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Theoretical Analysis on Modulation Bandwidth for Distributed Reflector Laser with Quantum Wire Structures

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Abstract

The rapidly growing information era has been augmented by a global network of optical fiber. By offering an enormous transmission bandwidth of about 10^{14} Hz and low signal attenuation, the low cost, glass-based single mode optical fiber provides an ideal transmission medium. Distributed Reflector (DR) laser consisting of a DFB (distributed feed back) laser with high reflection DBR(distributed Bragg reflector) at the rear end is studied by considering wirelike active region. Modulation bandwidth of GaInAsP/InP laser has been analyzed. Optimum structure for large modulation bandwidth observed is the DR laser with Double Quantum wire stack, 140µm cavity length and 120nm wire width. The proposed structure also provides good static characteristics such as threshold current of 0.416mA and differential quantum efficiency of about 56%. In this study highest modulation bandwidth of 16 GHz has been realized theoretically.

Key word-Distributed reflector laser, Modulation bandwidth, Quantum wire

1. Introduction

1.1 Distributed reflector Laser

Distributed reflector Laser with DFB section is widely used in optical communication. Thus the dynamic character is as important as the static character. To improve the performance the DR laser should have lower threshold current along with higher modulation bandwidth. High bandwidth of 30GHz on two-section 1.55 µm InGaAsP DBR lasers has reported.[1]Short-cavity $In_{0.35}Ga_{0.65}As/GaAs$ MQW lasers with modulation bandwidths up to 33 GHz using beryllium (Be) as p-dopant in the active region hes been reported.[2] DR lasers with wirelike active regions are potential candidate for a cost-effective light source for metro application and optical interconnection [3].

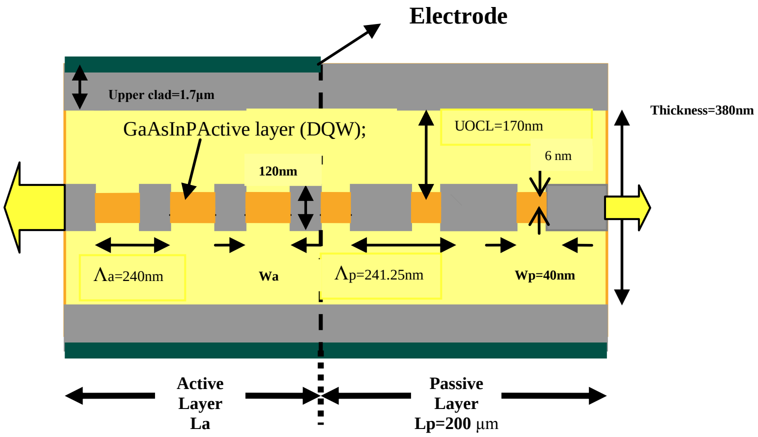

Figure1.1: Distributed reflector Laser

Fig. 1.1 shows the illustration and the grating structure of a DR laser, where *La* ,Λ*a* , and *Wa* denote the section length, the grating pitch, and the width of the wirelike active regions, respectively, and *Lp,* Λ*p,* and *Wp* denote those of the passive sections. This laser has an active section with a DFB grating (left-hand side) and a passive section with a Q-wire DBR (right-hand side).

In this structure the thickness of upper cladding layer is 1.7µm, lower cladding layer is also 1.7µm. Optical confinement layer (OCL) is 170nm on both sides. Thickness of a single well is 6nm and thickness of the barrier is 9nm. Lp is 200µm, Wp is 40 nm, Λp is 241.25nm. La and Wa are different for different conditions. Λa is 240nm.Thickness of the active layer is different for different number of quantum wire stacked.

