Mode Locking Of (GaAl)As Injection Lasers

Luis Figueroa, Kam Lau, Amnon Yariv

Luis Figueroa, Kam Lau, Amnon Yariv, "Mode Locking Of (GaAl)As Injection Lasers," Proc. SPIE 0269, Integrated Optics I, (29 July 1981); doi: 10.1117/12.959959

Event: 1981 Los Angeles Technical Symposium, 1980, Los Angeles, United States

Mode locking of (GaAl)As injection lasers

Luis Figueroa
Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, California 90265
Kam Lau, Amnon Yariv
California Institute of Technology, Pasadena, California 91125

Abstract

The important experimental parameters affecting the mode locking of a variety of (GaAl)As injection lasers operating in an external optical cavity are described. We find that short detector-limited pulses (less than 60 psec) with 100% modulation depth can only be obtained using lasers that exhibit either an anomalous narrow-band noise resonance or self pulsations. Little or no mode locking is observed in lasers having the normal broad noise resonance. The maximum frequency of the mode-locked pulses is $\sim$1 GHz and is limited by the laser and not the external cavity. The observed amplitude, pulse width, and frequency of the mode-locked pulses are correlated to the degree of self-pulsation and the external cavity length. The experimental results are in qualitative agreement with a model that uses the rate equations modified by either electron traps or saturable absorbers and a delayed feedback term. Our results appear to imply that mode locking in (GaAl)As injection lasers is related to saturable absorbing centers and is very similar to passive mode locking in dye lasers.

Introduction

In recent years, the mode locking of (GaAl)As injection lasers[1-7] has been reported. Pulses as short as 5 psec have been obtained by operating an injection laser in an external cavity.[4] A high-speed, compact optical pulse generator with high peak power can be used for injection locking microwave semiconductor sources at GHz rates; characterizing optical fiber systems (e.g., dispersion, loss, transient response); and characterizing high-speed electronic devices.

We have extensively characterized mode-locking in various commercial (GaAl)As injection lasers. We have observed that short detector-limited pulses (less than 60 psec) with 100% modulation depth and $\sim$1 GHz repetition rate can only be obtained in lasers having either a narrow-band noise resonance or self-pulsations. The amplitude and pulse width of the mode-locked pulses are a strong function of the external cavity length and the laser current.

Experimental Set-Up and DC Characteristics

Figure 1 shows the experimental arrangement for the external cavity geometry. We have used several different types of specially selected commercial (GaAl)As injection lasers (BH, CDH, CSP, and proton stripe), including some with one facet having an Al_2O_3 antireflection (AR) coating. The lasers operate cw at all times. The external resonator consists of a 40x microscope objective and a flat mirror. The experimental arrangement consists of mounting the laser at the end of a microstrip bias tee with a 47-Ω resistor placed in series with the rf input to provide impedance matching. The external cavity is aligned by collimating the output beam from one facet of the laser and adjusting the return beam so as to increase the laser output from the other facet. The final alignment can be easily accomplished using PZT-controlled micrometers; however, these are not essential. The light output from the second facet of the laser is collected onto a high-speed detector. We have used two high-speed detectors: a Telefunken APD (S171P) and a Spectral Physics (403B). The rf input to the laser is provided by an HP sweep oscillator (8690B). The maximum rf input to the laser is estimated to be less than a few milliwatts for the cases considered. The output from the high-speed detectors is fed to either an HP spectrum analyzer (8565A) or a Tektronix sampling oscilloscope (S11).

Figure 2 shows typical light output versus current characteristics for different types of laser structures operating with an external resonator (ER). For comparison, we have also shown the light output characteristics with no external cavity. Note that there is a reduction of the threshold current when the external cavity is aligned. Successful mode locking occurs when the dc bias is within the shaded region of Figure 2.

