SHORT PULSE GENERATION BY GAIN SIMULATION IN QCL

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ABSTRACT

Generation of Optical pulses in order of picoseconds by modeling the Quantum Cascade Laser with two level rate equations and theoretical accounting of gain switching is reported.QCL is simulated with different inputs such as sinusoidal, tangential hyperbolic, square and trapezoidal. Analysis of parameters like FWHM, maximum power is done using the Golden Section Search and Parabolic Interpolation algorithms for maximum power and shortest FWHM. Sinusoidal input produce short pulse of 27.62ps, 49.2mW.Trapezoidal pulse generates 17ps, 122.1mW.Optical pulse of value 13.15ps, 178.3mW pertaining to tangential hyperbolic is obtained. An output pulse with maximum power is observed in tangential hyperbolic waveform. The shortest optical pulse is obtained with square pulse for power less than 0.5W.

Keyword:- *Quantum cascade laser ,Gain switching,optical pulse,FWHM,Golden Section Search,Parabolic Interpolation.*

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1. INTRODUCTION

QCL are the lasers in which intra-sub band transitions happen that produce multiple photons per electron. QCLs have a high spectral efficiency, when compared with the conventional one, because of the cascading effect. They are capable of producing short optical pulses in the range of about 10ps.This generation of short pulses are achieved by the gain switching technique. In this technique the input carrier density is made to rise from a lower threshold to a higher value that is maintained in a turn-on delay time and finally an outburst of sharp optical pulses of minimum width is witnessed. The QCL is modeled using a two-level rate equation. The GSS algorithm is used to find the range interval of the search process and the PI algorithm is used to find out the intermediate points lying within the interval.

2.MODELING OF QUANTUM CASCADE LASER

The QCL consists of two injector regions and one active region in which the incident electron hits and transition happens after which the tunneling occurs. This process is represented using the rate equations below in equation 1,2 and 3. These equations show how the electrons move from the higher state to the lower state and how finally the non radiative transitions happen. I represents the input current,N_2 and N_3 represent the number of electrons present in the level 2 and level 3 respectively. G is the gain coefficient per stage which in turn depends on the optical confinement factor and P is the photon number.τ_{ij} represents the transition where the lifetime between the levels of i and j. τ_{sp} represents the spontaneous lifetime emission and β is the spontaneous emission factor. The search point for the input bias current is obtained from the GSS and PI algorithms and the step size is reduced after each search. A seed point is fixed to start with. After each iteration the oldest point is replaced with a new search point. Later the minimum and the maximum points are deduced from this interval.

$$\frac{dN_3}{dt} = \frac{I}{e} - \frac{N_3}{\tau_3} - \mathrm{G}(N_3 - N_2)P \tag{1}$$

$$\frac{dN_2}{dt} = \left(\frac{1}{\tau_{32}} + \frac{1}{\tau_{sp}}\right)N_3 - \frac{N_2}{\tau_{21}} + \mathrm{G}(N_3 - N_2)P \tag{2}$$

$$\frac{dP}{dt} = GN(N_3 - N_2)P + N\beta\frac{N_3}{\tau_{sp}} - \frac{P}{\tau_p} \tag{3}$$

2.1 Steady state and Transient state

The rate equations are solved using the ODE solver in the MATLAB. Steady state response is obtained by solving these equations under the steady state condition. The graph in the figure 1 is plotted with the various input bias currents against the output power. The input current is varied from a range of 0A to 2A where the input threshold current is found to be1.1108A for the device. In the figure 2a and figure 2b it is observed that the electron number N_3 increases, holds constant for a certain period and decreases abruptly and again remains constant.N_2 gradually increases and finally stays constant. The figure 3 depicts the transient response of the device where the graph is plotted against the time and various other parameters. The response is that it increases gradually and finally settles to a constant value.

