Direct modulation and active mode locking of ultrahigh speed GaAlAs lasers at frequencies up to 18 GHz

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(Received 24 September 1984; accepted for publication 12 November 1984)

It is demonstrated that an ultrahigh speed window buried heterostructure GaAlAs laser fabricated on a semi-insulating substrate can be used as a narrowband signal transmitter in the Ku band frequency range (12–20 GHz). The modulation efficiency can be increased over a limited bandwidth by a weak optical feedback. A stronger optical feedback enables one to actively mode lock the laser diode at a very high repetition rate up to 17.5 GHz, producing pulses ~ 12 ps long.

Significant progress has been made recently in operating semiconductor laser diodes at very high frequencies. A quantity of major significance in the small-signal modulation regime is the − 3 dB modulation bandwidth, which is a direct measure of the rate at which information can be transmitted by the laser. However, one can obtain a high modulation depth at frequencies beyond the − 3dB point by driving the laser with sufficient rf drive power to compensate for the drop-off in the modulation response of the laser. This technique is very useful in generating repetitive optical pulses from a laser diode at a very high repetition rate, although the repetition rate itself has no significance in terms of true information transmitting capacity of the laser. A means to reduce the rf drive power required for modulating the laser to a high optical modulation depth at high repetition rate is the technique of mode locking. The laser diode is coupled to an external cavity whose round-trip time corresponds to the modulation frequency. The modulation frequency in this case is limited to a very narrow range around the round-trip frequency of the external cavity. Recent experimental work has extended the small-signal − 3dB direct modulation bandwidth of a solitary laser diode to ~ 12 GHz using a specially developed window buried heterostructure laser on semi-insulating substrate (BH on SI),[1] while large signal direct modulation has been reported at repetition rates up to 10.6 GHz.[2] Active mode locking of laser diodes in an external cavity has been reported at repetition rates up to 7.2 GHz in a $LiNbO_3$ directional coupler external cavity[3] and to 10 GHz in fiber cavity.[4]

In this letter, results of modulation of the high speed window BH on SI laser at frequencies beyond the − 3 dB point, in both the small signal and large signal regime, will be described. It will be shown that such lasers can be used as a narrowband signal transmitter at frequencies above the − 3dB point, with a reasonably flat response over a bandwidth of up to ~ 1 GHz. The overall response of the laser at such frequencies is substantially lower than in the midband range (i.e., at frequencies < the − 3 dB point) and consequently higher rf drivers are necessary to attain a certain modulation depth. It will be shown that a weak optical feedback from an external cavity can boost up the response by a substantial amount over a wide frequency range. A strong feedback induces a sharp spike in the response of the laser at the round-trip frequency. Under this condition, picosecond pulses can be generated by modulating the laser on resonance, which can be interpreted as active mode locking of the laser diode.

The laser used in this experiment is a window BH on SI laser reported previously.[1] The length of the laser is 300 μm, with an active region dimension of $2\mu m \times 0.2\mu m$. The presence of the window near the end facet alleviates the problem of catastrophic damage and enables the laser to operate at very high optical power densities. The tight optical and electrical confinement along the length of the laser cavity (except at the window region) enables maximum interaction between the photon and electrons to take place and results in a very high direct modulation bandwidth. The small-signal modulation bandwidth of this device biased at an optical output power of 10 mW is shown as the heavy curve in Fig. 1. Here, the "small-signal" regime is loosely defined as that when the modulation depth of the optical output is $\lesssim 80\%$. The − 3 dB bandwidth, as shown in Fig. 1, is 10.3 GHz. The response drops to − 10 dB at − 13.5 GHz and to − 20 dB at 18 GHz. The fall-off in the modulation response is due to a combination of the intrinsic laser response and effects due to parasitic elements. Figure 2 shows the sweep frequency modulation response of the laser, in a 1-GHz band, centered at 16 GHz. The response is relatively flat over the 1-GHz band (to within ± 2 dB), and is within ± 1 dB over a 100-MHz bandwidth. It is thus possible to use this laser as an optical transmitter operating in a narrow bandwidth in the upper *X*-band frequencies.

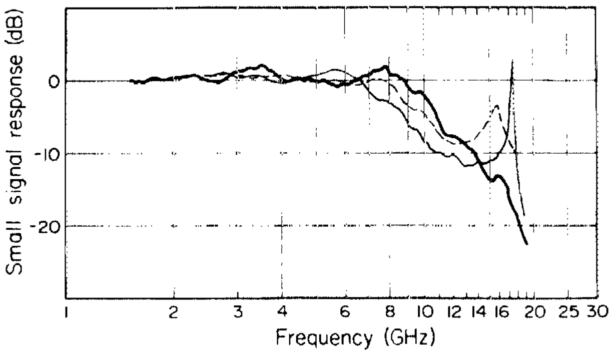

FIG. 1. Small-signal modulation response of a window BH on SI laser: (a) intrinsic laser response (dark solid curve); (b) weakly coupled to an external fiber cavity (dotted curve), and (c) with increased coupling (light solid curve).

