Design of monolithically integrated InGaAsP/InP passively-modelocked linear quantum well lasers in an active-passive integration scheme

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In this paper simulation results of Fabry-Perot mode-locked lasers are presented that are based on measured modal gain data of InGaAsP quantum well optical amplifiers. Gain spectra were measured for various values of injected current density. The gain spectra were fitted to an analytical formula to describe the spectra using a few parameters. These were used as input parameters in a series of simulations of mode-locked lasers. The performance of three-section passively mode-locked lasers (amplifier, saturable absorber and passive waveguide) was studied for various lengths of the absorber and passive waveguide sections as well as various reflectivity values of the resonator mirrors.

Introduction

Short-pulse generation by semiconductor mode-locked lasers has a large number of applications in areas such as data communications, metrology and high-resolution imaging. In order to apply mode-locked lasers to viable applications, lasers with controlled properties such as repetition rate, output power, operating wavelength should be developed. Passive mode-locking can be achieved by combining two elements, a semiconductor optical amplifier (SOA) and a saturable absorber (SA), in a cavity which can have a number of different geometries [1], [3]. In order to increase the field intensity profile in the SA, a colliding pulse configuration is applied. For a linear laser in such a configuration the SA is typically placed in the middle of the cavity or next to a high-reflectivity facet *-[1]. However, it was theoretically predicted [2] that placing the SA section close to the output coupler facet with reduced reflectivity (e.g. 20%) leads to a significant increase in output power and a reduction in amplitude and timing jitter. To implement such a design in a an photonic integrated circuit with active-passive integration, mirror structures (distributed Bragg reflector or MMI reflector) should be used that are of a finite length. The presence of such additional passive sections in the resonator can have a significant influence on the interaction of the pulse with itself in the absorber.

In this work the performance of Fabry-Perot mode-locked lasers with the SA placed close to the output coupler of a finite length is studied. Experimentally obtained gain characteristics from quantum well optical amplifiers were used as input parameters for the simulations.

Gain measurements

The gain spectra measurements were performed on quantum well InGaAsP/InP SOAs with four quantum wells in the layer stack for a range of injection currents. The measurement method is based on the analysis of amplified spontaneous emission (ASE) spectra from different lengths of SOA as described by [4], [5]. Using this method the gain spectra can be measured over a wide range of injection currents. The gain ***G*** for each wavelength can be extracted from the dependency of ASE power ***P*** on the length of SOA ***L*** as:

$$P = \frac{P_{sp}}{L}\left(e^{GL} - 1\right),$$

where $\mathbf{P_{sp}}$ is the spontaneous emission power. The ASE spectra were measured for four different lengths of SOA (100 – 200 – 400 and 800µm) at constant current density. This series of amplifiers of different lengths was available on a single chip that was fabricated using active-passive integration technology.

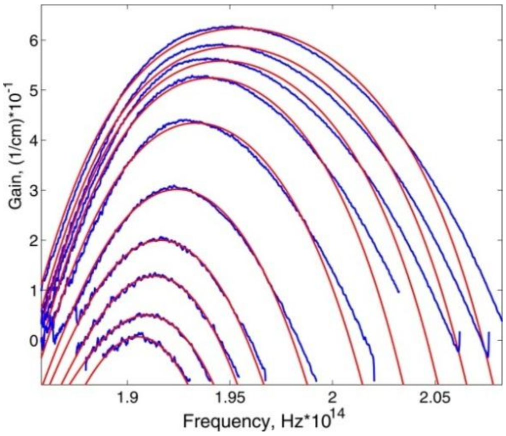

Fig.1. Experimentally obtained gain spectra (blue curve) for injected 1880 A/ cm^2, 2000 A/ cm^2, 2200 A/ cm^2, 2400 A/ cm^2, 3000 A/ cm^2, 4000 A/ cm^2, 5000 A/ cm^2, 6000 A/ cm^2, 7000 A/ cm^2, 8000 A/ cm^2, which are fitted (red curves) by formula (1).

