Theoretical Comparison of the Dynamical Behavior between Bulk and SQW GaAs/AlGaAs Laser with pumping of Nd: YVO4 Crystal

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Abstract:

In this work, a theoretical comparison was made for the dynamical behavior of the bulk and SQW GaAs/AlGaAs lasers, in which the peak modal gain and threshold current density are studied with varying the active region thickness d=(0.02to 0.3)μm at two reflectivities of (R=0.32 and0.8) and the well widths L_z=(200, 150, 100, and 75) Å for the SQW laser, both at a bandgap discontinuity of ΔE_c of 0.1 eV and at a temperature of T=300°K.

It was found that the highest value of bulk laser of the peak modal gain is g_{max}=240 cm^{-1} and that the increasing of the facet reflectivity will be minimized the value of the threshold current density, while increasing the value of the thickness of the active region at fixed reflectivity will result in an increase in the value of the threshold current density, while for the SQW laser it was found that the highest value of the peak modal gain g_{max}=400 cm^{-1} is achieved at L_z=75 Å, the lower value to achieve transparency N_{tr}=0.5×1018 cm^{-3} at L_z=200 Å, and that the optimum value for QW width to achieve the lower threshold current density J_{th}=481.5 A/cm^2 at the same injected carrier density is L_z=100 Å.

In the experimental work as an application 808 nm (2Watt) bulk and 810 nm (1Watt) QW laser used as pumping sources to a Nd:YVO4 Disk crystal with dimensions of (4*5*1 mm) with an output coupler with 90% reflectivity, and ROC=400mm using V-shape technique. From the experimental work the optimum resonator length was found to be 14.5 cm which achieves a maximum output power of 58 mW, with a slope efficiency of 11.3%, using bulk diode laser the efficiency was found to be 3.2%, with a maximum output power of 29 mW, this draws us to the fact that QW laser source is more efficient and suitable for pumping solid state media.

Keywords: GaAs/AlGaAs diode laser, Peak gain, Threshold current density, Diode pumping, Nd:YVO_4, Face pumping.

I. Introduction:

Quantum-well (QW) semiconductor lasers offer the advantages of low threshold current density and high-power capability with good efficiency, [1]. Quantum well (QW) lasers are attractive for research because they are both physically very interesting and technologically important. QW technology allows the crystal grower for the first time to control the range, depth, and the arrangement of the quantum mechanical potential wells. In the last decade, the importance of the quantum well laser has steadily grown until today it is preferred for most semiconductor laser applications, [2].

Their growing popularity is because, in almost every respect, the quantum well laser is somewhat better than conventional lasers with bulk active layers. One obvious advantage is the ability to vary the lasing wavelength merely by changing the width of the quantum of the QW. A more fundamental advantage is that the QW lasers delivers more gain per injected carrier than conventional lasers, which results in lower threshold currents,[2,3].

A principal feature of the QW laser is the extremely high optical gain that can be obtained in the QW for very current densities. This arises partly from greater population inversion at a given carrier density because of the lower quantized density of states, but mostly from the high carrier density in the QW because of its small width, [1].

In general, the QW lasers have the extremely high optical gain because of their high carrier confinement. The optical confinement factor of the QW lasers is relatively low due to their thin active region. To predict the lasing behavior, we must evaluate the modal gain of the QW lasers. The modal gain of QW lasers is determined by their optical confinement factor and their ability to collect injected carriers efficiently, [4].

Semiconductor diode lasers, due to the inherently high efficiency of these laser sources (overall optical- electrical efficiencies larger than 60%), are now commonly used (diode laser pumping). Quantum well (QW) lasers are attractive for research because they are both physically very interesting and technologically important. QW technology allows the crystal grower for the first time to control the range, depth, and the arrangement of the quantum mechanical potential wells. In the last decade, the importance of the quantum well laser has steadily grown until today it is preferred for most semiconductor laser applications, [5].

