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The Dynamical Behavior of Semiconductor Lasers Under Current Modulation

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Abstract

We investigate the occurrence of various laser outputs from semiconductor laser ranging from the usual output obtained from such devices, periodic, multi-periodic, aperiodic and chaotic one as a result of the modulation of injection current .

Keywords : Semiconductor Laser, Modulation, Chaos output.

1. Introduction

Semiconductor laser diodes are popular and widely – used sources due to their high power, low cost, tunability, and easy integration with miniaturized electronics. They can also serve as flexible signal sources of high-frequency oscillations and pulsations [1-3].

One of the methods used to enhance instabilities in semiconductor laser is the modulation of injection current. For example, high-frequency modulation of the injection current is often employed to

reduce the relative intensity noise induced by optical injection. It is well known that under current modulation, optical feedback, or optical injection, semiconductor lasers exhibit rich variety of nonlinear behaviors [4].

In the present work we study the effect of current modulation by varying the DC and the AC components of injection current and frequency of modulation on the dynamical behavior of semiconductor laser.

2. Model

The rate equations governing the temporal dynamics of semiconductor laser under current modulation can be written as follows [5-7]:

$$\frac{d E(t)}{dt} = \frac{1}{2} G_N [N(t) - N_{th}] E(t) \quad \dots\dots (1)$$

$$\frac{d \phi(t)}{dt} = \frac{1}{2} \alpha G_N [N(t) - N_{th}] \quad \dots\dots (2)$$

$$\frac{d N(t)}{dt} = \frac{I}{qV} - \frac{N(t)}{\tau_c} - G_N [N(t) - N_o] |E(t)|^2 \quad \dots(3)$$

$E(t)$, $\phi(t)$ and $N(t)$ are the Electric field in side the cavity, Phase of electric field of the laser and Carrier density respectively. G_N is the differential gain function. N_{th} and N_o are the carrier density at threshold and at transparency respectively. α is the line-

width enhancement factor. I and q are the injection current and the electronic charge respectively. τ_c is the Carrier life time and V is the volume of active region.

The injection current, I , can be written as:

$$I = I_{dc} + I_{ac} \sin(\omega t) \quad \dots\dots (4)$$

Where

I_{dc} = Direct component of the injection current

I_{ac} = Alternative component of the injection current

$\omega = 2\pi f$ = Angular modulation frequency

f = Frequency of modulation

3. The Laser Parameters

The parameters used in solving the set of equations (1-3) together with eq. (4) are given in table (1).

Table 1. Parameters used in the calculations

Symbol	Parameter	Value	Unit
q	Electronic charge	$1.6 * 10^{-19}$	C
V	Volume of active region	$6.75 * 10^{-17}$	m^3
τ_c	Carrier life time	2	ns
α	Line width enhancement factor	3	--
G_N	Gain function	$1.62 * 10^{-12}$	$m^3 \text{ sec}^{-1}$
N_{th}	Carrier density at threshold	$1.2 * 10^{24}$	m^{-3}
N_o	Carrier density at transparency	$1 * 10^{24}$	m^{-3}
λ	Laser wavelength	1550	nm

4. Simulation results and Discussion

The set of equations (1-3) together with equation (4) are solved using the MATLAB function ODE45, where the only control parameter examined is the injection current, I , by varying I_{dc}, I_{ac} and the angular frequency of modulation, ω . These three parameters were varied respectively

through the ranges (1-10) mA, (1-20) mA, and ($10^6 - 10^{11}$) Hz.

Representative results are shown in figs (1-8) for the usual behavior expected from semiconductor lasers except figs (5-8) where the behavior developed into self – pulsing or breathing [8].

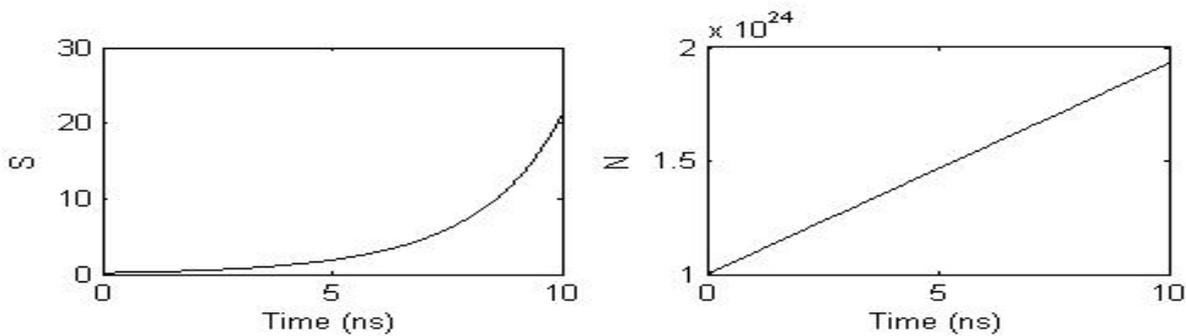


Figure 1. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 1 \text{ mA}$, $I_{ac} = 1 \text{ mA}$, $\omega = 10^6 \text{ Hz}$

