Optical ASK and FSK Modulation By Using Quantum Well Transistor Lasers

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ABSTRACT—**In this paper, transistor lasers (TLs) are used as an optical modulator for generation of ASK(Amplitude Shift Keying) and FSK (Frequency Shift Keying) optical signals. Our analysis is based on continuity equation, rate equations, and the theory of discontinuity of quasi-fermi level at the abrupt junction. Our simulation results indicate that, the specification of ASK and FSK optical signals, are affected by dynamical behavior of TL. Also our simulation results indicate that, the collector-emitter voltage amplitude should be small enough that the nonlinear properties of TLs do not destroy the modulated optical signals.**

KEYWORDS: Quantum well transistor laser (QWTL), ASK (Amplitude shift keying), FSK (Frequency Shift Keying), Optical Modulation.

I. INTRODUCTION

In digital optical communications, the ASK(Amplitude Shift Keying) and FSK (Frequency Shift Keying) modulation formats are often used. The optical communication systems based on ASK and FSK modulations, are attractive because like all coherent systems they show an improved receiver sensitivity over direct detection and the inherent frequency selectivity of the optical receiver enables a close channel wavelength spacing[1-3].In ASK system, the carrier amplitude is changed in response to bit information, one particular amplitude for bit '1' and another amplitude for bit '0'[3].

In FSK system, the carrier frequency is changed in response to bit information, one particular frequency for bit '1' and another frequency for bit '0'[3]. The generation of FSK optical signals in semiconductor laser by employing an electrical equalizing circuit, has been reported[3]. Also an optical FSK transmitter based on an integrated distributed feedback (DFB) laser was proposed [4].

Recently, it is found that, nonlinear mixing in a twin-base-contact transistor laser (TL) is able to generate output mixing frequencies up to 8 GHz in the laser threshold region[5]. Also it is found that, the tunnel junction -TL enables a new nonlinear signal processing (adding and mixing) device operating above laser threshold for improved optical output power[6].The purpose of this paper is to present a theoretical analysis of quantum well transistor lasers used as modulator for generation of ASK and FSK optical signals. To our knowledge, for the first time, this paper describes the transistor laser as a digital modulator. Our analysis is based on continuity equation, rate equations [7],[8], and the theory of discontinuity of quasi-fermi level at the abrupt junction [9].

The organization of the paper is as follows: in section II, we develop the main formulation for the ASK and FSK modulation, in section III, results are discussed, in section IV, conclusions are presented.

II. METHOD AND THEORY

A schematic of quantum well TL is shown in Fig. 1. The device, consist of n-AlGaAs emitter, followed by p-GaAs layer as base. There is one quantum well (QW) that is located in the middle of the base region. Also the intrinsic GaAs layer acts as a collector.

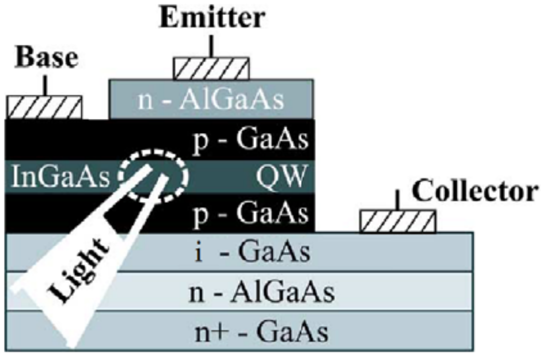

Fig. **1**. Schematic of HBTL.

The structure parameters of TL used in this paper are defined in Table 1.

Table **1**. Material Specification of HBTL used in simulation [7], [10].

Region	Doping	Material	Width
Base	4×10^{18}	P^{+} -GaAs	100nm
QW	-	i-InGaAs	10nm
Emitter	5×10^{17}	n-AlGaAs	500nm
Collector	-	i-GaAs	105nm

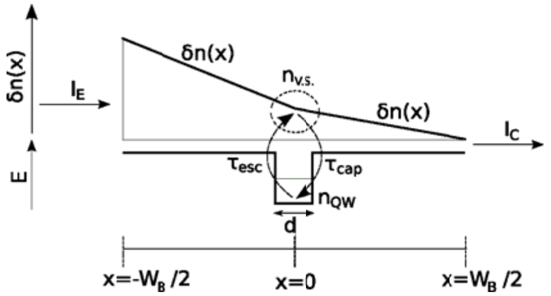

Fig. **2** Schematic of carrier diffusion and quantum capture in the QW, and the conduction band energy of the base region.

