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OPTICAL FREQUENCY COMB GENERATION IN SEMICONDUCTOR LASERS USING Q-SWITCHING AND MODE LOCKING TECHNIQUES

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ABSTRACT

This work introduced a numerical simulation of Optical Frequency Comb (OFC) in semiconductor lasers, were OFC is generated and investigated for a laser with 1.55 μm wavelength using Q-switching and mode locking techniques. The study shows that OFC generated depends on the frequency of the open- close frequency of the shutter used to produce Q-switching. OFC generated depends on mode locking technique shows that the OFC properties depend on the laser cavity length.

KEYWORDS: Frequency comb, semiconductor lasers, Q-switching, mode-locking.

INTRODUCTION

Optical frequency combs have attracted more attention in the last decade. Because it became a useful tool for many applications viz., optical atomic clocks [1], comb spectroscopy [2–5], a new microwave generation [6, 7], communication such as 5G and 6G, synchronization of many optical systems [8, 9], etc., Optical frequency combs (OFCs) are coherent light of evenly spaced pulses in the spectral domain. It can be described to be a mirror that reflects the field shape inside the gain curve of multi-longitudinal mode lasers. There are several ways to produce OFCs in semiconductor lasers viz., modulated signal as injection current, Q-switching, mode-locking technique, external optical injection [10] and phase turbulence [11]. Optical frequency comb and the spectral properties of semiconductor lasers were studied by direct modulation and optical feedback [12-16] and lasers synchronization [17,18].

In this work we studied the generation of OFCs in semiconductor lasers by using Q-switching and mode locking techniques, investigated their dependence on the injection current, shutter open-close cycle and the laser cavity length respectively.

Theory:

The rate equation that describes semiconductor lasers dynamics can be written as [19]:

$$\frac{dN(t)}{dt} = \frac{I(t)}{qV_{act}} - \left[g_0(N(t) - N_0)\left(1 - \epsilon\, S(t)\right)S(t)\right] - \frac{N(t)}{\tau_n} + \frac{N_e}{\tau_n} \quad (1)$$

$$\frac{ds(t)}{dt} = \Gamma g_0\left[(N(t) - N_0)\left(1 - \epsilon\, S(t)\right)S(t)\right] + \frac{\Gamma\beta N(t)}{\tau_n} - \frac{S(t)}{\tau_p} \quad (2)$$

$$P(t) = \frac{S(t)V_{act}\eta hc}{\Gamma\tau_p\lambda_0} \quad (3)$$

Where N(t) is the carrier density, S(t) is the photon density, P(t) is the output power, the other parameters were defined in Table (1).

Mode locking technique:

When we have a laser source that operates with a large number of longitudinal modes that fall within the gain frequency range. The distance between one pattern and another, which is called the pattern separator, is given by:

$$\Delta\omega = \frac{c}{2l} \quad (4)$$

Where, c is the light velocity, l is the laser cavity length, then the final field of all optical modes oscillate in the cavity can be formed as following:

$$\mathrm{E}(t) = \sum_{q=-n}^{n} E_q \exp\left[i\left(\omega_q t + \varphi_q\right)\right] \quad (5)$$

Where, E_q و ω_q و φ_q are the q-mode amplitude, frequency and the phase shift from the central mode respectively. If the amplitudes E_q are the same for all modes, then eq. (5) can be written as:

$$E(t) = E_0 \sum_{q=-n}^{n} \exp\,[i(\omega_q t + \varphi_q)] \quad (6)$$

If $\omega_q = \omega_0 + q.\Delta\omega$, where ω_0 is the central frequency, $\Delta\omega$ is the mode spacing difference, then eq.(6) becomes as follows:

$$E(t) = E_0 e^{i\omega_0 t} \sum_{q=-n}^{n} e^{i(q\Delta\omega t + \varphi_q)} \quad (7)$$

Results and discussion:

Equations (1-3) were solved numerically using Runge-Kutta method, using the semiconductor laser parameters shown in Table (1).

