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Optical frequency comb generation in semiconductor lasers using optical injection locking technique

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Abstract:

This study presented a simulation of optical frequency comb (OFC) generated in semiconductor lasers (SCLs), where the OFC was obtained by using a laser of a wavelength 1.55μm and using optical injection locking technique. This study showed that OFC generated shape and repetition frequency depend on the factor of linewidth enhancement, frequency detuning and on the optical injection ratio. The study proved that the slave dynamics follows the master one. The symmetry distribution of the OFC was found as affected strongly by the optical injection ratio, detuning and the linewidth enhancement.

KEYWORDS: Optical frequency comb, Semiconductor laser, Optical injection locking.

Introduction:

Optical Frequency Comb (OFC) is a light emission characterized by equally spaced narrow optical lines [1]. A frequency comb generator produces a spectrum that consists of a series of equally spaced sharp lines with known frequencies. OFC has many applications in various fields such as communications, astronomy, spectroscopy, etc. [2-5].

OFC has been studied in semiconductor lasers using Q-switching and mode locking techniques [6], OFC also is generated by direct modulation, optical feedback [7-11] and synchronization between two lasers [12,13].

Optical injection locking (OIL) is an optical frequency and phase synchronization technique that relies on a photon-photon interaction when external light is present in the laser cavity. The optical injection system consists of the Master laser and the slave laser, the master provides external light to affect the slave. The master light is injected into the slave laser either in a circular manner or in an isolation method to avoid any unwanted reflection back to the master laser [14,1]. To produce OFC in the slave, the master laser must be mode locked. To locking optical injection, part of the output of the master after mode locking is injected into the slave laser cavity, where synchronization occurs between the two lasers so that the phase difference between their outputs is small, then the two lasers are synchronized with each other at the same optical frequency under the appropriate conditions such as detuning between the frequency of the master and that of the slave, coupling strength and the injection strength [15].

In this work we studied the generation of OFC in semiconductor laser by using optical injection locking technique and investigated its dependence on the linewidth enhancement, frequency detuning and the injection ratio respectively.

Theory:

To achieve OIL, a system of two lasers, master and slave are used, where amount of the master output is injected into the master as shown in figure (1). An isolator is localized between the two lasers to ensure uni-directional interaction. In this work the master will be mode locked, this cause the slave output to be a chaotic in general.

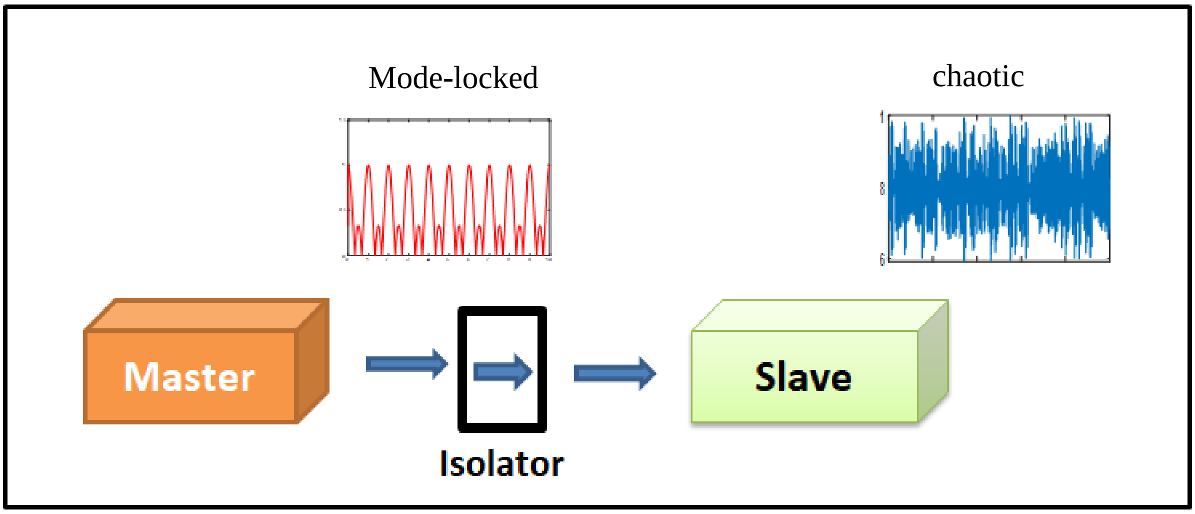


Figure (1): Optical Injection Locking scheme

To describe the OIL between two SCLs, the rate equations of amplitude (A), phase (ϕ) and carrier density (N) of the slave is used, which can be written as [16,17]:

$$\frac{dA(t)}{dt} = \frac{1}{2} g[N(t) - N_{th}]A(t) + kA_{inj} cos\phi(t) \quad (1)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2}\{g[N(t) - N_{th}]\} - k\frac{A_{inj}}{A(t)} sin\phi(t) - \Delta\omega \quad (2)$$

$$\frac{dN(t)}{dt} = J - \gamma_N N(t) - \{\gamma_p + g[N(t) - N_{th}]\}A(t)^2 \quad (3)$$