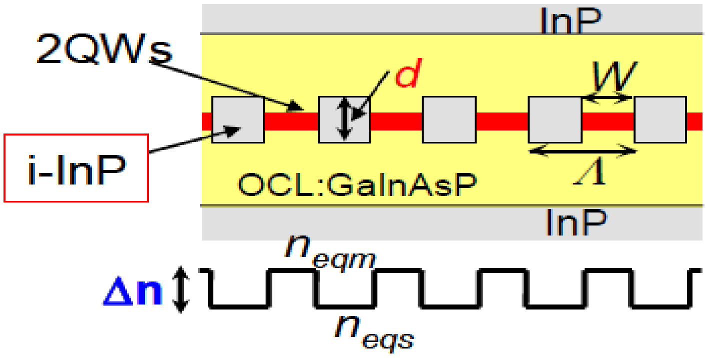

Figure 1.2: Refractive index profile

Figure 1.2 shows the refractive index profile of the active region where the equivalent refractive indices of gain and non-gain regions are denoted as n_{eqm} and n_{eqs}, respectively. The difference of these two equivalent refractive indices has been denoted as Δ*n* as mentioned earlier. For a wire like DFB region with a wire width ratio (*Wa*/ Λ a) of 0.5 and Δ*n*=0.03 (n_{eqm}= 3.21, n_{eqs}=3.18), the maximum value of the index coupling coefficient becomes approximately 400 cm^{-1}. However, as the number of Quantum well increased the depth of the groove is also increased. For SQW depth of the groove is 104nm, for DQW it is 120 nm, for 5QW it is 164 nm and for 10 QW it is 240 nm. The equivalent refractive index (n_{eqs}) of the etched region is decreased due to increased volume of InP, while the refractive index of the gain region (n_{eqm}) remains (approximately) the same; therefore, net Δ*n* value is enhanced. In our study we calculate refractive index (n_{eqs}) of the etched region and gain region (n_{eqm}) using C programs. For single Quantum well n_{eqm}= 3.23065, n_{eqs} = 3.20136 for double Quantum well n_{eqm} = 3.2356,n_{eqs} = 3.201356 for 5 Quantum well n_{eqm} = 3.25, n_{eqs} = 3.1989 for 10 Quantum well n_{eqm} = 3.272 , n_{eqs} = 3.1955.

1.2. Modulation Bandwidth

Modulation bandwidth is the maximum rate of change in the output frequency that can be attained. The directly modulated laser is a simple and reliable source for high speed optical information transmission. It is especially useful in medium to short distance applications (e.g. local area networks and optical interconnects) where the excess pulse dispersion due to laser chirp is not a critical issue.

Transfer function of laser is represented by the equation (1.1)

$$\frac{P_{ac}(\omega)}{I\ (\omega)} = \frac{\eta_d h\nu/q}{1-(\omega\ /\omega_R)^2 + j(\omega/\omega_R)[\omega_R\tau_p\ \ +1/\omega_R\tau]} \qquad 1.1$$

Where ω_R is the resonance frequency. It is represented by $\omega_R = \frac{\omega_{3dB}}{\sqrt{1+\sqrt{2}}}$. 3dB cut off frequency is represented by the equation (1.2).f_{3dB} represents the modulation bandwidth of laser for optical communication.

$$f_{3dB} \approx \frac{1.55}{2\pi}\left[\frac{\Gamma v_g a \eta_i}{h\nu V \eta_d}\right]^{1/2} \sqrt{P_o} \qquad 1.2$$

η_i is assumed 65% in this study. hv= **1.5eV**, a is the differential gain which is $\mathbf{6\times10^{-16}cm^{2}}$, V is the volume of the active region. V= cavity length × Strip width × thickness × (W/Λa) Cavity length is different for different conditions. Strip width is **2µm**.Γ is the confinement factor which is 1% for per quantum well. W is the wire width (90nm-130nm used in our study). Λa is the period which is **240nm**. Thickness is different for different number of Quantum wells. For Single Quantum well, thickness=**364nm,** for Double Quantum well, thickness=**380nm,** for 5 Quantum well, thickness=**424nm,**for 10 Quantum well, thickness =**500nm.**In this study Po=**100mW**. Photon lifetime τ_P is given by ,

$$\frac{1}{\tau_p} = v_g(\alpha_m + \langle \alpha_i \rangle) \qquad 1.3$$

Where v_g is the group velocity. For InP it is $0.89\times10^{-10}\,\text{cms}^{-1}$, α_m is the mirror loss and α_i is the internal mode loss. It is assumed that α_m=**60cm^{-1}** and α_i= **5cm^{-1}**. τ_p is 1.85×10^{-12}**s.** Carrier lifetime τ can be represented by the following equation,

$$\tau = \frac{N_{th} q V}{\eta_i I_{th}}. \qquad 1.4$$

τ depends on the active volume of the active layer. N_{th} is the threshold carrier density. For GaAsInP N_{th} is $\mathbf{1.5\times10^{18}}$ per **cm^{-3}.** [4]

2. Calculation of modulation Bandwidth:

2.1 Modulation Bandwidth considering minimum threshold current

We use C program to measure the cavity length, threshold current and quantum efficiency for different number of QW stack for different wire width. We took the cavity length of the active region where the threshold current I_{th} is the lowest. Differential quantum efficiency η_d is also taken at that cavity length. Calculations are performed for different wire width (60nm-130nm) of active region.