Table (1) Semiconductor laser parameters [19].

Symbol	Description	Value	Unit
N(t)	Carrier Density	-	cm^{-3}
I(t)	Injection Current	-	mA
S(t)	Photon Density	-	cm^{-3}
Q	Electronic charge	$1.602x10^{-19}$	C
V_{act}	Active Region Volume	$9x10^{-11}$	cm^{-3}
g_0	Gain Coefficient	$3x10^{-6}$	cm^{-3}/s
N_0	Carrier Density at Transparency	$1.2x10^{18}$	cm^{-3}
$\in$	Gain Compression	$3.4x10^{-17}$	cm^{3}
N_e	Equilibrium Carrier Density	$5.41x10^{10}$	cm^{-3}
τ_n	Carrier Lifetime	$3x10^{-9}$	sec
Γ	Optical Confinement Factor	0.44	-
β	Spontaneous Emission Coupling Factor	$4x10^{-4}$	-
τ_p	Photon Lifetime	$1x10^{-12}$	S
η	Differential Quantum Efficiency	0.1	-
λ_0	Lasing Wavelength	1.55	µm

Q-switching:

In order to obtain the behavior of the laser output Q-switching technique, the shutter opening and closing frequency were changed, when the frequency value is 100 MHz, the changes that occurred in each of the photons, the density of carriers and the laser output spectrum as shown in Figure (1), it can be seen that there is one peak at 1550 nm,. When the shutter opening and closing frequency were value is increased to 1GHz, an emergence of other new secondary frequencies in addition to the original frequency around the central wavelength 1550 nm and the comb generated in the wavelength domain have a small spacing which means in turns a wide spacing (FSR) in the frequency domain as it can be seen in Figure (2). By increasing the closing and opening frequency to 10 GHz, multi-pulses can oscillate in the laser cavity where the photon and the carrier densities have smooth and periodic pulses with short repetition per time (rpt) shorter than the former cases, and the optical comb generated becomes with more oscillated modes extended in the wavelength domain with a wide spacing, i.e. shorter one in the frequency domain as it shown in Figure (3).

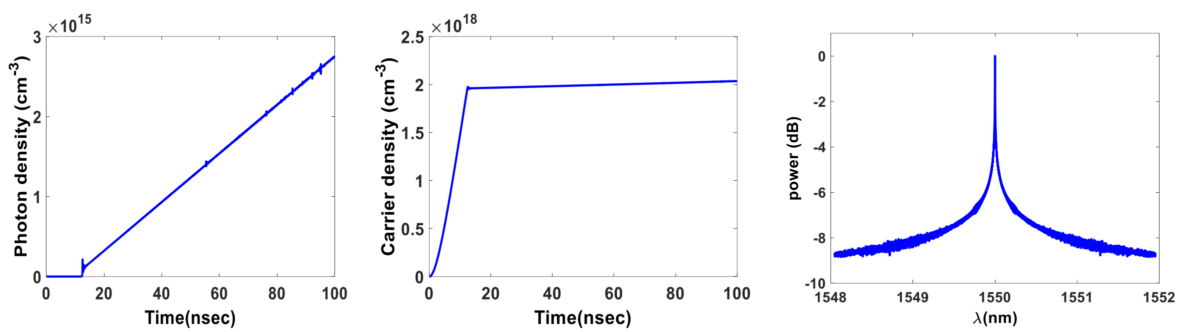

Figure (1): Photon density, Carrier density and the optical frequency comb with at opening-closing shutter cycles 100 MHz.

