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VARIATION OF MODULATION RESPONSE WITH GAIN COMPRESSION OF SPONTANEOUS AND STIMULATED EMISSION IN 1.55µM DFB LASER

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Abstract— **We have observed and quantified the gain compression effects on the modulation response of directly modulated DFB laser. The gain compression severely degrades the modulation response and is the limiting factor for achieving maximum modulation bandwidth. In this paper, the variation of modulation response with gain compression of spontaneous emission and stimulated emission is investigated by simulation. We have identified that damping from both stimulated and spontaneous emission contributes to the overall damping and the gain compression enhances both. It is shown that by modulating the spontaneous emission coupling ratio in a small cavity volume, the spontaneous emission rate increases via stimulated emission rate. The former enhances the modulation bandwidth. Finally, it is shown that higher maximum gain is the key point for reducing the effects of gain compression.**

Keywords — Distributed Feedback Laser, Gain Compression Coefficient, Modulation Bandwidth, Resonance frequency, Damping, Spontaneous emission factor.

I. INTRODUCTION

High speed directly modulated semiconductor lasers have gained importance due to increasing demand for high transmission data rates [1]-[3]. We study small signal modulation response of a single mode, single frequency 1.55µm DFB laser. Small signal analysis allows analyzing a number of device parameters, such as spontaneous emission lifetime, photon lifetime, gain compression etc. Small signal response is also useful in estimating the device performance and the fundamental characteristics of the directly modulated laser. The aim of this study is to investigate the variation of modulation response with gain compression of spontaneous emission and stimulated emission of 1.55µm DFB laser. The gain compression is very important in describing the modulation response of a diode laser and is the dominant effect that introduces the damping in the modulation response [4]-[5], which physically comes from the redistribution of carriers. Measurements of damping in the modulation response of lasers have been modeled by assuming that gain is reduced at high photon densities by a factor of $1/(1+\varepsilon S_0)^p$ where p varies from 0 to 1. However p = 1 is best suited [6]. This analysis is restricted to single frequency lasers, which can be described by single mode rate equations.

II. LASER MODEL

The modulation dynamics of the laser are modeled by coupled rate equations, which describe the relation between the photon and the electron density as [7].

$$\frac{dN}{dt} = \frac{I}{qV_{act}} - \frac{N}{\tau_n} - v_g g_0 \frac{N - N_t}{1+\varepsilon S} S \qquad (1)$$

$$\frac{dS}{dt} = \left\{ \Gamma v_g g_0 \frac{N - N_t}{1+\varepsilon S} - \frac{1}{\tau_p} \right\} S + \frac{\Gamma \beta N}{\tau_n} \qquad (2)$$

where N and S are the instantaneous electron and photon concentrations respectively, I is the current injected into the active layer, q is the electron charge, β *is* the fraction of spontaneous emission coupled into the lasing mode, g_0 is the differential gain coefficient (cm^2), N_t is the electron density (cm^{-3}) at which net gain is zero, Γ is the optical confinement factor given by the ratio of the active region volume to the modal volume, and τ_p is the photon lifetime(s), τ_n is the electron lifetime (s), ε is the gain compression coefficient, V_{act} is the volume of the active layer (cm^3). The parameter ε (with units of volume) specifies the gain compression characteristics of the active region.

Simulation Model

A block diagram of the digital light wave system is shown in Fig. 1 and is based on the laser rate equation component for simulating the modulation dynamics of the single mode DFB laser. The signal generator is used to produce the bit sequence at a modulation rate of 5 Gbit/s. The modulation technique used is NRZ format. The laser simulation parameters used in the experiment are shown in Table 1 [7].

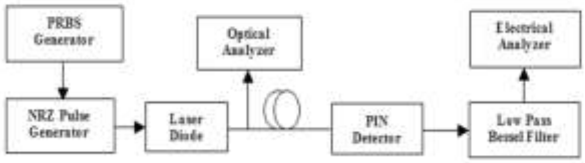

Fig. 1. Simulation setup for the single mode laser.

III. SMALL SIGNAL ANALYSIS: INTENSITY MODULATION

A block diagram of the digital light wave system is shown in Fig. 1 and is based on the laser rate equation component for

Table 1. Parameter values for laser diode.

