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NONLINEAR TIME DELAY CHARACTERISTICS FOR SEMICONDUCTOR INJECTION LASERS

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A simple theory is developed taking into account an exponentially decaying time dependent loss in addition to the constant loss in order to explain long time delays observed in weakly guided semiconductor injection lasers. It is found that this theory is capable of satisfactorily accounting for the nonlinearities reported in the time delay characteristics of these lasers.

1. Introduction

A time delay between the application of a current pulse and the onset of the stimulated emission is always observed in almost all types of semiconductor injection lasers. Strongly guided semiconductor lasers like double heterostructure type show population inversion time delays at all operating temperatures while weakly guided lasers like homostructure and some single heterostructure show time delays much higher than these when operated at temperatures greater than some critical temperature[1].

Population inversion time delay is defined as the time required to achieve population inversion and this delay, t_{inv}, is given by the relation[2]

$$t_{inv} = \tau_e \ln \left(\frac{I}{I - I_{th}} \right) \tag{1}$$

where I and I_{th} are the current values of the pulse above and at threshold and τ_e is the average value of an electron life time. Taking the value of τ_e as 2 ns, the population inversion time delay at a current value of $1.05 \times I_{th}$ becomes 6 ns[2]. The time delays much higher than these may be called long time delays. Rossi et al.[3] have also reported that a double heterostructure laser, when antireflection coated at one end, may become a weakly guided laser showing long time delay. The observed time delay t_d against $\ln (I/(I - I_{th}))$ characteristics for most of the semiconductor injection lasers as reported in the literature are nonlinear[2-10]. Although various successful theoretical models on time delays and related phenomena are developed[9-12] but no systematic explanation on the nonlinearities observed in the time delay characteristics is described in these models.

In this paper we present an expression for long time delay taking into account an exponentially decaying time dependent loss in addition to the usual constant diffraction and end a losses. This expression on time delay was found to explain satisfactorily the nonlinearities observed in the time delay characteristics as reported in the literature.

2. *Expression for time delay*

Observation of long time delays in semiconductors injection lasers suggest a time dependent loss to be present in the waveguide in addition to the usual constant diffraction and end losses. For simplicity it is assumed that the time dependent loss $L(t)$, is given by

$$L(t) = w e^{-(t/\tau)} \tag{2}$$

where w is a constant and τ ($> \tau_e$) is a time constant, associated with the setting up to the waveguiding and responsible for long time delays. The total constant loss, L (const), is given by

$$L(\text{const}) = u. \tag{3}$$

The gain $g(n)$ is taken as a linear function of electron concentration n, as follows[13]

$$g(n) = An, \tag{4}$$

where A is a constant.

The rate equations for electron concentration n in the conduction band and photon density N in a single lasing mode can then be written as

$$\frac{\mathrm{d}n}{\mathrm{d}t} = P - \frac{n}{\tau_e} - g(n)\,N$$

$$\frac{\mathrm{d}N}{dt} = g(n)\,N - (L(\text{const}) + L(t))\,N + r_{spon}$$

where P is the pumping rate and r_{spon} is the spontaneous emission of photons in the lasing mode. Substituting the expressions for gain and loss terms, the rate equations will become

$$\frac{dn}{dt} = P - \frac{n}{\tau_e} - An\,N$$

$$\frac{dN}{dt} = An\,N - (u + we^{-(t/\tau)})\,N + r_{spon}.$$

Time delay is defined as the time when gain becomes equal to the total losses of the laser, that is, when the condition

$$An = u + we^{-(t/\tau)}, \tag{5}$$

is satisfied.

The value of the threshold carrier concentration, n_{th}, when the time dependent loss reduces to zero, becomes

$$n_{th} = \frac{u}{A}, \tag{6}$$

The expression for time delay may be deduced from equation (5) as follows

$$t = t_d = \tau \ln \frac{w}{An - u} = \tau \ln \frac{w}{An - An_{th}}$$

or

$$t_d = \tau \ln \frac{n}{n - n_{th}} + \tau \ln \frac{w}{An}. \tag{7}$$

This is the required equation which gives nonlinear long time delay characteristic.

3. *Comparison with experimental results*

Substituting $w = 4 \times 10^{12}\ s^{-1}$, $u = 10^{12}\,s^{-1}$, $A = 10^{-5}\,cm^3\,s^{-1}$ and $\tau = 35$ ns in equation (7), the plots of $\tau \ln (w/An)$, $\tau \ln (n/(n - n_{th}))$ and that of t_d each against $\ln (n/(n - n_{th}))$ are given in Fig. 1. For comparison the experimental result for an antireflection coated double heterostructure laser showing long time delay as reported by Rossi et al.[3] is also given in this figure. The time delay observed for diffused homostructure laser by Dyment and Ripper[10] and here reproduced from Rossi et al.[3] is compared with the theory in Fig. 2, where $w = 2 \times 10^{12}\,s^{-1}$, $u = 10^{12}\,s^{-1}$, $A = 10^{-5}\,cm^3\,s^{-1}$ and $\tau = 24$ ns. The above two results are the

