11-GHz direct modulation bandwidth GaAlAs window laser on semi-insulating substrate operating at room temperature

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We have demonstrated a direct modulation bandwidth of up to 11 GHz in a window GaAlAs buried heterostructure laser fabricated on a semi-insulating substrate, operating at room temperature.

Interest in the optical transmission of microwave signals up to X-band frequencies has stimulated considerable effort in pushing the intrinsic direct modulation bandwidth of semiconductor lasers to higher frequencies. A basic relation between the modulation bandwidth B and the various parameters of the operating laser is as follows[1]:

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

where A is the differential optical gain constant of the optical mode, P_0 is the steady state photon density at the active region, and τ_p is the photon lifetime. Equation (1) points to three obvious ways to increase the modulation bandwidth: (1) by decreasing τ_p, which we have demonstrated before by a short cavity structure, resulting in a 8-GHz bandwidth.[1] (2) by increasing the differential gain A, which we have recently accomplished by lowering the operating temperature of the laser to − 50° which results in a direct modulation bandwidth[2] up to 12 GHz, and (3) increasing P_0 by increasing the bias optical power. As we pointed out before, increasing the optical power can bring about undue degradation or even catastrophic damage to the laser unless the structure of the laser is suitably designed. One common means of raising the ceiling of the reliable operating power of semiconductor lasers is by means of a large optical cavity.[3] The mechanism responsible for a higher catastrophic damage power in these devices is by lowering the optical power density at the active layer, since such damage commonly originates from the active layer near the crystal facet. This maneuver, however, serves little to increase the modulation bandwidth because the quantity of concern here, the photon density *within* the active region [P_0 in Eq. (1)], remains unchanged. A laser suitable for high speed operation should therefore be one with a tight optical confinement in the active region along the entire length of the laser, with a transparent window at the end regions able to withstand much larger photon densities without catastrophic damage. The use of a transparent window structure to increase the catastrophic damage level has already been demonstrated before.[4,5] Using a window buried heterostructure laser fabricated on a semi-insulating substrate, we demonstrate here for the first time a direct modulation bandwidth of beyond 10 GHz for a semiconductor laser operating at room temperature.

The laser used in this experiment is shown in Fig. 1. The device is structurally similar to the buried heterostructure laser on semi-insulating substrate as reported previously,[6] except that here the end regions near the facets are covered by a layer of unpumped GaAlAs which forms a transparent window. The laser was fabricated using a two-step liquid phase epitaxial (LPE) growth process. In the first step, four layers were grown on top of a semi-insulating GaAs substrate: an n^+-GaAs buffer layer and a conventional GaAlAs double heterostructure. Mesa stripes with a stripe width of 1–2 μm were then etched in the $\langle 1\bar{1}0 \rangle$ direction down to the n^+GaAs layer. Part of this stripe was deleted in order to grow the GaAlAs windows. In the second LPE growth two blocking GaAlAs layers were grown. The top p-GaAlAs cladding layer was then diffused and metallized (Cr-Au) while the second Au-Ge/Au contact was applied to the buffer layer after etchings to form the structure as shown in Fig. 1. Individual devices were fabricated using a precise cleaving technique in the window regions within several microns from the edge of the double heterostructure. The optical wave propagates freely in the end window region. As a result of diffraction, only a small amount of light reflected from the crystal facet couples back into the active region. This reduces the effective reflectivity of the end mirrors of the laser. The exact value of the effective reflectivity depends on the length (L) of the window region. The theoretical value of the effective reflectivity, assuming a fundamental Gaussian beam profile, is reduced to 5% for $L = 5$ μm. The actual values of L for the devices fabricated lie around this value. It has been predicted theoretically[7] and demonstrated experimentally[8] that in the modulation characteristics of a laser with a reduced mirror reflectivity, the relaxation oscillation resonance is suppressed. This feature, as shown in what follows, is demonstrated by the present device.

The cw light versus current characteristic of a window laser is shown in Fig. 2. The threshold current of these devices ranges from 14 to 25 mA. The threshold transition is softer than a regular laser of the same structure, which is a

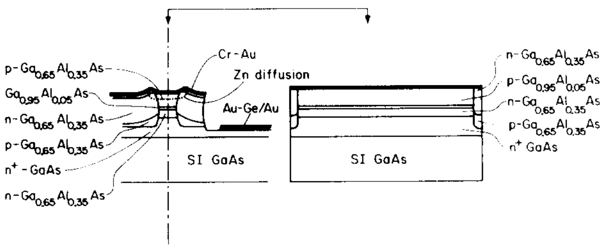

FIG. 1. Schematic diagram of the window buried heterostructure laser on a semi-insulating substrate.

