OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 10, No. 9-10, September-October 2016, p. 616 - 618

Direct modulation response of a 1.55 µm InGaAsP ridge waveguide laser

M. S. ÖZYAZICI*
Bahcesehir University, Electrical and Electronics Eng. Dept., 34353 Besiktas, Istanbul, Turkey

The high frequency direct modulation response and the -3 dB bandwidth of a 1.55 µm InGaAsP ridge waveguide laser are investigated by using a mathematical model based on single-mode rate equations including Auger recombination, nonradiative recombination and gain compression parameters. The effect of each laser parameter on the laser modulation response and the -3 dB bandwidth are determined. It is found that among all parameters the gain compression and Auger recombination are the most effective parameters affecting the direct modulation response and the -3 dB bandwidth.

(Received July 10, 2015; accepted September 29, 2016)

Keywords: Direct modulation, Bandwidth, Ridge waveguide, Semiconductor laser

1. Introduction

The radio over fiber (RoF) technology has recently attracted considerable attention as an integration of wireless and optical systems and consequently as a solution to enhance the communication bandwidth to support integrated services [1]. However, enhancing the bandwidth of RoF links with directly modulated semiconductor lasers is limited by the available modulation bandwidth of semiconductors lasers. Therefore, considerable attention has been focused on the increasing direct modulation bandwidth of semiconductor lasers. Increasing the differential gain is an efficient technique to increase the modulation bandwidth [2]. Modulation up to a frequency of 25 GHZ was achieved [3]; however a record of 40 GHZ response is challenging. High frequency modulation beyond 40 GHz by the technique of injection locking was demonstrated [4].

The linear relationship of dc excitation current to the light output of semiconductor lasers leads us the direct modulation of semiconductor lasers. The static, spectral and dynamic characteristic of semiconductor lasers and their dependence on various device parameters are described by a pair of rate equations. For optimum design of optical communication systems, the required dc excitation, rf current and the effect of various device parameters on the modulation response and the -3 dB bandwidth of semiconductor lasers should be determined.

In this work, single-mode rate equations are solved numerically by using fourth order Runge-Kutta-Fehlberg method [5]. The important parameters of 1.55 µm InGaAsP semiconductor lasers such as Auger recombination, nonradiative recombination and gain compression are taken into account. The effect of laser parasitics on the modulation response is also included in calculations. The direct modulation response of the laser diode is simulated by use of computer. The -3 dB bandwidth of the laser diode is determined from the direct modulation response. Standard device parameters are taken for 1.55 μm InGaAsP ridge-waveguide structure laser. The parameters effecting the modulation response and -3 dB bandwidth of the laser diode are identified.

2. Theoretical analysis

Laser dynamics are commonly described by a pair of rate equations governing the photon and carrier densities inside the laser medium. To get a good approximation to the experimental results in InGaAsP semiconductor lasers, some extra terms should be added to the rate equations. Auger recombination which is important due to narrow band gap structure of InGaAsP laser diodes and nonradiative recombination (recombination through traps) are included in the rate equations. An extra term incorporating an optical field dependent gain saturation or compression is also included in the rate equations. The inclusion of a gain compression term is phenomenological approach in that it can represent a number of mechanisms including spatial hole burning and lateral carrier diffusion [6, 7], spectral hole burning and other nonlinearities [8]. Hence the single-mode rate equations including these terms are written as [9]

$$\frac{dN_e}{dt} = \frac{I}{qV_a} - g^{'}(N_e - N_t)N_p - (\frac{1}{\tau_{nr}} + B_r N_e + C N_e^2) N_e \quad (1)$$

$$\frac{dN_p}{dt} = \Gamma g^{'}(N_e - N_t)N_p - \frac{N_p}{\tau_p} + \Gamma k_s B_r N_e^2 \quad (2)$$