Dynamic Characteristics of Injection Lasers Operating in an External Cavity

The dynamic characteristics of injection lasers operating in an external optical cavity have been discussed by many authors.[8] Broom et al.[9] obtained self-induced sinusoidal resonances at a frequency corresponding to either the inverse transit time or a harmonic of the relaxation oscillation resonance. The experimental results were explained by assuming an interaction between photons, injected carriers, and longitudinal mode effects. No account of the delayed feedback from the external cavity was considered. Paoli and Ripper[10] characterized the operation of self-pulsing lasers operating in an external cavity. They concluded that sharp pulsations could be obtained by using either electrical or optical feedback. Pulses as short as

180 psec (detector limited) were obtained. Furthermore, they obtained frequency locking and jumping effects. Recently, several workers have observed a sharp pulsation of the light output when the injection laser is driven at the inverse transit time f_c of the external cavity.[1-7] The initial demonstrations have attributed this effect to active mode locking and were able to generate pulses 20 psec in width at a 3-GHz repetition rate.[1] Recently, Ippen et al.[4] have demonstrated that pulses 5 psec in width can be generated from (GaAl)As injection lasers having a high density of saturable absorbing centers.

The question arises as to the mechanism responsible for the observed effects: are there any relationships between self-pulsations, induced resonances, and the recent mode-locking experiments? We believe the answer is yes.

We have observed a direct relationship between lasers that exhibit either an anomalous narrow-band noise resonance or self-pulsations and the ability of those lasers to be mode locked. Figure 3 shows a typical light output versus frequency plot for a "well-behaved" (GaAl)As injection laser. Several observations can be made. Every laser studied exhibits a relatively broad noise resonance that occurs above 500 MHz and varies with current. The amplitude of the noise resonance tends to decrease as current increases above threshold. Figure 4 shows the light output versus frequency when the laser is placed in an external optical cavity. The figure shows that resonances corresponding to harmonics of the inverse transit time, f_c, can be induced. The resonance bandwidth is typically 50 MHz or greater. To attempt to mode lock the injection laser, we introduced an external rf signal into the laser. The frequency of the rf signal was adjusted to correspond to f_c. Figure 5 is a photograph displaying the light output; it shows that the pulse width is not very sharp. We should further note that it is always possible to obtain a pulse output by applying a large rf signal and operating the laser near threshold. However, this phenomenon is predicted by the conventional rate equations and is produced by harmonic distortion. In this mode of operation, the pulse amplitude and width are relatively insensitive to frequency (over a 100-MHz bandwidth). Thus, we conclude that mode locking is very weak or not present at all in lasers having a regular noise resonance.

Figure 6 shows a typical photograph displaying the light output versus frequency plot for a laser displaying narrow-band noise resonances. The measurements were taken without an external cavity. The sharp resonances develop at a current slightly above threshold, and in some of the lasers studied the output breaks into a self-pulsation similar to that reported by previous workers.[11,12] The bandwidth of the resonance is typically less than 10 MHz. When the laser is operated in an external cavity and the current lies within the shaded region of Figure 2, sharp resonances can be induced at the inverse transit time f_c and at harmonics. This is shown in Figure 7. The bandwidth of the induced resonance can be less than 1 MHz. For the laser described in Figure 7, a sharp pulsation of the light output can be induced when the current is modulated at the inverse transit time f_c. A typical temporal display is shown in Figure 8(a). Figure 8(b) shows a high-resolution temporal display. Note that the pulse width is detector limited ($\tau_{p1/2} < 60$ psec) and the modulation depth is close to 100% for those lasers having a sharp noise resonance. We have obtained efficient mod-locked pulses with frequencies ranging from 400 MHz to 1.2 GHz. The optimum frequency depends on the actual laser structure used.

