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Generation of picosecond optical pulses from single heterostructure GaAs diode laser and their emission characteristics

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Abstract. Emission characteristics of a single heterostructure GaAs diode laser are reported using a simple driver circuit. It provides a single picosecond time duration optical pulse, a pulse train or a broad optical pulse depending on the amplitude and time duration of the electrical pump pulse. Results show that relaxation oscillation frequency depends on the amplitude of pumping current pulse as well as on some inherent property of diode laser, which seems to be the level of impurity in lasing medium. Variation of relaxation oscillation frequency with amplitude of current pulse shows only the qualitative agreement with the reported theoretical predictions.

Keywords. Optical pulses; emission characteristics; oscillation frequency.

PACS Nos **04·30; 04·80**

1. Introduction

Diode lasers are a low cost, compact and efficient optical source which can provide optical pulses of picosecond time duration at high repetition rate. These devices play an important role in the studies of ultrafast processes, optical communication as well as the testing of temporal behaviour of fast opto-electronic devices. It is therefore important to study in detail the emission characteristics of these lasers.

Picosecond pulse generation by semiconductor lasers has been investigated by several authors [1–13]. Various methods have been used to obtain these ultra short pulses, such as mode locking using external optical resonator [2] or by simpler gain switching methods. Two methods of gain switching have been demonstrated as injection of a short current pulse [1, 4, 11] or a sinusoidal RF wave in the presence of DC bias [5–10, 12]. Many types of diode lasers emitting in visible [13] as well as in infrared [1–12] wavelength regions have been used for this purpose. A large number of investigations related to picosecond optical pulse generation have been performed by RF current modulation technique or with an ultra short (picosecond) time duration electrical pulses [9] in the presence of a DC bias voltage. Paulus *et al* [9] have reported that the optical pulse width from laser diode first decreases and then remains constant at a certain minimum with an increase in the amplitude of the pumping current pulse. However, the pulse width (optical) first decreases up to a certain value and then increases with an increase in the DC bias current. These observations have been supported by numerical analysis. On the basis of theoretical calculations, MacFarlane [10] has reported that the time duration of the optical pulse first decreases and then attains a constant value, when time duration of electrical pulse was decreased.

However, the nature of variation remains same with a new value of optical time duration when the DC bias current was changed. According to Baker [11] the optical pulse generation combining the relaxation oscillation phenomenon of laser diode with large current pulse capacity of avalanche transistors could lead to optical pulses of < 100 ps pulse width. It has been reported that if the current impulse of the avalanche transistor returns to zero before the occurrence of the second oscillation of the laser diode, an optical impulse will be generated and if a current step is applied to the laser diode a train of pulses with decreasing optical amplitude will be generated. In another investigation Yariv [8] and Lau *et al* [7] have presented an analysis about the relaxation oscillation frequency observed in the laser diode, which was found dependent on the amplitude of the pumping electrical pulse as well as on the power emitted from the laser diode respectively. The latter relation fits better with the experimentally observed data.

The aim of this study is to verify the results of Paulus *et al* [9], Baker [11], Yariv [8] and Lau *et al* [7] when the laser diode is operated using a pumping pulse of subnanosecond (~ 800 ps) to 15 ns time duration. For this purpose, a single heterostructure GaAs laser diode was used to investigate the detailed emission characteristics of the laser diode with the amplitude and pulse width of the pumping electrical pulse.

