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Saturation Gain Characteristics of Quantum-Well Semiconductor Optical Amplifier

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Abstract:

Recently, there is an increasing interest on quantum well (QW) semiconductor optical amplifier in optical communications and optical signal processing applications. This paper addresses the dependence of saturation power on QW structure parameters. Expressions are given to assess this dependency and the results indicate that the saturation power is a decreasing function of number of wells, well thickness, and amplifier length and it is almost independent of barrier thickness.

Key Words: Quantum-well semiconductor optical amplifier.

1. Introduction

The application of semiconductor quantum well (QW) devices in optoelectronics has progressed significantly in recent years, driven by the expectation of superior device performance with reduced dimensionality [1]. For example, QW semiconductor optical amplifiers (SOAs) offer many advantages over bulk counterparts such as high differential gain, ultra fast gain recovery, and low noise operation [2-4]. These devices are exploited in optical networks as active nonlinear elements for all-optical signal processing at high speed [5, 6]. Such applications require knowledge of the saturation power characteristics which affect the ultrafast gain dynamics.

The saturation power characteristics of QW amplifiers have been investigated experimentally by different research groups [7-9]. However, the dependence of saturation power on structure parameters of the QW amplifier is not addressed implicitly in the literature. This issue is addressed in this paper

2. Theory

Figure 1 shows a simplified schematic diagram for the QW optical amplifier. The amplifier is assumed to be fabricated in InGaAsP material system with negligible facet reflectivity to ensure a travelling wave (i.e., single-pass) operation at 1550nm. The optical gain coefficient g depends on injection current and input optical power [10, 11]

$$g = g_s/[1 + (P_{in}/P_{sat})] \qquad (1)$$

where g_s is small-signal gain coefficient which is a function of carrier density (i.e., injection current), P_{in} is the input optical power, and P_{sat} is the saturation power. Note that $g = g_s$ when $P_{in} \ll P_{sat}$ and $g = 0.5g_s$ when $P_{in} = P_{sat}$.

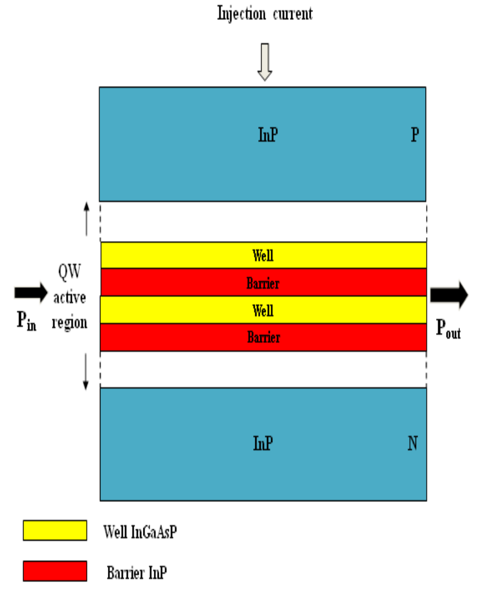


Fig. 1 QW optical amplifier [3].

The dependence of g_s on carrier density n is expressed as [12]

$$g_s = \Gamma a(n - n_o) \qquad (2)$$

where Γ is the optical confinement, a is the material gain constant, and n_o is the carrier density for transparency. The injection current is related to carrier density by

$$I = qVn/\tau_c \qquad (3)$$

where q is the electron charge, V is the volume of active region, and τ_c is the carrier lifetime. The parameter τ_c has a nonlinear dependence of n due to the presence of Auger nonradiative recombination in InGaAsP material system [13]

$$\tau_c = 1/(A_{nr} + Bn + Cn^2) \tag{4}$$

where A_{nr} is nonradiative recombination coefficient, B is bimolecular radiative recombination coefficient, and C is Auger nonradiative recombination coefficient.

The saturation power is related to device structure and material parameters [14]

$$P_{sat} = (hc_o wd)/(\lambda_o \Gamma \tau_c a) \tag{5a}$$

$$= (hc_o V)/(\lambda_o \Gamma \tau_c aL) \tag{5b}$$

where h is Planck's constant, c_o is the speed of light in vacuum, and λ_o is the operating wavelength. Further, the amplifier active region has length = L, width = w, thickness= d, and volume V = Lwd.

Investigating eq. (5b) reveals that P_{sat} is proportional to the volume of the active region and inversely proportional to $(\Gamma \tau_c)$.