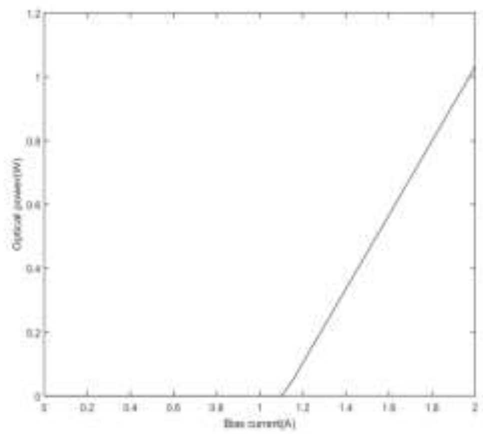


Fig-1: Steady State response

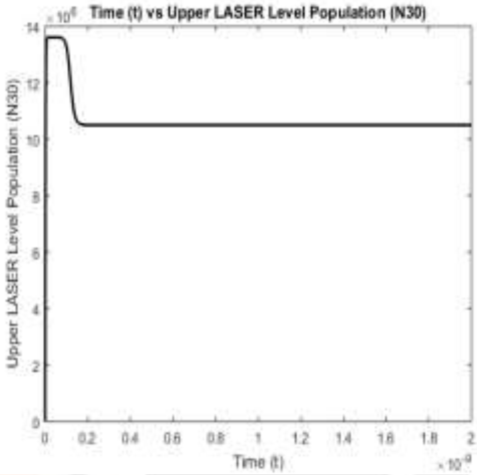


Fig-2a: Transient characteristics of N_2

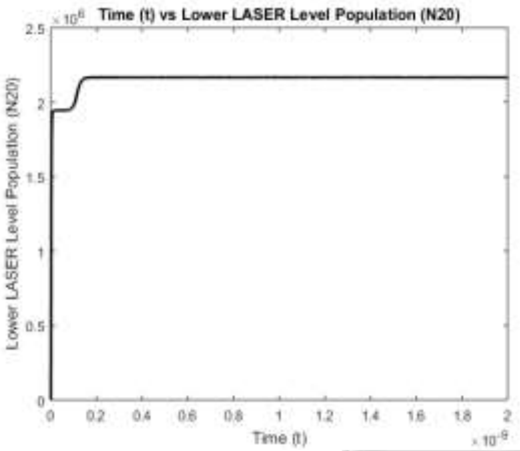


Fig-2a: Transient characteristics of N_3

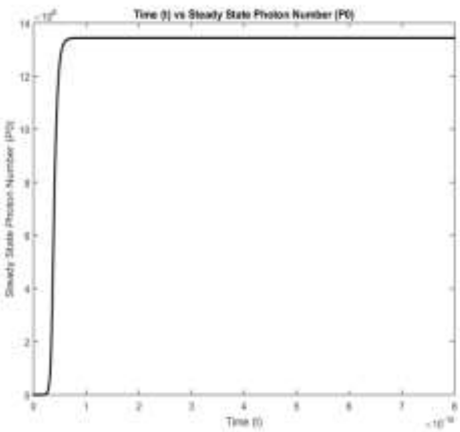


Fig-3: Transient characteristics of photon number

2.2 Output power and various amplitude responses

The four different types of electrical pulse is applied to the QCL and the short optical pulse of certain amplitude and power is noted. Later the input amplitude is increased in series of steps and the corresponding output pulse is plotted. This is repeated for the square,sinusoidal,trapezoidal and tangential hyperbolic inputs.

2.2.1 For square input:

The short optical pulse of power 48.16mW is obtained when amplitude of $1.4I_{th}$ is applied to the device. The output pulse is depicted in the figure 4. The FWHM value is noted as 10.2ps. $1.8I_{th,}$ $2I_{th}$ and $3I_{th}$. after which the output pulse starts following the input pulse and becomes flattened finally. The variations in the amplitude of the output pulse are shown in the figure 5.

