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Effect of Junction Capacitance on the Rise Time of LED's and on the Turn-on Delay of Injection Lasers

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The space-charge capacitance of the forward-biased junction has been found to play a major role in (i) the apparent rise time of the emission from small-area, high-radiance LED's and (ii) the apparent turn-on delay of stripe-geometry DH-structure laser diodes. For a zero-bias capacitance of 200 pF, a typical value for such devices made by oxide-masking techniques, the measured rise time of an LED that is fully turned on and the turn-on delay time of injection lasers may be as much as twice the limitation imposed by the spontaneous carrier recombination time. A proposed method to reduce these delays by preshaping the driving pulse is analyzed, and a reduction of the delay by a factor of 2 or better is predicted. These results are in agreement with experiments.

I. INTRODUCTION

Among the optical sources presently available for optical communication applications, AlGaAs light-emitting diodes[1,2] and injection lasers[3,4] are probably the most compatible with low-loss optical fibers.[5,6] The possibility of direct pulse modulation of the optical output of these devices by varying the driving current is a major advantage, and the intrinsic radiative recombination time suggests that very high modulation rates are possible. Fractional-nanosecond rise times and modulation rates to 100 Mb/s for LED's[7,10] and modulation rates to hundreds of Mb/s for injection lasers[11–17] have been reported. Faster rise times and higher modulation rates are more difficult to attain.

For an ideal LED, if the injected carriers arrive instantaneously at the recombination (diffusion) region, the rise time of the spontaneous emission is governed solely by the spontaneous recombination time of the carriers. However, in driving a practical diode, the junction capacitance and the stray capacitance cause delay in the arrival time of the injected carriers at the recombination region. Thus, the rise time of the spontaneous emission in an LED and the delay time of the stimulated emission in a laser diode would be either (*i*) material-limited by the spontaneous recombination time τ_s or (*ii*) circuit-limited by the time constant τ_c of the driving circuit (including the junction capacitance of the diode). The space-charge capacitance effect has been reported previously in large-area GaAs LED's[18] and in $GaAs_{0.6}P_{0.4}$ LED's.[19]

In a previous report, Dawson and Burrus[20] measured the rise time of small-area GaAs LED's.[1,2] They showed that the rise time decreased with the capacitance of the unit. For instance, a GaAs diode with a junction capacitance of 200 pF had a rise time of 5.5 ns; when the capacitance was reduced to 20 pF by etching away the excess area of the junction, the rise time was reduced to 3.5 ns. They also observed that the rise time decreased with driving current. More recently, in doing the modulation experiment for LED's, Dawson employed a low-impedance driver to improve the speed of modulation. A rate of 48 Mb/s[21] with approximately 1-ns rise time was obtained using a driver with an output impedance of 2 to 4 ohms. At the higher rate of 280 Mb/s[22] a snap-diode driver with an effective impedance of 1 to 2 ohms was used to produce a train of short pulses. The apparent rise time of the observed optical pulses was 0.7 ns. However, the peak power was less than that for dc drive, since the LED was not fully turned on in this case. Also, White and Burrus[8] used a low output-impedance transistor driver that produced a light pulse with 2.5-ns rise time.

In view of the previous experimental results, the present work studies the junction capacitance effect in detail and correlates theory with experiments. The effect on the turn-on delay of injection lasers is studied similarly. The expected reduction of such delays by means of a preshaped driving pulse is calculated.

In practical applications for high modulation rates, a combination of the following techniques can be used: (*i*) constructing diodes to have low capacitance, (*ii*) employing drivers with low output impedance (to match the diode impedance) and (*iii*) properly shaping the driving current pulse.

One additional point in the results of this work is that, in determining the spontaneous recombination lifetime by the measurement of laser turn-on delay,[23] good results can be expected if (*i*) the junction capacitance is less than about 10 pF and (*ii*) the laser is operating in a single filament.[24,25] The latter requirement is necessary because the distribution of current among filaments and the determination of the threshold become ambiguous in diodes lasing in multifilaments.

II. DESCRIPTION OF THE DIODES AND THE EQUIVALENT CIRCUIT

The LED used in the study was a Zn-diffused n-type GaAs ($N_d > 3 \times 10^{18}$ cm^{-3}) diode made by C. A. Burrus.[1,2] In this structure, p-n junction is formed in the entire wafer of about 1.44×10^{-3} cm^2 area, and the SiO_2 layer masks most of the p^+ surface except for a small window where the contact is made to the junction. The current is restricted to flow largely in the small contact region, resulting in a small emitting area of $2 - 3 \times 10^{-5}$ cm^2. In our investigation of the rise time, the current density in the primary emission region ranged from 5 kA/cm^2 to 80 kA/cm^2.

