Temperature dependence of the frequency response of InGaAsP/InP semiconductor laser : Theoretical approach

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Abstract
THis paper investigates theoretically the temperature effect on the frequency response of a semiconductor laser . The theoretical results are compared to the published ones where a fair agreement is noticed in particular of the 3 dB frequency .

I - Introduction
The high power efficiency and high speed capabilities of III-V semiconductor lasers have made signal transmission in both digital and analog optical fiber communication systems a reality [1] .The development of silica optical fibers, that have lowest transmission loss and lowest dispersion in the 1 - 1.7 µm , region has stimulated more interest in the quaternary In Ga As P materials because the resulting band gap-wavelength covers the above spectral region [2] .The particular compostion $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ of the active layer which lattice matches In P is chosen because its band gap (E_g =0.96 ev , λ = 1.3 µm) is at region of low loss and minimum dispersion in optical fibers [3] .
In the present work , the temperature dependence of the frequency response of semiconductor lasers is theoretically investigated .

II - Small-Signal Modulatoin of a Semiconductor Laser
The frequency response of a semiconductor laser can be predicted by appropriate rate equations describing the electron N and the photon S densities in the active region of the laser [4] :

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{g_0}{1+\epsilon S}(N-N_T)S - \frac{N}{\tau_n} \qquad (1)$$

where I is the injected current , q is the electronic charge , V is the active region volume , g_0 is the unsaturated gain , ϵ is the gain compression parameter , N_T is the electron density at transparency , and τ_n is the electron lifetime ,
and :

$$\frac{dS}{dt} = \frac{g_0}{1+\epsilon S}\Gamma(N-N_T)S - \frac{S}{\tau_p} + \beta\Gamma\frac{N}{\tau_n} \qquad , (2)$$

where Γ is the confinement factor , β is the spontaneous emission

- constant , and τ_p is the photon lifetime given by [5] :

$$\tau_p = \frac{n_r}{c} \cdot \frac{1}{\alpha_{tot}} \tag{3}$$

where n_r is the refractive index in the active region , c is the light speed in free-space , and α_{tot} is the total losses which can be obtained through [6] :

$$\alpha_{tot} = \alpha_i + \frac{1}{L} \ln\left(\frac{1}{r}\right) \tag{4}$$

with α_i the internal optical losses , L the cavity length , and r the mirror reflectivity .

The use of small signal analysis in eqs.(1)and(2) yields the laser frequency response without parasitic effect (intrinsic effect) as [7] :

$$\frac{s}{i} = \frac{A}{\omega^2 + j B \omega + C} \tag{5}$$

where A , B , and C are real quantities depending on the previously mentioned factors. The normalized magnitude of the frequency response , in dB , at any frequency referred to the dc value is :

$$\frac{\left| \frac{s}{i} \right|_f}{\left| \frac{s}{i} \right|_{f=0}} = 20 \log \frac{|C|}{\sqrt{(\omega^2 + C)^2 + (B\omega)^2}} \tag{6}$$

III - *Temperature Dependence of the Affecting Parameters*

Many factors influence the values of both the quantum efficiency η and the electron lifetime τ_n . This clearly appears in the Auger recombination process [8] , in which η and τ_n are , respectively , given by :

$$\eta = \frac{1}{1 + N\,(C_a / B_r)} \tag{7}$$

and

$$\tau_n = \frac{1}{B_r N + C_a N^2} \tag{8}$$

where C_a is the Auger coefficient and B_r is the radiative recombination rate ; both are temperature dependent.