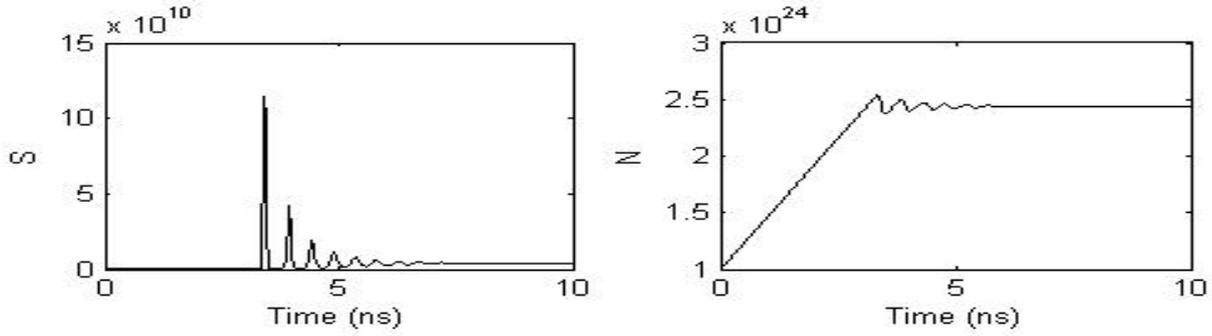


Figure 2. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 5\text{ mA}$, $I_{ac} = 1\text{ mA}$, $\omega = 10^6\text{ Hz}$

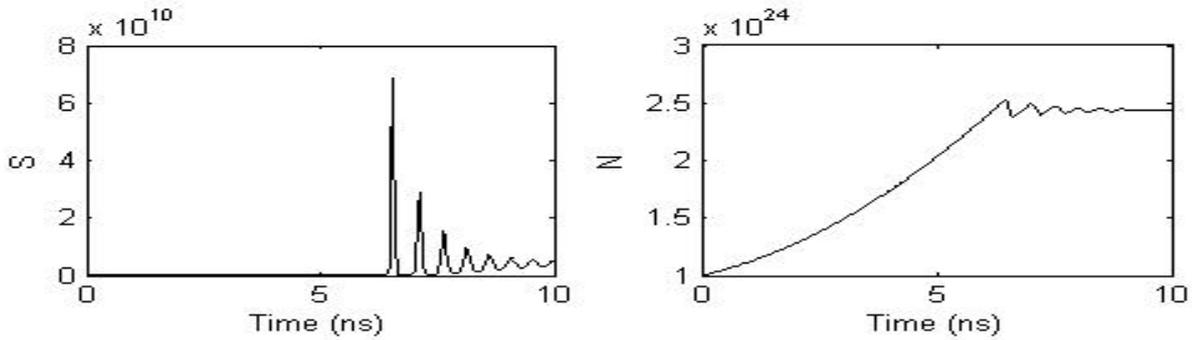


Figure 3. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 1\text{ mA}$, $I_{ac} = 5\text{ mA}$, $\omega = 10^8\text{ Hz}$

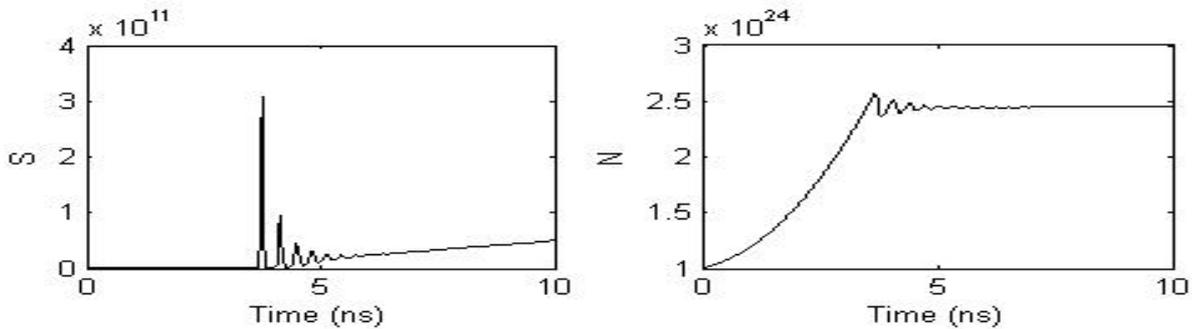


Figure 4. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 1\text{ mA}$, $I_{ac} = 20\text{ mA}$, $\omega = 10^8\text{ Hz}$