Fig. 2 shows the conduction energy band of the base and dc excess minority carrier distribution $[\delta N(x)]$, in the base region. The carriers injected from the emitter, diffuse across the base and reach the quantum well (QW). The unbounded carriers at x=0 are located at the virtual bound states.

We use the diffusion equation for the excess carriers in the base region[7],[8]:

$$\frac{\partial \delta N}{\partial t} = D_n \frac{\partial^2 \delta N}{\partial x^2} - \frac{\delta N}{\tau_B} \tag{1}$$

Eq. (1) is solved subject to the boundary conditions[7]:

$$J_E = qD_n \frac{\partial \delta N}{\partial x} \quad \text{at} \quad x = -\frac{W_B}{2} \tag{2}$$

$$J_C = qD_n \frac{\partial \delta N}{\delta x} \quad \text{at} \quad x = \frac{W_B}{2} \tag{3}$$

$$\delta N\left(0^-\right) = \delta N\left(0^+\right) = N_{V.S} \tag{4}$$

$$\delta N\left(\frac{W_B}{2}\right) = N_w \tag{5}$$

$$\delta N\left(-\frac{W_B}{2}\right) = N^+ \tag{6}$$

$$J_{V.S} = qD_n \frac{\partial \delta\left(0^-\right)}{\delta x} - qD_n \frac{\partial \delta\left(0^+\right)}{\partial x} \tag{7}$$

$$J_E = J_C + J_B \tag{8}$$

In above equations, D_n is the diffusion coefficient in the base, τ_B is the carrier recombination lifetime in the base region, J_E is the emitter current, J_C is the collector current, J_B is the base current, W_B is the base width, $N_{V.S}$ is the virtual states carrier concentration, and $J_{V.S}$ is the current to the virtual states due to diffusion.

From the concept of discontinuity of quasi-Fermi level at the base-emitter junction, we have[9]:

$$N^+ = N_0\left(e^{qV_{BE}/KT} - 1\right) + \frac{J_E e^{\Delta/KT}}{ev_R} \tag{9}$$

$$N_w = N_0\left(e^{qV_{BC}/KT} - 1\right) \tag{10}$$

where N_0, is the initial electron density at equilibrium, Δ is the conduction band discontinuity, v_R is the richardson velocity given by $v_R = \sqrt{KT/2\pi m}$, with m as the effective mass of electrons in the base. V_{BE}, and V_{CB} are the base-emitter and collector-base voltages, respectively. Using Eq. (1) and above boundary conditions, the carrier concentrations can be found:

$$\delta N_1 = \frac{N_{V.S}.e^{W_B/2L_D} - \left(L_D/qD_n\right)J_E}{2\cosh\left(W_B/2L_D\right)} e^{x/L_D} + \frac{N_{V.S}e^{-W_B/2L_D} + \left(L_D/qD_n\right)J_E}{2\cosh\left(W_B/2L_D\right)} e^{-x/L_D} \quad (11)$$

$$\delta N_2 = \frac{N_w - N_{V.S}\exp\left(W_B/2L_D\right)}{2\sinh\left(W_B/2L_D\right)}\exp\left(x/L_D\right) + \frac{N_{V.S}\exp\left(W_B/2L_D\right) - N_w}{2\sinh\left(W_B/2L_D\right)}\exp\left(-x/L_D\right) \quad (12)$$

where δN_1 and δN_2 are the dc carrier concentrations in the regions before the QW and after the QW, respectively, and L_D is the diffusion length defined as $L_D^2 = D_n \tau_B$.

Table **2**. Parameters of transistor laser [7]-[10].

