Experimental study of the stability of a linear passively mode-locked laser

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Measurements on a monolithic extended cavity linear passively mode-locked laser in two configurations are presented. We investigated the theoretical prediction that placing the saturable absorber close to the output mirror instead of the high reflecting mirror leads to a reduction of amplitude and timing jitter. Our results seem to confirm there are indeed advantages. For both configurations mode-locking was observed. A beat tone with a 10 dB linewidth of 19 kHz was observed.

Introduction

Semiconductor passively mode-locked lasers (PMLs) became subject of interest as compact and robust sources of short optical pulses and wide coherent optical combs. Both of these properties find their application in such areas as telecommunication, generation of microwave, clock recovery and high speed gas spectroscopy. For all these applications low phase noise is necessary to fulfil the requirements. However, semiconductor PMLs still represent a theoretical and experimental challenge **[1]** especially regarding stability of the pulse train. Several techniques have been devised in order to bring this area forward. One of them is self-colliding passive mode-locking. In this scheme a saturable absorber (SA) is placed close to the high reflectivity facet, which allows the pulse to interact with itself within the SA. However in **[2]** theoretically it was shown that placing the SA next to the low reflectivity mirror leads to a better performance of the laser due to the weaker saturation of the gain and enhanced modulation of the SA. The prediction is that amplitude and timing jitter are reduced. For the fixed SA voltage the enlargement of the stable mode-locking current range was shown. However, the output properties of PML vary significantly with various voltages applied on the SA. In this paper we present an experimental study of both self- and anti-colliding passive mode-locking schemes for various bias conditions.

Linear passively mode-locked laser

Passive mode-locking can be achieved by combining a semiconductor optical amplifier (SOA) which provides gain that saturates at high intensities and a saturable absorber (SA). The combination of saturation processes in the SOA and the SA can lead to optical pulse formation [1]. In this work we present the linear laser design which includes not only a SOA and a SA but also passive waveguides. A schematic sketch is shown in Figure 1. The repetition rate is determined by the total length of the cavity and can be varied by the change of the length of low-loss passive section. In the case of low repetition rates the use of passive waveguides allows to overcome or reduce self-phase modulation effects caused by propagation through active section.

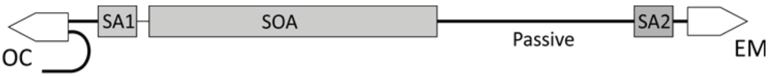

Figure 1. Sketch of linear passive mode-locked laser. Multimode interference reflectors (MIR) with 50% and 100% reflection were used as a mirror. Three active sections (grey) were positioned in the way that colliding and anti-colliding designs were realized.

Multimode interference couplers (MIR) of 50% and 100% reflections were used as output coupler (OC) and end-mirror (EM) respectively. The laser contains two short active sections (SA1 and SA2) and one longer section (SOA) which were based on a multi-quantum well waveguide core. The active sections SA1 and SOA are electrically isolated. Such a design allowed for realizing two configurations in the same device. The SA can be located near the OC or near the EM. The 'SA near OC' configuration can be achieved by the applying a reverse bias on SA1 and a forward bias of the same current density on the SOA and SA2 sections. In order to investigate the performance of the laser when the SA is placed at the high reflectance facet SA1 and the SOA must be forward biased and SA2 must be reversely biased. The total length of the cavity was 5.55 mm (7.4 GHz repetition rate). The SOA section was 2 mm long and SA1 and SA2 had equal length of 100 μm. The device presented here was fabricated within a multiproject wafer run available through an Oclaro foundry service.

