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OPTOELECTRONICS FOR OPTICALLY CONTROLLED PHASED-ARRAY SYSTEMS

Columbia University

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13. ABSTRACT (Maximum 200 words)
This work is concerned with removing some of the major obstacles in practical application of fiber-optic techniques to microwave systems. Specifically, the problems addressed are that of RF throughput and Noise Figure of a microwave fiber-optic link. Due to the nature of the link and the characteristics of the optoelectronic devices, the RF throughput and Noise Figure of existing fiber-optic links are anywhere between unsatisfactory and unacceptable. Much of this originates from the intrinsic modulation efficiency of the optical source. It may be thought that this limitation is fundamental, since the devices in question already are approaching 100% quantum efficiency. Indeed, without new technological breakthroughs this problem may well be intractable. This report describes such a breakthrough, using a newly discovered effect in quantum well lasers known as "gain-lever" effect. Laser diodes constructed with "gain-level" incorporated into its structure shows efficiency enhancement of well over 40dB, in addition to the fact that its intensity noise is actually reduced. Combining these two factors, and with proper impedance matching, it is shown that it is possible to construct a passive microwave fiber-optic link (defined as one without active electrical or optical amplification) exhibiting a RF throughput gain of up to 50dB and a noise figure approaching 0dB.

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0. Introduction

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1. Ultra-high Efficiency Microwave Signal Transmission using Tandem-contact Single Quantum Well GaAlAs Lasers

Abstract

We show theoretically and experimentally that enhancements of up to 40dB in the efficiency of optical transmission of microwave signals can be obtained by using a single quantum well laser transmitter whose contact is segmented into two sections, and modulation is applied to one of the sections. The improvement is dependent fundamentally on the relaxation oscillation frequency of the device, with the improvement factor dropping to around 15dB at relaxation oscillation frequencies approaching 10GHz.

Recent advances in high speed semiconductor lasers[1] have made possible the use of optical transport and control in microwave systems such as phased arrayed radar[2], various microwave subcarrier multiplexed networks schemes[3] as well as cable television distribution[4]. For a typical laser with a differential efficiency of 0.4mW/mA and emitting xmW of CW power, a microwave power of $(-8+20\log_{10}x)$dBm is required in a 50Ω system for full optical modulation. This is much higher than typical received signal powers from microwave antennae, and considerable cost is incurred in providing the necessary amplification at the undersirable location of an antenna horn.

It is therefore of immense interest to develop schemes of ultra-high efficiency optical transmission at microwave frequencies. Narrowband impedance matching and proper facet coatings of the laser (and photodiode) obviously help. In this paper we show theoretically and experimentally that substantial efficiency improvement is possible by ultilizing the non-linear gain characteristic of single quantum well lasers. The device under consideration, which has electrically isolated tandem contacts, is shown in Fig. 1 together with a typical gain vs carrier density characteristic of a single quantum well laser. Section b, referred to as the "gain" section, is biased at a high gain level, and section a, the modulation section, is biased at a low gain.

The modulation performance of this device is described by the rate equations:

$$P = P\left(\Gamma G_a(1-h) + \Gamma G_b h - \frac{1}{\tau_p}\right) \tag{1a}$$

$$N_a = \frac{J_a}{ed} - BN_a^2 - G_a P \tag{1b}$$

$$N_b = \frac{J_b}{ed} - BN_b^2 - G_b P \tag{1c}$$

where P, $N_{a,b}$, $J_{a,b}$, $G_{a,b}$ are the photon density, carrier densities, injection currents and optical gain in the respective sections; Γ is the optical confinement factor; h is the fractional length of the gain section (Fig. 1) and a bimolecular recombination is used which is shown experimentally to be appropriate for quantum well structures[5]. A small signal analysis yields the following expression for the photon density modulation amplitude p

$$\frac{p}{J_a} = \frac{\Gamma G'_{a0} P_0 (1-h)(s+\gamma_b)/ed}{s^3 + (\gamma_a + \gamma_b)s^2 + A_1 s + A_2} \tag{2a}$$

where

$$A_1 = G_{a0}G'_{a0}(1-h) + G_{b0}G'_{b0}h + \gamma_a\gamma_b \tag{2b}$$

$$A_2 = \Gamma P_0(G'_{a0}G'_{a0}\gamma_b(1-h) + G'_{a0}G'_{a0}\gamma_a h) \tag{2b}$$

and $G_{a0/b0}$, $G'_{a0/b0}$ are the gain and differential gain of the two sections, P_0 is the CW photon density, j_a is the amplitude of the modulation current density into section a, and

$$\gamma_{a,b} = \frac{1}{\tau_{a,b}} + G'_{a0,b0}P_0 \qquad \text{where} \qquad \frac{1}{\tau_{a,b}} = 2BN_{a0,b0} \tag{3}$$

are the inverse lifetimes. A further relation exists between the $G_{a0,b0}$'s:

$$G_{a0}(1-h) + G_{b0}h = G_0 = \frac{1}{\Gamma\tau_p} \tag{4}$$

If the device is pumped uniformly, $G_{a0}/G_0 = G_{b0}/G_0 = 1$. Using measured values[6] of $G_{a0/b0}$ and $G_{a0/b0}'$, the modulation response is plotted in Fig. 2(a) for various values of G_{a0}/G_0. One observes an increase in the modulation efficiency while the relaxation oscillation frequency f_r remains largely unchanged. The constancy of f_r can be explained as follow: consider modulation frequencies $\omega \gg 1/\gamma_a, 1/\gamma_b$. Eq. (2) can be expressed approximately as $p/j_a \sim 1/(s^2+\omega_r^2)$ where

$$\omega_r^2 = \Gamma P_0(G_{a0}G'_{a0}(1-h) + G_{b0}G'_{b0}h) \tag{5}$$

is the resonance frequency ($=2\pi f_r$). Note that for a linear gain function, $G'_{a0} = G'_{b0} = G'$ and $\omega_r^2 = G'P_0/\tau_p$ which is the standard formula for relaxation oscillation frequency[1]. Because of the near-parabolic shape of the gain characteristics of single quantum well[6,7], $G_{a0}G'_{a0} \cong G_{b0}G'_{b0}$ except for very large and very small $G_{a0,b0}$'s. As a result, ω_r is approximately constant, according to Eq. (6). Using the actual measured gain curve[6], we plot in Fig. 2(b) ω_r versus G_{a0}/G_0 for various values of h. One observes that if (1) the gain section occupies a larger fraction of the cavity (h>0.5) and (2) G_{a0}/G_0>0.2, the relaxation oscillation frequency remains virtually unchanged from that of a uniformly pumped device.

The relative modulation efficiency at frequencies below relaxation oscillation can be obtained from Eq. (2):

$$\eta = \frac{\frac{p}{j_a}}{\frac{p}{j_a}\big|_{h=0}} = \frac{\gamma_b}{(1-h)\gamma_b R + \frac{h\gamma_a}{g}Q} \tag{6}$$

where i_a is the modulation current amplitude, $R = G_{a0}/G_o$, $Q = G_{b0}/G_o$ and $g = G'_{a0}/G'_{b0}$. The quantities R and Q are related via Eq. (4): $Q = (1-(1-h)R)/h$. This modulation efficiency η is normalized to that of a uniformly pumped device: when h=0, R=1 and Q=0, then we obtain η=1. To gain further insight into Eq. (6), consider cases near h=1. Equation (6) is simplified to

$$\eta = \frac{\gamma_b}{\gamma_a} g = \frac{\frac{1}{\tau_b} + \omega_r^2 \tau_p}{\frac{1}{\tau_a} + g\omega_r^2 \tau_p} g \tag{7}$$

For a laser operating at a low ω_r, $\eta = \frac{\tau_a}{\tau_b} g$. This is a substantial improvement over uniform pumping since for single quantum well lasers, with the sections biased as shown in Fig. 1, g is large (>10), while the large difference in the electron density results in $\tau_a >> \tau_b$. However, for higher frequency operation $\eta \to 1$. The dependence of η on the relaxation oscillation frequency of the device is illustrated in Fig. 3, which plots η versus h at f_r=2,5 and 10GHz. For each f_r, three values of g (1, 5, 20) are shown. Figure 3(a) is plotted for a 400μm long device while Fig. 3(b) is for a 100μm device. For these plots, it is assumed that the modulation section is biased at a gain = 1/10 of the threshold gain, i.e., R=0.1. As h is varied, the gain section is biased to whatever level is necessary to maintain a constant optical power. Note that under this assumption, the situation $h \to 0$ is NOT equivalent to uniform pumping, which explains why $\eta \neq 0$ as $h \to 0$ in Fig. 3.

It is interesting to note that a large η can be obtained even with g=1, due to a large ratio of τ_a/τ_b. Thus a non-linear gain characteristics is actually not essential, as long as one can kill the lifetime of the gain section. However, this is usually quite unhealthy for laser reliability, whereas single quantum well lasers offers a natural means of achieving the same effect through an exceptionally low transparency electron density and a non-linear gain characteristic.

We experimentally demonstrate the efficiency improvement using GaAlAs single quantum well buried heterostructure lasers. These lasers were from the same batch used previously for ultra low threshold demonstration[6]. Stripes of 25μm wide were photolithographically opened in the p-contact, and the devices were cleaved into various lengths. The modulation responses were measured using a standard setup, first with the two sections connected, and then biased separately. The laser bandwidth is between 3 and 6GHz at output power levels up to 4mW, as shown by curves labelled "uniform" in Fig. 4(a) for a 400μm laser and (b) for a 220μm device. The two sections are then biased separately, with the bias current into the modulation section reduced and that into the gain section increased correspondingly to keep the output power constant. The relaxation oscillation frequency changes slightly, and are shown in the data points plotted in Fig. (2b) for a device with h=0.45. Microwave modulation is applied to the modulation section whose gain is estimated to be 0.2 that of threshold gain. The modulation responses are plotted in Fig. 4(a) and (b) as shown by curves labelled "tandem". The improvement for lower f_r and for shorter devices are evident. The largest improvement observed was about 23dB, with the 220μm device at $f_r \cong$ 3GHz.

It is apparent that considerable improvement can be obtained in the modulation efficiency by the tandem modulation configuration described above, but only with the laser operating at a low bandwidth (and hence low optical power, below a few mW). The bandwidth limitation can be improved by using a shorter laser device. In theory, improvements of about 15dB is possible at 10GHz for a short cavity laser of about 100μm.

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Figure Captions

Fig. 1 Schematic diagram of the tandem contact single quantum well laser, with the gain vs carrier density curve shown.

Fig. 2 (a) Modulation response with different bias on the modulation section. (b) Relaxation oscillation frequency as a function of modulation section gain, for various h.

Fig. 3 Calculated modulation efficiency improvement versus h, at relaxation oscillation frequencies of 2, 5 and 10GHz and for each case three values of g=1,5,20 are shown. (a) Laser cavity = 400μm and (b) 110μm.

Fig. 4 Measured modulation response at output powers of 1.5mW and 4mW. Thin curves: uniformly pumped, thick curves: tandem pumped with $G_{a0}/G_0 \approx 0.2$. (a) a 400μm cavity with h=0.45, (b) a 220μm cavity with h=0.65.

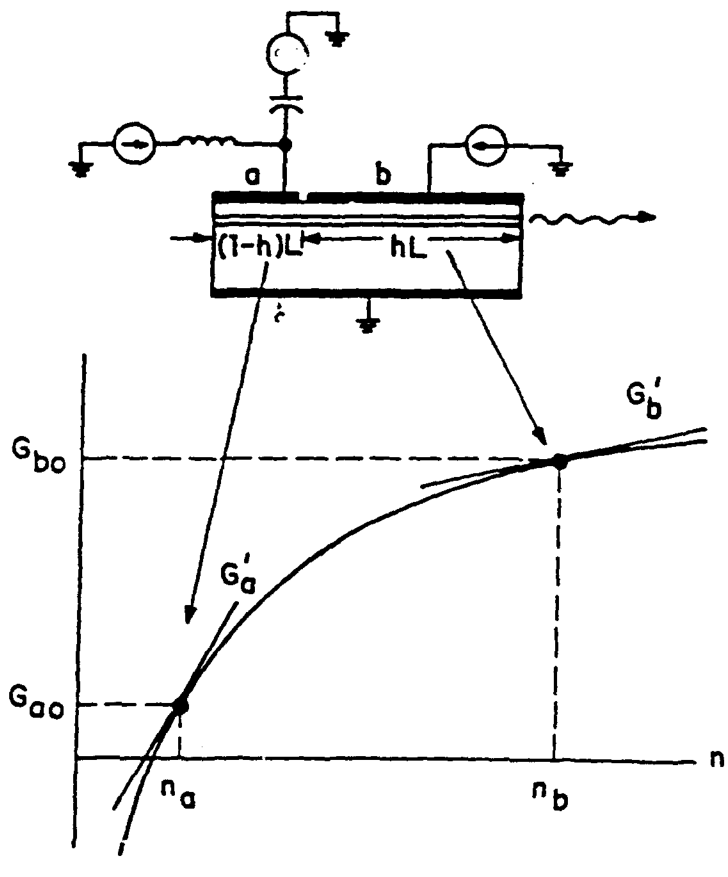


Fig. 1

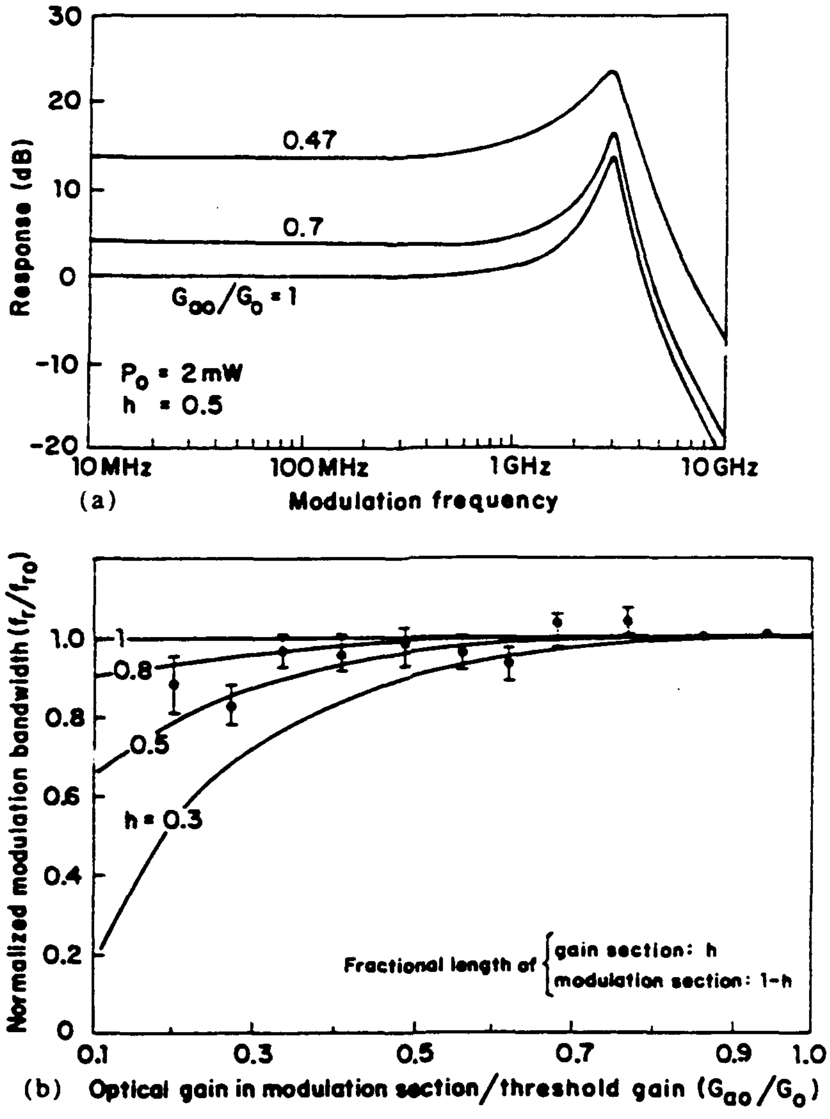
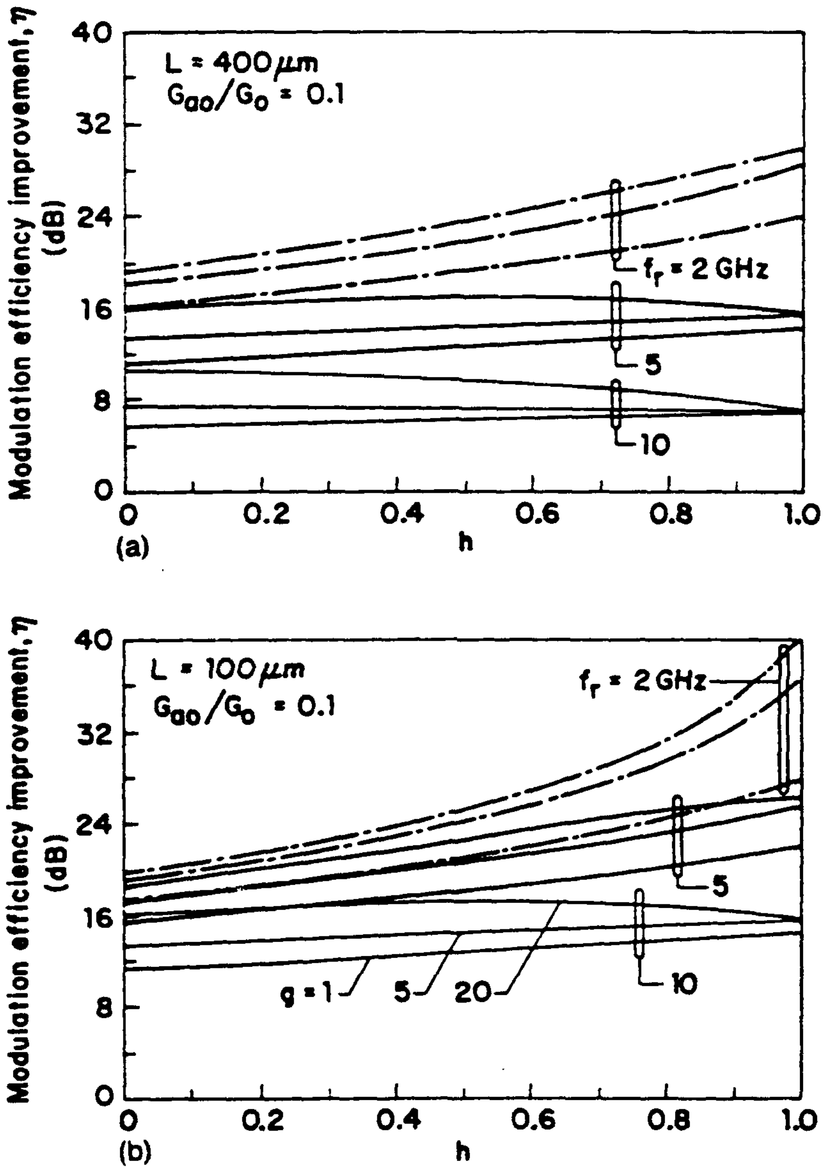
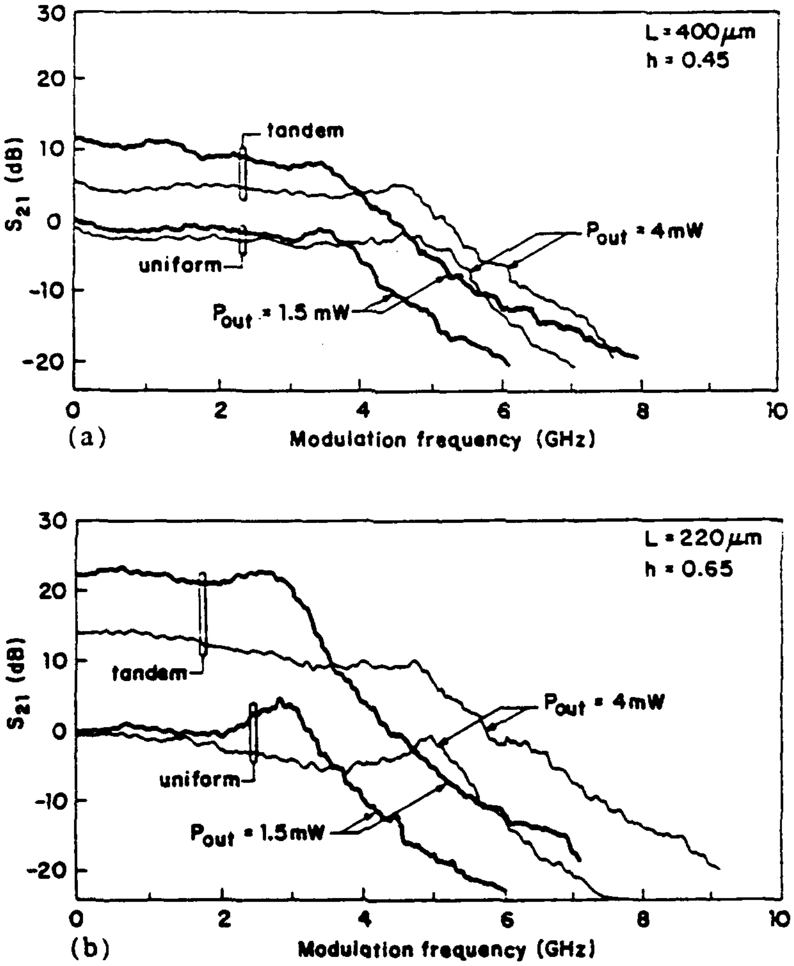

30
20
10
0
-10
-20
Response (dB)
0.47
0.7
$G_{ao}/G_0 = 1$
$P_0 = 2\,mW$
$h = 0.5$
10MHz
100MHz
1GHz
10GHz
(a)
Modulation frequency
Normalized modulation bandwidth (f_r/f_{ro})
1.0
0.8
0.6
0.4
0.2
0
1
0.8
0.5
h = 0.3
Fractional length of
gain section: h
modulation section: 1-h
0.1
0.3
0.5
0.7
0.9
1.0
(b)
Optical gain in modulation section/threshold gain (G_{ao}/G_0)

Fig. 2



L = 400 μm
Gao/Go = 0.1
fr = 2 GHz
5
10
Modulation efficiency improvement, η (dB)
h
(a)
L = 100 μm
Gao/Go = 0.1
fr = 2 GHz
5
10
g = 1
5
20
Modulation efficiency improvement, η (dB)
h
(b)

Fig. 3



L = 400μm
h = 0.45
tandem
uniform
Pout = 4mW
Pout = 1.5 mW
S21 (dB)
(a)
Modulation frequency (GHz)
L = 220μm
h = 0.65
tandem
uniform
Pout = 4mW
Pout = 1.5mW
S21 (dB)
(b)
Modulation frequency (GHz)

Fig. 4

2. Intensity Noise in the Ultrahigh Efficiency Tandem-contact Quantum Well Lasers

Abstract

We present theoretical and experimental results describing the intensity noise in the ultrahigh efficiency tandem-contact single quantum well alser. We find that the substantial increase in the modulation efficiency of these lasers is accompanied by only a marginal increase in the intensity noise.