Symbol	Description	Value
τ_S	Spontaneous emission lifetime	200ps
τ_B	recombination lifetime in base	200ps
τ_{cap}	Carrier capture time in QW	1ps
τ_{esc}	Carrier escape time from QW	10ps
τ_p	Photon lifetime in the cavity	4ps
τ_s	Spontaneous emission lifetime	200ps
G_0	Differential optical gain	10^{-5} cm^{3}s^{-1}
Γ	Optical confinement factor	0.05
Area	Area of the TL	16µm
β	Spontaneous emission factor	10^{-5}
L	Cavity length	200µm
R_1, R_2	Facet reflectivity	0.6
α_i	intrinsic absorption coefficient	4cm^{-1}
c	Speed of light	3×10^{10}cm/s
n_r	Reflective index	3.5

Solutions for J_E and J_B are obtained as:

$$J_E = N_{V.S}\frac{qD_n}{L_D}\left[\sinh\left(\frac{W_B}{2L_D}\right) + \left(\frac{\cosh^2\frac{W_B}{2L_D}}{\sinh\frac{W_B}{2L_D}}\right)\right] + J_{V.S}\cosh\left(\frac{W_B}{2L_D}\right) - \frac{qD_n}{L_D}N_w\coth\left(\frac{W_B}{2L_d}\right) \quad (13)$$

$$J_B = 2N_{V.S}\frac{qD_n}{L_D}\sinh\left(\frac{W_B}{2L_D}\right) + J_{V.S}\cosh\left(\frac{W_B}{2L_D}\right) \quad (14)$$

The Eq. (14) states that the base current has two component. The first term of Eq. (14), is the (radiative or nonradiative) recombination of carriers. The second term is the additional (radiative) recombination due to laser operation.

The rate equations describing the QW current, virtual states, QW bound states, and photon densities are [7]:

$$\frac{J_{QW}}{qd} = \frac{N_{V.S}}{\tau_{cap}} - \frac{N_{QW}}{\tau_{esc}} \quad (15)$$

$$\frac{dN_{V.S}}{dt} = \frac{J_{V.S}}{qd} - \frac{J_{QW}}{qd} - \frac{N_{V.S}}{\tau_s} \quad (16)$$

$$\frac{dN_{QW}}{dt} = \frac{J_{QW}}{qd} - \frac{N_{QW}}{\tau_s} - G_0\left(N_{QW} - N_{tr}\right)S \quad (17)$$

$$\frac{dS}{dt} = \left(\Gamma G_0\left(N_{QW} - N_{tr}\right) - \frac{1}{\tau_p}\right)S + \frac{\Gamma\beta N_{QW}}{\tau_s} \quad (18)$$

where J_{QW} is the current from the virtual states to the 2D bound states within the QW, N_{QW} is the QW carrier density, S is the photon concentration, Γ is the optical confinement factor, d is the QW width, N_{tr} is the carrier density at optical transparency, d is the QW width, τ_{cap} is the capture lifetime for the carriers falling from the virtual states to the QW states, τ_{esc} is the escape lifetime from the QW to the virtual states, τ_s is the spontaneous emission lifetime, G_0 is the optical gain .The photon lifetime in cavity τ_p is written as :

$$\tau_p^{-1} = \left(c / n_r\right)\left[\alpha_i + \ln\left(1 / R_1 R_2\right) / \left(2 L_{ca}\right)\right] \qquad (19)$$

where R_1 and R_2 are the cavity reflectivities, L is the cavity length, and α_i is the internal loss of cavity[7]. For our analysis, we consider a typical TL with material and geometrical parameters as given in Table 2 [7]-[10].

III. RESULTS

A. *Electrical responses of TL*

The C-V (current-voltage) analysis of transistor laser is done by solving Eqs. (9)-(18) numerically. The collector current of TL versus collector-emitter voltage, for different base current, is shown in Fig.3. The plot indicates the three regions of operation: The cut off, active, and saturation regions.

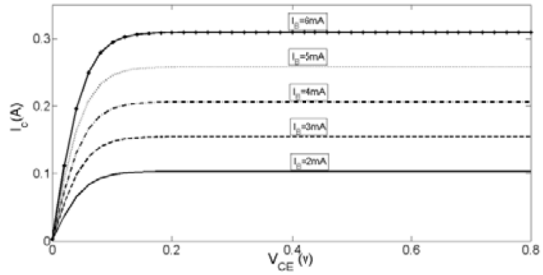

Fig. **3** Collector current versus collector-emitter voltage for different base current.

In active region, collector current is constant with increasing collector-emitter voltage. Indeed, it only depends on base current. In saturation region, the collector current depends on both the base current and collector-emitter voltage. From the Fig.3, it can be found that, the dc current gain $\left(\beta_{dc} = I_C / I_B\right)$ is approximately 50. This tendency aggrees with previous report [7].

