Optical Modulation Bandwidth Enhancement of Heterojunction Bipolar Transistor Lasers Using Base Width Variation

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Abstract— **In this paper an analysis of a typical Heterojunction Bipolar Transistor Laser (HBTL) with a 160Å quantum-well in the base is developed to describe the Base width effect on optical frequency response and current gain using a charge control model. We have found that base width has an optimized value of about 1000Å for the highest -3db optical bandwidth. It will also be shown that, this procedure can similarly be extended to other Transistor Lasers. Finally It will be mentioned that, the current gain decreases with base width increment like other HBTs.**

Keywords-Transistor Laser; Quantum-well;HBTL; Base width; Optical frequency response

I. INTRODUCTION

The invention of transistor lasers (TL) in year 2006, made possible creation of an electronic device which works as transistor and laser with two optical and electrical output simultaneously [1-2]. Heterojunction Bipolar Transistor Lasers (HBTL) Performances such as optical frequency response and current gain (β) can be enhanced by optimizing its various parameters. Previous publications show optimization in quantum well (QW) position [3]. In this paper, a TL charge control modeling will introduce in section II, Base width effects on frequency response will be analyzed in section IV and the effect of base width on β will be mentioned in section V.

II. TL MODELING

Fig.1.a shows a schematic of an n-p$^+$-i (InGaP-GaAs-GaAs) typical transistor laser which is used in this work. Most of the recombination of electrons and holes in the base is occurred in the QW, which its width is shown by W_{qw}. x_{qw} is its distance from B-E junction. Base width which is optimized in this work will be shown by W_b. Geometry factor gives the fraction of base charge captured in the QW and define as : $\upsilon = (W_{qw} / W_b)(1 - x_{qw}/W_b)$. The TL is in active mode means that its B-E junction is under forward bias and B-C junction is under reverse bias. Fig.1.b shows charge control model for the base region. Two processes of electron and hole recombination are seen in this figure. The First is direct recombination outside the QW with lifetime of τ_{rb0} , and the second is direct recombination inside the QW. In the second one, the electrons are captured in the QW with lifetime of τ_{cap} and, recombine with the holes with life time of τ_{qw}^{eff}, which define as (1).

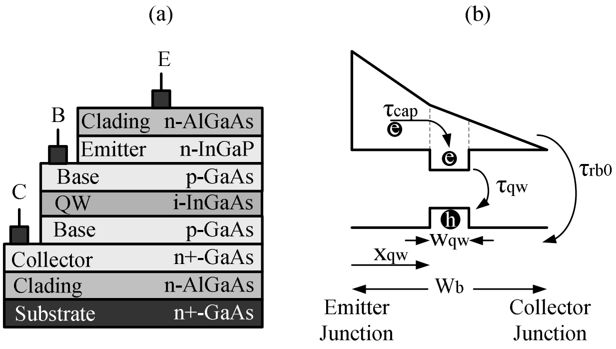

Figure 1. (a) Shematic of a typical Transistor Laser (Not to Scale). (b) Charge Control Model for the Base region of this HBTL under active bias.

$$\tau_{qw}^{eff} = \left(\frac{1}{\tau_{qw}} + \frac{1}{\tau_{st}}\right)^{-1} \qquad (1)$$

In (1), τ_{qw} is lifetime of spontaneous emission and τ_{st} is stimulated emission lifetime which occurs when base current is above threshold value. QW is considered, as a two level system in which recombination occurs only between electron and hole ground states, so $\tau_{st} = [\Omega N_p(t)]^{-1}$ where Ω is differential gain factor and N_p is photon density. For describing TL action, following coupled rate equations can be used: [4]

$$\frac{dn(t)}{dt} = \frac{\nu Q_b(t)}{\tau_{cap}} - \frac{n(t)}{\tau_{qw}} - \Omega[n(t) - n_{nom}]N_p(t) \qquad (2)$$

$$\frac{dN_p(t)}{dt} = \Omega[n(t) - n_{nom}]N_p(t) + \frac{\theta n(t)}{\tau_{qw}} - \frac{N_p(t)}{\tau_p} \qquad (3)$$

$$\frac{dQ_b(t)}{dt} = \frac{J(t)}{q} - \frac{Q_b(t)}{\tau_{rb}} \qquad (4)$$

$$\frac{1}{\tau_{rb}} = \frac{1-\nu}{\tau_{rb0}} + \frac{\nu}{\tau_{cap}} \qquad (5)$$

Equations (2),(3) are the coupled rate equations for electron-photon interaction in the QW. In (1), $\nu Q_b(t)/\tau_{cap}$ is base charge captured by the QW, $n(t)/\tau_{qw}$ is electron spontaneous recombination rate inside the QW, $\Omega[\, n(t) - n_{nom}\,]\, N_p(t)$ is the

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stimulated emission rate and n_{nom} is the transparency electron density. In (3), θ is fraction of spontaneous emission which is coupled to the cavity mode and $N_p(t)/\tau_p$ is photon loss. In (4), J(t) is base current density, and $Q_b(t)/\tau_{rb}$ is the base charge loss in which $1/\tau_{rb}$ is base charge loss rate which is weighted sum of the loss rate caused by the recombination outside the QW and by the QW capture process and is mentioned in (5). [4] The values of model parameters in this paper are the values of a typical HBTL and are: $\Omega=0.5cm^2/s$, $n_{nom}=10^{12}cm^{-2}$, $\tau_p=3.5ps$, $\tau_{rb0}=150ps$, $\tau_{cap}=1ps$, $\tau_{qw}=100ps$, $W_{qw}=160Å$, $x_{qw}=510Å$ [4],[6].