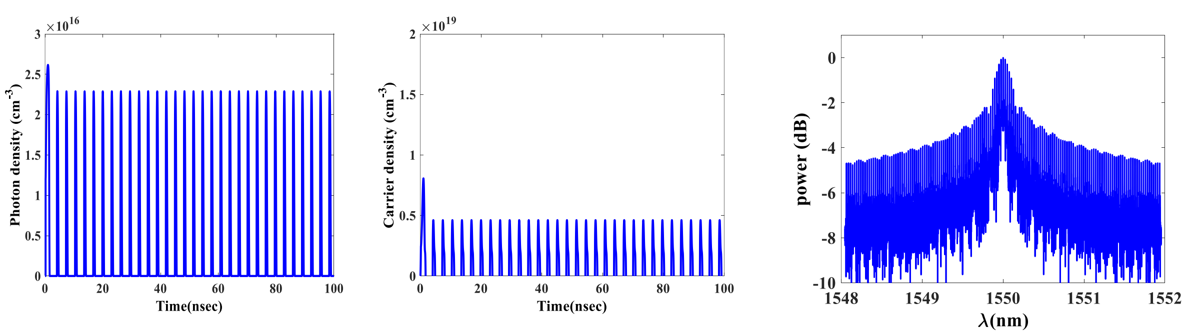

Figure (2): Photon density, Carrier density and the optical frequency comb with at opening-closing shutter cycles 1 GHz.

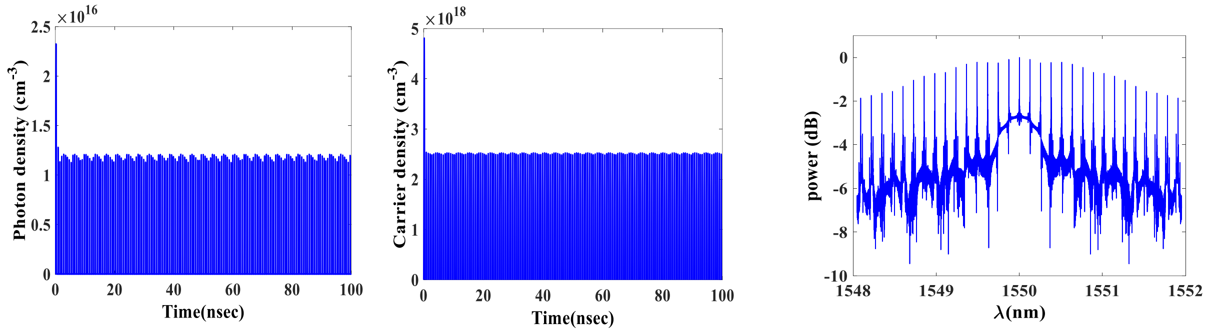

Figure (3): Photon density, Carrier density and the optical frequency comb with at opening-closing shutter cycles 10 GHz

Mode locking:

The simulation were carried out depending on the cavity length effect on the optical frequency generated using the mode locking technique. At cavity length equals to L=1 cm. Figure (4) shows the laser intensity before mode locking (to the left), it can be seen that there is arbitrary configuration in the modes oscillated in the laser cavity, in the (middle) the intensity is plotted after mode locking where the pulses being symmetry and equally spacing, the optical frequency comb can be seen in the intensity plot against the wavelength (to the right), the figure shows that the frequency repetition is 15 GHZ. If the cavity length L=3 cm, each locked mode being closed to the other one and the modes overlapping as it in the middle plot of Figure (5), also the frequency repetition decreases to 7.5 GHz as it seen to the right of figure (5). As L increased to L=10 cm, the number of modes oscillated in the cavity are increased, and the frequency repetition became 3 GHz as it can be seen in figure (6).

