Direct modulation of Photonic Crystal Vertical-Cavity Surface-Emitting Lasers (PC-VCSELs)

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Abstract :

The occurrence of various laser outputs from photonic-crystal vertical-cavity surface-emitting lasers (PC-VCSELs) was investigated 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. The study proved that PC-VCSEL dynamics is strongly affected by the variation injection current signals and exhibits dramatic changes in the laser output.

Key word: Microcavity lasers,Photonic crystal,VCSEL,Direct modulation,

The article is a part of an ongoing M.Sc research

Introduction :

Photonic crystals are dielectric or metallo-dielectric nanostructures with spatially periodic dielectric constant. Because of the periodicity in between similar dielectric constant regions, some wavelengths of light in the material are not allowed to travel through the structure, giving rise to photonic bandgaps [IshitaM.,2010].

Photonic crystal confinement is a method ofintroducing a very controlled lateral index change into a VCSEL cavity through the addition of small holes in the top Distributed Bragg Reflector (DBR) [Aaron J. D.,*et al.*,2004].Fig(1.a) shows a schematic of a single defect PC-VCSEL. The two-dimensional (2D) photonic crystal consists of a triangular or square array of etched air holes as shown in Fig (1.b) for single defectPC-VCSEL.

Photonic crystal nanocavities can be formed by modifying one or more holes (i.e., bychanging the hole size or the refractive index) or neglecting one or more holes. Such a break in the periodicity of the lattice introduces new energy levels within the photonic band gap. This is analogous to the creation of energy levels within the semiconductor energy band gap by the addition of dopant atoms in semiconductor crystals [Hatice A.,2012].

Lasers based on photonic crystal (PC) technologies have attracted much attention because thephotonic crystal cavity provides a small mode volume,a high Q-factor,high efficiency,small threshold current and high bandwidth, result from the nature of spontaneousemission in a wavelength-sized cavity named Purcell effect [Josep C.etal.,2006]. Furthermore, photonic crystal technologies enable the researchers to obtainvarious functional devices with extremely small energy [Shinji M.*et al.*,2011;Alejandro G.,2007].

Optical microcavities are micro or nanoscale structures that are able to confine light toa volume of the order of the wavelength of light, by resonant recirculation. Because ofthis light confining property, optical microcavities can control the distribution of theradiated power and spectral width of the emitted light, which is useful in enabling long distance data transmission over optical fibers [Alejandro G.,2004].

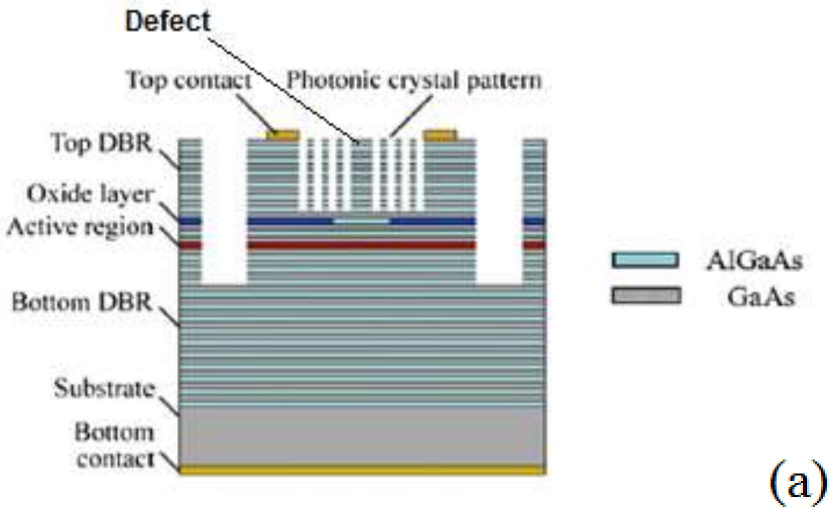

Figure 1: (a). sketch PC-VCSEL of two dimensionalPhotonic crystal (b) Single-defect photonic crystal cavity laser

Optical microcavities can also enhance or suppress spontaneous emission rates of photons, and control the directionality of emission[Alejandro G.,2004], even for single photon sources. This property is particularly important in developing quantum encryption systems[Alejandro G.,2004] .The Photonic crystals(PC) in the VCSEL confines transverse electric field and converts multi-mode intosingle mode[XuXingSheng*et al.*,2007].PC- VCSEL can reduce the thermal resistance, improve the thermal characteristics and enhance the modulation rate.

High-speed direct modulation of a VCSEL is desired to further increase the transmission capacity of communication networks. Incorporation of a PC structure into a VCSEL enables engineering the index guiding and improves the modulation bandwidth by reducing optical modal volume and increasing laser efficiency[Kent D.*et al.*,2011].

The direct current modulation in semiconductor lasers was studied brifly by [abather R.,2013], [Hassan H. A. etal] studied the modulation of the convential VCSEL. While PC-VCSEL modulation was studied by [Meng P. T., 2013]

The use of direct modulation meansthat the laser becomes a driven nonlinear system with potentiallycomplicated dynamics. Indeed, it is well known thateven simple high-frequency modulation of sufficiently large amplitude can lead to nonlinear phenomena such asperiod doubling cascades, period tripling, and chaos [Lucas I. and Matthew B.,2004].

In this work, we study direct modulation response of photonic-crystal vertical-cavity surface-emitting lasers (PC-VCSEL) by varying the DC and the AC components of injection current and frequency of modulation on the dynamical behavior of photonic-crystal vertical-cavity surface-emitting laser .

The numerical model :

The rate equations that describe the time rate of change of the carrier density, N, and the photon density,N_p, in a laser, and describe the supply and loss of the carriers and photons within the active region, these equations may be written as [Hatice A. and Jelena V.,2005; Golden L. A. and Corzine S.W.,1995]:

$$\frac{dN}{dt} = \frac{\eta_i I}{q V} - \frac{N}{\tau} - V_g\, g\, N_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\frac{dN_p}{dt} = \Gamma V_g\, g\, N_p + \Gamma\beta_{sp}\frac{N}{\tau_r} - \frac{N_p}{\tau_p} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

$$\text{with}\ \frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Where Nis the carrier density,$N_p$is the photon density, η_i is the injection efficiency, Iis the terminal current, qis the electronic charge, Vis the volume of the active region,τis the carrier lifetime, V_g is the group velocity, g is the gain, Γis the confinement factor, β_{sp} is the spontaneous emission factor, $\tau_p$is the photon lifetime,$\tau_r$is the radiative recombination time and$\tau_{nr}$is the nonradiative recombination time . The gain function (after neglecting the gain compression factor), is given by:

$$g = g_0 (N - N_{tr}) \ldots\ldots\ldots\ldots..(3)$$

where$g_o$is the differential gain, N_{tr} is the transparency carrier density.

