Picosecond Mode-Locking And X-Band Modulation Of Semiconductor Lasers

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Picosecond mode-locking and X-band modulation of semiconductor lasers

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Abstract

Recent developments in two areas of high speed semiconductor lasers will be addressed: (1) passive mode-locking of a segmented-contact semiconductor laser with a reliable, controllable saturable absorber which produces stable picosecond optical pulses, and (2) realization of very high frequency (X-band) direct analog modulation of a semiconductor laser diode.

I. Introduction

Two aspects of high speed semiconductor lasers will be described. First, a novel method to passively mode lock a semiconductor laser will be described. We present experimental results of GaAlAs buried heterostructure semiconductor lasers with a split contact coupled to an external cavity. The split contact structure is used to introduce a controllable amount of saturable absorption which is necessary to initiate passive mode locking. Unlike previous passive mode locking techniques, the moethod presented does not rely on absorption introduced by damaging the crystal and is consequently inherent more reliable. We have obtained pulses with a full width of half-maximum of 35ps at repetition frequencies between 500 MHz and 1.5 GHz. Secondly, we will describe recent experimental and theoretical studies which indicate that a high frequency laser with bandwidths up to X-band frequencies ($\gtrsim$ 10 GHz) should be one having a short cavity with a window structure, and preferably operating at low temperatures. These designs would accomplish the task of shortening the photon lifetime, increasing the intrinsic optical gain, and increasing the internal photon density without inflicting mirror damage. A modulation bandwidth of >8GHz has been achieved using a 120μm laser without any special window structure at room temperature.

II. Passive mode locking of buried heterostructure lasers with nonuniform current injection

Ultrashort optical pulses generated with semiconductor lasers are of great interest for applications such as very fast optical signal processing and high bit rate communication. Pulses in the picosecond range have been obtained by such diverse methods as microwave current injection,[1] pumping with short electrical pulses,[2] or by mode locking the lasers in an external optical cavity. Mode locking has been achieved either by modulating the gain at a frequency corresponding to the cavity roundtrip time (active mode locking[3-5]) or by placing a nonlinear element such as a saturable absorber in the cavity (passive mode locking[6-8]); the shortest pulses to date have been generated by the passive mode locking technique. An absorber with the desired characteristic can be obtained by damaging the GaAs crystal and introducing defects. One method for obtaining such defects (dark line defects) is to age a laser to the point of severe degradation. Pulses as short as 1.3ps have been achieved with this technique.[8] Unfortunately the concentration of these defects increases at this stage rapidly and short pulses are only obtained with lasers at the verge of failure. Another method is to introduce these saturable defects by damaging the crystal near one mirror through proton bombardment[9] and 15-ps-long bursts of subpicosecond pulses have been generated by this technique.[7]

We report on a method for producing picosecond pulses which does not rely on any damage of the crystal and which is consequently inherently more reliable. The picosecond pulses are generated with a laser with nonuniform current injection obtained through a split contact structure.[10] We have shown that for a complete description of such an optoelectronic device the electrical aspect has to be included that a nonuniform pumped laser can either be bistable or pulsating depending on the biasing condition.

The GaAlAs buried heterostructure lasers with a split contact were fabricated as described earlier.[10] Under the usual operating conditions one section is heavily forward biased (gain section) and the other section is only slightly biased thus introducing loss (absorber section). An SiO antireflection (AR) coating was applied to one mirror facet in order to facilitate the coupling to the external optical cavity and to suppress the effects of the short cavity. The gain section was pumped with a constant current (I_1) and the absorbing section was biased with a voltage source (V) with a resistor in series (R_2) as shown in Fig. 1.

The optical cavity length was varied between 10 and 30 cm corresponding to a pulsation frequency between 500 MHz and 1.5 GHz. From the changes in the threshold current of the uniform pumped laser we estimated that the mirror reflectivity was reduced <5% after deposition of the AR coating and that the effective mirror reflectivity in the external cavity was around 6%. The light emitted from the back facet of the laser was collimated and focused on a wide bandwidth avalanche photodiode (AEG-Telefunken S171P) with a calibrated rise time of 120ps. The width of the optical pulses was measured with an autocorrelator employing phase matched second harmonic generation in a $LiIO_3$ crystal.

