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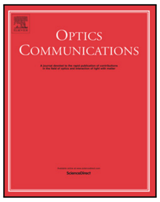

Effect of quantum well position on the distortion characteristics of transistor laser

S. Piramasubramanian *, M. Ganesh Madhan *, V. Radha, S.M.S. Shajithaparveen, G. Nivetha

Department of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India

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ABSTRACT

The effect of quantum well position on the modulation and distortion characteristics of a 1300 nm transistor laser is analyzed in this paper. Standard three level rate equations are numerically solved to study this characteristics. Modulation depth, second order harmonic and third order intermodulation distortion of the transistor laser are evaluated for different quantum well positions for a 900 MHz RF signal modulation. From the DC analysis, it is observed that optical power is maximum, when the quantum well is positioned near base–emitter interface. The threshold current of the device is found to increase with increasing the distance between the quantum well and the base–emitter junction. A maximum modulation depth of 0.81 is predicted, when the quantum well is placed at 10 nm from the base–emitter junction, under RF modulation. The magnitude of harmonic and intermodulation distortion are found to decrease with increasing current and with an increase in quantum well distance from the emitter base junction. A minimum second harmonic distortion magnitude of −25.96 dBc is predicted for quantum well position (230 nm) near to the base–collector interface for 900 MHz modulation frequency at a bias current of 20 I_{bth}. Similarly, a minimum third order intermodulation distortion of −38.2 dBc is obtained for the same position and similar biasing conditions.

1. Introduction

RF modulated optical signal transmission through fiber finds many applications in the present communication systems. They include antenna remoting, Cable Television (CATV) and phased array radar. In such schemes, fiber replaces coaxial medium due to its huge bandwidth, low loss and less cost [1–3]. This technology is termed as Radio over Fiber (RoF) which utilizes both long and short range analog optical fiber links. In Fiber-to-the-Home (FTTH) networks, optical fiber is used to transmit video signals and data from the head end to subscribers. Optical fiber is installed between central base station and remote antenna units in the case of mobile cellular applications. Radio over fiber is also found useful for Global Positioning System (GPS) over fiber for indoor applications and distributed antenna system in aircraft cabin [4–9]. RF to RF link efficiency is the parameter that indicates the effectiveness of the RoF systems. Higher modulation depth is required in the optical modulator to increase the overall link efficiency [3]. Fiber loss and photodiode responsivity are other factors that affect the RF to RF link efficiency. Direct modulation of laser diode is preferred in the most of the fiber links than external modulation due to its reduced complexity and less cost. The modulation index is found to be higher when the laser is biased near to its threshold current in the case of direct modulation. However, biasing the laser diode in this region also produces non linear distortion, when modulated by two or more number of RF tones. Harmonic and intermodulation distortion from the optical source affect the performance of the radio over fiber link. Second harmonic distortion (2HD) analysis is mandatory for the optical source in the case of CATV applications. Fourth and higher order harmonics are not considered in many applications as their magnitudes are quite less. The level of distortion should be less than −50 dBc for analog video signal transmission [7]. Hence, many linearization techniques are used in the laser diode to reduce these distortions. They include predistortion, feed forward and feedback harmonic injection techniques [7].

The Transistor Laser (TL) is a semiconductor device that functions as a normal transistor with an electrical input and generates simultaneous optical and electrical output signals.

The transistor laser was invented by Holonyak and Feng and most of the publications on transistor laser are from the same author group [10–15]. It can be considered as a three port device with electrical input port along with optical and electrical output ports. The transistor laser consists of single or multiple quantum well in its base region

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* Corresponding authors.
E-mail addresses: spirama@annauniv.edu (S. Piramasubramanian), mganesh@annauniv.edu (M. Ganesh Madhan).

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which produces infrared light by radiative recombination. A reflective cavity in the device leads to lasing action. The quantum well captures the electrons injected in the device and allows it to recombine with positively charged holes in the base region. The device produces photons through stimulated emission process which results in laser beam generation from the cavity. The electrons that are not captured in the quantum well are swept into the collector which produces electrical output [16–19]. As transistor laser is characterized by fast recombination life time, large optical bandwidth, it is envisaged as a potential candidate for analog optical link applications. Low distortion, large dynamic range and minimum noise are the important requirements for optical sources in analog applications. In the literature [17,19], the effect of Quantum Well (QW) position in the base is analyzed for power current characteristics and frequency response characteristics. However their influence in modulation depth and distortion performance has not been previously investigated. The analysis of transistor lasers is carried out by using charge control model [20–22].

In this work, modulation and distortion characteristics of transistor laser are analyzed for different positions of Quantum Well in the base region. The location of quantum well is varied from base–emitter interface to base–collector interface. The position of single quantum well is an important parameter along with quantum well width, that affect the base charge life time [16]. It is well known that the modulation characteristics of any optical source depends on carrier life time. The rate equations which incorporate charge control model of the transistor laser are numerically solved to determine the basic TL characteristics. Based on the same model, we proceed further to investigate the effect of position of the quantum well on the modulation depth, second harmonic and third order intermodulation distortion performance of the TL. Harmonic distortion and modulation analysis are carried out at 900 MHz. Third order intermodulation distortion (IMD3) is calculated for two tone frequencies at 890 MHz and 910 MHz respectively. These frequencies are considered, as they correspond to the carrier frequencies of Global System for Mobile communication (GSM) 900 based cellular communication. The Transistor Laser is assumed to be the optical transmitter for cellular based radio over fiber link.