2. Experimental details

Short duration optical pulses were generated [14, 15] by a single heterostructure GaAs laser diode (LD-62) obtained from Laser Diode Incorporated, USA. Laser diode was

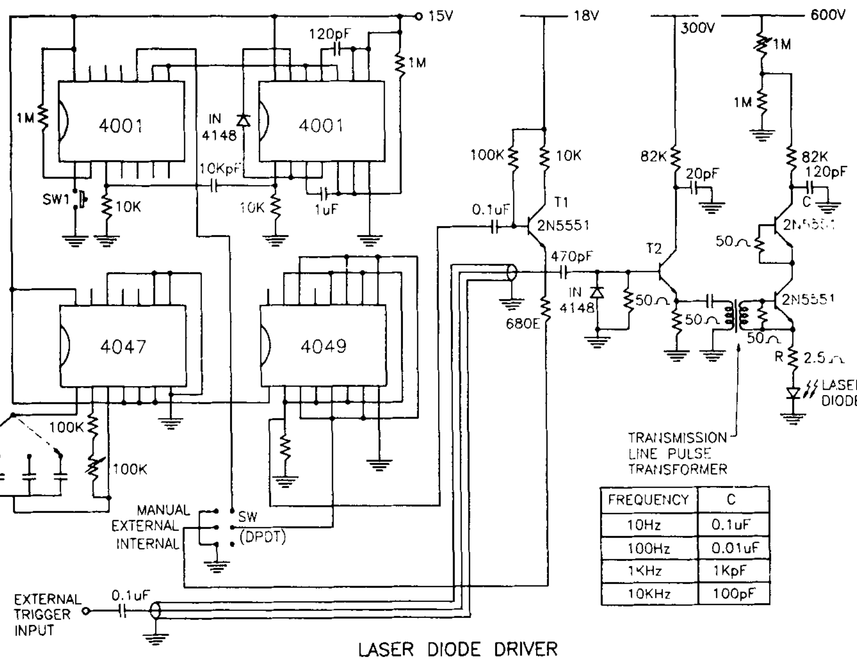


Figure 1. Circuit diagram of diode laser driver.

driven by a simple driver (figure 1) where current pulse was generated by discharging a capacitor C (charged up to ~ 600 V) by switching the stack of two transistors (2N5551) connected in series. Two transistors were used to increase the amplitude of the current pulse. These transistors act as a switching element when operated in avalanche mode and were selected carefully such that they had same rise time ($\sim 1{\cdot}5$ ns) and breakdown voltage (~ 300 V). It was also noticed that the best transistors [16] were those having h_{FE} value ~ 120. However, the correlation of transistor parameter h_{FE} with the avalanche mode breakdown was not known. The actual peak current passing through the laser diode was adjusted by changing the charging voltage or the value of the capacitor C. This follows from the fact that the injection current to the diode is decided by the product of C and the charging voltage V, whereas the duration of the current pulse is decided by the product of C and the resistance in the discharging path. The rise time of the pulse is decided by the inductance of the circuit which was minimized in this case using a specially designed PCB. The laser diode was mounted on an aluminium plate which acts as a heat sink for the laser diode. The above circuit could be triggered by a pulse of ~ 5 V amplitude, but we used ~ 24 V amplitude trigger for a reliable triggering with a reduced time jitter. The trigger pulse was applied through a fast transmission line pulse transformer to the base of one of the transistors in the stack. The pulse transformer was made by wrapping four turns of co-axial cable of 50 Ω impedance where the outer shield acts as primary and the central wire as secondary of the transformer. It was operated either in manual single shot mode or at ~ 10 Hz repetition rate. The output emission from laser diode was detected using MRD 510 photodiode in combination with 100 MHz digital storage oscilloscope L and T Gould model 4074 (400 MS/S sampling rate) and a newly developed picosecond optical streak camera [17] having $S1$ photocathode. This streak camera provides a streak speed of ~ 15 mm/ns with a time resolution $\leqslant 17$ ps. The schematic diagram of the experimental set up to record the optical pulses from laser diode using streak camera is shown in figure 2. The image from the intensifier screen was captured using a CCD camera where