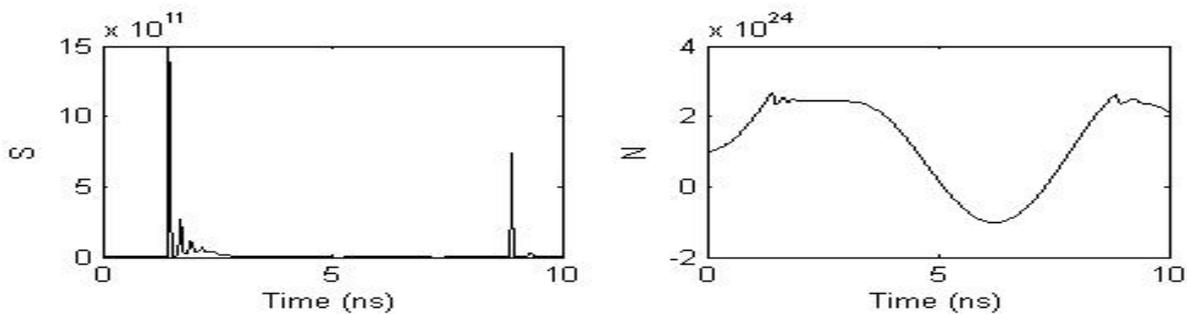


Figure 5. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 1\text{ mA}$, $I_{ac} = 20\text{ mA}$, $\omega = 10^9\text{ Hz}$

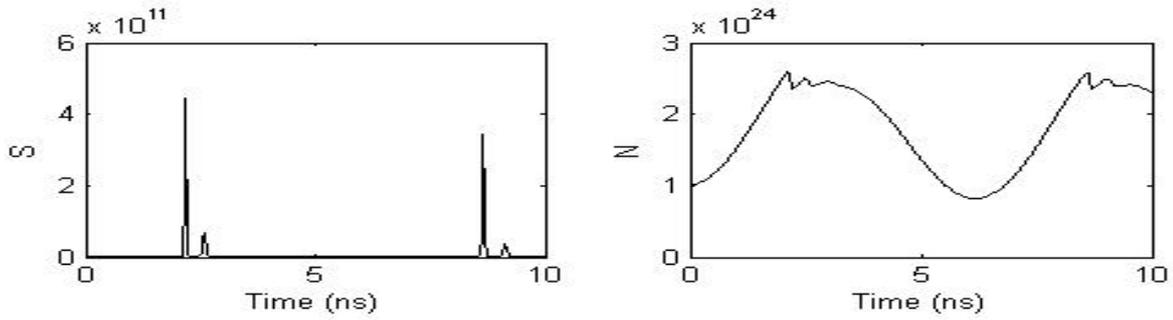


Figure 6. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 1\text{mA}$, $I_{ac} = 10\text{mA}$, $\omega = 10^9\text{ Hz}$

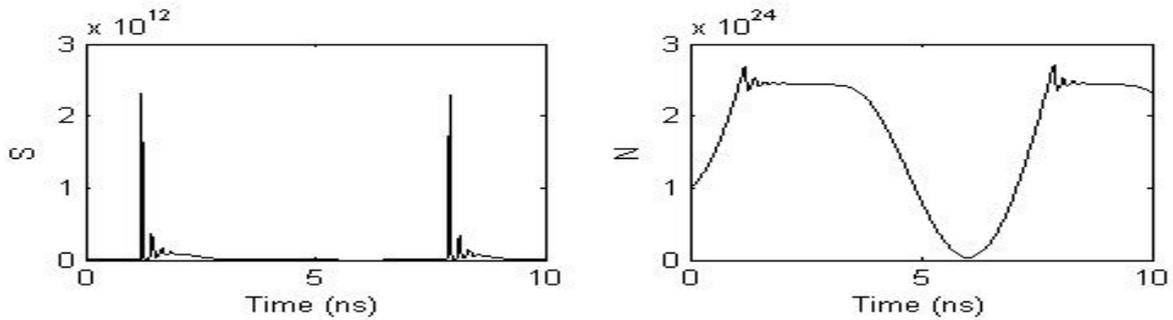


Figure 7. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 5\text{mA}$, $I_{ac} = 2\text{mA}$, $\omega = 10^9\text{ Hz}$