The average light output as a function of current through the gain section (I_1) is shown in Fig. 2. As reported earlier[11] the characteristic depends dramatically on the biasing resistor R_2 which is in series with the absorber section. When R_2 is large (R_2 = 200kΩ), a condition to which we will refer as current biasing, the pump rate is constant and the device displays bistability with a large hysteresis. When R_2 is small (R_2 = 330Ω), i.e., voltage biasing, the carrier density in the absorber section is clamped and the device displays a region with a very high differential quantum efficiency (light jump). It is in this biasing mode that successful passive mode-locking can be accomplished. The shortest pulses were observed when the laser was biased just above the light jump and the pulses observed with a sampling oscilloscope were detector limited 150ps long with a modulation depth close to 100%.

A typical second order correlation trace is shown in Fig. 3. The laser voltage biased and operated at a current I_1 just above the light jump in a cavity with a length of 30cm. The correlation trace consists of a relatively broad peak with a width of $\Delta\tau$ = 53ps upon which is superimposed a series of extremely sharp spikes with a width of $\Delta\tau_1$ = 1.4ps and a separation of t_2 = 5.5ps. Since the second order correlation has an intensity ratio of 1:2:3 this trace corresponds in the time domain to a pulse with some noisy periodic substructure. Assuming Gaussian shapes and transform limited pulses we obtained a full width at half-maximum of Δt_1 = 37ps and a spectral width of $\Delta\nu_1$ = 12 GHz ($\Delta\lambda_1$ = 0.3Å). This means that around 20 longitudinal modes of the external cavity are phase locked. The separation t_2 between the spikes corresponds to the round trip time in the semiconductor cavity (L = 200μm).

III. Direct amplitude modulation of short-cavity GaAs lasers up to X-band frequencies

The practical direct modulation bandwidth of semiconductor lasers is commonly accepted to be in the lower GHz range ($\lesssim$ 2GHz). Recent experiemntal work[12] has shown that a modulation bandwidth of 4-5 GHz is possible in a number of common laser structures. However, achieving that kind of modulation bandwidth requires that the lasers be biased at a level well above their nominal ratings, dangerously close to the point of catastrophic damage. Experimental and theoretical results presented below show that modulation bandwidths in the X-band ($\lesssim$ 10GHz) can be achieved with lasers operating reliably within the limits of their ratings, provided that a number of features are incorporated in the lasers.

The modulation bandwidth of semiconductor lasers is widely accepted to be equal to ν_{rel}, the relaxation oscillation frequency. A small signal anaysis of the common rate equations gives:

$$\nu_{rel} = \frac{1}{2\pi}\sqrt{Ap_o/\tau_p} \tag{1}$$

where p_o is the steady state photon density in the active region. Equation (1) suggests three obvious ways to increase the relaxation frequency - by increasing the optical gain coefficient or the photon density, or by decreasing the photon lifetime. The gain coefficient A can be increased roughtly by a factor of five by cooling the laser from room temperature to 77K[13]. Biasing the laser at higher currents would increase the photon density in the active region, which simultaneously increases the optical output power density I_{out}. Catastrophic mirror damage occurs at a power density of $I_{out,cat} \cong 1MW/cm^2$ for a laser with a mirror reflectivity of R = 0.3. This sets an upper limit on the maximum permissible photon density, and hence the maximum modulation bandwidth. This limit can be increased very considerably by using a window structure, such as the crank TJS[14], the window stripe[15] or the window buried laser[16].