Recently, it has been demonstrated that inhomogeneously pumped tandem-contact single quantum well (SQW) laser exhibits enhanced modulation efficiency relative to the same, but uniformly pumped laser[1,2]. The improvement is made possible by the gain engineering of the nonlinear gain characteristics of the single quantum well lasers. This development is important for a variety of applications which have a limited RF power budget, such as phased-array radar[3], microwave subcarrier multiplexed networks[4] and cable television distribution[5]. However, any such improvement in the modulation efficiency could be offset by the corresponding increase in the noise. In this letter, we present results for the intensity noise in these lasers, and shownthat for properly designed lasers increase in SNR of well over 10dB is possible.

The schematic of the device is shown in Fig. 1 together with a typical gain versus carrier density characteristic of the single quantum well laser. Gain section, b, is biased at a high gain level, whereas modulation section, a, is biased at low gain. Since the total gain is clamped above the threshold, save for the spontaneous emission, a small change in carriers in the modulation section will produce a much larger swing in the electron number in the gain section and, consequently, in the total photon number. The experiment and the analysis based on the rate equations[1] have shown the modulation enhancement of up to 20dB.

In order to analyse the noise of this laser we follow a procedure similar to the analyses carried out for the uniformly pumped device[6,7]. Basically, we start with the rate equations and include the noise through the Langevin noise terms. The rate equations are given by

$$\dot{P} = P(\Gamma G_a(1-h) + \Gamma G_b h - 1/\tau_p) + \Delta(t) \tag{1a}$$

$$\dot{N}_a = J_a/ed - BN_a^2 - G_a P \tag{1b}$$

$$\dot{N}_b = J_b/ed - BN_b^2 - G_b P \tag{1c}$$

P, $N_{a,b}$, $J_{a,b}$, $G_{a,b}$ are the photon density, carrier densities, injection currents and optical gains in the gain and modulation sections, respectively; Γ is the optical confinement factor; τ_p is the photon lifetime; h is the fractional length of the gain section as shown in Fig. 1. Bimolecular recombination is used since it has been shown experimentally to be the most appropriate for the quantum wells[8]. Δ is the Langevin noise source due to spontaneous emission given by its spectral density function:

$$<|\Delta(\omega)|^2> = R_{sp}P_0 \qquad (2)$$

where P_0 is the steady state photon density and R_{sp} is the spontaneous emission rate. Upon linearizing and solving these equations with the small-signal analysis we obtain the following result for the relative intensity noise (RIN) in the inhomogeneously pumped tandem-contact single quantum well laser:

$$RIN(\omega) = \frac{R_{sp}}{P_0}\frac{(\omega^2+\gamma_a^2)(\omega^2+\gamma_b^2)}{\omega^2(\omega^2-(\omega_R^2+\gamma_a\gamma_b))^2+(\omega^2(\gamma_a+\gamma_b)-\omega_R^2\Xi)^2} \qquad (3)$$

where

$$\gamma_i = 1/\tau_i + G'_i P_0 \qquad i = a, b, h \qquad (4a)$$

$$1/\tau_i = 2BN_i^2 \qquad (4b)$$

are electron lifetimes in the modulation section, gain section and homogeneously pumped laser, respectively; ω_R is the relaxation resonance frequency, shown to be almost independent of the enhancement factor for the wide range of parameters[1]:

$$\Xi = h\gamma_a + (1-h)\gamma_b \qquad (5)$$

is the measure of the effective asymmetry of the two sections, and

$$g = \gamma_a/\gamma_b \qquad (6)$$

This function is plotted in Fig. 2 for several values of the g parameter which correspond roughly to the modulation efficiency enhancements of 0,10,20 dB. These plots should be compared to the experimental results shown in Fig. 3. The pictures show the spectrum of the photodetector output with tandem-contact SQW laser biased at the constant optical output power P_{out}=1.5mW but at different currents in the gain and modulation sections. The top picture is the RIN of the uniformly pumped SQW laser. The middle has gain current

I_b=15mA, control current I_a=2.5mA and the modulation efficiency increase η=9dB. The bottom has gain current I_b=19mA, control current I_a=2mA, and the modulation efficiency increase η=19dB. The laser used in this experiment is similar in structure to the ultralow threshold SQW laser which has been described in more detail elsewhere[1,9]. The horizontal scale of the plots in Fig. 3 is 2-4GHz, which corresponds to the upper half of the theoretical plot. Theory predicts that with the increasing efficiency the noise peak moves slightly to the lower frequency and the DC value of the RIN increase but by an amount substantially less than the increase in efficiency itself. Both the shift and the increase saturate for large g's. These are exactly the effects observed in our experiment.

For many applications it is important to maximize the signal-to-noise (SNR) ratio. Consider the DC value of RIN. The ratio R between te inhomogeneously and homogeneously pumped laser RIN is given by

$$R = (\gamma_a \gamma_b / \gamma_h \Xi)^2 \tag{7}$$

where all the terms have been defined above. To further simplify Eq. (7), we assume that the gain of the SQW laser above transparency follows approximately a square root dependence:

$$G = A\sqrt{n - n_{tr}} \tag{8}$$

This is supported by measurements[9]. We lump all the global laser parameters in one, d. Then the inverse electron lifetime γ_i. Then the inverse electron lifetime γ_i is a function of the normalized electron density in the respective sections only.

$$\gamma_i = \frac{n_{tr}}{2B}\left(\frac{n_i}{n_{tr}} + \frac{d}{\sqrt{n_i/n_{tr} - 1}}\right) \tag{9a}$$

$$i = a, b, h; \qquad d = \omega_R^2 2B / A\sqrt{n_{tr}} \tag{9b}$$

For typical laser parameters, d=1-5. As can be seen from Fig. 4, γ increases rapidly when electron density is approaching transparency. However, for higher densities it is essentially flat over a range of densities, so we can claim $\gamma_b = \gamma_h$.

Intuitively, it is easy to see that the electron lifetime has tow contributions - one proportional to the electronic concentration, and the other to the differential gain. For small changes away from the operating point, the two contributions will cancel each other. Then

$$R = \left(\frac{g}{hg + (1-h)}\right)^2 \tag{10a}$$

$$R \sim 1/h^2 \tag{10b}$$

The DC increase in the intensity noise is shown in Fig. 5 as a function of the fractin length of the gain section and the g value which is proportional to the modulation efficiency. Quite simply, to maximize the SNR the ratio of the length of the gain to control section should be maximized, because the noise increase is minimized and the modulation efficiency increase is maximized.

In conclusion, we have shown that the enhanced modulation efficiency in a tandem-contact laser is not associated with a corresponding increase in the intrinsic intensity noise, which makes this device extremely useful for applications where the drive power is limited.

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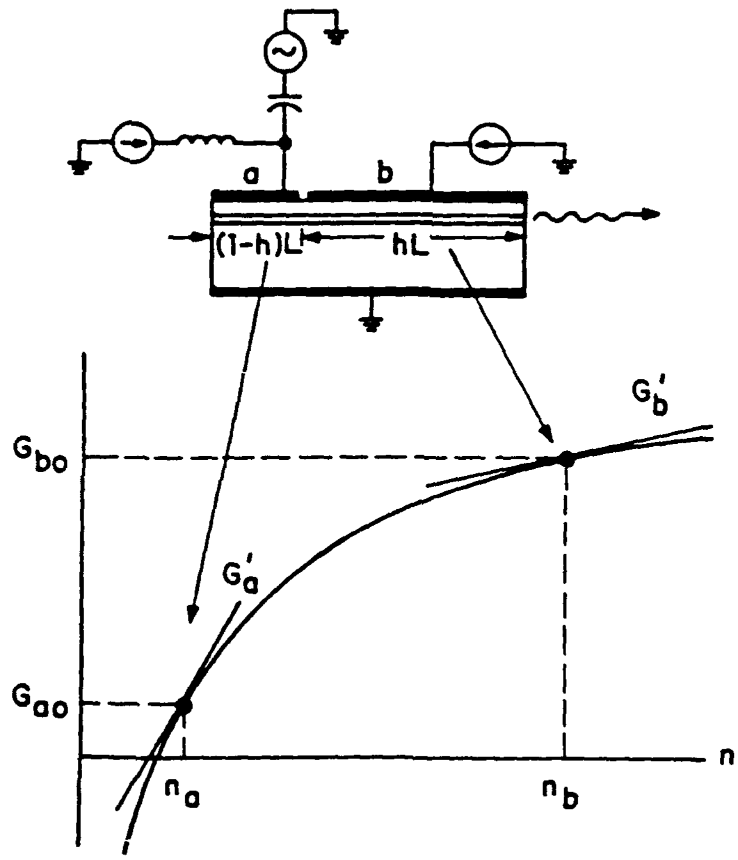


Fig. 1

Figure Captions

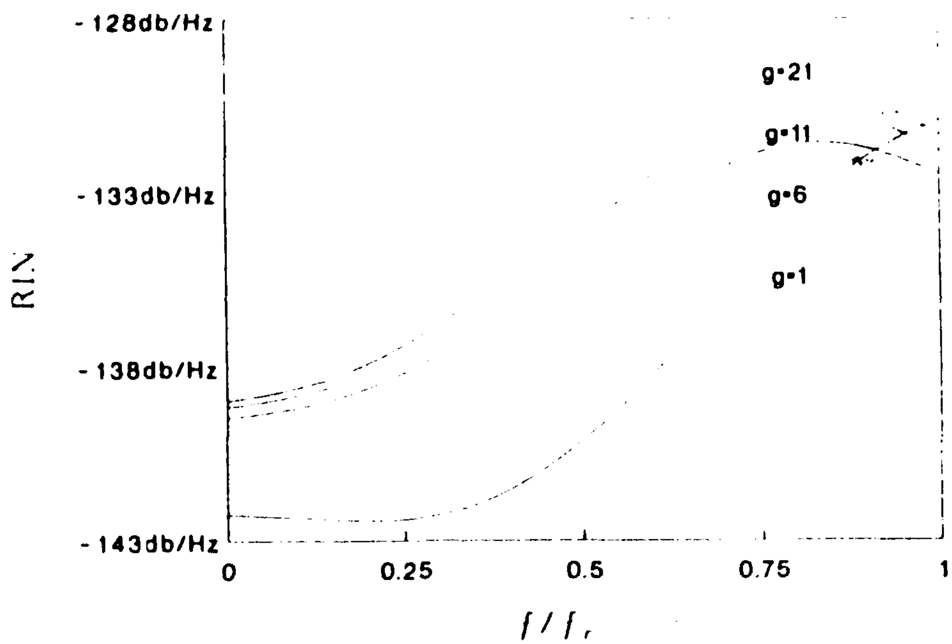
Fig. 1 Schematic diagram of the tandem-contact SQW laser with the gain vs carrier density plot.

Fig. 2 Spectral plot of the tandem-contact SQW laser RIN for different g values.

Fig. 3 Experimental results - photodiode spectral output at constant P_{out}=1.5mW with horizontal scale 2-4GHz. Top: I_a=I_b=10mA, η=0dB; middle: I_a=2.5mA, I_b=15mA, η=9dB; bottom: I_a=2mA, I_b=19mA, η=19dB. Note that the reference level of the bottom picture is at -56dBm, so that the trace is lifted upward by 2 divisions relative to the top and middle pictures.

Fig. 4 Inverse electron lifetimes γ as a function of the normalized electron density above transparency; d a parameter contains all the global laser parameters.

Fig. 5 Relative increases of the DC RIN versus gain section fraction length with g, the ratio of control and gain inverse electron lifetimes, as a parameter.



RIN
-128db/Hz
-133db/Hz
-138db/Hz
-143db/Hz
0
0.25
0.5
0.75
1
f / f_r
g=21
g=11
g=6
g=1

Fig. 2

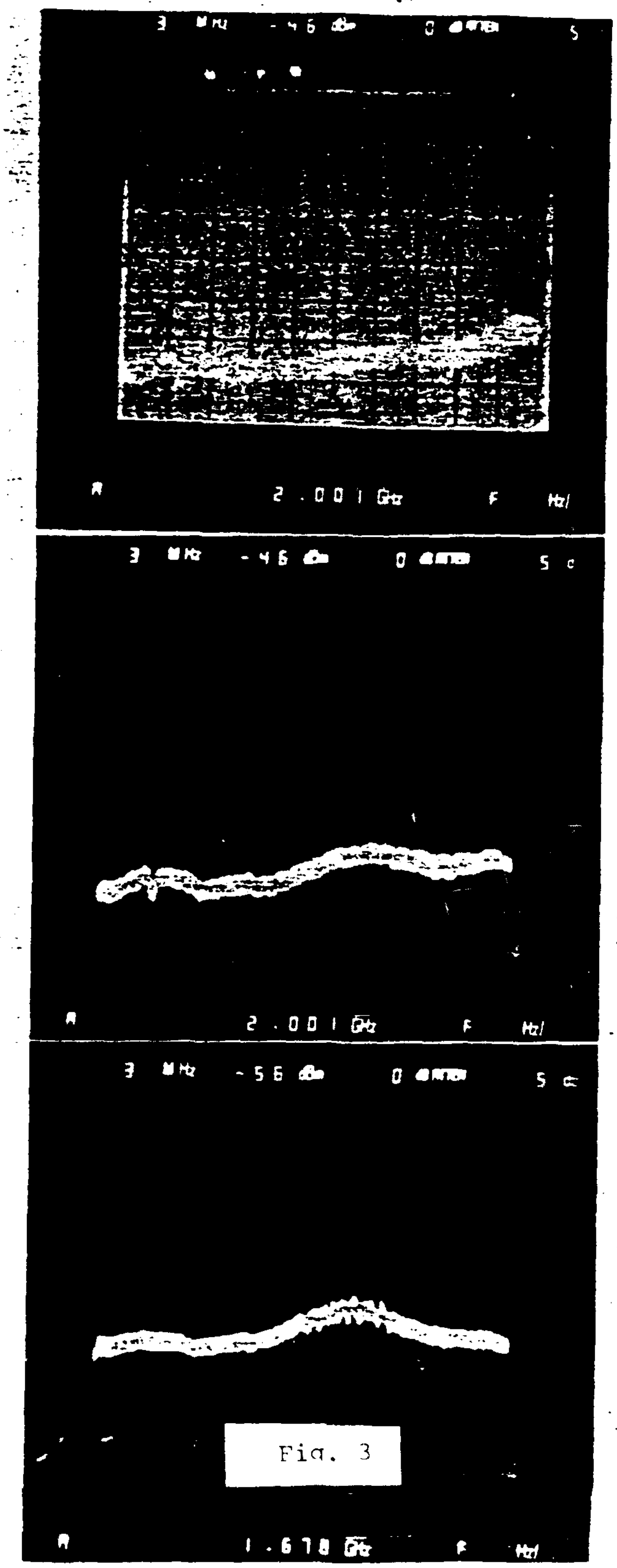


Fig. 3

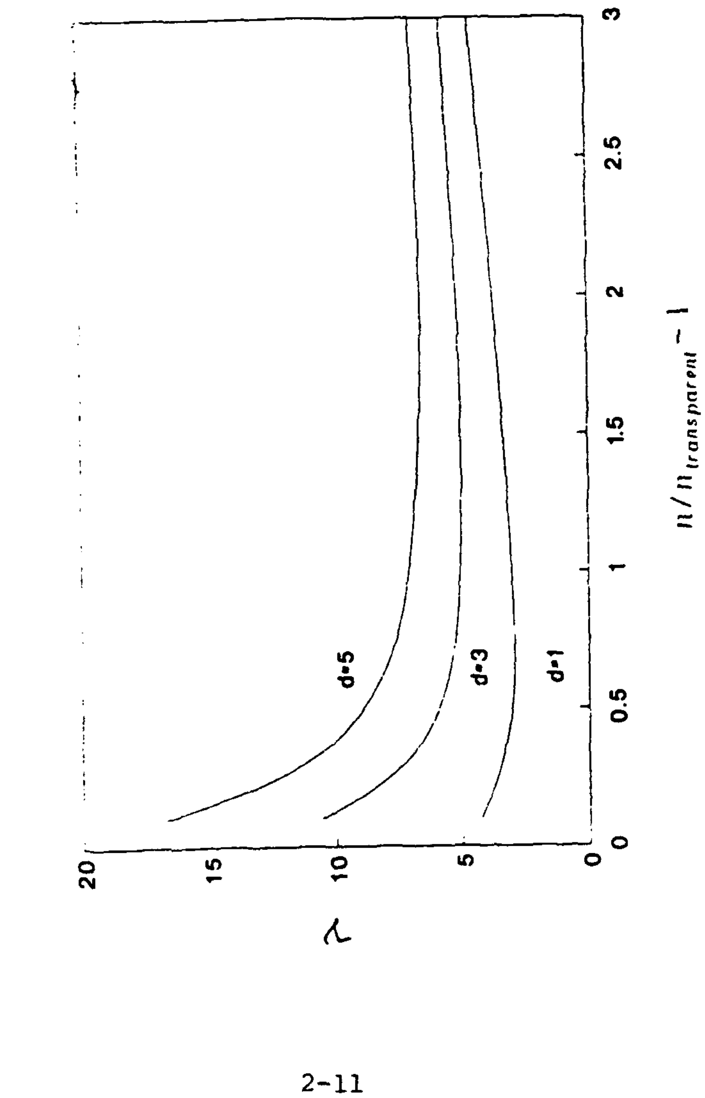
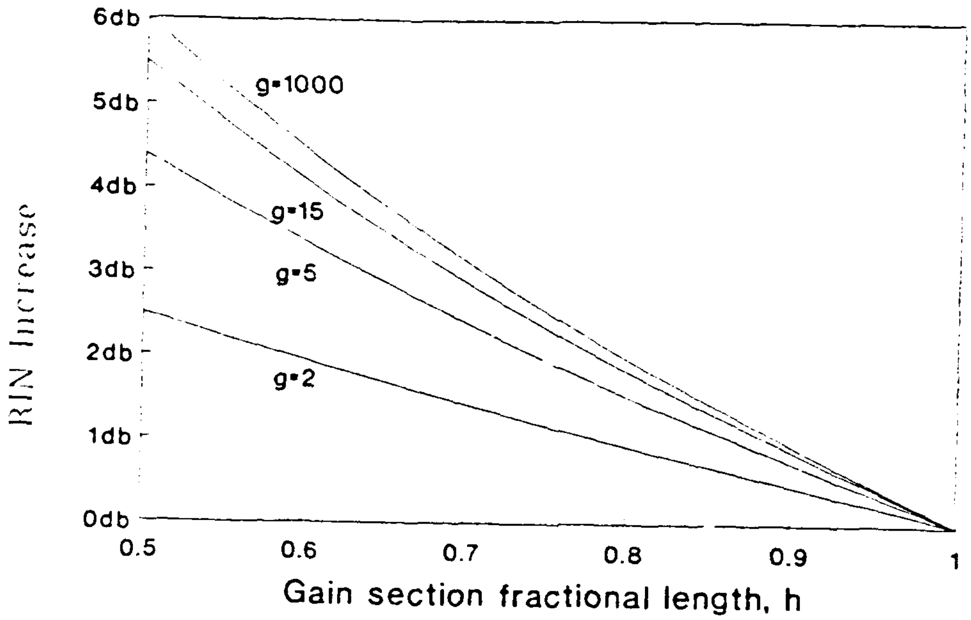


Fig. 4



6db
5db
4db
3db
2db
1db
0db
0.5
0.6
0.7
0.8
0.9
1
g=1000
g=15
g=5
g=2
RIN Increase
Gain section fractional length, h

Fig. 5

3. Frequency Modulation and Linewidth of Gain-levered 2-section Single Quantum Well Lasers

Abstract

The "gain lever" effect in 2-section single quantum well lasers can be used in enhancing the frequency modulation (FM) efficiency of the laser **without** a corresponding increase in the FM noise, i.e., linewidth. Theoretical and experiemtal results of the FM efficiency, speed, tuning range and linewidth will be discussed and compared to other tunable laser structures.

