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Gain-Switched Versus Regular Pulse Trains in a Semiconductor Laser with Optoelectronic Feedback

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Abstract—Optoelectronic feedback on a laser diode is demonstrated to generate two distinct modes of pulse-train formation depending on the injection current \( J \) of the laser. For \( J \) close to the threshold current \( J_{th} \), the pulse repetition rate is the inverse of the loop delay. This behaviour is attributed to feedback-induced gain-switching. In contrast, for \( J \gg J_{th} \), the repetition rate is observed to be related to the relaxation-oscillation frequency \( f_{RO} \). The potential to generate pulse trains and associated microwave combs may find use in metrology, optical communications, sampling, and spectrosopy.

Index Terms—Self-modulation, Optical pulses, Optoelectronic feedback, Semiconductor Laser, Gain-switching.

I. INTRODUCTION

THE generation of short optical pulses by semiconductor lasers (SL) is of interest in communications, spectroscopy, plasma formation, medicine, and elsewhere [1]–[3]. If the pulses are periodically spaced, the power spectral density of the photodetected optical intensity \( I(t) \) forms a microwave (MW) frequency comb (MWC). Pulse-train formation—and consequently MWCs in SLs may arise from Q-switching [4], gain-switching [5]–[7], or mode-locking [8]–[10].

Gain-switching, of relevance to the present study, is achieved by modulating the carrier density while operating close to the lasing threshold; it occurs due to a slow (ns timescale) accumulation of carriers in the active region followed by fast (ps timescale) depletion of the photon population by stimulated emission. External modulation, by electrical injection [11] or optical injection [6] may be used to achieve gain-switching. In addition, self-modulation induced by optoelectronic (OE) feedback [5], [7], may result in gain switching. In this last case, the repetition rate is given by the inverse \( f_R \) of the feedback loop delay time \( \tau \). Much higher repetition rates determined by the relaxation-oscillation (RO) frequency \( f_{RO} \), and not related to the gain-switching mechanism have also been observed in a laser with OE or optical feedback [8], [12], [13].

It is attractive to generate directly MWCs using SLs directly, i.e., without external modulation, is attractive. At least one of the three references cited hereafter do have external modulation. Please adapt However, the majority of the reports Is it really the majority? on MWCs with semiconductor laser employs master-slave laser configuration to initially generate an ‘all right’ comb and feed it to a second laser to redistribute its spectral energy among the comb teeth to improve the bandwidth and flatness [14]–[16]. The best reported MWC have bandwidth extends up to several tens of gigahertz with comb-teeth space up to is “up to” appropriate here? few gigahertz [include references].

Although MWCs based on SLs have been demonstrated involving a variety of setups and mechanisms, self-optical pulsing resulting from more than one mechanism with the same experimental setup has not to date been reported. The present work demonstrates experimentally that a SL subjected to delayed OE feedback can access two distinct regimes of pulse-train formation, viz., with repetition rate \( f_p \) determined by \( f_R \) (henceforth \( f_R \)-pulsing) or by \( f_{RO} \) (\( f_{RO} \)-pulsing). \( f_R \)-pulsing occurs when the SL is biased close to the threshold and results from gain switching due self-modulation by the feedback on the laser current. This kind of pulse train has been relatively sparsely explored [3], [7]; interestingly, the repetition rate can be tuned continuously by varying the delay and MWC with comb-teeth spacing as low a few tens of megahertz can be obtained [Do you have a ref for the tens of hundreds of MHz or is this a conjecture?]. By contrast, \( f_{RO} \)-pulsing is observed when the SL is biased much higher than threshold [18], [19]. In this case, the repetition rate is not solely dependent on the delay in the feedback loop, but is related to the internal SL dynamics and the relaxation oscillations between carrier and photon populations. More generally, various dynamical states have been observed when a SL with OE feedback is biased well-above threshold; including periodic dynamics with frequency \( f_p \) given by rational fractions of \( f_{RO} \) and \( f_R \) [13], [20], [21], quasiperiodicity and chaotic pulsing [give references for the latter two].