The ASE spectra were measured for injecting current densities from 500 A/cm^2 till 8000 A/cm^2 at 20 ^{o} C. Figure 1 (blue curve) presents the gain spectra for different current densities. The red curve in Figure 1 corresponds to the fitting results which were obtained using the formula presented by [3]:

$$G(\omega, N) = a\left[\arctan\left(\frac{\omega-\omega_0}{\gamma}\right) - 2\arctan\left(\left(\frac{\omega-\omega_0}{\gamma}\right) - \frac{N}{N_0}\right) - \frac{\pi}{2}\right] + losses, (1)$$

where a = $G\chi_0$, χ_0 is maximal saturated gain, ω is frequency, N – career density, N_0 – carrier density at band gap frequency ω_0, γ is width of optical transition. Parameters ω_0, N_0, γ and χ_0 extracted from the fitting are (1.855±0.02)*10^{14} Hz, (3.8±0.2)*10^{23} m^{-3}, (0.06±0.015)*10^{14} Hz, 100±20 cm^{-1} respectively.

Simulations of a linear modelocked laser with repetition rate 40 GHz have been performed using the FreeTWM (Travelling Wave Model) software [7]. The length of the simulated device was 1.04 mm and refractive group index 3.6. The injected current was set at 19 times the amplifier transparency current I_{tr}.

Simulations were performed for different lengths of passive section between the reflector and SA (25µm long). These have shown that the power and stability of pulse intensity grows with decreasing of length of passive section (see e.g. Figure 2). Stable pulses are still obtained for a passive section length of 100 µm. When using a DBR grating as an output coupler, the reflectance around 20% can be achieved with a 100 µm length DBR (κ = 50 cm^{-1}). In the following simulations the resonator consists of 100 µm length passive section and a mirror with R = 20%, a short SA, the SOA and a high reflectance facet at the side of the SOA with R= 80%**.**

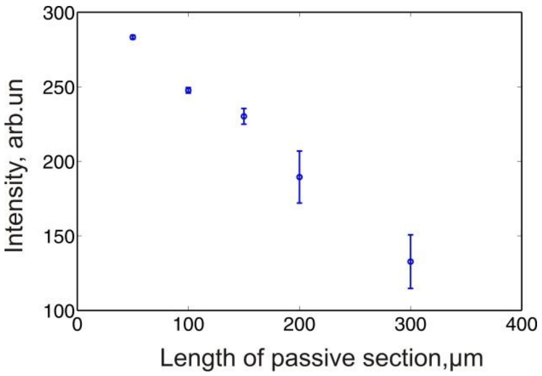

Fig.2. The peak intensity dependency on the length of passive section. The error bars correspond to the deviation of intensity with time.

Influence of absorber length and output coupler position

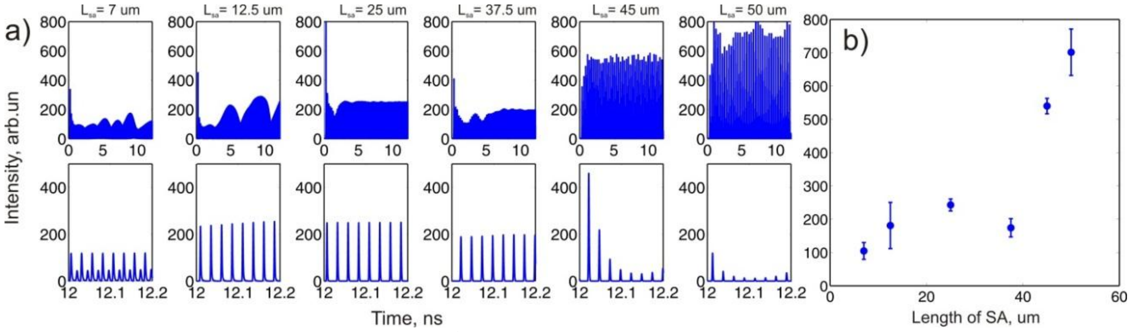

Fig.3. a) Output intensity time traces for the Fabry-Perot resonator with various absorber length between 7 um and 50 um. The lower row of figures represents the same dependency but in a different time scale. b) The peak intensity dependency on the length of SA. The error bars correspond to the deviation of intensity with time.