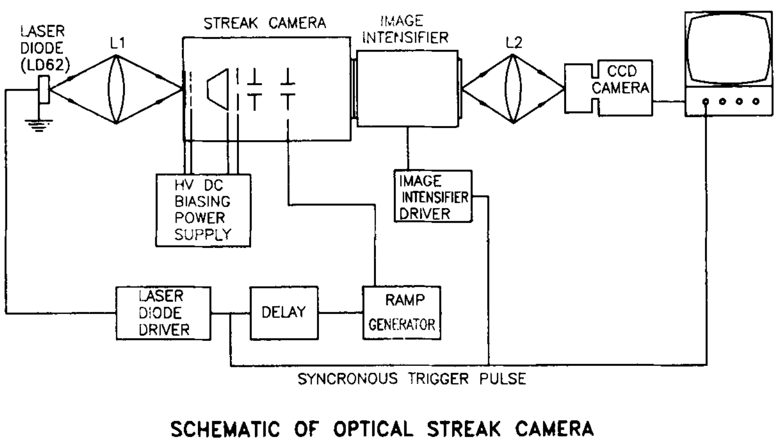


Figure 2. Schematic diagram of experimental set up.

an intensity profile was obtained on a PC monitor screen with the help of 'PROMISE' (Profile Measurement of Image Size and Edge Location) software programme [18].

3. Results and discussion

3.1 *Electrical properties of diode laser driver*

A simple fast rising current pulse is used to pump the diode laser to get a short duration optical pulse. These fast electrical pulses were obtained by the circuit given in figure 1 as described in previous section. However, before the study of emission characteristics of diode laser, study of electrical pulse is necessary. Two combinations of avalanche transistors were used as a switching element to drive the diode laser. In the first combination only two transistors connected in series acts as the switching element for discharging the capacitor C. Actual shape of current pulse was obtained by recording the shape of voltage pulse across $1{\cdot}5\,\Omega$ resistance connected as a dummy in place of diode laser. Electrical pulses were recorded by a digital storage oscilloscope L and T Gould model 7074 (400 MS/S) which has low temporal resolution $\sim 3{\cdot}5$ ns. Figure 3 shows the shape of electrical pulse obtained across $1{\cdot}5\,\Omega$ when $C = 120$ pF capacitor charged to 600 V was discharged by triggering one of the transistors in the stack. This provides an electrical pulse of ~ 10 ns time duration along with some of the oscillating pulses having decreasing amplitude. An increase in the value of C as 60, 100 and 270 pF shows corresponding increase in time duration of the electrical pulse as $\sim 6, 8$ and 15 ns which is expected. It was also noted that any change in the charging voltage does not show any effect on the FWHM of the electrical pulse. Minimum rise time of ~ 1 ns and pulse duration ~ 3 ns were measured for the capacitors of value $\leqslant 20$ pF. However, 20 pF capacitor in two transistor circuit did not provide detectable intensity from diode laser.

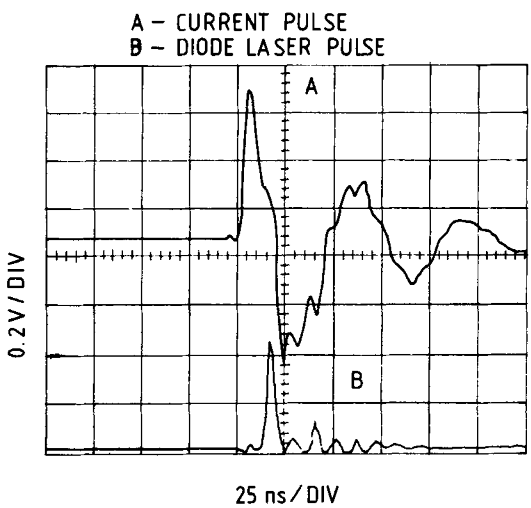


Figure 3. Oscillogram of the electrical pump pulse when series stack of two transistors (2N5551/2N5550) were used as switching element and the optical pulse obtained from diode laser.