Section II provides a description of the experiment, Sec. III presents the experimental results, while Sec. IV gives our conclusion.

II. EXPERIMENT

A single-mode DFB edge-emitting SL based on an InGaAsP/InP strained-layer multi quantum well (MQW) is used. Its facets are anti-reflection-coated. It operates at 1550 nm and has low beam divergence. A regulated current source (Thorlabs LDC201CU) drives the thermally stabilized SL. The external quantum efficiency is 0.22 mW/mA with minimum nominal output power of 20 mW at 200 mA and a measured threshold current of \( J_{th} \sim 20 \) mA at room temperature. The experimental setup is depicted in Fig. 1 [see Ref. [22] for models of the devices].

The output of the SL is fed to a photodetector (PD, Model); the optical path is composed of a collimating lens, a fiber
coupler, and an optical isolator to avoid unwanted optical reflections into the laser. The light incident to the PD is converted to an electrical output and amplified by an integrated low-noise amplifier. To enhance the feedback strength, the output of the PD is sent to a cascade of two 30-dB inverting amplifiers (Microsemi UA0L30VM – 30 GHz). Further, to avoid saturating the laser, a 12 dB attenuator (Minicircuits BW-S6W2+, DC-18 GHz) is employed. The signal at the output of the attenuator is then routed to the MW input (26.5 GHz bandwidth) arm of the bias tee (BT) which adds the DC injection current $J$ to the feedback signal before delivering it to the SL through an electrode (GSG 400, Cascade Microtech). The feedback is positive and we operate in a regime where the only significant nonlinearities arise in the SL itself. A delay time ($\tau$) of 32.87 ns is used for temporal characterization while a second delay of 9.89 ns is introduced later for $f_p$-pulsing.

We will focus on operation of the laser slightly below threshold, giving the $f_p$-pulsing regime, and on the second regime ($f_{RO}$-pulsing) which is observed around twice the threshold current. Can you add info on the range of currents for which you have the second regime? The pulse repetition rate $f_p$ is measured from the MW spectrum of the output $I(t)$ of the PD. We now focus on characterizing the pulse trains. Specifically, we wish to characterize them by means of figures of merit that may impact the exploitation of the pulse-train generation for MWCs. Of note, all characteristics discussed here are obtained from the photodetected optical intensity $I(t)$, and not from the optical field or optical spectra; therefore we make no claims about optical combs.

We are interested in the jitter characteristics of the pulse trains \cite{23, 24}. The amplitude and timing jitter are denoted by $\sigma_{amp}$ and $\sigma_{tim}$ respectively; they are calculated as the standard deviation (STD) of the instantaneous variation in the amplitude $I(t)$ or period ($T_{th}$) with respect to the mean \cite{24}, respectively, i.e., $\sigma_{amp} = \text{STD}[I(t) - \langle I(t) \rangle]$, $\sigma_{tim} = \text{STD}[T_{th} - \langle T_{th} \rangle]$. We also characterize the full width at half maximum (FWHM) of the pulses. The MWC bandwidth is determined by the difference between the highest and lowest MW frequencies that fall within a predefined tolerance band (we set the band to $\pm 10$-dB around the mean). As for flatness, although frequently used to describe MWCs in a qualitative manner, we have used a numerical approach common in audio engineering for tonal purity. A figure of flatness is obtained by dividing the arithmetic mean of the peak heights in the magnitude spectra by their geometric mean. For a perfectly flat MWC both geometric and arithmetic means would be equal, leading to a flatness of 1.

We first turn to characterize the pulse trains for $f_p$-pulsing ($J \leq J_{th}$ with $J_{th} = 20$ mA). (a) $J = 17.93$ mA. Photodetected time series $I(t)$ showing a pulse train with repetition rate $f_p = 32.87$ ns. (b) $J = 39.53$ mA. Photodetected time series $I(t)$ showing a pulse train with repetition rate closely around the first subharmonic of $f_{RO}$.