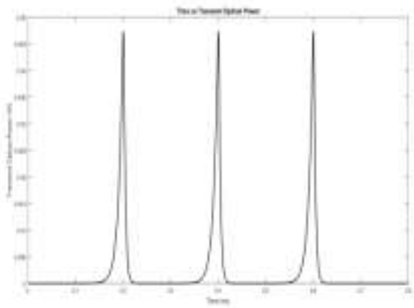


Fig-4: Transient output power

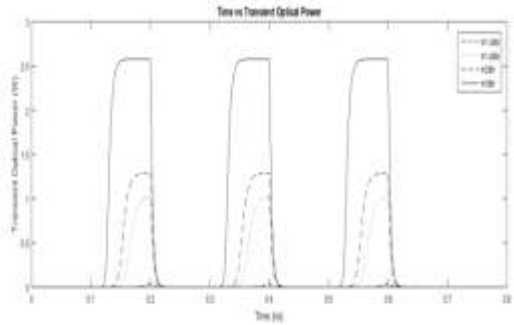


Fig-5: Optical power for different amplitudes

2.2.2 For sinusoidal input:

Sinusoidal input of amplitude $0.83I_{th}$ is applied to the QCL with a time period of 0.2ns. The output obtained is the optical power of amplitude 50.1W and FWHM of 27.7ps. The simulation results are seen in the figure 6.Then in uniform steps, the input bias current is increased in amplitude value and the output pulse is shown in the figure 7. The amplitude is varied from $0.83I_{th}$,$1I_{th}$,$1.5I_{th}$,$2I_{th}$. With the results obtained in the simulation we can conclude that the input amplitude can be varied only to a certain maximum value for instance up to $3I_{th}$. Even after increasing the values it is observed that no proper waveform is obtained.

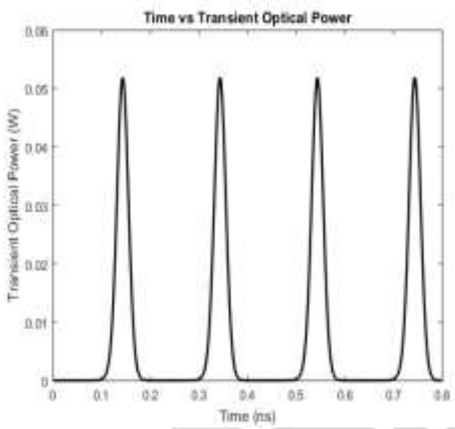


Fig-6: Transient output power

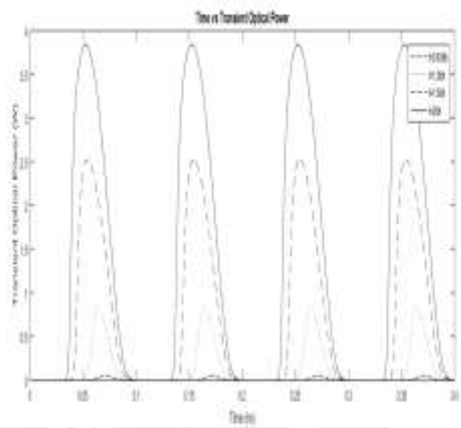
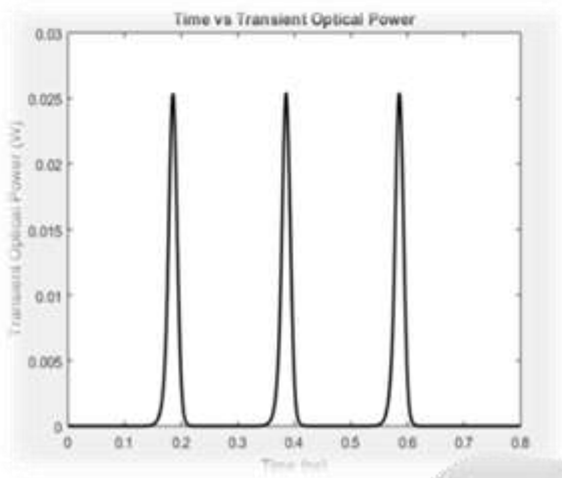


Fig-7: Optical power for different amplitudes

2.2.3 For Trapezoidal input:

The trapezoidal input of amplitude $1.64I_{th}$ is given with a rise time and fall time of about 25ps, the pulse width is 75ps. The transient output power is obtained for this input amplitude. This is portrayed in the figure 8.Then the input amplitude is slowly increased in series fashion from $1.64I_{th}$, $1.9I_{th}$,$2.2I_{th}$,$2.6I_{th}$ and $3I_{th}$. The parameters measured from the transient output power is the amplitude of 50.7mW and a pulse width of about 17.05ps.If the amplitude is increased over $2I_{th,}$then it is observed that the output pulse starts following the input pulse and starts becoming flattened. The transient optical power for different trapezoidal waveform amplitudes is obtained and is depicted in the figure 9.