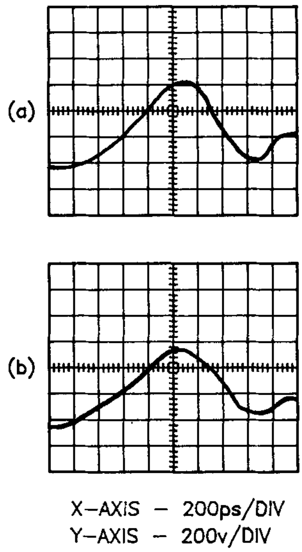


Figure 4. Oscillogram of the pump pulse when series stack of nine transistors (2N5551/2N5550) were used as switching element in the driver circuit. Capacitor was charged up to (a) 2·7 kV, (b) 2·5 kV.

It was observed that for low value of capacitor higher charging voltage is required which is possible only by increasing the number of transistors in the stack.

In order to improve the rise time and time duration of the pump electrical pulse another combination of switching element was used which has a series stack of nine transistors (2N5551/2N5550). This circuit uses 20 pF capacitor charged up to 2·7 kV. Electrical pulses obtained from this circuit for the charging voltage of 2·7 kV (figure 4a) and 2·5 kV (figure 4b) were recorded by Tektronix model 7104 oscilloscope. Figure 4a has a rise time and time duration of the pulse as $\sim$ 600 ps (10%–90%) and $\sim$ 800 ps respectively whereas figure 4b shows the rise time as $\sim$ 800 ps and time duration as $\sim$ 900 ps. These results indicate that rise time and duration of the pulse get improved by increasing the number of transistors in the switching stack. A small decrease in charging voltage increases the rise time and the pulse duration whereas no variation was observed in the rise time and pulse duration of the electrical pulse in the case of two transistors stack. However, similar variations are expected in both the cases but the small variation in two transistor case may not be observable. This improvement in the time duration of the pulse in the case of increased number of transistors in the stack seems to be due to change in the value of capacitance as a result of series connection of charging capacitor and junction capacitances of the switching transistors. However, rise time of the electrical pulse got improved due to the combined effect of decrease in effective junction capacitance of the switching transistors and decrease in the inductance of discharging path in the circuit.

3.2 *Emission characteristics of LD-62 diode laser*

The emission characteristics of the diode laser was investigated to understand the relationship between the driving current pulse at high amplitude and the shape of the

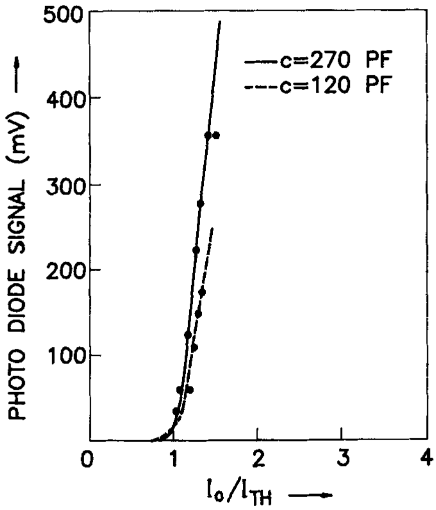


Figure 5. Variation of optical intensity emitted from laser diode with pumping current pulse (I_0/I_{Th}).

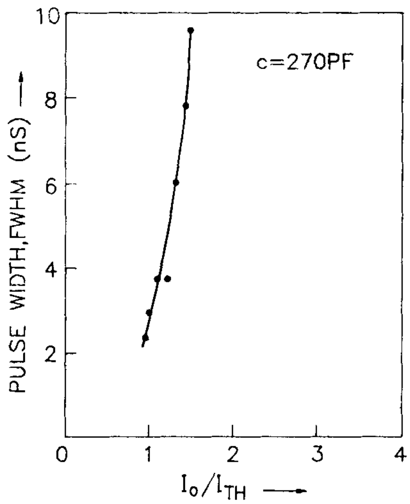


Figure 6. Variation of optical pulse width with the amplitude of the pump current (I_0/I_{Th}).