The laser diode we used was a GaAs–Al_xGa_{1-x}As double-heterostructure device with a stripe contact.[26] This geometry forces the current to flow only in a narrow region, thereby confining the laser actions to the small part of the junction below the contact. The wafer had an area about 2.5×10^{-3} cm^2, whereas the stripe contact area was about 1.25×10^{-4} cm^2 (500 μm $\times$ 25 μm). Room temperature threshold current density was about 3.5 kA/cm^2.

The common feature of both diodes is that the large junction over the entire wafer presents a space-charge capacitance comparable to the diffusion capacitance of the junction.

Figure 1 shows the equivalent circuit for study of the transient behavior of both diodes. A nonlinear resistor represents the $I - V$ characteristic of the diode, described by

$$i_d = I_0\left[\exp\left(\frac{qv_d}{nkT}\right) - 1\right], \tag{1}$$

where v_d is the junction voltage. The factor n is unity for an ideal diode diffusion current but, in our heavily doped p-n junction in GaAs, n is approximately 2. In the transient case, part of the injected carriers will replenish the carriers that recombine, and the rest will build up as stored charges. Thus, the stored charges will increase as $(1 - e^{-t/\tau_s})$,

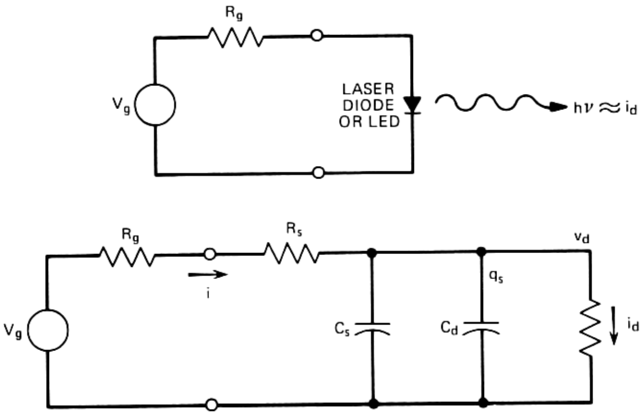

Fig. 1—The diode equivalent circuit.

where the time constant τ_s is the carrier spontaneous recombination time. This is equivalent to a capacitance, C_d, whose charge, $q_d(t)$, is equal to the stored charge and whose instantaneous charge-voltage relationship satisfies

$$q_d = Q_0\left[\exp\left(\frac{qv_d}{nkT}\right) - 1\right], \tag{2}$$

where v_d is the instantaneous junction voltage, and $Q_0 = I_0\tau_s$. To satisfy eq. (2), the diffusion capacitance is defined as

$$C_d = \frac{dq_d}{dv_d} = \tau_s\frac{di_d}{dv_d}. \tag{3}$$

In addition to the diffusion capacitance, there is the space-charge capacitance of the depletion layer. The space-charge capacitance, in parallel with C_d, is given by the usual form

$$C_s = \frac{(A - A_e)c_o}{(1 - v_{do}/\phi)^m} + \frac{A_e c_o}{(1 - v_d/\phi)^m}, \tag{4}$$

where c_o is the zero-bias capacitance per unit area, ϕ is the barrier voltage which is 1.26 volts from $C - V$ measurement, the exponent m is $\frac{1}{2}$, A is the total area, and A_e is the emitting (contact) area. At small forward voltages, the current spreads over the entire area of the diode chip. The current confinement in the contact area is obtained only at a voltage v_{do}, at which the junction resistance is less than the spreading resistance. Thus, the first term in eq. (4) accounts for the space-charge capacitance of the junction surrounding the emitting area, while the second term is the space-charge capacitance of the emitting area itself. Since $A \gg A_e$ and $v_d \approx v_{do}$, eq. (4) can be approximated by

$$C_s = \frac{C_0}{(1 - v_{do}/\phi)^m}, \tag{5}$$

where $C_0 = Ac_o$ is the total zero-bias capacitance.

Referring to Fig. 1 again, resistance R_s in the equivalent circuit accounts for the series resistance of the bulk material as well as the contact resistances. The driver output impedance is represented by R_g, and V_g is a rectangular voltage pulse amplitude. For completeness, the following circuit equations are included:

$$i = \frac{V_g - v_d}{R_g + R_s} \tag{6}$$

$$i_c = i - i_d \tag{7}$$

$$v_d = \int \frac{i_c}{C_s + C_d}\,dt. \tag{8}$$

Table I — Constants for diode parameters

	I_0	n*	m	R_s	R_g	C_0
LED	2.3×10^{-12}	2	0.5	5.6 Ω	50 Ω	150–250 pF
Laser	1.2×10^{-13}	2	0.5	0.6 Ω	50 Ω	130–200 pF

* For ideal diodes, $n = 1$ for the diffusion current at low injection and $n \approx 2$ at high injection. In our GaAs with heavily doped n-region ($N_d > 3 \times 10^{18}$ cm^{-3}), n is usually equal to 2.