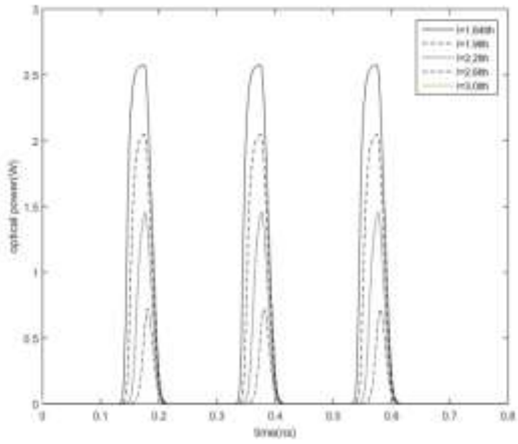
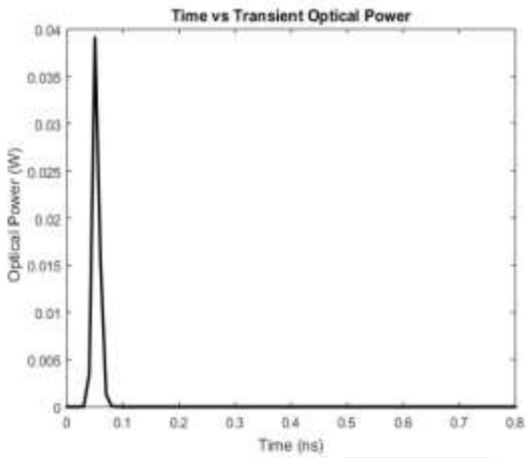


Fig-8: Transient output power **Fig-9**: Optical power for different amplitudes

2.2.4 For Tangential hyperbolic input:

The input bias is given with the use of tanh(t) profile current expression. It is possible to obtain continuous waveforms for the tangential hyperbolic input but here the output is taken for a single pulse because of the fact that the output pulse would be more complex if computed for various time periods. The input amplitude given is $1.2I_{th}$ with a time period of 0.2ns. The short optical pulse is the output with a maximum power of 59.5mW with a FWHM of 13.26ps which is shown in the figure 10.For the increased values of the amplitude the width increases and if it continues it starts resembling the input pulse. The variations in the amplitude are in uniform steps of $1.4I_{th}$,$1.6I_{th,}$$1.8I_{th}$ and $2I_{th.}$ Which is seen in the figure 11.



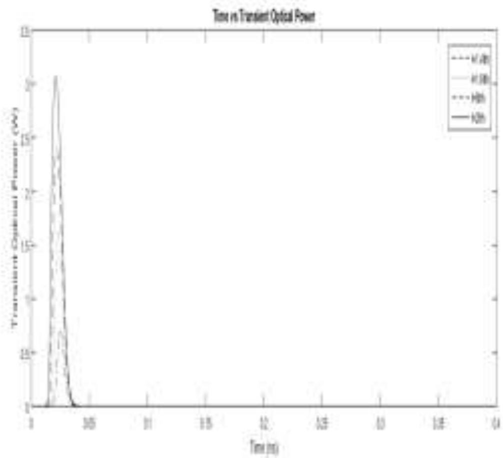


Fig-10: Transient output power **Fig-11**: Optical power for different amplitudes

2.3 FWHM for different waveforms

The technical term Full-Width Half-Maximum, or FWHM, is used to describe a measurement of the width of an irregular pulse like a Gaussian pulse,or when the pulse does not have sharp edges.
The FWHM characteristics is obtained for four different kinds of input like square, sinusoidal, trapezoidal and tangential hyperbolic waveform.The FWHM characteristics is plotted using the MATLAB software.

2.3.1 For square input:

The FWHM curve for the square input is plotted along with the Optical power output against the current ratio. From the design curves in the figure 12 the bias current required for providing a certain pulse width and power can be deduced. It is also evident from figure 12 that as the bias current is increased, the FWHM of the short pulses decreases to have a local minimum and then increase with increase in bias current. The output waveform is obtained for the square input pulse with an input amplitude of about $1.4I_{th}$ where I_{th} is the input bias current. For this particular value the FWHM is generated and the pulse width value is 10.2ps.