It was shown that based on the highly sublinear nature of the gain versus carrier density characteristics of single quantum well (SQW) lasers, one can obtain a large change in the carrier density in one section of the laser (the gain section) by a small change in injection current in the other section (the control section)[1,2]. The effect, referred to as the "gain lever" effect[1], can be used to enhance the intensity modulation efficiency in excess of 20dB. Both optical[1] and electrical[2] modulation has been demonstrated. Furthermore, this enhancement is achieved **without** a corresponding increase in the intensity noise[3]. These effects are potentially useful in microwave and radar fiber-optic applications where the signal power is severely limited.

This paper shows that the gain lever effect can be used in enhancing the frequency modulation (FM) efficiency and the wavelength tuning range of the laser **without** a corresponding increase in the FM noise, i.e., without increasing the linewidth. The large swing in the carrier density resulting from a small variation in the injection current causes a large change in the refractive index of the cavity, resulting in a large FM.

The behavior of the FM response of a general two-section laser has been published recently[4]. The FM index is proportional to the NET change in the electron density in both sections. To first order, the net gain in a lasing cavity must be clamped, and hence by symmetry the net change in the electron density must be zero - i.e., FM is NOT possible. In practice, FM is possible due to (1) imperfect gain clamping, due to spontaneous emission, gain compression, and high frequency dynamic effects, and (2) for a two section laser, a non-symmetry in the gain and α-parameters in the sections. Both have been taken into account in the analysis in [4]. (1) is responsible for FM in a uniformly pumped (and modulated) laser. A 2-section SQW laser operating under the gain-lever condition is an extreme example of (2).

We consider a SQW laser having a gain characteristic shown in Fig. 1, with the two sections biased as indicated. Section "b" is the gain section and "a" is the control section. The fractional lengths of the sections are r_a and r_b. Let $G_{a/b}$ and $G'_{a/b}$ denote the gain and differential gains, $\gamma_{a/b} = 1/\tau_{a/b} + G'_{a/b}P$ are the inverse effective lifetimes where $\tau_{a/b}$ are the spontaneous lifetimes and $G'_{a/b}P$ are the stimulated lifetimes, P being the average photon density. Furthermore, assume that the differential quantity $d\mu/dn$ is identical for the two sections[5].

where μ and n are the refractive index and the electron density respectively. The FM amplitude $\Delta\nu$ is

$$\Delta\nu = F(r_a n_a + r_b n_b)$$

where $n_{a/b}$ are the small signal electron densities, and F is a proportionality constant. Due to the high differential gain in section "a", the stimulated lifetime is in the sub-nanosecond range (measured value of ~0.1ns) while the spontaneous lifetime in section "b" is of a similar magnitude due to the very high carrier density there (>5×10^{18}cm^{-3}.) Thus for simplicity one approximates $\gamma_a = \gamma_b = \gamma$. Following an approach similar to [4], one obtains the following:

$$\Delta\nu = \frac{F j_a}{f(\omega)(i\omega+\gamma)} \frac{r_a(f(\omega)-1) + r_a r_b G_b(G'_b - G'_a)}{r_a G_a G'_a + r_b G_b G'_b} \tag{1}$$

where j_a is the modulation current density into section "a", $1/f(\omega)$ is the normalized intensity modulation response of the laser (normalized to unity at DC, exact expression given by Eq. 2 in [2]), and $g = G'_a/G'_b$. Furthermore, if one assumes the geometry which favors the minimum intensity noise, namely, $r_b \gg r_a$[3], the FM response is simiplified as follow:

$$\Delta\nu = F j_a r_a \frac{f(\omega)-g}{f(\omega)(i\omega+\gamma)} \tag{2}$$

For g>>1 as in SQW lasers, the qualitative form of the FM response is similar to Fig. 2 in [4], which has a single pole roll-off at $\omega = \gamma$ followed by a relaxation oscillation resonance. Quantitatively, one should note the following features in the gain-levered SQW device: a very high value of g (>10) (this parameter plays a role similar to Q_1 in [4]), and a high roll-off frequency of >1GHz for the single pole, due to the short stimulated lifetime of carriers in a heavily pumped SQW.

The FM enhancement can be observed using the tandem contact GaAs SQW laser used previously[2,3]. The FM characteristics of the laser was measured using a standard frequency discriminator arrangement consisting of a low-Q etalon. The result is plotted in Fig. 2 for a gain-levered and a uniformly pumped arrangement, at an identical optical power of 2mW/facet. The threshold of the uniformly pumped devices was 10mA, while under gain-levered operation the modulation and gain section was biased at 3mA and 20mA respectively. The physical lengths of the sections are 120μm and 250μm respectively. The low frequency roll-off in the uniformly pumped case is due to thermal effects. In the "midband" range the FM efficiency of the gain-levered laser is enhanced by a factor of almost 100, from about 0.2GHz/mA to 20GHz/mA. The uniformly pumped device has a resonance at around 3GHz, while the gain-levered device rolls off at around 2GHz. It is believed that in the latter case, the single-pole roll-off is partly offset by the rising slope of the relaxation oscillation, resulting in a fairly flat FM response up to 2GHz.

The linewidth of the laser is determined primarily by the low frequency part of the FM noise power spectrum. The FM noise can be computed by replacing the current drive by a Langevin source to the pnoton rate equations; the FM noise being proportional to the net electron density fluctuation. It can be shown in a straightforward manner that the ratio of the linewidth of the gain-levered laser to that of a uniformly pumped laser is as follow:

$$\frac{\delta\nu\,|_{\text{gain lever}}}{\delta\nu\,|_{\text{uniform}}} = \frac{G'_h(r_a G_a \gamma_b + r_b G_b \gamma_a)}{r_a G_a G'_a \gamma_b + r_b G_b G'_b \gamma_a} \tag{3}$$

where G'_h is the differential gain at the operating point of the uniformly pumped device. Under the condition $r_b \to 1$ as before, it reduces to

$$\frac{\delta\nu\,|_{\text{gain lever}}}{\delta\nu\,|_{\text{uniform}}} = \frac{G'_h}{G'_b} \tag{4}$$

If one examines the gain curve in Fig. 1, the operating point of the uniformly pumped device should be just slightly below that of G_b, because the modulation section occupies only a small fraction of the cavity and hence the gain section should be pumped just slightly harder to make up for the gain. Thus G'_b should be just slightly lower than G'_h, resulting in only a slight increase in the linewidth. This conclusion is verified in the linewidth measurements shown in Fig. 3. There is no discernable penalty in the linewidth beyond the scatter in the data points.

Although the device discussed in this paper does not contain any frequency selective elements such as distributed feedback (DFB) or Bragg reflector (DBR), there is no reason to believe that incorporation of such structures will drastically alter the FM characteristics. A brief comparison of the properties of this device with other existing wavelength tunable structures - single section DFB and 3-section DBR[6] lasers - is shown in Table 1. A conventional 2-section laser[4] is a limiting case of the gain-levered SQW device where the factor g is small and the stimulated lifetime is somewhat longer. A study of Table I shows that while each of the structures has its attributes and shortcomings, the gain-levered SQW laser has a good combination of properties in terms of linewidth, tuning efficiency, range and speed. (The range issue is rather complex, depending on whether continuous tuning is needed or not. See [5] for a detailed description).

For FM transmission schemes it is often desirable to obtain FM modulation of an optical source without an associated amplitude modulation (AM). This is not possible in a single section laser but is possible in multisection devices by suitable combinations of modulation currents[6]. For the present device it can be shown that a zero AM modulation will result if

$$r_a j_a G'_a \gamma_b = -r_b j_b G'_b \gamma_a \tag{5}$$

Under this condition, the FM amplitude is (neglecting a constant factor F for convenience):

$$\Delta\nu = \frac{r_a j_a (1-g)}{i\omega + \gamma} \tag{6}$$

But the total modulation current applied to the device is now

$$\Delta i = r_a j_a + r_b j_b \tag{7}$$

Assuming $\gamma_a \cong \gamma_b$, the FM modulation efficiency becomes

$$\Delta\nu = \frac{\Delta i}{i\omega + \gamma} \tag{8}$$

That is, the FM efficiency is identical to that due to a passive section with stimulated carrier lifetime $1/\gamma$. A brief comparison of the relative FM, AM and AM/FM ratio of the various tunable laser structures is shown in Table II, with the assumed values of the parameters shown. Thus under the zero-AM mode the 3-section passive tuning device has the highest FM efficiency. This efficiency is comparable to that of a gain-levered SQW laser, which has a finite but small AM/FM ratio (20 times less than that of a single section laser).

Table I - A comparison of characteristics of tunable/FM lasers

	linewidth	**tuning efficiency**	**tuning range[1]**	**FM speed**
single section (QW or bulk)	$(1+\alpha^2)\times$ (Schalow-Towns)	low, <1GHz/mA (gain clamping)	small (gain clamping)	multi-GHz (relaxation oscillation)
3-section DBR	a few times of single section (loss in passive section)	medium,~3GHz/mA (free carrier injection)	large (no restriction on free carrier density)	$1/\tau_s$ <1GHz (spontaneous lifetime)
2-section gain-levered SQW	same as single section (whole cavity under inversion)	high, >10GHz/mA (gain-lever)	large (gain-lever)	$1/\tau_{stim}$ >~1GHz (stimulated lifetime)

1 not counting thermal effects

Table II - AM and FM characteristics of FM lasers

	FM efficiency $\Delta\nu/\Delta i$	AM efficiency (differential quantum efficiency)	AM/FM (relative)
single section (QW or bulk)	$\tau_p\chi$[4] (1)	{mirror loss}/ {total loss} (1)	(1)
3-section DBR (passive tuning section)	τ_s (200)	(0)	(0)
2-section gain-lever	g/γ (200)	g (10)	(1/20)
2-section gain-lever, zero-AM	$1/\gamma$ (20)	(0)	(0)

Note:

The efficiencies are measured at the "midband" modulation frequency range.

Numerical values of modulation efficiencies (relative to that of the single section laser) are shown in paranthesis in table.

Assumed parameters: $\chi\tau_p$=10ps [4], τ_s=2ns, γ=1/(0.2ns), g=10.

Reference

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2. N. Moore and K.Y. Lau, Appl. Phys. Lett., **55**, 936 (1989).

3. D. Gajic and K.Y. Lau, submitted to Appl. Phys. Lett. (Manuscript #L7051)

4. M. Kuznetsov, A.E. Willner and I.P. Kaminow, Appl. Phys. Lett., **55**, 1826 (1989).

5. This assumption is quite valid. The α parameter, on the other hand, is proportional to $(d\mu/dn)/(G')$ which decreases with increasing G'.

6. For a review and complete bibliography, see T.L. Koch and U. Koren, IEEE J. Lightwave Tech., **JLT-8**, 274 (1990).

Figure Captions

Fig. 1 Schematic diagram of the 2-section single quantum well laser, with the gain vs carrier density curve shown.

Fig. 2 Measured FM modulation characteristic of a uniformly pumped and gain-levered SQW laser.

Fig. 3 Measured linewidth versus inverse power of a uniformly pumped SQW laser (dots) and the same device operated in the gain-levered mode (triangle).

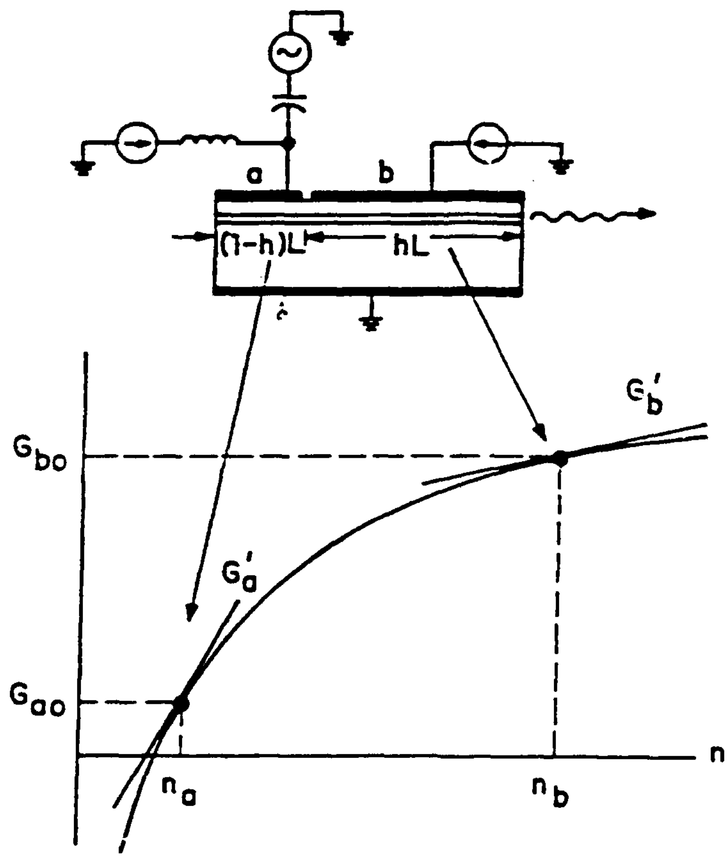

Fig. 1

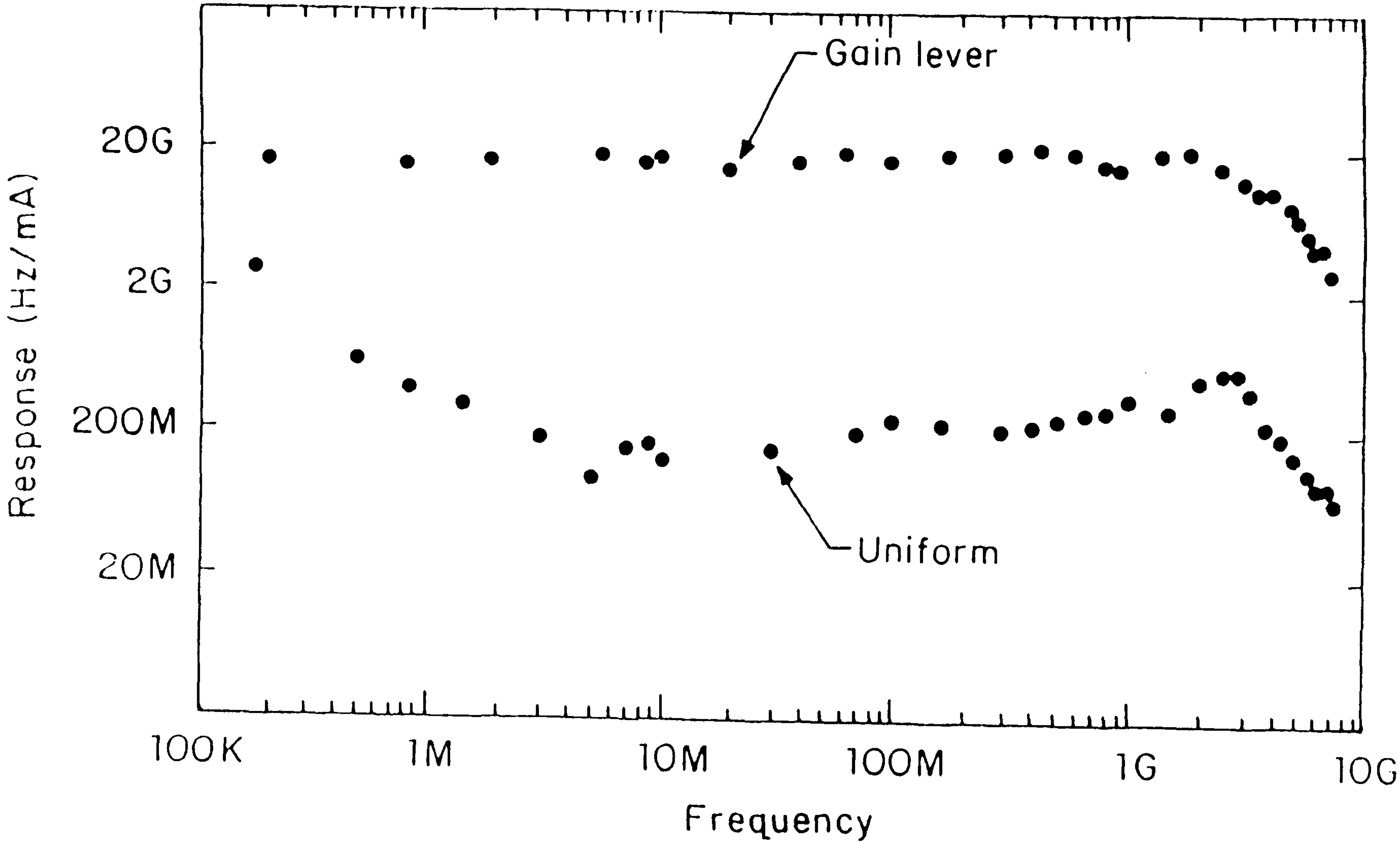
Gain lever
Uniform
20G
2G
200M
20M
Response (Hz/mA)
100K
1M
10M
100M
1G
10G
Frequency

Fig. 2

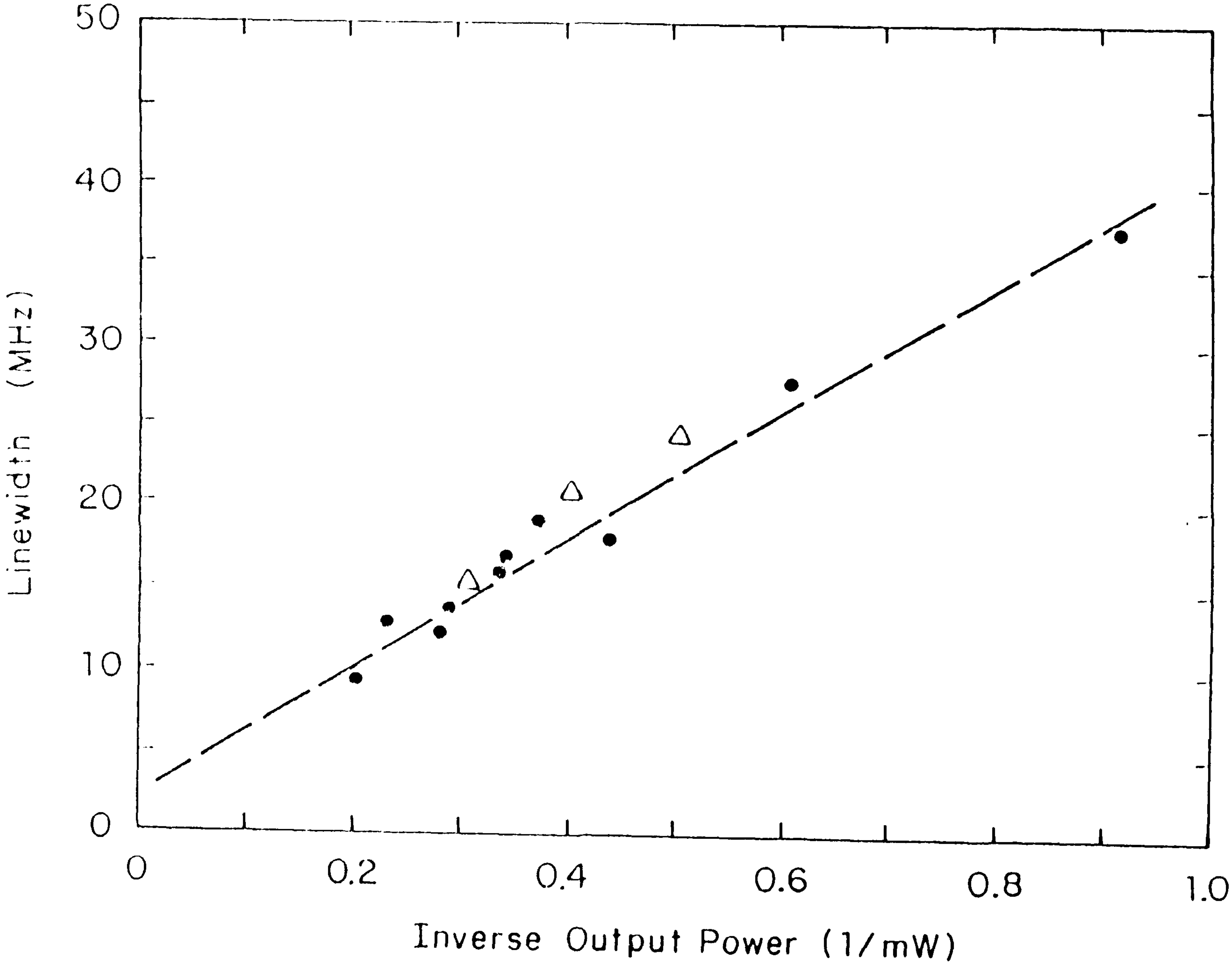
50
40
30
20
10
0
Linewidth (MHz)
0
0.2
0.4
0.6
0.8
1.0
Inverse Output Power (1/mW)

Fig. 3

4. Broad Wavelength Tunability in Gain-levered Quantum Well Semiconductor Lasers

Abstract

Using gain lever effect in a single quantum well laser, it was observed that the wavelength can be electronically tuned over a range of 90Å. Optimal device geometry that leads to a maximum tuning range was investigated.

