Study of Effect of Temperature and Spontaneous Emission Coupling Coefficient on the Working of Quantum Cascade Laser in Far Infrared Region

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***Abstract*—Acircuit model for a Quantum Cascade Laser is adopted from the work of Yong *et al*. A fabryperot resonator with the required characteristics is modeled and added to this circuit. The circuit is designed effectively to operate in the far infrared region. The model works as quite a universal model in which various effects can be studied with ease. The effect of coupling coefficient of spontaneous emission, beta, is observed on the DC, transient and modal characteristics of the output beam. The slope efficiency is seen to increase and the linewidth spectrum gets wider with increasing beta. The effect of temperature on the DC and modal characteristics is also studied. The slope efficiency decreases with increasing temperature. There is a modal shift towards higher wavelength observed with increasing temperature and the linewidth spectrumis seen to get slightly wider.**

***Index Terms*—Quantum wells, Quantum Cascade Laser, Fabry-Perot**

I. INTRODUCTION

The infrared region is of great importance because of the importance of applications it offers, for example, fiber optic communication, night vision, infrared imaging, long haul telecommunication, etc.

Since the focus is on communication in the long wavelength region, it has been found that there is very less attenuation in the mid infrared (2 to 5um) and far infrared (8 to 12um) windows in optical fibres as the attenuation is dominated by phonon absorption edge. Thus, reserachers have turned their attention to these windows for communication. In addition, it has been pointed out that in 3um-5um and 8um-13um windows the atmosphere is relatively transparent compared to near infrared wavelengths. This can facillitate free space communication without heavy attenuation.

In order to achieve mid and far infrared communication, it is necessary to have a source which can work efficiently in those windows. . It should have desirable characteristics (as described at length in [16]) such as: stable output i.e., not much dependence on ambient conditions such as temperature; linear output; highly directional beam; should emit light at desired wavelength; must couple enough optical power; should have narrow spectral beamwidth; should be capable of simple signal modulation, especially direct modulation; size should be low and should be easy to fabricate at a low cost; must accurately track the electrical input to minimize distortions and noise.

The present work aims at the studies on behavioural characteristics of a QCL.A simple circuit model proposed by Yong *et al.* in [15] is adopted and further customized to incorporate a fabry perot resonator. The various effects due to change in some important parameters such as temperature and spontaneous emission coupling coefficient were then studied. The analysis is performed in LTSPICE.

II. EQUIVALENT CIRCUIT MODEL OF QCL WITH FABRY PEROT RESONATOR

The model of quantum cascade structure is adopted from Yong *et al* in their work [15]. Another model was suggested by Chen *et al.*[10], however, the model proposed by Yong *et al.* is more universal to study various effects.

This model is based on simple two level rate equations.

where $G_{stim} = eKG(\bar{N}_3 - \bar{N}_2)\bar{P}$; $G_{spon} = e\beta\bar{N}_3/\tau_{sp}$; $G_3 = e(1/\tau_{32} + 1/\tau_{sp})\bar{N}_3$; $R_3 = \tau_3/e$; $R_2 = \tau_{21}/e$; $C_3 = C_2 = e$; $C_P = eKG\tau_P$; $R_P = 1/(eKG)$.

III. .MODELING OF FABRY PEROT RESONATOR

The circuit of a fabry perot resonator was modeled to create feedback loop using simple opamp phase shift oscillator.

As seen in figure 1, a fabry perot gain medium acts like a positive feedback resonator which produces phase shift of 180 degrees each time the wavefront gets reflected by a mirror.Thus, a fabry perot gain medium can be modelled with the help of an opamp phase shift oscillator producing phase shift of 180 degrees with the help of three stage RC filter.