Symbol	Quantity	Values	Units
v_g	Group velocity	8.5e-9	cm^2/s
α	α-factor	5	
V_{act}	Active layer volume	20e-12	cm^3
η_0	Quantum efficiency	.2	
g_0	Differential gain coefficient	0.176e-15	cm^2
N_t	Carrier density at transparency	1e-18	cm^{-3}
Γ	Mode con inement factor	0.2	
τ_n	Carrier lifetime	1	ns
τ_p	Photon lifetime	1	ps
β	Spontaneous emission factor	0.0001	
ε	Gain compression factor	5e-18	cm^3
I_m	Peak Modulation current	28	mA
I_{th}	Threshold current	18	mA

simulating the modulation dynamics of the single mode DFB laser. The signal generator is used to produce the bit sequence at a modulation rate of 5 Gbit/s. The modulation technique used is NRZ format. The laser simulation parameters used in the experiment are shown in Table 1[7]

$$H(\omega) = \frac{\omega_R^{\;2}}{\omega_R^{\;2} - \omega^2 + j\omega\gamma} \quad (3)$$

where

$$\omega_R^{\;2} = \frac{g_0 S_0}{\tau_p (1 + \varepsilon S_0)} \quad (4)$$

and

$$\gamma = \frac{1}{\tau_p}\frac{\varepsilon S_0}{1 + \varepsilon S_0} + \frac{\beta \Gamma I_{th}}{q V_{act}} \quad (5)$$

These two parameters, the electron photon resonance frequency (ω_R) and the damping factor (γ) describe the modulation response of the laser at a particular current bias. Fig. 2 shows the modelled IM response for bias currents above threshold. The response curves show typical resonant behaviour described by the equation (3). The laser will have a flat response at low modulation frequencies, because charge carriers follow the bias current giving rise to a peak near ω_R, within the peak region the carriers interact with photons leading to laser resonance and then roll-off at high frequencies, as the phase of the photon lags behind the injection current.

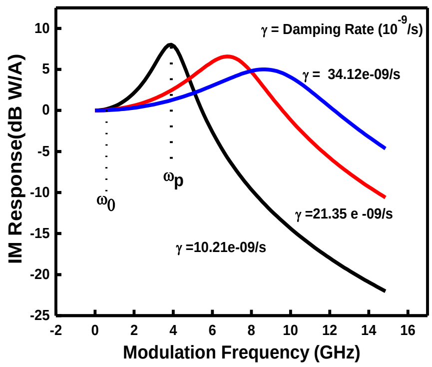

Fig. 2. Simulated modulation response of 1.55μm DFB laser for direct current modulationabove threshold.

Modulation response below and above threshold

The Fig. 3(a) shows that the relaxation oscillation peak (resonant frequency) moves to a higher frequency as the bias level is swept from below to above threshold. A significant feature of the laser is that at high bias current the peak modulation response decreases. This decrease is attributed to the enhancement of damping mechanism, which is governed by gain compression effects. Damping of the resonance is controlled by the coefficient of the jω in the denominator of equation (3). If the damping coefficient is small, the height of the peak resonance is large. If the damping coefficient is large, the height of the peak is reduced.

At low bias (I_b < I_{th}), the spontaneous emission is large, subjected to gain compression effects [8], and the response is reduced by gain compression of spontaneous emission. For bias current above threshold, the peak height decreases due to damping of the stimulated emission. In Fig. 3(b), measured peak IM response is plotted against the bias current both below and above threshold. As seen in Fig. 3(b), the measured peak IM response increases with bias current below threshold (This trend is opposite to that of laser biased well above threshold). This is due to the fact that damping of spontaneous emission decreases with bias current and is plotted in Fig 3(c). The Fig.