The "gain-lever" effect, first reported in an optically modulated[] and subsequently electrically modulated laser diode[1], is based on the highly sublinear optical gain characteristics of a quantum well and gain clamping above lasing threshold. It was used to substantially enhanced the efficiency of direct intensity modulation (IM)[2] and frequency modulation (FM)[3], all achieved without a corresponding increase in the intensity noise[4] and frequency noise (linewidth)[3]. It was pointed out in [3] that the large FM response results from the ability of the gain-levered laser to vary the average electron density in the laser cavity over a large range, a phenomenon prohibited in a conventional laser due to gain clamping. It was also pointed out that[3] the same argument should lead to a large wavelength tuning range. (Here we consider only monolithic devices with electronic tuning. External cavity devices with mechanical tuning[5] is excluded in this discussion.) Indeed it was recently reported that[6] a distributed feedback (DFB) strained quantum well laser operated in the gain-levered mode can be tuned continuously over a 6.1nm range at 1530nm, the largest reported to date. This paper examines in detail the mechanisms responsible for broad wavelength tunability and the conditions necessary to achieve it.

The generic device geometry for a gain-levered laser is shown in Fig. 1. The physical length of the device is L and the two sections occupy fractional lengths of h and $(1-h)$ respectively. For a DFB laser, the physical lengths of the two sections should be replaced by the "effective lengths"[7]. The two sections are pumped differently and have different electron densities n_1 and n_2. The lasing wavelength shift is a function of the average change in the electron density along the length of the cavity[8]:

$$\Delta\omega \sim \bar{n} = hn_1 + (1-h)n_2 \qquad (1)$$

where the assumption has been made that the change in the refractive index of the optical mode is related to the change in electron density by a simple proportionalilty constant over the range of electron density under consideration. Equation (1) holds for a Fabry-Perot (FP) laser as well as a DFB laser. Furthermore, gain clamping requires that

$$hg(n_1) + (1-h)g(n_2) = g_{th} \qquad (2)$$

where $g(n)$ is the gain characteristics of the quautum well, and g_{th} is the threshold gain. For a FP laser the threshold gain is the inverse of the simple photon lifetime; for a DFB laser the grating coupling constant enters the picture. As the injection current into, say, section 1 is varied, n_1 and n_2 varies under the constraint of Eq. (2), and due to the sublinear nature of $g(n)$ leads to a large change in $\bar{n}$.

To experimentally study the limit of the tuning range the setup in Fig. 2 was used. The laser was a FP type single quantum well laser with tandem contact similar to the ones used in earlier studies[2-4]. The laser operates in a predominantly single longitudinal mode with a mode rejection ratio of 10:1. The frequency of the longitudinal modes are proportional to integral multiples of $\bar{n}$. Since this is a conventional FP device, one does not expect the dominant mode to tune continuously but in a series of slews and hops. However, by setting the spectrometer at a fixed wavelength a few tens of angstroms away from the dominant mode peak, one can observe the side modes "sweeping" by as $\bar{n}$ is ramped, in form of an oscillatory output from the spectrometer (example shown in Fig. 3). Since the spacing between modes is known, by counting the number of cycles in the spectrometer output one can deduce the shift in wavelength of the longitudinal modes. Had the laser been constructed with a DFB structure this will be the continuous tuning range of the dominant mode[9]. The data in Fig. 3 was obtained with a $300\mu m$ long FP device with $h \sim 0.3$ and an estimated threshold gain of approximately $35 cm^{-1}$. The modal separation was approximately 3Å, and the tuning range was therefore about 90Å as i_1 is swept from a few mA to 30mA. Similar measurements were taken with devices that were coated with high reflectivity layers. For a device with 0.8 reflectivity coatings on both facets the tuning range was about 35Å. Repeated measurements with various devices made it apparent that lower threshold devices in general have a narrower tuning range. It is also worth noting that tuning can be done at a constant optical power by ramping i_1 and i_2 simultaneously in opposite directions with a suitable ratio[3].

To understand the relation of device geometry to tuning range we go back to Fig. 1. The electron densities at the operating points of the two sections are governed by Eq. (2). Thus, given a gain characteristic $g(n)$, subjected to the constraint of Eq. (2) one seeks the condition for which the largest variation in $\bar{n}$ is obtained by varying n_1 (or equivalently, n_2). The gain function $g(n)$ was based on a simple gain calculation of a single quantum well[10]. Figure 4(a) shows $\bar{n}$ (expressed in sheet density) versus n_1 for various length ratios h. To facilitate inspection, the curves for $h = 0.3$, 0.5 and 0.7 are upshifted from each other; to obtain the true values, downshift the curves so that the dot at the lowest points of the curves line up with the diamond. The curves are bounded to the left by the requirement that n_1 should at least equal to the transparency electron density. At this point n_2 is large so as to compensate for the lack of gain in section "1". As n_1 is increased, n_2 decreases according to Eq. (2) until $n_1 = n_2 = n_{th}$, represented by the lowest points of the curves in Fig. 4. For larger values of n_1, the situation is identical to that obtained by reversing n_1 and n_2 and replacing h with $1-h$. In fact the upper limit in the tuning curves of Fig. 4 is the situation in which the longer section is biased just above transparency while the shorter section is forced to a high electron density such that it alone provides the gain needed for threshold. The lower limit occurs, as explained before, when $n_1 = n_2 = n_{th}$. It is obvious that the upper limit can be raised by raising the threshold gain. As a matter a practicality, there is a limit to the bias current one can inject into a section, in additional to the fact that at sufficiently high injection level the second quantized state of the QW contributes to additional gain thus negating the gain lever effect. For the parameters chosen in Fig. 4(a), $g_{th} = 30cm^{-1}$ which is typical for a $300-400\mu m$ long device, the optimal value of h appears to be around 0.3 (or 0.7). Figure 4(b) shows the case when g_{th} is lowered to $15cm^{-1}$. The marked decrease in the tuning range is evident. The approach to design a device with large tuning range is thus to first determine the maximum gain that a section can sustain, and then to choose g_{th} and h such that when the longer section is biased at just above transparency the other section is operating at or near the maximum gain.

The simple arguments above apply well for a FP laser and are in general valid for a multisection DFB laser. Obviously the DFB laser entails more subtleties due to spatial hole burning effects and subsequent variations in the effective lengths of the sections as the device is tuned. A more complete analysis of the DFB device including these effects is underway.

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9. T.L. Koch and U. Koren, IEEE J. Lightwave Tech., **JLT-8**, 274 (1990).

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Figure Captions

Fig. 1 Generic device geometry of a gain-levered laser for wavelength tuning. g_{th} and n_{th} are the threshold gain and the corresponding electron density.

Fig. 2 Experimental setup for observing the wavelength tuning range for a FP laser.

Fig. 3 Spectrometer output as i_1 is ramped.

Fig. 4 Calculated average electron density $\bar{n}$ when n_1 is varied. The densities are expressed in sheet densities. The curves corresponding to h =0.3,0.5 and 0.7 are upshifted for easy observation. (a) a single quantum well laser with threshold gain of $30cm^{-1}$, (b) same with threshold gain of $15cm^{-1}$.

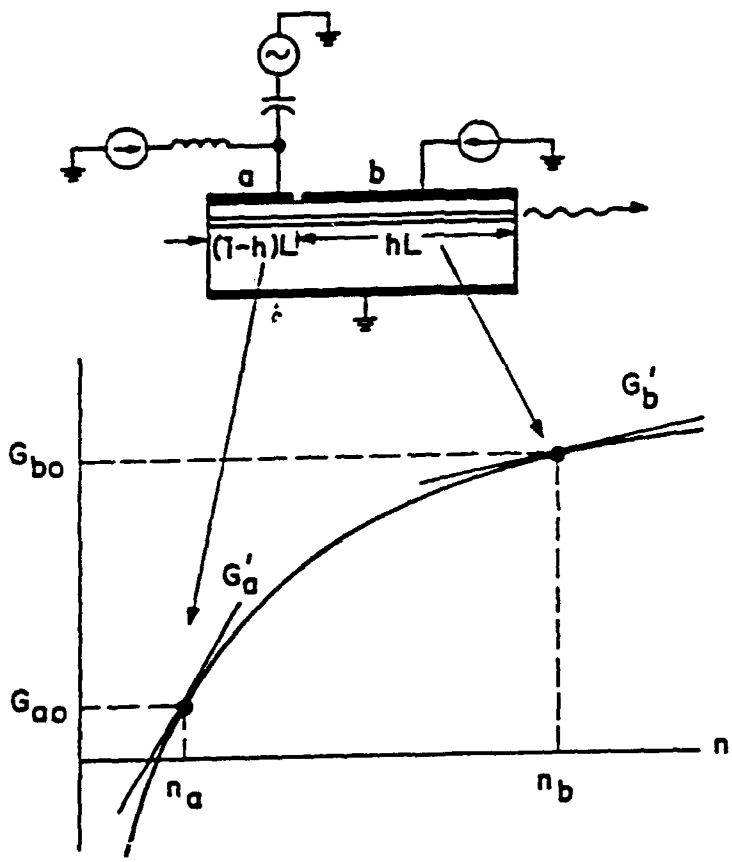


Fig. 1

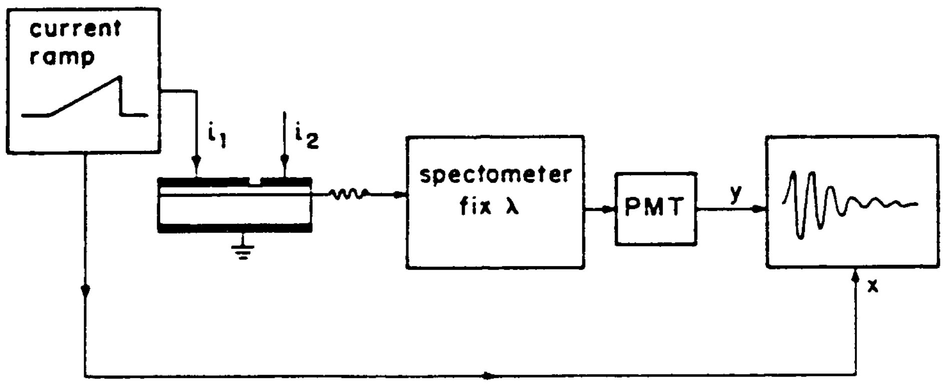


Fig. 2

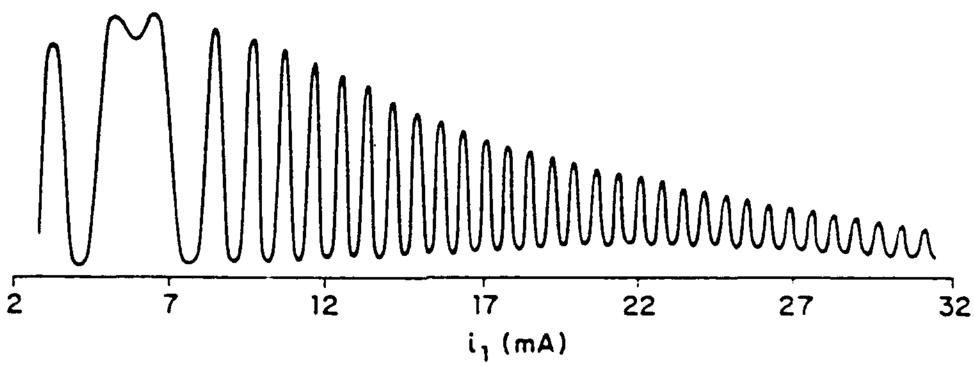
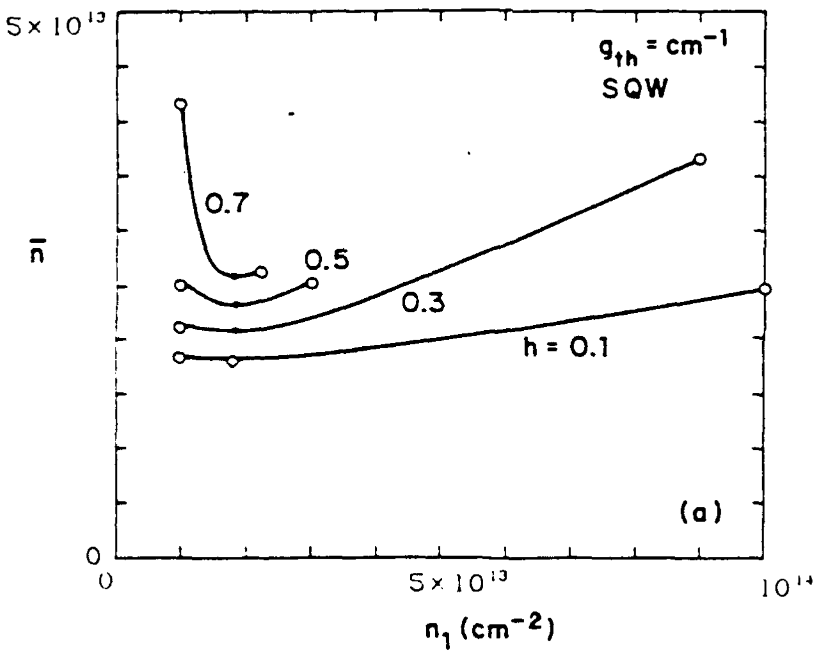


Fig. 3



Fiq. 4a

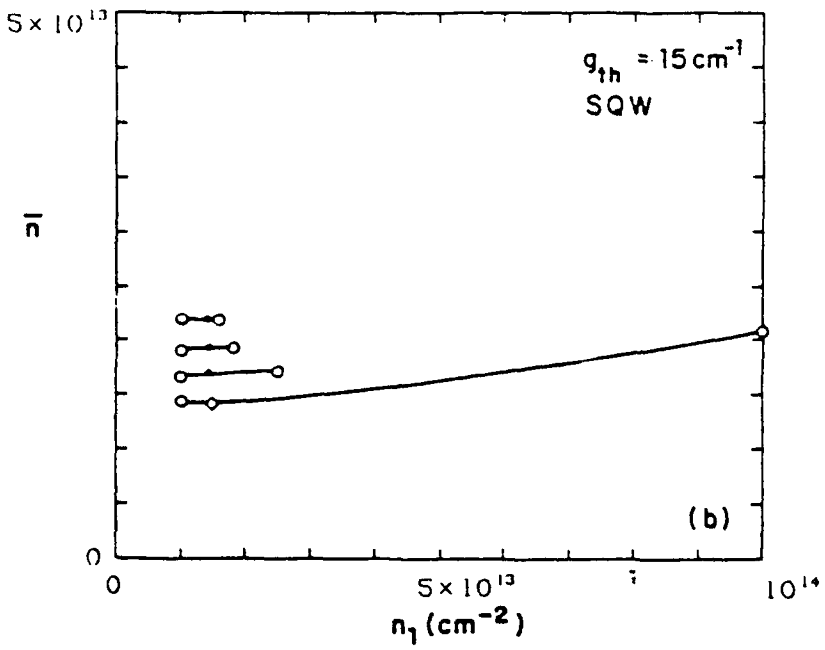


Fig. 4b

5. The "inverted" Gain-Levered Semiconductor Laser - Efficient Frequency Modulation with a Very Low Residual Intensity Modulation

Abstract

A variation of the gain-levered quantum well laser, called "inverted" gain lever, is introduced. It is shown to outperform normal gain-levered laser as a FM laser transmitter in terms of residual intensity modulation, optical power and modulation bandwidth.

The "gain-lever" effect[1,2] was used to substantially enhance the efficiency of direct intensity modulation (IM) and optical frequency modulation (FM) of a 2-section quantum well laser without a corresponding increase in the intensity and frequency noise (linewidth)[3,4]. Furthermore, the usual carrier clamping condition for a laser above threshold does not apply (although gain-clamping still does) and leads to a very large wavelength tunability for these lasers[5].

A high FM efficiency achieved electronically is desirable for coherent or wavelength multiplexed systems, since it minimizes drive signal requirements and overwhelms thermal effects which eliminates the associated low frequency hump in the FM response. Furthermore, one desires a FM modulation source with a minimal accompanying IM, since the effect of the latter is often deleterious in a coherent detection system. We have examined before the relative merits of different FM laser configurations[4] from the viewpoints of FM efficiency, speed and IM/FM ratio. We found that gain-levered lasers offer good performances in all categories. The large FM in these lasers is accompanied by a large IM, although its IM/FM ratio is still an order of magnitude below that of a uniformly pumped laser. Nevertheless, gain-lever is effective only at low optical power (below 1-2mW), and it is desirable to further reduce the IM/FM ratio as well as improving its FM response to beyond 1-2GHz. A further order-of-magnitude reduction in the IM/FM ratio is made possible by a variation of the normal gain-lever, which we call "inverted" gain-lever. With this arrangement, the IM/FM ratio approaches that of a 3-section tunable laser using a below-bandgap phase modulation section for wavelength tuning[6]. The modulation bandwidth of the latter device is limited by the carrier lifetime to a few hundred megahertz, while the inverted gain-lever laser maintains a FM bandwidth of 4-5GHz. Furthermore, while the efficiency enhancements of a normal gain-lever laser diminish at optical power levels higher than approximately 1mW, an inverted gain-lever actually favors operation at higher optical power. There are thus numerous attributes for the inverted gain-lever laser, as the results described below will clarify.

In contrast to the familiar gain-lever effect, the "inverted" gain-lever effect is obtained by inverting the role of the gain and modulation sections. Let G_a, G_b denote the gain of the respective sections as shown in Fig. 1, G_h the threshold gain, $G'_{a,b,h}$ their derivatives with respect to carrier density, and $r_{a,b}$ the fractional lengths, with modulation applied to section "a" and with $r_a \ll 1$, $r_b \to 1$. The threshold condition

$$r_a G_a + r_b G_b = G_h \tag{1}$$

applies. As illustrated in Fig. 1, in the normal gain-lever mode,

$$G_a \to 0, \qquad G_b > G_h, \qquad G'_a \gg G'_b \tag{2a}$$

while in the inverted mode,

$$G_a > G_h, \qquad G_b < G_h, \qquad G'_a \ll G'_b \tag{2b}$$

Note that the inverted lever mode can be obtained only with a very low threshold device (by mirror coatings, for example), since section "b", which occupies a majority of the physical length and supplies the majority of the gain, must be biased at a low level in order to maintain a large G'_b.

First, consider the noise behavior of these lasers. It has been shown that[3,4] for an optimally designed device with $r_a \to 0$ and $r_b \to 1$, the IM and FM fluctuations of a gain-levered (either normal or inverted) laser are almost identical to that of a uniformly pumped laser. In this sense, an inverted gain-lever laser has noise properties comparable to that of a low threshold laser with a high cavity-Q - the two factors which leads to low IM and FM noise[7]. The noise behavior of the inverted gain-lever laser is thus expected to be at least equal if not better than that of normal gain-lever.

Next, consider modulation. Let p and ν denotes the small signal IM (photon density) and FM amplitudes, respectively, j_a the modulation current density into and r_a the fractional length of section "a". At frequencies well below cutoff (a few GHz), the IM and FM modulation responses of a gain-levered laser are[1,2,4]:

$$\frac{p}{r_a j_a/(ed)} = \frac{G'_a \gamma_b}{r_a G_a G'_a \gamma_b + r_b G_b G'_b \gamma_a} \tag{3}$$

$$\nu = -\alpha \omega_c p \tag{4a}$$

$$\text{where} \quad \omega_c = \frac{r_b}{\tau_{stim,b} \gamma_b \tau_p}\left(\frac{G'_b}{G'_a} - 1\right) \tag{4b}$$

The quantity $\rho = p/P_0$ is the optical modulation depth, P_0 being the average photon density, $\tau_{stim,b} = G'_b P_0$ is the stimulated lifetime of section "b", τ_p is the photon lifetime, $\gamma_{a/b} = 1/\tau_{s,a/b} + 1/\tau_{stim,a/b}$ are the inverse of the effective carrier lifetimes of the two sections, $\tau_{s,a/b}$ being the spontaneous lifetimes. Equations (3) and (4) apply for both normal and inverted gain-levered lasers.

The parameter ω_c in Eq. (4) has the significance that $|\alpha\omega_c|$ is the angular frequency deviation at 100% IM (i.e., $p = P_0$). The inverse of this quantity is thus the percentage of IM modulation per unit frequency deviation, a figure of merit for a FM laser which directly determines system penalty for coherent transmission.

To quantify the various parameters, we use an experimentally measured gain characteristic of a single quantum well laser[8] and assume a threshold gain of 60cm^{-1} (mirror reflectivities =0.3, length=0.025cm, internal loss=12cm^{-1}). Assume that for normal gain-lever, r_a=0.1, the mirrors are uncoated, and sections "a" and "b" are biased at 16cm^{-1} and 65cm^{-1} respectively. For inverted gain-lever, the mirrors are coated to reflectivities of 0.8, resulting in a threshold gain of 21cm^{-1}, and sections "a" and "b" are biased at 65cm^{-1} and 16cm^{-1} respectively - i.e., a symmetric inversion of the parameters of the gain and modulation sections. Thus from [8], G'_a/G'_b is approximately 10 for normal gain lever and 0.1 for inverted lever. In addition, the spontaneous lifetimes are estimated from [9]. Values of various parameters can then be computed and are shown in Table I. These values are then used to compute the FM efficiency, IM efficiency relative to a uniformly pumped laser, and the parameter ω_c. The results are shown in Table II. One notes from Table II that normal gain-lever has the higher IM and FM efficiencies but has a comparatively low FM/IM ratio, as measured by the parameter ω_c; whereas inverted gain-lever has a reduced IM efficiency but a much higher FM/IM ratio.