The output power (P_{out}) can be calculated using the relation [Alejandro G.,2007]:

$$P_{out} = F\, V_g\ \alpha_m\ h\ \nu N_P V_P \qquad \dots\dots\dots\dots (4)$$

Where Fis the proportion of photons exiting the output photonic crystal mirror ascompared to the opposite mirror,ν is the laser output frequency, V_P is the cavity volume, h is the Planck constant, α_m is the light lost from the photonic crystal mirror. Note that equation (4) explicitly illustrates the direct dependence of the output power on the cavity volume. The injection current (I) can be written as:

$$I = I_0 + m \sin(\omega t) \ \dots\dots\dots\dots (5)$$

Where $I_0$is the dc part of the injection current and m is the ac part , $\omega=2\pi f$is the angular frequency, f is modulated signal frequency.

Results and discussion:

The set of equations (1-3) were solved numerically usingRunge-Kutta method within MATLAB system, the parametersvalues used in the simulation are given in table (1)[Alejandro G.,2007, Yinang Gong etal,2010]. where the only control parameter examined is the injection current (I), by varyingI_0, m and the frequency of modulation(f). These three parameters were varied respectively through the ranges (10^{-6}-10^{-5}) A, (10^{-6} -10^{-4}) A, and (1 MHz -100 GHz).
Fig (2) shows direct injection current against time for the modulation frequency1 GHz for sinusoidal wave and square wave**.**

The power spectra have been evaluated for two types of current modulation: sinusoidal andsquare wave. To obtain the following results we have used sinusoidal wave and square waves:

A- Small signal modulation using sinusoidal wave (m <I_0):

In this part modulation a sinusoidal wave of small amplitudes m = 10^{-6} A was studied.The dc part of the injection currentwas at thresholdI_0=10^{-5} A. The usual output(without modulation) form generated from PC-VCSEL is shown in fig (3.a) and the corresponded power spectrumin fig (3.b). The modulation effect on PC-VCSEL output at f=100 MHz,can be seen in fig (3.c). By increasing the modulation frequencyto f=500 MHz, the laser operates in the period 1, as can be seen in (fig 3.e). The same behavior can be seen for f=(2,5) GHz (figures 4.a-c). At a higher value for the modulation frequency,f=100GHz, severe chaotic state appears (fig 4.e).The power spectrum under a direct modulation current is shown in figures (3.d,f) and fig(4.b,d,f) for sinusoidal wave. The study showed that increasing the modulation frequency leads to oscillating other modes or lasing frequences around the central frequency(ω_0).The effect of direct current modulation on the carrier density of PC-VCSEL is shown in fig (5) for various values of amplitudes and frequency. It is seen that N followed the variation of the injection current and dramatic changes in the carrier evolutions was observed.

B- Small signal modulation using square wave (m <I_0) :

Figures (6-8) shows output power against time for variation of modulationfrequency in the range (100 MHz-100GHz) of a square wave at $I_0 = 10^{-5}$ A and m = 10^{-6} A. Without modulation the output power is shown in fig(6.a) and the corresponding power spectrum in fig(6.b). By increasing the modulationfrequency for uniform square wave the output power occursto switch to various types of square wave as can be seen from the figures above. Chaotic output occurs whenincreasing the modulationfrequency at f=(10-100)GHz as seen in figs(7-8).

C- Large signal modulation using sinusoidal wave (m >I_0):

In this section, the dc part of the injection current wasfixed below the threshold i.e.$I_0=10^{-6}$ A, while the signal amplitude is greater thanI_0,(m = (10^{-5}-10^{-4}) A). For frequencies less than 1GHz the output power doesn't shows significant changes. Atfrequency f=1 GHz for m= 10^{-5},period 1 state appears as in fig (9.a). At m= 2x10^{-5} A the period 1 state recovered on a more then period 2 and period 3 occurs fig (9.c,e). The power spectrum under a direct modulation current for large signalshows that more lasing frequencies are grown up inside the laser cavity.

Figures (10-11) shows modulated output power with time at m = 10^{-5} A, and the frequency changes in the range (100 MHz-100GHz). For small values of modulationfrequency (100-150)MHz andthe ac partm = 10^{-5} A andthe dc part of the injection current $I_0=10^{-6}$ A period 3 state appear fig (10.a,b). At f=500 MHz the laser operates in the period 2 (fig 10.c). By increasing the modulationfrequency,f=1 GHz, the laser operates in the period 1 , as can be seen in (fig 10.d). At higher value for the modulationfrequency in the range (5 -100)GHzsevere chaotic state appears (fig 11).

Table (1) parameters used in the calculations[Alejandro G.,2007, Yinang Gong *et al.*,2010]

Definition	**Symbol**	**Value**	**Units**
Injection efficiency	η_i	1.3 x10^{-5}	-
Electronic charge	q	1.6 x10^{-19}	C
Volume of the active region	V	9.42x10^{-17}	cm^3
Spontaneous emission factor	β_{sp}	0.05	-
Group velocity	V_g	1 x10^{10}	cm/s
Confinement factor	Γ	0.03	-
Nonradiative recombination time	τ_{nr}	9	ns
Photon lifetime	τ_p	7.1	ps
Radiative recombination time	τ_r	3	ns
Gain coefficient	g_o	2100	cm^{-1}
Number of carrier at transparency	N_{tr}	7.9 x10^{15}	cm^{-3}
Wavelength	λ	980	nm
Cavity volume	V_p	3. 6x10^{-16}	cm^3
Output mirror to opposite mirror	F	0.98	-
Mirror losses	α_m	1	cm^{-1}

Conclusion:

The effect of the Direct modulation of photonic-crystal vertical-cavity surface-emitting lasers was studied via the variation of the dc and ac parts of injection current and the frequency of modulation forsinusoidal wave and square wave.Various output forms are generated from the laser under current modulation including the usual output expected from this laser, multi-periodic and chaotic one, The study prove that the modulation injected current affect strongly the output of PC-VCSEL.