The optical amplifier gain $G \equiv P_{out}/P_{in}$ is computed from

$$G = \exp[(g - \alpha)L] \tag{6a}$$

where P_{out} is the output power and α is the internal cavity loss coefficient. Similarly, the small-signal amplifier gain G_s is given by

$$G_s = \exp[(g_s - \alpha)L] \tag{6b}$$

From eqs. (2) and (6b)

$$n = n_o + \frac{\alpha + (\ln G_s/\Gamma)}{\Gamma a} \tag{7}$$

Equation (7) determines the required carrier density to achieve a specific value of small-signal optical gain G_s.

Inserting eq. (7) into eq. (4) and using the result into eq. (5a) yields

$$P_{sat} = (hc_o wd/\lambda_o \Gamma a)\left[A_{nr} + B\left(n_o + \frac{\alpha + (\ln G_s/\Gamma)}{\Gamma a}\right) + C\left(n_o + \frac{\alpha + (\ln G_s/\Gamma)}{\Gamma a}\right)^2\right] \tag{8}$$

Equation (8) reveals that P_{sat} depends nonlinearly on $\ln G_s$.

The saturation gain characteristics of optical amplifiers are usually characterized by a lumped parameter, namely the output saturation power $(P_{sat})_{out}$. The decrease of amplifier gain G with input optical power is expressed as [15, 16]

$$G \equiv P_{out}/P_{in} = G_s/[1 + (P_{out}/(P_{sat})_{out})] \tag{9a}$$

$$= G_s/[1 + (GP_{in}/(P_{out})_{sat})] \tag{9b}$$

Note that when $P_{out} = (P_{sat})_{out}$, the amplifier gain G reduces by 3dB compared the small-signal gain G_s [15]. Equation (9b) can be used to estimate $(P_{sat})_{out}$ when G_s, P_{in}, and G are known

$$(P_{sat})_{out} = G^2 P_{in}/(G_s - G) \tag{10}$$

It is clear from eq. (5b) that P_{sat} is inversely proportional to the optical confinement factor Γ. For multiquantum well (MQW) semiconductor laser, the optical confinement is related to the thickness and refractive indices of different layers in the active region [17]

$$\Gamma = \gamma N_w d_w/(N_w d_w + N_b d_b) \tag{11a}$$

$$\gamma = 2\pi^2 (N_w d_w + N_b d_b)^2 \tag{11b}$$

where d_w is the well thickness, N_w is the number of wells, μ_w is the well refractive index, d_b is the barrier thickness, N_b is the number of barriers, μ_b is the barrier refractive index, and μ_c is the cladding refractive index.

In eq. (11b), $\bar{\mu}$ represents the effective refractive index in the active region [17]

$$\bar{\mu} = (N_w d_w \mu_w + N_b d_b \mu_b)/(N_w d_w + N_b d_b) \tag{12}$$

For a single quantum well (SQW) laser, $N_w = 1$ and $N_b = 0$.
Then

$$\Gamma_{SQW} = 2\pi^2 N_w^2 d_w^2 (\mu_w^2 - \mu_c^2)/\lambda_o^2 \tag{13}$$

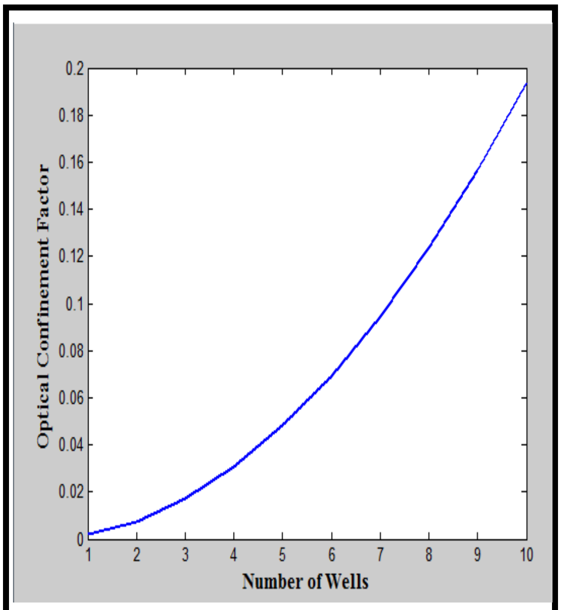
3. Numerical Results

This section presents numerical results to describe the dependence of QW amplifier saturation power on device structure parameters. Unless otherwise stated, the parameters values used in the calculations are listed in Table 1 and they are typical parameters for InGaAsP QW amplifier operating at 1550nm wavelength.