The disk lasers are characterized in that the light is amplified passing through a thin disk active layer, [6,7]. Such lasers are under intensive research for both pulsed and continuous- wave operation. Such geometry allows the efficient heat sink at small distortions of the wavefront, therefore the scalability to high power is expected, the purpose of face- pumped disk amplifiers is to provide a uniform gain distribution over a very large cross- section. The majority of modern solid-state lasers use neodymium (Nd) doped materials such as Nd:YAG (Yttrium Aluminum Garnet which is $Y_3Al_5O_{12}$), Nd:YVO4, Nd:Glass, and others. The general limit of power scaling comes from the overheating, the surface loss and the amplified spontaneous emission (ASE), [6]. With the geometry of a thin disk for the laser active medium, the ratio of the cooling surface to pumped volume is increased compared to rod lasers, which is a basic advantage to extract high output power from a small volume, [8,9]. The thin disk laser concept is a laser design for diode- pumped solid- state lasers, which allows the realization of lasers with high output power, having very good efficiency and also excellent beam quality, [10,11].

In this paper, the primary goal was to make a comparison between the bulk and SQW GaAs/AlGaAs laser and to point such differences in terms of the peak modal gain and the threshold current density at a bandgap discontinuity of ΔE_c of 0.1 eV, and then finding the optimum value for QW width to achieve the lower threshold current density J_{th}.

Using the structure of the GaAs/AlxGa1-xAs with x=0.2 for the barrier layer and a layer thickness of (d=0.2μm), x=0.6 for the cladding layer (d=1μm) and (d>0.02μm) for the active region for the bulk structure, (d<0.02μm) for the active region for the SQW structure.

II. Theoretical Concept:

In section II we describe the theoretical concept that was used to do our calculations for both the bulk and SQW laser. In section III we present experimental work which includes the setup and performance of diode pumped disk laser using bulk and QW sources in CW with V-shape pumping scheme, section IV consists of two parts: A. includes the computational results obtained theoretically which shows the dynamical behavior of both the bulk and SQW GaAs/AlGaAs lasers, B. includes the experimental results of pumping Nd:YVO4 crystal. Finally, in section V, we discuss these results.

The present model calculates the laser gain on the basis of band-to-band transitions, the following assumptions are used in this model: 1. the bandgap discontinuity is (ΔEc/ΔEv=0.67/0.33), 2. the wells in the conduction and valence bands are approximated by infinitely deep square wells, 3. transitions to light and heavy hole subbands, 4. transitions from subbands with the same quantum numbers, (2,3,and 4 relates to the QW laser only).

Within the parabolic band approximation, the energy E_c in the conduction band, measured from the bottom of the band upwards, can be written as, [4]:

$$E_c = \frac{\hbar^2 k^2}{2m_c} \quad ,………...(1)$$

where mc is the effective mass of the electron at the bottom of the conduction band. Likewise, energy in the valence band, measured from the top of the band downward, can be written as, [4]:

$$E_v = \frac{\hbar^2 k^2}{2m_v} \quad , ……..…(2)$$

where mv is the effective mass of the electron at the top of the valence band and *k* is Boltizman constant.

The density of states function ρ(E) (the number of the electronic states per unit energy interval per unit crystal volume) is determined from the conservation of state relation, [12]:

$$\rho_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} E^{1/2}, \ldots\ldots\ldots(3)$$

In a laser the amount of gain that actually prevails is clamped by the phenomenon of saturation to a value equal to the loss [12].

$$\gamma_{\max} = B(N - N_{tr}), \ldots\ldots(4)$$

where:

γ_{max} is the peak gain,
N_{tr} is the carrier density at transparency,
N is the injected carrier density,
B is differential gain coefficient of the semiconductor.

Now we introduce the QW laser equations, for each quantized level, there is a continuum of energies arising from the lateral kinetic energy of the carriers in the plane of the QW. Associated with each discrete level, the resulting sheet density of states for energies above the minimum level is, [13]:

$$\rho_{QW}(E) = \sum_{n=1}^{all\,states} \frac{m_c}{\pi\hbar^2} H(E - E_{nc}) ,\ldots\ldots\ldots(5)$$

where:

E_n is the energy of subband n,

Since ρ_{QW} is constant in each subband, the density of electrons N_e and holes N_h can be calculated analytically and the result will be, [2]:

$$N_e = kT\sum_n\left(\frac{m_c}{\pi\hbar^2 L_z}\right)\ln\left[1+\exp\left(\frac{E_{Fc}-E_{nc}}{kT}\right)\right], \ldots\ldots\ldots\ldots(6)$$

$$N_h = kT\sum_n\left(\frac{m_v}{\pi\hbar^2 L_z}\right)\ln\left[1+\exp\left(\frac{E_{Fv}+E_{nv}}{kT}\right)\right], \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where:

E_F is Fermi energy,
L_z is the layer thickness, of the QW,

Under steady- state conditions the rate at which carriers are injected into the active region must equal the electron-hole recombination rate, [4]:

$$\frac{J}{q} = \frac{NL_z}{\tau} ,\ldots\ldots\ldots\ldots(8)$$

where:

J is the injected carrier density,

q is the charge of the electron,

τ is the electron-hole recombination time.

The optical gain is calculated using standard perturbation theory Fermi's Golden Rule, (neglecting the effect of intraband scattering). Since the gain anisotropy favors lasing in TE modes, we calculate the gain only for this polarization. The spectrally dependent gain coefficient for the quantum well region is, [1]:

$$g(E)=\frac{q^2|M|^2}{E\varepsilon_o m^2 c_o \hbar L_z}\sum_{i,j} m_r C_{ij} A_{ij}\left[f_c-(1-f_v)\right]H(E-E_{ij}),\ldots\ldots\ldots(9)$$

where:

$|M|^2$=bulk momentum transition matrix element,

ε_o =free-space permittivity,

m=free electron mass,

c_o=vacuum speed pf light,

N=effective refractive index,

i,j= conduction, valence quantum numbers (at Γ),

m_r=spatially weighted reduced mass,

C_{ij}=spatial overlap factor between states i and j,

A_{ij}=anisotropy factor for transition i, j,

f_c=Fermi population factor for conduction electrons,

f_v=Fermi population factor for valence holes,

H= Heaviside step function,

E_{ij}=transition energy between states i and j.

The bulk averaged momentum matrix element between conduction and valence states is, [2]:

$$|M|^2=\frac{m^2E_g(E_g+\Delta)}{6m_c(E_g+2\Delta/3)},\ldots\ldots(10)$$

where:

$$E_g=\left[E_o-\frac{5.405\times10^{-4}\times T^2}{T+204}\right],\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

E_g = direct bandgap,

E_o = bandgap constant,

T = operating temperature,

Δ_{s-o} = split-off band separation,

III. Experimental Work:

The 4*5*0.5 mm^3 Nd:YVO_4 crystal, which is AR coated for the wavelength of the pump and laser radiation at the front side and HR coated for both wavelengths at the back side. This crystal was placed on Al plate from its front surface and this plate contains a hole of diameter of 4 mm at its centre to permit the radiation comes from the pumping source to incident on the crystal, this hole makes the crystal acts like a disk, also a Cu plate is on its back surface with indium material of 0.1 mm thickness as a thermal adhesive, those plates serves as heat sink.

The ray direction for V-shape face pumping, was illustrated in Fig.(1), where the disk crystal and the output coupler mirror were placed at 45^o, and the bulk diode laser were used as a pumping source once in CW mode and once in pulsed mode with internal and external triggering, while the QW diode laser was used as a pumping source in CW mode. Proper focusing lenses were used with the two pumping sources to focus the highly diverging beam from these sources.

A 808 nm GaAlAs in bulk (2W) and QW (1W) design are used as the pumping source for such pumping scheme.

IV. Results and Discussion:

A. Theoretical Results:

In this section the results obtained by using the above equations are for the proposed structure mentioned earlier of the bulk GaAs/AlGaAs laser. Fig.(2) shows a plot of peak gain coefficient versus the density of injected carriers at different temperatures, which can be approximated by a linear relation; $g_{max}=\sigma(N-N_{tr})$, where $\sigma=dg/dN$ is the differential gain, at $T=300^oK$, $N_{tr}=0.03e19cm-3$.