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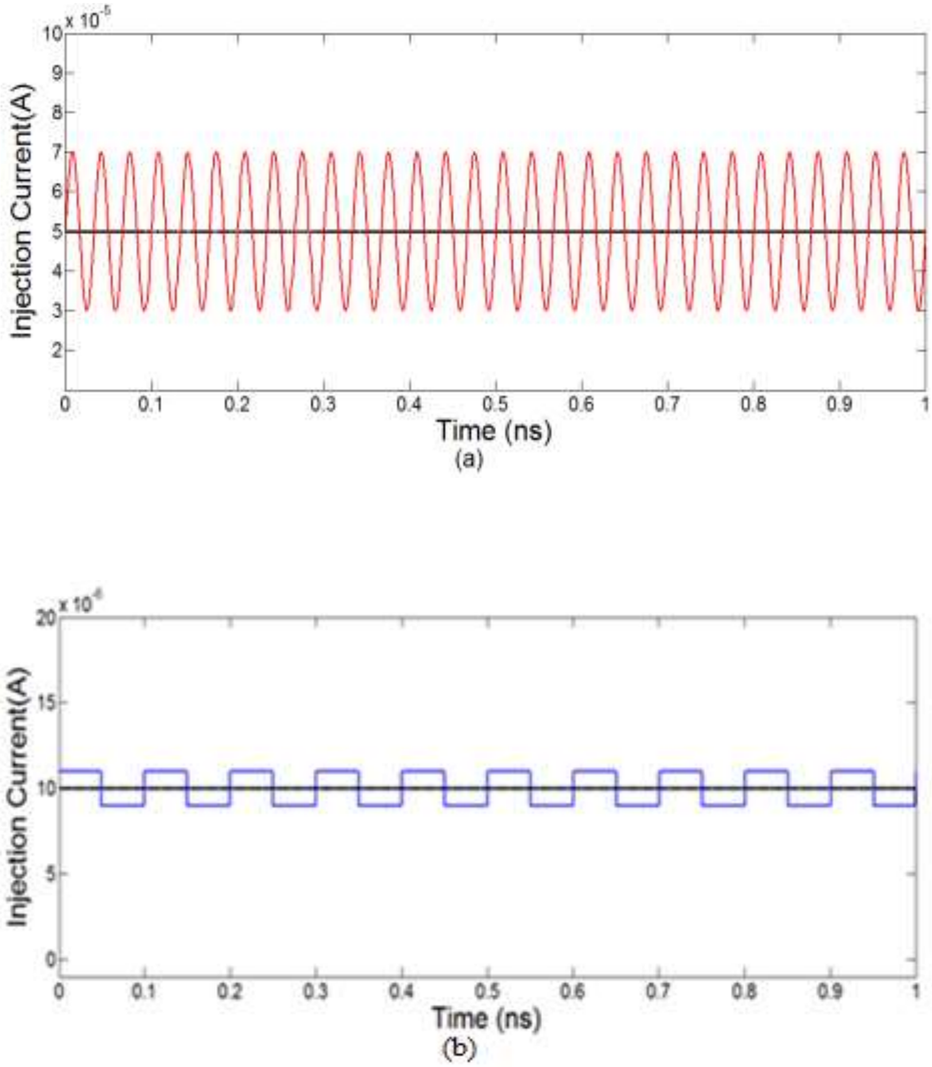


Fig (2) :Injection current against timefor the modulation frequency 1 GHz (a) sinusoidal wave (b) square wave

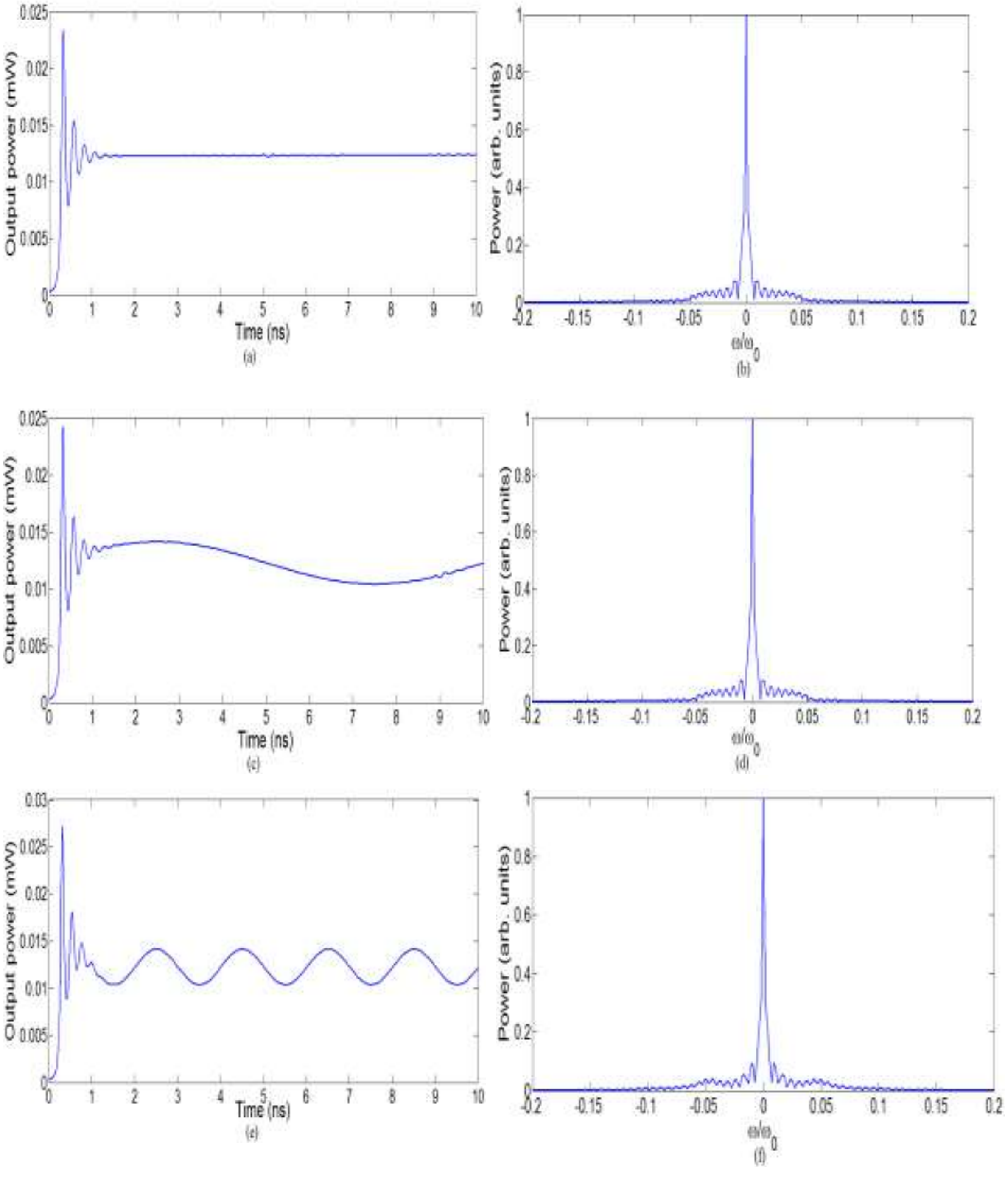


Fig (3):(Left): Output power against time for $m=10^{-6}$ A,$I_0=10^{-5}$ A for the modulation frequency (0 MHz , 100 MHz ,500 MHz)(Right): The corresponding power spectrum of PC- VCSEL.