light pulse. Figure 3 shows the shape of the current pulse obtained after discharging a capacitor of ~ 120 pF and the optical pulse detected using photodiode MRD 510. Time duration of the electrical and optical pulse was measured as ~ 10 ns and ~ 5 ns, respectively. Here one can notice that the oscillations observed in the electrical current pulse did not generate corresponding optical pulses. However, at a higher current value, the amplitude of oscillations in current pulse crosses the lasing threshold and provides corresponding optical pulses. Figure 5 shows the variation of the optical pulse amplitude with an increase in the ratio of injection current and the threshold lasing current I_0/I_{Th} for discharging capacitor of value ~ 120 and 270 pF. When charging voltage on the capacitor decreases, then, as a result of decrease in the current pulse amplitude, the pulse width (figure 6) as well as intensity of the optical pulse decreases (figure 5). It was found (figure 5) that for getting a similar photodiode signal with both the charging capacitors, required current (charging voltage) is more in the case of smaller value of charging capacitor (~ 120 pF). Even the threshold for lasing is also high in the case of lower value of capacitor. An increase in the duration of the optical emission with large amplitude and ns time duration pumping current pulse (figure 6) may be due to two reasons: firstly, due to an increase in the temperature as a result of large current passing through the diode which is in agreement with the earlier reported results [1, 4], and secondly, due to the occurrence of multiple pulsation or relaxation oscillations [3, 7–13] which will be discussed in detail afterwards. The observation of figure 6 is contrary to the experimental and numerical results reported by Paulus *et al* [9] where picosecond pulses were used for pumping the laser diode. It seems that the small time duration pumping pulses are not producing multiple pulsation or producing it at very large amplitude of exciting current pulse. However, first decreasing (transition from spontaneous to stimulated emission) and then increasing (due to multiple pulsation) nature in optical pulse duration has been reported with an increase in the DC bias voltages [9] in the presence of a picosecond pump pulse. We are getting only increasing nature in optical pulse width with an increase in the amplitude of the current pulse. However, a small increase in optical pulse width at lower amplitude of the current pulse is possible near the threshold of lasing (near breakdown voltage of transistor stack) in our case also. Because a decrease in charging voltage, below breakdown voltage of transistor stack (to decrease the current) increases the rise time and pulse duration of the current pulse (figure 4) and consequently the time duration of the optical pulse. However, this change may not be observable due to the band-width

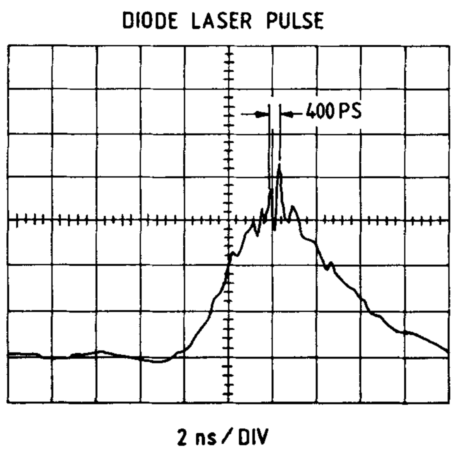


Figure 7. Time profile of laser diode emission (for $I_0/I_{Th} \sim 1.32$) recorded using photodiode and oscilloscope (L and T Gould 100 MHz oscilloscope model 4074).

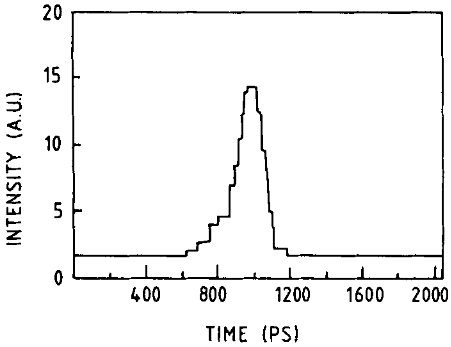


Figure 8. Single optical pulse from laser diode recorded using streak camera.

