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**IEEE Photonics Technology Letters**

*DOI:*
10.1109/LPT.2024.3386585

Accepted/In press: 15/05/2024

Publisher's PDF, also known as Version of record

*Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):*
Fan, Y., Shore, K. A., & Shao, X. (in press). Optical Frequency Comb Generation in Gain Switched Semiconductor Nanolasers With Optical Injection. *IEEE Photonics Technology Letters*, *36*(10), 661-664. https://doi.org/10.1109/LPT.2024.3386585

# Optical Frequency Comb Generation in Gain Switched Semiconductor Nanolasers With Optical Injection

Yuanlong Fan, K. Alan Shore, *Life Senior Member, IEEE*, and Xiaopeng Shao

***Abstract*— In this letter, we study the generation of optical frequency combs (OFCs) by optically injecting gain switched (GS) semiconductor nanolasers (SNLs). Calculations have been performed using rate equations, which include the Purcell cavity-enhanced spontaneous emission factor $F$ and the spontaneous emission coupling factor $\beta$. In the analysis, the influence of $F$ is evaluated for varying the injection strength and frequency detuning between the master and slave nanolaser. It is observed that, in general, injection locking regions can be achieved due to optical injection over a wide range of parameter space in which the generated OFCs have a broad 10 *dB* frequency span ($f_{10}$), high carrier to noise ratio (CNR) and narrow linewidth. Moreover, $f_{10}$ and CNR can be further enhanced by increasing the injection strength. Furthermore, $f_{10}$ and CNR respectively decreases and increases with the increase of $F$. These novel findings underpin the development of simple and compact OFC sources using optically injected GS SNLs in photonic integrated circuits.**

***Index Terms*— Gain switching, optical frequency combs, semiconductor nanolasers.**

## I. INTRODUCTION

OPTICAL frequency combs (OFCs) are optical spectra consisting of a series of repeating, equally spaced spectral lines which have found their applications in various [1]. There are several methods of generating OFCs, among which using gain switched (GS) semiconductor lasers (SLs) have been advancing rapidly in recent years [2], [3], [4] due to their merits of low cost, easy implementation and high flexibility. This method can also be extended to use optical injection (OI) technique to improve the spectral quality of the generated OFCs [5]. In the OI arrangement, light from a source master laser with low phase noises is injected into a target slave laser which is gain switched by a microwave frequency alternating current coupled with a direct bias current.

Depending on the strength of the injected light and the frequency detuning between the master and slave laser frequency, phase noises of all the comb lines in the OFCs can be locked to that of the master laser [5]. This locking effect arising from OI has been investigated using a variety of SLs, including distributed feedback (DFB) lasers [6], vertical cavity surface emitting lasers (VCSELs) [7], discrete mode (DM) lasers [8] and Fabry-Perot (FP) lasers [9].

The purpose of this letter is to explore theoretically the impact of OI in GS semiconductor nanolasers (SNLs) using, where possible, experimental parameters. SNLs generally refer to miniaturized SLs that have sizes smaller than the free-space laser wavelength in all three dimensions [10]. In recent years, considerable attention has been given to the development of SNLs [11]. The main driver for such activity is the need for miniaturized lasers compatible with general applications of nano-photonics. On the other hand, SNLs are anticipated to exhibit enhanced dynamical performance due to the Purcell effect [12] which accelerate the interactions between the gain medium and the laser mode, leading to an enhanced coupling efficiency of spontaneous emission into the lasing cavity mode. This effect can further accelerate the temporal response when SNLs are subject to high-frequency modulation [13]. In our recent work [14], this unique dynamical performance has been identified to generate broadband OFCs when the SNL is gain switched. It is therefore of interest to investigate GS SNLs under OI.

## II. MODEL

The dynamics of GS SNL with OI can be described by the temporal evolution of its photon density $S(t)$, optical phase $\phi(t)$ and charge carrier density $N(t)$, where $t$ is the time. In this letter, the temporal evolution of these variables is simulated using a modified form of single mode rate equations, where the Purcell enhanced spontaneous emission factor $F$ and spontaneous emission coupling factor $\beta$ have been included [15]. The rate equations to simulate OFCs generated by a GS SNL with OI are:

$$\frac{dS(t)}{dt} = \frac{\Gamma F \beta N(t)}{\tau_n} + \left\{ \Gamma g_n \left[ N(t) - N_0 \right] - \frac{1}{\tau_p} \right\} S(t) + 2k_{inj}\sqrt{S(t)S_m(t)}\cos\left[\phi_m(t) - \phi(t)\right] + F_s(t) \quad (1)$$

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Manuscript received 19 December 2023; revised 2 April 2024; accepted 5 April 2024. Date of publication 9 April 2024; date of current version 19 April 2024. This work was supported by the Proof of Concept Foundation of Hangzhou Institute of Technology, Xidian University, under Grant GNYZ2023QC0402. *(Corresponding author: Yuanlong Fan.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2024.3386585.