where N_e is the electron density (cm^{-3}), N_p is the photon density (cm^{-3}), I is the current (A), q is the electronic charge (As), V_a is the volume of the active region (cm^3), N_t is the electron transparency (cm^{-3}), τ_{nr} is the nonradiative recombination lifetime (s), B_r is the radiative recombination coefficient (cm^3/s), C is the Auger recombination rate (cm^6/s), Γ is the optical confinement factor (fraction of the optical mode lying inside the active region), τ_p is the photon lifetime (s) and k_s is the fraction of spontaneous emission into the mode. The gain compression is given by [9]

$$g' = \frac{g_o}{1+\varepsilon_c N_p} \tag{3}$$

where g_0 is the gain constant (cm^3/s) and ε_c is the gain compression parameter. Equation (1) and Equation (2) are normalized by using the equations given in [9] as

$$\frac{dn_e}{dt'} = i - \frac{1}{1+\varepsilon_c' n_p}(n_e - n_t)n_p - (1+B_r' n_e + C' n_e^2)n_e \tag{4}$$

$$\frac{dn_p}{dt'} = \alpha\left[\frac{\Gamma}{1+\varepsilon_c'} - n_p + \Gamma k_s B_r' n_e^2\right] \tag{5}$$

where B_r' is $B_r\tau_{nr}/g_o\tau_p$, C' is $C\tau_{nr}/(g_o\tau_p)^2$, α is τ_{nr}/τ_p and ε_c' is $\varepsilon_c/g_o\tau_n$.

If the gain compression is neglected, the normalized steady-state electron, photon densities and threshold current are

$$n_{es} = \frac{1}{\Gamma} + n_t \qquad \text{for} \qquad i_b > i_{th} \tag{6}$$

$$n_{ps} = i_b - i_{th} \qquad \text{for} \qquad i_b > i_{th} \tag{7}$$

$$i_{th} = (1 + B_r' n_{es} + C' n_{es}^2)n_{es} \tag{8}$$

where i_b is the normalized dc bias current. The applied current i with a small sinusoidal signal is taken as

$$i = i_b + i_{rf} P(\omega)\sin(\omega t' \tau_{nr} + \phi(\omega)) \tag{9}$$

where i_{rf} is the applied rf current and ω is the radian frequency. $P(\omega)$ and $\phi(\omega)$ are used to take into account the effect of laser parasitics [10] on the modulation response.

3. Results and conclusions

The normalized rate equations with an input current i are solved numerically for frequencies ranging from 250 MHz to 20 GHz and the standard parameter values. The standard parameter values used in the numerical analysis are typical for a ridge waveguide structure 1.55 μm InGaAsP laser. The parameter values are given in the Table 1. The values have been obtained from [9].

Table 1. The standard parameter values of ridge waveguide 1.55 μm InGaAsP laser diode

Parameter definition and units	Symbol	Value
Optical confinement factor	Γ	0.3
Radiative recombination coefficient (cm^3/s)	B_r	0.9×10^{-10}
Auger recombination coefficient (cm^6/s)	C	6×10^{-29}
Optical gain coefficient (cm^3/s)	g_o	3.2×10^{-6}
Electron transparency density (cm^{-3})	N_t	1×10^{18}
Photon lifetime (s)	τ_p	1×10^{-12}
Nonradiative recombination lifetime (s)	τ_{nr}	15×10^{-9}
Spontaneous emission factor	k_s	2×10^{-4}
Gain compression parameter (cm^3)	ε_c	6.7×10^{-17}
Active volume (cm^3)	V_a	2×10^{-10}

The computed photon density at each frequency is plotted to obtain the modulation response of the laser diode. The following graphs are obtained when laser diode is biased for the same output power and modulated with a 6.54 mA rf current.

The threshold current for the standard parameter values is calculated as 32.7 mA from Equation (6) and Equation (8).