The third way to increase the modulation bandwidth is to reduce the photon lifetime by decreasing the length of the laser cavity. Such a laser has to be driven at higher current densities and thermal effects due to excessive heating will limit the maximum attainable modulation bandwidth. To illustrate these points the relaxation frequency as a function of the cavity length and the pump current density is plotted in Fig. 4(a). Also plotted in Fig. 4 is the power density at the mirror. As an example, a common laser with a cavity length of 300μm operating at an output optical power density of 0.8MWcm^{-2} possesses a bandwidth of 5.5GHz, and the corresponding pump current density is 3kA/cm^2. Operating at an identical power density, the bandwidth is 8GHz for a shorter laser with a cavity length of 100 μm, but the corresponding current density is 6kA/cm^2. A higher current density alone may not be a cause for rapid degradation of lasers. For example, lasers with increased optical damage threshold as described above can operate at increased current densities without appreciable degradation of their reliability. Figure 4(b) shows plots of the same functions as in Fig. 4(a) but for a laser operating at liquid nitrogen temperature. The increase in bandwidth is a direct result of the increase in A. It can be seen that a modulation bandwidth beyond 20 GHz can be achieved, however, incorporation of a short optical cavity and/or a window structure is imperative under these operating conditions.

Experiments have been performed to determine the modulation bandwidth achievable in a short-cavity laser. The laser used were buried heterostructure lasers fabricated on a semi-insulating substrate (BH on SI)[17]. In addition to a low lasing threshold (typically $\leq$ 15mA) which is necessary to avoid excessive heating when operated at high above threshold, these lasers possess very low parasitic capacitance[18] which otherwise would obscure modulation effects at high frequencies ($\gtrsim$5GHz). The lasers were mounted on a 50 Ω stripeline. Microwave s-parameter measurements show that electrical reflection from the laser diode accounts to no more than a few dB ($\lesssim$ 5dB) of variations in the drive current amplitude over a frequency range of 0.1 to 8.5 GHz. A sweep oscillator (Hp8350) was used in conjunction with a network analyser (Hp8410 series) and a microwave s-parameter test-set (Hp8746B) to obtain the modulation data. The photodiode used was a high speed GaAs pin diode fabricated on semi-insulating substrate. Its response was carefully calibrated from 0.1 to 10GHz.

The observed modulation response of the laser is normalized by the photodiode response at each frequency. Figure 5(a) and (b) shows the cw light vs current characteristic of a short-cavity (120 μm) BH on SI laser, and the modulation responses at various bias points as indicated in Fig. 5(a) is shown in Fig. 5(b). The modulation bandwidth can be pushed to beyond 8GHz as the catastrophic damage point is approached. Figure 6 shows the relaxation oscillation frequency of this laser as a function of $\sqrt{P_O}$ where P_O is the output optical power, together with that of similar lasers with longer cavity lengths. All the lasers tested suffered catastrophic damage between 6-8mW/facet. The advantage of a short-cavity laser in high frequency modulation is evident.

In conclusion, an absolute modulation bandwidth (at the point of catastrophic failure) of >8GHz has already been observed in a 120 μm laser without any special window structure at room temperature. For reliable operation, however, the laser should be operated at only a fraction of its catastrophic failure power. That fraction depends on laser structure and amounts to 1/2 to 1/3 for commercial devices of comparable construction. This would place the useful modulation bandwidth of these short-cavity BH on SI lasers between 4.6 and 5.7GHz. The same laser at 77K without a window should have a modulation bandwidth of ≈12GHz.

IV. Acknowledgement

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V. References

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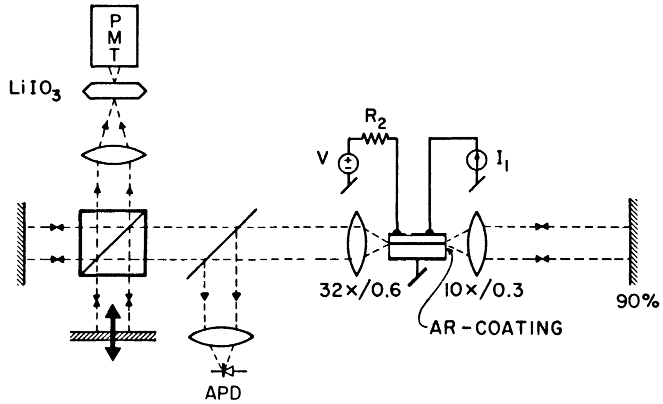


Fig. 1 Experimental arrangement of a double contact laser which is passively mode locked in an external optical cavity.