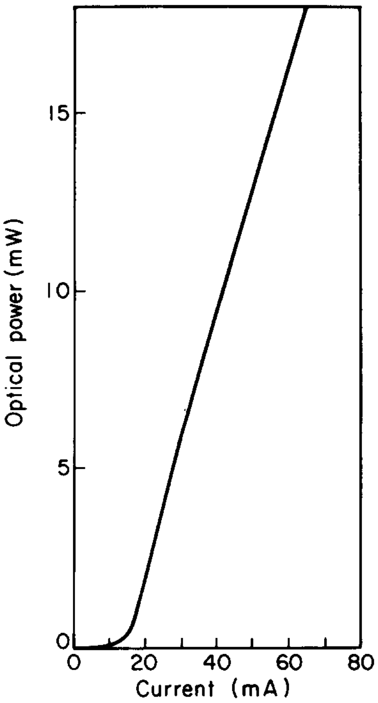

FIG. 2. cw light vs current characteristics of a window buried heterostructure laser on a semi-insulating substrate.

direct result of the reduced reflectivity as described before.[7,8] The catastrophic damage threshold in these devices is beyond 120 mW under pulse operation. Under cw operation, the maximum operating power is limited by heating to 50 mW. The microwave modulation characteristics of the devices were measured with a standard experimental arrangement as shown in Fig. 3. The photodiode used was an improved version of the one reported previously[1,9] and was fully calibrated up to 15 GHz by recording the output signal on a microwave spectrum analyzer when the photodiode is illuminated by a picosecond mode-locked dye laser. The electrical system was calibrated up to 15 GHz by removing the laser and photodiode and connecting point *A* directly to point *B* as shown in Fig. 3. In this way, every single piece of electrical cable and connector, each of which will contribute at least a fraction of a dB to the total system loss at frequencies as high as 10 GHz, can be accounted for. The modulation data are first normalized by the electrical system calibration using a storage normalizer, and are then normalized by the photodiode response. The normalized modulation response of a window laser is shown in Fig. 4(a), at various bias optical power levels. The conspicuous absence of the relaxation oscillation peak should be contrasted with the responses of similar devices which are capable of being modulated to comparably high frequencies (~10 GHz), examples of which are a short cavity version of the present device without a window, or a regular device operating at low temperature. In both of the latter instances, a strong resonance occurs when the frequency of the resonance is below ~7–8 GHz, while the effect of parasitic elements is at least partially responsible for the reduction of the resonance amplitude at higher frequencies. The absence of relaxation oscillation in the window BH on SI lasers at all bias levels is due, as mentioned earlier in the paper, to superluminescent damping effect due to the presence of the window. A plot of the −3 dB modulation bandwidth of the window buried heterostructure laser against the square root of the bias optical power is shown in Fig. 4(b). Contributions from parasitic elements are believed to be at least partly responsible for the departure of the observed data from a linear relationship at high frequencies.

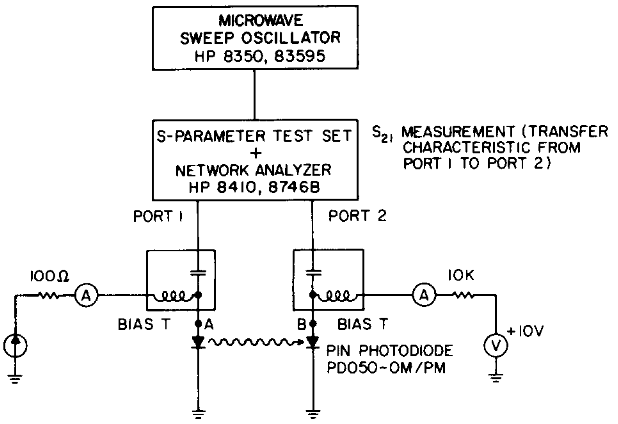

FIG. 3. Measurement system for high-frequency characterization of semiconductor lasers.

