

Influence of Optical Feedback on Frequency Response of GaAs / AlGaAs Quantum Cascade Laser

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$(9 \mu\text{m})$ GaAs/Al_{0.45}Ga_{0.55}As

Abstract

A theoretical analysis of the optical feedback from external reflector influence on the Frequency response of GaAs/Al_{0.45}Ga_{0.55}As triple quantum well Quantum Cascade Laser emitting at ($\lambda=9 \mu\text{m}$) is presented. The employed theoretical model was based on Schrodinger equation. To demonstrate the effects of external cavity, many of the external cavity parameters were controlled such as the length of the external cavity, the proportion of optical feedback and the relative phase difference.

1- Introduction

Optical feedback is introduced into a diode laser by returning some portion of the optical output back into the device. The introduction of such feedback has been found to have dramatic and varied effects on the



operating characteristics of the solitary diode laser. Feedback can be disadvantageous, as it may cause unwanted instabilities in the laser output, or advantageous, as under certain conditions it can improve various features of the solitary laser, such as increasing the sidemode suppression ratio and narrowing the linewidth^[1]. As for the modulation characteristics of external cavity semiconductor laser (ECSL), many contributions, such as the modulation response of semiconductor laser with an external cavity^[2]. The influence of current modulation on the dynamics of semiconductor lasers with optical feedback is of interest for many applications. For example, high-frequency modulation of the injection current is often employed to reduce the relative intensity noise induced by optical feedback^[3,4]. It is well known that under current modulation, optical feedback, or optical injection, semiconductor lasers exhibit a rich variety of nonlinear behavior^[5]. The effects of optical feedback on the operating characteristics of a diode laser depend on several parameters. These include the level of the feedback in comparison to the diode laser output power, the relative phase of this feedback, the length of the external cavity, and the injection current of the solitary diode laser^[1,6]. It is found that there are five distinct regimes that are defined by the level of the feedback power ratio. In general, the boundaries between the regimes also depend on the internal parameters of the solitary diode laser, such as the linewidth enhancement factor, the diode dimensions, and the facet coatings^[1].

The quantum cascade laser (QCL) is an excellent example of how quantum engineering can be used to design new laser materials and related light sources. It is a unipolar semiconductor laser and based on intersubband transitions between excited states of coupled quantum wells and on resonant tunneling as the pumping mechanism^[7]. The population inversion between the states of the laser transition is achieved by engineering the electron intersubband scattering times. In contrast to all other laser sources, the wavelength is entirely determined by quantum confinement in coupled quantum wells rather than by the chemical properties of the material^[7,8]. Therefore, the wavelength can be tailored over a very wide spectral range using the same heterostructure material^[8]. As a result, the emitted photon energy is determined by the thicknesses of the wells and barriers and can be tailored by band-gap engineering^[9]. Laser wavelengths ranging from 4 to 11 μm have been demonstrated in the two material systems GaAs/AlGaAs and InGaAs/InAlAs^[7,9]. This important spectral range has so far been accessible mainly with relatively unreliable and expensive lead salt based diode lasers. Applications include gas sensors for pollution monitoring and industrial process control for environmentally safe manufacturing because many hazardous and toxic chemicals have optical absorption fingerprints at these



wavelengths^[6]. There are also several transmittance windows of the atmosphere in this spectral range which allow for laser communication between earth and satellites as well as for distance measurements in avionic^[8]. In this article we will study the modulation response in GaAs/Al_{0.45}Ga_{0.55}As material quantum cascade laser with wavelength equal (9 μm), with optical feedback from external reflector, and taken into account the influence of many parameters such as external cavity length, strength of optical feedback and relative phase of this feedback.