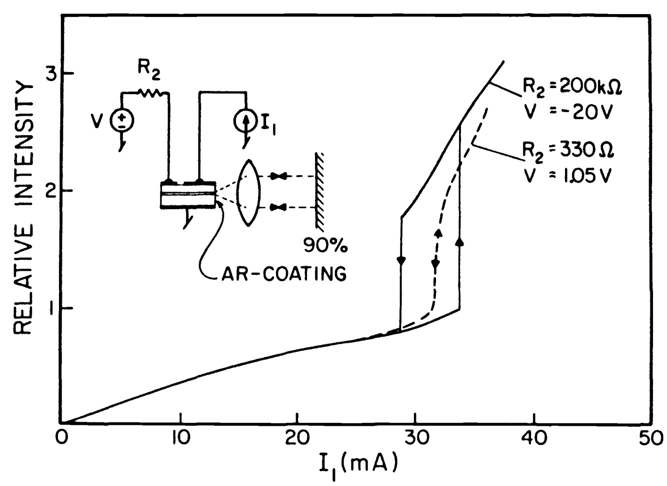


Fig. 2 Light-current characteristic of a double contact laser in an external cavity for current biasing (R_2=200kΩ and V=-20V) and voltage biasing (R_2=300Ω and V=1.05V).

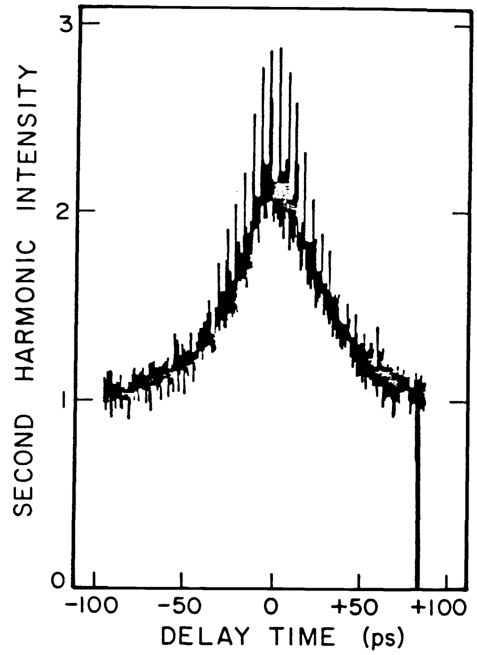


Fig. 3 Autocorrelation trace of the passively mode locked diode laser. FWHM of the pulse is around 35ps.

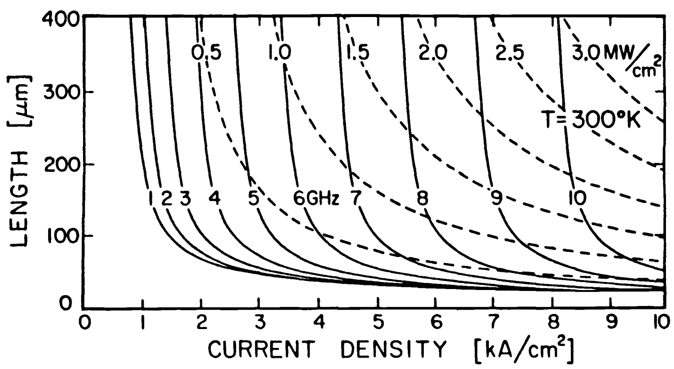


Fig. 4(a). Relaxation frequency ν_{rel} (solid lines) and optical power density outside the mirrors (dashed lines) as a function of cavity length and pump current density at T=300K.