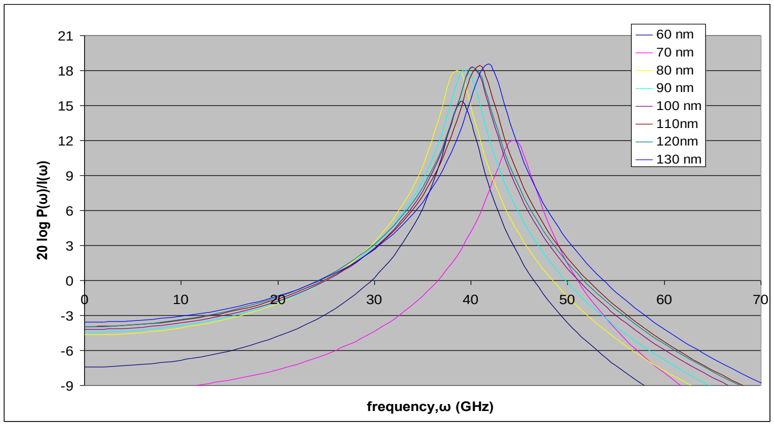

Figure 2.1: angular frequency versus transfer function for SQW

For Single Quantum well as shown in figure 2.1 maximum angular frequency ω_{3dB} obtain at 130 nm wire width is 65 GHz. So f_{3dB} is obtained at 130nm wire width is 10.3 GHz where cavity length is 260µm, threshold current I_{th} is 0.396mA, η_d is 44.2% . So, theoretically maximum f_{3dB} is obtained at 130nm wire width. However to keep the active volume low 70nm-120nm wire width is more preferable So, in this case at 120nm wire width the highest modulation bandwidth is obtain where cavity length is 260µm, I_{th} is 0.396mA, η_d is 44.2%and f_{3dB} is10.2GHz.

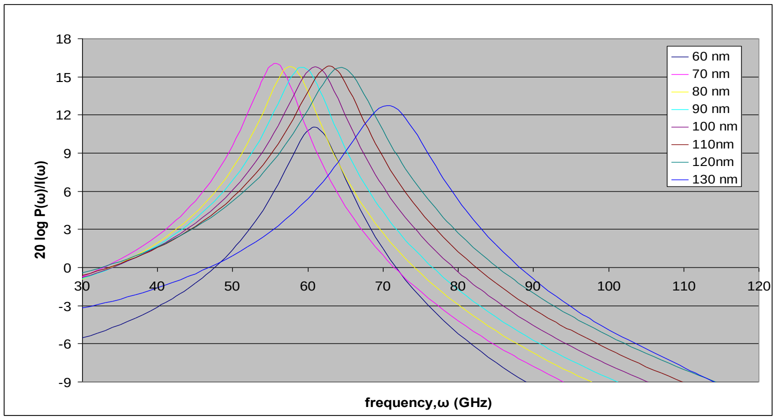

Figure 2.2: angular frequency versus transfer function for DQW

For double Quantum well from figure 2.2 maximum angular 3dB cut off frequency ω_{3dB} is obtain at 130 nm wire width is 107GHz .So in this case we find that maximum f_{3dB} is achievable at 130nm wire width where cavity length is 200µm, I_{th} is 0.574mA, η_d is 38 %, f_{3dB} is 17GHz. But 130nm wire width is not ideal to keep the active volume low.Here highest modulation bandwidth is obtained at 120nm wire width where cavity length is 180µm, I_{th} is 0.53mA, η_d is 49.501% and f_{3dB} is 16.2GHz.

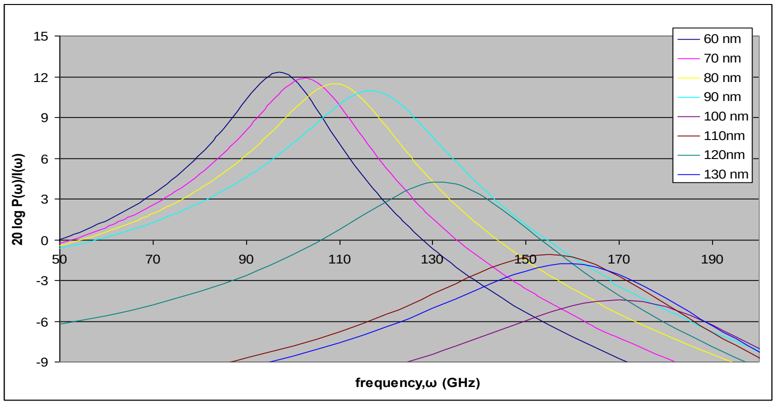

Figure 2.3: angular frequency versus transfer function for 5QW

For 5 Quantum well as shown in figure 2.3 highest modulation bandwidth is achieved at 90nm wire width where cavity length is 120µm I_{th} is 0.372mA, η_d is 51.31% and ω_{3dB} is 168 GHz. Hence f_{3dB} is 26.7 GHz. But 120µm CL is very short. So, 80nm wire width is preferable where cavity length is 140µm, I_{th} is 0.371mA, η_d is 50.67% and f_{3dB} is 24.9 GHz. At 100nm,110nm,120nm and 130nm wire width η_d is very less. So, the operating power is very low.