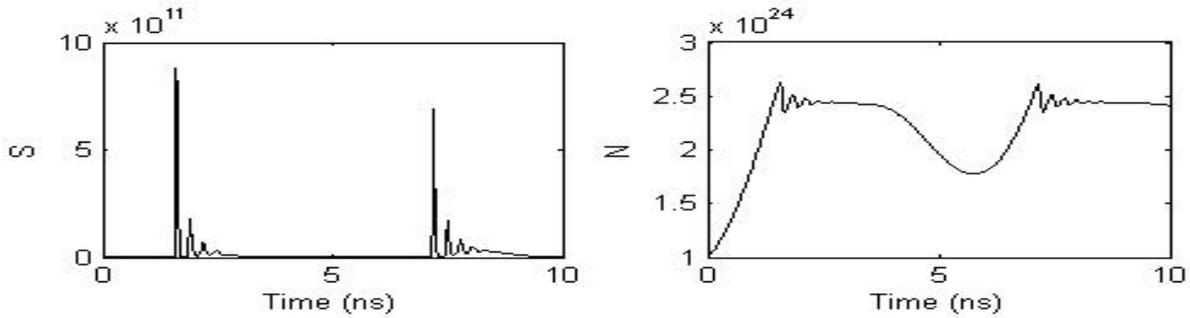


Figure 8. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 5\text{mA}$, $I_{ac} = 10\text{mA}$, $\omega = 10^9\text{ Hz}$

Figs (9-15) show another trend of behavior where the output breaks into stable, multi stable, aperiodic and chaotic behaviors in.

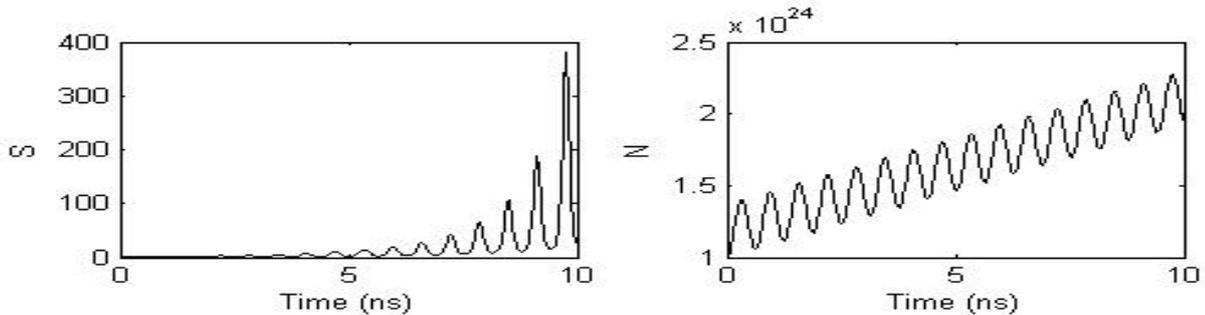


Figure 9. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 1\text{mA}$, $I_{ac} = 20\text{mA}$, $\omega = 10^{10}\text{ Hz}$

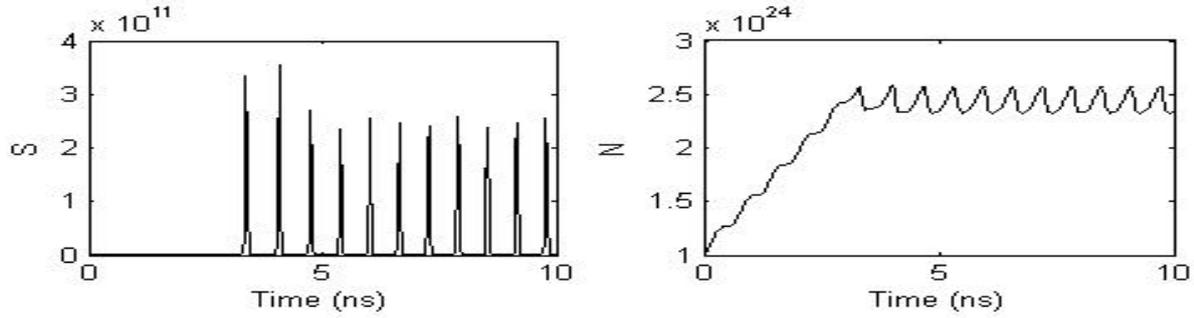


Figure 10. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 5\text{ mA}$, $I_{ac} = 5\text{ mA}$, $\omega = 10^{10}\text{ Hz}$