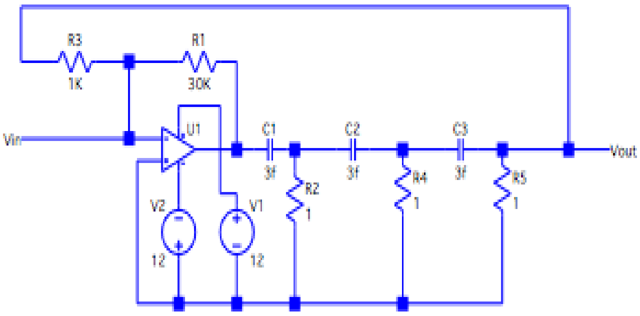

Fig.1. Equivalent circuit model of a Fabry Perot Resonator

R3 = Rin (input resistance) ; R1 = Rfb (feedback resistance); U1 = opamp in inverted configuration ; C1=C2=C3=C ; R2=R4=R5=R

We know that the condition for the gain of an opamp phase shift oscillator is that Rfb/Rin >= 29, thus, the values of R3 and R1 are so chosen as shown in figure 1.

The operating wavelength is chosen to be around 9um which falls in the far infrared region. The length of the gain medium is chosen to be nearly 45um.

We know that in single RC stage, the reactance Xc due to capacitance would be

$Xc = \frac{1}{2\pi.Fosc.C}$, where Fosc is oscillating frequency (1)

And the $Fosc = \frac{1}{2\pi.RC.\sqrt{6}}$ (2)

So the phase shift per stage is $\emptyset = \tan^{-1}\frac{Xc}{R}$ (3)

If phase shift per stage is 60 degrees then

$\frac{Xc}{R}=1.732$ (4)

Which means $\frac{1}{2\pi.RC.Fosc}= 1.732$ (5)

Where $\sqrt{6}$comes from $\sqrt{2N}$ where N is the number of RC filter stages.

$Fosc=\frac{q.c}{2.n.L}$ (6)

Where q= number of longitudinal modes
n = refractive index of the medium
L = length of the gain medium
c = phase velocity of wave in vacuum

Effectively, c/n gives the phase velocity of the wave inside the medium. However, n can be ignored here as it does not affect the order of the values of R and C.

Thus, $Fosc = \frac{q.c}{2.L}$(7)

And $L = \frac{q.c}{2.Fosc}$ (8)

Therefore, Fosc = c/λ = 30Thz (approx.)

Thus, by eqn. 13, q/L = 220000 and RC = 3x10^{-15} ohm-farad or 3f ohm-farad.

Thus, R is taken as 1 ohm and C as 3fF.

IV. STUDY OF THE EFFECT OF COUPLING COEFFICIENT OF SPONTANEOUS EMISSION

A. Effect on Threshold Current

It is observed that there is a very small shift of 0.3mA in the threshold for beta=1 than that of beta = 0.01, which is not so noticeable. It can be seen in the figure 7. However, the slope efficiency for higher beta is seen to be high. This means that the gain of the output is more for higher beta.

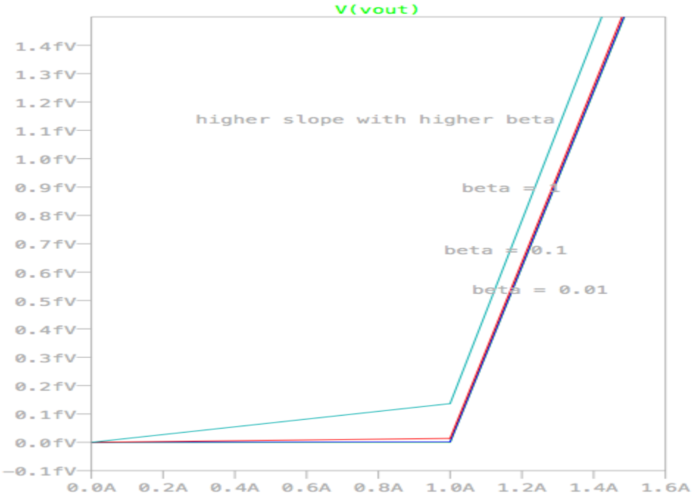

Fig. 7.Threshold current and slope of the V-I characteristics

B. Effect on Modal Characteristics

On observing the modal characteristics shown in figure 8, it is concluded that the spacing between the modes increases for higher beta while it is low for lower β value. This means that the linewidth spectrum gets wider for a higher beta than that for lower one which is an intuitive result. Also, it is seen that there is no modal shift.

