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TIME DELAY CHARACTERISTICS FOR SEMICONDUCTOR INJECTION LASERS

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Semiconductor injection lasers of the homostructure and single heterostructure type have shown time delays larger then the population inversion time delays. The time delay characteristics observed for these lasers are nonlinear. Through the rate equation approach it is explained that this nonlinearity and long time delays are due to the presence of a time dependent loss in the waveguide.

1. Introduction

Semiconductor injection lasers show time delays between the application of a current pulse and the onset of the stimulated emission. These delays could be the well known population inversion time delays or higher delays due to other causes.

The population inversion time delay t_{inv}, is the time required to achieve population inversion given by the relation[1)]

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

where I and I_{th} are the current values of the pulse above threshold and at threshold and τ_e is the average value of an electron life time. The value of $\tau_e = 2$ ns has been deduced from the plot of t_{inv} versus $\ln | I/ | I - I_{th} ||$ for a GaAs laser operated at 77 K, showing population inversion time delay at a current value of 1.1 $1.1 \times I_{th}$[1].

The plot of t_{inv} versus $\ln | I/ | I - I_{th} ||$ has to be linear, but the experimental data indicated a nonlinear plot[1]. This nonlinearity in the time delay t_d ($\geqslant t_{inv}$) again $\ln | I/ | I - I_{th} ||$ characteristics can also be seen in most of the data obtained for various types of GaAs semiconductor injection lasers[2-8]. In these published results, apart from assigning nonlinearity to the error in the measurements, no other explanation has been offered. In this paper we present time delay measurements on GaAs homostructure and single heterostructure (*SH*) lasers. The time delays are found to be much higher than the expected population inversion time delays and the time delay characteristics are found to be nonlinear. We suggest that the long time delays (higher than the population inversion time delays) and the nonlinearity in the time delay characteristics result from a time dependent loss mechanism in the waveguide. Simple rate equations including time dependent loss term are solved to support both of these suggestions.

2. *Experimental*

Time delay measurements ware made at room temperature. Lasers were operated with a rectangular current pulse of 80 ns duration with a rise and fall time of less than 1 ns and a pulse repeat frequency of 100 Hz. The laser light output was passed through one slit of the monochromator (*Monospek* 1000) and was detected by a photomultiplier tube (*RCA* 7102, rise time ≈ 2 ns) at the other slit. Both the light output pulse and current pulse were displayed on the sampling oscilloscope (*Phillips PM* 3400). The time delay was obtained by subtracting the duration of the light output pulse from that recorded for the current pulse. The value of the threshold current was determined from the emergence of single mode peak from the spontaneous spectrum of the diode output. Slits of the monochromator were adjusted to ensure a narrow lasing spectrum of a width between 0.5 to 1.5 nm. The laser used in the present study were commercially available lasers.

3. *Results*

Time delay t_d against $\ln | I/ | (I - I_{th}) ||$ characteristics for a homostructure laser ($I_{th} = 6.25$ A) and *SH* laser ($I_{th} = 8.8.$ A) are given in Figs. 1 and 2, respectively. The time delays are 10 ns at a current value of $1.1 \times I_{th}$ and are found to be much higher than the time required to achieve population inversion[1]. It can be seen that the curves are nonlinear and two slopes are evident in each plot. At higher currents, the slope is smaller than the slope at lower currents for the homostructure laser and vice versa for the *SH* laser. It can be thought that this nonlinearity is due to an error in the measurements. Since the slope in each of the plot passes through the origin, the error in the measurements of t_d could be ignored.