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2}\Gamma g_n\left[N(t) - N_0 - \frac{1}{g_n\tau_p}\right] - 2\pi\,\Delta f_{\text{det}}$$
$$- k_{inj}\sqrt{S_m(t)/S(t)}\,\sin\left[\phi_m(t) - \phi(t)\right] + F_\phi(t) \quad (2)$$
$$\frac{dN(t)}{dt} = \frac{I(t)}{eV_a} - \frac{N(t)}{\tau_n}\left[F\beta + (1-\beta)\right]$$
$$- g_n\left[N(t) - N_0\right]S(t) + F_N(t) \quad (3)$$

In Eqs. (1)-(3), $S_{\text{m}}(t)$ and $\phi_{\text{m}}(t)$ are the photon density and the optical phase of the master SNL respectively. The injected modulation current $I(t) = I_0[1 + m\cos(2\pi f_{\text{m}}t)]$, where $I_0$ is the bias current, $m$ is the modulation index and $f_{\text{m}}$ is the modulation frequency. Unless stated otherwise $m = 2$ and $f_{\text{m}} = 25\ GHz$ are maintained in this letter. $F_S(t)$, $F_\phi(t)$ and $F_N(t)$ are Langevin noise sources as defined and calculated in [16]. The injection rate controlling the optical injection into the slave laser is, $k_{inj} = (1-r)(r_{inj}/r)^{1/2}c/(2nL_{in})$, where $r_{inj}$ is the injection parameter, $r = 0.85$ is the reflectivity of the laser, $c$ is the speed of light in the free space, $n = 3.4$ is the refractive index and $L_{in} = 1.39\ \mu m$ is the SNL internal cavity length. $\Delta f_{\text{det}}$ is the frequency detuning between the master and slave SNL. The optical pulses can be observed from the temporal waveforms of the photon density $S(t)$ after the cessation of transient effects. The optical spectra of the pulses can be calculated to show the OFCs from the Fourier transform of the slow varying envelope of the laser output. All other parameters are fixed as follows using the device parameters from [17]: The confinement factor $\Gamma = 0.65$, the carrier life time $\tau_n = 2.00 \times 10^{-9}\ s$, the differential gain $g_n = 1.65 \times 10^{-12}\ m^3/s$, the carrier density at transparency $N_0 = 1.10 \times 10^{24}\ m^{-3}$, the photon life time $\tau_p = 0.36 \times 10^{-12}\ s$, the linewidth enhancement factor $\alpha = 6$, the elementary charge $e = 1.6 \times 10^{-19}\ C$ and the volume of the nanolasers' active region $V_a = 3.96 \times 10^{-19}\ m^3$.

## III. RESULTS

Firstly, an example of OFC generated by the GS SNL with OI is presented in Fig. 1 to demonstrate its capability for improving the spectral quality of OFC when the master SNL has the same phase noises as the slave SNL, *i.e.*, $\beta = 1 \times 10^{-3}$. Fig. 1 (a) shows two OFCs generated by a GS SNL without (in red) and with (in blue) OI respectively when $F = 20$. Fig. 1(b) is an enlarged view of the two comb lines close to the zero frequency. For the GS SNL with OI, $\Delta f_{\text{det}}=0\ GHz$ and $r_{inj} = -9.2\ dB$. The linewidth ($\Delta f$) is given by the 3 $dB$ width of the comb line based on a smoothed fit with a spline interpolation which reduces the influence of intensity noise and yields a good description of the spectral behaviour [3].