Fig.(3) is a plot of the threshold current density with the thickness of the active region with variable facet reflectivity, it can be seen that the increasing of the facet reflectivity will minimize the value of the threshold current density, while increasing the value of the thickness of the active region at fixed reflectivity will result in an increase in the value of the threshold current density, i.e. coating the facet of the laser diode is very important.The results obtained by using the equations for the proposed structure of SQW GaAs/AlGaAs laser are shown below. Fig.(4a, b, c, d) shows the peak modal gain versus the injected carrier density at well thickness of L_z =(200, 150, 100, 75) Å, respectively. The high gain sensitivity of gmax to changes in the number of injected electrons for different well widths. Because of their high density of states, narrow wells could be useful when high gain values are needed.Fig.(5) shows the relation between the value of the zero gain injection (transparency) versus the well thickness obtained from Fig.(4), from this figure the value of transparency shifts down to a lower injection current as Lz increases, these results are approximated by a linear relationship, $\gamma_{max} = B(N_t - N_{tr})$, [8], where γ_{max} is the peak gain, N_{tr} is the carrier density at transparency, N_t is the injected carrier density, B is differential gain coefficient of the semiconductor. Fig.(6) shows the relation between the radiative current density for different QW thickness (L_z=75 Å, 100 Å, 150 Å, 200 Å) was drawn against the injected carrier density, to obtain the spectral gain maximum versus current density, the radiative component of the current is calculated by integration of the spontaneous emission, at higher injection levels the situation becomes more favorable, because the radiative current increases more rapidly due to bimolecular nature roughly proportional to N^2.

It can be seen that increasing the carrier density for Lz=200 Ǻ will result in a decrease of the value of the injected carrier density, from these four figures we can see that the optimum value for QW width to achieve the lower threshold current density Jth=481.5 A/cm2 at the same injected carrier density is Lz=100 Ǻ..

B. Experimental Results:

In this section, the results obtained from the experimental work were illustrated and investigated with the pumping configuration that is proposed for V-shape laser as shown in Fig.(1)**,** once the pumping source used was the 808 nm bulk diode laser operating in CW mode and also the 810nm QW GaAlAs diode laser was also used. Fig.(7) shows the relation between the operating current and the CW power emitted from the bulk diode laser, where the measured differential efficiency was found to be η_D=0.87 W/A.Using the bulk diode laser, the measured radiation transfer efficiency was found to be η_r=53%, the measured value for the both the upper state efficiency and the absorption efficiency was found to be $\eta_u\eta_a$=7%**.**

Fig.(8) shows the relation between the operating current of the bulk diode laser and the 1064nm CW laser output power at resonator length of L=13 cm**.** From this graph it was found that the maximum output power obtained was 29mW, the measured optical to optical slop efficiency $\eta_{o\text{-}o}$=1.7%, and the measured threshold power Pth was found to be ≈25mW. The slope efficiency is found to be 5.13%, with a maximum output power of 29 mW, at a pumping power of 1800 mW.

For QW diode laser the threshold current was found to be Ith=70mA and the differential efficiency was found to be η_D≈0.66 W/A which is lower than the typical value given by the company (0.75W/A) due to the fact that the maximum power attained from the QW was 873mW instead of 1000mW. Fig.(9) shows the relation between the driving current of the QW diode laser and the CW output power.

Now using the QW diode laser as a pumping source instead of the bulk one, two focusing lenses of focal lengths f=(6,3) cm were used to focus the rhombic spot of the QW diode laser onto circular spot of d=4mm in order to occupy the whole face of the disk which is allowed to be pumped, the radiation transfer efficiency measured was found to be ≈67%, and the measured efficiency was found to be $\eta_u\eta_a$=7%.

The relation between the pumping power from the QW diode laser and the obtained 1064 nm laser output power using an output coupler of R=90% with different resonator lengths is shown in Fig(10) below. From the above figure it is found that the maximum output power obtained at L=14.5cm and the measured threshold power is found to be P_{th}=37mW, the maximum output power obtained from this configuration is found to be =58mW. From this curve the maximum measured optical to optical slope efficiency is found to be ≈7% which is higher than that of the bulk diode laser. The slope efficiency is calculated to be 11.3%.