The amplitude, pulse width, and frequency of the mode-locked pulses depend on several factors. First, assuming that lasers displaying a narrow band noise resonance have a high density of saturable absorbing centers, then it follows that we can describe the process using the conventional rate equations modified by two important parameters: (1) the effects of saturable absorbing centers in the manner of Copeland[13] and (2) the effect of the external cavity by introducing a delayed feedback term.[14] Numerical calculations[14,15,16] predict that pulsations can be induced when the density of saturable absorbers is high and the optical coupling from the external cavity is above a certain level. We expect the amplitude, pulse width, and frequency of the induced pulsations to vary both with the external cavity length and the injection current. Experimentally, we find that in weakly self-pulsing lasers the mode-locked pulses are relatively wide ($\tau_{p1/2} \sim 400$ psec), as shown in Figure 9. In strongly self-pulsing lasers with very well defined noise resonances, it is possible to induce pulsations without an external rf signal. This is shown in Figure 10. Blocking the external cavity quenches the mode-locked pulses, while application of an rf signal at f_c tends to stabilize the pulses. This result implies a type of passive mode-locking similar to that observed in dye lasers.

Conclusions

In this paper we have described the process of mode-locking in (GaAl)As injection lasers. We have observed that detector-limited pulses ($\tau_{p1/2} < 60$ psec) and 100% modulation depth can only be obtained in lasers having either a narrow band noise resonance or self-pulsations. Little or no mode locking is observed in lasers having the regular noise resonance. Our results imply that mode locking in (GaAl)As injection lasers is related to saturable absorbing centers within the laser cavity.

Acknowledgments

The author is very grateful to D. Botez of the RCA Research Laboratories, Princeton, New Jersey, for providing the special CDH lasers used in this study. The author is also grateful to Peter Hankin and C.J. Hwang of General Optronics Corporation, South Plainfield, New Jersey, for providing some of the specially selected proton-stripe lasers used in this study. The author also wishes to thank R.V. Schmidt, G.L. Tangonan, and T.R. Ranganath for helpful discussions. Finally, the author wishes to thank C.W. Slayman for his valuable assistance with high-resolution pulse measurements and D.L. Lewis for experimental assistance. This work was partially supported by DARPA Contract N00173-78-C-0192, which was monitored by the Naval Research Laboratory.

References

1. P.T. Ho, L.A. Glasser, E.P. Ippen, and H.A. Haus, "Picosecond Pulse Generation with a cw (GaAl)As laser diode," Appl. Phys. Lett., Vol. 33, pp. 241-243, Aug. 1978.
2. L.A. Glasser, "C.W. Mode Locking of a GaInAsP Diode Laser," Elect. Lett., Vol. 14, pp. 725-726, November 1978.
3. P.T. Ho, "Coherent Pulse Generation with a GaAlAs Laser By Active Mode Locking," Elect. Lett., Vol. 15, pp. 527-528, August 1979.
4. E.P. Ippen, D.J. Eilenberger, and R.W. Dixon, "Picosecond Pulse Generation by Passive Mode-Locking of Diode Lasers," Appl. Phys. Lett., Vol. 37, pp. 267-270, August 1980.
5. M.B. Holbrook, W.E. Sleat, and D.J. Bradley, "Bandwidth-Limited Picosecond Pulse Generation in an Actively Mode-Locked GaAlAs Diode Laser," Appl. Phys. Lett., Vol. 37, pp. 59-61, July 1980.
6. J.P. Van der Ziel and R.M. Mikulyak, "Mode-Locking of Strip Buried Heterostructure (AlGa)As Lasers Using an External Cavity," J. Appl. Phys., Vol. 51, pp. 3033-3037, June 1980.
7. H. Ito, H. Yokoyama, and H. Inaba, "Bandwidth Limited Picosecond Optical Pulse Generation from Actively Mode-Locked AlGaAs Diode Laser," Elect. Lett., Vol. 16, pp. 620-621, July 1980.
8. R.P. Salathe, "Diode Lasers Coupled to External Resonators," Appl. Phys., Vol. 20, pp. 1-18, August 1979.
9. R.F. Broom, E. Mohn, C. Risch, and R. Salathe, "Microwave Self-Modulation of a Diode Laser Coupled to an External Cavity," IEEE J. Quant. Elect., Vol. QE-6, pp. 328-334, June 1970.
10. T.L. Paoli and J. Ripper, "Frequency Stabilization and Narrowing of Optical Pulses from cw GaAs Injection Lasers," IEEE J. Quant. Electron., Vol. QE-6, pp. 335-339, June 1970.
11. T.L. Paoli, "Changes in the Optical Properties of cw (GaAl)As Junction Lasers During Accelerated Aging," IEEE J. Quant. Electron., Vol. QE-13, pp. 314-322, May 1977.
12. G. Arnold and K. Peterman, "Self-Pulsing Phenomena in (GaAl)As Double-Heterostructure Injection Lasers," Appl. Phys., Vol. 10, pp. 311-322, 1978.
13. J.A. Copeland, "Semiconductor-Lasers Self-Pulsing Due to Deep Level Traps," Elect. Lett., Vol. 14, pp. 809-810, December 1978.
14. L. Figueroa, K. Lau, and A. Yariv, "Intensity Self-Pulsations in (GaAl)As Lasers Operating in an External Cavity," Appl. Phys. Lett., Vol. 36, pp. 248-250, February 1980.
15. L. Figueroa, K. Lau, H.W. Yen, and A. Yariv, "Studies of (GaAl)As Injection Laser Operating With an Optical Fiber Resonator," J. Appl. Phys., Vol. 51, pp. 3062-3071, June 1980.
16. K. Lau, L. Figueroa, and A. Yariv, "Generation and Quenching of Intensity Pulsations in Semiconductor Lasers Coupled to External Cavities," to be published in IEEE J. Quant. Electron., December 1980.