In Fig. 1(b), the linewidth of the comb line for the GS SNL with OI is $\Delta f = 38.43\ MHz$ which is more than 22 times narrower than the one of without OI ($\Delta f' = 855.06\ MHz$). The significant linewidth reduction is also observed for all the other comb lines of the OFC generated by the GS SNL with OI. Moreover, the 10 $dB$ frequency span $f_{10}$ (as shown in Fig. 1(a)) and the carrier to noise ratio CNR (as shown in Fig. 1(b)) are also enhanced. $f_{10}$ is defined as the continuous frequency range within which the power of each comb line is within a 10 $dB$ window of the spectral peak. CNR is defined as the average value of the power differences between comb lines within $f_{10}$ and the noise level of their next valley.

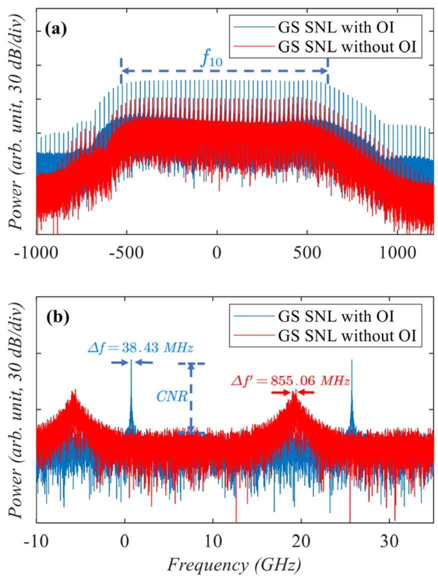

Fig. 1. (a) Two OFCs generated by a GS SNL with (in red) and without (in blue) OI respectively when $F = 20$ and $\beta = 1 \times 10^{-3}$. For the GS SNL with OI, $\Delta f_{\text{det}} = 0\ GHz$ and $r_{inj} = -\ 9.2\ dB$. (b) An enlarged view of the two comb lines close to the zero frequency.

The improvement of the OFC in GS SNL with OI is due to the injection-locking between the master and the slave SNL which process is presented in Fig. 2. From Fig. 2, with OI, equally spaced new frequency components appear in the spectrum (see Fig. 2(b)-(d)) which are caused by the injected free-running CW master field being gain-modulated due to gain switching [5]. Moreover, from Fig. 2(b)-(c), with the increase of the injection strength, the power of the new components increases with the increase of the injection strength and the GS slave SNL comb shifts closer to the new components. Finally, in Fig. 2(d), the injection-locking process completes when the slave comb is fully merged with the new components and a new OFC having the same linewidth as the master SNL is formed.

From Fig. 2, the linewidth of the CW master can also be preserved in those new frequency components and does not change with the increase of injection strength. We attribute this phenomenon to the intrinsic Purcell enhancement of the SNL which is not the same as using GS conventional lasers with OI. This can be corroborated by the frequency (or phase) noise power spectral density (PSD) [5]. Figure 3(a) presents the evolution of the frequency noise PSD with the variation of the injection parameter $r_{inj}$. All the other parameters are the same as those used in Fig. 2. From Fig. 3(a), when without OI, the frequency noise is larger than the one of the free running master CW SNL (the blue line with circles in Fig. 3(a)), hence inducing the increase of the linewidth in the gain switched SNL (as shown in Fig. 2(a)). As $r_{inj}$ increases, the low-frequency (below about 800 $MHz$) phase fluctuations that is responsible for the linewidth broadening are all suppressed to that of the master SNL. However, for the GS conventional laser with OI, the phase noise decreases with the increase of

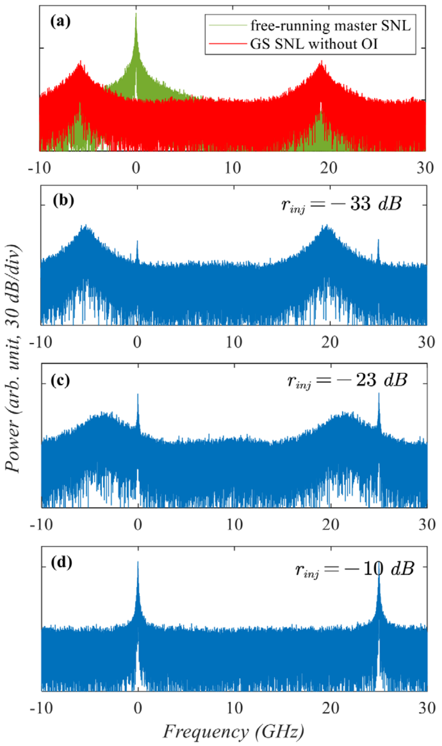

Fig. 2. Evolution of OFCs due to injection-locking in GS SNL with OI when $F = 20$ and $\Delta f_{\mathrm{det}} = 0$ *GHz* for different values of $r_{inj}$. (a) spectra of GS slave SNL without OI and the free-running master CW SNL. (b)-(c) the OFC of the GS slave SNL shifts closer to the master SNL field when $r_{inj}$ increases. (d) with a further increase of $r_{inj}$, the OFC of the GS slave SNL is eventually locked to the master SNL field.