B. *Threshold Current*

At threshold condition, $S = 0$, and $N_{QW} = N_{th}$. Using Eq. (18) :

$$G_0\left(N_{th} - N_{tr}\right) = \frac{1}{\Gamma \tau_p} \qquad (20)$$

Using Eq. (20), and Eqs. (15)-(18) at steady state condition, output photon numbers is:

$$S_0 = \left(\Gamma \tau_P / qd\right) J_{QW} - \left(1 / \tau_s\right) N_{th} \qquad (21)$$

The simulation results indicated that threshold base current is 1mA approximately [7], [8].

C. *Optical responses of TL*

By solving Eqs. (9)-(18), the output photon numbers can be found. The output photon number of TL versus collector-emitter voltage, for different base emitter voltages is shown in Fig. 4.

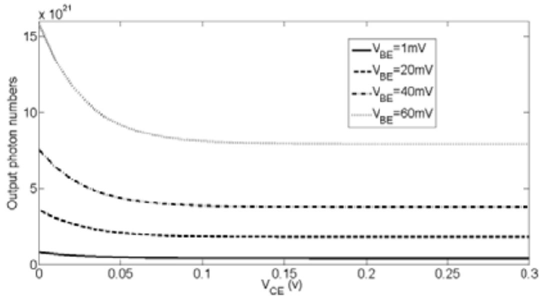

Fig. **4**. Output photon numbers versus collector-emitter voltage for different base-emitter voltage

As we can see, by increasing base-emitter voltage, the output photon numbers become higher. This increment of output photon numbers, occurs due to the increase in base current for larger V_{BE}. It can be found that, in saturation region, and for small collector-emitter signals, the linear relationship exists between output photon number and collector-emitter voltage.

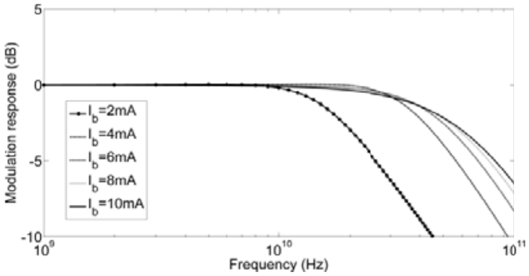

Fig. **5**. Modulation response of TL for different base current

The Modulation response of TL in the common base (CB) configuration is done by calculating the CB modulation transfer function $\left[s(jw) / j_e(jw)\right]$.

The small signal relationship between photon density and emitter current is found by linearizaition of Eqs. (13)-(18) and applying appropriate manipulations. The effect of base current on the small signal frequency response of TL in CB configuration is shown in Fig. 5. As shown in the figure, lower base current results in a degraded frequency response.

D. *ASK modulation by using TL*

The optical ASK modulator is shown in Fig.6**.** As we can see, the digital bits are applied to the base-emitter junction. Also the sinusoidal signal is applied to collector-emitter junction.

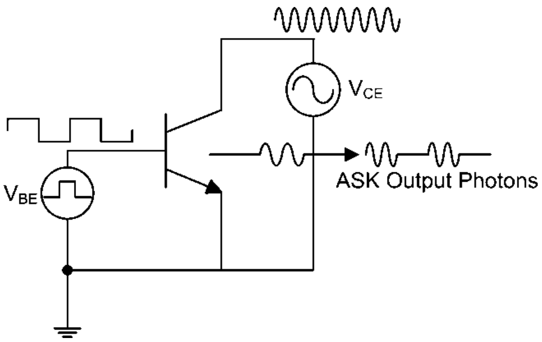

Fig. **6**. Schematic of ASK modulator using TL.

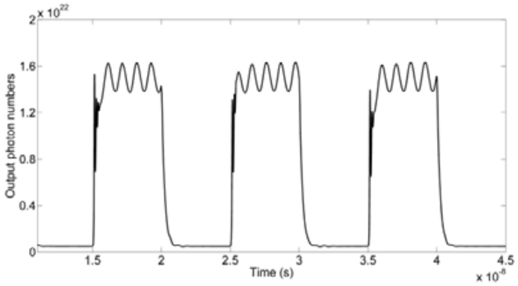

Fig. **7.** ASK optical signal versus time.