limitation of the recording oscilloscope. A comparison of our results with those of the Paulus *et al* [9] indicates that the large amplitude of the pumping pulse combined with its large time duration, has similar effect as the DC bias has in the presence of picosecond time duration electrical pulses. Figure 7 shows the photodiode signal recorded in equivalent time sampling mode at an injection current ratio $I_0/I_{\mathrm{Th}} \sim 1{\cdot}32$ which provides a broad optical pulse along with a modulation of intensity at the top of the pulse. The small time duration pulsation occurs at nearly equal time intervals which is ~ 400 ps in the present case. Further increase (decrease) in the current pulse amplitude shows corresponding decrease (increase) in the time interval between the pulsations. A single optical pulse (figure 8) of ~ 180 ps duration was observed using a streak camera when laser diode was operated just above the threshold current value. However, smallest optical pulse duration of ~ 120 ps was recorded by discharging a 20 pF capacitor through diode laser (figure 4). At $I_0/I_{\mathrm{Th}} \sim 1{\cdot}32$ a pulse train having pulses of duration ~ 180 ps was observed on the streak camera separated with the time interval of ~ 400 ps (figure 9a). Here again we note that the time period between the pulses decreases with an increase in I_0/I_{Th}. It was observed that at large injection current the optical pulse gets broadened (pulses merge together) in such a way that the train of the pulses got converted into a single large time duration pulse with intensity modulation at the top. The broad optical pulse has a similar shape as that of the current pulse. These observations indicate that emission of a short duration single pulse, a pulse train or a broad pulse with intensity modulation are the function of ratio I_0/I_{Th}. The difference in the shape of pulses at $I_0/I_{\mathrm{Th}} \sim 1{\cdot}32$ in figures 7 and 9a is due to the difference in the temporal resolution of the recording systems. Experiments were repeated many times and results were found reproducible. The time duration of these optical pulses were changed using different values of the capacitors. Figures 9a and 9b show the intensity profile of two similar laser diodes connected in parallel and operated with the same current pulse in single shot operation by pumping the diodes simultaneously. A slight change was noticed in the intensity, time period of pulsation and time duration in the case of single pulse or in the pulse train when different laser diodes of the same specifications were tested using the same current pulse. In order to see the effect of improvement in the rise time and shortening the time duration of the pumping electrical pulse on the emitted optical pulse, we used a short time duration electrical

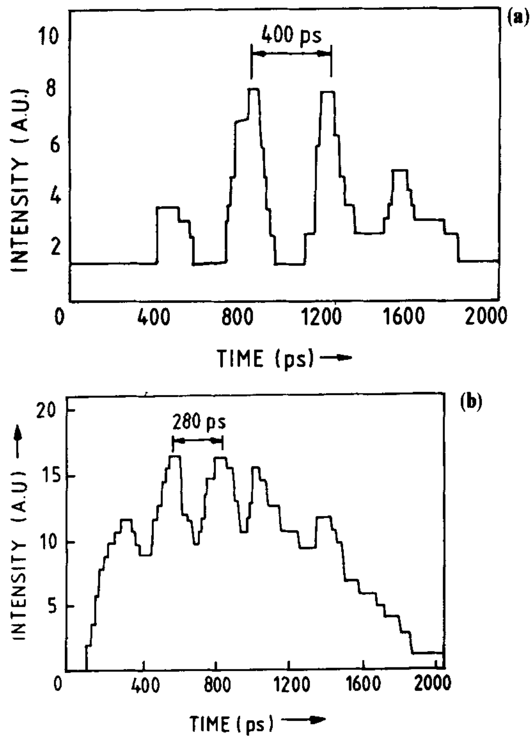
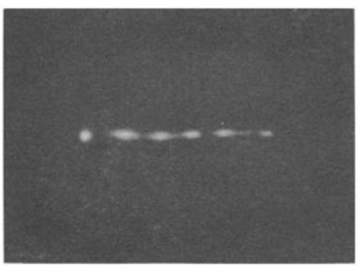


Figure 9. Multiple pulsation emitted from laser diode (for $I_0/I_{Th} \sim 1{\cdot}32$) and recorded using streak camera. (a) Laser diode I; (b) Laser diode II.



