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Effect of Collector Voltage on the Large and Small Signal Modulation Characteristics of 980 nm Transistor Laser

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ABSTRACT

Theoretical analysis of Transistor Laser is carried out and the static and frequency responses for different collector voltages, under common emitter configuration are determined. The threshold current (I_{th}) is observed as 33mA and it increases linearly with reverse collector to base voltage (V_{CB}). Meanwhile, the output optical power is found to decrease proportionately when V_{CB} is increased. A maximum of 18.7GHz modulation bandwidth is observed when an input base current of 95 mA is applied at a fixed value of V_{CB} (1V). The modulation bandwidth is found to decrease with increase in reverse V_{CB}. The turn on delay increases with collector voltage. However, it decreases with increase in base current.

Keywords: Transistor laser; F-K (Franz-Keldysh) effect; Modulation response; Large signal analysis; Small signal analysis

1. INTRODUCTION

The most common sources for optical communication include light emitting diode (LED) and LASER diode. However, the recent invention of Transistor Laser has made a significant improvement in optical sources, by producing light and electrical output simultaneously, for an electrical input[1].

The Transistor Laser's structure resembles that of an n-p-n hetero-junction bipolar transistor (HBT) with a base layer that contains an active region. With the introduction of optical cavities , the light emitting transistor (LETs) eventually turned into transistor laser (TL)[2]. Feng group[3,4] invented the TL having a quantum well (QW) in the base region of a HBT. Under forward bias, the electrons in the emitter are diffused, and the carriers are injected sufficiently into the base to create population inversion. A portion of the carriers recombines at the base region which leads to lasing. The rest of the carriers that are not recombined will be swept out to the collector terminal, contributing collector current in the TL. The maximum transmission data rate of Laser diode is limited to 40Gbps under direct modulation, which is overcome in the case of Transistor Laser. The demand for the resonance-free optical response combined with the high data rate transmission is met out by TL which provides the choice of both voltage and current modulation[4]. The harmonic and distortion analysis of the Transistor Laser based on the position of quantum well in the base region were investigated in detail[5-8].

Due to the significant presence of electric field in the intrinsic reverse biased collector-base region, there is an enhanced optical absorption of the photons which were generated in the active region. This occurs when the energy of the emitted photons is equal to band gap energy of the intrinsic reverse biased collector base junction and this is referred as Franz-Keldysh (FK) absorption effect[9,10]. The photon gain established by carrier injection will be more predominant than the photon absorption for the weaker base-collector junction field.

In the case of the stronger electric field in the reverse biased base-collector junction, there is a substantial reduction of optical output and it is been subsequently put out by Franz-Keldysh absorption. A plausible and relatively flat optical response is obtained in the experiments which were conducted by many authors by using voltage modulation[9,10]. In this paper, a rate equation based analysis is carried out to envisage the frequency response and pulse modulation characteristics under Franz-Keldysh effect in a 980 nm transistor laser.

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2. RATE EQUATIONS

To understand the dynamics of TL under different magnitudes of collector junction voltage, the rate equations incorporating Franz – Keldysh (F-K) effect is used[9,10].

$$\frac{dN}{dt} = \frac{\eta_i}{e}\frac{i_B}{V_a} - R - V_g g N_p + \eta_{BC}\frac{\Gamma_{J_{BC}}}{\Gamma_a} V_g \alpha N_p \quad (1)$$

$$\frac{dN_p}{dt} = \Gamma_a V_g g - \frac{N_p}{\tau_p} + \Gamma_a \beta_{sp} R_{sp} - \Gamma_{J_{BC}} V_g \alpha N_p \quad (2)$$

The parameter N_p is the photon density and N is the electron density. Injection efficiency is η_i, the base current is i_B, e is the charge of an electron and the volume of active region is V_a. The recombination rate of the carrier R represents the rate of spontaneous emission, $R_{sp} = \frac{N}{\tau_{sp}}$ .The group velocity is V_g and the optical gain $g = \frac{a_0(N - N_{tr})}{(1 + \varepsilon N_p)}$. The hole injection efficiency from the collector to base is η_{BC} and optical confinement factors of the active region and collector-base junction are Γ_a and $\Gamma_{J_{BC}}$ respectively. The lifetime of photons is τ_p and the spontaneous emission factor is β_{sp} . The spontaneous lifetime τ_{sp} is in the order of sub-nanoseconds and hence the threshold current density of TL is higher compared to laser diodes. However, this also leads to higher modulation bandwidth in case of TLs compared to LD's[2].