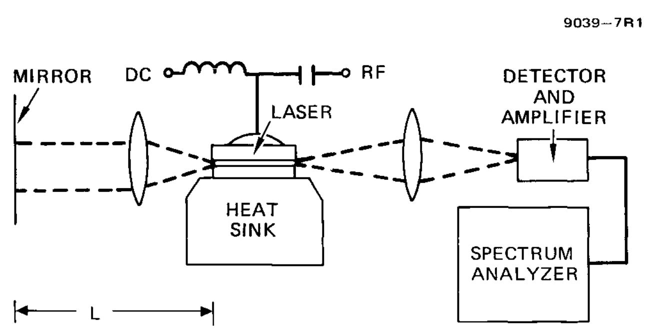

Figure 1. Experimental set-up graphically displaying the external cavity arrangement.

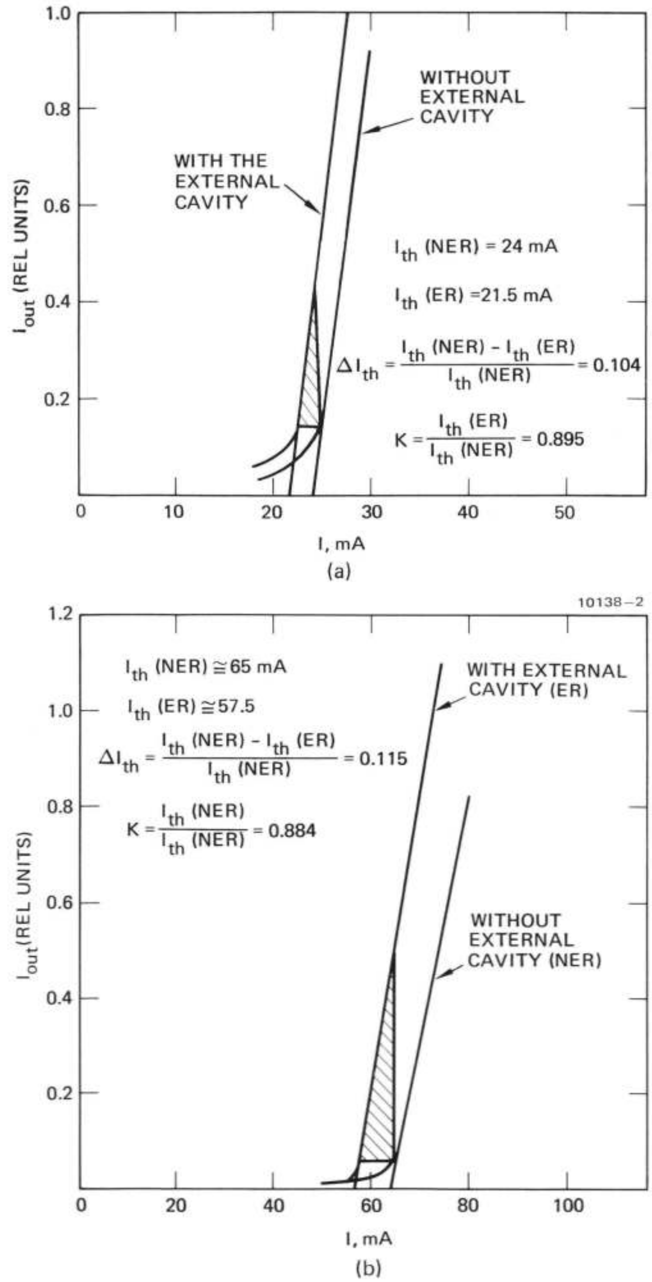

Figure 2.
Experimental light output versus current characteristics, show relatively low threshold lasers ($I_{th} \sim 20$–30 mA) and lasers with higher threshold ($I \sim 60$–100 mA.

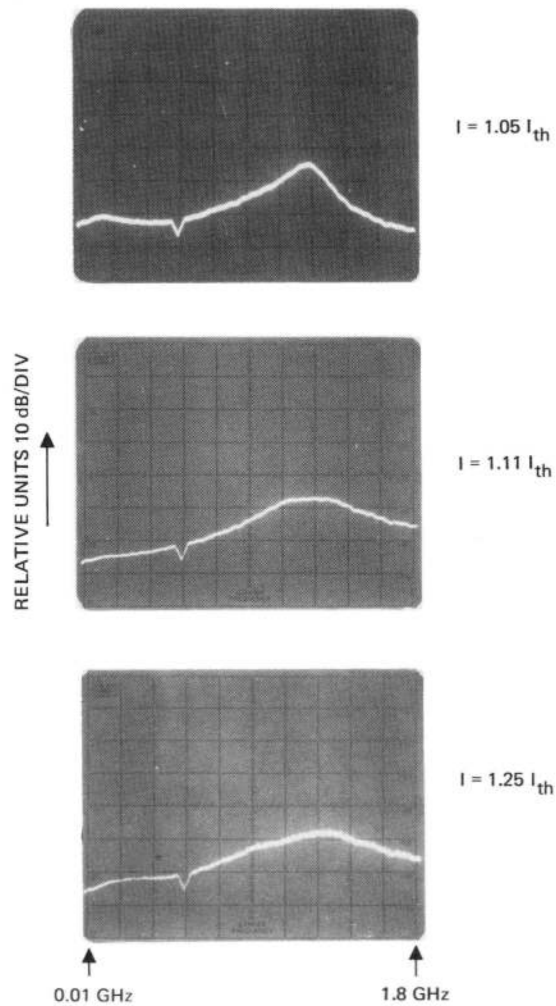

Figure 3.
Experimental light output versus frequency plots for a laser displaying a "well behaved" response. The plot gives the noise frequency response versus current. No external cavity is present.

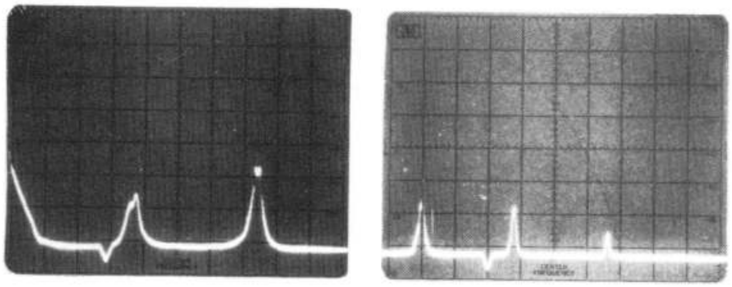

Figure 4. Experimental light output versus frequency plot when an external cavity is aligned with the lasers described in Figure 3.