A further consideration is the FM modulation bandwidth. It can be shown that the FM response of a gain-levered laser is

$$\frac{\nu(\omega)}{r_a j_a/(ed)} = \alpha G'_b \frac{(f(\omega)-1)(i\omega+\gamma_b) + \left(1 - \frac{G'_a\gamma_b}{G'_b\gamma_a}\right)i\omega + \gamma_b\left(1 - \frac{G'_a}{G'_b}\right)}{f(\omega)(i\omega+\gamma_a)(i\omega+\gamma_b)} \qquad (5)$$

where $1/f(\omega)$ is the normalized dimensionless IM response, which consists of a zero and three poles[2], although in practice the form of the response function does not differ drastically from that of the well known second-order lowpass response. Using the parameters listed in Table II, Fig. 2 plots the FM frequency responses for a normal and an inverted gain-lever laser, the former at a an output optical power of 1mW/facet and the latter at 2mW/facet (although taking into account of the difference in facet reflectivities, the internal power density of the inverted gain-lever laser is 10 times that of the normal gain-lever laser). Figure 3 shows a FM figure of merit $1/|\alpha\omega_c|$, expressed in percentage modulation depth in IM per GHz deviation in FM, plotted as a function of modulation frequency. The higher frequency response for inverted gain-lever arises primarily from a shortened stimulated lifetime at high photon densities (see Table I). The advantages of using inverted gain-lever for FM applications is clearly seen from this figure.

Experimentally, single mode (17dB side-mode rejection) GaAs single quantum well lasers with tandem contacts were used. The modulation and gain sections were 120μm and 400μm long respectively. The laser intended for a normal gain-lever operation is uncoated, while both mirrors of the one for inverted gain-lever was coated to reflectivities of about 0.7. The normal gain-levered laser operates at a nominal output power/facet of 1mW, while for the inverted lever it was operated at about 3mW/facet. IM and FM frequency responses were obtain in a standard manner by a microwave s_{21} measurement using direct detection in the former case and detection through a low-Q etalon in the latter. The results are shown in Fig. 4(a). The measured IM responses normalized to the FM responses are shown in Fig. 4(b), expressed in percentage IM per GHz FM as in Fig. 3 previously. The general trend of Fig. 4(a) and (b) closely follows that of Figs. 2 and 3, although the exact numerical values show some discrepency. This is not unexpected since the numerical values of the parameters entered into the calculations are not known accurately.

In conclusion, it is shown that although gain-levered lasers have very high IM and FM efficiencies, its use for a pure FM application is not as desirable as that of an inverted gain-levered laser with respect to IM/FM ratio, optical power and frequency response. The inverted gain-levered laser has overall characteristics that approaches an ideal FM laser.

TABLE I

normal gain-lever :	section "a"	section "b"
inverted gain-lever :	section "b"	section "a"
G	$16cm^{-1}$	$65cm^{-1}$
G' (relative)	10	1
τ_s	5.1ns	0.52ns
$G'P_0$ @ 1mW/facet (1)	1/(0.2ns)	1/(2ns)
γ @ 1mW/facet (1)	$5.2ns^{-1}$	$2.5ns^{-1}$
$G'P_0$ @ 2mW/facet (2)	1/(0.02ns)	1/(0.2ns)
γ @ 2mW/facet (2)	$50.2ns^{-1}$	$7ns^{-1}$

(1). Facet reflectivities of 0.3, for the case of normal gain-lever.

(2). Facet reflectivieies of 0.8, for the case of inverted gain-lever. The *internal power density* is 10 times that of (1).

TABLE II

	FM efficiency $-\frac{\alpha}{\gamma_a}(G'_b - G'_a)$	IM efficiency[1] $\frac{G'_a \gamma_b}{G'_b \gamma_a}$	$\Delta\nu$ at 100% IM, $\lvert\alpha\omega_c\rvert/2\pi$
Gain-lever (facet reflectivities = 0.3; 1mW/facet)	**22 GHz/mA**	**4.81**	**7.2 GHz**
Inverted gain-lever (facet reflectivities = 0.8; 2mW/facet)	**16.4 GHz/mA**	**0.72**	**112 GHz**

(1) IM efficiency normalized to that of a uniformly pumped laser.

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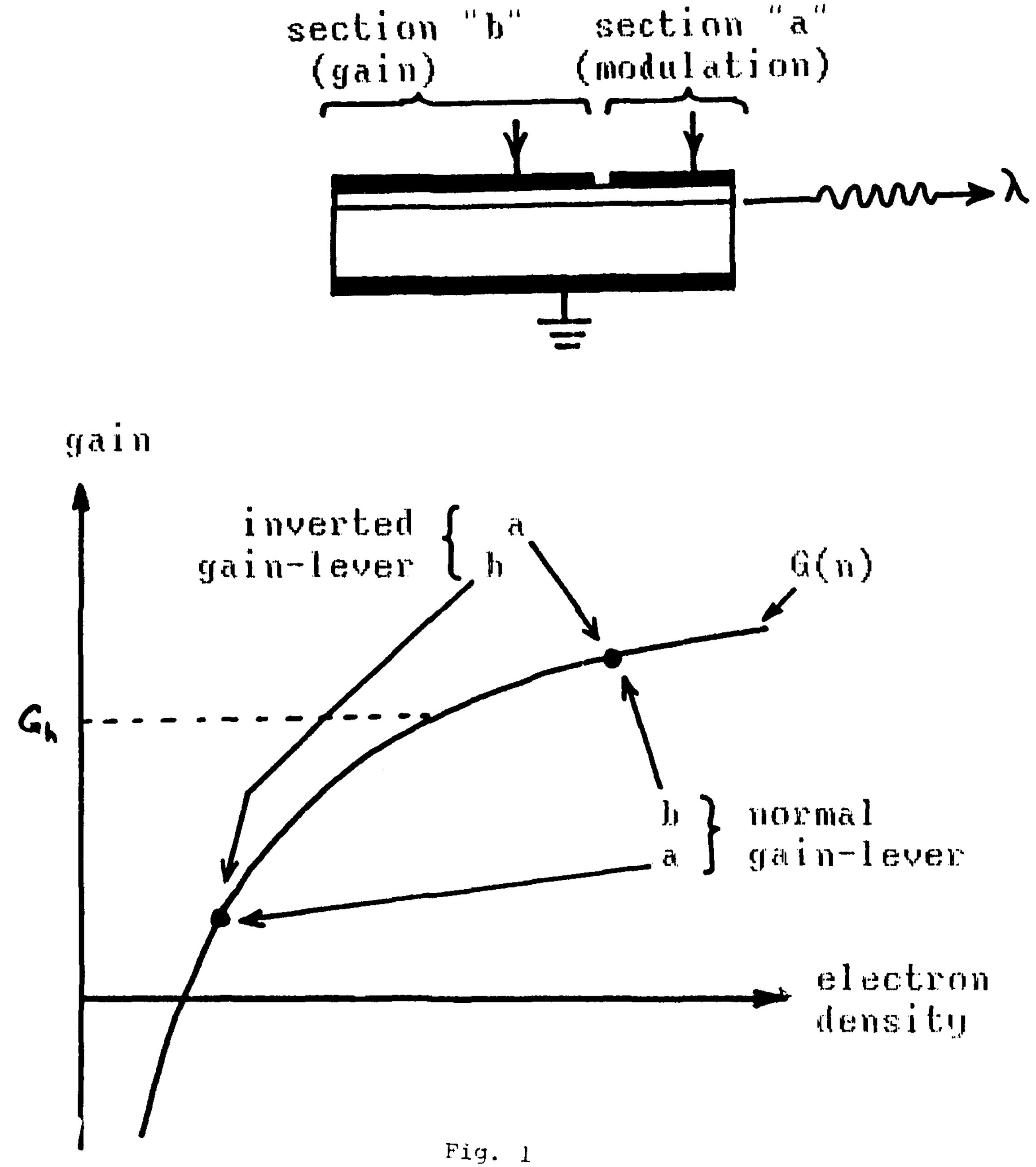
Figure Captions

Fig. 1 The gain-lever and the "inverted" gain-lever operation of a 2-section quantum well laser. G_{th} is the threshold gain.

Fig. 2 Theoretical FM responses for a normal gain-levered laser at an optical power of 1mW/facet, and for an inverted gain-levered laser (high reflectivity-coated, 80% each facet) at 2mW/facet.

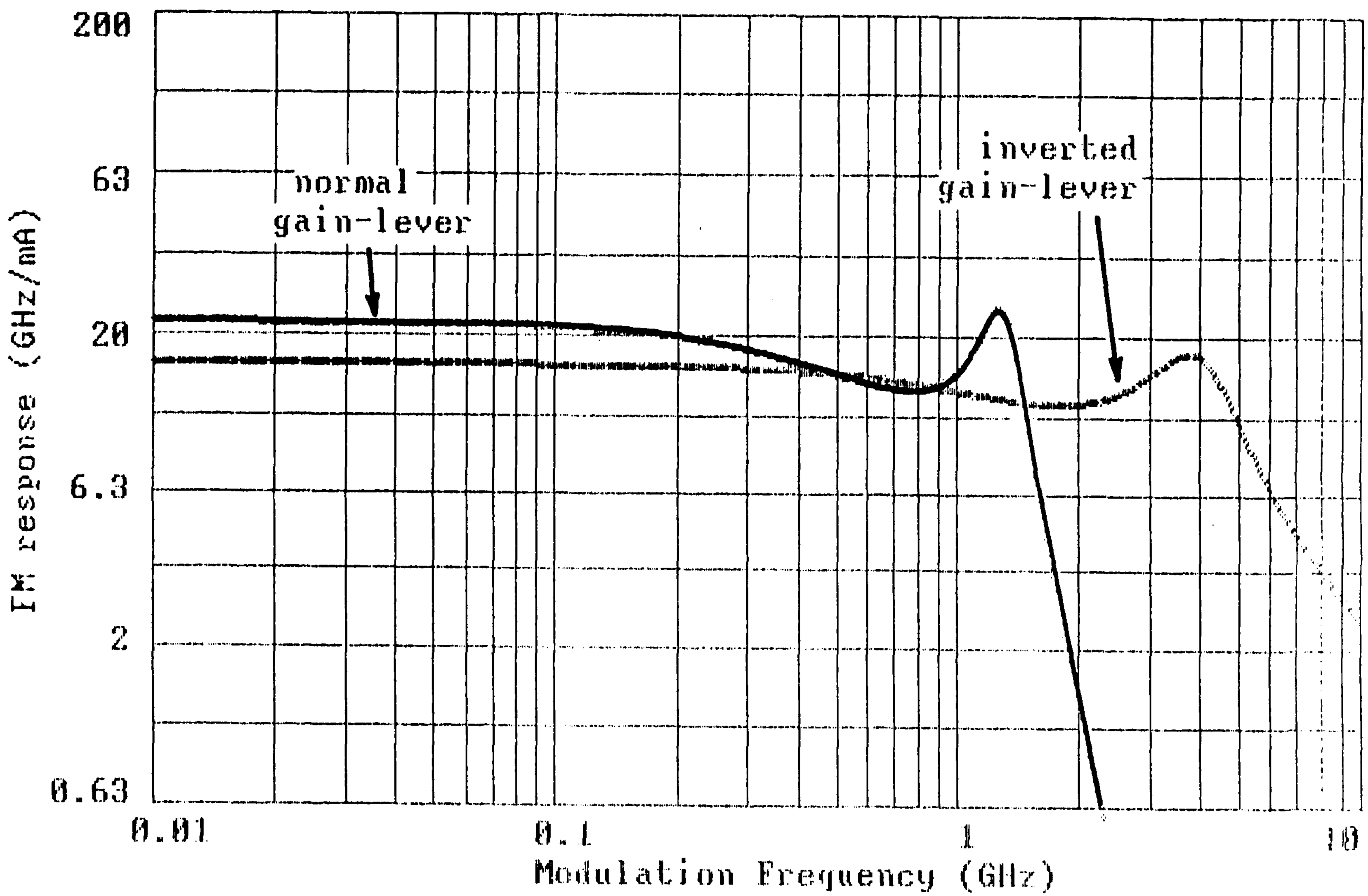
Fig. 3 Plot of $1/\omega_c$, percentage modulation depth of IM per GHz deviation in FM, as a function of modulation frequency, for normal and inverted gain lever.

Fig. 4 Experimentally observed (a) and (b) IM/FM ratio, the latter expressed in percentage IM per GHz in FM, for normal and inverted gain lever, at 1.0mW and 3mW output power per facet respectively. For normal gain lever, i_a=3mA, i_b=23mA, for inverted gain lever, i_a=11.5mA, i_b=11mA. Dimensions of the sections are shown in text.



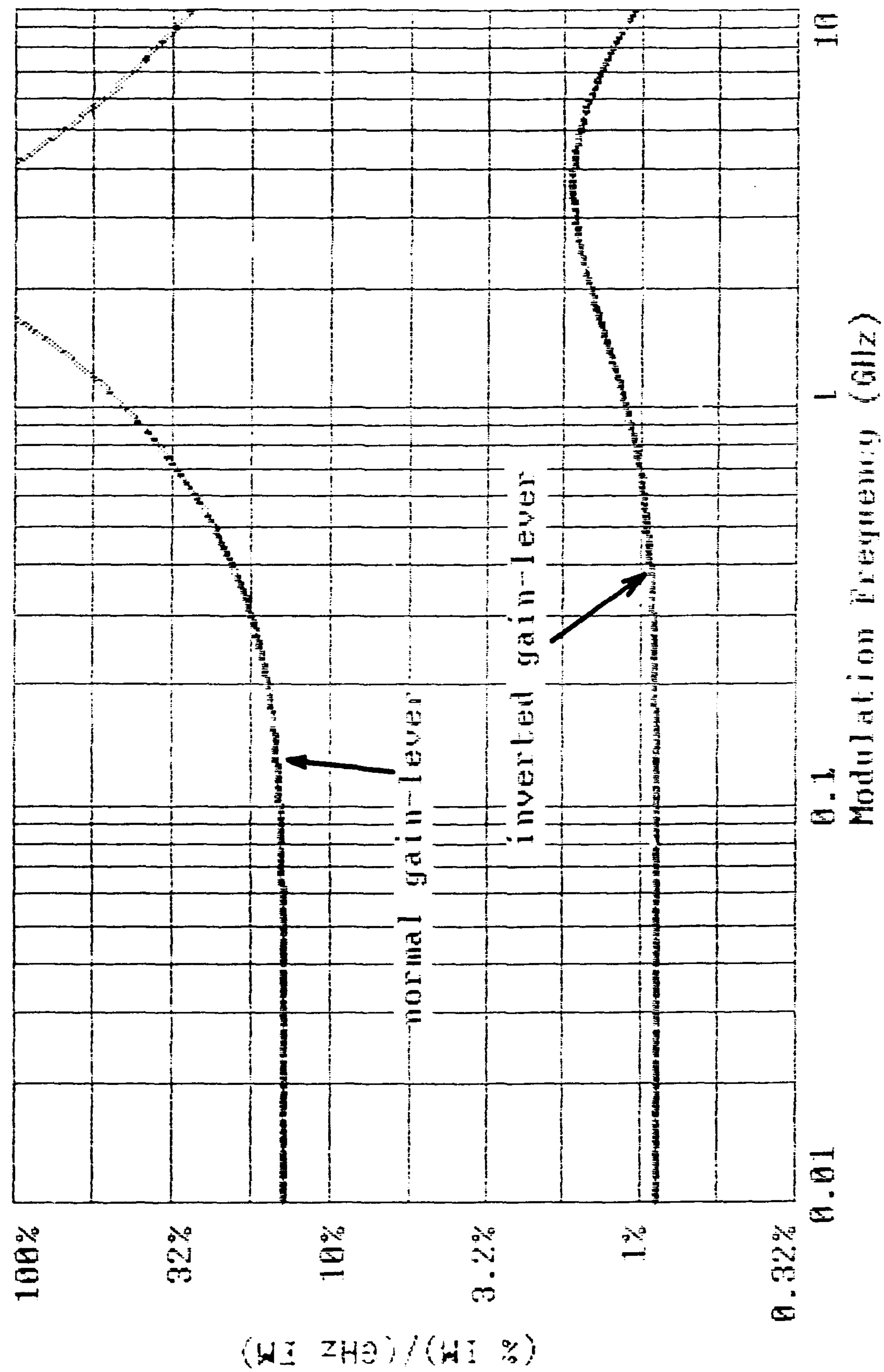
section "b"
(gain)
section "a"
(modulation)
λ
gain
inverted
gain-lever
a
b
G(n)
G_h
b
a
normal
gain-lever
electron
density

Fig. 1



200
63
20
6.3
2
0.63
FM response (GHz/mA)
normal
gain-lever
inverted
gain-lever
0.01
0.1
1
10
Modulation Frequency (GHz)

Fig. 2



100%
32%
10%
3.2%
1%
0.32%
(% IM)/(GHz FM)
0.01
0.1
1
10
Modulation Frequency (GHz)
normal gain-lever
inverted gain-lever

Fig. 3

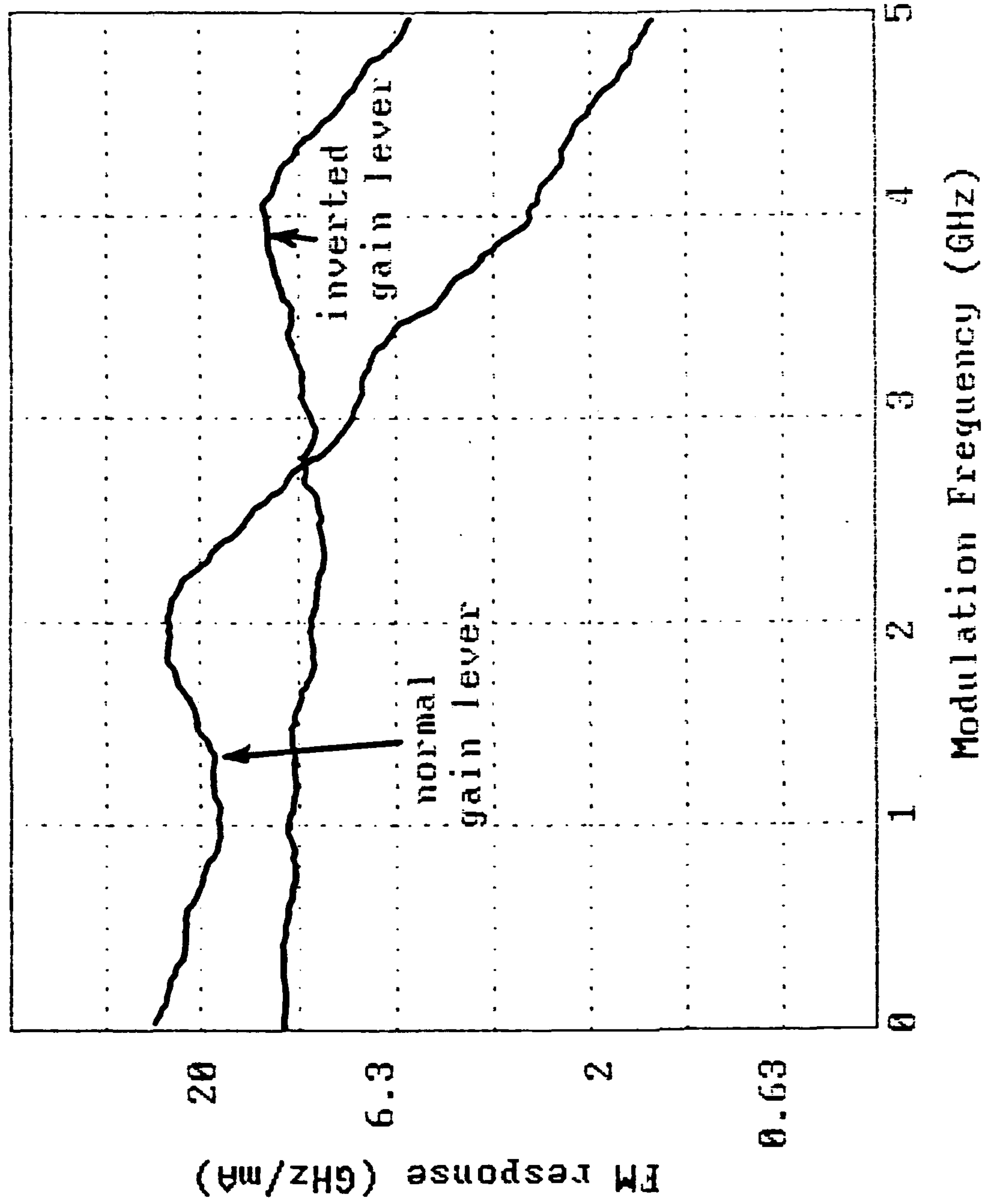
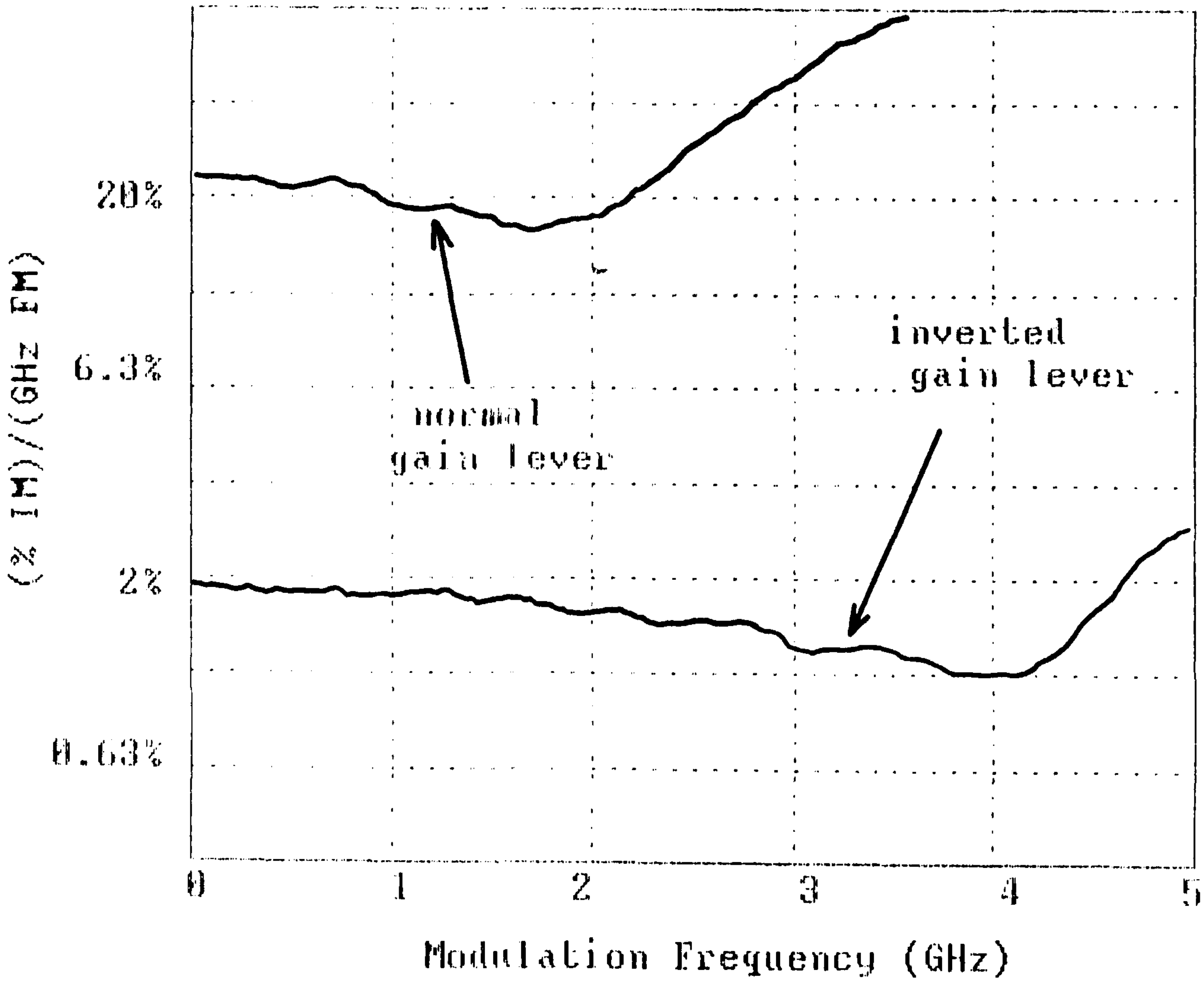

inverted
gain lever
normal
gain lever
Modulation Frequency (GHz)
0
1
2
3
4
5
FM response (GHz/mA)
20
6.3
2
0.63

