Direct modulation of semiconductor lasers at $f > 10$ GHz by low-temperature operation

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Using a 175-μm-long buried-heterostructure laser fabricated on a semi-insulating substrate operating at -50 °C, a direct amplitude modulation bandwidth in excess of 10 GHz has been achieved.

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Development of semiconductor lasers of multigigahertz bandwidth will make possible new areas of applications involving transmission of microwave signals through optical fibers. Such means of microwave transmission is especially advantageous when long distances or light weight are part of system requirements. Early works on high frequency modulation were limited by the intrinsic properties of the laser diode to the lower gigahertz range. However, major interests in the higher frequency ranges such as the *C* (3.9–6.2 GHz) and the *X* (5.2–10.9 GHz) bands have stimulated efforts to extend the modulation bandwidth of semiconductor lasers to these frequency ranges. Following a theoretical reevaluation of the relevant physics, a direct modulation bandwidth of close to 8 GHz has recently been attained.[1] The relaxation oscillation frequency is given by[1]

$$f = (1/2\pi)\sqrt{AP_0/\tau_p}, \qquad (1)$$

where A is the differential optical gain, P_0 the internal photon density, and τ_p the photon lifetime. The intrinsic differential optical gain A can be increased by lowering the temperature of the laser, and the photon lifetime τ_p can be reduced by shortening the length of the cavity. The maximum extent to which the photon density P_0 can be increased is limited by catastrophic mirror damage, while electrical heating places a lower limit on the cavity length. In very low threshold lasers as those reported in Ref. 1, the optical catastrophic damage is the dominant limiting factor for devices whose length is larger than $\sim 150\,\mu$m.

In this letter, we describe experimental results on direct amplitude modulation of low threshold buried-heterostrucure lasers fabricated on semi-insulating substrates,[2] operating at below room temperature. For the first time, a direct modulation bandwidth of beyond 10 GHz is attained.

The lasers are mounted on a specially designed microwave package in thermal contact with a cold finger. The entire fixture resides in an enclosure in which room-temperature dry nitrogen circulates continuously. A thermocouple in close proximity to the laser recorded the actual operating temperature, which can be varied from -140 °C to room temperature. The laser emission is collected by a 20× objective lens from a window in the enclosure and is focused on a high-speed GaAlAs *pin* photodiode. The photodiode is an improved version of the one described previously[3]; its frequency response was calibrated from dc to 15 GHz using a mode-locked dye laser and a microwave spectrum analyzer. The -3-dB point of the photodiode response is at 7 GHz and the -5-dB point at 12 GHz.

The light versus current and current versus voltage (*I-V*) characteristics of a 175-μm-long laser at various temperatures are shown in Figs. 1(a) and 1(b). The lasing threshold current at room temperature is 6 mA, dropping to ~ 2 mA at -70 °C. The *I-V* curves reveal a drastic increase in the series resistance of the laser below ~ 60 °C. This is believed to be due to carrier freeze out at low temperatures since the dopants used, Sn (*n* type) and Ge (*p* type) in GaAlAs, have

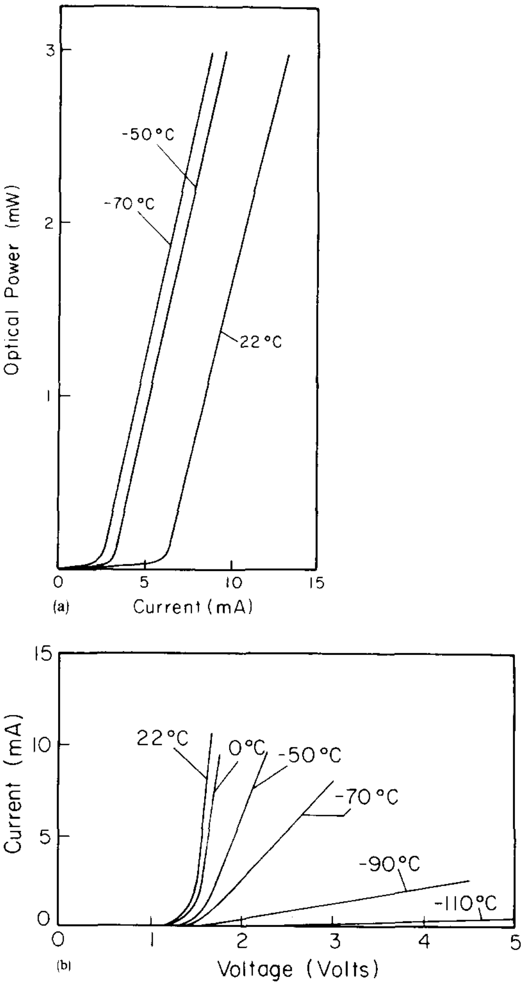

FIG. 1. (a) Light vs current characteristics of a 175-μm laser at various temperatures; (b) *I-V* characteristics of the same laser.