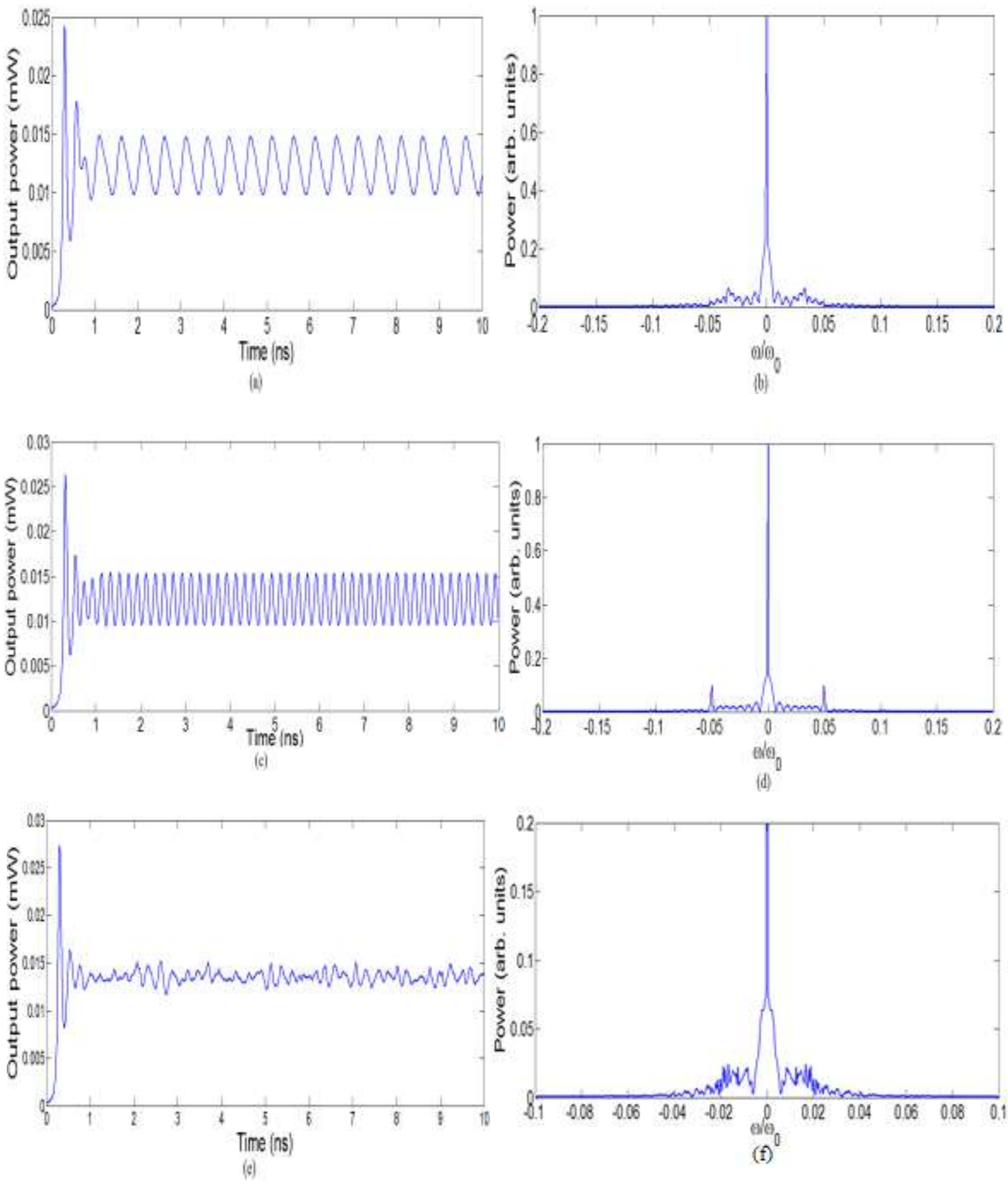


Fig (4(Left): Output power against time for m=10^{-6} A,I_0=10^{-5} A
for the modulation frequency (2GHz , 5GHz ,100 GHz) .(Right): The corresponding power spectrum of PC- VCSEL.

