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Monolithic 2.5 GHz Quantum Well InGaAsP Extended Cavity Modelocked Ring Laser with an Integrated Phase Modulator

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***Abstract*— A passively modelocked extended cavity quantum well ring laser at 1.58 µm with repetition rate of 2.5 GHz in the form of a photonic integrated circuit is presented. The device is realized using InP based active-passive integration technology. The 33mm long cavity contains gain, saturable absorption and passive waveguide sections as well as a phase shifter sections to enable fine tuning of the spectral position of the lasing modes. Passive mode-locked operation and with wavelength tuning of the laser modes are experimentally demonstrated. This laser is the lowest reported repetition rate for a monolithically integrated ring laser.**

Keywords—modelocked lasers, semiconductor lasers, photonic integrated circuits

I. Introduction

Integrated passively modelocked semiconductor lasers are in principle ideal for realizing compact devices for dual frequency comb spectroscopy [1]. Two identical modelocked lasers can be integrated on a single chip. This will allow for a wider application of the spectroscopic technique. There are a number of requirements that must be met by the laser. The bandwidth of must be sufficiently wide to be of interest, the line width of the modes in the comb must be a few MHz or less and the relative positions of the lines in the two combs must be accurately stabilized with respect to each other. The spacing between the modes determines the spectral resolution and this must be at most a few GHz. With this application in mind we developed a 2.5 GHz integrated laser with an option to accurately control the position of the mode comb. The active passive integration technology allows for short amplifier sections in the cavity which when driven at a relatively high current density can provide a wide gain spectrum [2], [3].

II. Photonic Integrated Circuit

A ring mode-locked laser (RMLL) was designed as a photonic integrated circuit (PIC) in order to support repetition rates of 2.5 GHz and allow for spectral positioning of the optical output. The resulting ring laser cavity has a total length of 33 mm and features a symmetrical arrangement of the components with respect to the saturable absorber (SA) and output coupler as presented in Fig. 1(a). Such a configuration

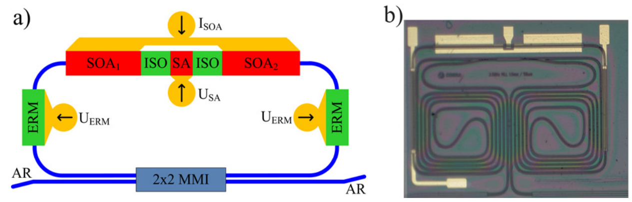

Fig. 1. a) Schematic diagram of the photonic integrated circuit based ring mode-locked laser; **b)** A microscope image of the fabricated device.

assures optimum operation in colliding pulse mode-locking regime [3], [4]. The 50 µm saturable SA is surrounded by two gain sections (SOA) each being 725 µm long and both sharing an electrical contact for current injection. The ring is closed by used of deeply etched passive waveguides which allows for a small bending radius, two 810µm long electro refractive modulators (ERM) and a 2x2 multimode interference coupler (MMI) used for coupling out optical signals in both directions. The output ports of the MMI are guided to angled output ports at the opposite edges of the PIC chip. The PIC as presented in Fig. 1(b) was fabricated within a multi project wafer (MPW) run by SMART Photonics.

III. Passive Mode-Locking at 2.5 GHz

The PIC was mounted on an aluminum sub-carrier and electrical contacts were wire-bonded to a printed circuit board (PCB) for an ease of electrical control of the device. The metal sub-carrier was water cooled at room temperature to stabilize the temperature. The optical output was collected with a lensed fiber and fed to the measurement instruments via an optical isolator. A range of operating conditions was found for which modelocking was observed. As an example we present an operating point where the SOA sections were injected with a total DC current I_{SOA}=90 mA and the SA was reverse biased at U_{SA}= -4.1 V. The ERMs were grounded. A multimode spectrum presented in Fig. 2(a) was recorded using a high resolution (100 MHz) optical spectrum analyzer (OSA). The OSA clearly resolves the laser modes with a free spectral range (FSR) of 2.5 GHz. An electrical beat signal was produced on a fast (50 GHz) photodiode connected to an electrical spectrum analyzer (ESA). The recorded spectrum show clear tones (signal to noise ratio in excess of 30dB at fundamental) at