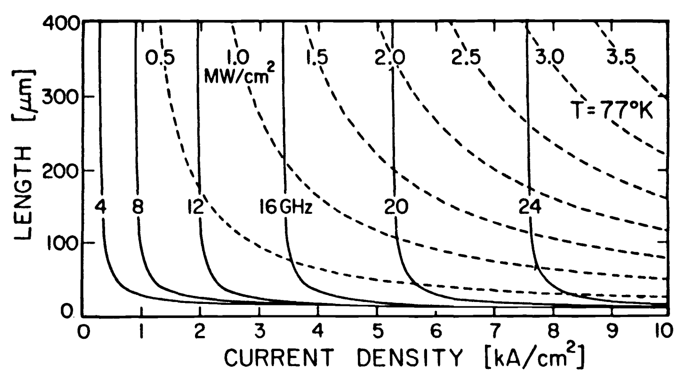
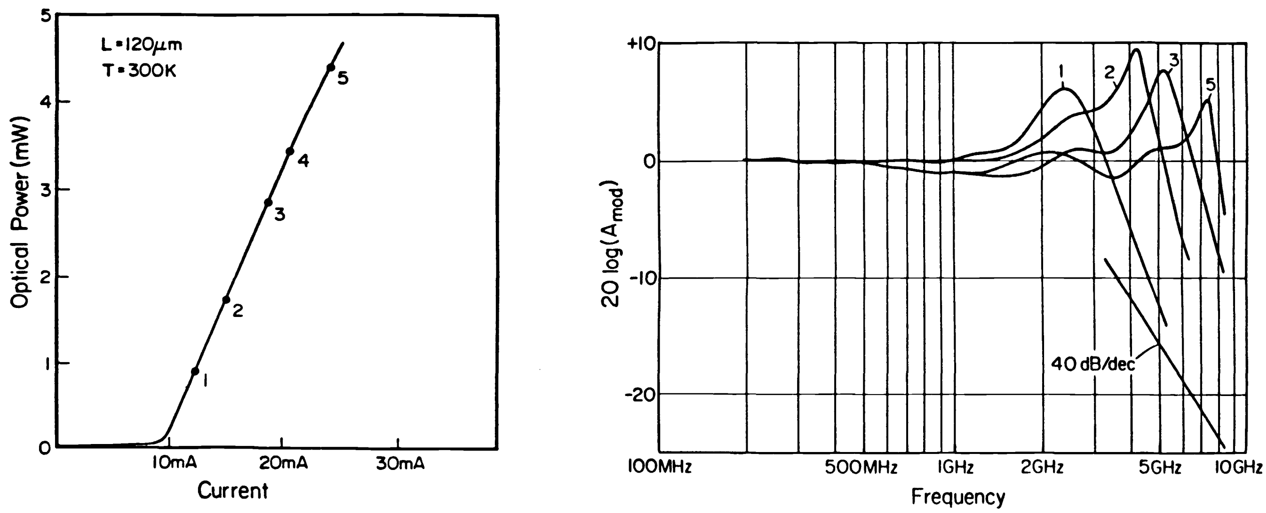


Fig. 4(b). same as above but at T=77K.



(a) (b)

Fig. 5(a). cw light vs current characteristic of a BH on SI laser. Length of laser = 120 μm. Modulation characteristics of this laser at various bias points indicated in (a) are shown in Fig. 5(b).

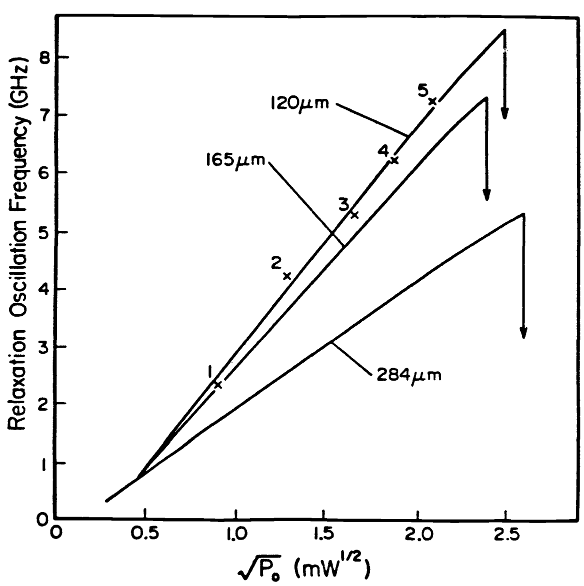


Fig. 6. Measured relaxation resonance frequency of lasers of various cavity lengths, as a function of $\sqrt{P_0}$, where P_0 is the cw output optical power. The points of catastrophic damage are indicated by downward pointing arrows.