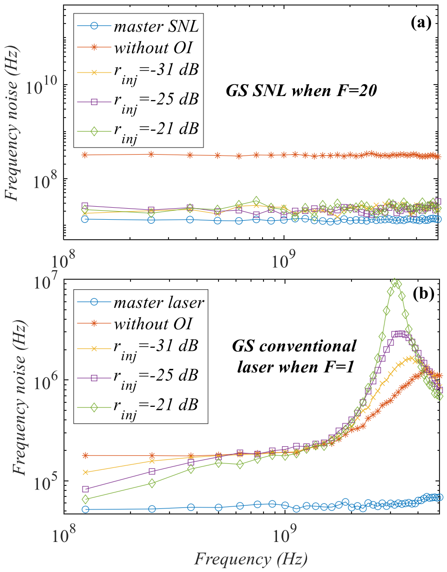

Fig. 3. The evolution of the frequency noise power spectral density of GS lasers with the variation of the injection parameter $r_{inj}$. (a) GS SNL when $F = 20$. (b) GS conventional laser when $F = 1$.

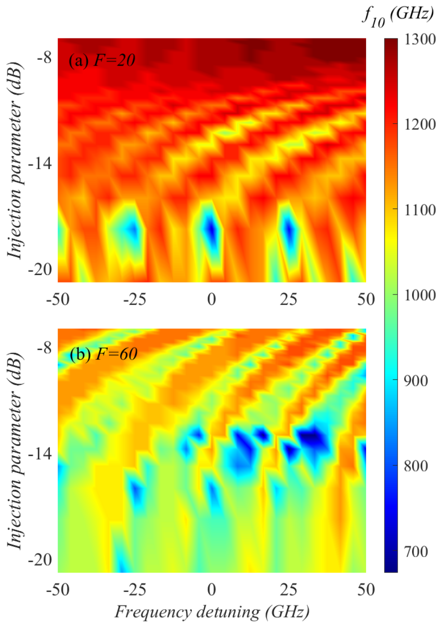

Fig. 4. The evolution of $f_{10}$ with respect to the injection parameter and frequency detuning for two different values of $F$, (a) $F = 20$, (b) $F = 60$.

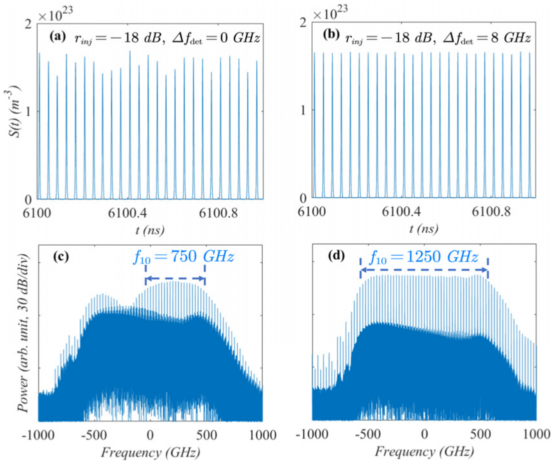

Fig. 5. The effect of frequency detuning on the generated pulses and OFCs from the slave GS SNL for two different values of frequency detuning chosen from Fig. 5(a) when $r_{inj} = -18$ *dB*. (a) and (c): $\Delta f_{\mathrm{det}} = 0$ *GHz*, (b) and (d): $\Delta f_{\mathrm{det}} = 8$ *GHz*.

the injection strength, as shown in Fig. 3(b) when $F = 1$ which has the same trend of [5] (see Fig. 5 in [5]).