Where $A(t)$, is the field amplitude which is related to the photon number $S(t)$, $\varphi_s(t)$ and $\varphi_{inj}(t)$ are the phases of the slave and master lasers, respectively, $\phi(t)$ is the phase difference between the internal and injected field, expressed by $\phi(t) = \varphi_s(t) - \varphi_{inj}(t)$, $\Delta\omega = \omega_{inj} - \omega_s$ is the angular frequency offset between the free-running slave lasers (ω_s) and the injected light (ω_{inj}). Equation (3) governs the carrier change which is the same as standard rate equation, where $N(t)$ is the number of carriers in the slave laser [14,2].

Results and discussion:

Equations (1-3) were solved numerically using 4th order Runge-Kutta method, using MATLAB for a semiconductor laser parameters shown in Table (1).

Table (1): Parameters of the semiconductor laser used in this study [16,17].

Symbol	Description	Value	Unit
N(t)	Active Region Carrier Density	-	cm^{-3}
S(t)	Photon Density	-	cm^{-3}
k	Coupling Coefficient	-	-
α	Linewidth Enhancement Factor	3-5	-
g	Gain Coefficient	$3x10^{-3}$	-
N_{th}	Carrier Density at Transparency	$1.2x10^{18}$	cm^{3}
γ_p	Photon Decay Rate	-	-
J	Pump Current Normalized by Electron Charge e	-	-

e	Electronic Charge	$1.602x10^{-19}$	C
γ_N	Carrier Recombination Rate	-	-
λ	Lasing Wavelength	1.55	µm

Linewidth enhancement (α):

By fixing the parameters of the semiconductor laser as mentioned in Table (1), as well as fixing the value of the phase difference $\Delta\omega$ =1GHz and the optical injection ratio $I_{inj}= k\frac{A_{inj}}{A(t)}$ =1.2, the effect of the linewidth enhancement factor (α) was studied, the value of α of the slave laser was changed within the range (3-5) , at α = 3, the slave laser was injected with a mode locked output of the master as shown in figure (2.a), the output of the slave is shown in figure (2b), which represents the frequency comb formed in the slave laser, it can be seen that there are several wavelengths (≥ -3dB) in addition to the main wavelength of 1.55µm, i.e. several frequencies will be oscillated inside the slave cavity. It can be seen also that the comb is almost symmetrical around the central wavelength (frequency). The upper figure of (2.c) represents the power of the slave laser output, and the lower figure represents the density of its carriers with time.