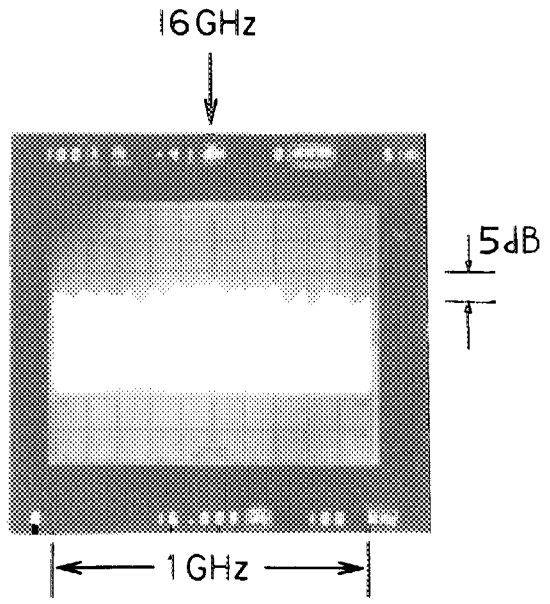

FIG. 2. Sweep-frequency modulation response of the intrinsic window BH on SI laser at 16 GHz, over a 1-GHz band.

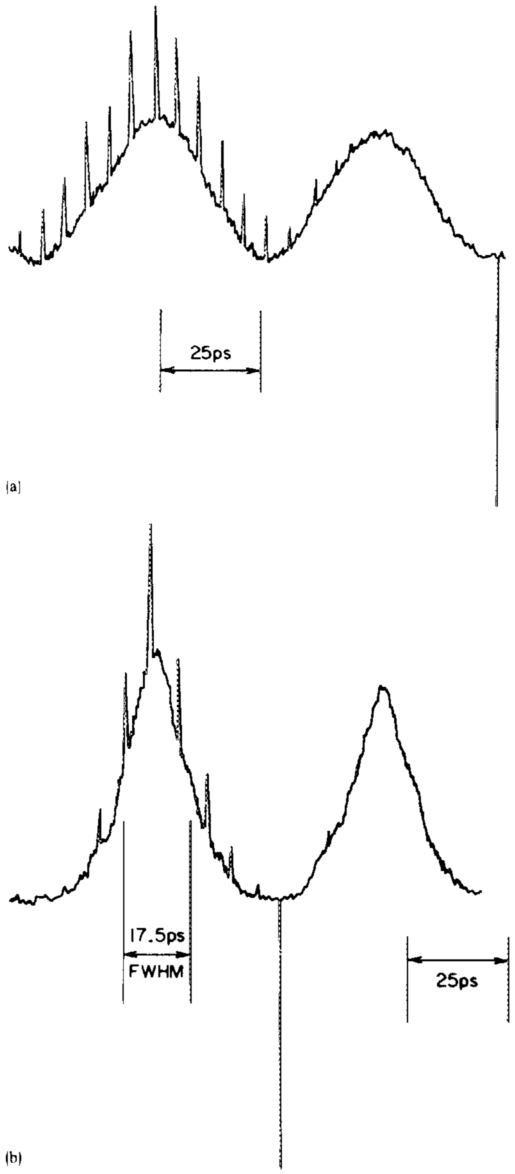

FIG. 3. Autocorrelation of the optical output of the window BH on SI laser coupled to an external fiber cavity under (a) 4-dBm microwave drive and (b) 14-dBm microwave drive at 17.5 GHz.

The intrinsic modulation response curve in Fig. 1 shows that at 16 GHz, the response is approximately 13 dB below the midband value. (The small peak in the modulation response at around 16 GHz is probably due to electrical reflections arising from imperfect impedance matching of the laser.) This loss in modulation efficiency can be partially compensated by coupling the laser to an external cavity of the appropriate length. In this experiment the external cavity is composed of a short length (6.3 mm) of standard graded index multimode fiber of 50-μm core diameter,[4,5] with a high refractive index hemispherical lens attached to one end of the fiber to facilitate coupling. The far end of the fiber is cleaved but not metallized. The amount of optical feedback into the laser in this arrangement is expected to be below 1%, and produces no substantial reduction in lasing threshold or differential quantum efficiency. The feedback, however, induces a broad resonance in the frequency response at ~ 16 GHz—the round-trip frequency of the fiber cavity—as shown by the dashed curve in Fig. 1. The full width of the resonance is about 1.5 GHz, measured at the upper and lower -3 dB points. At the peak of the resonance the modulation efficiency is enhanced by ~ 10 dB. The -3 dB bandwidth of the resonance is approximately 1.5 GHz.