Characterization of linear PM laser with MIR reflector

The device was mounted on a copper chuck and the temperature was stabilized at 18° C. The output light was collected using lensed fibers with antireflection coating. Optical isolators were used to prevent back reflections into the cavity. The optical comb of longitudinal modes and beat signals of these modes were observed under various operating conditions. The optical spectra were recorded using a 100 MHz resolution spectrum analyzer. RF beat tones were generated in a 50 GHz photodiode and recorded using a 50 GHz electrical spectrum analyzer. Figure 2 (a, b) shows examples of a RF and an optical spectrum recorded at I_{SOA}= 96 mA and U_{SA1}=-0.6 V. The RF spectrum in Figure 2 (a) shows a clear peak at the fundamental frequency 7.4 GHz. The inset shows full span RF spectrum with second and third harmonics at 14.8 GHz and 22.2 GHz respectively. The observed peak had a 36.5 dB height over low frequency components and a 73 kHz width measured at -10 dB (~25 kHz FWHM). The optical spectrum in Figure 2 (b) shows optical comb of longitudinal modes separated by 7.4 GHz.

The different operational regimes observed depend on the bias conditions. Figure 2 shows maps of the height of the RF peak (in dB) at the fundamental frequency of 7.4 GHz over the low frequency noise as a function of I_{SOA} and U_{SA} when SA1 Figure 2(c) or SA2 Figure 2(d) is used as the SA. The limit of injected current was determined by the maximum power of the heat dissipation in the SA caused by the absorbed optical power. It was shown [2] that in the 'SA near EM' configuration the average power of the pulse in SA is much lower than the 'SA near OC' configuration. This allows for higher pumping currents in the 'SA near EM' scheme (Figure 2 (d)). The blue zone indicates continuous wave (CW) operation (RF peak heights of 0 dB).

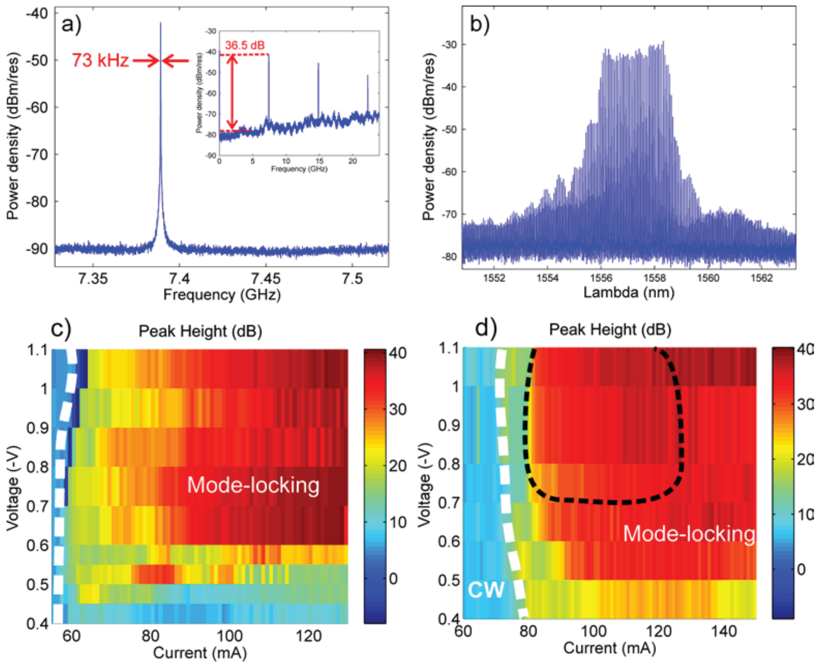

Figure 2. a) RF spectrum recorded at I_{SOA}= 96 mA and U_{SA}=-0.6 V for the case when absorber is placed to the low reflectivity output mirror. Inset: Broadband RF spectrum showing second and third harmonics. b) The optical spectrum at the same operating conditions as in (a). A map of the RF peak height as a function of bias conditions measured for the case when SA is placed at the output coupler (a) and when SA is at the end mirror (b).