SCALE - 15mm = 1 ns

Figure 10. Contact photograph of multiple pulsation when diode laser was pumped by discharging a 20 pF capacitor charged at 2·7 kV using a series stack of nine transistors (2N5551/2N5550) as a switch.

pulse (figure 4) for pumping the diode laser. Figure 10 shows the contact photograph of the laser diode emission taken using a streak camera on the polaroid film, which has a train of pulses emitted from the diode. The first pulse of the train has a time duration < 120 ps, which seems to be due to an improvement in the electrical pulse time duration and rise time. Here again we observed that duration of optical pulses increases when charging voltage was decreased from 2·7 kV to 2·5 kV. This behaviour is similar to what has been observed in the two-transistor case. It was however noted during these experiments that multiple optical pulses of picosecond time duration were obtained always whenever the laser diode was driven by a large amplitude current pulse obtained by switching the transistors in the avalanche mode (figure 9) whereas it provided a single optical pulse of picosecond time duration with a slowly rising intensity at the leading edge of the pulse (figure 8), when transistors were operated below avalanche breakdown voltage whether a two-transistor or nine-transistor stack was used. The slow rise in the intensity at the beginning of the optical pulse may be due to spontaneous emission, which occurs as a result of an increase in the rise time and decrease in the amplitude of the electrical pulse.

3.3 *Comparison with theoretical results*

It is generally accepted that the modulation band-width of the semiconductor laser is equal to ν_{rel}, the relaxation oscillation frequency [7, 8] which varies from laser to laser. However, this frequency limits the useful band-width of the diode laser below relaxation oscillation frequency. Figure 11 shows the variation of relaxation oscillation frequency with the pumping current for some of the typical parameters of the diode laser. Frequencies have been calculated using a widely accepted formula [8].

$$2\pi\nu_{rel} = \left[\frac{\Gamma n_{tr} A\tau_P + 1}{\tau_s \tau_P}\left(\frac{I_0}{I_{Th}} - 1\right)\right]^{1/2} \tag{1}$$

and

$$\tau_P = \frac{1}{v}\left(\alpha + \frac{1}{L}\ln\frac{1}{R}\right)^{-1}$$

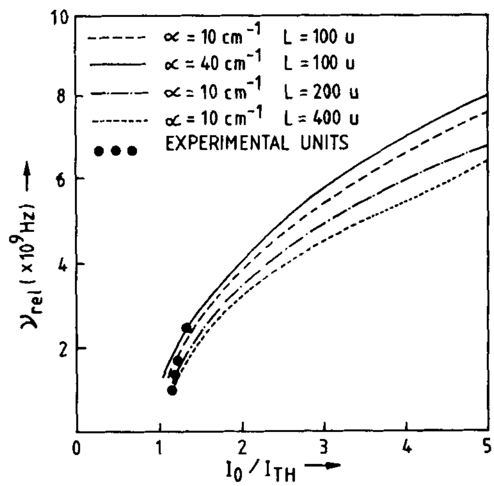


Figure 11. Variation of measured and calculated relaxation oscillation frequencies with pump current (I_0/I_{Th}).

where I_0 and I_{Th} are the pumping and threshold current for the occurrence of laser, τ_s and τ_P are the spontaneous carrier and photon life time respectively, Γ is the optical confinement factor, A is the optical gain co-efficient and n_{tr} is the carrier density at which the material becomes transparent. v is the group velocity of the light, α is the distributed loss, L is the length of the cavity and R is the mirror reflectivity.