Fig. 4a



20%
6.3%
2%
0.63%
(% IM)/(GHz FM)
normal
gain lever
inverted
gain lever
0
1
2
3
4
5
Modulation Frequency (GHz)

Fig. 4b

6. Ultra-high Efficiency Optical Modulation (>20W/A) by Interferometric Frequency → Intensity Conversion of Gain-levered Semiconductor Lasers

Abstract

It is theoretically and experimentally demonstrated that a peculiar amplitude/phase coupling characteristic between the modulated and noise output of gain-levered lasers leads to a simultaneous increase in the modulation efficiency and a reduction in the intensity noise by interferometric frequency→intensity conversion.

The quest for an optical transmitter with high modulation efficiency and low intensity noise is motivated, amoung other things, by the fact that the Noise Figure of an analog optical transmission link - a measure of its fidelity - is proportional to the quotient (intensity noise)/(modulation efficiency). Gain-lever is an effect which ultilizes the highly sublinear nature of the quantum well gain characteristic to accomplish very high modulation efficiencies in intensity modulation (IM) and frequency modulation (FM), as well as broad wavelength tunability[1-5]. Since the large IM in the modulated output of a gain-levered laser is accompanied by a very large FM[4], it is natural to consider further enhancing the IM efficiency by interferometrically converting the large FM into IM[6]. Since the IM and FM are correlated in a semiconductor laser, the converted FM can either add to or subtract from the existing IM. By the same token, the interferometrically converted phase noise can either enhance or suppress the intensity noise[7]. Thus whether or not the noise figure can be improved at the interferometer output depends on the IM-FM correlation characteristics of the modulation and noise at the laser output.

The generic geometry of a gain-levered laser is shown in Fig. 1. When section "a", the modulation section, is biased near transparency, it is refered to as the "normal" gain-lever[1-5], in which high IM and FM efficiencies are obtained. When section "a" is biased at a higher gain then section "b", it is refered to as the "inverted" gain-lever[8], in which a high FM/IM ratio is obtained despite a lower IM efficiency. The former is desirable if raw efficiencies are desired, the latter is suitable for FM modulation with a minimal residual IM. Let G_a, G_b denote the gain of the respective sections, $G'_{a,b}$ their derivatives with respect to carrier density. For an optimally designed gain-lever laser, section "b" occupies a majority of the physical length and supplies the majority of the gain, hence G_b is approximately the threshold gain. It follows that an inverted gain-lever laser is one with a very low threshold (by application of high reflectivity coatings, for example)[8].

First, consider the noise behavior of these lasers. Let δp and $\delta\nu$ denote the intrinsic intensity (actually photon density) and frequency fluctuations. It has been shown that[3,4] since the Langevin noise driving these fluctuations originates mainly from the majority section "b", the IM and FM fluctuations of a gain-lever (either normal or inverted) laser are almost identical to that of a uniformly pumped laser, which are correlated as[7]:

$$\delta\nu = \alpha\omega_p\delta p + \Delta_r \tag{1}$$

where α is the linewidth enhancement factor evaluated for a similar but homogeneously pumped device,

$$\omega_p = 1/(\gamma_b\tau_{stim,b}\tau_p) \tag{2}$$

where τ_p is the photon lifetime, $\tau_{stim,b} = G'_bP_0$ is the stimulated lifetime of section "b" where P_0 is the average photon density, $\gamma_{a/b} = 1/\tau_{s,a/b} + 1/\tau_{stim,a/b}$ are the inverse of the effective carrier lifetimes of the two sections where $\tau_{s,a/b}$ are the spontaneous lifetimes. In Eq. (2), Δ_r is a fluctuation term consisting of the Langevin force and the power-independent linewidth contribution[7]. Note that since the inverted gain-lever laser is operating at a higher photon density and lower lasing threshold, both the IM and FM noise behavior are considerably better than that of the normal gain-lever.

Next, consider modulation. Let p and ν denotes the small signal IM (photon density) and FM amplitudes, respectively, j_a the modulation current density into and r_a the fractional length of section "a". At frequencies well below cutoff (a few GHz), the IM and FM modulation responses of a gain-levered laser (either normal or inverted) are[1,2,4]:

$$\frac{\rho}{r_aj_a/(ed)} = \frac{1}{G_bP_0}\left(\frac{G'_a\gamma_b}{G'_b\gamma_a}\right) \tag{3}$$

$$\nu = -\alpha\omega_c\rho \quad \text{where} \quad \omega_c = \omega_p\left(\frac{G'_b}{G'_a} - 1\right) \tag{4}$$

where $\rho = p/P_0$ is the optical modulation depth. Equations (3) and (4) apply for both normal and inverted gain-levered lasers.

Define $\eta = p/(r_aj_a/ed)$ as the IM modulation efficiency. For comparison, for a homogeneously injected laser,

$$\eta^{homo} = 1/(G_bP_0) \tag{5}$$

$$\nu = -\alpha\omega_c^{homo}\rho; \quad \omega_c^{homo} = \frac{1}{2}\left(\frac{\xi}{\tau_{stim}} + \theta\right) \tag{6}$$

where ξ and θ are the gain compression parameter and the intrinsic Schawlow-Townes linewidth, respectively[9]. Typical numbers are $\xi = 6$ and $\theta \leq$MHz.

Based on Eqs. (3), (4) and (6), the correlation characteristics betweer IM and FM in the modulation and noise are shown geometrically in Fig. 2. The ellipse represents the strongly but incompletely correlated IM and FM noise, nearly identical for all three cases. The slopes of the lines representing IM-FM modulation qualitatively demonstrates the relative strength and phases of IM and FM in each of the three cases.

Next, consider the consequences of performing an interferometric FM→AM conversion on these lasers. Let ρ_{in}, ρ_{out} be the IM modulation depths at the input and output of the interferometer respectively, and let $\delta\rho_{in}$, $\delta\rho_{out}$ be the corresponding relative IM noises (RIN). It can be shown that[7]

$$\rho_{out} = \left(1 - \alpha\frac{T'_r}{T_r}\omega_c\right)\rho_{in} \quad ; \quad \delta\rho_{out} = \left(1 + \alpha\frac{T'_r}{T_r}\omega_p\right)\delta\rho_{in} \tag{7}$$

and

$$\frac{<\delta\rho^2_{out}>}{<\delta\rho^2_{in}>} = \left(1 + \frac{T'_r}{T_r}\frac{\alpha}{\gamma_b\tau_{stim.b}\tau_p}\right)^2 + (1+\beta)\left(\frac{T'_r}{T_r\gamma_b\tau_{stim.b}\tau_p}\right)^2 \tag{8}$$

where T_r and T'_r are the transmission coefficient of the interferometer and its derivative with respect to optical frequency, respectively, and β is a parameter representing the residual power-independent linewidth[7].

Geometrically, in performing a pure intensity detection one projects the noise ellipse and modulation lines in Fig 2 onto the intensity-axis whereby the corresponding S/N ratio can be obtained. For a pure frequency detection one rotates the observation plane by 90° onto the frequency-axis. An interferometric device produces a linear combination of IM and FM (Eq. (7)) and corresponds to rotating the observation plane to an intermediate angle (Fig. 2). It is easy to see that in the case of inverted gain-lever, an optimal situation can be found in which the signal can be maximized while the intensity noise is simultaneously minimized.

Figure 3(a) and (b) show the interferometrically enhanced IM efficiency and noise of normal and inverted gain-levered lasers as compared to a homogeneously pumped laser, $20\log(\eta_{out}^{lever}/\eta^{homo})$ and $10\log(<\delta\rho_{out}^2>/<\delta\rho_{in}^2>)$ respectively, plotted against T'_r. One observes that there are two useful modes of operation: (1) using normal gain-lever (Fig. 3(a)) at large T'_r, a large enhancement in modulation efficiency is obtained, and although the enhancement in noise is also substantial, the former about 10dB higher than the latter; (2) using inverted gain-lever (Fig. 3(b)) at the optimal T'_r, a simultaneous enhancement in modulation (15dB) and reduction in noise (5dB) is possible, resulting in an improvement in the signal/noise performance of about 20dB.

Experimentally, single mode (17dB side-mode rejection) GaAs single quantum well lasers with tandem contacts were used. The modulation and gain sections were $120\mu m$ and $400\mu m$ long respectively. The laser intended for a normal gain-lever operation is uncoated, while both mirrors of the one for inverted gain-lever was coated to reflectivities of about 0.7. The normal gain-levered laser operates at a nominal output power/facet of 1mW, while for the inverted lever it was operated at about 3mW/facet. Current modulation at 1GHz at an input level of -47dBm (into 50Ω) was applied to the modulation section. The laser output was detected by a high speed photodiode and displayed on a microwave spectrum analyser after amplified by 20dB using a low noise RF amplifier.

Three sets of data each were recorded for normal and inverted gain lever: (1.) uniform injection, direct detection; (2.) gain-lever, direct detection and (3.) gain-lever, with a low-Q Fabry-Perot inserted before detector. Care was taken to ensure that the DC photocurrents were nearly identical in all three cases, to facilitate a direct comparison of the noises and modulation efficiencies. The value of T'_r was about 1/95GHz, as determined by operating the laser cw and scanning the Fabry-Perot. The results are shown in Fig. 4(a) and (b). In these plots, the three curves are slightly offset horizontally from one another to facilitate inspection. The enhancements in efficiencies can be clearly seen from these data, and the overall signal/noise enhancement (over that of a homogeneously pumped device) is approximately 8dB for both normal and inverted gain-lever laser with interferometric FM→IM conversion. The low frequency hump in the noise observed in latter mode is believed to be mode-partition noise since the laser is not truely single-mode in the strict sense. The effective modulation efficiency observed is 24mW/mA, an enhancement of a factor of over 50 (34dB) over a uniformly injected laser.

It should be noted that the interferometer used in this experiment was far from the optimal value as predicted from analysis, so that the optimal situation of simultanuous modulation enhancement and noise suppression in the inverted gain-lever mode was not observed. It should also be noted that in theory, although inverted gain-lever gives approximately the same level of enhancement in the signal/noise ratio (about 8dB experimentally, Fig. 4 15dB theoretically, Fig. 3), its operation at higher optical power in a higher Q cavity yields a lower relative intensity noise to start with, which gives it additional advantages from a systems point of view. These results will be discussed elsewhere.

Reference

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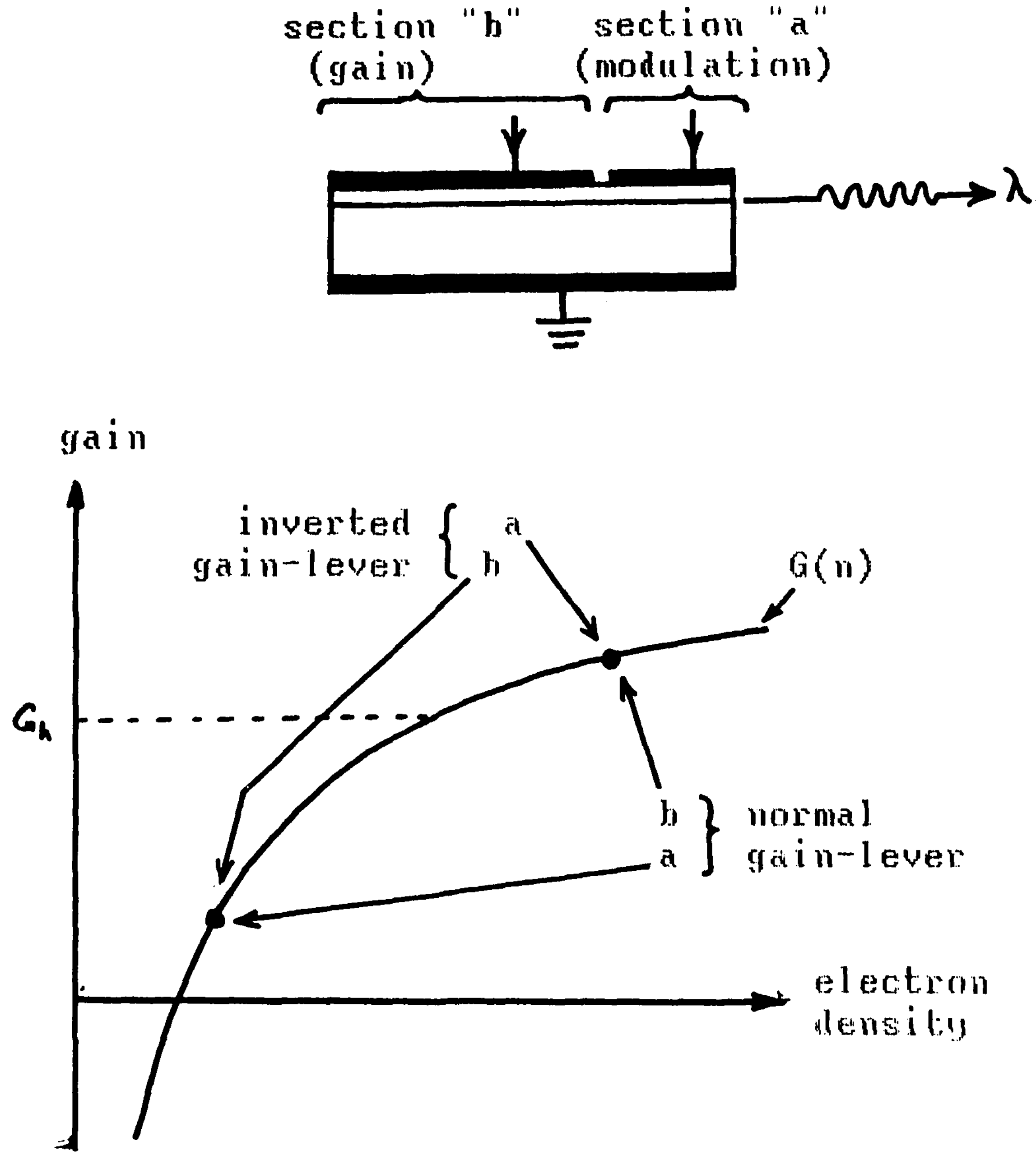
Figure Captions

Fig. 1 The gain-lever and the "inverted" gain-lever operation of a 2-section quantum well laser. G_{th} is the threshold gain.

Fig. 2 IM-FM correlation characteristics of modulation and noise in a uniformly pumped, 2-section gain-lever and inverted gain-lever lasers.

Fig. 3 (a) Theoretical IM efficiency and noise enhancement in normal gain-lever laser with interferometic FM→IM conversion; (b) for an inverted gain-lever laser. Parameters used: For (a), output power/facet=1mW, τ_p=2.2ps, γ_b=2.5ns^{-1}, $\tau_{stim,b}$=2ns, G'_b/G'_a=10, α=-4, β=0.5, T_r=0.5. For (b), output power = 2mW/facet, α and T_r are the same as in (a), τ_p=6.3ps, γ_b=50.2ns^{-1}, τ_{stim}=20ps, G'_b/G'_a=0.1, β=5.

Fig. 4 (a) Observed RF spectrum of photodiode output for a uniformly pumped laser (trace labelled "A"), normal gain-lever laser with ("C") and without ("B") interferometric conversion at T'_r=1/(95GHz); (b) corresponding spectrum for an inverted gain-lever laser with T'_r=1/(95GHz). Resolution bandwidth of the displays: 1MHz.


section "b"
(gain)
section "a"
(modulation)
λ
gain
inverted
gain-lever
a
b
G(n)
G_h
b
a
normal
gain-lever
electron
density

Fiq. 1

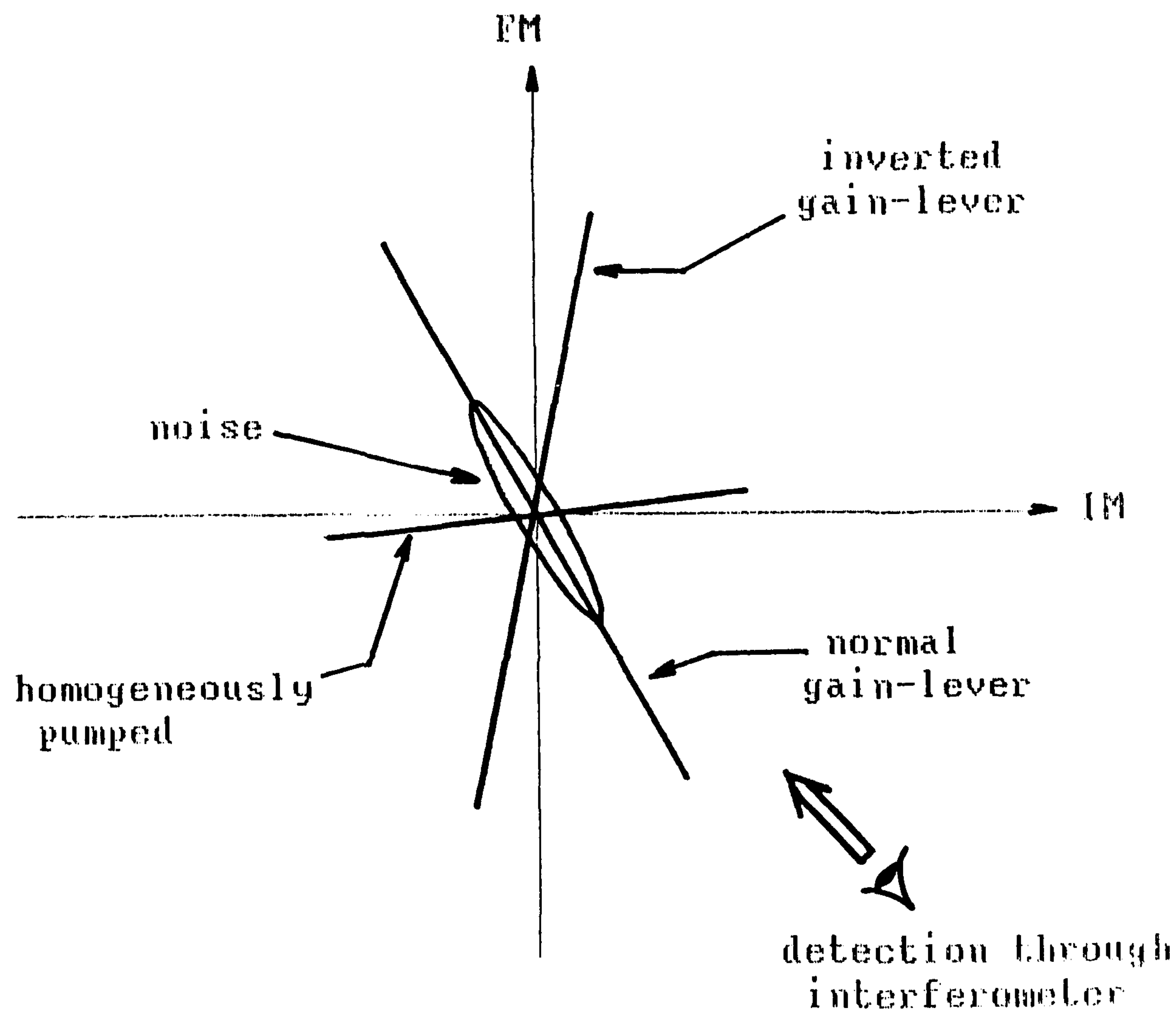

FM
IM
inverted
gain-lever
noise
homogeneously
pumped
normal
gain-lever
detection through
interferometer