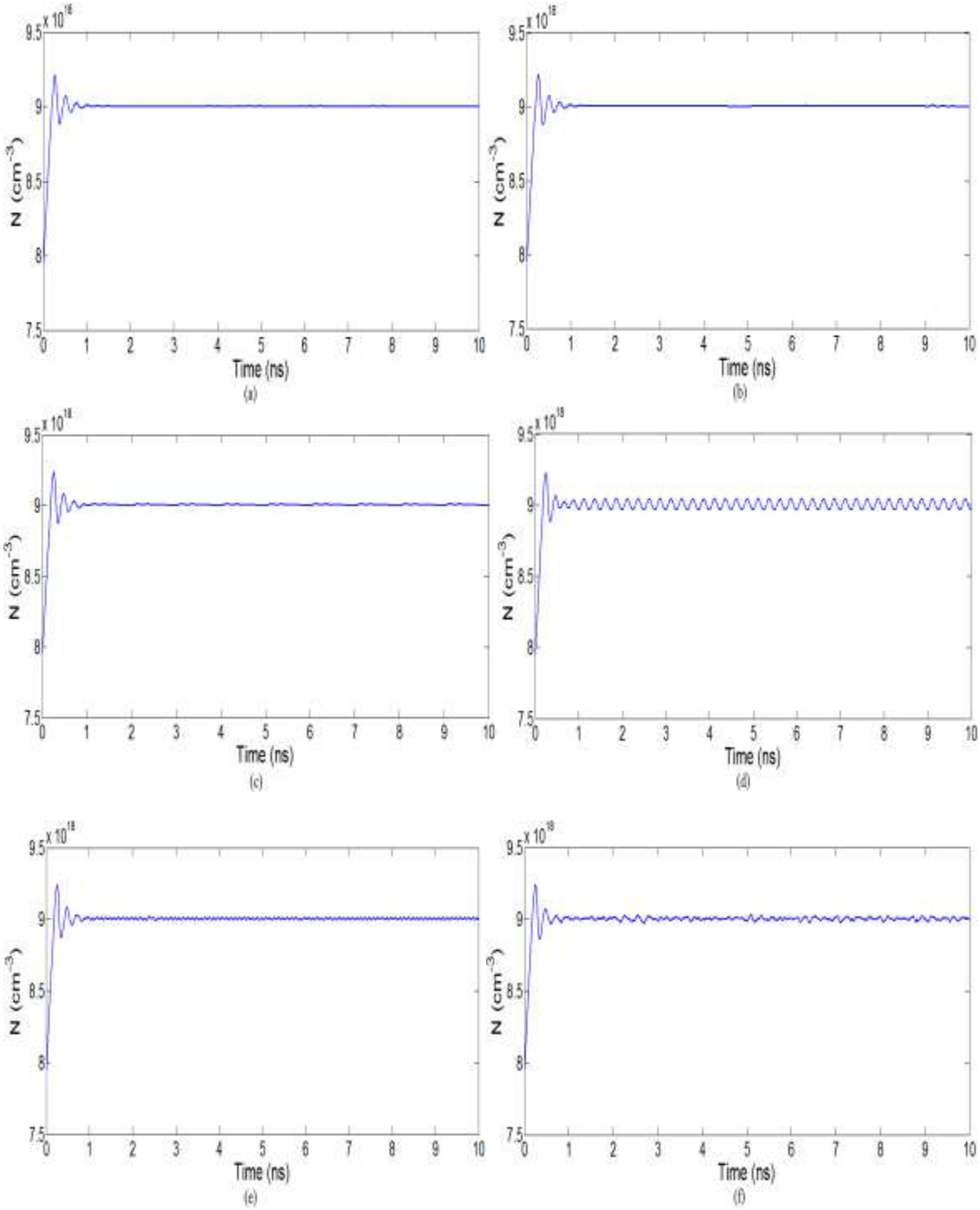


Fig (5): The variation of carriers density (N)with time at m=10^{-6} A,I_0=10^{-5} A
for the modulation frequency (a) 0 MHz, (b) 100 MHz, (c)500 MHz, (d) 2GHz, (e) 5 GHz, (f) 100 GHz

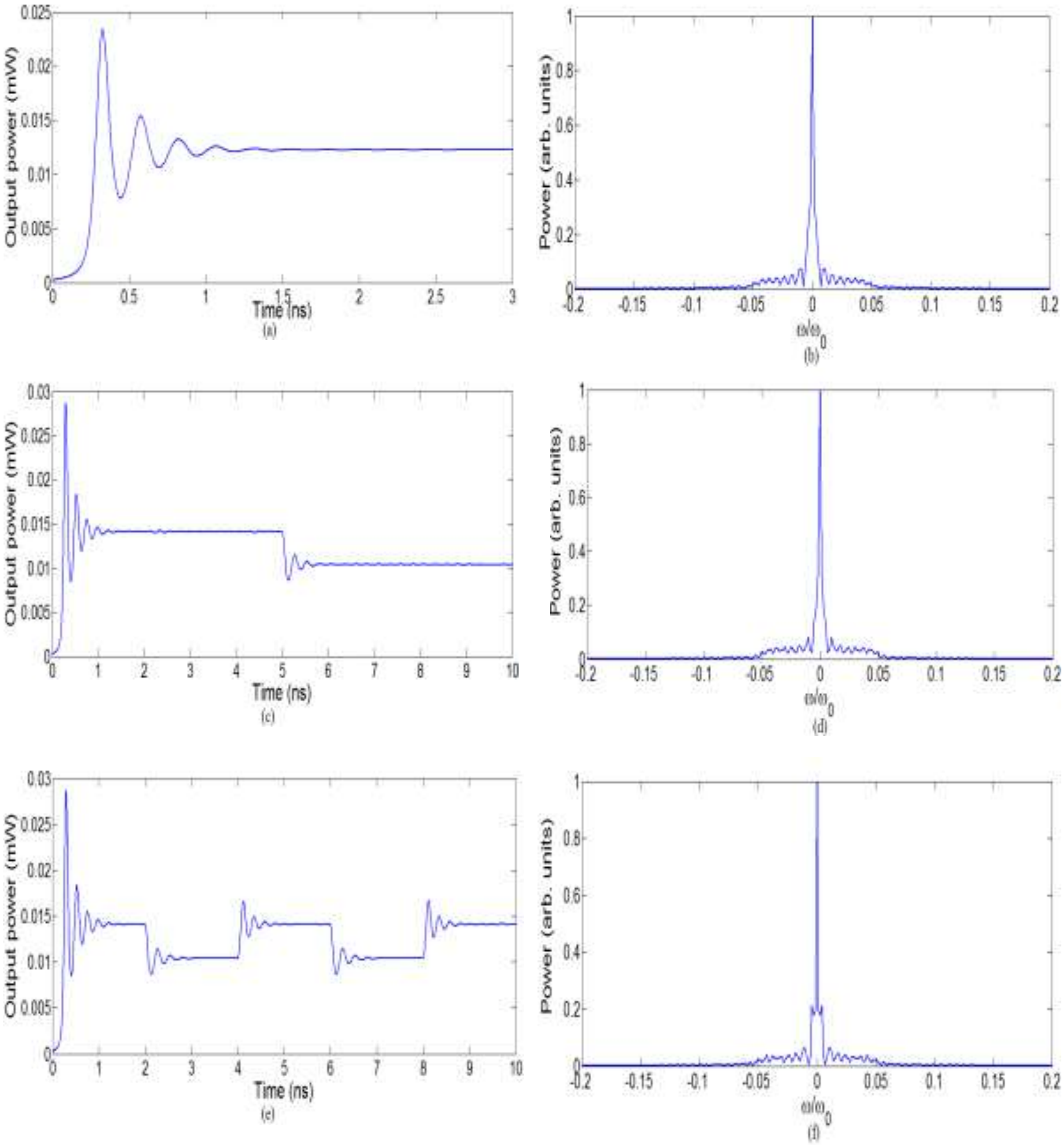


Fig (6): (Left): Output power against time for $m=10^{-6}$ A, $I_0=10^{-5}$ A for the modulation frequency (0 MHz , 100 MHz ,250 MHz) . (Right): The corresponding power spectrum of PC- VCSEL.