Numerical solutions to the system of eq. (1) through (8) have been obtained using the experimentally determined constants for both LED's and laser diodes, as tabulated in Table I. Since the spontaneous emission is proportional to the diffusion current, the time dependence of emission can be found from the time response of i_d.

III. EXPERIMENTAL SETUP

The diode was mounted at the end of a 50-ohm microstrip line (in series with either a 50-ohm resistor for the laser diode or a 47-ohm resistor for the LED chosen experimentally to minimize the reflections), and was driven by a Tektronix* 110 pulse generator that produced a rectangular pulse with a rise time less than 250 picoseconds and ripple below 1 percent. The pulse width used was 20 ns, and the repetition rate was 300 p/s. The output was detected by a p-i-n photodiode with a rise time better than 150 picoseconds and displayed on a 90-picosecond rise-time sampling oscilloscope.

IV. NUMERICAL RESULTS AND COMPARISON WITH EXPERIMENTS

4.1 Characteristics of LED response

The diffusion current, as a function of time, resulting from a step input voltage to the LED can be obtained by solving eqs. (1) to (8). Using the measured diode parameters given in Table I, we obtain the dependence of the rise time, between the 10- and 90-percent points of the light pulse, and the delay time between the application of the current pulse and the 10-percent point of the light pulse. These quantities are functions of driving current density and the junction capacitance. Such dependence for various values of zero-bias space-charge capacitance is shown in Fig. 2a. It is seen that, for very large current densities, the rise time is unaffected by C_0 and approaches an asymptotic value of $2\tau_s$, slightly faster than an ideal exponential rise of the form $(1 - e^{-t/\tau_s})$. The delay time is largely due to the space-charge capacitance as clearly shown in Fig. 2b, and it approaches zero at very

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* Trade name of Tektronix Corporation.

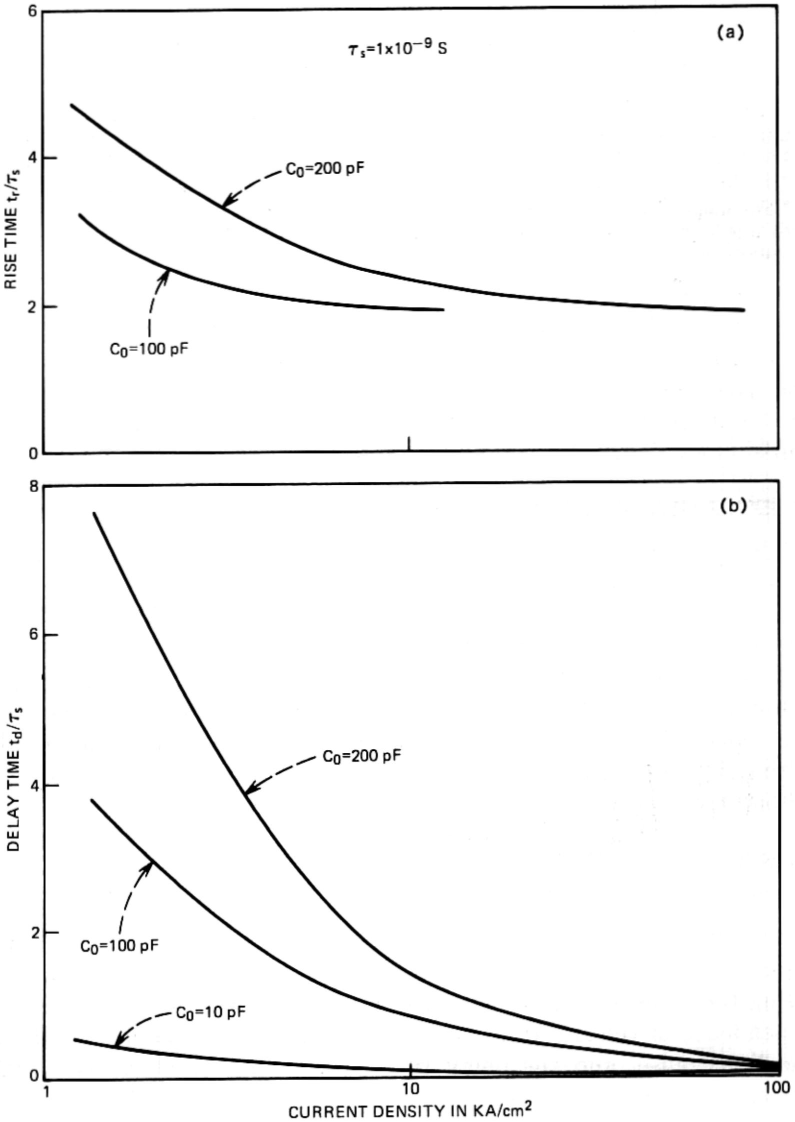

Fig. 2—(a) Rise time of LED output. (b) Delay time of LED output as a function of current density for various zero-bias diode capacitances.

