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Realization and Modeling of a 27 GHz Integrated Passively Modelocked Ring Laser

Y. Barbarin, E.A.J.M Bente, M.J.R. Heck, J.H. den Besten, G. Guidi, Y.S Oei, J.J.M. Binsma and M.K. Smit

Abstract— We present a realization and the modeling of a 27 GHz integrated extended cavity ring laser that is passively modelocked. The modelocked ring laser is fabricated with active-passive integration. Experimental results show that internal reflections are the major factor affecting operation stability. CW, self-pulsating and in small windows of operation modelocked regimes have been observed. Similar regimes have been observed in our bidirectional laser model. This model describes the semiconductor amplifier and the saturable absorber using rate equations. Our experimental and theoretical results are compared and discussed.

Index Terms— mode locked lasers, semiconductor waveguide, integrated optics, active-passive integration.

I. INTRODUCTION

Modelocked lasers are key components for high bit rate telecommunication. Optical Time Domain Multiplexing (OTDM) is a solution to increase the rate of a WDM channel up to 160 Gbit/s or higher. The application of OTDM requires clock recovery and clock division for demultiplexing the signals. In our project we are developing an All Optical Clock Recovery (AOCR) device based on an injection seeded passively Modelocked Laser (MLL). For this application the ring configuration has two advantages. Firstly, the repetition rate of the laser is controlled accurately by photolithography as opposed to a device with cleaved facet mirrors. Secondly the ring laser configuration is more suitable for the injection seeding process that is at the centre of the AOCR. The butt-joint active-passive integration technology [1] allows to have two waveguides types, one for active and one for passive elements. We used this technology to make the laser design suitable for further integration with other devices such as an all-optical switch. In this paper we present the first integrated extended cavity passively modelocked ring laser using active-passive integration and its modeling.

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II. MODELLOCKED LASER DEVICE

A modelocked ring laser has been realized in the InP/InGaAsP material system with active-passive integration. A picture of the fabricated device is given in Fig. 1; waveguides are visible as dark lines. To better understand the layout, one must realize that the positions and sizes of the active regions were predetermined through the re-growth process. The white bar at the bottom is the metallization of a 500 μm long amplifier. To realize a 30 μm saturable absorber a waveguide was positioned to cross at an angle the second active area. Light is coupled out from the ring cavity using a Multi-Mode Interference Coupler (MMI). For this design, the ring laser Free Spectral Range (FSR) could not be over 27 GHz due to the minimum ring length that could be fitted through the active regions.

Deep and shallow etched waveguides were used in order to combine deep etched waveguides for small (100 μm) bending radii with low propagation loss in shallow waveguides. To reduce facet reflectivity, output waveguides (not visible in the Fig. 1) are angled by 7° with respect to the facets normal and contain mode filters [2].

Fig. 1 Photograph showing a top-view of the fabricated device.

III. MODELLING

To simulate the performance of our device, a numerical bidirectional model has been developed. The amplifier and the absorber are described using rate equations. The ring is divided into 1500 segments that are equal in optical length. (Fig. 2). Every 25fs the photon densities (CW and CCW) and carrier densities are calculated for all segments. Then the photon densities are transferred to the next segments and the carrier density values are saved in active segments for the next step. A digital Bessel filter (14th order) simulates the gain bandwidth limitation. The filter transmission spectrum is close to the measured gain spectrum (Fig. 3) and it is numerically stable. Small reflections ($2 \cdot 10^{-4}$) at the different active passive butt-joints interfaces [3] and at the MMI inputs [4] are included in the modeling.

Fig.2: Structure of the representation of the MLL in the model.

Fig.3 Spectra of the spontaneous emission from a similar amplifier and the transmission of the digital Bessel filter used in the model.

The SOA is described using the standard rate equations and the logarithmic gain-current density validated in [5].

$$\frac{\delta P^{CW,CCW}(x,t)}{\delta t} = P^{CW}(x,t) \cdot \left[\sigma_{amp} \cdot \ln\left(\frac{N(x,t)}{N_0}\right) \cdot Vg \cdot \Gamma - \frac{Loss_{seg}(N(x,t))}{\tau_{seg}} \right] + B \cdot \Gamma \cdot N(x,t)^2 \cdot \beta$$

$$\frac{\delta N(x,t)}{\delta t} = - \left[P^{CW}(x,t) + P^{CCW}(x,t) \right] \cdot \sigma_{amp} \cdot \ln\left(\frac{N(x,t)}{N_0}\right) \cdot Vg - \frac{N}{\tau_{car,amp}} - B \cdot N(x,t)^2 - C \cdot N(x,t)^3 + W$$

Here $P^{CW,CCW}$ are the Clock Wise and Counter Clock Wise photon densities, N is the active region carrier density, W is the carrier density generated in the active layer by the injection current, N_0 is the carrier transparency density, Vg is the group velocity, σ_{amp} is the linear gain coefficient, $\tau_{car,amp}$ is the carrier lifetime, B is the bimolecular recombination coefficient, C is the Auger recombination coefficient, Γ is the confinement factor, $Loss_{seg}$ is the sum of the different losses for one segment (the scattering loss, the free carrier loss in the cladding, and the free carrier absorption within the active layer which depends of the carrier density), τ_{seg} is the time segment and β is the spontaneous emission coupling factor.