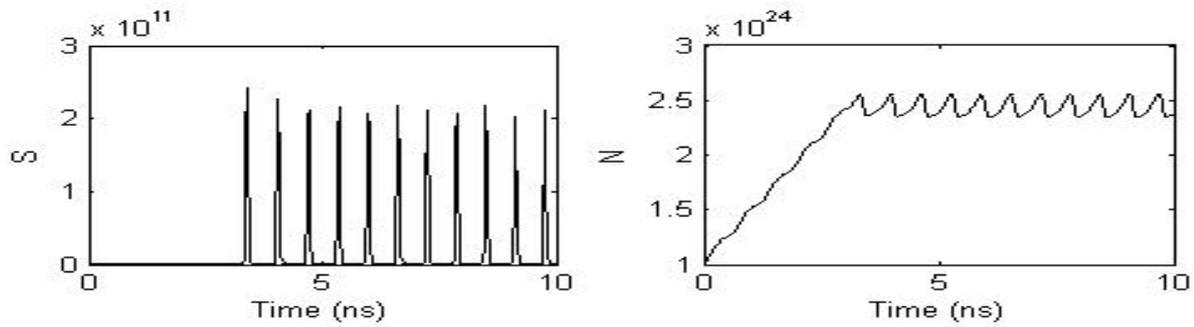


Figure 11. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 5\text{ mA}$, $I_{ac} = 3\text{ mA}$, $\omega = 10^{10}\text{ Hz}$

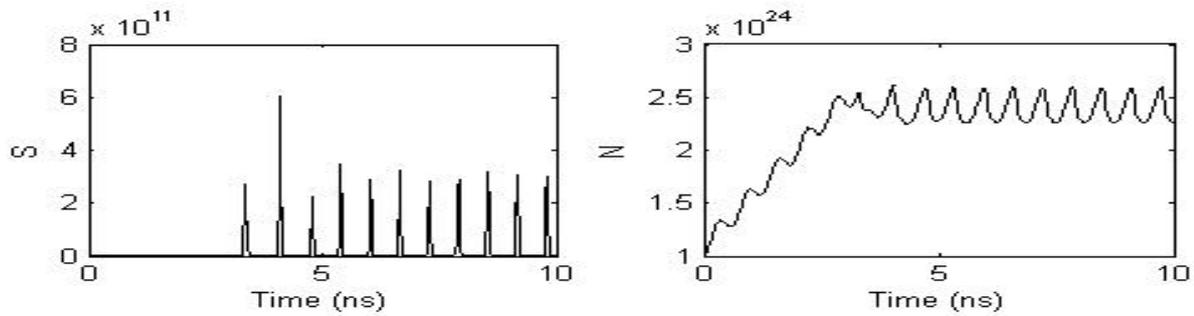


Figure 12. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 5\text{ mA}$, $I_{ac} = 10\text{ mA}$, $\omega = 10^{10}\text{ Hz}$

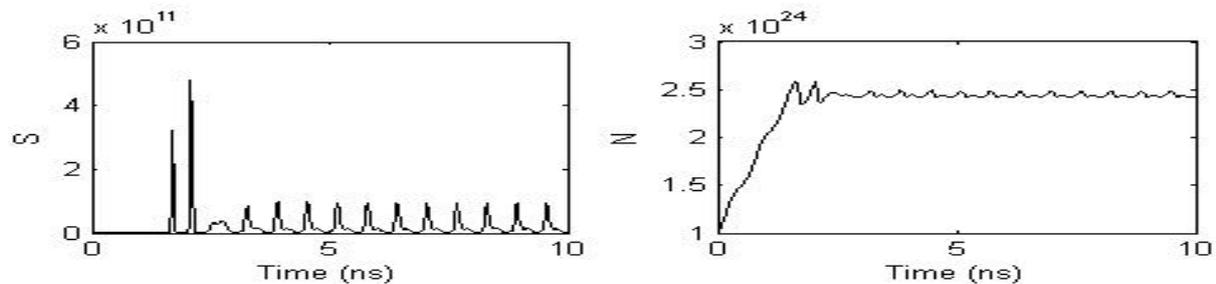


Figure 13. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N , for $I_{dc} = 10\text{ mA}$, $I_{ac} = 5\text{ mA}$, $\omega = 10^{10}\text{ Hz}$