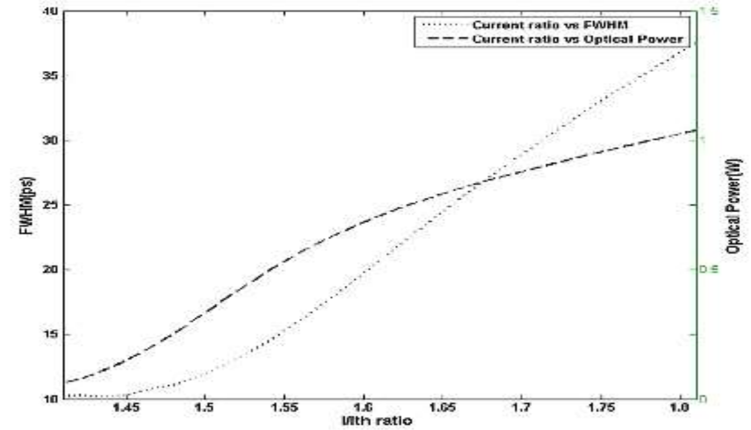


Fig-12: FWHM waveform

2.3.2 For sinusoidal input

From the design curve shown in figure 13, for a given pulse width or power, the necessary amplitude of bias current for producing the same can be deduced and can be applied as input. GSS-PI algorithm is used to find the optimum current for generating short pulses with a specific power.The Optical power is obtained by gradually increasing the current values from the range of $0.83I_{th}$ to $1.3I_{th}$. For the same values the FWHM is also plotted. It is evident from the figure 3.11 that the current is increased in uniform steps for obtaining the Optical pulse characteristics.

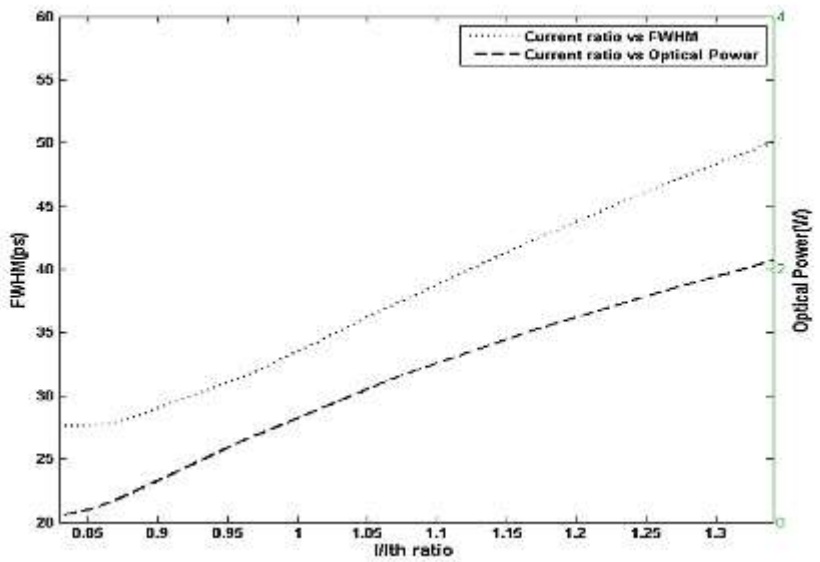


Fig-13: FWHM waveform

2.3.3 For trapezoidal input

The peak amplitude is varied from $1.64I_{th}$ to $3I_{th}$ as shown in the figure 14. The FWHM and output power design curves exhibit a piecewise linear behaviour as the bias current is increased. For a fixed FWHM or power, the bias current required to generate the short pulse can be computed from the figure 14.When the peak amplitude is slowly increased from a value of 1.8 to 3.3 the FWHM curve is found slowly increasing to a higher value which is followed with the same behaviour by the Optical power.A large value of peak power is obtained at high bias currents along with larger FWHM values. It is evident from the figure 14 that the current is increased in uniform steps for obtaining the Optical pulse characteristics.