Figure 2 (c) shows a region where the RF peak height has negative values (dark blue zone). It means that low-frequency components (between 25 MHz and 2 GHz) are present and exceed the RF peak at the fundamental frequency. A laser can exhibit Q-switched mode-locking when saturation process in the gain and SOA are not balanced within one round trip. For the both configurations the device enters the mode-locked state (red and yellow zone) with increasing I_{SOA}. Notice that the laser in the 'SA near OC' configuration (Figure 2 (c)) shows an increase of RF peak power from 20 to 40 dB over the low frequency noise with increasing I_{SOA}. This is related to the increase of total optical power. In this case the ratio between the AC and DC signal stays constant over a whole range of operating conditions which correspond to the mode-locking state. However, in the case of the 'SA near EM' configuration (Figure 2 (d)) the RF peak height does not grow with an increasing I_{SOA}. The AC/DC power ratio achieves maximal values at the bias conditions indicated by the black dashed contour. Further increase of I_{SOA} leads to the broadening and decrease of the RF signal at the fundamental frequency. This indicates decrease of mode-locking quality.
In order to compare the stability of the pulse train of both configurations, the linewidth of the RF peak for various operating conditions was measured. Figure 3 shows maps of the RF linewidth measured at the -10 dB level. Figure 3 (a) presents different zones indicating linewidths of the RF peak for the 'SA near OC' scheme. The dark blue zone

outlined by a red line represents the range of conditions where the RF peak linewidth was below 80 kHz. An RF peak with a minimum linewidth of 19 kHz was measured within this zone at I_{SOA}= 108 mA and U_{SA}= -0.7 V. The dark blue zone is surrounded by the colorful zone where RF peak linewidths from 80 kHz to 3 MHz were observed. The dark red background indicates the region with RF peak widths over 3 MHz.

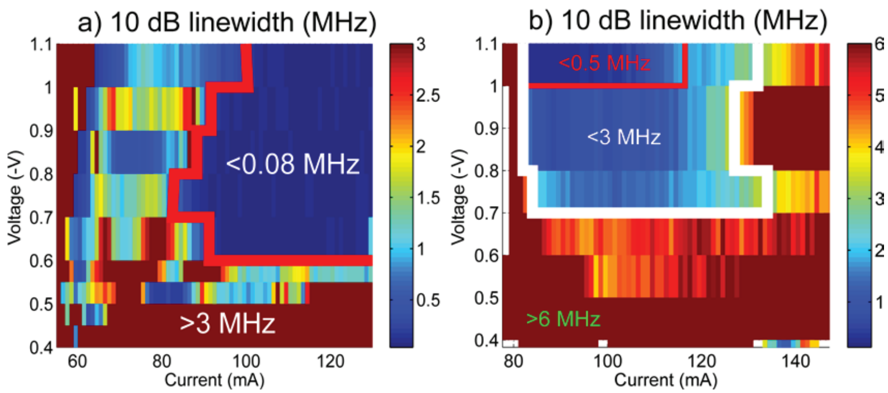

Figure 3. A map of the RF linewidth measured at 10 dB level for the case when SA is placed at the output coupler (a) and when SA is at the end mirror (b).

The best-quality mode-locking for the 'SA near EM' configuration was observed for the range of I_{SOA}= 90-110 mA and at the highest U_{SA}= -1.1 V. It showed an RF peak with a minimum 10 dB linewidth of 144 kHz. The operating region with an RF linewidth below 0.5 MHz is indicated by the red line. This region is surrounded by the blue-colored zone where RF peaks of the linewidth from 0.5 to 3 MHz were observed. Further increasing I_{SOA} and decreasing U_{SA} leads to more severe broadening of the RF peaks. The dark red background indicates RF peaks wider than 6 MHz.

In summary, we have studied experimentally the impact of the position of SA on the performance of extended linear cavity passively mode-locked laser. The analysis of RF spectra showed that when the SA is placed at the OC, the RF linewidth is reduced. This configuration also showed larger range of operating conditions where high-quality mode-locking was observed.

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References

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