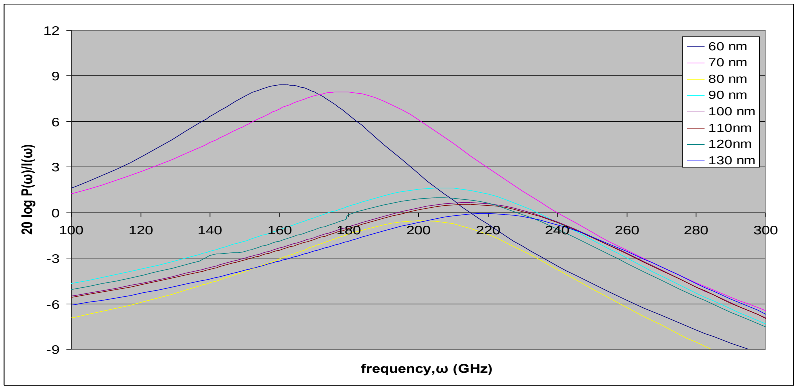

Figure 2.4: angular frequency versus transfer function for 10QW

For 10 Quantum well as shown in figure 2.4 maximum f_{3dB} is obtain at 70nm wire width where cavity length is 80µm, I_{th} is 0.381mA, and η_d is 53.81% and f_{3dB} is 42 GHz. But cavity length 80µm is very short. We cannot take such short cavity length as it is difficult to confine the active section to such shorter.

Table 1:Modulatio BW of different no of Quantum wire stacked DR laser (considering minimum threshold current)

No of well	Cavity length(µm)	Wire width(nm)	Modulation BW (GHz)
SQW	280	120	10.2
DQW	180	120	16.2
5QW	140	80	26.7
10QW	80	70	42

2.2 Modulation Bandwidth considering highest differential quantum efficiency

As high operating power is preferable for better output of laser modulation bandwidth is calculated using maximum differential quantum efficiency η_d. Cavity length and threshold current corresponding to that maximum η_d are considered. From the static characteristics it is found that maximum η_d is obtained at very short CL. Since for active region it is impractical to take such short cavity length. So, in this study, η_d's are considered for over 140µm CL. Since power consumption is also an important aspect that affects the laser's performance, we consider the cavity length where threshold current is low while differential efficiency is high.

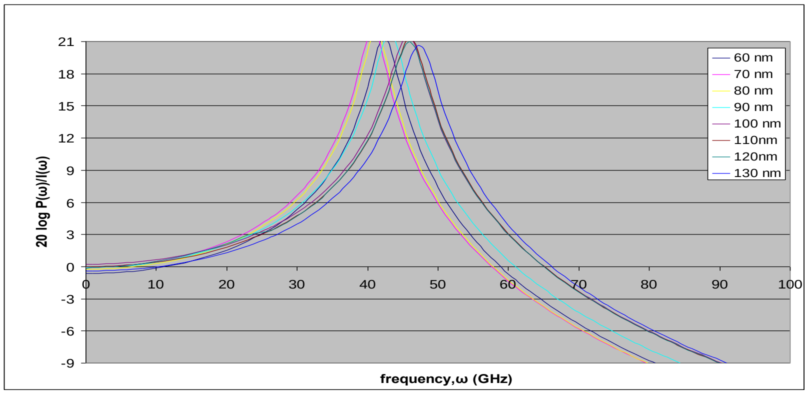

Figure 2.5: angular frequency versus transfer function for SQW

For SQW from figure 2.5 it is found that the maximum 3dB cut off angular frequency is 72 GHz at 120 nm wire width. Hence maximum f_{3dB} is obtained is 11.5 GHZ.