Fig. 2

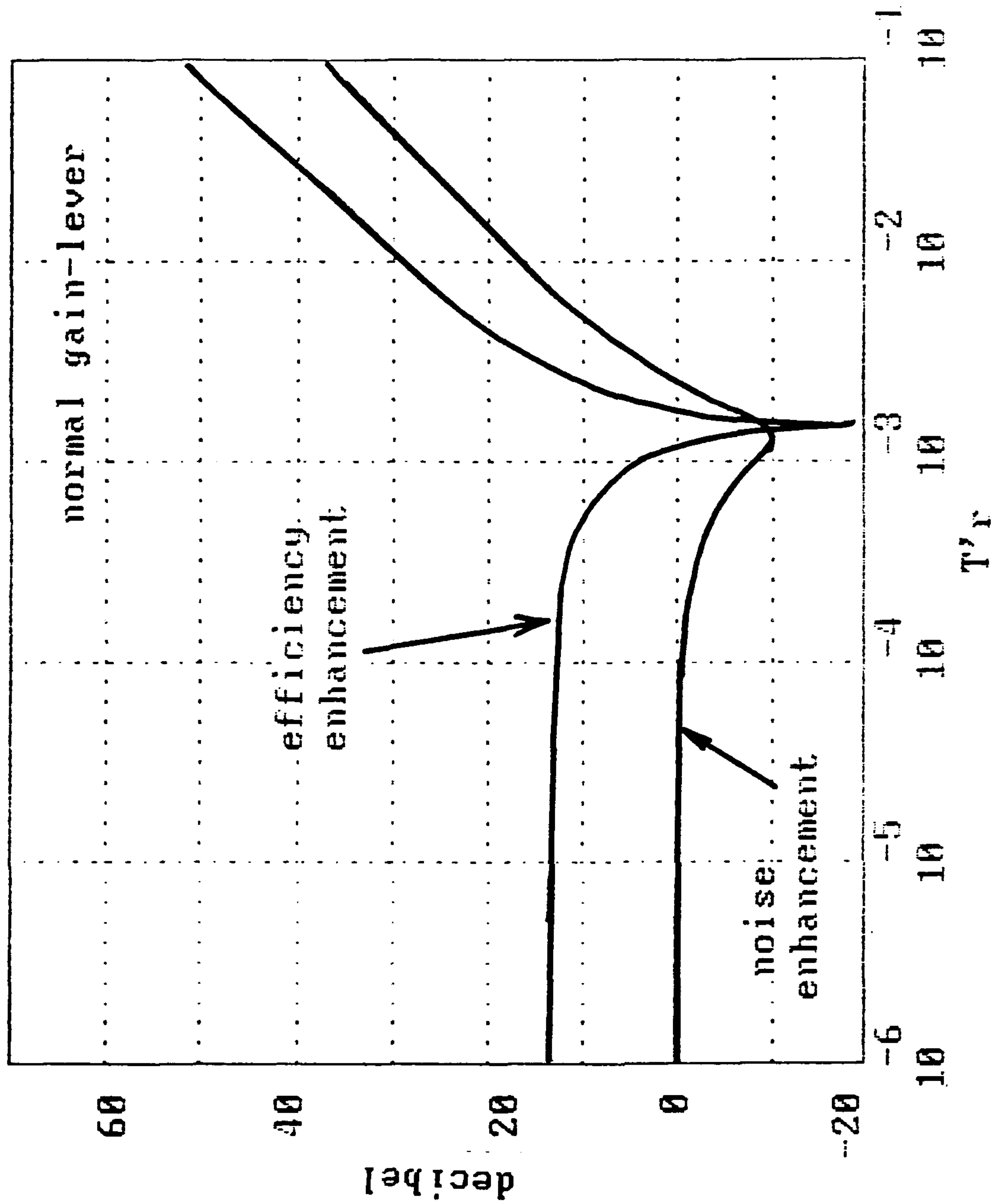
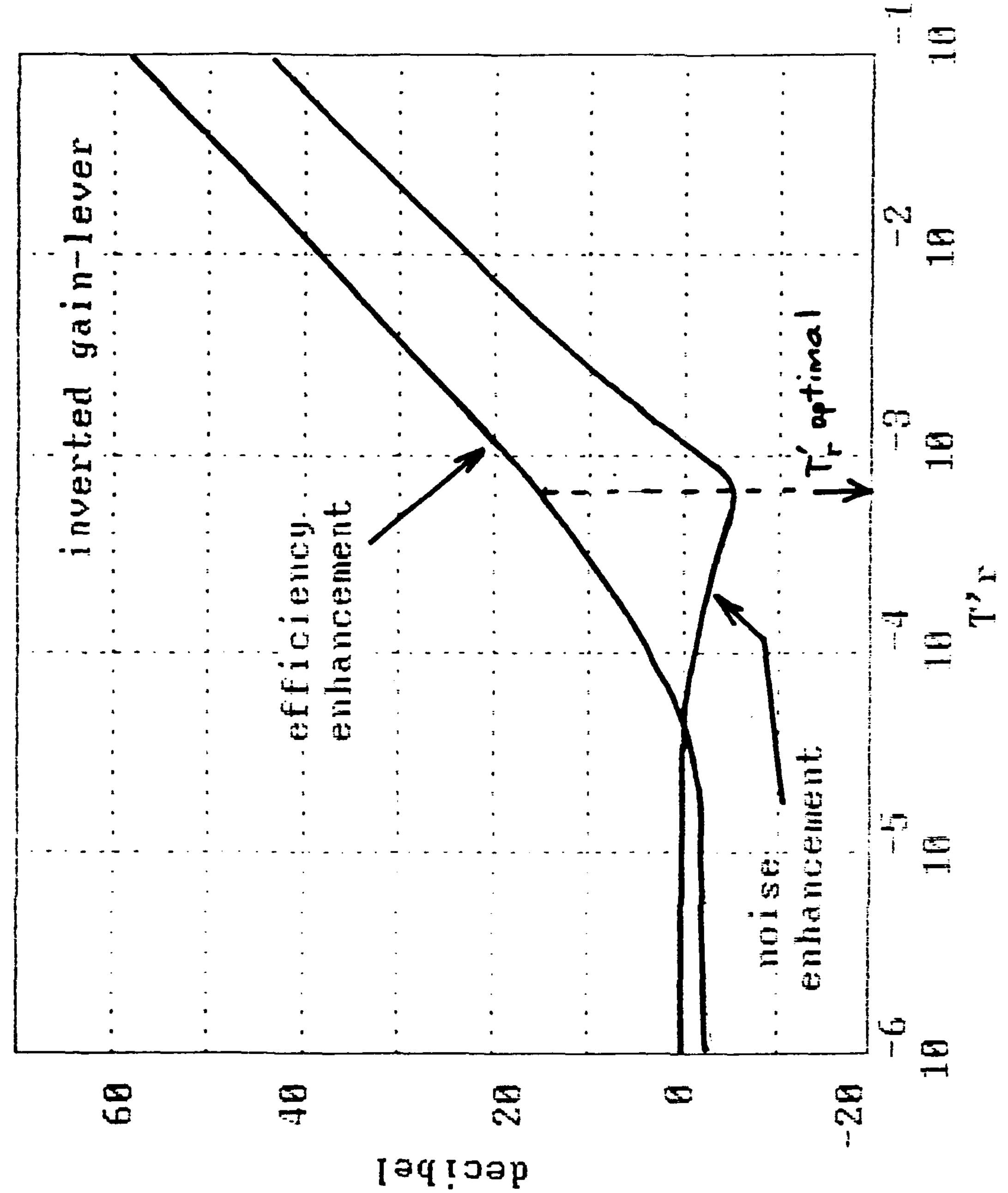

normal gain-lever
efficiency enhancement
noise enhancement
decibel
60
40
20
0
-20
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
T'r

Fig. 3a


inverted gain-lever
efficiency enhancement
noise enhancement
T'r optimal
T'r
decibel
60
40
20
0
-20
10^-6
10^-5
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10^-2
10^-1

Fig. 3b

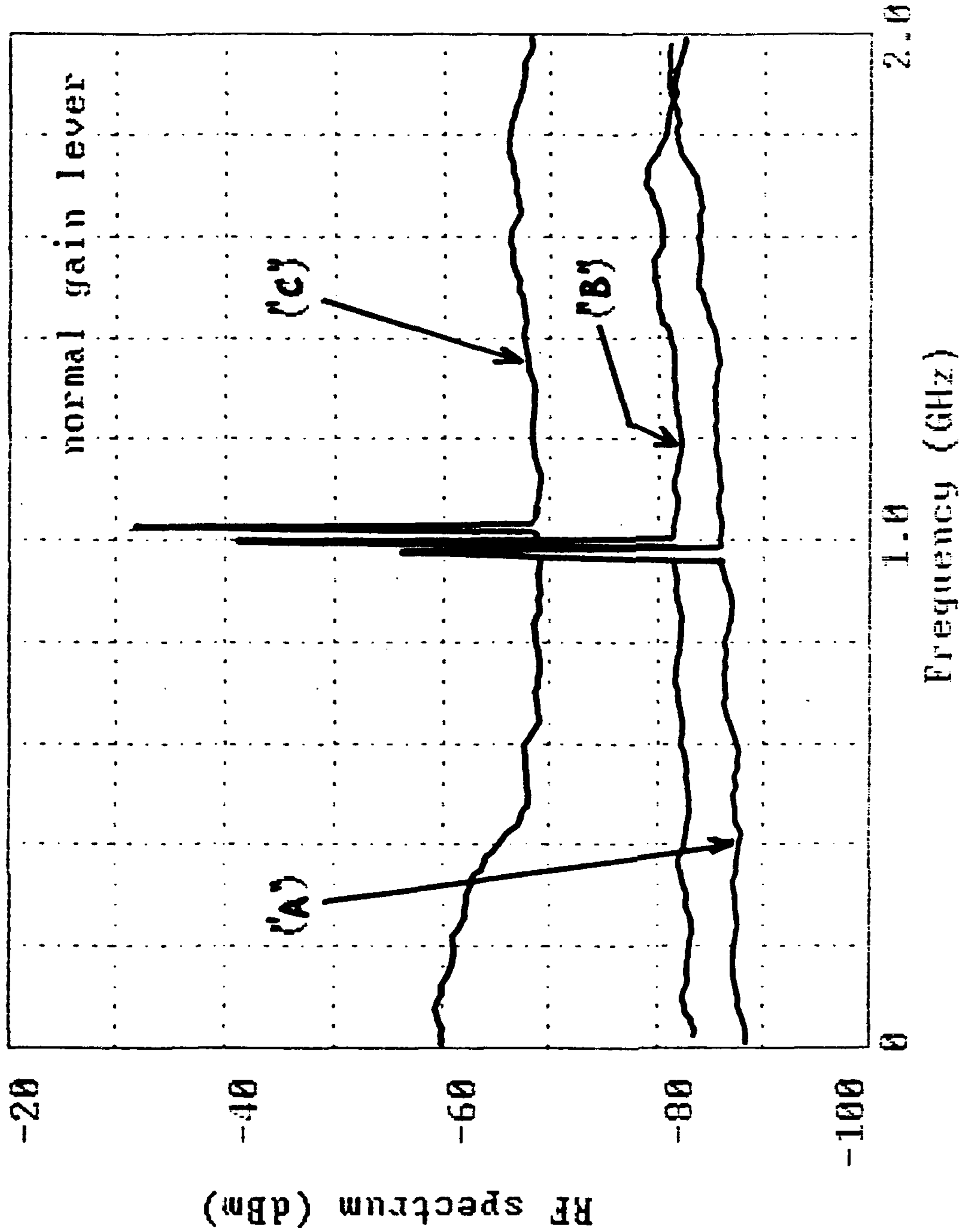
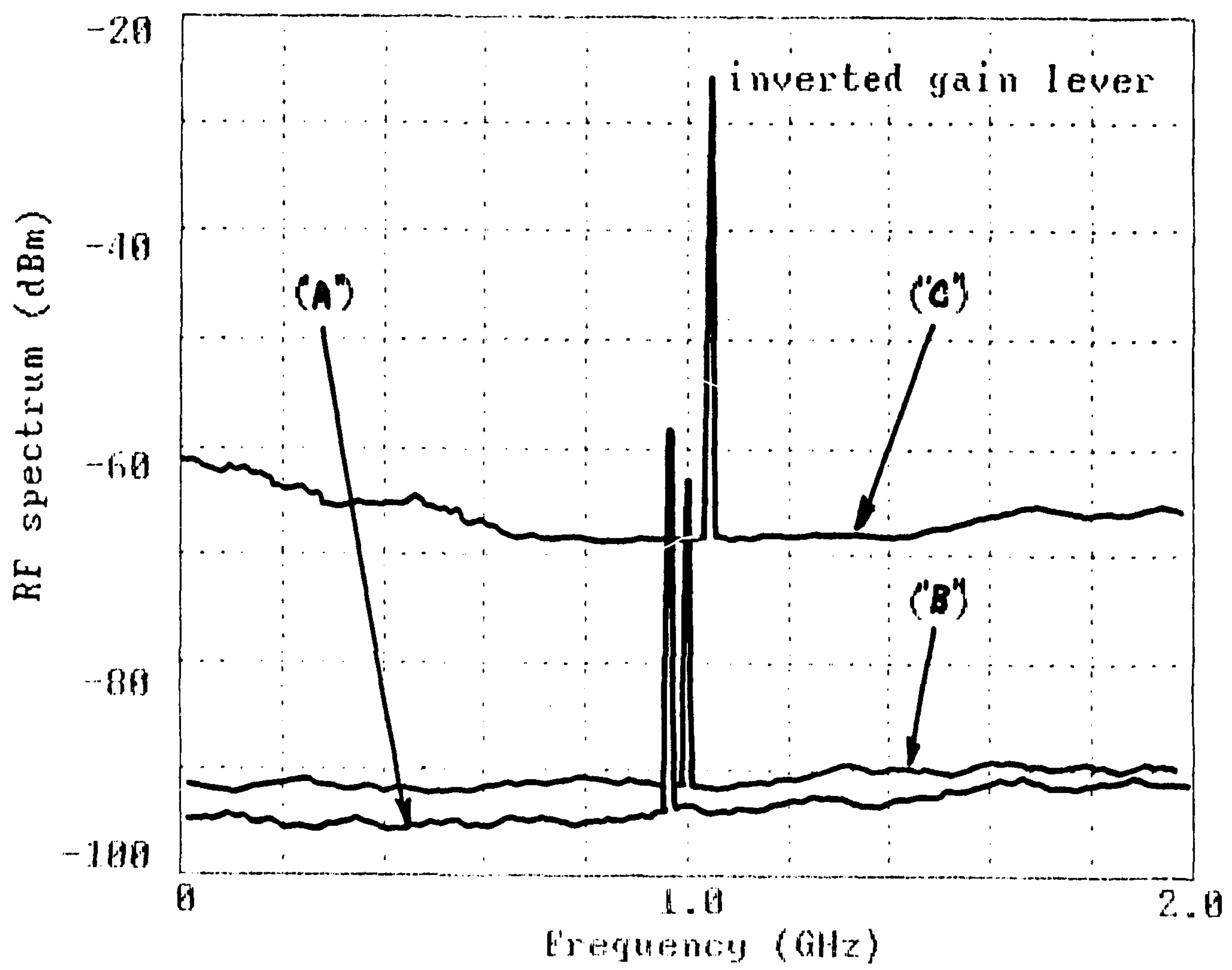

normal gain lever
("C")
("B")
("A")
RF spectrum (dBm)
-20
-40
-60
-80
-100
Frequency (GHz)
0
1.0
2.0

Fig. 4a



inverted gain lever
("A")
("B")
("C")
-20
-40
-60
-80
-100
RF spectrum (dBm)
0
1.0
2.0
Frequency (GHz)

Fig. 4b

7. Passive Microwave Fiber-optic Links with Gain and a Very Low Noise-Figure

Abstract

It is shown experimentally and theoretically that it is possible to construct a passive microwave fiber-optic link (defined as one without active electrical or optical amplification) exhibiting a RF throughput gain of up to 50dB and a noise figure approaching 0dB. The key ingredients are quantum well gain-lever laser transmitters and proper impedance matching. It is interesting to note that disregarding the optical transmission aspect of the link, it can be regarded as an RF low-noise pre-amplifier with performances competitive with conventional microwave amplifiers.

Developments in high speed semiconductor lasers, modulators and photodetectors operating in the tens of gigahertz range opened up possibilities of applying fiber-optic techniques to conventional microwave systems which require guided-wave transmission of microwave signals over macroscopic distances. Examples of these systems include phased-array radar, satellite station remoting, synchronization of antenna stations and very long baseline interferometry, to name a few[1]. However, such "microwave fiber-optic" systems face a number of major obstacles, the more serious ones include the high electrical (RF) throughput loss and a high noise figure (N.F.). The N.F., in particular, is a universal means of measuring the fidelity of any microwave component and represents an unrecoverable degradation in the signal quality upon passage through the device. The poor throughput arises from the unavoidable inefficiencies in optoelectronic devices and in optical coupling between components. To appreciate the magnitude of this loss one takes champion numbers[2] for laser and photodiode differential quantum efficiencies (DQE) (40% and 95% respectively) and an optical coupling coefficient of 90% (laser $\rightarrow$ fiber $\rightarrow$ photodiode), which results in an electrical throughput (RF) loss of 9.2dB. If one takes more typical numbers for state-of-the-art devices - laser and photodiode DQE's of 25% and 80% and fiber-coupling loss of 50%, then the RF loss increases to 20dB - a substantial penalty by microwave standard.

The (N.F.) is determined by the noise in the optical channel and the modulation efficiency of the transmitter. To see this, one starts with the defination of N.F. - the S/N ratio at the output of the device relative to that at the input, the "device" here being a laser transmitter and a photodiode receiver connected by an optical fiber. Let the RF input into the transmitter corresponds to a RF current (RMS) of i_{in}. The electrical noise at the input is basically thermal noise, $i_{thermal}$. The input S/N is thus $i_{in}^2/i_{thermal}^2$. Let the transmitter's modulation efficiency be ηW/A. The transmitter converts the RF input current into an optical modulation of amplitude $P_S = \eta i_{in}$, plus contributing its own noise which is typically expressed in terms of the Relative Intensity Noise (RIN) of the optical source: $P_N^2 = RIN \times P_0^2$ where P_0 is the average optical power. The detector converts the optical modulation and noise back into electrical current with a certain efficiency, and contributes thermal noise. Assuming that the received optical power is plentiful (>0.5mW for a 50Ω receiver, less for high impedance receiver) thermal noise can be neglected so that the output S/N is P_N^2/P_S^2 . The N.F. is thus:

$$\mathrm{N.F.} = \frac{i_{thermal}^2/i_{in}^2}{P_N^2/P_S^2} = \frac{RIN.P_0^2}{i_{thermal}^2\eta^2} \qquad (1)$$

But $(P_0/\eta)^2 = 2i_{(full\ mod)}^2$ where $i_{(full\ mod)}$ is the RMS current input into the transmitter for 100% intensity modulation. Hence

$$\mathrm{N.F.} = 2.\mathrm{RIN}(i_{(full mod)}/i_{thermal})^2 \qquad (2)$$

For a conventional laser diode transmitter operating in a Z_0 = 50Ω system at an average optical power of P_0 = 3mW, RIN=-150dB/Hz, η = 0.5mW/mA, $i_{thermal}^2 Z_0$ = -174dBm, resulting in a N.F. of 26.5dB. This is an unattractive figure by most microwave component standard.

The above discussions assumed a directly modulated laser diode in the transmitter. It is instructive to consider using a high power diode-pumped YAG laser with a Mach-Zehnder type external modulator, an alternative being considered seriously. Assume again state-of-the-art devices with an optical power of 50mW at the output of the modulator (coupling loss included, and a modulator with a half-wave extinction voltage of 3V. Furthermore, the RIN of the laser is at the shot noise level. Then it can be shown that the RF throughput loss is about 5dB and the N.F. is 15dB. These numbers are better than the directly modulated laser diode but are still somewhat unattractive by microwave standard.

It is clear from Eq.(2) that the only means to improve the N.F. is by enhancing the modulation efficiency and reducing the RIN of the laser transmitter. These appear to be very difficult tasks since the numbers quoted above are approaching the limit of performance for conventional devices. Two recent developments made substantial improvements possible: (1) proper impedance matching of the laser diode transmitter[2] and (2) discovery of the quantum well "gain-lever" effect[3,4] for quantum well laser diodes.