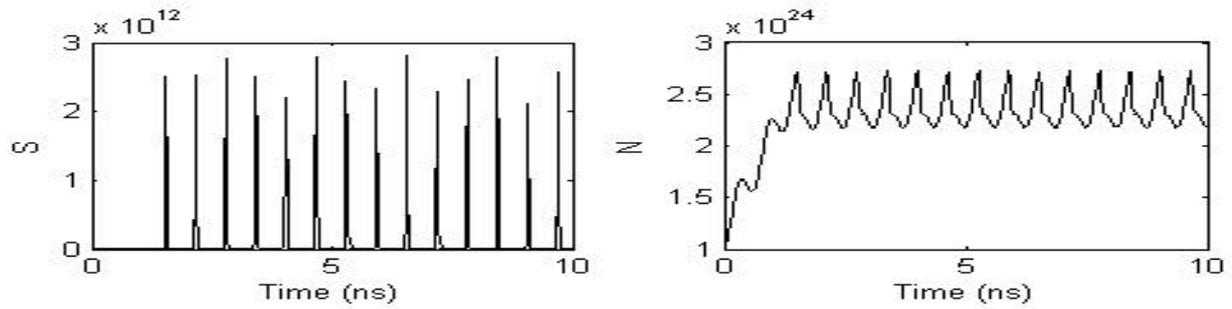


Figure 14. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 10\text{mA}$, $I_{ac} = 20\text{mA}$, $\omega = 10^{10}\text{Hz}$

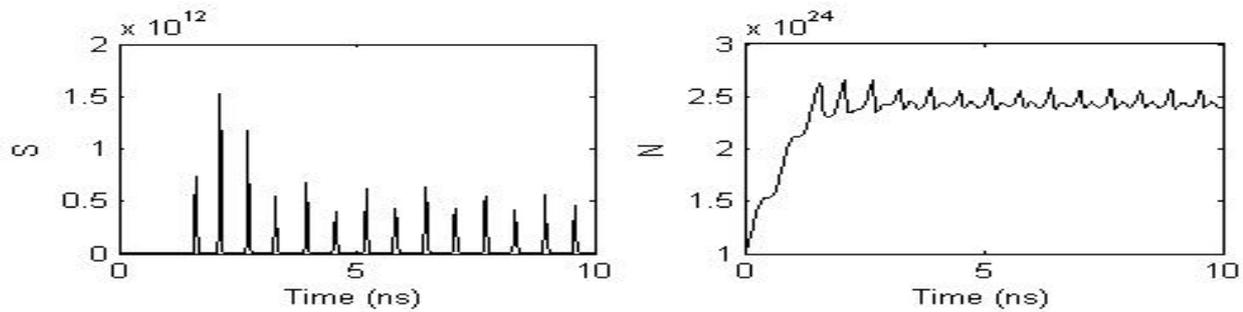


Figure 15. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 10\text{mA}$, $I_{ac} = 10\text{mA}$, $\omega = 10^{10}\text{Hz}$

Figs (16-20) the system retains its usual behavior as shown in

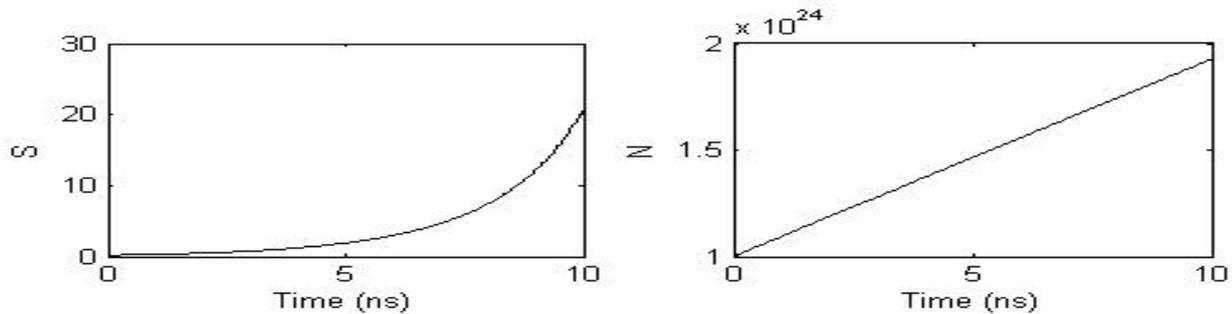


Figure 16. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 1\text{mA}$, $I_{ac} = 1\text{mA}$, $\omega = 10^{11}\text{Hz}$