**III. Results and Discussion**

We begin by presenting, in Fig. 2, the temporal representation of $I(t)$ in the two regimes. The $f_p$-pulsing regime [Fig. 2(a)] shows a series of bright pulses at repetition rate $f_p = f_r = 30$ MHz. $I(t)$ is near zero between pulses, since only when a pulse is fed back into the injection terminal from the OE feedback loop does the gain rise above threshold as in Ref. \cite{3}. By contrast, Fig. 2(b) illustrates an example of $I(t)$ for $f_{RO}$-pulsing with $J \gg J_{th}$ showing $f_p \sim 1.63$ GHz which is determined by $f_{RO}$. Be more specific. Give the value of $f_{RO}$ and show how $f_p$ is related to it.

![Fig. 1. Experimental setup. BT: Bias Tee, SL: Semiconductor Laser, CL: Collimating Lens, OE: Optical Isolator, LP: Linear Polarizer, FC: Fiber Coupler, PD: Photodetector, Amps: Amplifiers. The OE is inserted to prevent any back reflection to the LD. The injection current of the SL Substitute LD with SL in the Fig is self-modulated with a feedback signal injected through the BT. The fed back signal originates from the PD and is amplified before feeding it to the MW input arm of the BT. Measurements are performed after the PD. In the figure, the symbol of the Collimating lens should look like the symbol of a lens. Use the same symbol as the one of the FC.](image)

![Fig. 2. Pulse-train generation in the two regimes ($J \leq J_{th}$ and $J \gg J_{th}$) with $J_{th} = 20$ mA. (a) $J = 17.93$ mA. Photodetected time series $I(t)$ showing a pulse train with repetition rate $f_p = 32.87$ ns. (b) $J = 39.53$ mA. Photodetected time series $I(t)$ showing a pulse train with repetition rate closely around the first subharmonic of $f_{RO}$.](image)
gives the jitter normalized by their respective means, \( \tilde{\sigma}_{\text{amp}} = \sigma_{\text{amp}}/ <I(t)> \) and \( \tilde{\sigma}_{\text{tim}} = \sigma_{\text{tim}}/ <T_{I(t)}> \). \( \tilde{\sigma}_{\text{amp}} \) and \( \tilde{\sigma}_{\text{tim}} \) will be used to compare the FoMs between the \( f_2 \) and \( f_{RO} \) pulsing regions since both amplitude and period are considerably different for these two cases. Both \( \tilde{\sigma}_{\text{amp}} \) and \( \tilde{\sigma}_{\text{tim}} \) also show a consistent downward trend with increasing \( J \), demonstrating an improvement in the quality of the pulse train. As \( J \) increases, the peak amplitudes of \( I(t) \) vary from 100 a.u. to 130 a.u. while \( \tilde{\sigma}_{\text{amp}} \) varies by 15% to 5% and \( \tilde{\sigma}_{\text{tim}} \) varies in over 0.055% to 0.045%. An interpretation might be that as \( J \) increases and gets closer to \( J_b \), the directly injected carriers play a stronger role in the pulse dynamics comparatively to the random fluctuations caused by the noise present in the system.

The previous paragraph discusses \( f_2 \)-pulsing. Jitter characteristics for \( J \gg J_b \), as a function of \( J \), are shown in right column of Fig. 3. Describe here the relation of \( f_p \) to \( f_{RO} \) in the whole current range. We do not observe a clear trend in the variation of the jitters, not in the FWHM, with \( J \), in the range explored. However, we observe that the amplitude jitter, expressed as a percentage, is considerably smaller than in the \( f_2 \)-pulsing regime. The timing jitter is also considerably lower than in the \( f_2 \)-pulsing regime. Finally, FWHM is almost 10 ps smaller. This observation is consistent with observations reported in [25] which show that a MWC obtained by gain-switching through an external source performs worse than a mode-locked MWC. The inferior behavior of the gain-switched MWC could result from the fact that the shape, pulsewidth, and time interval of each pulse under gain-switching is slightly different due to the statistics of spontaneous emission when the gain is increased above threshold [26].