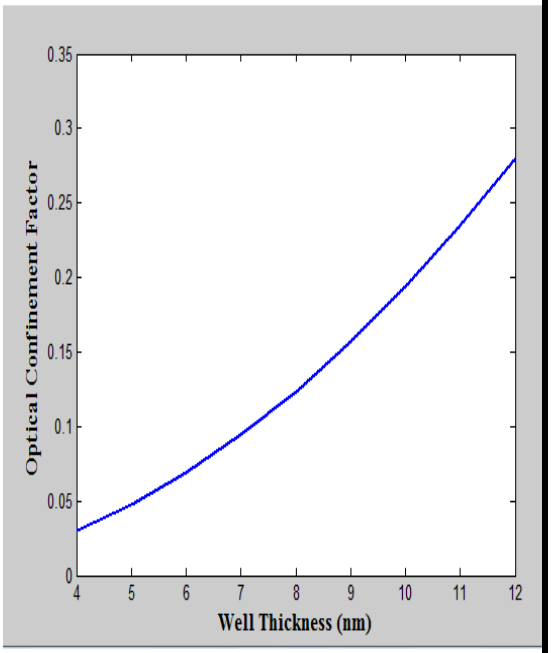
Table 1
Parameters values used in the simulation [8].

Parameter	Symbol	Value
Wavelength	λ_o	1550nm
Amplifier length	L	500μm
Active region width	w	1μm
Number of wells	N_w	10
Number of barriers	N_b	9
Well thickness	d_w	10nm
Barrier thickness	d_b	10nm
Material gain constant	a	$5 \times 10^{-16} cm^2$
Nonradiative recombination coefficient	A_{nr}	$1 \times 10^8 s^{-1}$
Bimolecular recombination coefficient	B	$1 \times 10^{-10} cm^3/s$
Auger recombination coefficient	C	$3 \times 10^{-29} cm^6/s$
Carrier density for transparency	n_o	$10^{18} cm^{-3}$
Well refractive index	μ_w	3.54
Barrier refractive index	μ_b	3.18
Cladding refractive index	μ_c	3.18
Intrinsic loss	α	$30 cm^{-1}$
Small-signal amplifier gain	G_s	30dB

Figures 2a-c show the dependence of optical confinement factor on number of wells N_w, well thickness d_w , and barrier thickness d_b , respectively. In these calculations, the number of barriers is taken as $(N_w - 1)$. As expected, the optical confinement factor is an increasing function of N_w and d_w , while it is almost independent of d_b. Recall that transversal cross section area of the active region depends on $N_w d_w$ and it is independent of d_b.

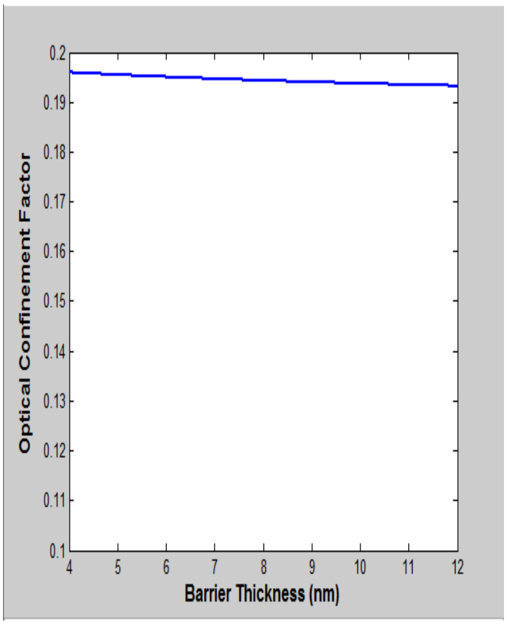


(a)



(b)

Fig. 2 Variation of optical confinement factor with number of wells (a) well thickness (b), and barrier thickness (c).