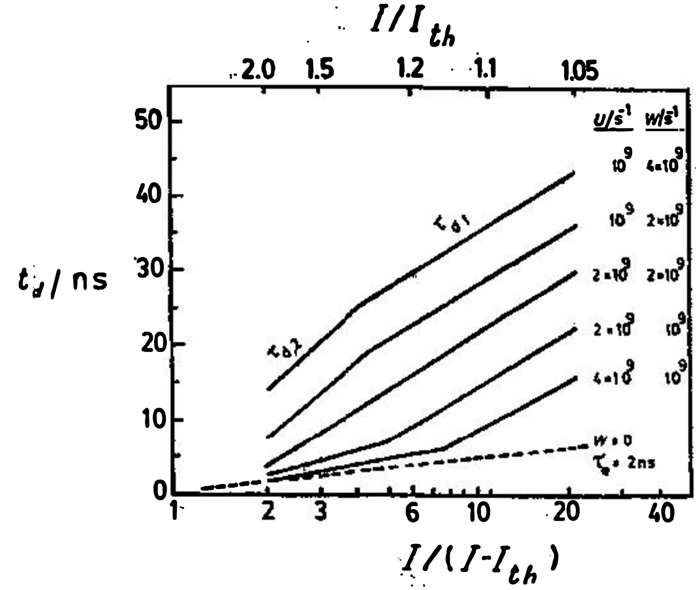

Fig. 1. Effect of the error in I_{th} of the time delay characteristic of a homostructure laser.

The threshold current is obtained from the spectral output and is taken as the current at which lasing emission starts. With this method, if care is taken to obtain as accurate a value as possible for the threshold current, the actual threshold may be less than the value obtained from the curve because there can be a negative value error for I_{th}. We have plotted this characteristics with an assumed-6% error in I_{th} (I_{th} = 5.8 7A) for a homostructure laser (Fig. 1), which could be the maximum error for this laser, but the plot is still not linear. Similarly, we show plots in Fig. 2 for a *SH* laser with a —4% error in I_{th} (I_{th} = 8.44 A) as well as with a + 4% error (I_{th} = 9.15 A). Neither of these error values make the plot linear. These results show that the nonlinearity observed in time delay characteristics is an experimental fact rather than due to an error in the measurement in I_{th} or t_d.

4. *Theory*

The observations of time delays longer than the population inversion time delay suggest a time dependent loss mechanism present in the waveguide. With time this loss decreases, the delay is over and lasing starts. For simplicity we assume this time dependent loss to be an exponentially decaying function of time. The time dependent loss term, loss (t), can be written as

$$\text{loss}\,(t) = w\mathrm{e}^{-t/\tau} \tag{2}$$

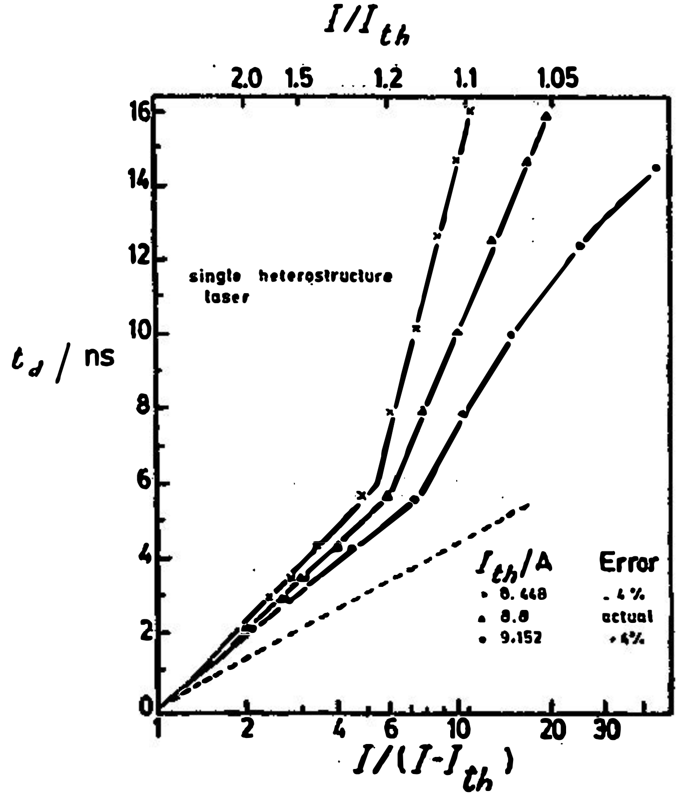

Fig. 2. Effect of the error in I_{th} on the time delay characteristic of a *SH* laser.