The optical absorption coefficient α based on Franz-Keldysh theory, under uniform electric field[9,10] is given by

$$\alpha = 1x10^4 \left(\frac{f}{n}\right)\left(\frac{2\mu}{m}\right) F^{\frac{1}{3}} \int_{\eta}^{\infty} |Ai(\eta)|^2 \, dz \tag{3}$$

The parameter $f \approx \left(1 + \frac{m}{m_v}\right)$ where, $m_v (= 0.087\ m_0)$ is the effective mass of the valence band light hole[11], electron mass in free space is $m\ (= m_o)$ and the refractive index n of GaAs is 3.5. The static electric field is given by $F = \frac{V_{CB}}{d}$ where, V_{CB} is the voltage between Base (B) and Collector (C) terminals (V_{CB}). The intrinsic GaAs collector-base junction thickness $d = 600^o A$. $\Gamma_{J_{BC}} V_g \alpha N_p$ in Eqn. (2) is the modal absorption rate. $\eta_{BC} \frac{\Gamma_{J_{BC}}}{\Gamma_a} V_g \alpha N_p$ in Eqn. (1) quantifies the injected supplementary charge carriers (electrons) from emitter into the base active region which eventually counterpoises the holes that are sent from collector to the base active region due to Franz-Keldysh absorption effect.

3. COMMON EMITTER CONFIGURATION

In Common emitter (CE) configuration, the emitter is made as the common terminal for both input and output ports. To define transistor laser in CE configuration, the input current is applied at base terminal. The optical output is taken from the base region and electrical output is taken from the collector terminal. The base current and voltage between collector and base (V_{CB}) are given as input to the rate equations (1)–(2) of the TL. The value of absorption co-efficient α changes according to the value of V_{CB}. Photon density and electron density can be calculated as the solution of rate equations. The optical power[1] is determined as follows,

$$P = \eta_i\, V_g\, \alpha_m\, N_p \left(\frac{hc}{\lambda}\right)\left(\frac{V_a}{\Gamma_a}\right) \tag{4}$$

where α_m is the mirror loss , c represents velocity of light, λ denotes the wavelength, V_g indicates group velocity, h, N_p and Γ_a represents Planck's constant, photon density and optical confinement factor of an active region respectively.

The TL is operated in active mode and its energy band structure is shown in Fig.1. The simulation parameters used in the rate equations[9] are given in Table 1.

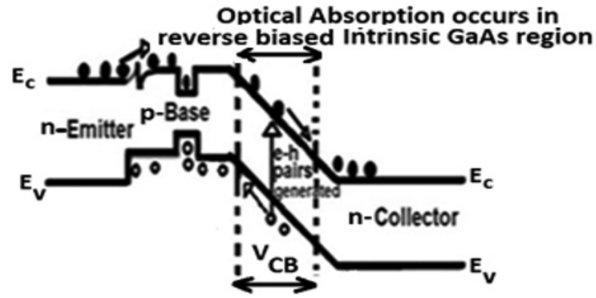


Figure 1. Band energy of TL with F-K effect[9].