large current densities. This is understandable since, for very large current densities, the space-charge would be completely neutralized. Such neutralization would require a current density on the order of

$$J = \frac{qN_dW_0}{\tau_s}\frac{A}{A_e}, \tag{9}$$

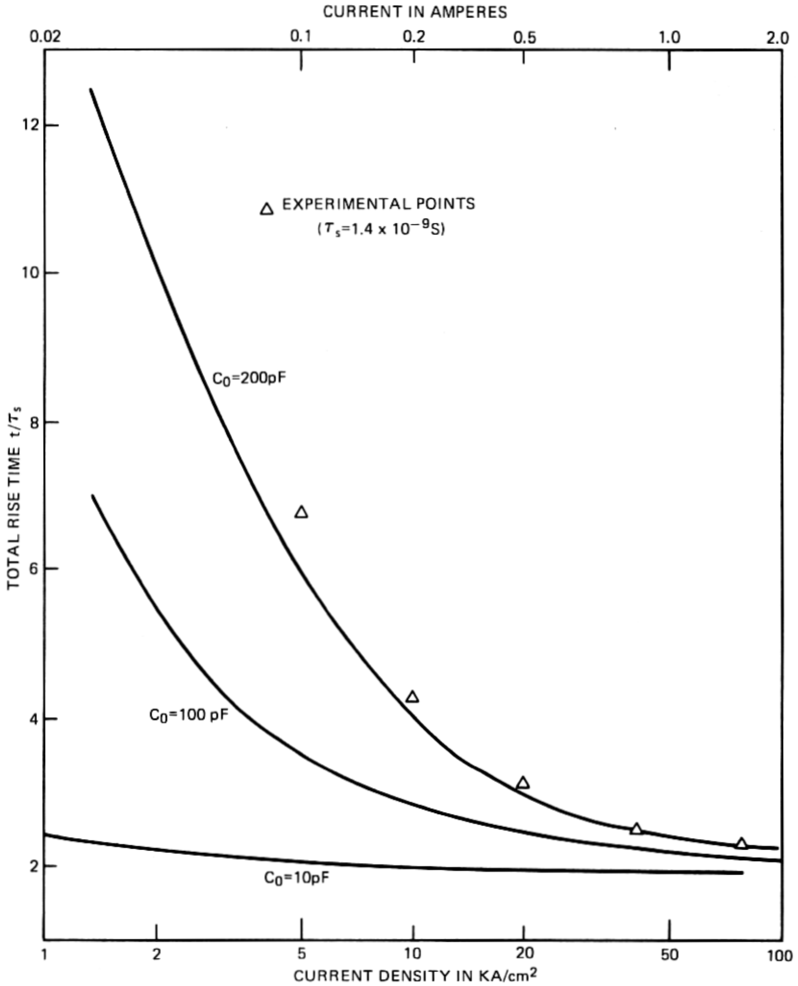

Fig. 3—Comparison of calculated total rise time ($t_d + t_r$) with measured values.

where W_0 is the space-charge width at zero-bias, N_d is the net donor density, A is the total junction area, A_e is the light-emitting area where the current flows, $W_0 = \epsilon_0 \epsilon_r A / C_0 = 0.66 \times 10^{-5}$ cm (for $A = 1.2 \times 10^{-3}$ cm, $C_0 = 200$ pF, and $\epsilon_r = 12.8$). If we use $N_d = 3 \times 10^{18}$ cm^{-3} and $\tau_s = 1.4 \times 10^{-9}$, we see the estimated current density is 9×10^5 A/cm^2, a value in good agreement with the curves of Figs. 2a and 2b.

The experimentally measured total rise time ($t_d + t_r$) indeed showed a current dependence similar to those calculated above. The spontaneous recombination time τ_s can be determined by noting that, at large current densities, the rise time approaches $2\tau_s$, independent of the junction capacitance. Figure 3 shows the experimentally observed current-dependent total rise time normalized to τ_s plotted against the current density. It is clearly seen that the experimental points can be matched to a calculated curve if C_0 is assumed slightly larger than 200 pF. This value of C_0 is in very good agreement with the measured value.

4.2 Laser turn-on delay

Below lasing threshold, the accumulation of injected carriers in a laser is similar to that in an LED. Thus, the spontaneous emission from a laser has a similar response to the emission from an LED. When the current increases to a level at which the laser has gain equal to the total loss of the cavity and mirrors, laser action commences and the light output increases sharply. The stimulated emission reduces the spontaneous lifetime considerably, so that the rise time of the stimulated emission is much shorter than that of the spontaneous emission. Thus, the delay time of the stimulated emission is just the response time required for the diode current to reach the lasing threshold. This delay time can be determined as a function of $I/(I - I_{th})$ by calculating the response of the diffusion current for experimental diode parameters and by determining experimentally the threshold current of the laser.