where w is a constant and $\tau\,(> \tau_e)$ is a time constant, which is associated with the setting up of the waveguiding. If τ is large the cavity takes a long time prior to sustaining the particular lasing mode. The constant loss term in the laser comprises; (a) loss due to free carrier absorption, (b) diffraction loss out of the active region and (c) end loss through the mirrors. These losses, loss (const), are given by the relation[9]

$$\text{loss (const)} = \frac{c}{\mu}\left\{a + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)\right\}. \tag{3}$$

c is the velocity of light, μ is the referactive index of the active region, a comprises free carrier and diffraction loss, $\frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$ is the cavity end loss with L the length of the cavity and R_1, R_2 reflectivities of the two laser mirrors.

We assume the gain $g(n)$ is a linear function of electron concentration n,[10]

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

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

$$\frac{\mathrm{d}n}{\mathrm{d}t} = P - \frac{n}{\tau_e} - g(n)\,N \tag{5}$$

$$t\frac{\mathrm{d}N}{\mathrm{d}} = g(n)\,N - |\,\mathrm{loss\,(const)} + \mathrm{loss}\,(t)\,|\,N + r_{spon} \tag{6}$$

where P is the pumping rate and r_{spon} is the spontaneous emission of photons in the lasing mode. Substituting the expression for gain and loss tems, the rate equations are

$$\frac{\mathrm{d}n}{\mathrm{d}t} = P - \frac{n}{\tau_e} - An\,N \tag{7}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = An\,N - (u + w\mathrm{e}^{-t/\tau})\,N + Fn \tag{8}$$

where $r_{spon} = Fn$ with F a constant.

In steady state the gain equals the loss and from equation (8)

$$an_{th} = u$$

or

$$n_{th} = \frac{u}{A} \tag{9}$$

where n_{th} is the threshold current density and is taken when the time dependent loss term $w\mathrm{e}^{-t/\tau}$ reduces to zero. The threshold value of the pumping rate is then given by

$$P_{th} = = \frac{n_{th}}{\tau_e}. \tag{10}$$

Numerical integration of the rate equations is performed for different values of P above P_{th}, using the Runge-Kutta numerical procedure. Time delay is taken as the time when gain equals the total lossos of the laser,

$$An = u + w\mathrm{e}^{-/\tau}\,. \tag{11}$$

Using the values given in Table 1, the plots of t_d against ln $|\,I/\,|\,I - I_{th}\,||$ are given in Fig. 3 for the values of u and w given along with the plots.

TABLE 1.

$A = 2 \times 10^{-5}\ \mathrm{cm^3\,s^{-1}}$	$\tau_e = 2$ ns
$c = 3 \times 10^{10}\ \mathrm{cms^{-1}}$	$\tau = 10$ ns
$\mu = 3 \cdot 6$	$F = 5 \times 10^4\ \mathrm{s^{-1}}$