The absorber is a short SOA that is reversely biased. It is described with the same rate equations as the amplifier without carrier injection. The carrier lifetime of the absorber depends of the reverse bias applied, but the relation has not been implemented in our model. Self-phase modulation effects and coherent effects in the absorber are not included.

IV. EXPERIMENTAL AND SIMULATION RESULTS

First experimental results of the modelocked ring laser depicted in Fig. 1 showed that small reflections in the cavity have a large influence on the spectrum of the laser. Small reflections are expected at the active-passive interface and at the inputs of the MMI coupler. The spectrum varies significantly with temperature and current in the SOA due the small changes in the optical path length between reflection points. This makes the laser operating in very small operating windows.

Using our numerical model, we have calculated the performance of the ring laser. A simulation of the self-starting laser is plotted in Fig. 4. The model shows bidirectional operation of the laser like observed from the real device. The simulation starts with relaxation oscillations and modelocking sets in more slowly. The difference in intensity between the clockwise (CW) and counterCW (CCW) output is determined by the order of the amplifier, absorber and output coupler in the cavity. A steady modelocked state is reached after 16 ns (450 roundtrips). As depicted in Fig. 5, in our model a modelocked state is easily achieved for a wide range of parameters, as opposed to the experimental observations. However continuous wave (CW), self-pulsating and modelocking operation did show up in the experiments and in the simulations. We attribute this difference to not having included the self-phase modulation in the model and having fixed optical path lengths between reflections.

According to the model the laser starts to be modelocked for an absorber carrier lifetime shorter than 30 ps. For a carrier lifetime over 14 ps and amplifier currents between 100 mA and 160 mA the model predicts stable modelocking with a pulse width between 3 ps and 8 ps. When the amplifier currents are above 180 mA the model shows self-pulsation.

Fig.4: Simulation result of the self-starting MLL at I=140 mA and T_{car}=20ps

Fig.5: Simulated regimes of operation of the MLL

Fig. 6 The simulated autocorrelation trace ($I_{amp}=160\text{mA}$ $T_{car}=1\text{ps}$), and the measured autocorrelation trace $I=169\text{mA}$ $V=-2.1\text{V}$

Below 11 ps absorber carrier lifetime the model predicts pulses shorter than 1 ps. We consider the model not to be valid in this region because of the approximations made.

A pulse length close to 1 ps has been observed (Fig. 6) when the laser was in an intermittent modelocked state for periods of one to a few seconds. This operating point was at the maximum current and maximum reverse bias voltage. Looking at Fig. 5, the observation of 1 ps at 169 mA agrees with the model for an absorber carrier life time between 14 and 11 ps. The instability is explained by the fact that we are close to the self pulsating regime. In Fig. 6, the second measured pulse is not fully visible due to a limit of the autocorrelator.

Fig. 7: Optical output spectrum of the laser at $I = 167.5\text{mA}$ $V = -2.0\text{V}$.

Fig. 8: Measured RF-spectrum $I = 167.5\text{mA}$ $V = -2.0\text{V}$ (a) and (b) figure

An operating point that was stable over 5 minutes has been found. We interpret it as a situation where the cavity contains 5 pulses with a 26.6 GHz modulation. The optical output spectrum is plotted in figure 7. The RF spectra are in Fig. 8a and Fig. 8b. A strong peak (40 dB over the noise floor) that is narrow (2 MHz at 20 dB) is observed at 26.6 GHz. This indicates modelocking. The spacing between most of the modes in the optical spectrum is 133 GHz, indicating there are five pulses in the cavity with a 26.6 GHz modulation over it. We attribute the generation of the five pulses to the intra-cavity reflections at the left butt-joint of the amplifier and the upper butt-joint of the absorber. The distance between these two reflections corresponds to one fifth of the cavity roundtrip time. We have attempted to recreate reproduce this regime in our model. A 5 pulses mode was found that was stable for 3 ns (80 roundtrips), but then one of the pulses became dominant and suppressed the other pulses.

V. CONCLUSION

We have presented the first integrated extended cavity passively modelocked ring laser using active-passive integration and its modeling. Experimental results show that intra-cavity reflections make it difficult to reach a stable modelocked state. However in small windows of operation modelocked regimes have been observed. The model predict much wider operating windows. However the observed modelocking point is in line with the model predictions.

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