Curves of delay vs current above threshold for various values of zero-bias diode capacitance are shown in Fig. 3. For $C_0 = 0$, the relationship is a straight line given by the usual delay-time formula[23]

$$t_d = \tau_s \ln \frac{I}{I - I_{th}}. \tag{10}$$

It is clear that the space-charge capacitance will further delay the laser turn-on time. For large C_0, the relationship deviates from the straight line, a phenomenon observed in past experiments* that has not been explained adequately. For $C_0 = 200$ pF, a typical value for the experimental diode, the delay time is about twice that for zero capacitance.

To determine τ_s experimentally from delay measurements, therefore, a correction for the effects of junction capacitance must be made. Using $C_s = 200$ pF, the corrected τ_s would be 1.8×10^{-9} for our particular laser diode. The measured delay time t_d, when normalized to τ_s as a function of $I/(I - I_{th})$, agrees well with the results calculated in this way.

4.3 Effect of driver output impedance

It is obvious that the resistance-capacitance time constant of the charging current can be shortened by either reducing the space-charge

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* In past experiments, the result that the straight line did not pass the origin was attributed to filamentary lasing or multimoding (Ref. 24). Perhaps the effect of the capacitance is also contributing to the undesirable results (Ref. 25).

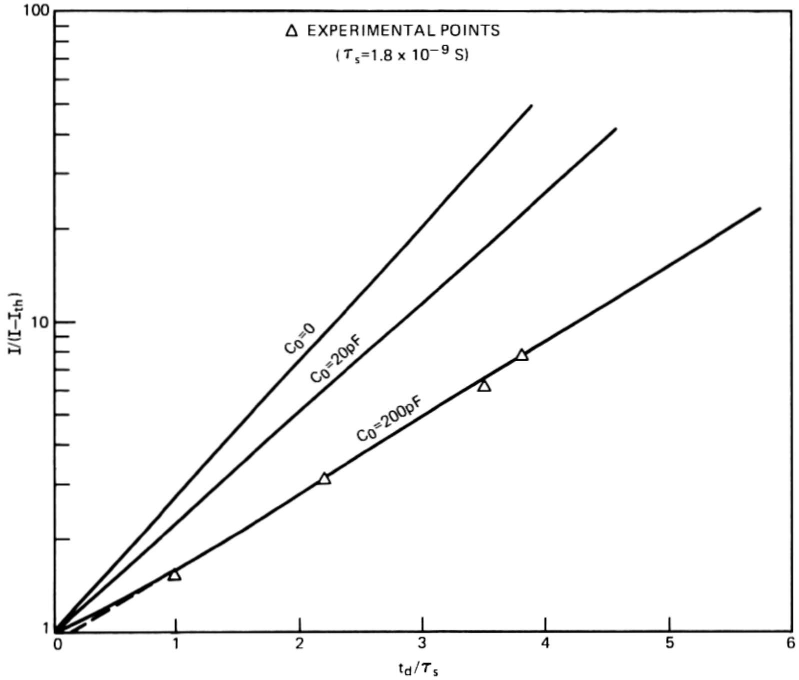

Fig. 4—Laser turn-on delay (normalized to the spontaneous recombination time τ_s) as a function of excitation currents above threshold for various zero-bias diode capacitances. Solid lines are calculated.

capacitance* or lowering the output impedance of the driver.[21,22] Using the same diodes, we varied the impedance of the driver by shunting the diode with a low resistance. Figure 4 shows a typical result of a laser diode. The turn-on delay time of the laser as a function of the shunt resistance for various driving currents and the luminescence rise time when the laser diode was operated below threshold were measured. To assure that the same amount of current was injected into the laser as the shunt resistance was changed, the light output was monitored first for 50 ohms (no shunt). For other shunt resistances, the driving current was increased until the same output was obtained. For a given diode current, the delay was shortened by lowering the driver impedance. The amount of reduction in delay reduced as the diode current increased. This is in line with the results indicated in Section 4.1 that the effect of space-charge capacitance decreased at higher currents. With

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[*] J. C. Dyment (Ref. 25) has observed independently that proton-bombarded stripe-geometry lasers with shallow penetration have delay times almost 1.5 times that of units with deep penetration. The unit with shallow penetration had a capacitance of about 75 pF, while those with deep penetration had 15- to 20-pF capacitance.

a 1-ohm shunt resistance, the capacitance effect should be negligible. The results in Section 4.1 showed that the luminescence rise time would be about $2.2\tau_s$. Thus, we can deduce from the rise time (4.1×10^{-9} s) that the spontaneous recombination time $\tau_s = 1.85 \times 10^{-9}$ s. Again, it agreed with the delay time measurement mentioned in Section 4.2.