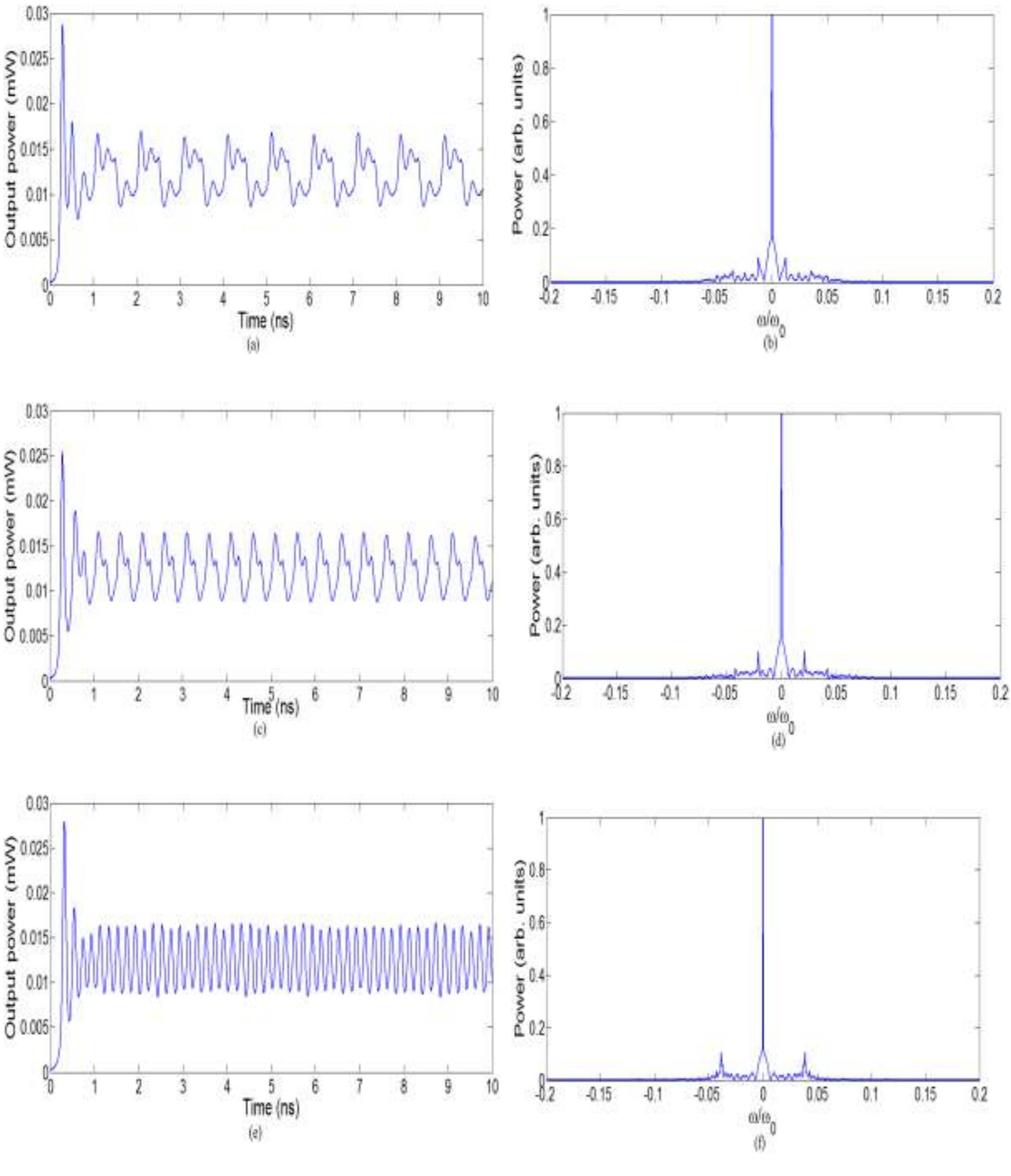


Fig (7): (Left): Output power against time for m=10^{-6} A,I_0=10^{-5} A for the modulation frequency (1 GHz , 2GHz ,5 GHz) . (Right): The corresponding power spectrum of PC- VCSEL.

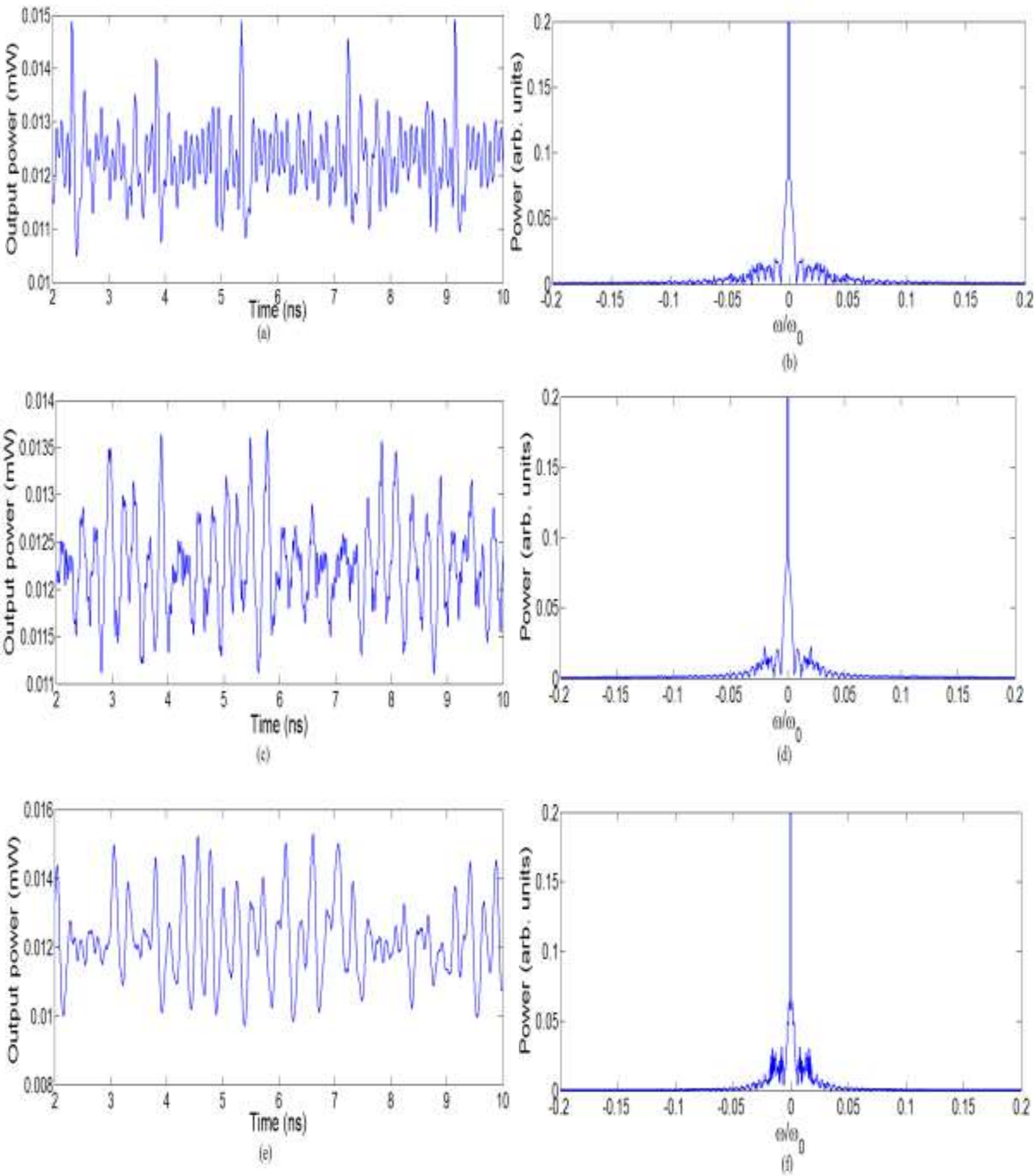


Fig (8): (Left): Output power against time for $m=10^{-6}$ A,$I_0=10^{-5}$ A for the modulation frequency (10GHz , 20 GHz ,100 GHz) . (Right): The corresponding power spectrum of PC- VCSEL.