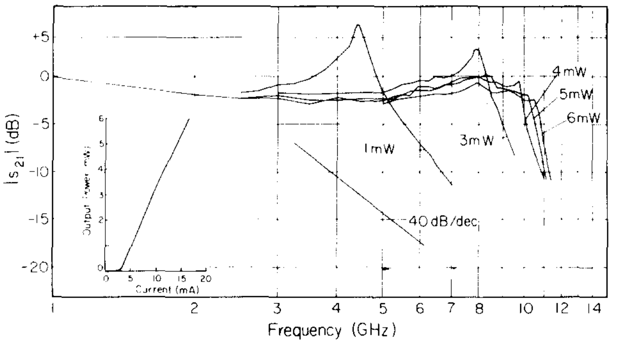

FIG. 2. Modulation response of a 175-μm buried-heterostructure laser on semi-insulating substrate operating at -50 °C.

relatively large ionization energies. Modulation of the laser diode becomes very inefficient as soon as freeze out occurs because of a reduction in the amplitude of the modulation current due to a higher series resistance.

The frequency response of the lasers was measured using a sweep oscillator (Hp8350) and a microwave s-parameter test set (Hp8410, 8746). Figure 2 shows the response of a 175-μm-long laser at -50 °C, at various bias levels. The responses shown here have been normalized by the *pin* photodiode frequency response. The relaxation resonance is quite prominant at low optical power levels. As the optical power is increased, the resonance gradually subsides, giving way to a flat overall response. The modulation bandwidth, taken to be corner frequency of the response (the frequency at the relaxation peak or at the -3-dB point in cases when it is absent), is plotted against the square root of the emitted optical power ($\sqrt{P}$) in Fig. 3, at room temperature and at -50 and -70 °C.

Since, according to Eq. (1), the corner frequency is directly proportional to $\sqrt{A}$ where A is the differential optical gain, the relative slopes of the plots in Fig. 3 thus yield values for the relative change in A as the temperature is varied. The ratio of the slope at 22 °C to that at -50 °C is 1.34 according to Fig. 3. This factor is fairly consistent (between 1.3 and 1.4) among all the lasers tested, even including those from different wafers. According to these measurements we deduce that the intrinsic differential optical gain increases by a factor of ~ 1.8 by cooling from 22 to -50 °C, assuming that the photon lifetime does not change with temperature. To check whether this result is consistent with previously calculated values, we use Fig. 3.8–2 in Ref. 4, in which the calculated optical gain is plotted against the carrier density for various temperatures. The differential gain coefficient A is the slope of the gain versus carrier concentration plots. From these theoretical results, the ratio of A at 160 K to that at 300 K is 2.51. A simple linear interpolation yields an increase by a factor of 1.87 for A at 223 K (-50 °C) over that at 300 K. This is consistent with the value obtained from the modulation measurements described above.

It is thus demonstrated that direct modulation bandwidths of beyond 10 GHz are practically feasible by using a short cavity laser operating at a modestly low temperature of -50 °C—attainable by standard thermoelectric coolers. In the lasers used in this experiment, attempts to further cool the laser encounters difficulties due to carrier freeze out. This is by no means a fundamental restriction, since the freeze-out temperature can be lowered by using different dopants. A very important aspect of the lasers used in these experiments is their fabrication on semi-insulating substrates, which substantially lowers the parasitic capacitance of the laser—which has been shown to be the most damaging parasitic element in high-frequency modulation.[5] In the lower GHz range it is a general and consistent observation that the modulation response of these lasers does not exhibit any dip as observed in other lasers.[6] Measurements of the electrical reflection coefficient (s_{11}) from the laser gave indications that effects due to parasitic elements are not appreciable until one goes beyond 7 GHz. This can account for the absence of a resonance peak in the modulation response at high optical powers (Fig. 2) and the slight discrepancy between the measured and the predicted at the high-frequency end (Fig. 3). The importance of minimizing parasitic elements by suitable laser design in attempting modulation at frequencies as high as 10 GHz cannot be overstated.