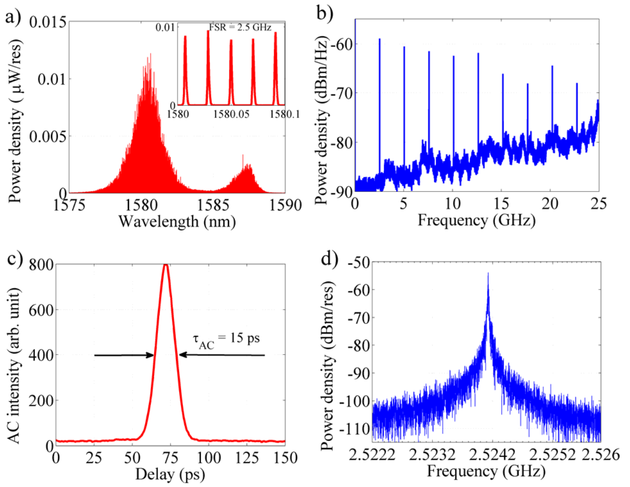

Fig. 2. a) Selected optical spectrum recorded with high resolution optical spectrum analyzer. Inset: A 3dB window showing lasing modes with FSR of 2.5 GHz. **b)** RF beat signal produced on a fast photodiode and recorded with electrical spectrum analyzer (RBW: 56 kHz, VBW: 560 kHz, ST: 7.4 s); **c)** An autocorrelation trace recorded at corresponding bias conditions; **d)** A detailed view of the fundamental frequency (RBW: 1 kHz, VBW: 10 kHz, ST: 4 s).

frequencies corresponding to the fundamental FSR and its higher order overtones as shown in Fig. 2(b). The strong overtones at higher harmonics show that an optical pulses train is formed resulting from passive mode-locking operation. This is confirmed by a background free optical autocorrelation (AC) trace presented in Fig. 2(c). It shows a clear optical pulse. The duration of the AC trace results with a full width at half maximum pulse duration of 11 ps assuming a $sech^2$ shape. For the use of AC the optical signal of 60 µW average power in fibre was amplified using an L-band erbium doped fiber based optical amplifier (EDFA). Fig. 2(d) presents the fundamental peak in the RF spectrum in detail.

IV. Tunability of the Laser

The effect of the intra cavity ERMs was investigated when the laser was operated in passive mode-locking regime. In addition to the DC bias conditions applied to the SOA and SA sections, a reverse DC voltage U_{ERM} is applied to the phase shifters and the optical output is recorded with use of the OSA and ESA. Fig. 3(a) presents three modes from the optical spectra recorded for the U_{ERM} in the range from 0 V to -10 V.

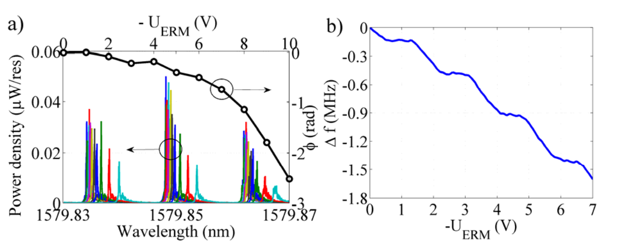

Fig. 3. a) Optical spectra in function of the phase shifter reverse bias U_{ERM}, recorded with 20MHz resolution with the axes at the bottom and left. The cavity mode phase shift $\Delta\phi$ with respect to applied U_{ERM} (solid black, top and righ); **b)** Beat frequency change profile as a function of applied U_{ERM}.

The comb lines exhibit a red-shift of 2.5 rad (~0.4 FSR) over the full range of the applied bias voltage. The average output power stayed near constant with changing U_{ERM}. The trend of the frequency shift is also nonlinear with respect to the U_{ERM} as demonstrated in Fig. 3(a) however the voltage to phase relationship in the ERM is mainly linear [2]. The repetition rate frequency of the laser f_0 recorded for a range of values of U_{ERM} from 0 V to -7 V is presented in Fig.3(b). The value of f_0 changes to lower values by 1.6 MHz with a nonlinear trend. The expected phase shift introduced by ERMs is in the range of π to 2π. A 2π change would lead to a change in f_0 of 31 kHz. This is fifty times smaller than we observe. This in combination with its non-linear behavior leads again to a conclusion that additional loss introduced into the laser cavity by reverse biased ERMs affects the overall repetition rate change similarly to the case described in [5]. The voltage dependent loss induced by the ERM dominates the effect it has on the laser performance. The broadening of the laser modes with increasing U_{ERM} may be attributed to a shift in output spectrum of the laser due to the changing loss of the ERM.

V. Conclusions

A low repetition rate modelocked laser with tunable optical comb lines and repetition rate was realized as a photonic integrated circuit. The device operates in a passive modelocking regime at 2.5 GHz repetition rate. Such a rate is up to the our knowledge the lowest demonstrated so far from a quantum well based InP integrated ring laser. Although the effect of the integrated phase modulator is nonlinear, which may lead to a more complex tuning mechanism, it allows for tuning of the position of the optical comb lines and repetition rate frequency of the laser. This control is required for the target application of dual frequency comb spectroscopy.

Acknowledgment

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