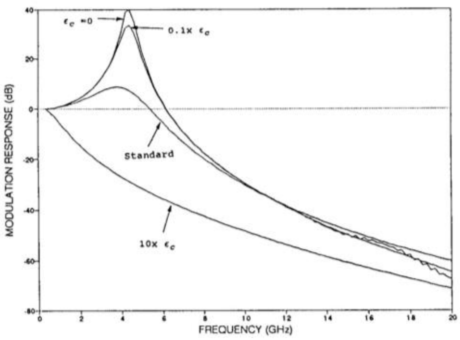

Fig. 1. The effect of gain compression on the modulation response

Fig. 1 shows the modulation response of the laser diode for various values of gain compression as a function of frequency. The -3 dB bandwidth of the laser diode for the values of gain compression parameter 0, 6.7×10^{-18}, 6.7×10^{-17} and 6.7×10^{-16} is found as 6.5 GHz, 5.75 GHz and 0.75 GHz, respectively. It is clear that increasing the gain compression decreases the bandwidth of the laser diode. When the gain compression is increased by ten times of its standard value, the bandwidth reduces to MHz range. This is due to the fact that increased gain compression decreases the optical gain as compared to the case when there is no gain compression. Hence, the bandwidth of the laser diode decreases considerably.

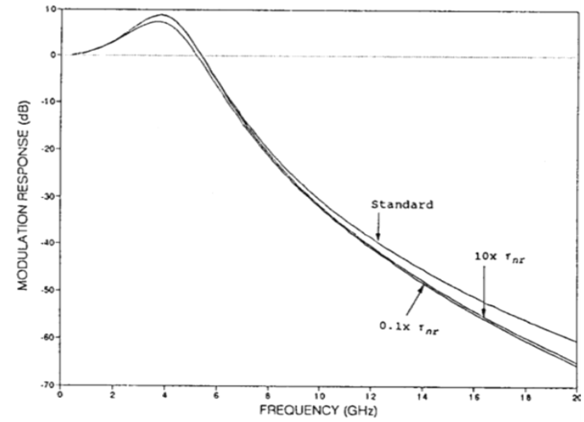

Fig. 2. The effect of nonradiative lifetime on the modulation response

Fig. 2 shows the modulation response of the laser diode for various values of nonradiative lifetime as a function of frequency. The -3 dB bandwidth of laser diode for the values of $\tau_{nr}=15\times10^{-8}$, 15×10^{-9} and 15×10^{-10} is found as 5.5 GHz, 5.75 GHz and 5.76 GHz, respectively. As it can be seen from Fig. 2, the variation of τ_{nr} does not change the bandwidth of the laser diode considerably. This is because the nonradiative recombination linearly effects the electron density in the rate equations.

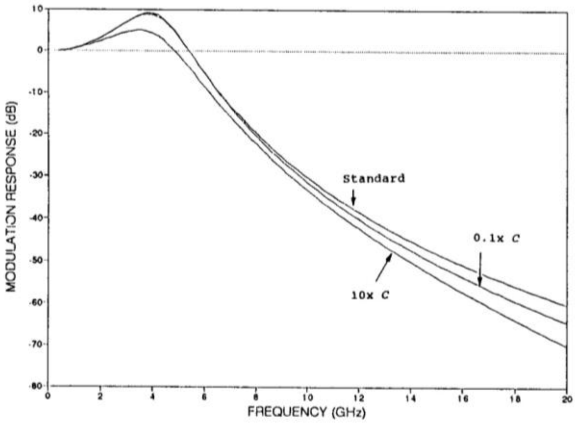

Fig. 3. The effect of Auger recombination on the modulation response

Fig. 3 shows the modulation response of the laser diode for various values of Auger recombination parameter as a function of frequency. The -3 dB bandwidth of the laser diode for the values of Auger recombination 6×10^{-30} and 6×10^{-29} is found as 5.76 GHz and 5.3 GHZ, respectively. Fig. 3 indicates that increasing Auger recombination decreases the bandwidth. This can be explained as follows. Auger recombination rate is proportional to the cube of the carrier density. If Auger recombination rate is increased, the carrier density in the active region decreases. Hence, the optical gain and the bandwidth of the laser diode decrease.

In conclusion, the computer results show that the gain compression and Auger recombination are the most effective parameters on the bandwidth of InGaAsP laser diodes. The results also show that the bandwidth of InGaAsP laser diodes can be increased by growing InGaAsP material with low Auger recombination rate and designing much better structure laser diode which will have low gain compression parameter.

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[*] Corresponding author: sadettin.ozyazici@eng.bahcesehir.edu.tr