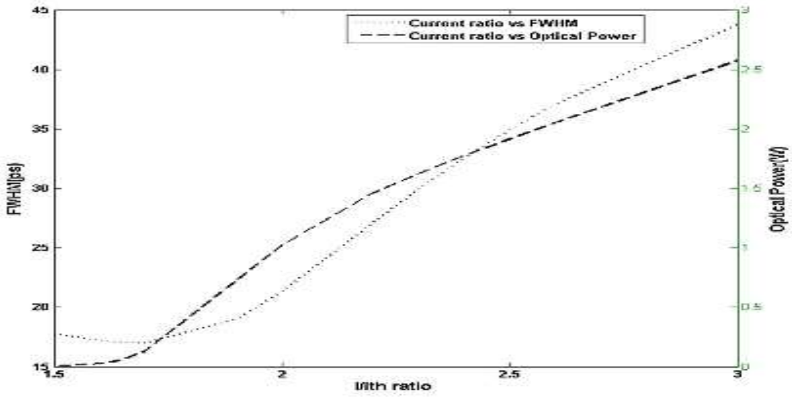


Fig-14: FWHM waveform

2.3.4 For tangential hyperbolic

The output graph is plotted for the trapezoidal input in the figure 15 with an input amplitude of about $1.4I_{th}$ where Ith is the input bias current. For this particular value the FWHM is generated and the pulse width value is 13.15ps.

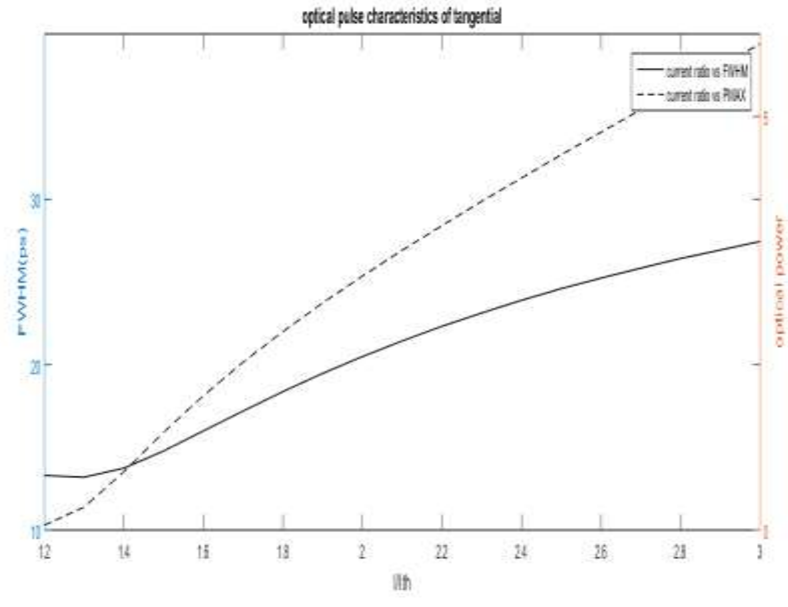


Fig-15: FWHM waveform

The minimum pulse power generated by the device is fixed at 50mW and maximum FWHM of the generated pulse is fixed at 50% of input electrical pulse width. With these conditions assumed the analysis is carried out to determine the pulse characteristics of the pulse input.

3.RESULTS AND DISCUSSIONS

The optimum current is obtained from the search interval through the GSS-PI algorithm. This optimum current gives the maximum power and the minimum FWHM. The results of this optimisation is presented into the table 1 showing how the GSS-PI techniques are accurate.

Table 1 Tabulation of parameters

Electrical Input	**Amplitude (A)**	**FWHM (ps)**	**Maximum power (mW)**
Trapezoidal	1.87	17	122.1
Sinusoidal	0.93	27.62	49.2
Square	1.57	10.1	66.9
Tangential hyperbolic	1.41	13.15	178.3

A comparative study of various input pulse waveforms is depicted in figure 1. It is observed that for a given power less than 0.5W, square waveform will always give the lowest pulse width. For power requirement more than 0.5W, it is observed that tangential hyperbolic signal provides lowest pulse width. The design curve as in figure 1 gives a clear understanding on the operating parameters of the device in terms of FWHM and Output power of the generated short pulses. Depending on the application requirements, the best input pulse that will provide a minimum FWHM and maximum power can be chosen.