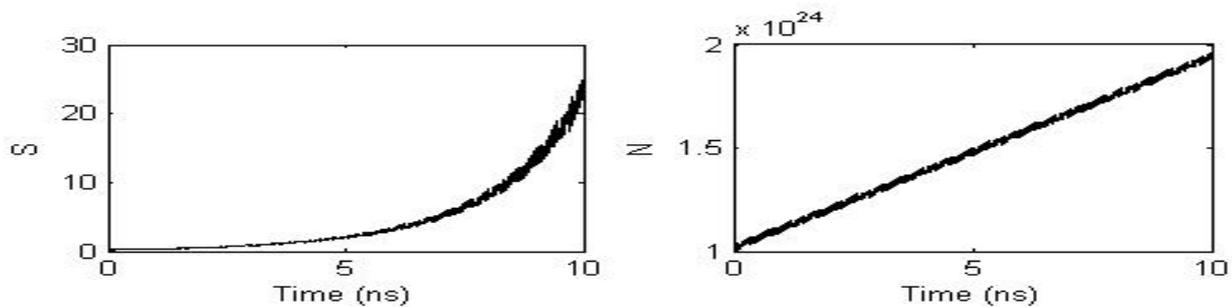


Figure 17. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 1\text{mA}$, $I_{ac} = 20\text{mA}$, $\omega = 10^{11}\text{Hz}$

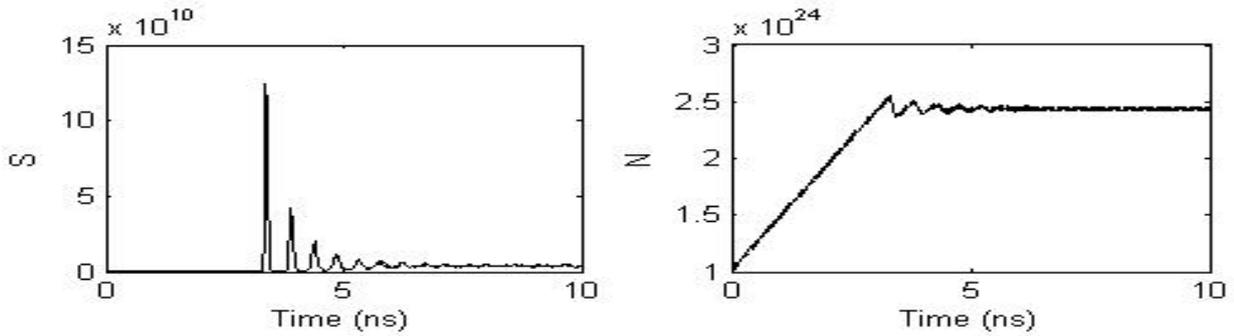


Figure 18. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 5 \text{ mA}$, $I_{ac} = 20 \text{ mA}$, $\omega = 10^{11} \text{ Hz}$

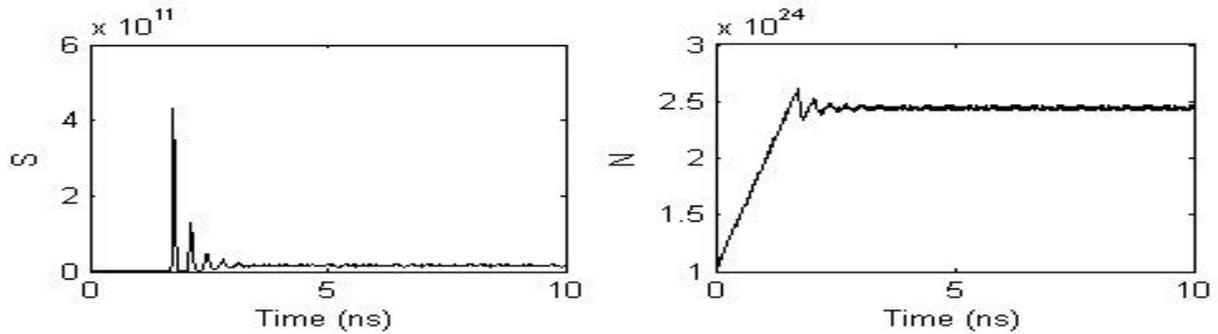


Figure 19. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 10 \text{ mA}$, $I_{ac} = 20 \text{ mA}$, $\omega = 10^{11} \text{ Hz}$