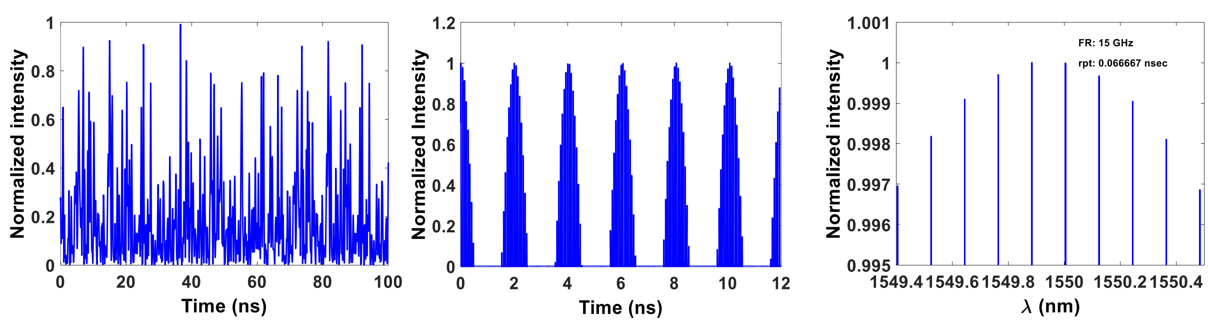

Figure (4): Unlocked intensity (left), Locked intensity (middle) and the optical frequency comb (right) at cavity length L=1 cm.

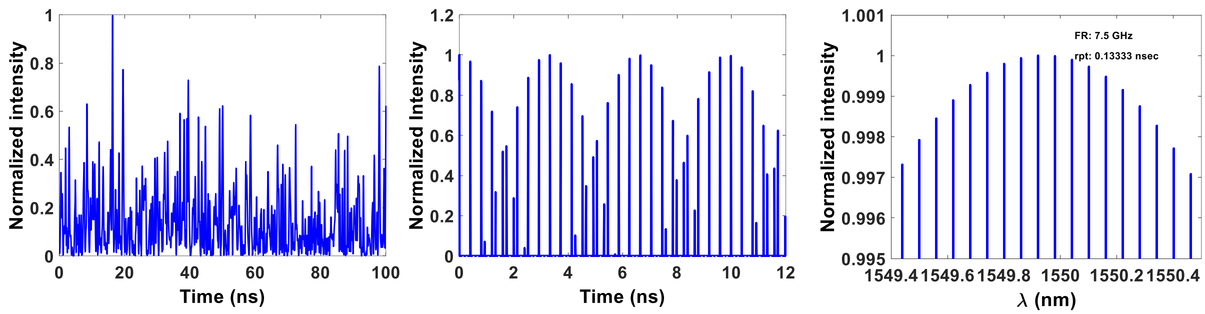

Figure (5): Unlocked intensity (left), Locked intensity (middle) and the optical frequency comb (right) at cavity length L=3 cm.

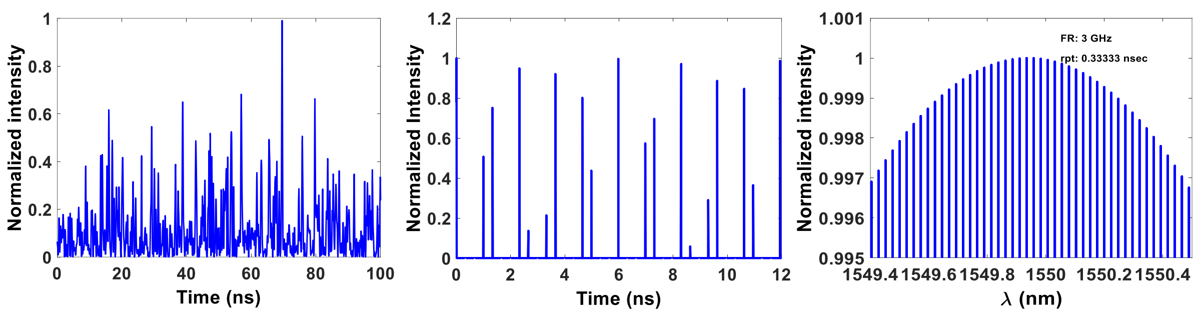

Figure (6): Unlocked intensity (left), Locked intensity (middle) and the optical frequency comb (right) at cavity length L=10 cm.

CONCLUSIONS:

In the Q-switching technique, the optical frequency comb were generated in the semiconductor laser, the shape and number of the comb frequencies that exceed -3dB and frequency repetition depend on the Q-switching shutter with different opening-closing cycle. For Mode-locking technique, the length of the laser cavity and hence the number of the modes oscillated in it effects the mode-locked laser output and it generated optical frequency comb.

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