operate in the hybrid mode-locking regime with its repetition rate locked to an external electronic oscillator and the integrated ERMs proven to allow for the frequency of the optical modes tuning. The extent and trend of the tuning have to be further investigated and need to be taken into account in order to allow for a sufficient control over a target tuning range which is crucial for application in the dual frequency comb spectroscopy.

Acknowledgment

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