A general form for the Auger coefficient , as a function of temperature T (°C) , can be obtained by using a computer program curve fitting for the data published in Ref.[8]. The best curve fitting yields the form :

$$C_a = (5.027 + 0.0278\ T + 0.0002\ T^2 - 8.122 \times 10^{-7}\ T^3 - 1.282 \times 10^{-8}\ T^4 + 3.505 \times 10^{-11}\ T^5 - 3.68 \times 10^{-13}\ T^6) \times 10^{-29} \quad cm^6 . s^{-1} \tag{9}$$

Similarly , and based on he data given in Ref.[9] , the radiative recombination rate B_r is obtained in the form :

$$B_r(T) = \left(\frac{300}{T + 273}\right)^{0.8} \times 10^{-10} \quad cm^{-3} . S^{-1} \tag{10}$$

The spontaneous emission factor , β , which appears in a given mode of an injection laser is given by [10] :

$$\beta = \frac{\eta_{th}\, g_o}{V B_r (N_{th} - N_T)} \tag{11}$$

where η_{th} and N_{th} are , respectively , the efficiency and electron density (concentration) at threshold.
The temperature dependence of all η, τ_n , and β is included through both C_a , eq.(9) , and B_r , eq.(10) .
Concerning the differential gain g_o , the transparent N_T , and the threshold electron density N_{th} we introduce two approaches :

Approach I
In this approach , the optical gain g has the form [9] :

$$g = a N - b \qquad cm^{-1} \quad , \tag{12}$$

where N is the electron density , a , and b are temperature dependent constants. Based on the data given in Ref[9] , one can express the constants a and b in the forms:

$$a = 1.35 \times 10^{-16} \exp \left(0.584 \left(\frac{298}{T + 273} - 1 \right) \right) \quad cm^2 \, , \tag{13}$$

$$b = 150 \exp \left(0.778 \left(1 - \frac{298}{T + 273} \right) \right) \qquad cm^{-1} \, . \tag{14}$$

Using eq.(12) , one can get :

$$g_o = \frac{c}{n_r} \cdot a \qquad cm^3.s^{-1} \quad . \tag{15}$$

From definition , the electron density at transparency N_T is the electron concentration at which the gain g is equal to zero , hence , eq.(12) gives :

$$N_T = \frac{b}{a} \qquad cm^{-3} \quad . \tag{16}$$

At threshold , the useful optical gain is equal to the total losses , and , after some algebraic manipulation , one can get the threshold electron density , N_{th} , as :

$$N_{th} = N_T + \frac{v \, \alpha_{tot}}{\Gamma \, g_o} \qquad cm^{-3} \quad , \tag{17}$$

Here , we must keep in mind that the temperature affects the values of g_o , N_T , and N_{th} through the constants a , eq(13) and b , eq.(14).

Approach II
In this approach , the optical gain g is expressed under the form [2] :

$$g = \alpha_1 N^2 + \beta_1 N + \gamma_1 \quad , \tag{18}$$

where α_1 , β_1 , and γ_1 are temperature dependent constants that when obtained [11] , they give the differential gain , g_o , and the electron density at transparency , N_T , as functions of temperature T (°C) , as :

$$g_o = (8.935 - 0.065\, T + 6.4355 \times 10^{-5} T^2 + 1.001 \times 10^{-7} T^3 + 1.060 \times 10^{-9} T^4) \times 10^{-6} \qquad cm^3.\, s \tag{19}$$

and :

$$N_T = (1.474 + 0.002\, T + 8.436 \times 10^{-6}\, T^2 - 5.974 \times 10^{-8} T^3 + 1.749 \times 10^{-10}\, T^4) \times 10^{18} \qquad cm^{-3} \tag{20}$$

Again, using eq.(17), the threshold electron density N_{th} can be expressed as a function of temperature T (°C).

IV- Results and Discussion

The device studied in the present work is a 1.3 μm InGaAsP vapor-phase-regrown buried heterostructure laser. A schematic diagram of our version, of a constricted-mesa laser, is shown in Fig. 1. To calculate the total frequency response, we adjust the value of the copmression factor ε to follow the experimental data.

We have applied the previous procedure at T = 20 °C and -60 °C based on the data given in Refs.[6,12], respectively. The obtained results are displayed in Figs. 2 and 3.

Figures 2 and 3 shows the obtained intrinsic frequency response in approaches I and II together with the measured ones, respectively, at T =20 °C [6] and at T = -60 °C [12].