Table 1. Parameters for 980 nm TL[9]

Parameters	Value
Absorption coefficient (α)	Variable (cm^{-1})
Group velocity (V_g)[1]	7.5×10^7 (m/s)
Differential gain (a_0)	6.1×10^{-20} (m^2)
Injection efficiency (η_i)	0.8
Injection efficiency of hole current from collector to base (η_{BC})	0.8
Photon lifetime (τ_p)	2.15 (ps)
Volume of active region (V_a)	16.08 (μm^3)
Confinement factor of BC junction (Γ_{JBC})	0.3659
Confinement factor of active region (Γ_a)	0.074481
Gain compression factor (ε)	1.5×10^{-23} (m^3)
Transparency carrier density (N_{tr})	7×10^{23} (m^{-3})
Spontaneous emission coupling factor (β_{sp})	8.69×10^{-5}

4. SIMULATION RESULTS

4.1 Steady state Characteristics

To find the steady state electron density and photon density for different input bias currents, the solutions of the coupled rate equation are obtained by solving them using 4th order Runge–Kutta method. The output optical power is calculated from Eqn. (4) which basically depends on the steady state photon density. The DC characteristics of transistor laser are obtained by providing the base current in the range of 0 to 100 mA, at different values of collector voltages, which is shown in Fig. 2(a).

The threshold value is found out to be 39 mA, for a collector base voltage of 0.5 V. The spontaneous emission will occur for the base current value less than of the threshold current value for the V_{CB} of 0.5 V. The stimulated emission occurs when the base input current is raised beyond 39 mA. These observations are in accordance with the literature[9] and hence validate our simulation. For a fixed base current, as the voltage V_{CB} surpasses a certain value, the device changes into an optical source that exhibit spontaneous-emission. Meanwhile, the collector current increases with reverse bias V_{CB}, as a result of the supplementary charge carriers (i.e., electrons) that are swept out to the collector terminal due to strong electric field across reverse biased collector-base junction. The threshold current values are found to increase with collector base voltage, due to the F-K absorption effect at appreciable values of V_{CB}. This observation is plotted in Fig. 2(b).

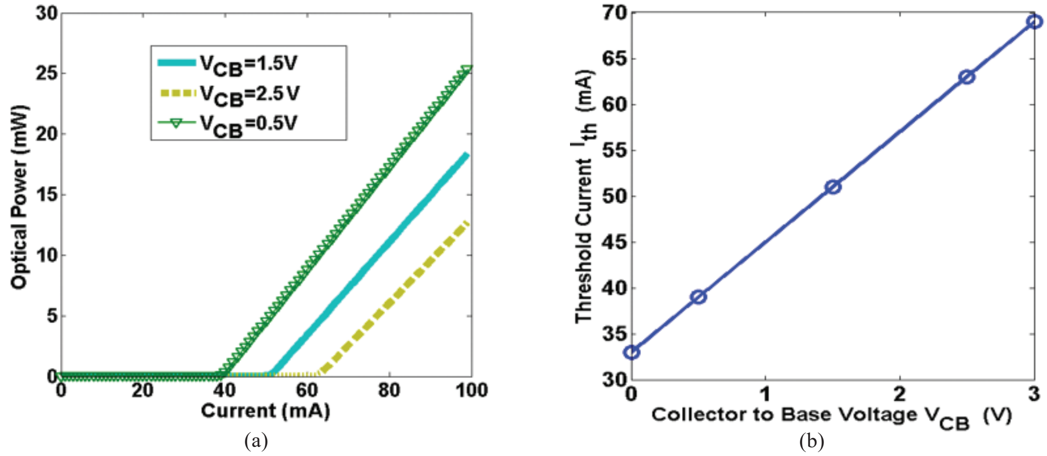


Figure 2. (a) Steady state optical power characteristics and (b) Variation of threshold current with V_{CB}.

4.2 Transient Characteristics

4.2.1 Subthreshold Region

Applying a step base current input of 30 mA (below threshold condition) with reverse collector to base bias voltage as 0.5 V, the electron density and the corresponding output power are determined and plotted in Fig. 3(a). A low output power before threshold in the order of microwatts is observed, which implies that the photon emission is due to spontaneous mode.

4.2.2 Above Threshold Region

Applying base current beyond threshold provides lasing action. An input step current of 80 mA with reverse collector to base bias voltage as 0.5 V is given to the device and the corresponding electron density and output optical power are evaluated and is shown in Fig. 3(b). During transient, the output produces an overshoot before it reaches the steady state.