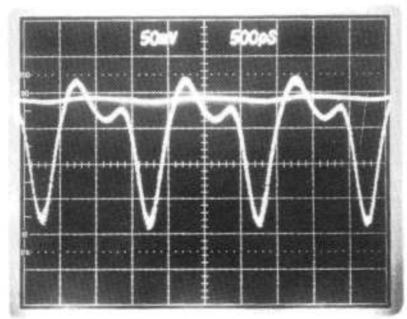

Figure 5. Experimental temporal display showing the light output when the laser described in Figures 3 and 4 are operated in an external cavity and modulated at f_c.

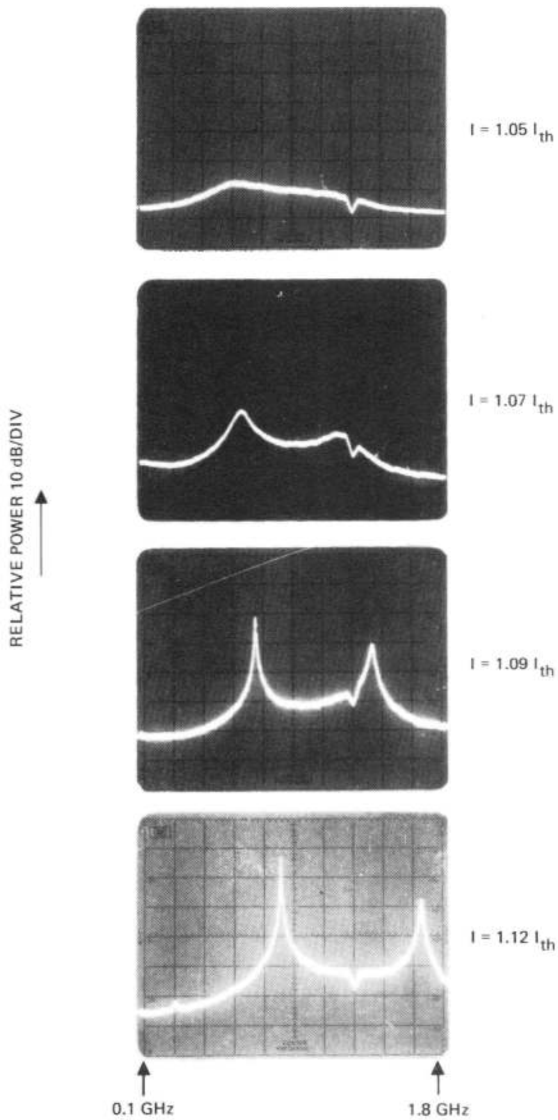

Figure 6. Experimental light output versus frequency for a laser displaying an anomalous noise frequency response. No external cavity is present.

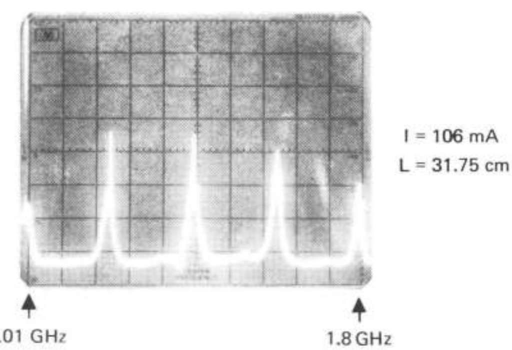

Figure 7. Experimental light output versus frequency plot when an external cavity is aligned with the laser described in Figure 6.