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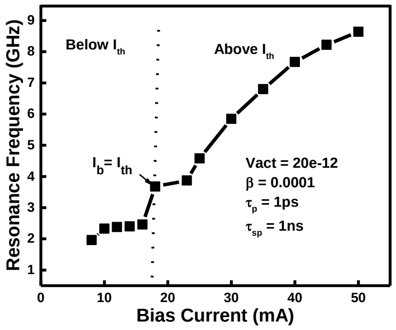
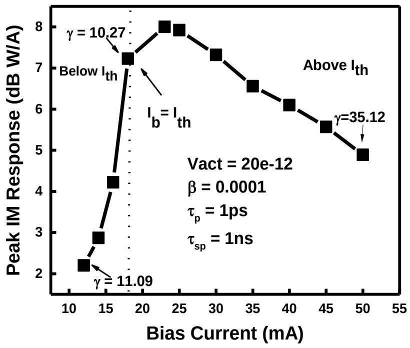
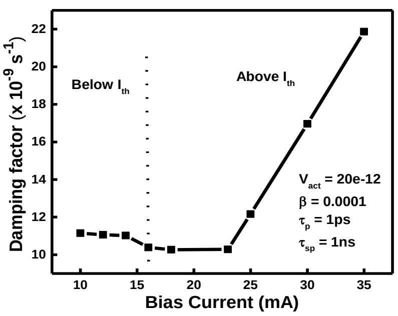
3(c) shows that at each bias the modulation response is damped, above threshold damping rate increases at much faster rate due to strong gain compression effects. Thus gain compression limits the modulation bandwidth both below and above threshold.



(a)



(b)

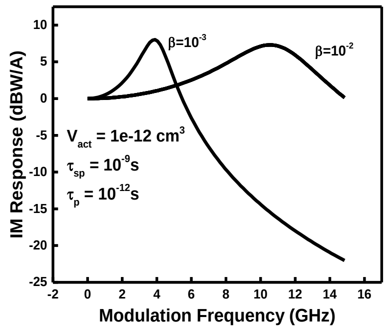


(c)

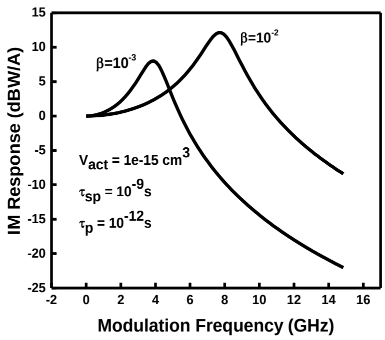
Fig. 3. Effect of bias current on (a) resonance frequency (b) peak IM response (c) damping rate, above and below threshold.

IV. MODULATION RESPONSE AND SPONTANEOUS EMISSION COEFFICIENT BELOW THRESHOLD

Below threshold, the stimulated emission can be neglected and the dynamics are governed by the spontaneous emission rate and photon lifetime [9]. In our investigation the intensity modulation is modulated by changing the estimated value of spontaneous emission coefficient (β) instead of bias current. Therefore, the distribution of the spontaneous emission inside the cavity is modulated by varying spontaneous emission coefficient (β) in a small cavity active layer volume. The modeled IM response against the modulation frequency at Vact = 1e-12 cm^3 and Vact = 1e-15 cm^3 is plotted in Fig. 4(a) and 4(b) respectively. As seen in Fig. 4, resonance frequency is high for high spontaneous emission factor (β) and the calculated bandwidth for β = 0.01 is 12.69 GHz and 22.47 GHz in case of figure 4(a) and 4(b) respectively. This is because the small active layer volume enhances the spontaneous emission rate and the cavity decay rate allowing high modulation response. Also, enhanced spontaneous emission increases stimulated emission rate, which in turn increases the maximum gain or gain coefficient (condition for large modulation speed).



(a)



(b)

Fig. 4. Simulated modulation response of 1.55μm DFB laser for β modulation at (a) V_{act} = 1e-12 (b) V_{act} = 1e-15.