4.3 Large Signal Pulse Characteristics

To understand the dynamic response of the TL for pulse input, a base current of 80 mA ($2.42I_{th}$) is provided and the variation of electron density and output optical power for various V_{CB} values are calculated and shown in Fig. 4. In the

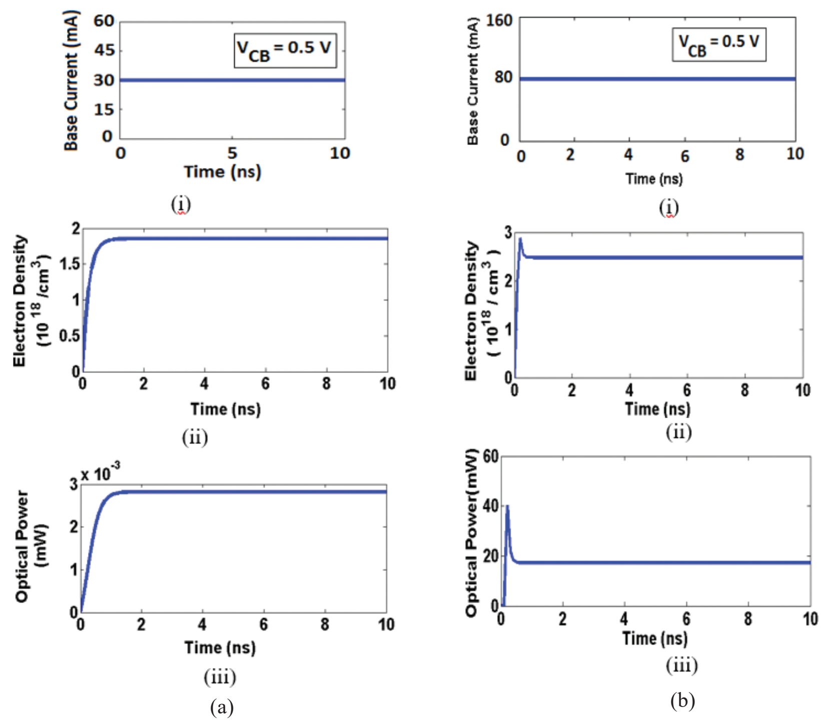


Figure 3. (a) Transient analysis below threshold for V_{CB}= 0.5V (i) Base current (ii) Electron density (iii) Output power and (b) Transient analysis after threshold for V_{CB}= 0.5V (i) Base current (ii) Electron density (iii) Output power.

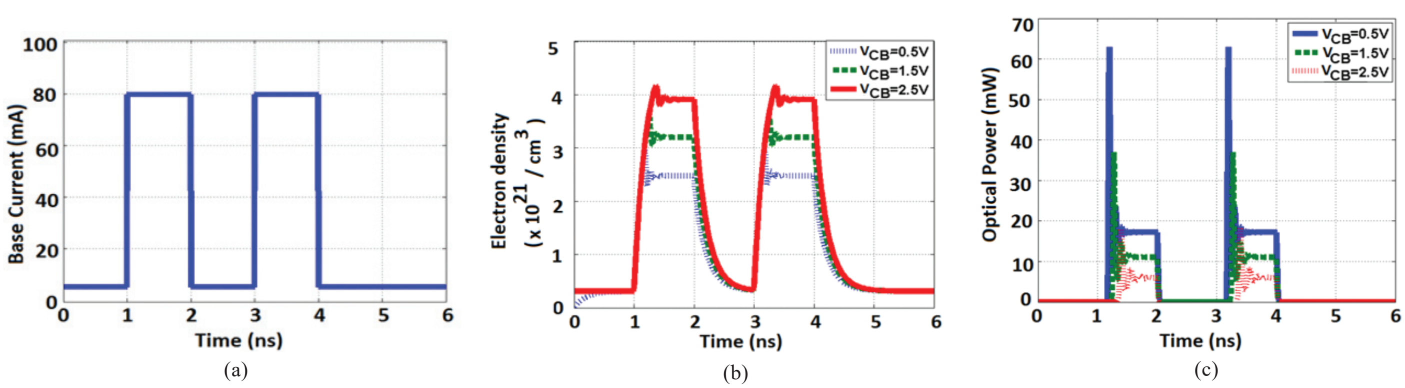


Figure 4. Temporal profile (a) Input base current pulse, (b) Electron density, and (c) Optical power at different values of collector to base voltage V_{CB}.