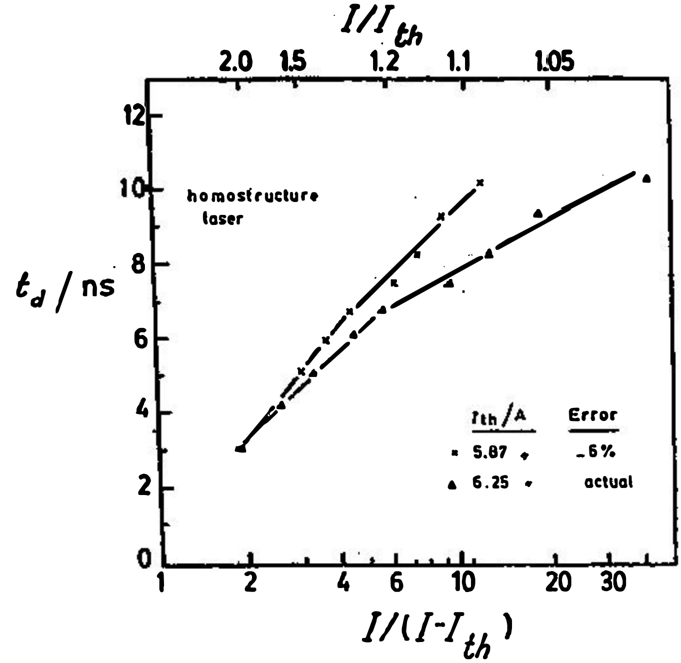

Fig. 3. Theoretical curves of time delay t_d against ln $| I/ | I - I_{th} | |$ for different values of the initial time dependent loss term, w, and the constant loss term u. The broken line gives the population inversion time delay with $\tau_e = 2$ ns.

The nonlinearity in the time delay t_d against ln $|I/|I - I_{th}||$ is evident and the effect of varying u and w can also be easily seen. The case of $w = 0$ which gives the population inversion time delay is shown by the dotted line. Let the two slopes of each curve are τ_{d1} and τ_{d2} with τ_{d1} at lower currents and τ_{d2} at higher currents. In the plots of Fig. 3 all the three cases of τ_{d1} being less, equal or greater than τ_{d2} are produced by the relative magnitudes of u, the constant loss term and w, the prefactor of the time dependent loss term. The relative magnitudes of τ_{d1} and τ_{d2} are summarized as follows:

For

$$u < w \qquad \tau_{d1} < \tau_{d2}$$

$$u = w \qquad \tau_{d1} = \tau_{d2}$$

$$u > w \qquad \tau_{d1} > \tau_{d2}.$$

5. *Comparison of theory with experimental results and conclusion*

The theoretical curves of Fig. 3 are in qualitative agreement with the results on various types of GaAs lasers already published by different workers and some of these are reproduced in Fig. 4 for comparison. It is worthwhile to notice the similarity between the asymmetric characteristic of a *SH* laser with $I_{th} = 9.15$ A (Fig. 2) and that of *AR* coated *DH* laser (Fig. 4). This suggest the error in the value of I_{th} as measured for *AR* coated *DH* laser. If this error is eliminated and the characteristi c is plotted with actual value of the threshold current, two linear slopes will be observed instead of an asymmetric curve.

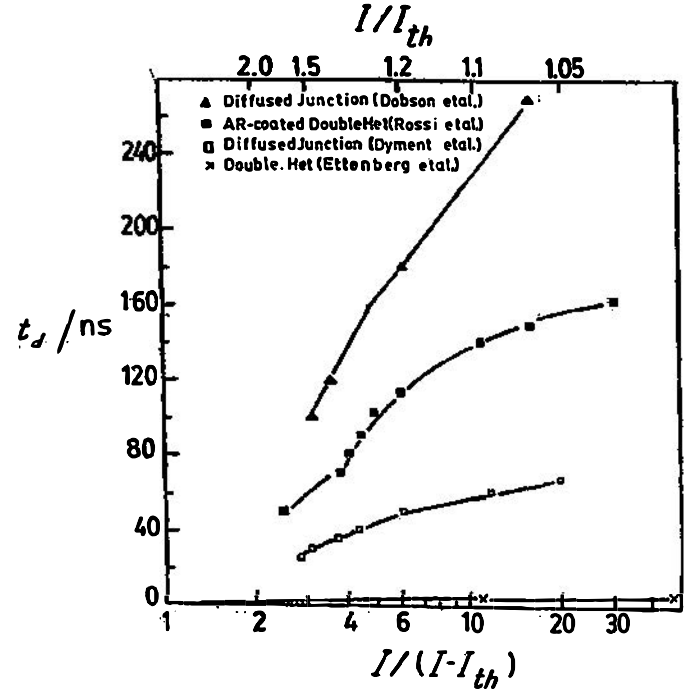

Fig. 4. Nonlinear time delay characteristics of various types of GaAs lasers reproduced from references 7 (Fig. 13) and 8 (Fig. 7). The characteristics for diffused junction diodes are from Dyment et al.[3] and Dobson et al.[4], and that of *AR* coated double heterostructure from Rossi et al.[7] and from Ettenberg and Kressel[8].