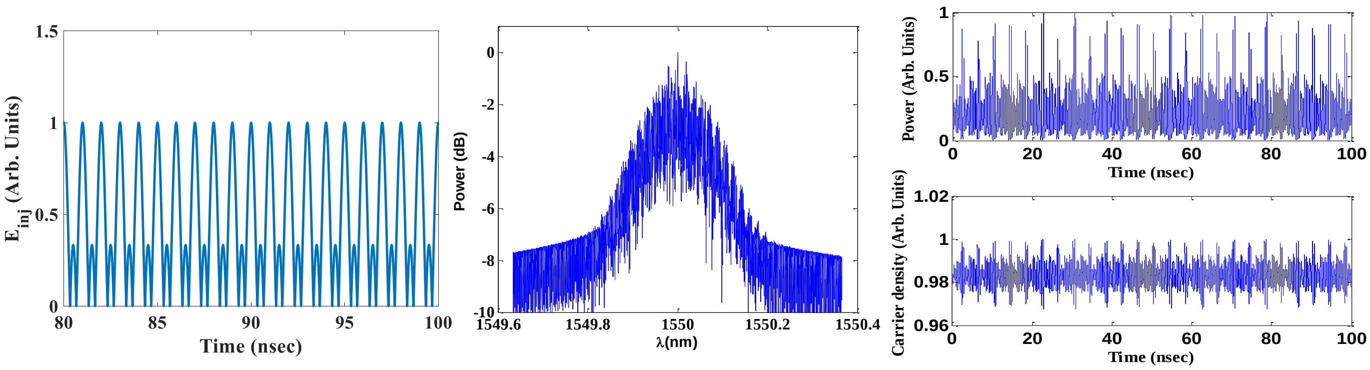
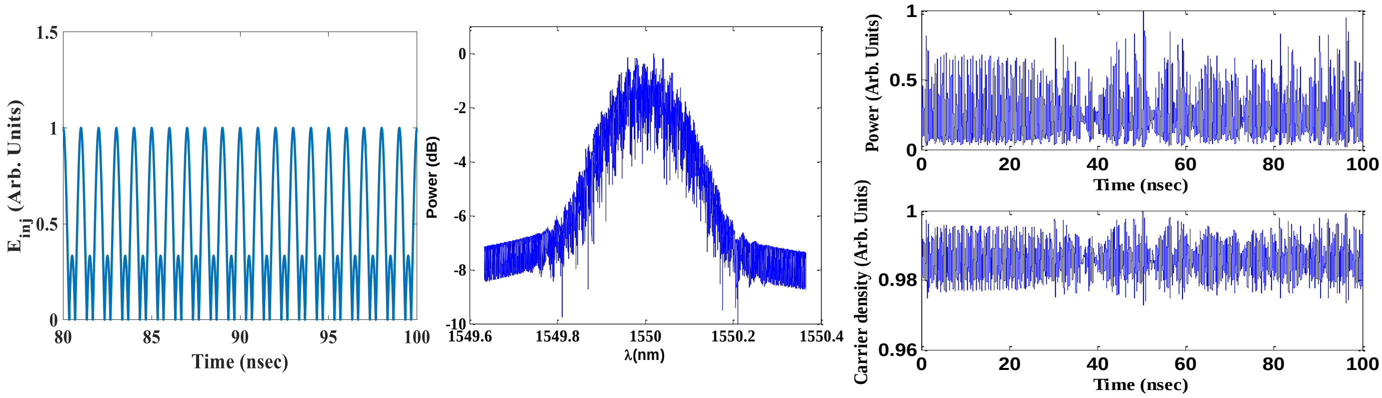


Figure (2): Laser output when (α=3), (I_{inj}=1.2) and ($\Delta\omega$=1GHz) (a) the mode-locked output of the master laser, (b) frequency comb generated by the slave, (c) the slave output power (upper), and the carrier density

When increasing the value of (α) to 5, as in figure (3), where (3.a) represents the mode locked output of the master laser, in which we notice an increasing in the number of pulses oscillated, (3.b) shows the frequency comb that has expanded compared to the previous α values, i.e. more pulses overcome -3dB, and fig. (3.c) shows dramatic changes in the time evolution of the output power (upper plot) and the carrier density (lower plot).

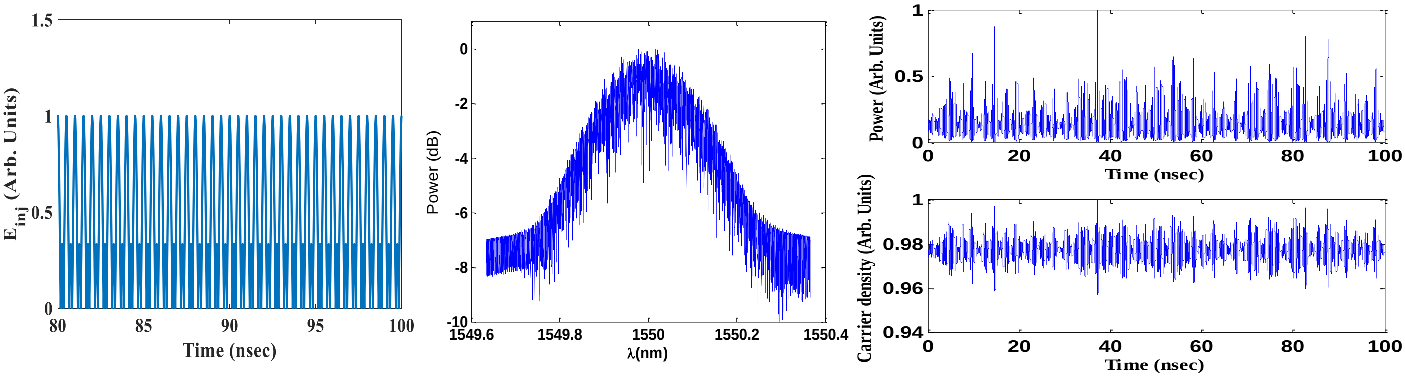


(a) (b) (c)

Figure (3): Laser output when (α=5), (I_{inj}=1.2) and (Δω=1GHz) and (a) the mode-locked output of the master laser, (b) frequency comb generated by the slave, (c) the slave output power (upper), and the carrier density.