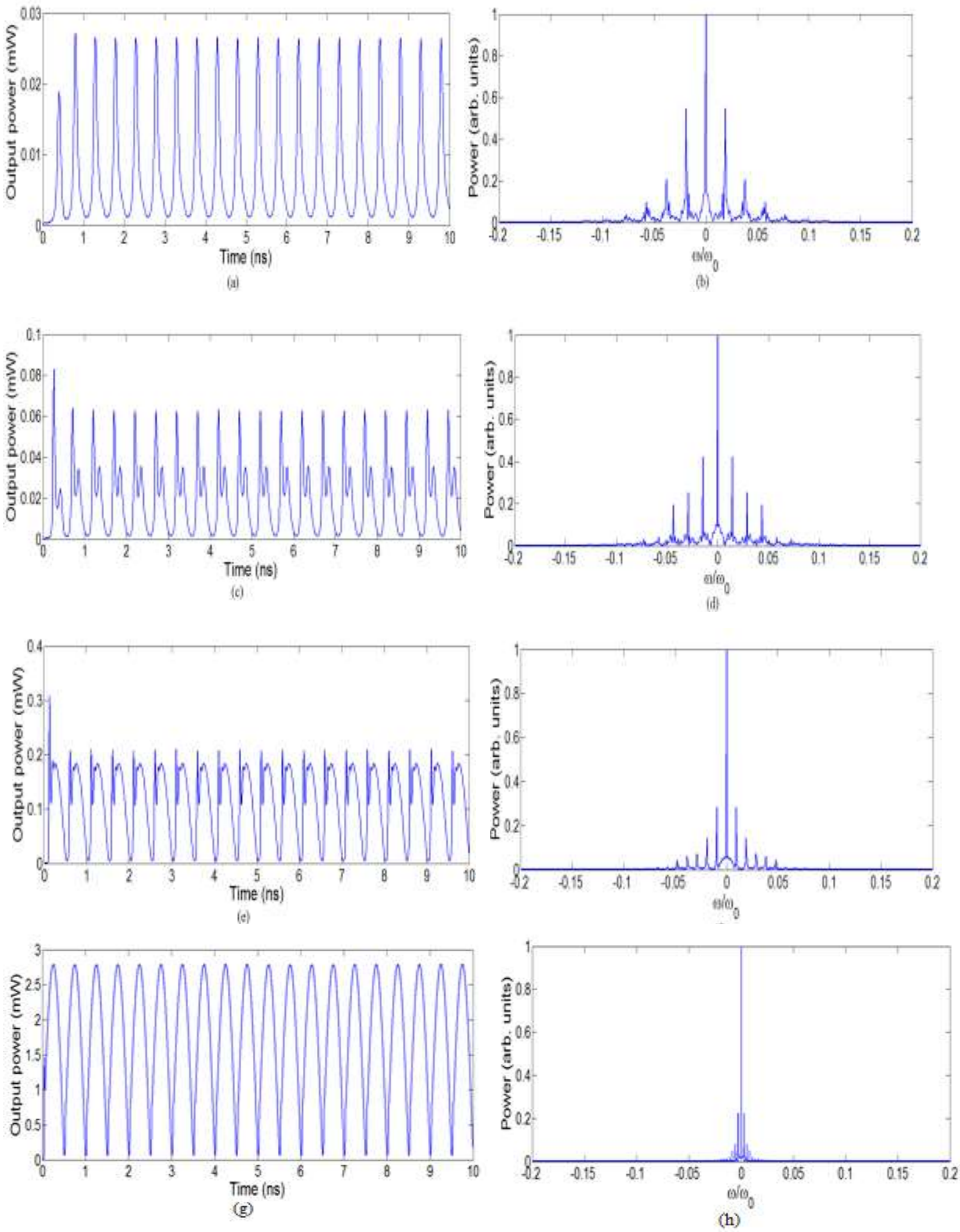
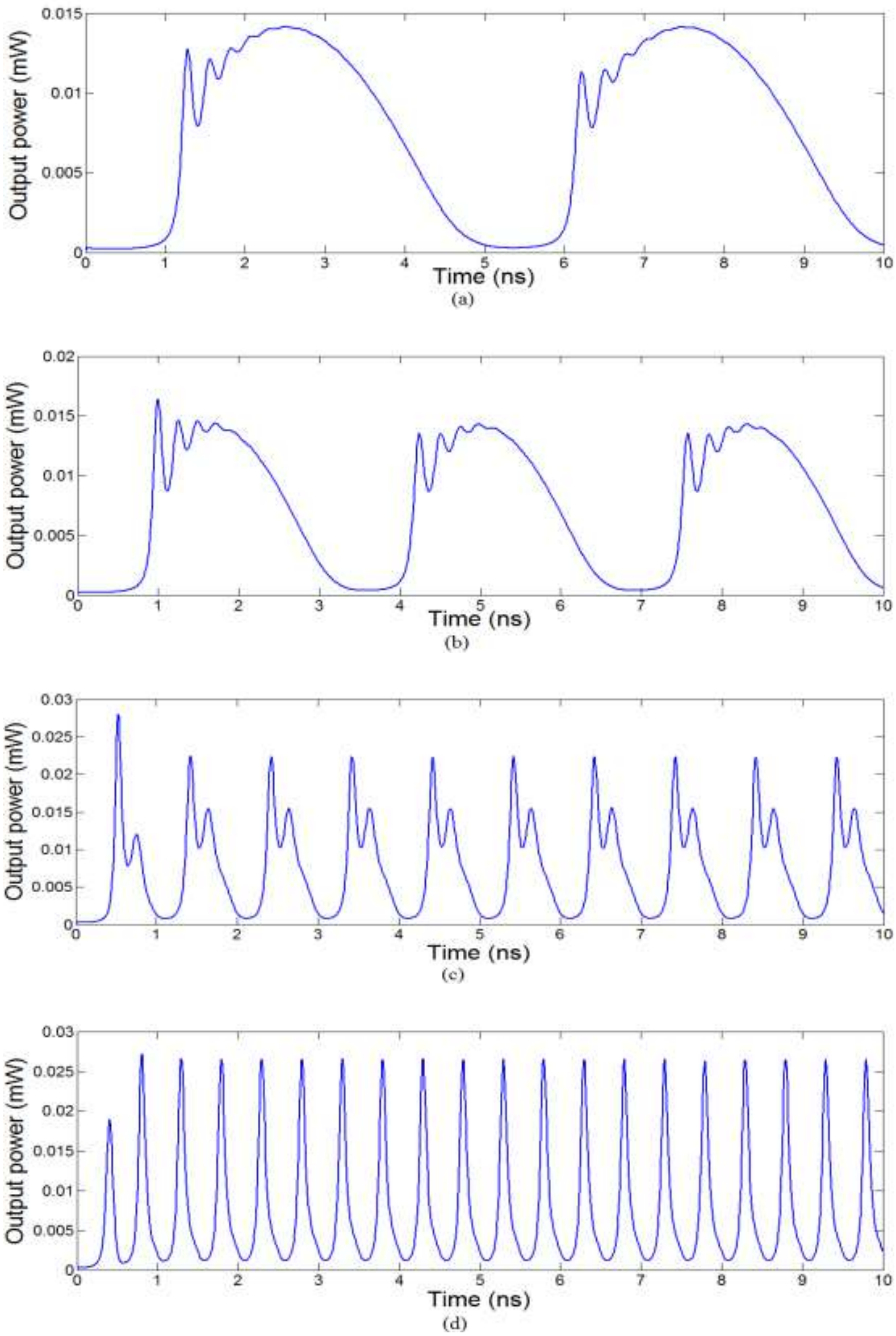
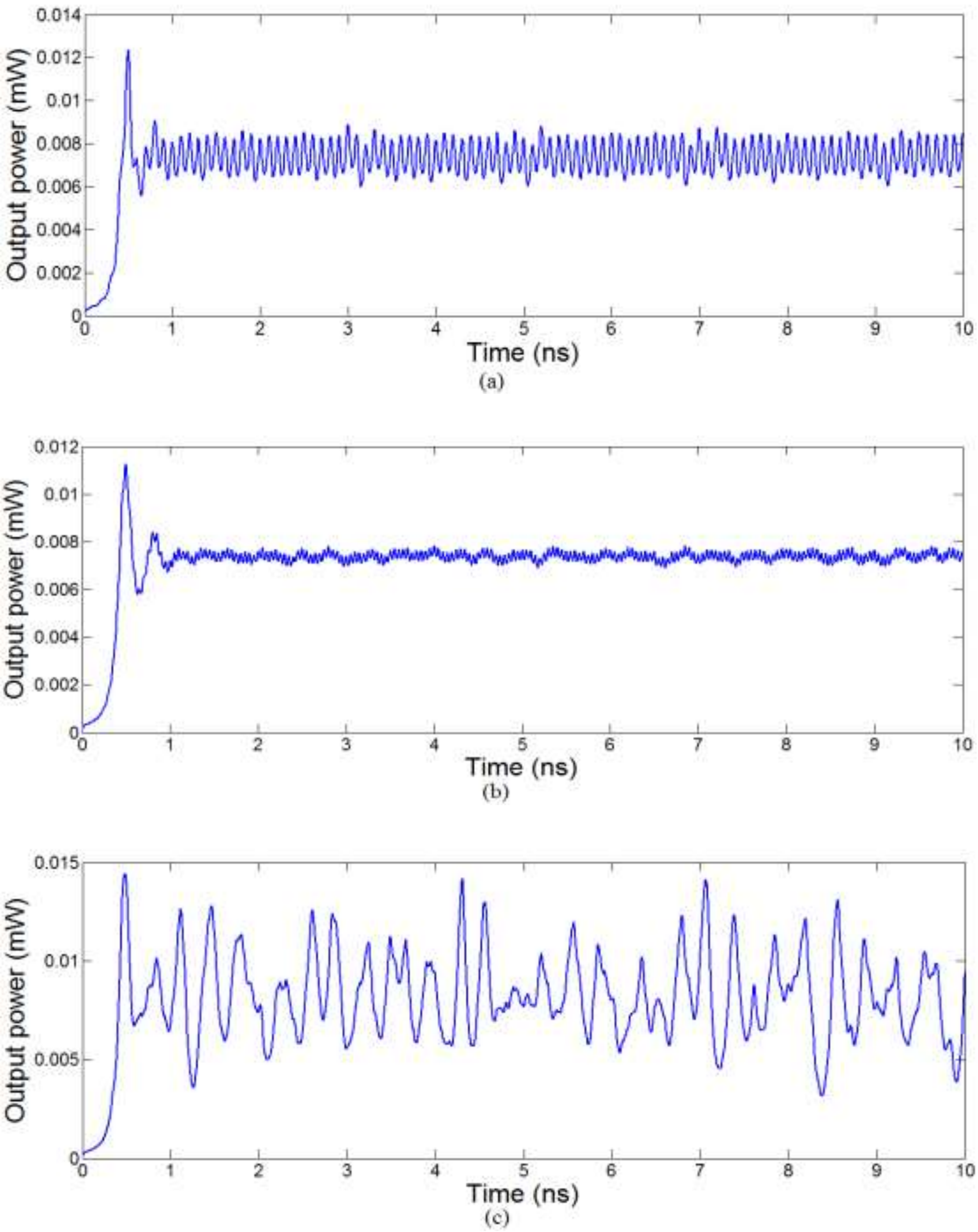