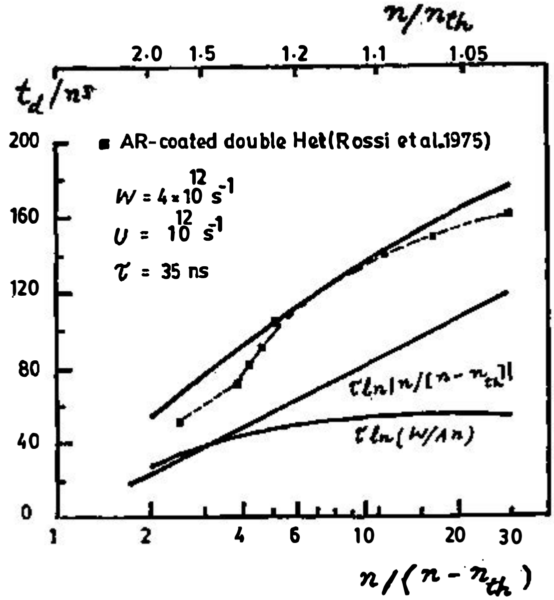

Fig. 1. Theoretical curves of $\tau \ln (w/An)$, $\tau \ln (n/(n - n_{th}))$ and of t_d each against $\ln (n/(n - n_{th}))$. For comparison nonlinear long time delay characteristic of AR-coated double heterostructure laser from Rossi et al.[3] is also shown.

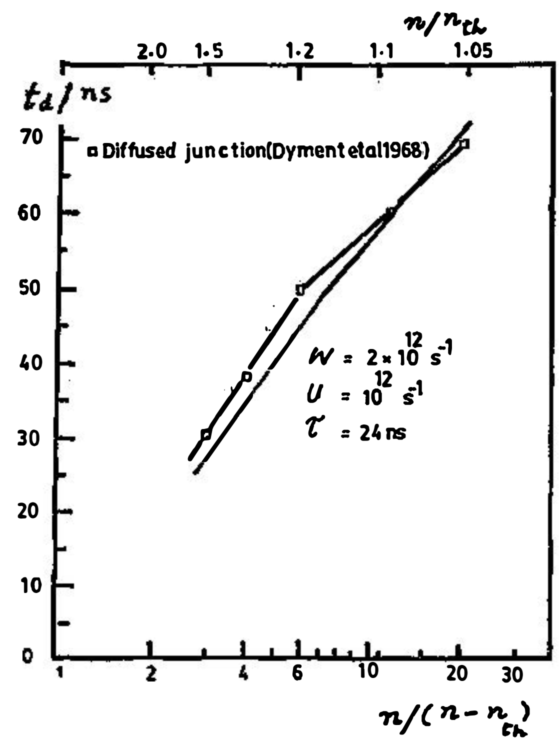

Fig. 2. Comparison of the theoretical time delay characteristic with the experimental result of a diffused junction laser from Dyment and Ripper[10] and here reproduced from Rossi et al.[3].

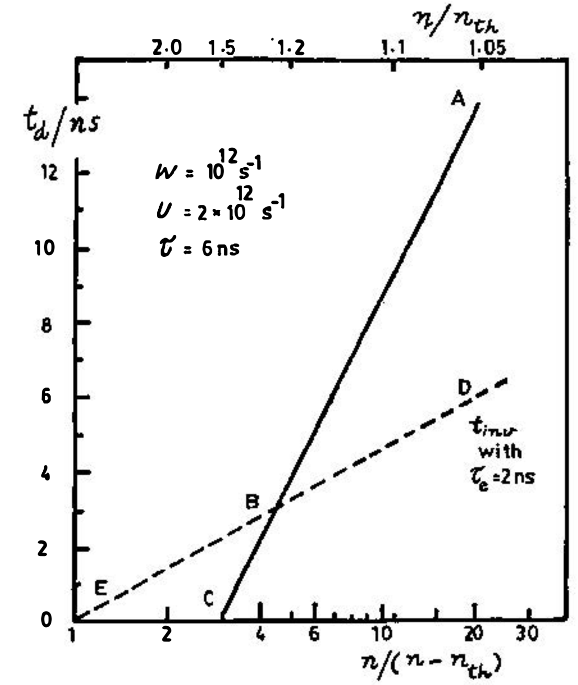

Fig. 3. Full line ABC gives the theoretical time delay curve and line DBE shows the population inversion time delay. The actual theoretical plot in this case will be ABE.

cases of nonlinear time delay characteristics where the slope at lower current values is less than that at higher current values. For the nonlinear case where the slope at lower current values is greater than at higher current values, the curve obtained from the theory is shown in Fig. 3. In this figure ABC is the plot of t_d against $\ln(n/(n - n_{th}))$ for $w = 10^{12}\,s^{-1}$, $u = 2 \times 10^{12}\,s^{-1}$, $A = 10^{-5}\,cm^3\,s^{-1}$ and $\tau = 6$ ns, the line DEB is the population inversion time delay with $\tau_e = 2$ ns and the actual theoretical curve in this case will be ABE, since t_d cannot be less than t_{inv}.

4. Conclusion

An expression for long time delay is developed from simple rate equations. Assigning various typical values to the parameters it is possible to fit the theoretical curves with experimentally observed nonlinear long time delay characteristics. The value of the time constant τ and that of w, the prefactor of the time dependent loss $we^{-(t/\tau)}$ are the determining factors for the magnitude of time delay greater than the population inversion time delay and of various slopes observed in non-linear long time delay characteristics.

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NELINEARNE KARAKTERISTIKE VREMENSKIH ZAKAŠNJENJA U POLUVODIČKIM INJEKCIONIM LASERIMA

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