Frequency Detuning (Δω):

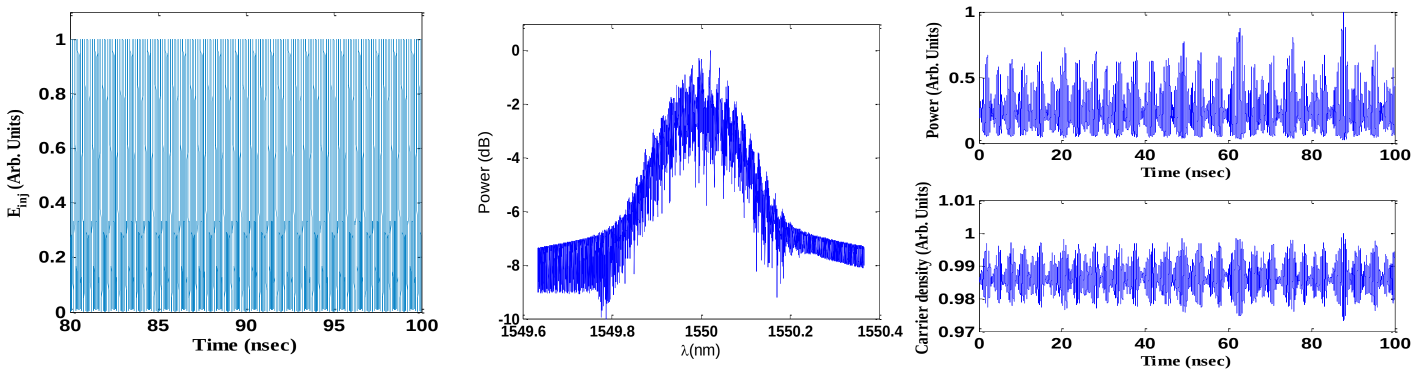
The value of Δω was changed in the range (2 -10) GHz while fixing the value of α=5, as well as the injection ratio I_{inj} = 1.2. At a value of Δω = 2GHz, figure (4. a) shows that the mode-locked output of the master laser pulses are duplicated, figure (4.b), shows that the frequency comb is more expanded, but it is starting losing its symmetry around the central wavelength, (1.550 μm), and figure (4.c), whose upper figure represents the power of the slave laser output, where it can be seen that the output of the slave laser work is unstable and then begins to stabilize in the form of pulse Regular periodicity about after 30 nsec and the figure below shows that the carrier density is following the changes in the photon density evolution represented by the power evolution.



(a) (b) (c)

Figure (4): Slave laser output when ($\Delta\omega$=2GHz), (α=5) and (I_{inj}=1.2) (a) the mode-locked output of the master laser, (b) frequency comb generated by the slave, (c) the slave output power (upper), and the carrier density evolution.

Increasing the value of $\Delta\omega$ to 7GHz, leads to increase the pulses train of the master laser output as in the figure (5.a), the frequency comb distribution is being loses it symmetry around the central wavelength, and also the interval between the comb teeth increases (decreases) in the wavelength (frequency) domain as seen in the figure (5.b), and from figure (5.c), it can be seen that the slave time evolution being more stable and semi periodic.

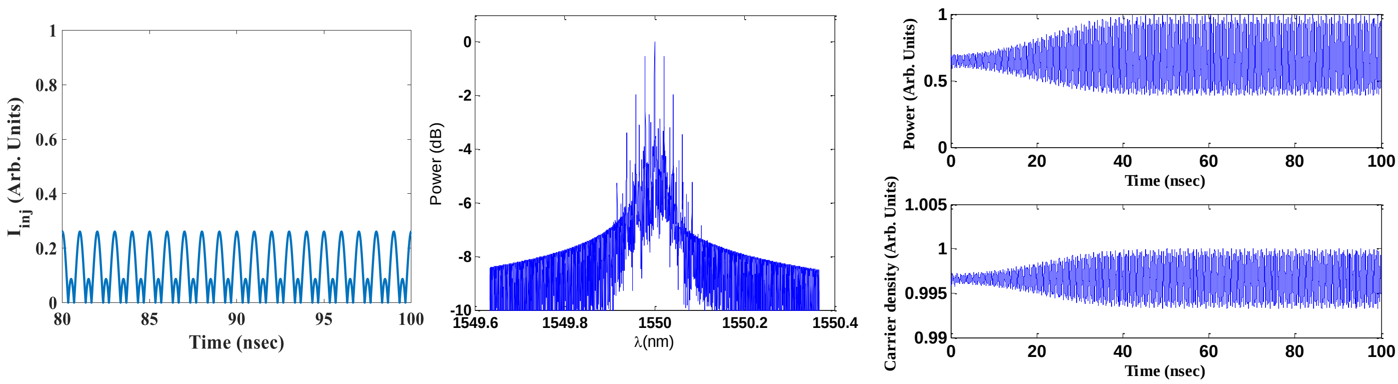


(a) (b) (c)