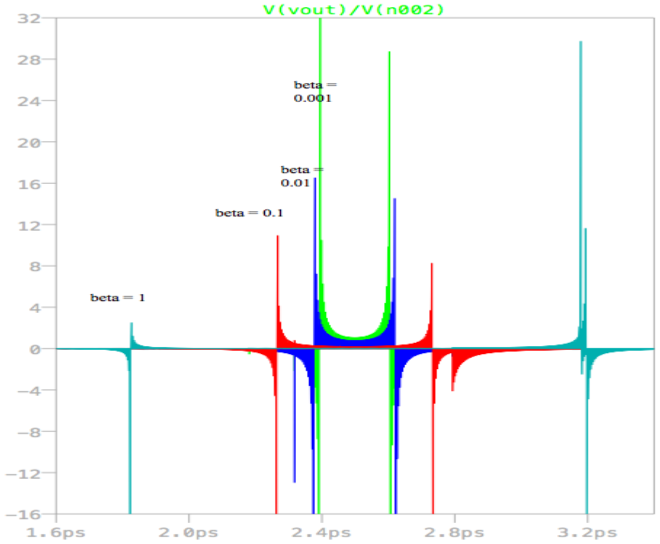

Fig. 8. Linewidth spectrum as obtained due to variation in beta

V.

V. STUDY OF THE EFFECT OF TEMPERATURE

A. Effect on Threshold Current

The temperature dependence is found out with the use of the knowledge that while determining the Einstein's coefficients of emission and absorptionwe obtain

$\frac{rate\ of\ stimulated\ \ emission}{rate\ of\ spontaneous\ \ emissi\ on}= \frac{1}{1-e^{\frac{hf}{KT}}}$ (16)

Where h = Plank's constant ; f= frquency; K= Boltzmann constant and T = absolute temperature.Using this relation, the temperature dependence of the output is studied.

As pointed out by one of the cofounders of QCL, Jerome Faist, in his study [13], there is no noticeable change in the threshold current. This means that the threshold current in a QCL depends very weakly on temperature. Figure 9 suggests a shift of 2.4mA towards higher threshold current temperature, T=200K when compared with T= 80K. The graph also suggests that there is higher slope efficiency for lesser temperature, hence, higher laser output at lesser temperature.

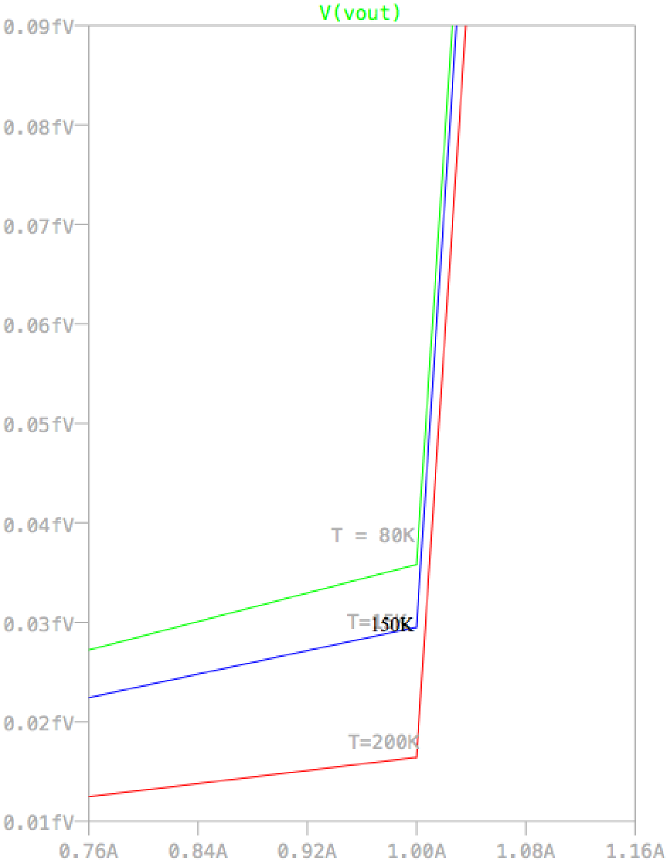

Fig. 9.Shift of threshold current towards higher current threshold for higher temperature

B. Effect on Modal Characteristics

The effect on modal characteristics can be observed from figure 10 in the form of modal shift towards the right as temperature increases. It is also observed that the linewidth spectrum widens slightly for higher temperature.