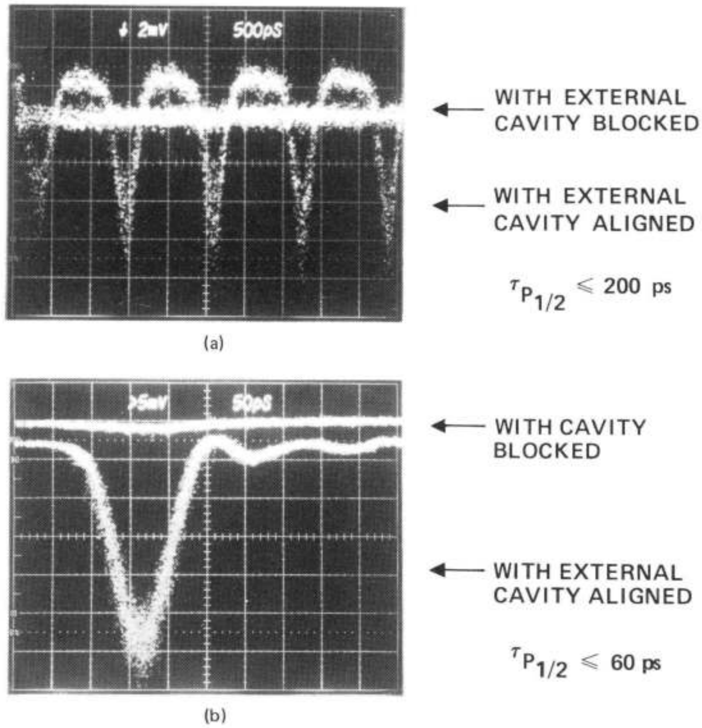

Figure 8. Temporal display when an rf signal with a frequency corresponding to f_c is applied to a laser similar to that described in Figures 6 and 7. In (a) we show the temporal display taken with a Si APD. In (b) we show a high resolution temporal display taken with a high-speed detector (Spectral Physics 403B).

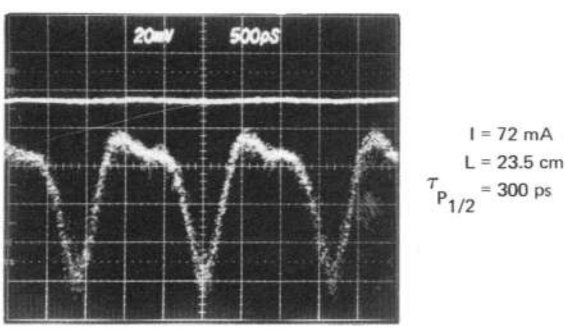

Figure 9. Temporal display corresponding to a weakly pulsing laser when operated in an external cavity and the current is modulated at f_c.

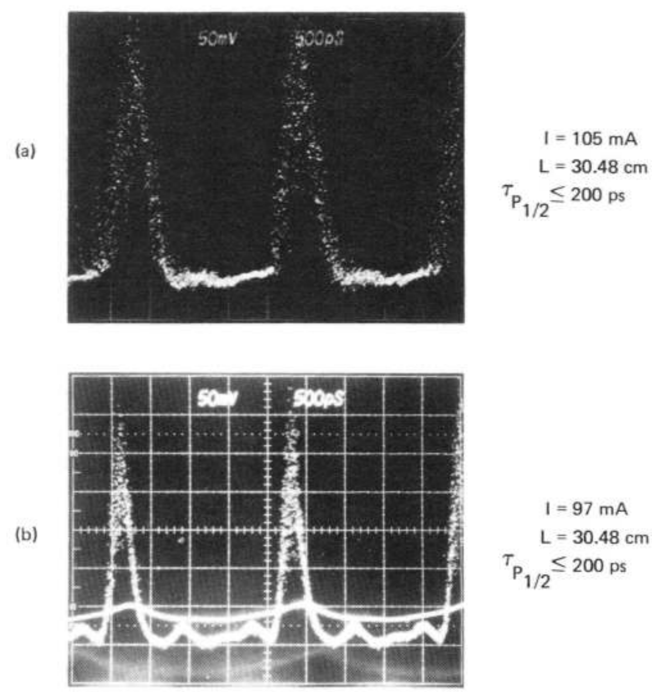

Figure 10. Temporal display of a strongly self-pulsing laser when operated in an external cavity. (a) No rf modulation is used. (b) modulated at f_c.