Figure 4 presents the evolution of $f_{10}$ with respect to the frequency detuning and the injection parameter for two different values of $F$. From Fig. 4, injection locking with large values of $f_{10}$ can be achieved for strong injection. The injection locking regions are separated tilted strips varying with the change of frequency detuning. This is because with the change of frequency detuning, the phase of the emitted light from the master SNL can approach or recede from that of the slave SNL so that the laser tends to be mode-locked or unlocked. This will affect the pulse amplitude and cause the pulsation of the slave GS SNL output with the rather complex waveform, hence changing the values of $f_{10}$.

To see the effect of frequency detuning on the generated pulses from the slave GS SNL, two cases are selected from Fig. 4(a) for $\Delta f_{\mathrm{det}} = 0$ *GHz* and *8 GHz* for a same value of $r_{inj} = -18$ *dB*. Their corresponding optical pulses and spectra are shown in the first and second row of Fig. 5 respectively. From Fig. 5 (a), when the detuning ($\Delta f_{\mathrm{det}} = 0$ *GHz*) recedes from the locking range, optical pulses with irregular amplitudes are generated and the frequency span ($f_{10} = 750$ *GHz*) of their corresponding OFC (shown as in Fig. 5(c)) is much narrower than the one ($f_{10} = 1250$ *GHz*,

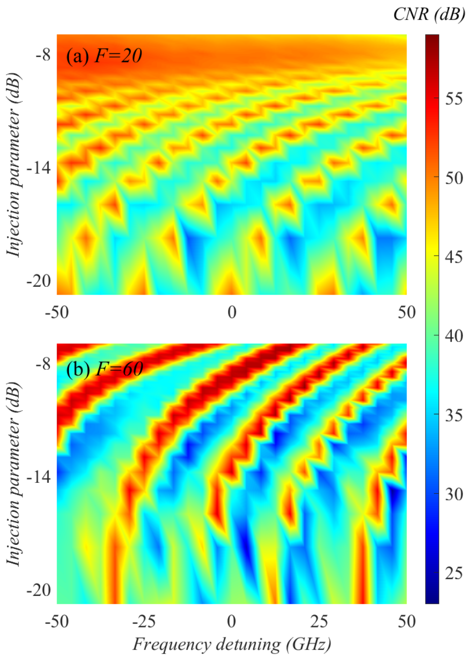

Fig. 6. The evolution of CNR with respect to the injection parameter and frequency detuning for two different values of $F$, (a) $F = 20$, (b) $F = 60$.

shown as in Fig. 5(d)) with detuning ($\Delta f_{\mathrm{det}} = 8$ $GHz$) within the locking range.

Attention is now given to the effect of Purcell factor $F$ on $f_{10}$. From Fig. 4, $f_{10}$ decreases with increase of $F$ which agrees with the results in our recent work [14]. This was attributed to the effective reduction of the carrier life time, resulting in an increase of pulse width, hence a decrease of $f_{10}$. Further improvement of $f_{10}$ is possible by increasing the spontaneous emission coupling factor $\beta$ which can induce a faster gain depletion to shorten the pulse width.

A similar trend of the evolution of *CNR* to that of $f_{10}$ can be anticipated. The trend is confirmed in Fig. 6 in which the generated OFCs have large values of CNR in the strips of the injection locking region. Moreover, CNR increases with increase of $F$. This is because a larger $F$ can increase the spontaneous emission into laser modes where the noises floor induced by the spontaneous emission are reduced, thus leading to an increase of CNR.

## IV. CONCLUSION

A novel optical frequency comb (OFC) generator using gain switched (GS) semiconductor nanolasers (SNLs) in the presence of external optical injection (OI) has been proposed in this letter. The effect of OI in SNLs has been numerically analysed giving particular attention to the role of Purcell enhanced spontaneous emission factor $F$ with varying the frequency detuning $\Delta f_{\mathrm{det}}$ and the injection parameter $\mathrm{r_{inj}}$. The results demonstrate that broadband OFCs with narrow linewidths can be generated by the GS SNL with OI due to the injection-locking phenomenon which regions are separated tilt strips varying with the change of $\Delta f_{\mathrm{det}}$ and $\mathrm{r_{inj}}$. Further analysis shows that the 10 dB frequency span $f_{10}$ and the carrier to noise ratio CNR of the OFCs can be enhanced by increasing $\mathrm{r_{inj}}$. Moreover, $f_{10}$ and CNR respectively decreases and increases with the increase of $F$. The analysis carried out here opens new possibilities for generating broadband OFCs with narrow linewidths, high CNR and low repetition rate for use, for example, in the general field of integrated radio-frequency photonics.

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