V. Conclusions:

We have studied the Dynamical Behavior of both the bulk and the SQW GaAs/AlGaAs Laser theoretically. By this study we had mode a comparison between the two lasers in terms of the peak gain and the threshold current density.

It was found that for the bulk laser that the highest value for the peak modal gain is g_{max}=240 cm^{-1} and that the increasing of the facet reflectivity will minimize the value of the threshold current density, while increasing the value of the thickness of the active region at fixed reflectivity will result in an increase in the value of the threshold current density, the peak modal gain and for SQW GaAs/AlGaAs laser was investigated with varying the well widths L_z=(200, 150, 100, and 75) Å, at a bandgap discontinuity of ΔE_c of 0.1 eV, it was found that the highest value of the peak modal gain g_{max}=400 cm-1 is achieved at L_z=75 Å, and the lower value to achieve transparency N_{tr}=0.5×1018 cm-3 at L_z=200 Å .

In this work, it was found that the optimum value for QW width to achieve the lower threshold current density J_{th}=481.5 A/cm2 at the same injected carrier density is L_z=100 Å.

From the experimental work the optimum resonator length was found to be 14.5 cm which achieves a maximum output power of 58 mW, with a slope efficiency of 11.3%, using bulk diode laser the efficiency was found to be 3.2%, with a maximum output power of 29 mW, this draws us to the fact that QW laser source is more efficient and suitable for pumping solid state media.

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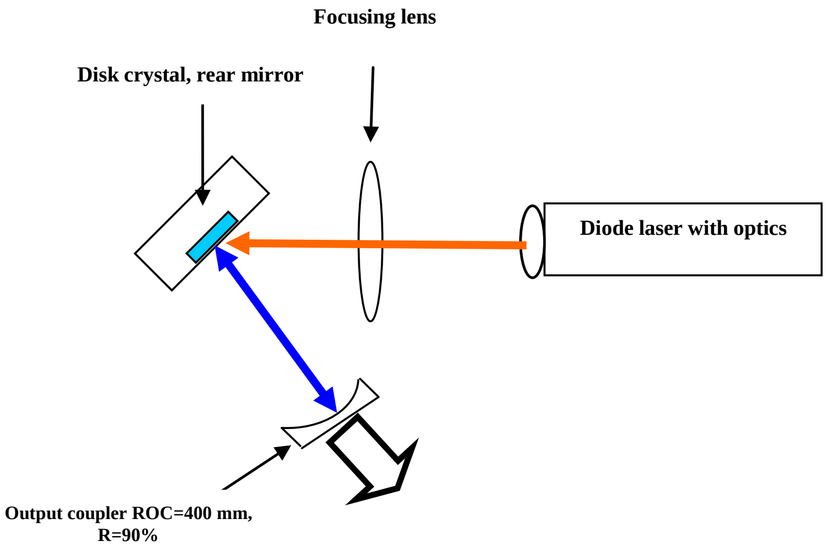


Fig.(1) the ray direction of the V-shape face pumping.