2. Transistor laser model

The schematic diagram of a transistor laser is shown in Fig. 1(a) [17]. The schematic of energy band diagram of the base region with different quantum well position in the device are shown in Fig. 1(b) and (c). The quantum well placed near to the base–emitter interface and base–collector interface are shown in Fig. 1(b) and 1(c) respectively.

The TL operation in the active region requires base–emitter junction to be forward biased and base–collector junction to be reverse biased. The three level rate equations with charge control model is considered in this work [16,17]

$$\frac{dn(t)}{dt} = \frac{vQ_b(t)}{\tau_{cap}} - \frac{n(t)}{\tau_{qw}} - \frac{v_g g_o}{(n(t)+N_s)(1+\varepsilon_{other}N_p(t))}[n(t)-n_{nom}]N_p(t) \quad (1)$$

$$\frac{dQ_b(t)}{dt} = \frac{I_b(t)}{qV} - \frac{Q_b(t)}{\tau_{rb}} \quad (2)$$

$$\frac{dN_p(t)}{dt} = \frac{\Gamma v_g g_o}{(n(t)+N_s)(1+\varepsilon_{other}N_p(t))}[n(t)-n_{nom}]N_p(t) + \frac{\theta n(t)}{\tau_{qw}} - \frac{N_p(t)}{\tau_p} \quad (3)$$

$$\frac{1}{\tau_{rb}} = \frac{1-v}{\tau_{rbo}} + \frac{v}{\tau_{cap}} \quad (4)$$

Where, $Q_b(t)$ represents the base charge density. $n(t)$ and $N_p(t)$ represent electron density and photon density in the active region of the transistor laser respectively. The base charge captured by the quantum well is given by $(\frac{vQ_b(t)}{\tau_{\mathrm{cap}}})$. The spontaneous recombination rate for electron inside the quantum well is represented by $(\frac{n(t)}{\tau_{qw}})$ and it is implemented by $(B_{\mathrm{eff}}n^2)$ in the analysis. The stimulated emission term in the rate equations is $\Omega\ [n(t)-n_{\mathrm{nom}}]\ N_p(t)$ and the photon loss is given by $(\frac{N_p(t)}{\tau_p})$. The value of base charge bulk life time (τ_{rbo}) is calculated from the parameter $(1/B_{\mathrm{eff}}\ N_b)$, where N_b is low p-doping density. A charge control model is used to describe the dynamics of the minority carrier charge stored in the base. A single quantum well is assumed in the base region of the transistor laser for this analysis. The geometry factor (v) which depends on the relative position of quantum well in the base is given by [16]

$$v = (\frac{W_{qw}}{W_b})(1 - \frac{x_{qw}}{W_b}) \quad (5)$$

v gives the fraction of the base charge captured in the quantum well. Here, W_{qw} is the quantum well width, W_b is base region width, and x_{qw} is the distance from the base–emitter junction to the quantum well.

Table 1
Model parameters [17].

Parameter	Description	Value
τ_{cap}	Electron capture time in quantum well	1 ps
τ_{esc}	Electron escape time in quantum well	1 ns
τ_{rbo}	Carrier life time in the base region	1 ns
n_{nom}	Transparency electron density	10^{18} cm^{-3}
τ_p	Lifetime of photon	4.1ps
N_s	Carrier density-fitting parameter	0.26×10^{18} cm^{-3}
W_{qw}	Well thickness	5 nm
$d_{barrier}$	Barrier thickness	10 nm
W	Stripe width	2 μm
W_b	Total base width	250 nm
L	Cavity length	250 μm
R	Reflectivity	0.3, 0.9
g_0	Material gain	3600 cm^{-1}
Γ	Optical confinement factor	0.011/well
α_1	Internal loss	5 cm^{-1}
ε_{other}	Gain compression factor	0.5×10^{-17} cm^3
B_{eff}	Recombination coefficient	1.55×10^{-10} cm^{-3} s^{-1}
θ	Spontaneous emission coefficient	10^{-6}
v_g	Group velocity	0.782×10^8 m/s

3. Simulation results

3.1. DC characteristics

In the rate equations (1)–(4), the values of $\frac{dn(t)}{dt}$, $\frac{dQ_b(t)}{dt}$ and $\frac{dN_p(t)}{dt}$ are fixed as zero and the equations are solved for static conditions. A fourth order Runge–Kutta method is used to solve the rate equations in the MATLAB® tool. The parameters used in this numerical analysis are given in the Table 1. The dimensions of our present work are similar to the work of Shirao et al. [17] and exactly similar device structure is used. AlGaInAs/InP material system of 1.3 μm transistor laser is used in our analysis which is similar to the work of Shirao et al. [17].

The steady state solutions of the electron density, base charge and photon densities are obtained for a base current variation between 0 and 15 mA. Further, optical power is evaluated for different quantum well positions in the range of 10 nm to 230 nm from the emitter base junction and plotted in Fig. 2(a). The optical power is found to decrease for a movement of the quantum well position towards base–collector interface. This is due to the fact that more charges are captured in the quantum well when it is near the base–emitter interface. Moreover better recombination occurs, which results in generation of more photons. The effect of position of quantum well in the base region on the threshold current of the device is analyzed. It is observed that the threshold current is found to increase with movement of quantum well position towards base–collector interface and is plotted in Fig. 2(b). A base threshold current of 2.1 mA and 2.4 mA are obtained for the quantum well position x_{qw} = 10 nm and 122.5 nm respectively. The