CONCLUSION

The circuit model of a quantum cascade laser using simple two level rate equations has been adopted from [15]. The model is simulated using LTSPICE circuit simulator for analysis. The results are validated with the findings demonstrated in [15] and other results previously published ([1] to [9] and [11] to [14]).

A fabry perot resonator is modelled and added in the circuit. The relation of the resonator parameters with the oscillating frequency, length of the gain medium and number of longitudinal modes in the cavity is thoroughly analysed. These equations obtained are validated with results obtained. The output characteristics due to application of a DC modulating and AC modulating signal are studied. The transient characteristics are obtained.

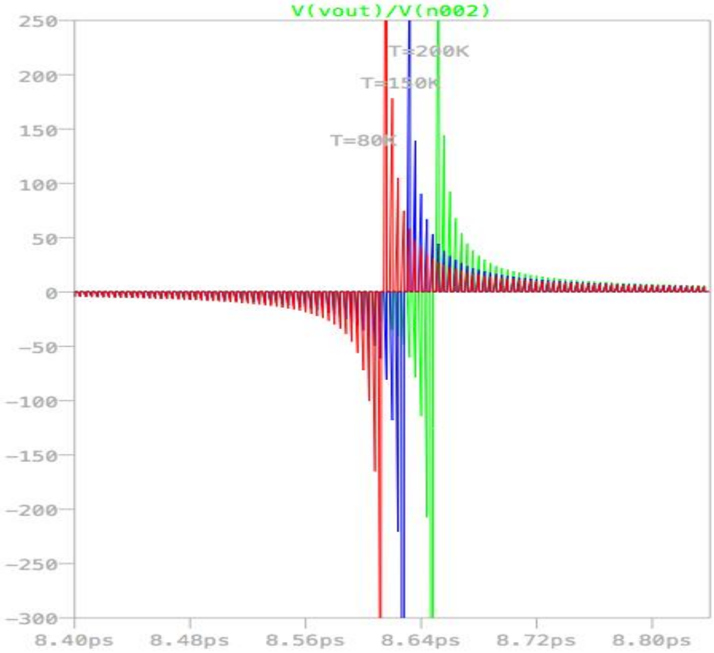

Fig. 10. Modal shift towards higher wavelength due to increase in temperature

It is also observed that the proposed laser model can perform direct modulation.

The modal characteristics of this type of arrangement are also studied at length. The type of transverse modes existing in the gain medium is found out.

The effect of the spontaneous coupling coefficient β on the response is studied. It is inferred that β does not affect the threshold current much, however, it does affect the slope efficiency of the output. As β increases, the slope efficiency also increases.

The effect of temperature on the response is studied. It is inferred that threshold current has very weak dependence on temperature. It is seen that lower temperature yields higher slope efficiency than a higher one.There is a modal shift observed towards the higher end due to increase in temperature. It is also seen that the linewidth spectrum gets broadened due to increase in temperature.

Looking at the modal characteristics and transient analysis of the lasing beam, it can be inferred that the Quantum Cascade Laser is capable of providing a highly directional beam which is suitable for long haul communication. Its major attraction is that it works efficiently in the mid and far infraredit works efficiently in the mid and far infrareduse in telecommunication in future.

FUTURE SCOPE

The driver circuit, the effect on transition lifetimes due to change in doping densities and material characteristics and its effect on the power coupling into optical link can be studied in detail. This would be helpful in characterising the behaviour of a Quantum Cascade Laser in more detail. Also, the scattering effects of the lasing beam inside the resonator can be studied at length in order to see its effect on the modulation bandwidth.Another important aspect that needs attention is the accurate circuit modelling of the resonator or optical cavity to allow the propagation of modes that are desirable.Not only Fabry Perot but other optical cavities used in quantum cascade lasers such as Distributed Feedback Resonator (DFB) and Distriuted Bragg Reflector Resonator (DBR) also need to be modeled andstudied. The efficiencies of all these resonators can be comapred and it can be concluded which one can serve as the best fit for a quantum cascade laser.

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