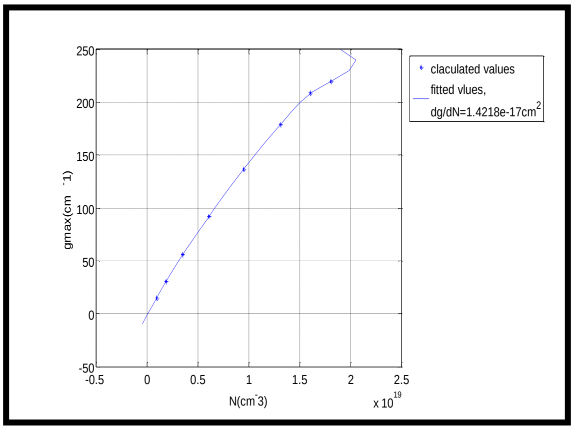


Fig.(2) Plot of the peak gain coefficient versus the injected carrier density

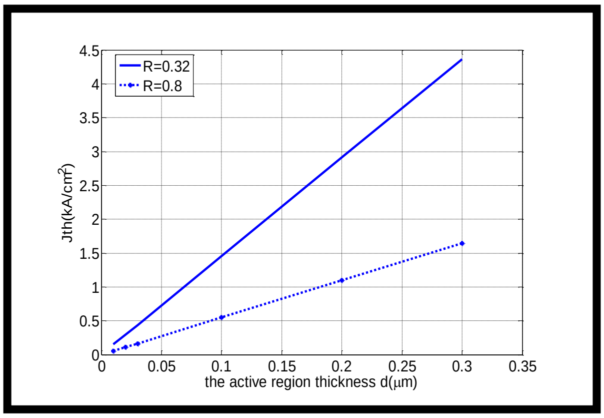
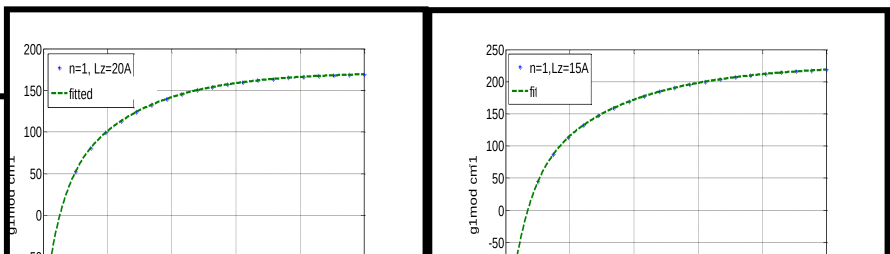


Fig.(3) Plot of the threshold current density versus the thickness of the active region at different output reflectivities for TE polarization.