2- Theory

Under lasing conditions, the diode cavity is filled with gain medium, which, to a large extent, compensates for the diode cavity loss. It, therefore, has substantially greater effective quality factor, and consequently, greater influence on the laser behaviors, than the passive external cavity. For this reason, the following form of field equation has been adopted for a compound cavity laser configuration, obtained by adding an external feedback term to a standard laser equation in complex form; that is,

$$\frac{d}{dt} E(t) e^{i\Omega t} = \left\{ i\omega_N(n) + \frac{1}{2} (G(n) - \Gamma_0) \right\} E(t) e^{i\Omega t} + k_A E(t - \tau) e^{i\Omega(t-\tau)} \dots\dots(1)$$

Here, $\omega_N(n)$ is the diode cavity longitudinal mode resonant frequency, which is defined with an integer n as

$$\omega_N = n\pi c / \eta l_D \dots\dots\dots(2)$$

c is the light velocity, η is the active region refractive index, l_D Diode cavity length, τ is the round trip time in the external cavity, Γ_0 is the cavity loss of the diode cavity, and Ω is the laser oscillation frequency. The last term on the right-hand side of equation (1) represents the external feedback Coefficient k_A is related to cavity parameters as

$$k_A = \alpha / 2\eta l_D \dots\dots\dots(3)$$

where parameter α , is defined with the facet and external mirror reflectivities R_2 and R_3 as

$$\alpha = (1 - R_2) (R_3 / R_2)^{1/2} \dots\dots\dots(4)$$

is a measure of the coupling strength between the two cavities. In the above expression for external feedback, multiple reflections in the external cavity have been neglected.

So the normalized photon density is given as:



$$P' = \frac{\beta N' / \tau_{sp}}{\frac{(1 - N')}{\tau_p} - \frac{2k_A}{\tau} - \cos(\omega\tau)} \dots\dots\dots(5)$$

Where

$$N' = N / N_{th} \dots\dots\dots(6)$$

$$P' = P / N_{th} \dots\dots\dots(7)$$

β is the spontaneous emission coefficient, τ_{sp} is the carrier lifetime according to spontaneous emission, τ_p is the photon lifetime, τ is the laser cavity roundtrip time, N is the number of carrier density, P is the photon density and N_{th} is the carrier density at threshold.

The frequency characteristics of semiconductor laser are very important under direct current modulation. Modulation characteristics will be obtained by using a noise-free single mode rate equation subjected to a small-signal injection current. The driving current is a sum of dc bias J_b and modulated components $J_m(t)$, as:

$$J = J_b + J_m(t) \dots\dots\dots(8)$$

$$J = J_b + \delta J \exp(i\omega t) \dots\dots\dots(9)$$

The effect of modulation current $J_m(t)$ introduces deviation in $\delta P(t)$ & $\delta N(t)$ which vary periodically at the modulation frequency ω . In the small-signal analysis $J_m(t)$ is assumed to be small enough so that the deviation from the steady state remains small at all times ($\delta P(t) \ll P$, $\delta N(t) \ll N$).

The small signal modulation transfer function (the ratio of photon density and modulated component of current) is given as follows:

$$H(\omega) = \frac{|\delta P|^2}{|\delta J|^2} = \left| \frac{D(0)}{D(\omega)} \right|^2 \dots\dots\dots(10)$$

Hence, the modulation transfer function is as follows

$$H(\omega) = \frac{\alpha_g}{(\omega_0^2 - \omega_m^2) + j\gamma\omega_m} \dots\dots\dots(11)$$

Where $\omega_0^2 = 2\alpha_g \bar{P} / \tau_p$ is the real root of the determinant, $\gamma = 2\alpha_g \bar{P}$ is the imaginary root of $D(\omega)$ which represent the damping rate, ω_m is the modulation angular frequency, α_g is the gain coefficient, \bar{P} is the optimum optical output power. The meaning and values of the other parameters are given in Table(1).