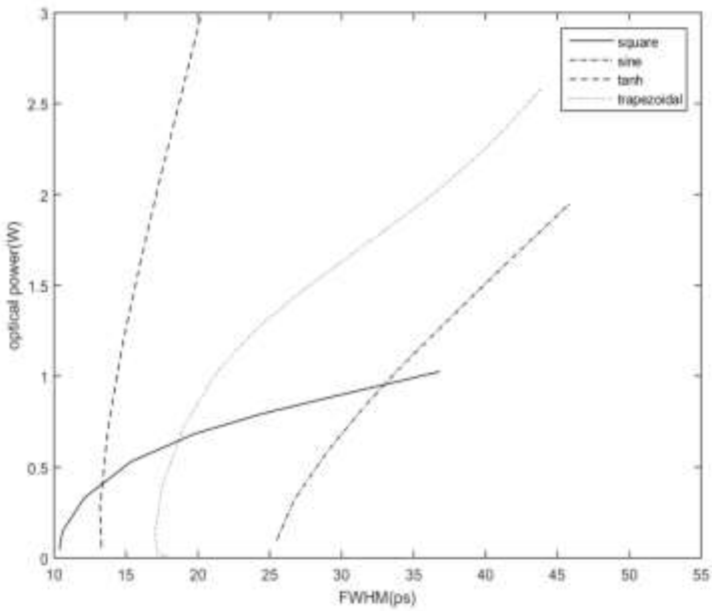


Fig-1: Combined FWHM waveform

3.1 Delay Time Characteristics

The delay time decreases linearly with the amplitude of pulse input as evident from figure 4.2.The time delay is computed for the output corresponding to square input alone where it is plotted for various values of delay time for different amplitudes value.

From the graph it is evident that the as the amplitude value is increased that is if the current ratio is increased the delay time slowly starts decreasing resulting in a decreasing smooth curve. As the amplitude increases in the figure 2 the pulses become more flat and starts resembling the input square pulse with a lesser delay time which is evident from the figure 2.

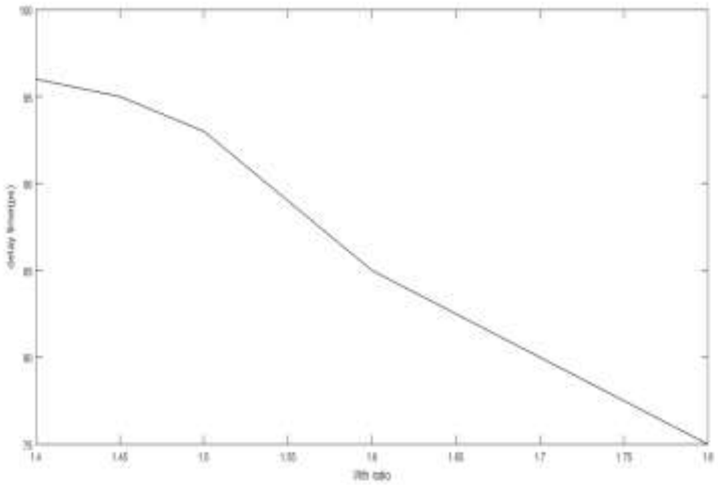


Figure 2 Delay Time Characteristics

Thus the generation of Optical pulses is completed when the Optical pulses have 50% of the width of the input drive current.

4. CONCLUSIONS

In this work, generation of short optical pulses using gain switching in QCL with maximum power and minimum spectral width is studied in detail. Numerical simulation of Gain Switching in Quantum Cascade Lasers (QCLs) for short pulse generation in the mid-Infrared region is reported. Four waveforms namely, square, sinusoidal, tangential hyperbolic and trapezoidal signals are considered for the analysis. The study accounts for generation of peak power of 1.04W, 2.07W, 2.94W and 2.05W for square, sinusoidal, tangential hyperbolic and trapezoidal inputs respectively when the optical pulses have 50% of the width of the input drive current. The optimum electrical pulse characteristics pertaining to generation of short pulses with maximum power and minimum pulse width are determined using Golden Section Search (GSS) and Parabolic Interpolation(PI) algorithm. The GSS-PI optimization procedure aims to narrow down the possibility of finding an optimum bias current for producing an optical pulse with the shortest FWHM. Minimum pulse width (FWHM) of 10.1 ps, 27.62 ps, 13.15 ps and 17 ps were obtained for with corresponding optical power of 66.9 mW, 49.2 mW, 178.3 mW and 122.1 mW under appropriate bias conditions. It is observed that tangential hyperbolic waveform provides the maximum power and minimum pulse width for the device considered for the study.

5. REFERENCES

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