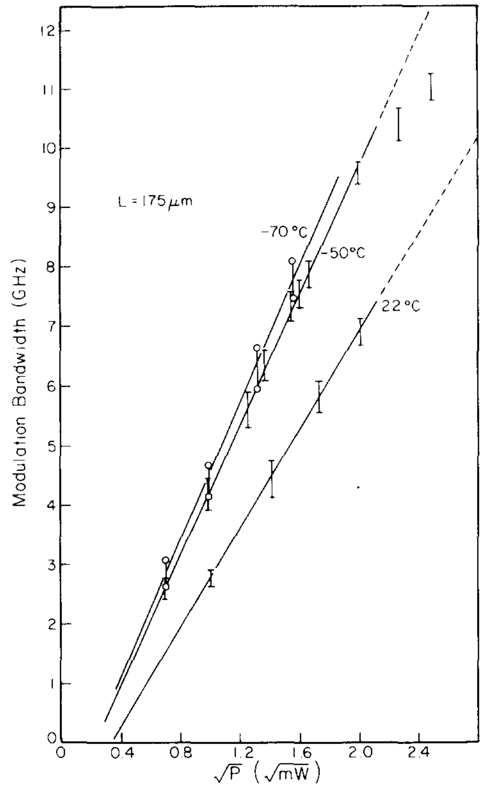

FIG. 3. Variation of modulation bandwidth (corner frequency of the modulation response) with the square root of the emitted optical power $\sqrt{P}$.

A still unanswered question is the problem of reliability and catastrophic damage levels at low temperatures. If, however, the defect-activation model used commonly in accelerated life test of lasers at high temperatures is any indication of how the laser would behave at lower temperatures, then lasers can only become more reliable at reduced temperatures. Further studies in this area will give a more definite answer to this question.

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Distributed Bragg reflector lattice-matched $Pb_{1-x}Sn_xTe/PbSe_yTe_{1-y}$ diode lasers

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Distributed Bragg reflector (DBR) lattice-matched $Pb_{1-x}Sn_xTe/PbSe_yTe_{1-y}$ diode lasers were fabricated using liquid phase epitaxy. These DBR lasers were operated within a limited range of heat-sink temperatures 8.5–38 K, and the threshold current density at 20 K was ~ 3 kA/cm^2. Single longitudinal-mode operation was obtained up to more than three times the threshold current. The DBR lasers exhibited continuous tuning over a relatively wide range of ~ 6 cm^{-1} near 775 cm^{-1} (12.9 μm). The average tuning rate was 0.21 cm^{-1}/K, and it was much smaller than the rate for corresponding Fabry–Perot lasers, which was 2.3 cm^{-1}/K.

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Conventional Fabry–Perot (FP) type lead salt diode lasers are usually characterized by multimode operation. This limits their usefulness as tunable sources for such applications as ultrahigh-resolution spectroscopy and infrared heterodyne detection. Even when single-mode operation of lead salt diode lasers is obtained, the continuous tuning of their wavelength is interrupted by mode hopping. This limits the continuous tuning range to about 1 cm^{-1}. Single-mode operation as well as a wide continuous tuning range of PbSnTe/PbTe double heterostructure lasers was demonstrated by using distributed-feedback (DFB) laser structures.[1–3] In these lasers, the optical feedback was provided by periodic corrugations which were fabricated along the pumped section of the device.[4] These heterostructure lasers, however, suffered from a high threshold current density (even at low temperatures) due to the lattice mismatch between the active layer and the confining layers.[5] In addition, the DFB configuration generally requires growing an epitaxial layer on top of the corrugations, and this step complicates the fabrication procedure.

In this letter we report the fabrication of lattice-matched PbSnTe/PbSeTe distributed Bragg reflector (DBR) diode lasers. In this laser structure, the corrugated section is located at one end of the device, acting as a frequency-selective distributed mirror, and it is virtually unpumped.[6,7] The lattice-matched laser structure used here had been used in the past for fabricating regular FP lasers. These single heterostructure (SH) lasers were found to have low threshold currents and a high external efficiency.[8] The PbSnTe DBR lasers exhibit essentially the same single-mode behavior and a wide continuous tuning range as their DFB counterparts. However, their fabrication does not require the growth of epitaxial layers on top of the corrugations, and hence it is easier to accomplish.

The lattice-matched Sh PbSnTe/PbSeTe laser was prepared by a single-step liquid phase epitaxy around 480 °C, on a (100) oriented p-type $Pb_{0.817}Sn_{0.183}Te$ substrate ($p \cong 10^{19}$ cm^{-3}). A p-type $Pb_{0.817}Sn_{0.183}Te$ active layer ($p \cong 10^{17}$ cm^{-3}), 1.5 μm thick, was grown on the substrate, followed by a 1.5-μm-thick In-doped $PbSe_{0.08}Te_{0.92}$ cladding layer ($n \cong 10^{17}$ cm^{-3}). The Se content in the cladding layer was selected so that this layer is lattice matched to the active layer. In this lattice-matched SH, the optical and the carrier confinement are provided by the higher majority-carrier concentration in the substrate material[9] and by the larger energy gap and lower refractive index of the cladding-layer material.

Indium stripes, each 1 mm wide, were fabricated on the top layer by conventional photolithography and electroplating. The indium stripes were aligned along the (100) direction. Next, about 1 μm of the top PbSeTe layer was removed, in the regions between the indium stripes, by using Ar$^+$ ion

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