When the digital bit is zero, the transistor laser is off, and TL cannot be able to emit photons. When the digital bit is one, the transistor laser is on. According to Fig.4, in saturation region, the output photon numbers have linear relationship with collector emitter voltage. Therefore the frequency of output photon numbers is equal to frequency of collector emitter voltage when the digital bits are one. It is noteworthy, that the collector emitter voltage amplitude should be small enough so that the nonlinear effects do not appear. In our simulation for ASK modulation, the continuous pulse (5ns width) varing between 0 and 60mV, is applied to base emitter junction. The 20mV DC bias voltage is applied to collector-emitter junction. Also a 6GHz sinusoidal signal with 10mV amplitude is applied to collector-emitter junction.

By solving Eqs. (9)-(18), the ASK optical signal can be found. The output photon numbers versus time, is shown in Fig. 7**.** It can be found that, the dynamical properties of TL, affect the output photon numbers, when the base-emitter voltage changes.

E. *FSK modulation by using TL*

The optical FSK modulator is shown in Fig.8 As we can see, the digital bits are applied to the base-emitter junction of first TL.

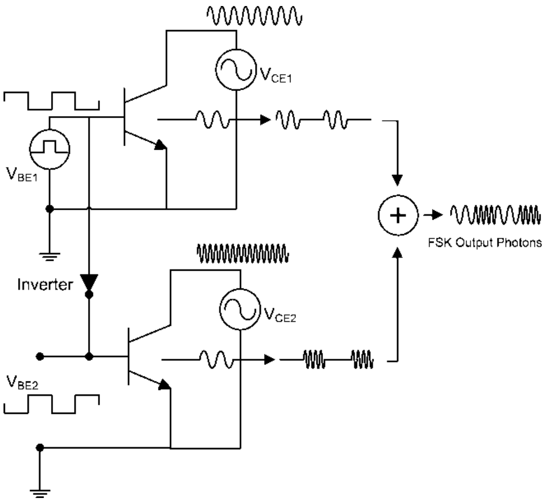

Fig. 8. Schematic of FSK modulator using TL

The digital bits are inverted by using the “NOT gate”. The inverted digital bits are applied to the base-emitter junction of second TL. Also the sinusoidal signals are applied to the collector-emitter junction of transistors. It is noteworthy that the frequency of sinusoidal signals should be different. Finally the output power of first and second TLs are added together and make the optical FSK signal. When the digital bits are zero, the first TL is off, and the second TL is on. In this case, the frequency of output power is equal to frequency of collector-emitter voltage of second transistor. When the digital bits are one, the first TL is on, and the second TL is off. In this case, the frequency of output power is equal to frequency of collector-emitter voltage of first TL

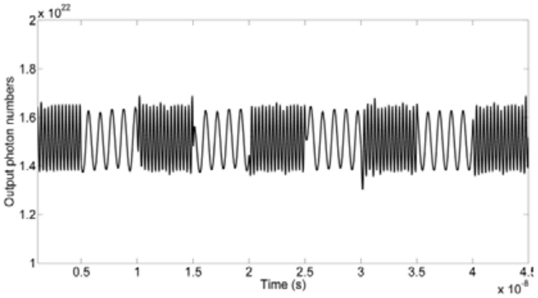

Fig. 9. FSK optical signals versus time

Indeed, the frequency of output power is changed, when the digital bits change from zero to one or from one to zero.

In our simulation for FSK modulation, the continuous pulse (5ns width) varing between 0 and 60mV, is applied to base emitter junction of first TL. Also the 6Ghz and 20Ghz sinusoidal signals with 10mV amplitude are applied to collector-emitter junction of first and second TLs respectively. The DC voltage bias for collector-emitter junction is 20mV. By solving Eqs. (9)-(18), the FSK optical signal can be found. The output photon numbers versus time, is shown in Fig. 9. It can be found that, the dynamical properties of TL, affect the output photon numbers, when the base-emitter voltage change.

The most important parameter, that limits the maximum bit rate, is transient response of TL.

Indeed, the pulse width must be greater than settling time of TL. From Fig.7, it can be found that settling time is 0.5ns. The settling time must be less than 25% of pulse width.

Therefore the maximum pulse width should be greater than 2ns and bit rate should be lower than 500 MHz. It is noteworthy that, this settling time amount, obtained from our simulation results with parameters defined in Table 2. Indeed, settling time depends on injected current level, and laser parameters.

IV. CONCLUSION

The optical ASK and FSK modulator are designed by using quantum well transistor laser. These modulators can be used in optical communication systems.

The results show that dynamical behavior of TL affects the specification of modulated optical signals. Also we found that, for linearity of response, carrier signal amplitude should be limit to small value.

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