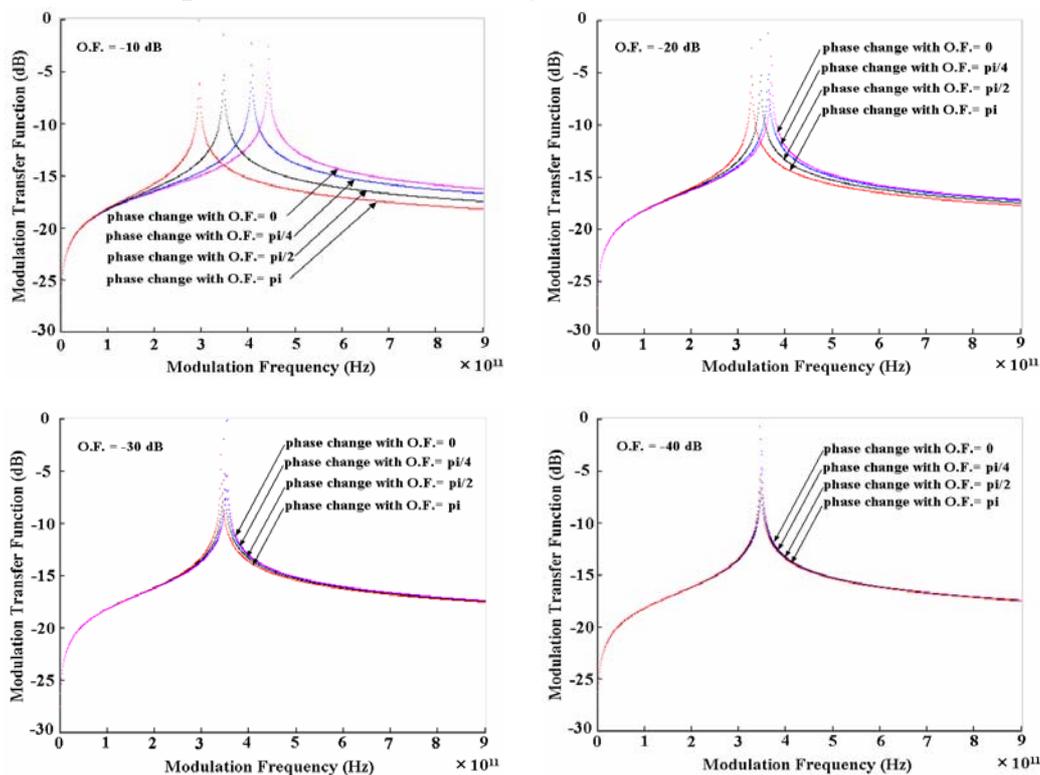
Table(1): Meaning and values of the different parameters appearing in the model.

Symbol	Meaning	Value
α_g	Gain coefficient , gain parameter	10^{-5} s^{-1}
L_1	Thickness of quantum well 1 (QW1)	4.8 nm
L_2	Thickness of quantum well 2 (OW2)	14 nm
L_3	Thickness of quantum well 3 (QW3)	8.7 nm
τ_w	Tunneling times between QWI/QW2 and QW2/QW3	0.5 ps
τ_t	carrier transit time through the structure	3.2 ps
τ_s	intersubband relaxation time	1.2 ps
τ_p	photon lifetime	1 ps

3- Results and Discussion

3-1 phase change

We studied the effect of phase change of the optical feedback for four values of optical feedback ratio (-10, -20, -30, -40)dB as shown in Figure (1). The first two values of optical feedback ratio (-10, -20)dB showed the peaks shifted clearly to the high modulation frequency with decrement of phase change. But, at optical ratio become moderate (-30, -40) dB, the shift becomes less and les and finally all the curve had the same peak, which showed clearly that at high optical feedback ratio the effect of optical feedback was neglected.



Figure(1): Modulation transfer function as a function of modulation frequency, for different values of phase change

3-2 External Cavity Length (roundtrip time)

Figure (2) shows the modulation transfer function against modulation frequency for several values of external cavity length ($L = 20, 40, 60, 80, 100$) cm or we can say the roundtrip time. We saw the shift of peaks to the low frequency with an of increasing the external cavity length i.e. decreasing optical feedback. This is because of the increasing of the optical loss with the increase in the length of the external cavity. Accordingly Figure (3) gives the nonlinear function, the second term is approximated by $(-0.0216 x)$.