(c)
Fig. 2 (Continued)

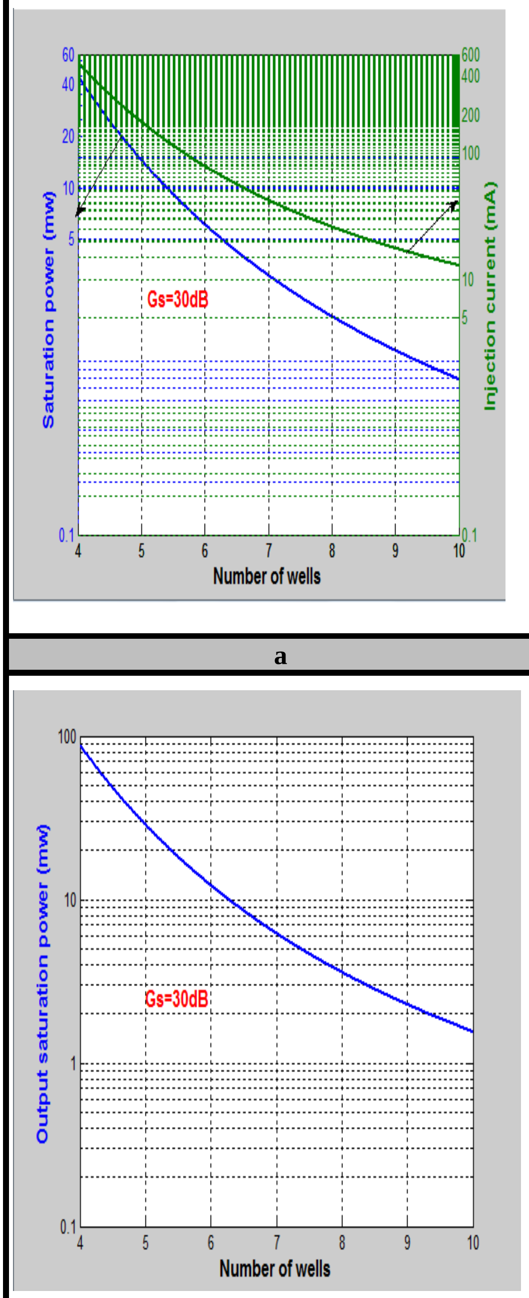
Figures 3-7 show the dependence of input saturation power P_{sat} and output saturation power $(P_{sat})_{out}$ on number of wells N_w, well thickness d_w, barrier thickness d_b, active region length L, and active region width w, respectively. The results presented when the amplifier is operating with 30dB small-signal gain. The required injection currents to ensure $G_s = 30\text{dB}$ are also included in these figures. Investigating these figures reveals the following findings

(i) The saturation power is a decreasing function of number of wells, well thickness, and amplifier length.

(ii) The saturation power is almost independent on barrier thickness.

(iii) The saturation power increases almost linearly with active region width.

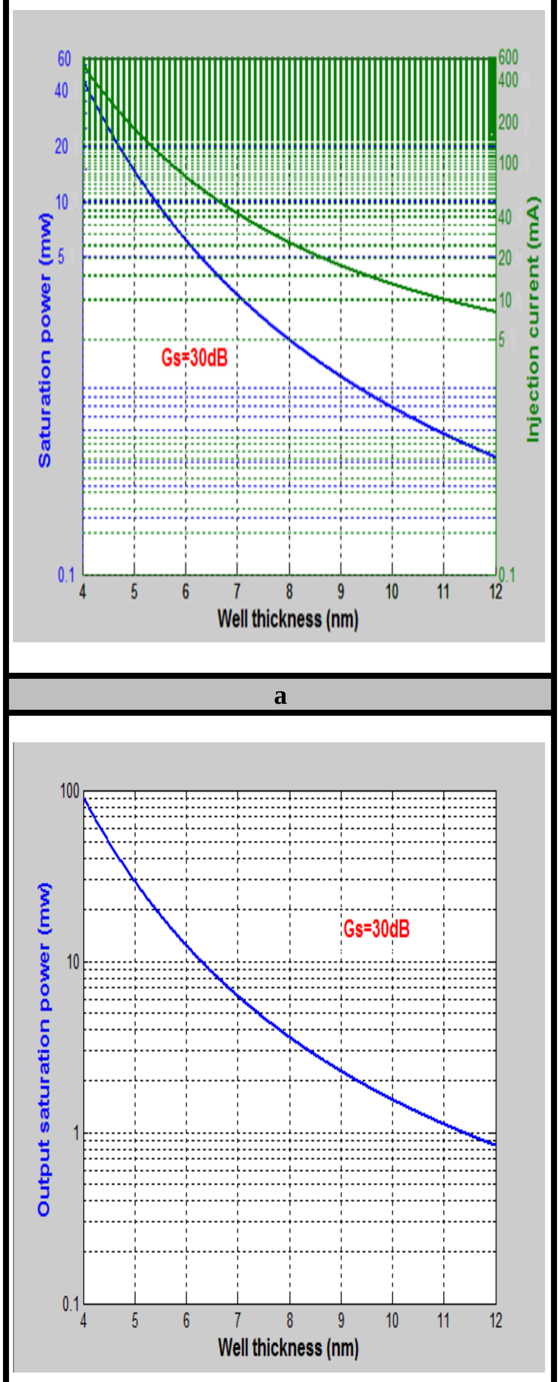
Figure 8 shows the dependence of saturation power and injection current as a function of amplifier small-signal gain G_s. Note that the input saturation power and injection current increase almost linearly with G_s. In contrast, the output saturation power increases rapidly with G_s. For example, $P_{sat} = 0.49\text{mW}, (P_{sat})_{out} = 0.27\text{mW}$ and $I = 5.363$ when $G_s = 10\text{dB}$. These values are to be compared with $0.63\text{mW}, 0.62\text{mW},$ and 8.67mA when $G_s = 20\text{dB}$ and $0.79\text{mW}, 1.56\text{mW},$ and 13.11mA when 13.11mA when $G_s = 30\text{dB}$.