In a separate experiment the far end of a fiber is cleaved and is butted to a gold mirror. This induces a very sharp resonance in the modulation response of the laser, as shown by the light solid curve in Fig. 1. When the laser is driven on resonance by a microwave source whose power output is $\lesssim 6$ dBm, the optical output is not fully modulated and the laser is operating in the small-signal regime. As the microwave drive power is increased to > 10 dBm the optical modulation depth approaches unity and the optical waveform becomes pulselike. The characteristics of the optical pulses cannot be resolved by the photodiode, whose output appears to be sinusoidal since only the fundamental frequency (17.5 GHz) of the modulated laser light can be detected with resonable efficiency. An autocorrelator using optical second harmonic generation is used to observe the optical output. Figure 3 shows autocorrection traces of the laser output under two microwave drive power level, (a) at 4 dBm and (b) at 14 dBm. The first trace is sinusoidal in shape, implying that the optical waveform is also sinusoidal, and that the optical modulation depth is less than unity. The latter case (b) clearly indicates the pulse behavior of the optical output, with a full width at half-maximum (FWHM) width 12.4 ps (computed from the FWHM of the autocorrection trace, assuming a Gaussian pulse shape). This, in effect, is active mode locking of a laser diode at a repetition rate of 17.5 GHz. The spectrum of the laser consists of a large number (~ 7) of longitudinal modes of the laser diode since there is no frequency selective element (such as an etalon) in the external cavity. The width of the individual mode is mainly determined by frequency chirping due to heavy carrier modulation and does not seem to correspond to the transformed value of the optical pulse width.

There is a subtle difference between short optical pulse generation by large signal modulation of a solitary laser diode and by active mode locking. In the former case, each optical pulse builds up from essentially spontaneous emission noise and therefore pulse to pulse coherence is very poor. In the latter case, each pulse builds up (at least partially) from stimulated emission of the previous optical pulse which returns from a round-trip tour of the external cavity, and hence the optical pulses should be coherent to one another. However, the autocorrelation traces of Figs. 3(a) and 3(b) show that pulse to pulse coherence is quite poor in the output of these very high rate actively mode-locked lasers. This is most likely due to (1) the large amount of frequency chirping due to variations in the refractive index of the laser material at such high modulation frequencies[6,7] and (2) the relatively small feedback from the external cavity.

In general, when attempting to actively mode lock a laser diode at very high repetition rates one has several avenues of approaches. One approach is to completely antireflection coat one facet of the laser and couple it to an external cavity. All the cavity submodes of the laser diode are suppressed, and lasing takes place soley between the laser facet and the external mirror. The difficulty is that this laser now has a much longer photon lifetime than a typical solitary laser diode, which aggravates the already difficult problem of driving the laser diode at frequencies of tens of gigahertz. It appears that a better approach would be the one described above—applying a relatively small amount of feedback to an unaltered ultrafast laser diode so that the high speed capability of the laser diode is not compromised. A second dilemma is that it is generally observed that active mode locking of laser diodes is achieved most easily when the laser is biased only slightly above threshold. An intuitive explanation for this result is that it is easier to fully modulate the output of the laser diode and force it into the large signal regime when the laser is only slightly above threshold. Since the modulation speed of the laser decreases with decreasing bias level, this approach also encounters difficulty when attempting to mode lock at tens of gigahertz. In our experiment, the laser was biased at a very high level at 10 mW so that the intrinsic speed of the laser can be maintained. The microwave drive power required to bring the optical output to full modulation is consequently high. This, however, should not be regarded as a penalty since the available optical power is correspondingly high.

In conclusion, we have demonstrated that suitably constructed high speed laser diodes can be used as narrowband signal transmitters in the Ku band frequency range (12–20 GHz). The modulation efficiency can be increased over limited bandwidth by a weak optical feedback. A stronger optical feeback enables one to actively mode lock the laser diode at a very high repetition rate up to 17.5 GHz, producing pulses ~ 12 ps long.

This research was supported by the Defence Advance Research Project Agency, the National Science Foundation under the Optical Communication Program, and by the Army Research Office.

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Cd diffused mesa-substrate buried heterostructure InGaAsP/InP laser

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(Received 22 October 1984; accepted for publication 4 December 1984)

A new type of buried heterostructure InGaAsP/InP lasers grown by a single-step liquid phase epitaxy on Cd diffused mesa substrate is described. These lasers exhibit excellent current and optical confinement. Threshold currents as low as 15 mA are achieved for a laser with a 2-μm-wide active region.

InGaAsP/InP double heterostructure lasers are used as light sources for optical fiber communications in long-wavelength range because of lower losses and dispersion of optical fiber in this range.[1-4] Low threshold current and a stable single transverse mode are necessary for such applications. Among the lasers developed to date the buried heterostructure lasers are very promising, owing to their very low threshold currents. However, the growth of conventional

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