The numerical values for these parameters have been obtained from references 7 and 8. The experimentally measured relaxation frequency data with pumping current has also been plotted on the same graph for comparison purpose. It was found that experimentally as well as theoretically obtained data are in qualitative agreement, that is, frequency increases with an increase in the pumping current. But experimental data do not fit correctly with any of the theoretically obtained curve. Figure 12 shows the variation of experimentally observed relaxation oscillation frequencies with the square root of the emitted light intensity, which is proportional to the photo diode signal. A linear variation of data points indicates better agreement with the relation given by Lau *et al* [7] for relaxation oscillation frequency as

$$\nu_{rel} = \left(\frac{1}{2\pi}\right)\left(\frac{AP_0}{\tau_P}\right)^{1/2}, \tag{2}$$

where P_0 is the steady state photon density in the active region. However a small deviation can be seen at the higher value of current in this experiment. The experimental observations, reported by Lau *et al* [7] for a burried heterostructure GaAs laser operated by current modulation at 0·1–8·5 GHz show a close agreement with (2). The data obtained from other laser diode (figure 9b) also show similar variation but provide entirely different frequencies for similar pumping current. The observed pulsation behaviour in both the diode lasers (figures 9a and 9b) were compared with the theoretical simulation results reported by Chik *et al* [3] who have taken into account the presence of defects (saturable absorber) in the cavity. Emission in figure 9b has a broad profile with intensity modulation on the top whereas figure 9a shows a higher order of modulation depth in intensity which seems to be due to the presence of large density of defects in figure 9a. The relaxation oscillation frequency obtained in

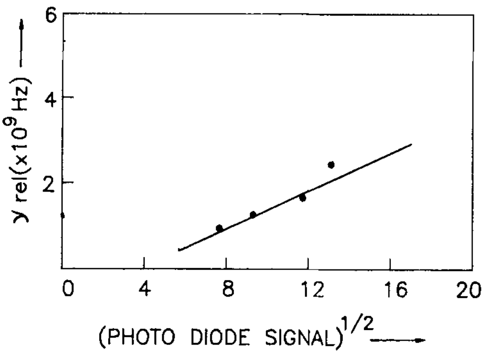


Figure 12. Variation of measured relaxation oscillation frequency with the square root of intensity emitted from diode laser.

figure 9b (3·6 GHz) is higher in comparison to figure 9a (2·5 GHz). This decrease in frequency may be due to an increase in the density of defects in the cavity, which is also in qualitative agreement with the results of Chik *et al* [3]. In view of the above mentioned observations and other reported results [3, 7–9], it is clear that the presence of defects in the laser cavity plays an important role in providing self-sustained pulsation behaviour in the semiconductor diode laser.

4. Conclusion

In summary, a short picosecond time duration pulse was obtained from a single heterojunction GaAs laser diode by injection of a current pulse of time duration ranging from subnanosecond to 15 ns obtained from a simple circuit. However time duration of the single optical pulse depends on the time duration of the pumping electrical pulse. The shortest optical pulse obtained was of $\leqslant 120$ ps. One can obtain a single pulse, pulse train or a broad pulse with intensity modulation on the top depending on the amplitude of the current pulse which is independent of the electrical pulse duration. However, threshold of lasing is dependent on pump pulse time duration (value of capacitor, C). It was found that occurrence of relaxation oscillation or self-sustained pulsation does not depend only on the duration of electrical pump pulse as is reported by Baker [11]. It has been shown that the high amplitude of electrical pump pulse with large pulse duration in these experiments and the electrical pulse of ultrashort time duration with a DC bias in the case of Paulus *et al* [9] provide similar results, that is, an increase in optical time duration. Variation in optical pulse duration with electrical pulse duration was found in agreement with the results of MacFarlane [10]. Experimental observations further indicate the need for modification in the theory (consideration of impurity factor) to explain the observed variations in relaxation oscillation frequencies with the amplitude of pumping electrical pulse. However, the study of laser diode (GaAs) emission with a better time resolution may provide more important information.

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