a

b

Fig. 3 Dependence of saturation power and injection current on number of wells for a 30dB amplifier.



a

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Fig. 4 Variation of saturation power and injection current with well thickness for a 30dB amplifier.

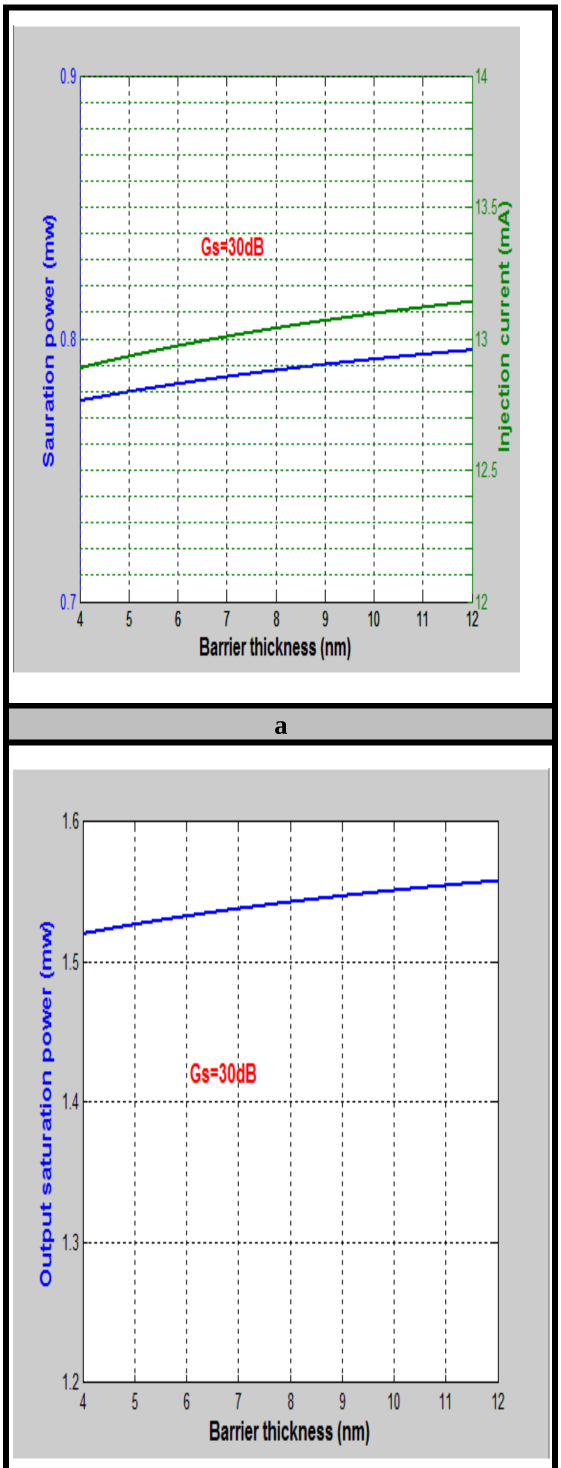

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Fig. 5 Effect of barrier thickness on saturation power and injection current