Comparison of the time delay characteristic obtained from the solution of the rate equations with the experimental result for a *SH* laser used in the present study is also made in Fig. 5. Usually two slopes are observed in such characteristics and the point at which these slopes meet is termed as the breakpoint. Solutions of the rate equations show that it is the relative magnitude of the time dependent loss and constant loss which is responsible for the different slopes and position of the breakpoint. For example a theoretical fit of these rate equations to the experimental result of a *SH* laser (Fig. 5) indicates that this laser has an initial time dependent loss which is less than the value of the constant loss. On the other hand comparison of the time delay characteristic for a homostructure laser (Fig. 1) with the theoretical curves (Fig. 3) indicates that this laser has an initial time dependent loss greater than the constant loss value.

These theoretical and experimental results therefore show that long time delay and nonlinearity observed in the time delay characteristics of weekly guided semiconductor injection lasers results from the presence of a time dependent loss in the waveguide.

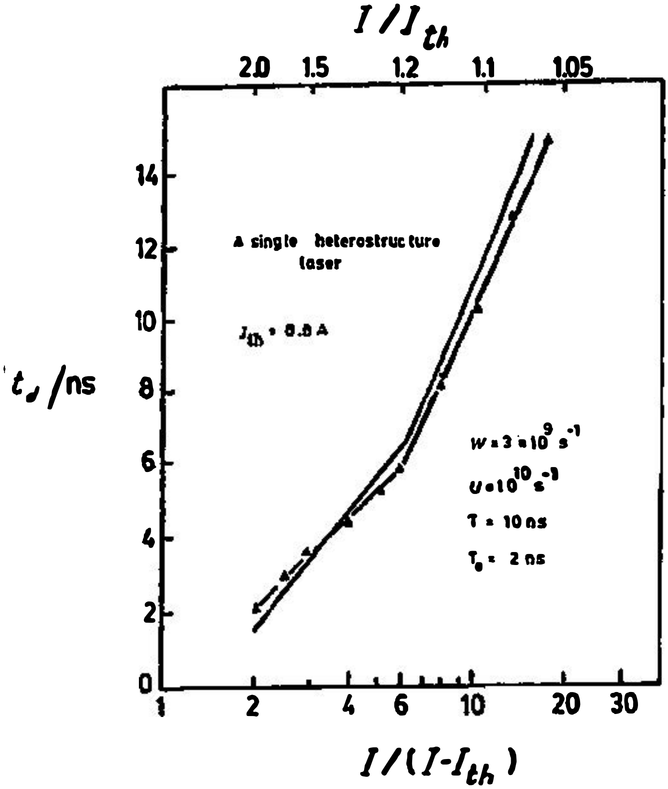

Fig. 5. Comparison of the time delay characteristic obtained from the solution of the rate equations with the experimental result for a *SH* laser. The broken line gives the population inversion time delay with $\tau_e = 2$ ns.

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KARAKTERISTIKE VREMENSKIH ZAKAŠNJENJA POLUVODIČKIH INJEKCIONIH LASERA

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Poluvodički injekcioni laseri homostrukturnog tipa i jednostrukog heterostrukturnog tipa pokazali su vremenska zakašnjenja veća od vremenskih zakašnjenja inverzije populacije. Karakteristike vremenskih zakašnjenja koje su opažene kod ovih lasera su nelinearne. Pomoću jednadžbi kontinuiteta je objašnjeno da su nelinearnost i vremenska zakašnjenja nastali radi prisutnosti vremenski ovisnih gubitaka u valovodu.