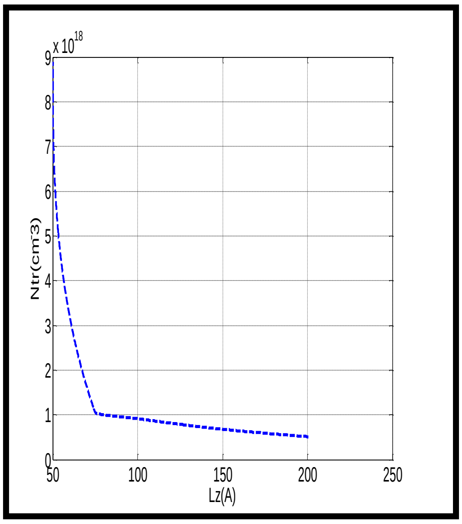


Fig.(5) Plot of the transparency carrier density versus the well

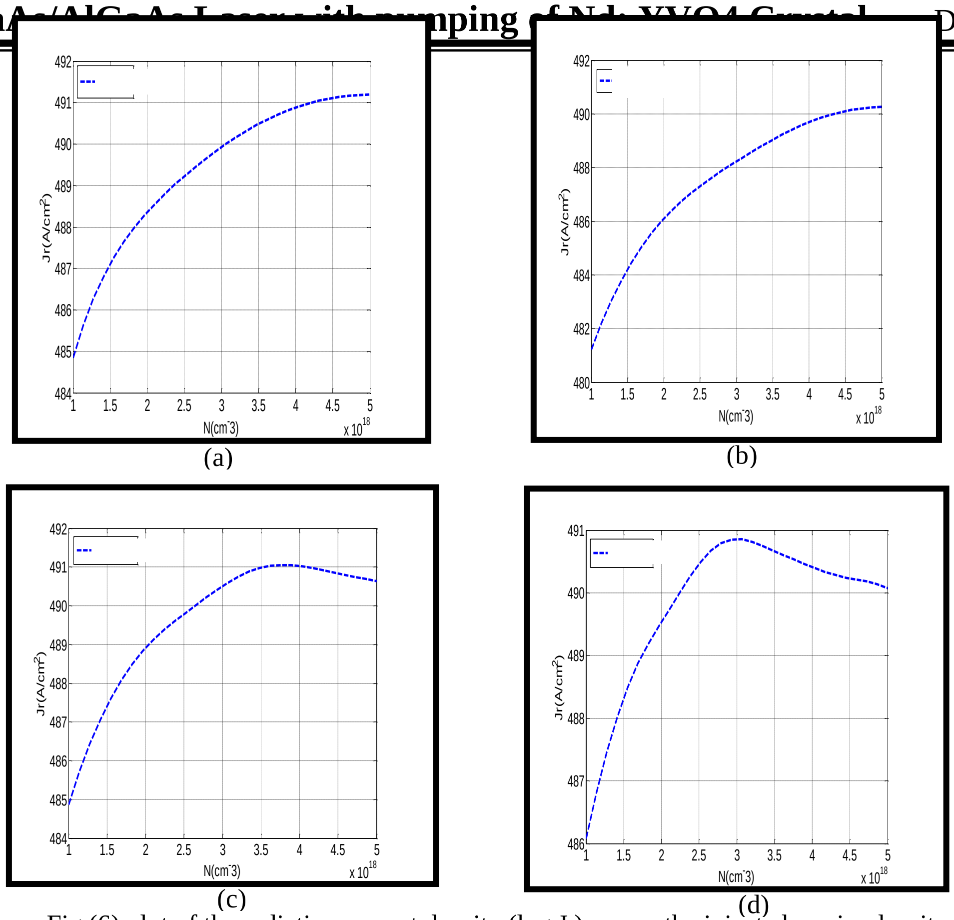


Fig.(6) plot of the radiative current density (log J_r) versus the injected carrier density at, (a)L_z=75 Ǻ, (b) L_z=100 Ǻ, (c) L_z=150 Ǻ, (d) L_z=200 Ǻ.

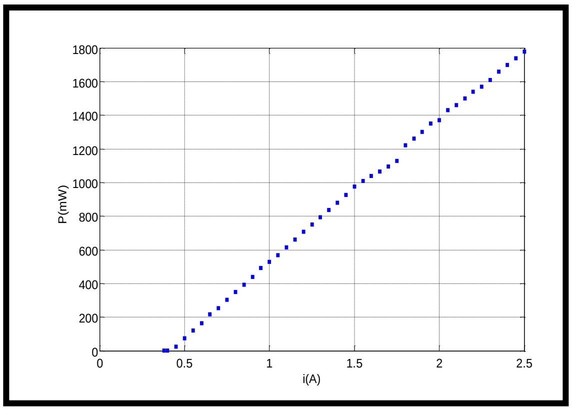


Fig.(7) L-I characteristics of the bulk diode laser operating in CW mode

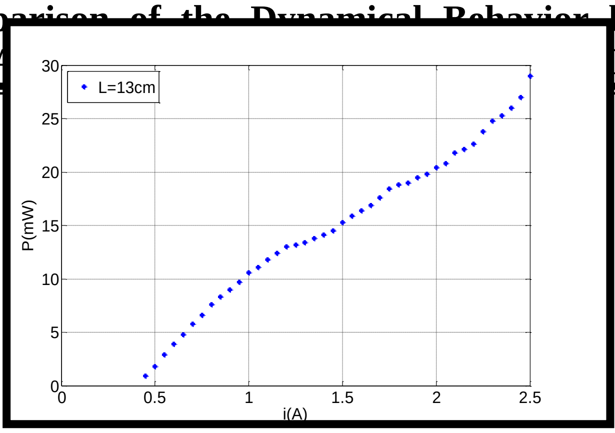


Fig.(8) The current vs. the laser output power at L=13 cm.

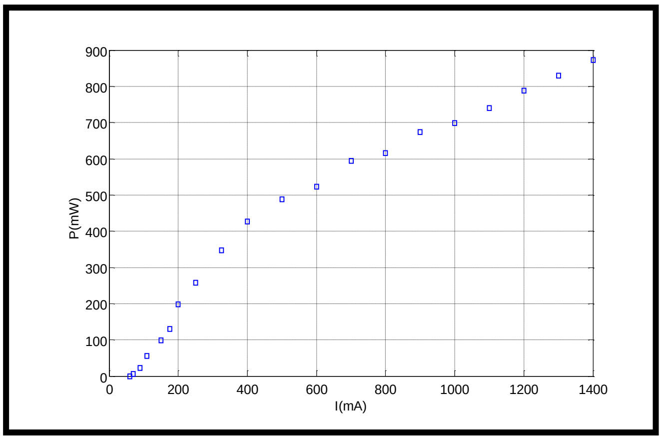


Fig.(9) L-I characteristics of the CW QW GaAlAs.