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V. GAIN COMPRESSION AND MODULATION RESPONSE: ABOVE THRESHOLD

The effect of gain compression above threshold on the modulation response is characterized through the damping mechanism. The modeled modulation response against the modulation frequency at gain compression coefficient 1e-17 and 30e-17 is plotted in Fig. 5. As seen in Fig. 5, the magnitude of the resonance peak is reduced for high gain compression due to significant damping of the relaxation oscillations. The gain compression can be expressed in terms of a saturated power as $\varepsilon S=\varepsilon P= P/P_{sat}$ [10]. This implies that at this power level, nonlinear effects start to be significant. The maximum resonance frequency can be deduced from the curve fitting as ω_R = $(AP_{sat}$ or $A/\varepsilon)^{1/2}$ and is expected to be 4.59 GHz. The effective gain compression coefficient is related to the gain of the stimulated emission as [11]

$$\varepsilon_{eff} = \varepsilon_S \frac{g_{\max}}{g_{\max} - g_{th}} \tag{6}$$

Equation (6) indicates that the gain compression is enhanced due to gain saturation by a factor g_{max}/g_{max}-g_{th}. Therefore, by properly choosing the ratio g_{max}/g_{th} (lower g_{th} and higher g_{max}, smaller the gain compression effect). Both g_{th} and g_{max} should be considered to design a laser with high differential gain and limited gain compression effects. In Fig. 6, the normalised gain compression is plotted as a function of g_{max}/g_{th}. As seen, higher the gain ratio, lower the effects of gain compression. If the $g_{max} \sim g_{th}$, the gain compression effects can be large and if sufficient gain is not provided, the gain compression effects are strengthened causing degradation to the laser bandwidth.

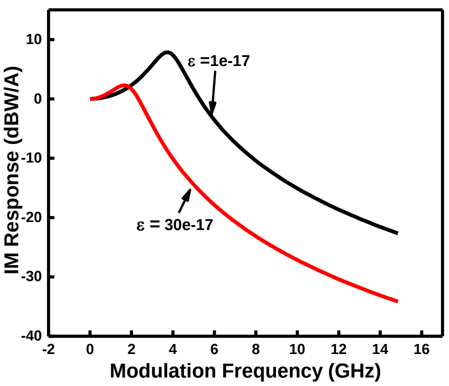

Fig. 5. Effect of gain compression on the IM response.

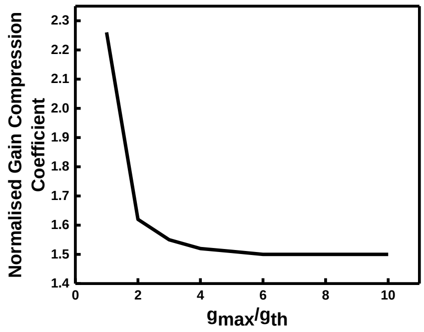

Fig. 6. Calculated normalized gain compression against the gain ratio.

VI. DESIGN CONSIDERATION: ACTIVE LAYER VOLUME

For high modulation rate, the spontaneous emission rate and the cavity decay rate into the lasing mode should be high. This can be accomplished by utilising the small active layer volume. By confining the gain in a small cavity, the spontaneous emission rate exceeds the stimulated emission rate, allows high modulation speed. Thus lasers with small cavity design increase the modulation bandwidth. In Fig. 7, the laser frequency bandwidth and damping rate are plotted against the active layer volume. As seen in Fig. 7, resonance frequency begins to increase for Vact < 2x10-14, the simultaneously increasing damping factor (governed by gain compression) suppresses the resonance frequency. Thus resonance frequency and damping are simultaneously enhanced by small cavity volume limiting the modulation bandwidth.

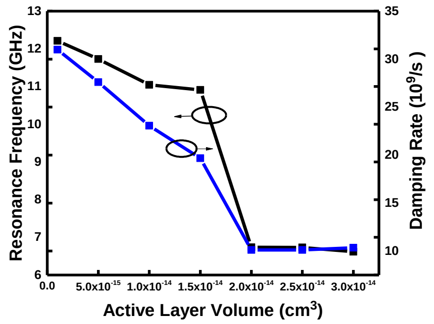

Fig. 7. Measured resonant frequency and damping rate against the active layer volume.

VII. CONCLUSION

The gain compression effect on the modulation response of 1.55µm DFB laser is investigated by simulation. We have observed that damping from both stimulated and spontaneous emission contributes to the overall damping and the gain compression enhances both. It is given that by modulating the distribution of spontaneous emission inside the small cavity, by varying spontaneous emission coefficient (*β),* the modulation bandwidth can be increased. The results showed that the resonance frequency begins to increase for small active layer volume. This is limited by the gain compression through the damping mechanism. Finally the maximum gain is the key point for reducing the effects of gain compression

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