The influence of the absorber length on the mode-locking regime was also studied. In Figure 3 (a) the time traces of the output intensity for the different lengths are presented. Simulations have been performed for various lengths of SA between 7 µm (0.7%) and 50 µm (5 %). Other parameters were kept the same as in the simulations above. The lower panel of figures shows intensity profile in the shorter time scale. Stable regime of mode-locking can be obtained for SA length around 25 µm. For the SA with a length around 40 µm and more, Q-switching is observed. For the shorter section of SA a second (satellite) pulse can be observed in the pulse train. The Figure 3 (b) shows the average output peak intensity as a function of the length of SA. The error bars represent the standard deviation. It can be seen that the most stable regime is obtained for the length of the SA around 25 µm (3%).

A comparison was made between the performance of the MLL with the output coupler (OC) next to the passive section and absorber and with the OC (ROC=20%) next to the SOA. The high reflector was set at 80%. The SA length is 25 µm and the length of passive section was taken 100 µm, other parameters also remained the same.

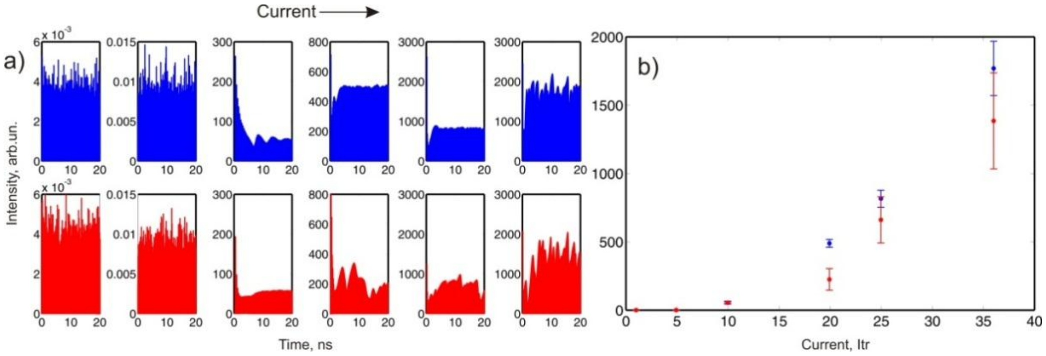

Fig.4. a) Output intensity time traces for the Fabry-Perot resonator under different injecting current between I_{tr} (transparency current) and 36*I_{tr}. The upper panel (blue curves) correspond to the output intensity time trace for the case when SA is placed close to the OC (set 1), lower panel (red curves) corresponds to set 2. b) The output pulse intensity versus the injection current value.

The configurations thus keep the cavity losses constant. Figure 4 shows the time behavior of pulse intensity for two different reflectivity sets. The calculated pulse trains for different injecting current values are shown on Figure 4 (a). The bottom row of figures with red lines represent situation 2 in which the SA is placed next to the high reflection facet and the top row of figures with the blue lines present the results for the opposite situation. The dependency of the peak intensity on the injected current is shown on Figure 2(b). It can be seen from Figures 4a) and 4b) that the intensity in both cases is growing with injection current. First two points when the $I = I_{tr}$ and $I = I_{tr} \cdot 5$ represent the situation when the pulses are not distinguishable. The mode-locking regime appears under the higher injected current (2, 3 and 4 subplot). When injected current is higher than $25 * I_{tr}$ Q-switching regime is again observed. The configuration with the SA placed close to the OC shows a larger current range for which the modelocking is stable and with a higher peak intensity in comparison.

Conclusion

From our simulations based on experimentally recorded gain spectra, we can determine an optimum length for the SA in the MLL. We can also conclude that even if there is up to 100µm distance between the OC and the SA there is a clear advantage to place the OC in the MLL close to the SA.

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