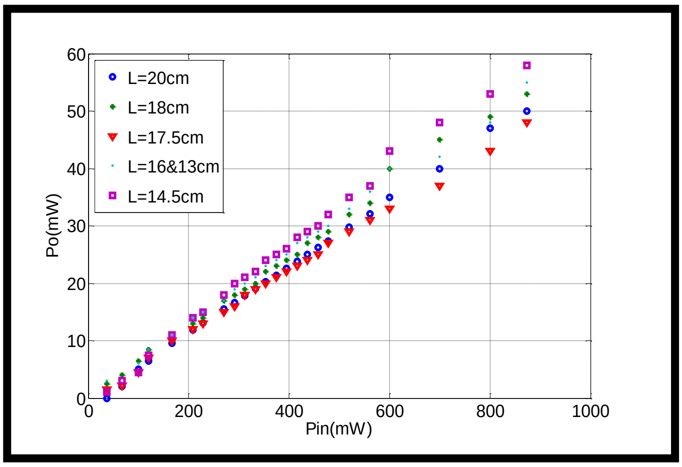


Fig.(10) The pumping power vs. the laser output power at different resonator lengths

مقارنة نظرية للتصرف الديناميكي بين ليزر شبه الموصل الاعتيادي و ليزر بئر الجهد الكمي SQW GaAs/AlGaAs لضخ بلورة Nd: YVO4 Crystal

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الخلاصة

الجزء النظري تضمن مقارنة نظرية للتصرف الديناميكي لليزر شبه الموصل الاعتيادي وليزر بئر الجهد الكمي حيث تم دراسة كل من موديل قمة الكسب وكثافة تيار العتبة مع تغير سمك المنطقة الفعالة (d=0.02 μm to 0.3) عند انعكاسية (R=0.32and 0.8)وعرض (Lz=200,150,100,75 Å) لليزر SQW مع فجوة طاقة مستمرة (0.1eV) ΔE_c لكلا نوعي الليزر عند درجة حرارة T=300K .بالنسبة لليزر لليزر شبه الموصل الاعتيادي فقد كانت اعلى قيمة لموديل قمة الكسب gmax=240 cm^{-1} وان الزيادة في الانعكاسية يقلل قيمة كثافة تيار العتبة،بينما زيادة سمك المنطقة الفعالة عند انعكاسية ثابتة يزيد من قيمة كثافة تيار العتبة ،بالنسبة لليزر ليزر بئر الجهد الكمي SQW وجد ان قيمة لموديل قمة الكسب gmax=400 cm^{-1} عند Lz=75 Å، وان اقل قيمة لتحقيق النفاذية Ntr=0.5x1018 cm^{-3} عند Lz=200 Å ، وان افضل قيمة لعرض الجدار الكمي SQW لتحقيق اقل قيمة لكثافة تيار العتبة تقدر Jth=481.5 A/cm^2. في الجزء العملي تم استخدام ليزر ثنائي الوصلة الاعتيادي المستمر بطول موجي(808nm(2Watt وليزرالجدار الكمي SQW بطول موجي (810nm(1Watt كمصدر ضخ لبلورة Nd:YVO4 ذات ابعاد (4x5x1mm) مع مراة خرج ذات انعكاسية 90% وقيمة Roc=400mm باستخدام تقنية V-shape . وقد وجدان افضل طول مرنان لتحقيق اقصى قدرة خارجة (58mW) هي (14.5cm)مع كفاءة ميل للقدرة الخارجة بحدود 11.3% باستخدام ليزربئر الجهد الكمي SQW .اما عند استخدام ليزر ثنائي الوصلة فقد وجد ان الكفاءة تصل الى 3.2% مع اعظم قدرة خارجة بحدود (29mW)وبذلك نلاحظ ان ليزربئر الجهد الكمي SQW اكثر كفاءة و استقرارية لضخ ليزر الوسط الصلب.