In the following, we focus on the MWCs observed in the MW spectrum of \( I(t) \). They are characterized by their bandwidth and spectral flatness; results are presented for the \( f_2 \)-pulsing regime only since MWCs in the \( f_{RO} \)-pulsing regime, based on optical-injection, have been widely explored [14]–[16], [27]. We consider two values for \( \tau \). In Fig. 4(a), \( \tau = \tau_1 = 32.87 \) ns and \( J = 17.90 \) mA. In Fig. 4(b), \( \tau = \tau_2 = 9.89 \) ns and \( J = 21.60 \) mA. The MW spectra appear to be both flatter and broader for the shorter time delay \( \tau_2 \) than for \( \tau_1 \) based on the \( \pm 10 \)-dB criterion. Give here the flatness and bandwidth for Fig 4(a) and 4(b). The change in bandwidth and flatness, for \( \tau_1 \) and \( \tau_2 \), as \( J \) is varied, is represented in Fig. 5. For the longer delay \( \tau_1 \), the bandwidth varies within the 7 to 8 GHz range while the flatness varies between 0.991 and 0.994; for the shorter delay \( \tau_2 \), the bandwidth of the MWC is between 8 to 10 GHz with a flatness between 0.993 and 0.997. We thus observe consistently that, in terms of bandwidth and flatness, shorter \( \tau \) tends to lead to higher quality MWCs. This phenomenon can be attributed to smaller losses in the delay line as evidenced by the increase in measured spectral magnitude by 20 dBm when the delay is varied from \( \tau_1 = 32.87 \) ns to \( \tau_2 = 9.89 \) ns. It appears, in addition, that there is a trade off between bandwidth and flatness as they show opposite trends for both delay values in Fig. 5(a) and (b).

The bandwidth we can achieve is limited both by the higher cutoff frequency of the PD (12 GHz) and the fact that the delay cannot be smaller than 9.89 ns, due to the size of the components. As a consequence, the raw results from our unoptimized system likely does not offer MWCs comparable to Refs. [14]–[16]. Specifically, the report in Ref. [16] shows \( f_{RO} \)-pulsing can be made to produce MWCs as broad as 33.6 GHz using a master-slave laser configuration. In comparison, a single SL in OE scheme in our experiment offers a bandwidth of only 10 GHz with the \( f_\tau \)-pulsing regime. However, this regime offers comb-teeth space as small as few megahertz, which can be used in cases where precision measurement of frequency in a narrow bandwidth is necessary. In addition, the trend shows it is possible to have larger bandwidth using a
Fig. 5. (a) bandwidth and spectral flatness is presented for $\tau_1 = 32.87$ ns and (b) the same is presented for $\tau_2 = 9.89$ ns. The range of injection current where the periodic pulsing is found for the two cases are different significantly and shorter delay offers wider range of injection current for gain-switched regular pulses.

smaller $\tau$, which could be expected to be as small as few ns by careful design of the setup and with proper placement and integration of components whenever possible.

IV. Conclusion

In conclusion, we report optical pulse-train generation in a SL diode with OE feedback in two regimes. When $J \gg J_{th}$, the repetition rate is much higher and governed by the relaxation oscillation frequency of the laser. The temporal characterization shows better jitter performance and pulse width in this regime. When $J \leq J_{th}$, the self-gain-switching leads to a repetition rate $f_r$ that is solely determined by the length of the delay loop. We show that by decreasing the delay, the repetition rate increases while improving the bandwidth and flatness of the MWC. Moreover, by slightly increasing the current, while remaining close to threshold, jitter characteristics improve. Despite the presence of noisy component (e.g. amplifiers) in the OE feedback loop, the MW spectra observed experimentally show a flat sequence of equally spaced lines that may be of interest for metrology, optical telecommunications, sensing, spectroscopy, and MW photonics.

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References