V. EQUALIZATION OF LASER TURN-ON DELAY

As discussed above, the accumulation of charges in the recombination region is approximately exponential with an effective time constant τ_{eff}. This time constant may be larger than or equal to the spontaneous lifetime τ_s, depending on whether the space-charge capacitance is significant. To reduce the delay from τ_{eff}, a driving current with amplitude many times higher than I_{th} would be necessary, and this would require a driver with high power capability if its output impedance is larger than that of the diode laser, which is about a few ohms. An alternative is to preshape the current pulse to equalize the delay. One of such a pulse shape, the exponential decay shown in Fig. 5a, has been investigated.

Using the exponentially decaying pulse, $I = I_a e^{-t/\tau_c} + I_0$, shown in Fig. 5 as the driving current pulse, and using the same approach as

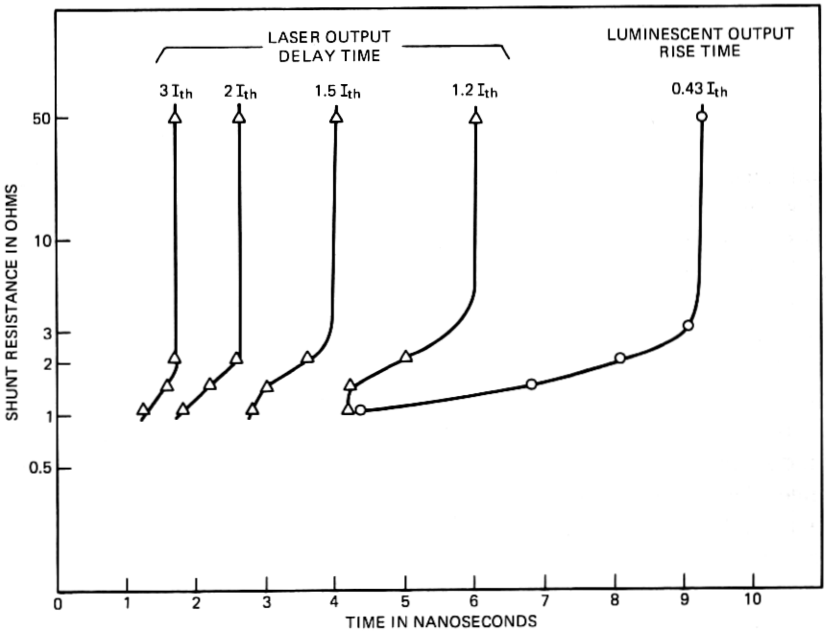

Fig. 5—Laser output delay time and luminescent rise time as a function of the shunt resistance for various excitation currents.

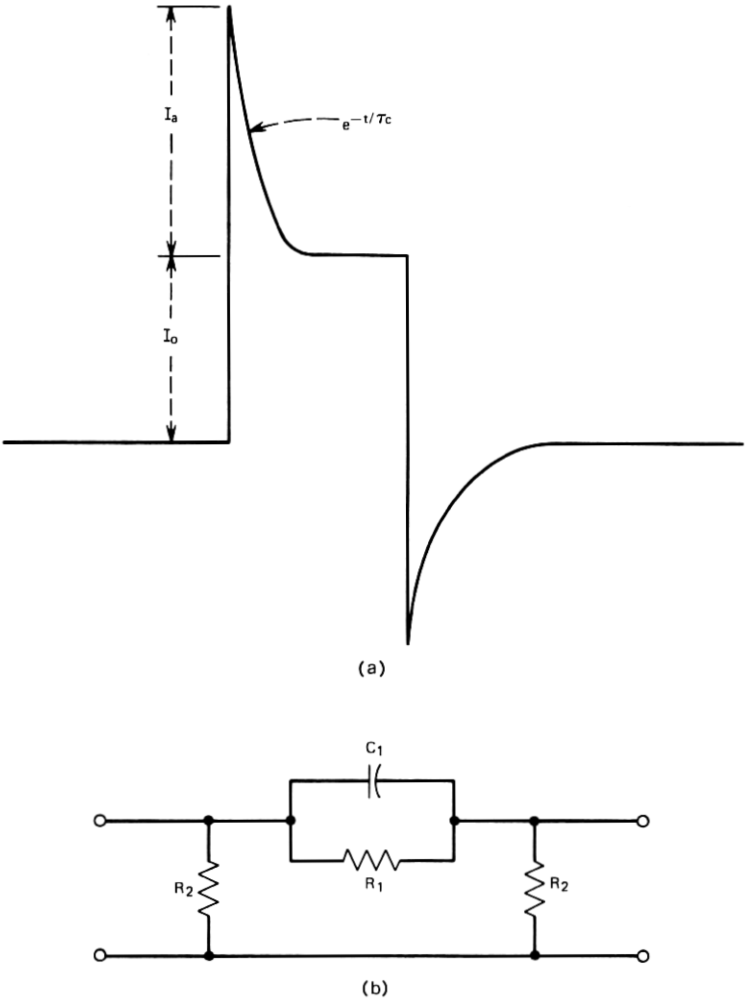

Fig. 6—(a) Current waveform for delay reduction of laser diodes. (b) The pulse shaping network used in the experiment.