First, consider the latter. The gain-lever effect ultilizes the quantum well gain characteristic and gain clamping in a laser to control a large flow of electrons and photons by a small variation in the current injected into one section of the laser[3,4]. The result is a very large intensity and frequency modulation (IM and FM) efficiency enhancement, by the order of 20dB and 40dB respectively, over a conventional laser diode, all achieved without a simultaneous increase in the IM and FM noise (RIN and linewidth). Furthermore, it was recently shown that by interferometrically converting FM into IM of an "inverted" gain-lever laser, the effective modulation efficiency can be further enhanced while simultaneously reducing the RIN[5,6]. This transmitter configuration is hereafter refered at as the "gain-lever transmitter". Figure 1 shows a plot of the calculated RIN and modulation efficiency (the latter expressed as the current input to the laser needed to drive the optical output from the interferometer to 100% IM) of the gain-lever transmitter, derived from [6]. The quantities are plotted as a function of T'_r, the derivative of the interferometer transmission with respect to optical frequency. The values at $T'_r \to 0$ is approximately that of a conventional laser transmitter. The enhancement in modulation efficiency is easily understood as a straightfoward translation of FM to IM by the interferometer. The origin of the dip in the RIN is more subtle and arises from the strong correlation in IM and FM noise in a laser diode[7]. Simultaneous enhancement in signal and suppression of noise can take place due to the opposite sign between the IM/FM noise and modulation correlation functions. These topics have been investigated in detail elsewhere[6].

Using Fig. 1, the N.F. of the gain-lever laser transmitter is shown in Fig. 2(a). To obtain the lowest N.F., one chooses the optimal T'_r, resulting in N.F.=3dB, a 23.5dB improvement over a conventional laser diode transmitter, and superior to that of the external modulator system. On the other hand, if a very high RF throughput is desired, then one should choose a large T'_r. Figure 2(b) shows the RF throughput, computed using Fig. 1, of a link using a gain-lever transmitter and assuming an optical loss of 50% and a photodiode efficiency of 80%. One notices that this "passive" link, which does not contain any conventional electrical or optical active amplification, actually exhibits RF gain at large T'_r. The N.F. at large T'_r approaches 9dB (Fig. 2(a)), not quite as low as the optimum but is still 17.5dB lower than that of the conventional laser transmitter.

Experimentally, a single mode (17dB side-mode rejection) single quantum well laser was used in the "inverted" gain-lever mode as described in [5,6], with an average output power of 3mW/facet. The modulation section of the laser is driven by a 50Ω RF signal generator at 1GHz. A low-Q Fabry-Perot etalon was inserted between the laser and a high speed photodiode, whose output was displayed on a microwave spectrum analyser after amplified by 20dB using a low noise RF amplifier. The value of T'_r was about 1/95GHz, as determined by operating the laser cw and scanning the Fabry-Perot. Next, the RF input drive into the laser is varied and the effective IM modulation depth at the output of the Fabry-Perot is recorded. The result is shown in Fig. 3. The projected RF drive needed for 100% IM is -42dBm for a gain-lever transmitter. The corresponding number for been a conventional laser is approximately -0.5dBm. The measured RIN for the gain-lever transmitter was -124dB/Hz versus -145dB/Hz for a conventional laser. Thus from Eq. (2), the

N.F. was 10.1dB for the former and 31dB for the latter. Assume that the transmitters were used in a fiber-optic link with a 50% optical coupling loss and a 80% quantum efficiency photodiode. Then the RF output from the photodiode is shown on the right vertical axis of Fig. 2(b). For the gain-lever transmitter the throughput gain would be 25dB.

Further improvement in N.F. and throughput gain can be accomplished using impedance matching. It was recently demonstrated that applying simple impedance matching circuit to a conventional laser and photodiode can result in a net RF throughput gain Of 0.13dB[2]. The ideal throughput gain of a fiber link with optimal impedance matching is given by[2]:

$$G_{match} = G_0\left(\frac{Z_0}{R_l}\right)\left(\frac{R_p}{Z_0}\right) \tag{3}$$

where G_0 is the RF throughput without impedance matching, R_l and R_p are the laser series resistance and photodiode parallel resistance in their respective equivalent circuits, and Z_0 is the system impedance (50Ω). The first factor in () on the right side of Eq. (3) represents the gain resulting from an ideal matching of the laser, while the second factor is due to matching of the photodiode. Typical numbers are R_p=1.5kΩ and R_l=4Ω so that an enhancement in RF throughput of 25dB is possible in principle. If this were applied to a gain-lever transmitter, then a net RF gain of 50dB would result (see Fig. 2(b)). On the other hand, the N.F. is affected only by matching on the transmitter side, which means that the N.F. can be improved by a factor of Z_0/R_l= 11dB through proper matching. This would reduce the N.F. of an inverted gain-lever laser to below 0dB at large values of T'_r , see Fig. 2(a). In practice, the N.F. never falls below 0dB because the thermal noise at the input of the laser modulates the laser output along with the input signal, a factor not included in the above analysis.

In conclusion, experimental and theoretical results using recently discovered gain-levered quantum well laser transmitters with interferometric FM $\rightarrow$ IM conversion, along with proper impedance matching of the laser and photodiode, suggest that a passive microwave fiber-optic link can achieve a RF throughput gain of up to 50dB and a noise figure approaching 0dB. It is interesting to note that disregarding the optical transmission aspect of the link, it can be regarded as an RF low-noise pre-amplifier with performances competitive with conventional microwave amplifiers.

Reference

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Figure Captions

Fig. 1 For the "gain-lever transmitter", an "inverted" gain-levered quantum well laser followed by an interferometric FM→IM convertor, plot of theoretical RIN and modulation current input needed to drive the optical output to 100% IM as a function of T'_r, transmission slope of the interferometer.

Fig. 2 (a) Noise Figure and (b) RF throughput of a link using a "gain-lever transmitter" and a photodiode receiver with DQE of 80%. The optical loss of the link is assumed to be 3dB (optical). The results of perfect impedance matching of the laser and photodiode are also shown.

Fig. 3 Experimental optical modulation depth as a function of input RF drive into the laser. Cases shown are (1) "gain-levered transmitter", (2) conventional laser diode transmitter, (3) projected response with impedance matching of the "gain-lever transmitter".

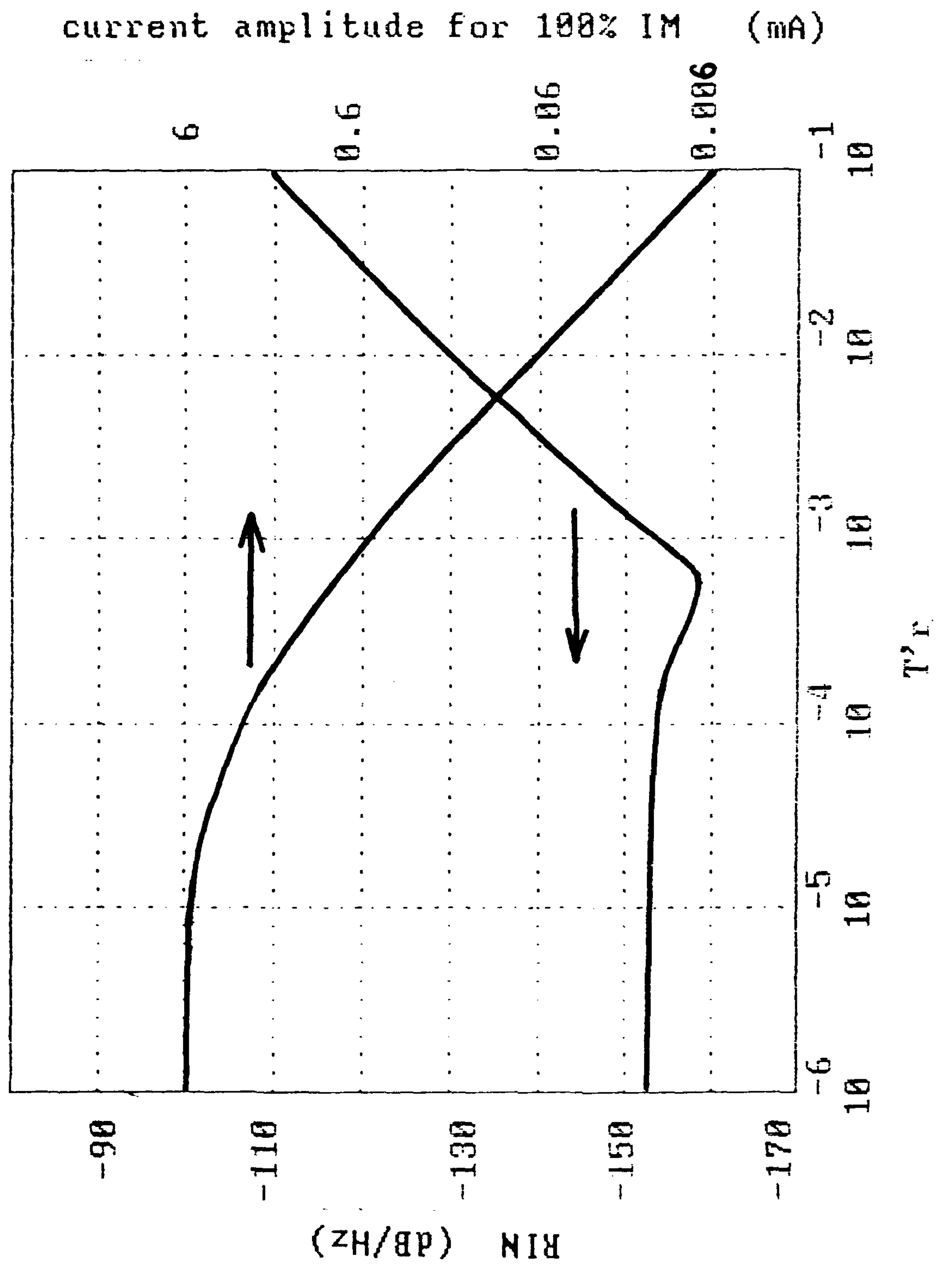
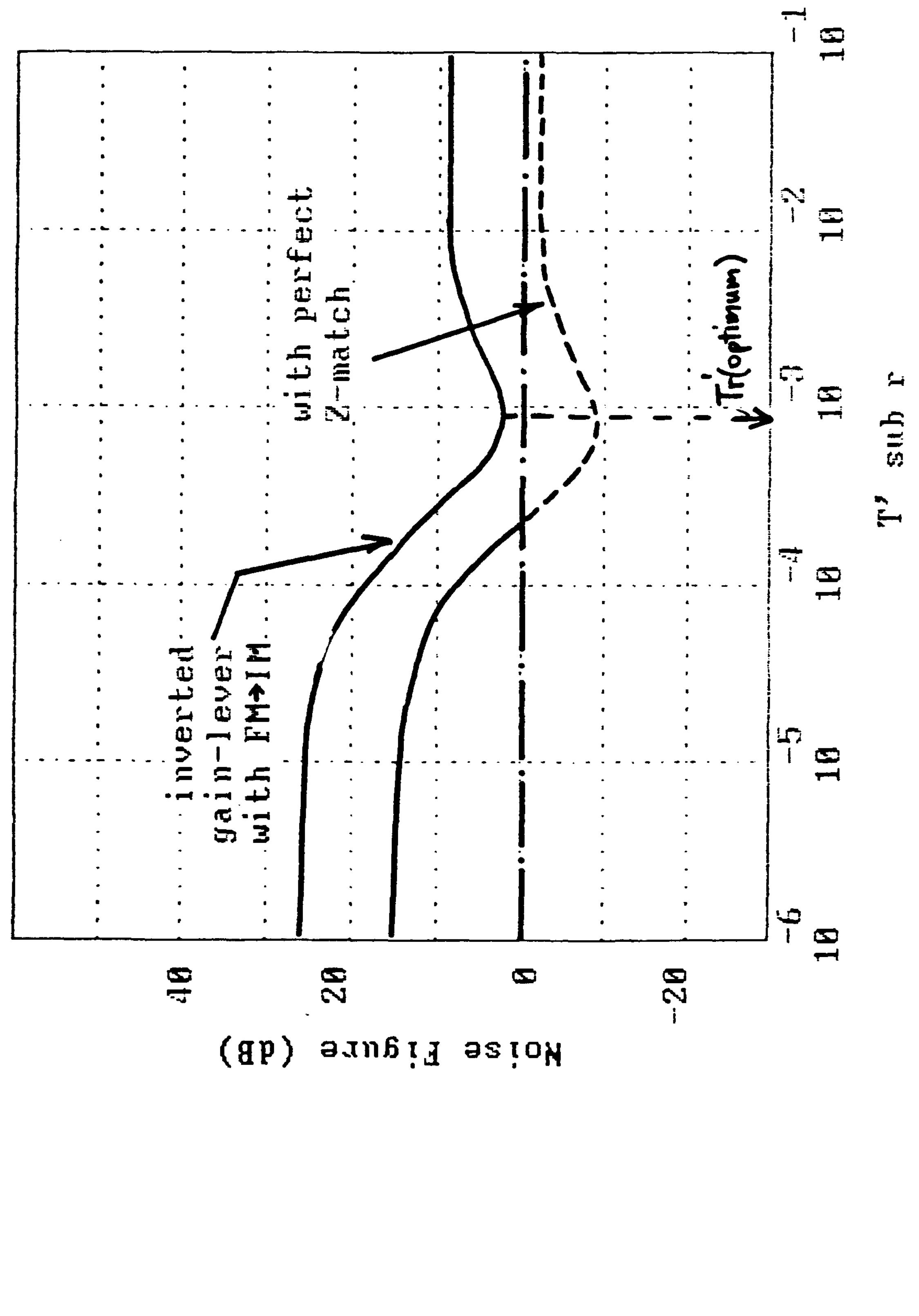
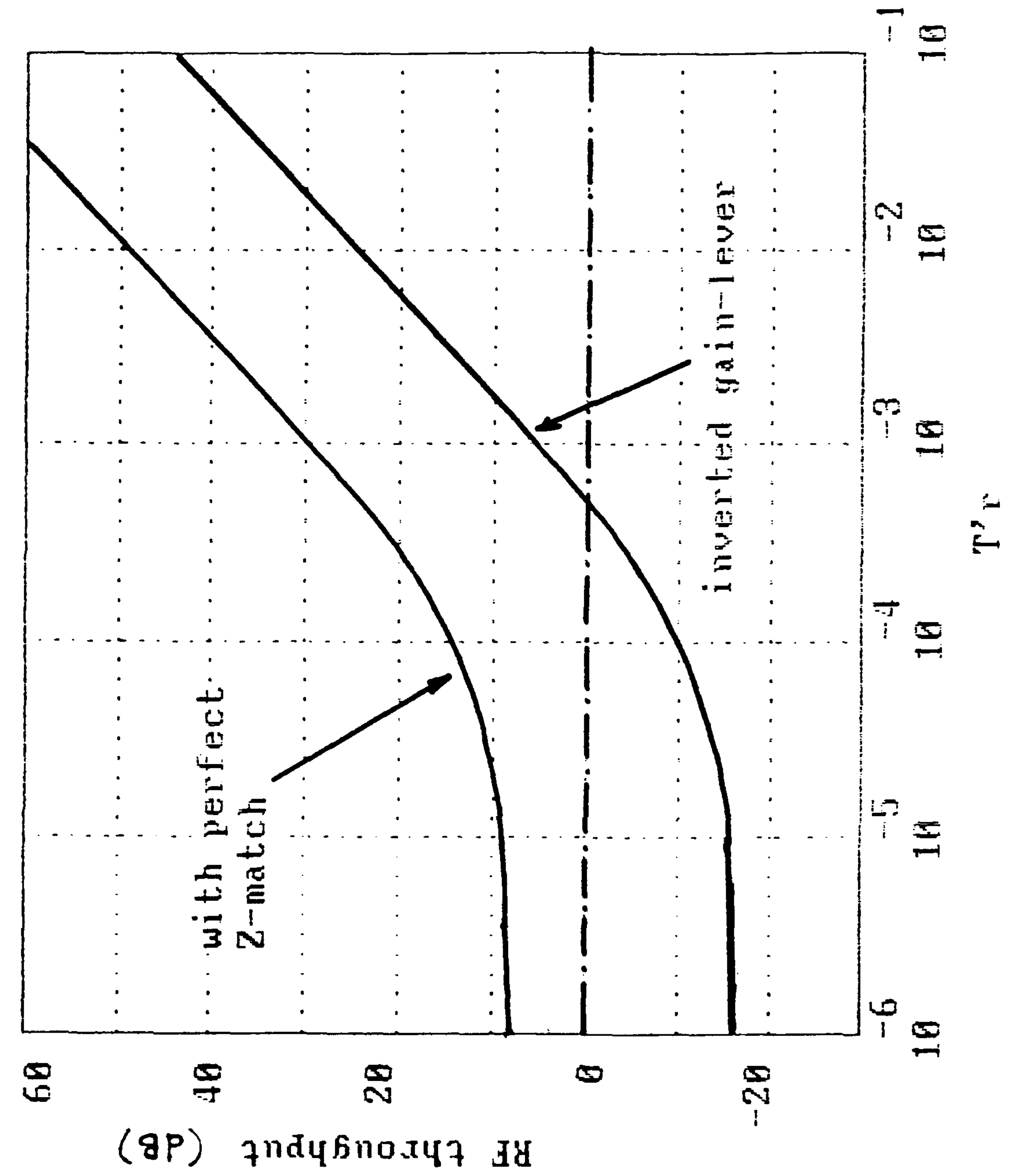

current amplitude for 100% IM (mA)
6
0.6
0.06
0.006
RIN (dB/Hz)
-90
-110
-130
-150
-170
T'r

Fig. 1



Noise Figure (dB)
40
20
0
-20
inverted
gain-lever
with FM→IM
with perfect
Z-match
Tr(optimum)
T' sub r

Fig. 2a



RF throughput (dB)
60
40
20
0
-20
with perfect
Z-match
inverted gain-lever
T'r

Fig. 2b

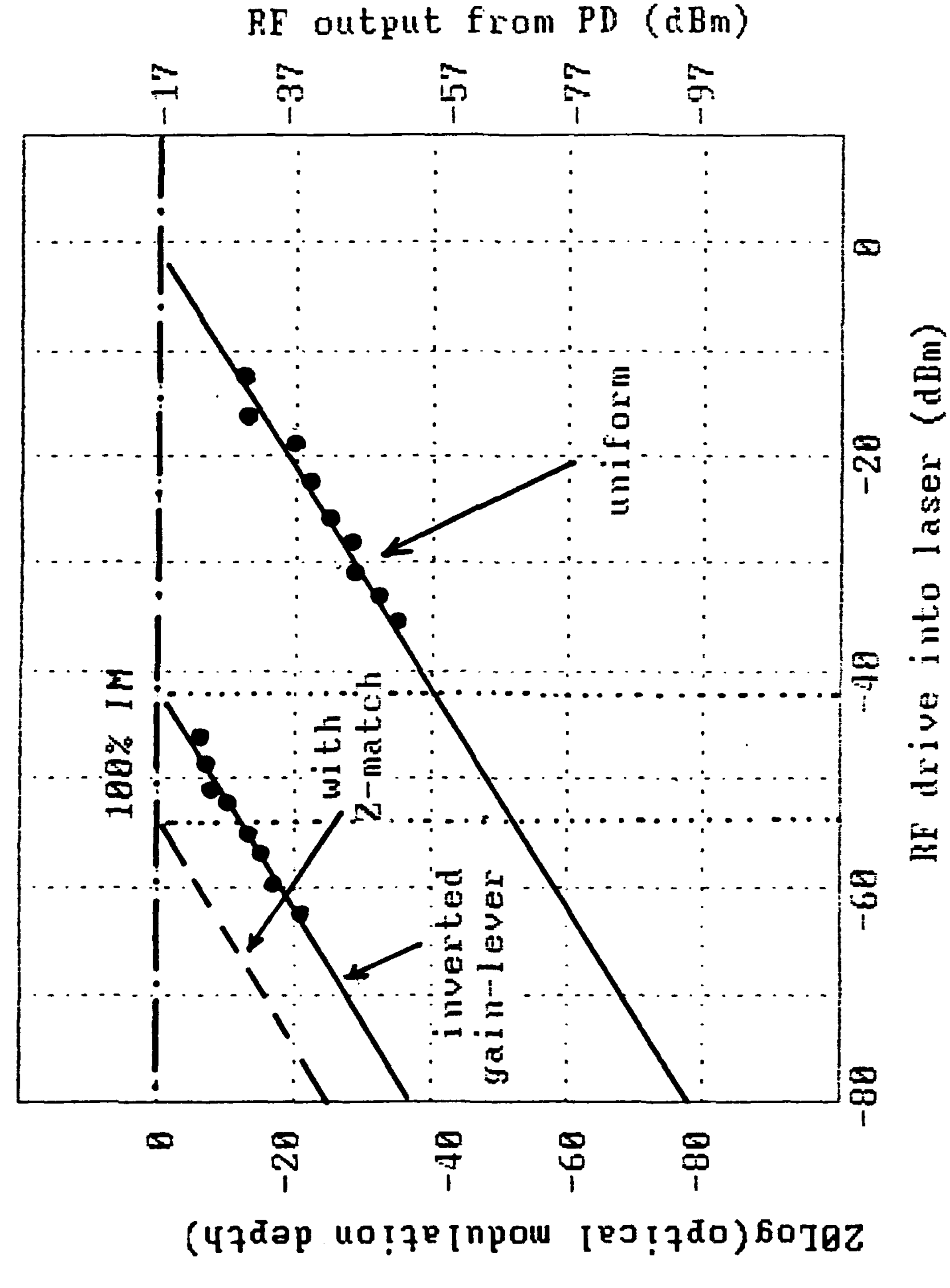

RF output from PD (dBm)
-17
-37
-57
-77
-97
RF drive into laser (dBm)
0
-20
-40
-60
-80
20Log(optical modulation depth)
0
-20
-40
-60
-80
100% IM
uniform
with
Z-match
inverted
gain-lever

Fig. 3

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