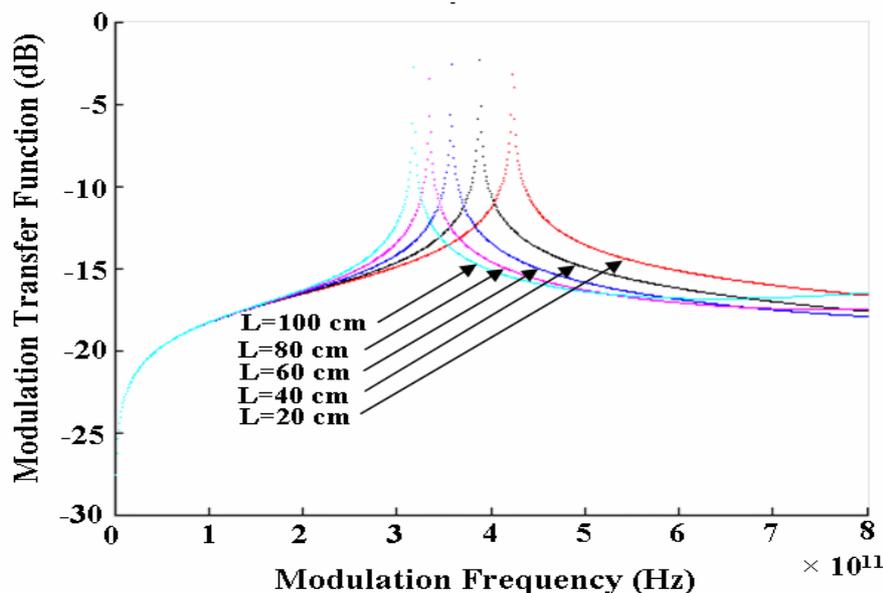


Figure (2): Modulation transfer function as a function of modulation frequency, for different values of external cavity length

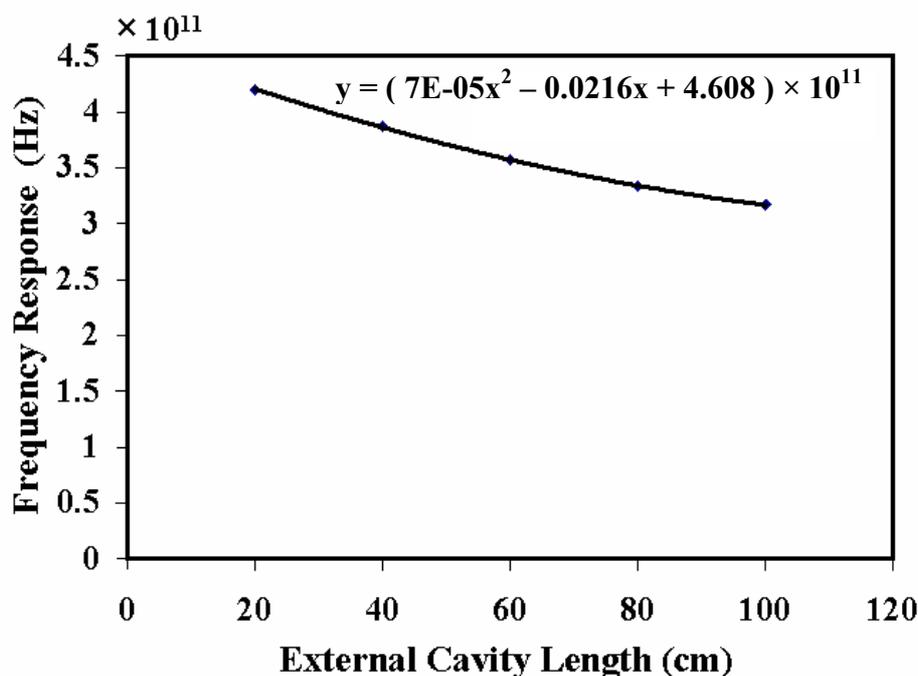


Figure (3): Frequency response peak as a function of external cavity length



3-3 Optical Feedback Ratio.

Finally we see from Figure (4) that the modulation transfer function is pushed to the high modulation frequency with an increasing of the optical feedback ratio especially at high optical feedback (-10 dB) and we see the wide space between the (-10 dB) and other value. Also the space become narrow when we transfer between (-20 dB) to (-30 dB). This space is narrower between (-30 dB) and (-40 dB). This happens at phase change equals zero. This means that at high optical feedback, the gain overcomes the lose.