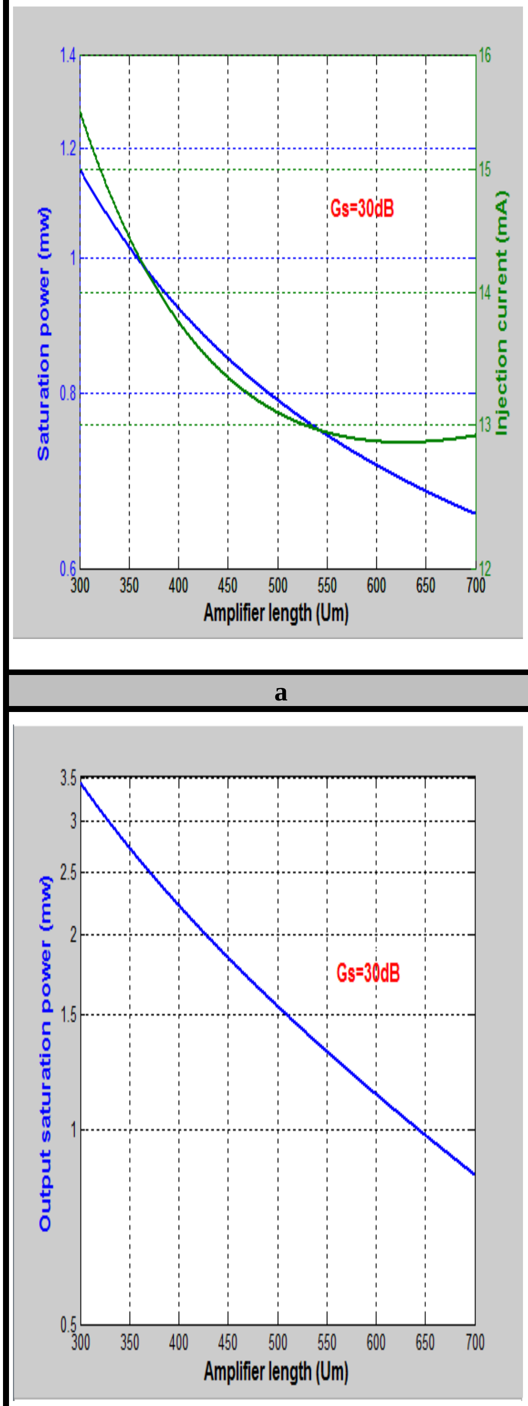

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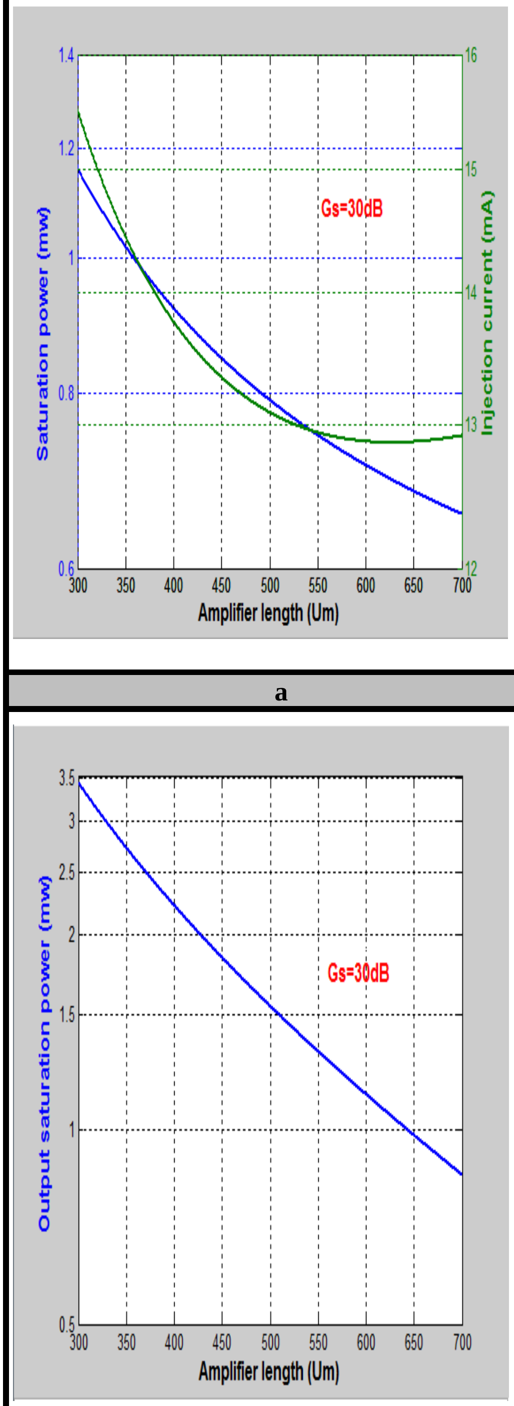
Fig.6 Effect of amplifier length on saturation power and injection current