in Ref. 23, the laser turn-on delay can be derived as

$$\frac{I_a}{I_{th}}\frac{e^{-T_d/T_c}}{1-T_d/T_c}-\left(\frac{I_a}{I_{th}}\frac{1}{1-1/T_c}+\frac{I_0}{I_{th}}\right)e^{-T_d}+\frac{I_0}{I_{th}}=1, \qquad (11)$$

where I_a is the amplitude of the exponential portion of the current pulse, I_0 is the constant portion of the current pulse, and I_{th} is the threshold current with a rectangular current pulse. $T_d = t_d/\tau_{\rm eff}$ is the normalized delay time, and $T_c = \tau_c/\tau_{\rm eff}$. Since the parameters I_a and τ_c are independent, we considered two cases: (*i*) Set $\tau_c/\tau_{\rm eff} = 1$, and find the decrease of t_d with I_a. (*ii*) Set $I_a = I_0$ and find the decrease of t_d with τ_c. The results are shown in Figs. 6a and 6b, respectively. In Fig. 7a, for each I_0, the curves start on the Y-axis at a value of t_d/τ_{eff} that equals the normalized delay for a rectangular pulse given by (10). As I_a increases, the delay decreases and approaches 0.1 τ_{eff} at $I_a = 8\, I_{th}$. This implies that a sharp spike in the driving current pulse would help considerably in reducing the delay.

Figure 7b shows the reduction of t_d as a function of $T_c(= t_c/\tau_{\text{eff}})$. For a very small value of T_c, the exponential portion of the current is too fast for the charge to respond, and the reduction of t_d is marginal. For $T_c \gg 1$, t_d asymptotically approaches 0.287 τ_{eff} at $I_a = I_0 = 2\, I_{th}$.

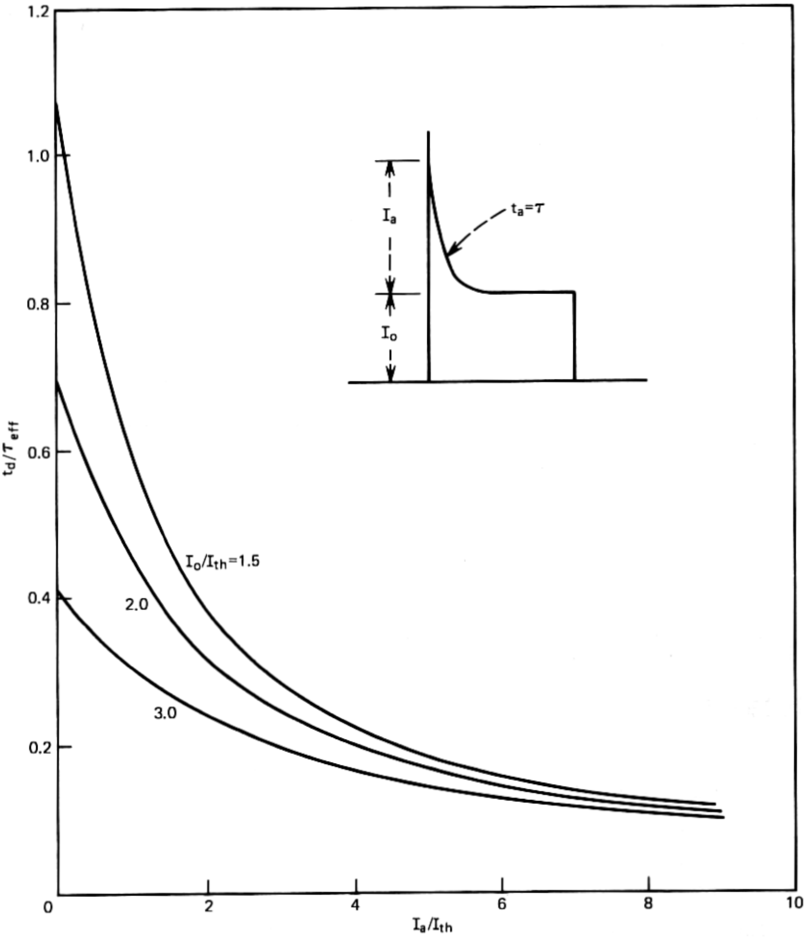

Fig. 7a—Reduction of delay time as a function of the peak pulse amplitude.