Figure (5): Slave laser output when ($\Delta\omega$=7GHz), (α=5) and (I_{inj}=1.2) (a) the mode-locked output of the main laser, (b) the frequency comb, and (c) the output power (upper), and the carrier density.

Optical Injection Locking (I_{inj}):

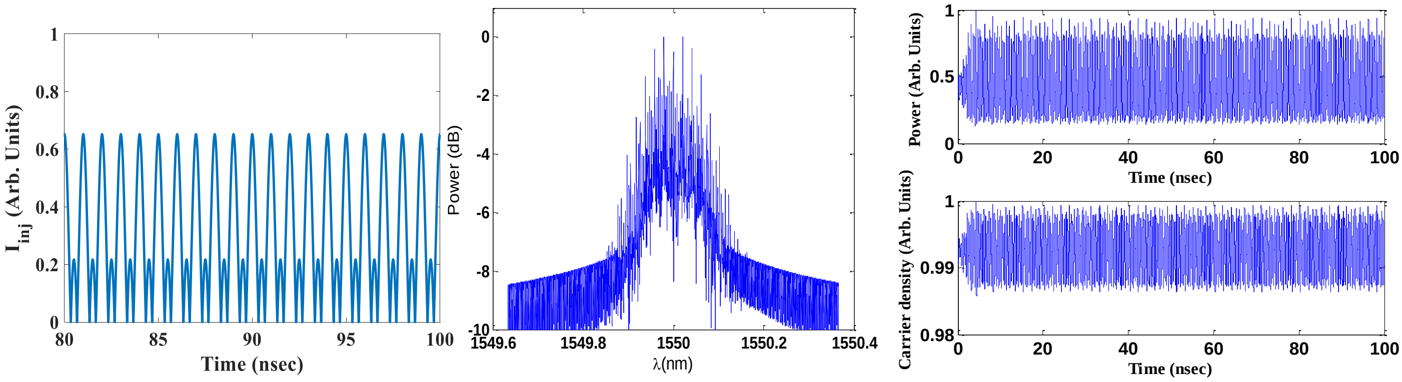
When the value of the optical injection was changed from (0.2-1.2) and the value of α was fixed at the value 5 and the value of $\Delta\omega$ at the value 1GHz, the injected field were decreases as in figure (6.a). In this case the comb generated in the slave shrinks towards the central wavelength, with sharp, separated teeth as it can be seen in figure (6.b). As the injection ratio were decreased, the field of the slave will decreased also, in figure (6.c),it can be seen that the power pulses begins with low power, then the power increases with time to be stable after about 40 nsec.



(a) (b) (c)

Figure (6): laser output when (I_{inj}=0.2), (α=5) and ($\Delta\omega$=1GHz (a) the mode-locked output of the master laser, (b) frequency comb generated by the slave, (c) the slave output power (upper), and the carrier density.

When the injection current is increased to 0.5 figure (7.a), i.e., that the optical field in the master will grows rapidly in time and in its power value. The repetition rate time of the sharped pulses increases (decreases) in the wavelength (frequency) domain, the power and the carrier evolution will increase also as in figure (7.c).



(a) (b) (c)

Figure (7): lasers output when (I_{inj}=0.5), (α=5) and (Δ*ω*=1GHz) (a) the mode-locked output of the master laser, (b) frequency comb generated by the slave, (c) the slave output power (upper), and the carrier density.

Conclusions:

We noticed that when the value of the enhanced line width (α) increases, the number of wavelengths at which the laser works increased, and the comb is almost symmetrical around the central frequency. When increasing the value of the frequency detuning (Δ*ω*), we noticed that the frequency comb became asymmetrical distributed around the center frequency, and when the value of the injection current was increased, we noticed that the comb became asymmetrical in the distribution around the central frequency, as well as an increase in the frequency interval between the comb teeth. We believe that the master gives rise to a various behavior in the slave dynamics, we suggest that some synchronization between the two laser leads the master following the master dynamics.

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