temporal profile, there is initially a ringing effect (relaxation oscillations) which is followed by steady state in the electron density and output optical power. From the simulation results, it is observed that the electron density increases with increase in V_{CB} due to F-K absorption effect. While, the output optical pulse amplitude decreases with increase in V_{CB}. Further, the oscillation and ringing is significant for lower values of V_{CB}.

The turn-on delay time (t_d) is evaluated for different values of V_{CB}, under various injection current and the plot is shown in Fig. 5. It is observed that, the turn-on delay time (t_d) increases with increase in V_{CB}, for a given base current. This, once again proves the significance of F-K absorption effect which alters the threshold current (I_{th}) proportionately. Moreover, when the injection current is raised appreciably, the turn-on delay time is reduced substantially, which in turn results in improvement of the maximum achievable bandwidth.

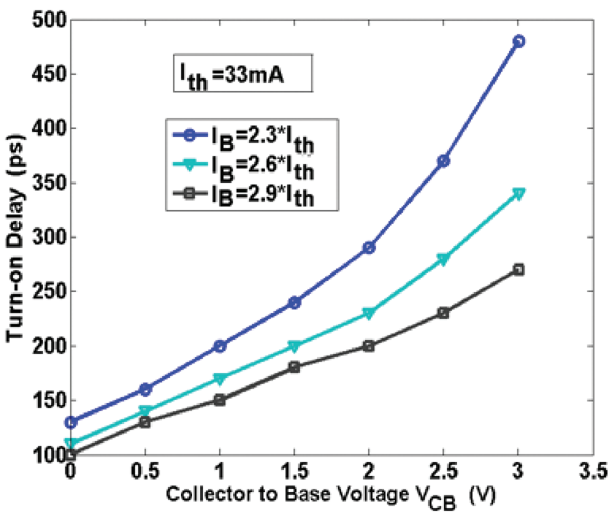
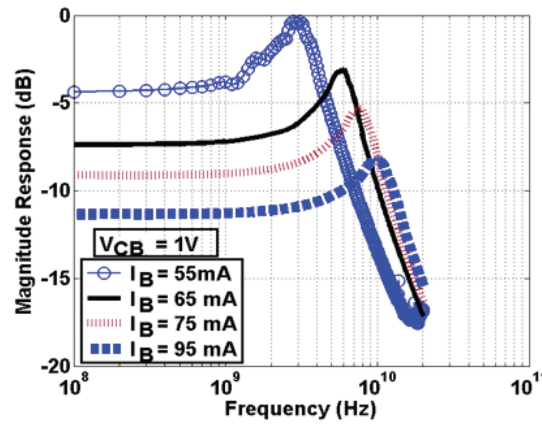


Figure 5. Turn-on delay Vs V_{CB} for various values of I_B.

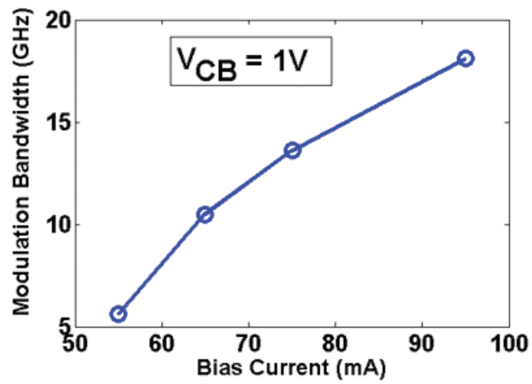
4.4 AC Characteristics of Transistor Laser