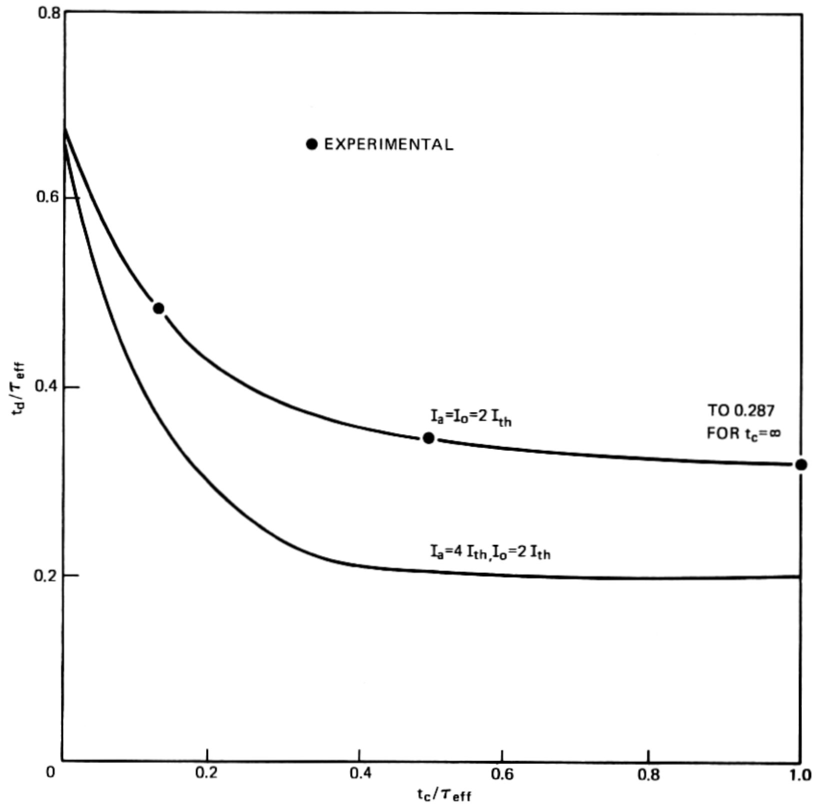

Fig. 7b—Reduction of delay time as a function of the pulse decaying time constant.

At $T_c = 1$, $t_d = 0.316\ \tau_{eff}$. Thus, a factor of 2.2 reduction in t_d can be realized with this shaped pulse compared to that obtainable with a rectangular pulse.

Experimentally, we have realized the pulse shape in Fig. 6a by shaping a rectangular pulse with the network shown in Fig. 6b as an example. This pulse shape not only serves to reduce delay, but its negative after-pulse serves to turn the laser off faster than a rectangular pulse. The resistors R_1 and R_2 are necessary for matching to our 50-ohm measuring system. The capacitor C_1 may be chosen to provide different time constants. Table II summarizes the experimental and calculated results, and it can be seen that the agreement is excellent.

VI. CONCLUSIONS

Both theoretical and experimental investigations of the effect of junction capacitance on the rise time of LED's and the delay time of

Table II — Comparison of experimental and calculated delay reduction

I/I_{th}	Rectangular Pulse, $I_0 = 2I_{th}$		Exponential Pulse, $I_a = I_0 = 2I_{th}$					
	τ_{eff} (ns)	$t_d(I = 2I_{th})$ (ns)	t_c (ns)	R_1 (Ω)	R_2 (Ω)	C_1 (pF)	t_d Measured (ns)	t_d Calculated (ns)
	3.8	2.4	0.25	100	82	5	2.3	2.2
			0.5	100	82	10	1.6	1.8
			1.95	100	82	39	1.2	1.3
			3.9	100	82	79	1.0	1.1

injection lasers lead to the conclusion that the apparent response delays in these devices can be attributed largely to the shunting capacitance of the junction itself. The effects are greatest in devices operating at relatively low currents. Thus, in the more efficient double-heterostructure devices, the response time is much larger than would be expected from the spontaneous recombination time of the carriers. Homostructure devices, normally operated at much higher current densities, are affected less.[27]

Practically, the effects can be minimized by constructing devices to have low capacitance (by isolation of the active junction through the use of mesa structures or proton bombardment, for example) and by providing the lowest possible impedances in the driving circuits. Furthermore, in certain systems applications where short delay is required, a simple delay equalization (in the form of a shaped driving pulse) can be employed in conjunction with a driver that has low-output impedance.

It should be pointed out, however, that our definition of rise time is the time required for the light output to reach 90 percent of its fully developed steady-state value, when the diode is driven by a step current. In many practical applications, the LED can be modulated at much higher speed than that imposed by the spontaneous recombination time.[28] In such cases, the light output would not reach the steady-state value before the driving pulse is off, resulting in an apparently narrower output pulse but smaller amplitude. The price one pays, of course, is the reduced driving efficiency.[29]

In addition to the effects of the capacitance on the pulse modulation of these devices, it is also pointed out that great care must be exercised in determining the semiconductor carrier recombination time by measurement of the delay time of junction lasers. To assure good results, the junction capacitance must be less than 10 pF, and the device must be operating in a single filament.

VII. ACKNOWLEDGMENTS

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