Fig (9): (Left): Output power against time for f=1GHz,I_0=10^{-6} A (a)m=10^{-5}A (c)m=2*10^{-5}A(e)m=10^{-4}A (g) m=15*10^{-4}A.(Right): The corresponding power spectrum of PC- VCSEL.



Fig(10) : Modulated output with time , m = 10^{-5} A , I_0=10^{-6} A , (a) f=100 MHz (b)150 MHz (c) 500 MHz (d) 1 GHz



Fig(11) : Modulated output with time , m = 10^{-5} A , $I_0=10^{-6}$ A , (a) f=5 GHz (b)10 GHz (c) 100 GHz

التضمين المباشر لليزرات الانبعاث السطحي ذات التجويف الشاقولي ذات البلورة الفوتونية

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الخلاصة

تم في هذا البحث دراسة نظرية لإمكانية حدوث انواع مختلفة من الخرج في ليزرات الانبعاث السطحي ذات التجويف الشاقولي ذات البلورة الفوتونية. اعتبرنا حالة تضمين تيار الحقن لليزر لموجة جيبية وموجة مربعة كمسبب اساس لظهور الخرج الاعتيادي والفوضوي في خرج هذا النوع من الليزرات، تحت تأثير عدد من عوامل السيطرة الواردة في الانموذج الرياضي. اوضحت الدراسة ان التضمين يؤثر وبشدة في خرج الليزر.