One can generalize the above procedure for any temperature between -60 °C and 20 °C for output power from 10 to 16 mw assuming that the compression factor ε varies linearly with both temperature T and output power P. Hence, one can write a general form for ε as:

For approach I:

$$\varepsilon(T,P) = 1.8489 \times 10^{-17} - 8.202 \times 10^{-16} P - 6.01 \times 10^{-19} T + 4.3421 \times 10^{-17} PT \quad (21)$$

and for approach II:

$$\varepsilon(T,P) = 9.799 \times 10^{-17} - 5.254 \times 10^{-15} P - 6.005 \times 10^{-19} T + 4.342 \times 10^{-17} PT \quad (22)$$

V - Conclusion

A theoretical model for the temperature dependence of the parameters affecting the frequency response of a semiconductor laser is introduced. Using this model, the frequency response for a semiconductor laser can be predicted at any temperature in the range -60 °C to 20 °, and at an output power that varies from 10 to 16 mw.

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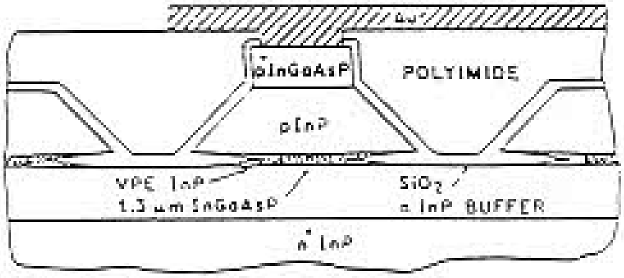
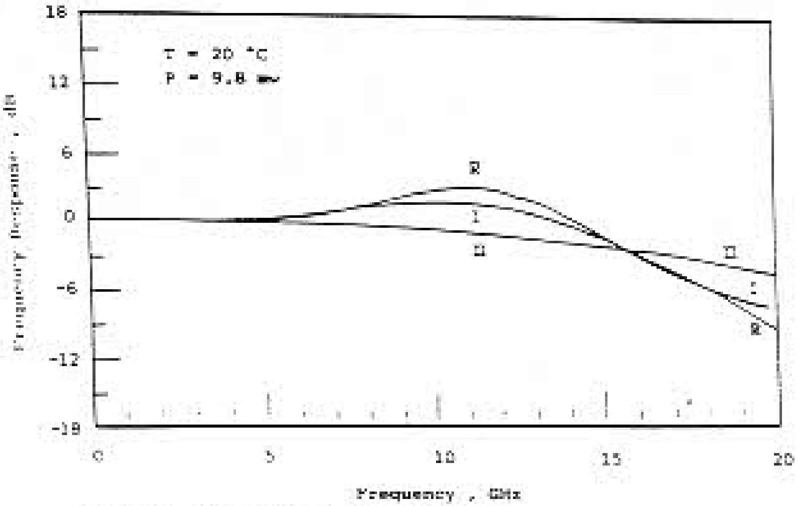
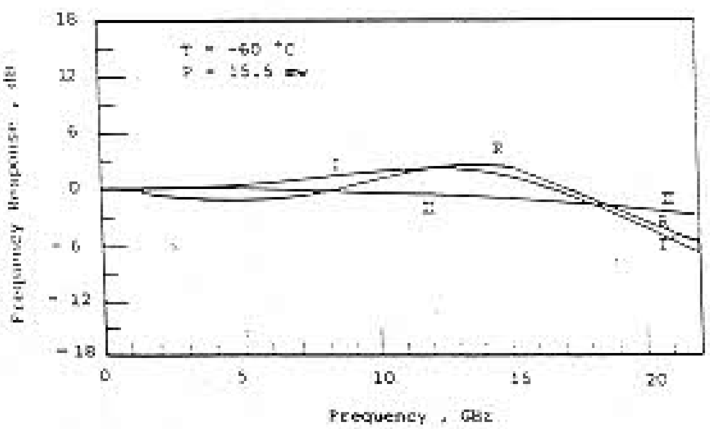


Fig.1 Schematic diagram of a constricted-mesa laser



R : Measured according to Ref.[6].
I : Calculated in the present work , approach I .
II: Calculated in the present work , approach II.

Fig.2 The laser frequency response



R : Measured according to Ref.[12].
I : Calculated in the present work , approach I .
II: Calculated in the present work , approach II.

Fig.3 The laser frequency response