The AC analysis of Transistor laser is performed for various input currents. The input bias current $I(t)$ can be expressed as $I(t)=I_B+I_m \sin(\omega t)$, where I_B is the dc input base current bias and I_m is the RF current amplitude. The frequency response characteristics are determined for different input bias currents for a fixed value of V_{CB}=1V, is shown in Fig. 6(a). The resonance frequency and modulation bandwidth are identified. For higher values of bias current, larger value of photon density is obtained and hence the resonance frequency increases. This leads to an improvement in the modulation bandwidth in Transistor Laser. The variation of modulation bandwidth under different base current bias, for the fixed value of V_{CB} =1V is shown in Fig. 6(b).

The magnitude response at different collector to base voltage V_{CB}, for a fixed value of I_B= 75 mA is computed and shown in Fig. 7(a). It is observed that, under appreciable reverse bias voltage V_{CB}, there is a significant F-K absorption effect and hence the emission of photons reduces. Therefore, the modulation bandwidth is found to decrease with V_{CB} for a fixed value of I_B and the corresponding plot is shown in Fig. 7(b).



(a)



(b)

Figure 6 (a) Frequency response of TL under various values of IB with fixed V_{CB}=1V and (b) Modulation Bandwidth under different I_B values with fixed V_{CB}=1V.

5. CONCLUSIONS

In this work, the static and dynamic characteristics of TL under F-K effect is studied in detail by considering the standard two-level rate equation model. A threshold current (I_{th}) of 33mA is obtained for V_{CB}= 0V and it is found to increase linearly with V_{CB}. Subsequently, the output optical power decreases proportionately due to F-K effect as V_{CB} is raised, making the device to turn into spontaneous-emission mode. The turn-on delay time reduces from 470 ps to 280 ps when the injection current is increased from 2.3 I_{th} to 2.9 I_{th} for a fixed value of V_{CB}=3V. However, turn-on delay time is found to increase when V_{CB} is raised. A modulation bandwidth of 18.7 GHz is achieved when an input base current of 95 mA is applied for a fixed value of V_{CB}=1V. Further, the modulation bandwidth is found to decrease when V_{CB} is raised, due to F-K effect.

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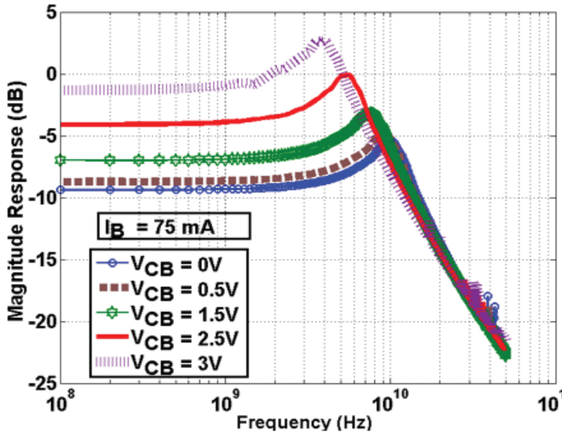
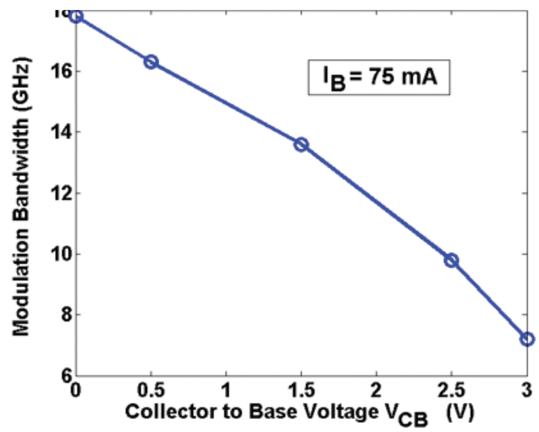


(a)



(b)

Figure 7. (a) Frequency response of TL under various values of V_{CB} with fixed I_B =75 mA and (b) Modulation bandwidth under different V_{CB} values with fixed I_B =75 mA.

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