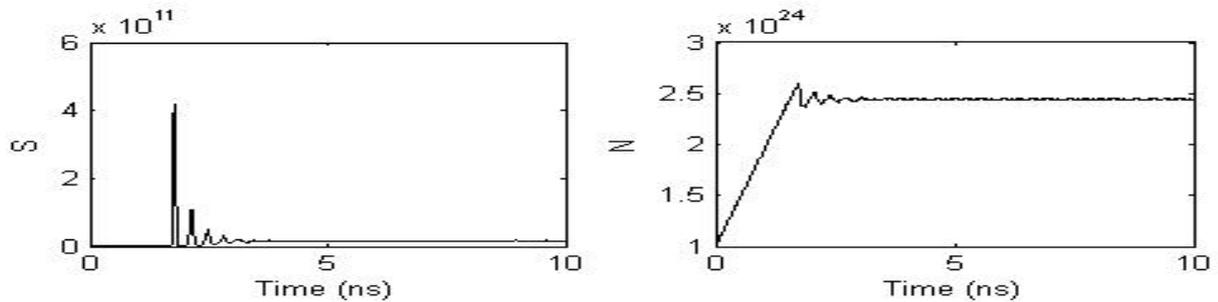


Figure 20. Temporal behavior of laser output, $S = |E(t)|^2$, and population inversion, N ,
for $I_{dc} = 10 \text{ mA}$, $I_{ac} = 10 \text{ mA}$, $\omega = 10^{11} \text{ Hz}$

In the range $\omega = 10^6 \text{ Hz}$, $I_{dc} = 1 \text{ mA}$, $I_{ac} = 1 \text{ mA}$ to $\omega = 10^8 \text{ Hz}$, $I_{dc} = 10 \text{ mA}$, $I_{ac} = 20 \text{ mA}$ we have produced the usual behavior expected from semiconductor laser near and above threshold.

In the range $\omega = 10^9 \text{ Hz}$, $I_{dc} = 1 \text{ mA}$, $I_{ac} = 1 \text{ mA}$ and $\omega = 10^9 \text{ Hz}$, $I_{dc} = 10 \text{ mA}$, $I_{ac} = 20 \text{ mA}$, unexpected behavior

appears where the system reproduces another laser signal or breathing effect (figs 5-8). It can be seen that the population inversion (N) grew to high value then reduces to lower one, followed by another peak in the inversion and lower one, leading to two laser signals of the same type. During the range $\omega = 10^{10} \text{ Hz}$, $I_{dc} = 10 \text{ mA}$, $I_{ac} = 20 \text{ mA}$, periodic, multi periodic, a

periodic and chaotic behavior appeared (see figs 9-15)

For the range $\omega=10^{11}$ Hz, $I_{dc}=1$ mA, $I_{ac}=1$ mA to $\omega=10^{11}$ Hz, $I_{dc}=10$ mA, $I_{ac}=20$ mA the system produced the same usual behavior expected from the semiconductor laser.

According to the obtained result, it seems that when the modulation frequency is less than the relaxation oscillation frequency of the laser (10^9 Hz) i.e. (10^6-10^8 Hz) the laser system is not affected by the modulated Ac component of the injection current as can be seen in Figs (2-4). When $\omega=10^9$ Hz which is compared to the system relaxation oscillation frequency the noticed behavior is seen to occur, i.e. breathing. At frequency 10^{11} Hz the system behaves chaotically. As the modulation frequency exceeds the relaxation oscillation frequency by two orders of magnitude, the system is no longer able to follow the modulation, the usual behavior reappears.

When the level of modulation is low, the output from semiconductor lasers follows the modulation of the injection current. On the other hand when the level of modulation is strong the output from such lasers shows number of properties such as harmonic distortion, bistability, period

5. Conclusion

Various output forms are generated from semiconductor laser under current modulation including the usual output expected from these lasers, multi-periodic

doubling and quasi-period-doubling to chaos [9].

When the semiconductor laser acts under a dc bias its output is generally stable without any type of instabilities. One method to enhance instabilities is the addition of a third degree of freedom since the semiconductor laser belongs to class B lasers where the population vanishes quickly [10].

Physically, it is believed that modulation of injection current, induces or enhances a modification in the spatial distribution of the carriers or is the population inversion in the shape of diffraction grating. The spatial frequency of this grating and its depth are functions of the AC part of the injection current [11] and its frequency. The central part of the semiconductor laser medium refractive index is higher than the cladding, so the variations in the refractive index induced by the variations in the population inversion as a result of modulation have drastic effect on the laser output. This situation makes the interaction between the electric field oscillating inside the laser cavity and population inversion so complex to enhance nonlinear variations in the laser system which appear in the laser output in comparison with case of non modulation.

and chaotic one. Breathing effect seems to occur too.

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السلوك الديناميكي لخرج ليزرات شبه الموصل بتأثير تيار التضمين

أباذر رحمن أحمد

قسم الفيزياء ، كلية التربية ، جامعة البصرة ، البصرة ، العراق

الخلاصة

درسنا امكانية حدوث أنواع مختلفة من الخرج في ليزر أشباه الموصلات تراوحت بين الخرج الاعتيادي المتحصل من هذه الليزرات والدوري و متعدد الدوريات واللا دوريات والفوضوي كنتيجة لتضمين تيار الحقن.