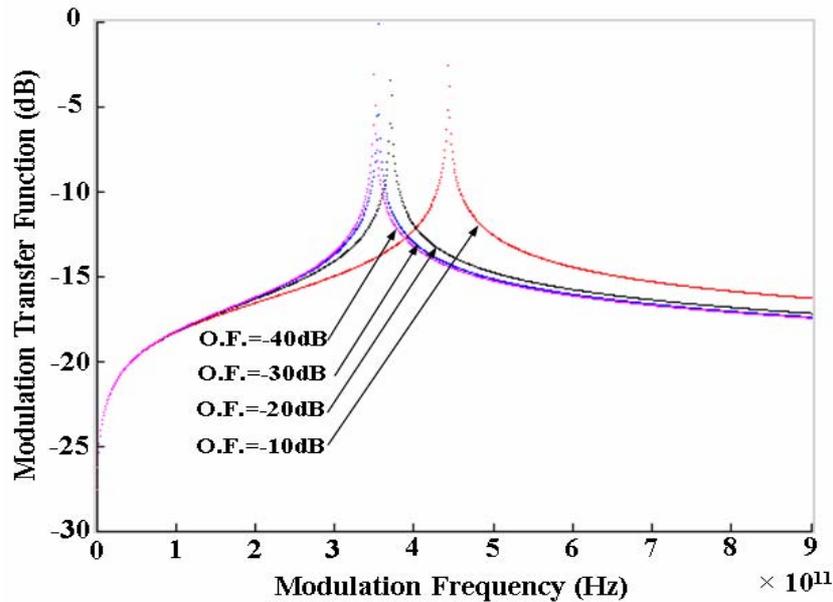


Figure (4): Modulation transfer function as a function of modulation frequency, for different values of optical feedback ratio

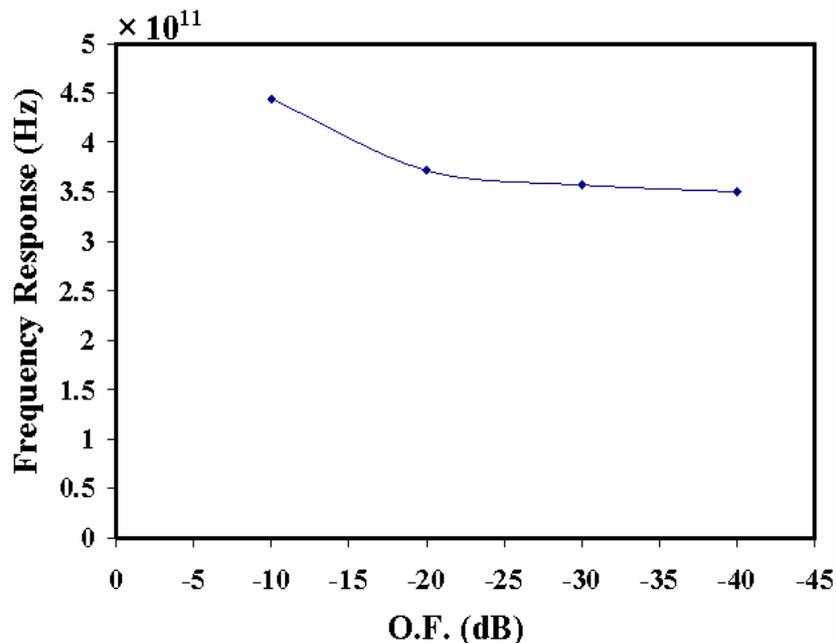


Figure (5): Frequency response peak as against optical feedback ratio



Conclusions

It has shown that the modulation transfer function of the intersubband lasers is dependent upon optical feedback ratio and exhibits a unique dependence upon the optical output power of the laser. In contrast, there is a fine balance between the contribution of the resonance frequency and the damping factor in the determination of the maximum modulation frequency.

Analytical results obtained indicate the significant impact which is caused by the optical feedback ratio of the frequency modulation value in these lasers. Moreover, we find that the amount of the impact of phase change depends on the optical feedback ratio. Finally, we can say that it is possible to increase the modulation frequency bandwidth of the quantum cascade by using the optical feedback phenomena, with an appropriate choice of the length of external cavity and the relative phase change.

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