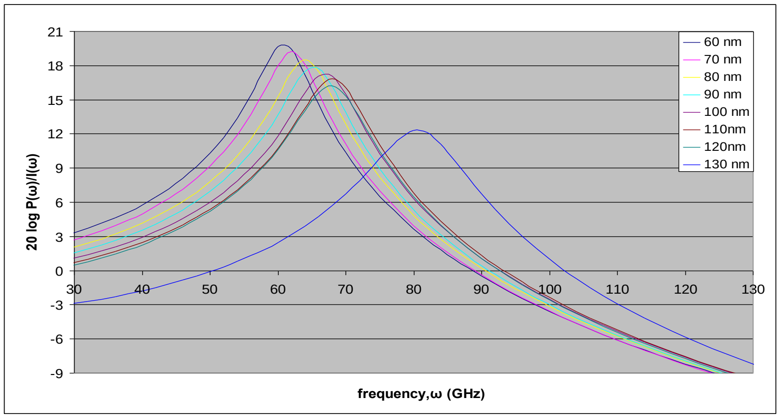

Figure 2.6: angular frequency versus transfer function for DQW

For DQW it is convenient to take 70-120 nm wire width where CL is 140µm and f_{3dB} is 15-16 GHz (shown in figure 2.6)

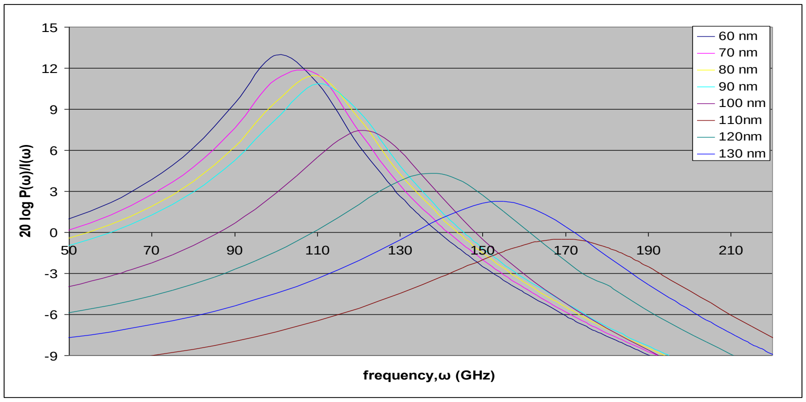

Figure 2.7: angular frequency versus transfer function for 5QW

For 5QW from figure 2.8 maximum ω_{3dB} is obtained at 100 nm wire width where cavity length is 160µm, I_{th} is 1.39mA, and η_d is 35.6% and ω_{3dB} is 160GHz.Therefore f_{3dB} is 25.46 GHz. For higher wire width maximum η_d's are very low.

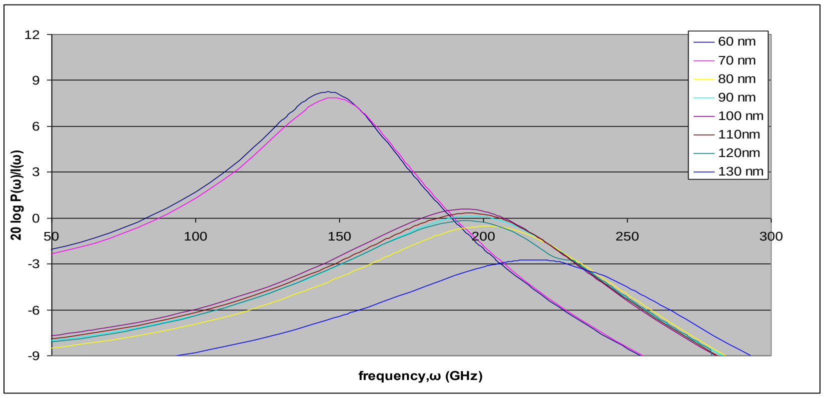

Figure 2.8: angular frequency versus transfer function for 10QW

Frequency response of 10 Quantum well for different wire width is shown in figure 2.8. Maximum ω_{3dB} obtained is about 208 GHz at 70nm wire width. So for 10 QW it is found that the maximum f_{3dB} is obtained at 70nm wire width where cavity length is 140µm, I_{th} is 0.46mA, and η_d is 45.6% and f_{3dB} is 33GHz.

Table2: Modulation BW of different no of Quantum wire stacked DR laser (considering highest differential quantum efficiency)

No of well	Cavity length (µm)	Wire width (nm)	Modulation BW (GHz)
SQW	140	120	12.5
DQW	140	120	16.23
5QW	140	90	25.45
10QW	140	70	33

Conclusion

After all these analysis it is observed that DR laser with moderate number of quantum well shows better performance- as cavity length is neither too long nor too short threshold current is low and differential efficiency is reasonable where modulation bandwidth is high as well as high peak in the transfer function. As the number of well increased modulation band width increases. As large number of quantum well is complicated for fabrication and the structure become complex DQW structure is preferable. Highest modulation bandwidth observed is about DQW with 140µm cavity length gives modulation bandwidth around 16GHz for 100nm-120nm wire width.

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