a

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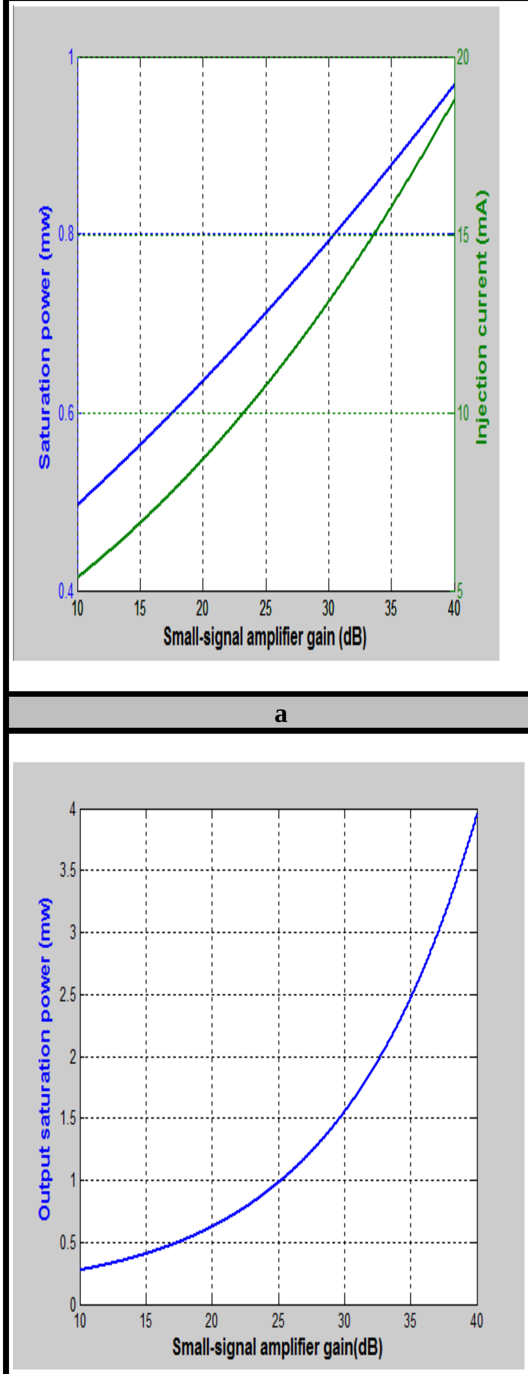
Fig.6 Effect of amplifier length on saturation power and injection current



a

b

Fig. 8 Variation of saturation power and injection current with small- signal amplifier gain.

4. Conclusions

Expressions are derived to assess the dependence of input and output saturation powers on QW semiconductor optical amplifier structure parameters. The results indicate that the saturation power is a decreasing function of number of wells, well thickness, and amplifier length and it is independent of barrier thickness. Thus to ensure small saturation power, the amplifier must be designed with few number of wells and small well thickness.

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خصائص الربح المشبعه للمضخم شبه الموصل البصري ذو البئر الكمي

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الخلاصه

هنالك اهتمام كبير بأستخدام المضخم شبه الموصل البصري (SOA) ذو البئر الكمي (QW) في تطبيقات الأتصالات البصريه و معالجة الاشاره بصرياً.

يدرس هذا البحث اعتمادية القدرة المشبعة على معالم بناء البئر الكمي لمضخم .اعطيت تعابير لتقييم هذه الاعتمادية وتشير النتائج ان القدرة المشبعة هي دالة متناقصة لعدد الابار وسمك البئر وطول المضخم وفي اغلب الاحيان لاتعتمد على سمك الحاجز.