III. FREQUENCY RESPONSE

From the coupled rate equations (2)-(5), and phasor analysis, the optical output S(ω) can be obtained. The result is mentioned in (6):

$$S(\omega)=\frac{\Delta N_p(\omega)}{\Delta J(\omega)}=\left(\frac{1}{1+j\omega\tau_{rb}}\right)\frac{A}{\omega_r^2-\omega^2+j\omega\gamma} \tag{6}$$

where :

$$A=\frac{\Omega\nu N_{po}\tau_{rb}}{q\tau_{cap}} \tag{7}$$

$$\omega_r=\left(\frac{\Omega N_{po}}{\tau_p}\right)^{0.5} \tag{8}$$

$$\gamma=\frac{1}{\tau_{qw}}+\Omega N_{po} \tag{9}$$

|S(ω)| shows the small signal modulation response, and the frequency in which |S(ω)| is decreased to -3db for the first time is the cutoff frequency (f_{3db}). Fig(2) shows the optical frequency response of TL for different base widths. It can be seen that, when W_b is 1000Å the BW is larger than other cases. The cutoff frequency of TL as a function of W_b is plotted in Fig(3a). The optimum point of 1000Å is obvious in this plot too.

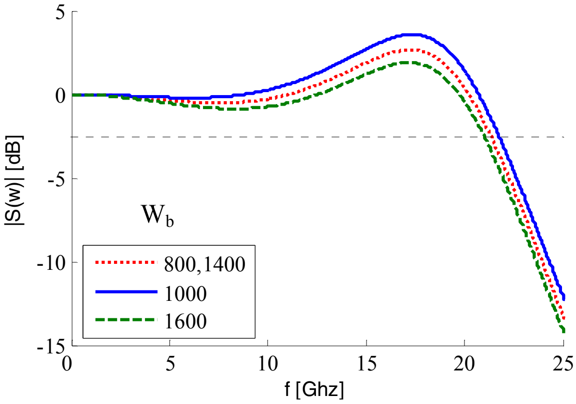

Figure 2. Optical Frequency Response of TL for four different Wb. It is seen that for Wb=800Å and Wb=1400Å, the two plot is completely matched, and for Wb=1000Å the highest f_{3db} will achieve.

IV. CURRENT GAIN

The current gain(β) of HBTs is defined as $\beta = I_C/I_B$ and it can be obtained from $\beta = \tau_n/\tau_b$,where τ_n is the base recombination life-time and τ_b is the base transit time [5]. In the case of HBTLs, β similarly can be defined as $\beta = \tau_{TL}/\tau_t$, where τ_{TL} is effective base recombination lifetime. In this work we assumed that $\tau_{TL}\approx\tau_{rb}$ [6]. From Eq(10) τ_t is base recombination life time and , so the β can be wrote as Eq(11).

$$\tau_t=\frac{W_b^2}{2D} \tag{10}$$

$$\beta=\frac{\tau_{TL}}{\tau_t}=\frac{\tau_{rb}\times 2D}{W_b^2} \tag{11}$$

According to Eq(11), β is a function of W_b, because instead of Wb term in the denominator, τ_{rb} is also a function of W_b since ν is related to W_b. (see (5)). Fig.3.b shows β as a function of W_b. It is clear that whit increasing W_b, the current gain of TL is decrease.

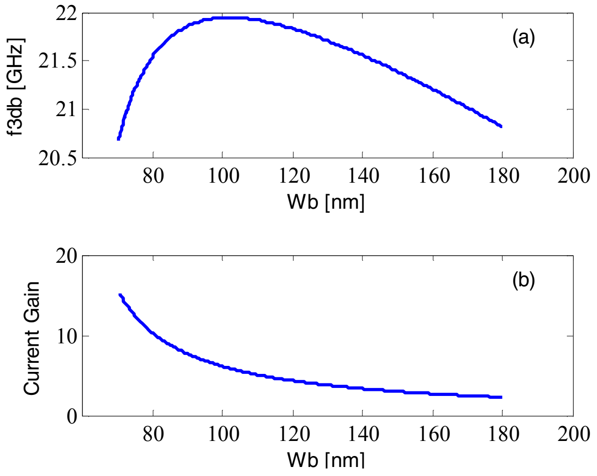

Figure 3. (a) f_{3db} of the typical TLwhich mentioned in this paper as a function of W_b. (b)current gain(β) of the same TL as a function of W_b.

V. CONCLUSION

We have shown that for a HBTL, the base width has an specific value for which reaches the largest bandwidth. We obtain this value for a typical HBTL as 1000Å using a charge control model. We also investigated the base width variation effect on current gain (β) of the mentioned HBTL.

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