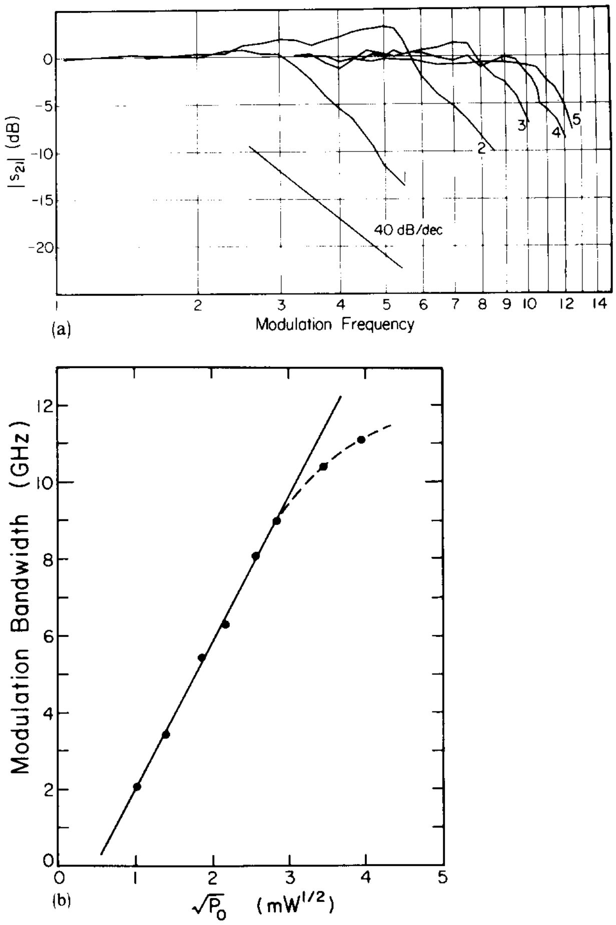

FIG. 4. (a) Modulation characteristics of a window buried heterostructure laser on a semi-insulating substrate at various bias optical power levels at room temperature. Curves 1–5 correspond to bias optical powers of 1.7, 3.6, 6.7, 8.4, and 16 mW. (b) The −3 dB modulation bandwidth vs the square root of the emitted optical power.

In conclusion, we have demonstrated for the first time direct modulation of semiconductor lasers at frequencies beyond 10 GHz with the laser operating at room temperature. This work, together with earlier works,[1,2] completes the verification of the modulation bandwidth dependence on three fundamental laser parameters as given in Eq. (1). With these results in hand, it is quite conceivable that the direct modulation bandwidth of semiconductor lasers can be extended to the 20-GHz range by optimizing all of the three parameters simultaneously according to the theoretical results in Ref. 1.

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Spectral characteristics of (GaAl)As diode lasers at 1.7 K

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The spectral broadening as a function of output power for transverse junction stripe (GaAl)As diode lasers has been measured at 1.7 K. The power-independent linewidth was observed to be about 30 MHz in reasonable agreement with the model involving electron number fluctuations in the device.

We report here on comprehensive linewidth studies of (GaAl)As transverse junction stripe (TJS) diode lasers at a temperature of 1.7 K and a comparison of the results with various models. These low-temperature measurements are necessary to help understand the basis for the various mechanisms that contribute to line broadening in semiconductor diode lasers. In the case of the power-dependent linewidth, the observed variation at 1.7 K was within a factor of 2.5 of the Schawlow–Townes width and the exact dependence was in close agreement with the theory of Henry[1] in the same way as previously reported[2] for measurements made at 273, 195, and 77 K. The power-independent linewidth had a measured value of about 30 MHz at 1.7 K. This is consistent with a phenomenological model involving electron number fluctuations[3] in the device.

The power-dependent linewidth in semiconductor lasers occurs via a number of mechanisms that are due to spontaneous emission photons that modulate the laser field intensity. The first is the well known Schawlow–Townes linewidth ($\nu_{\rm ST}$) that comes about from instantaneous phase fluctuations while the second is due to delayed phase fluctuations that occur as the laser field intensity returns to its steady-state value (amplitude phase coupling). During the time it takes to restore the field intensity to its steady-state value there will be a change in both the real and imaginary parts of the refractive index that leads to an enhanced line broadening given by

$$2\Gamma = \nu_{\rm ST}\, n_{\rm sp}(1+\alpha^2), \tag{1}$$

where 2Γ is the Lorentzian full width at half-maximum, α is the linewidth enhancement factor, and $n_{\rm sp}$ is the spontaneous emission factor[2] which is unity at 1.7 K. Equation (1) is explicitly written in terms of the operating parameters as

$$2\Gamma = \left(\frac{h\nu}{8\pi P_0}\right)\left(\frac{c}{nL}\right)^2(\ln R - aL)(\ln R)\,n_{\rm sp}(1+\alpha^2), \tag{2}$$

where ν is the laser frequency, P_0 is the single-ended, single mode stimulated output power, c/n is the phase velocity, R is the facet reflectivity, $n_{\rm sp}$ is the spontaneous emission factor, a is the distributed internal loss, and α is the linewidth enhancement factor.

The linewidth enhancement factor α is the ratio of the change in the real part of the refractive index ($\Delta n'$) to the change in the imaginary part ($\Delta n''$) due to spontaneous emission events in a given time interval. The real part of the refractive index change can be related to laser mode shifts ($\Delta\lambda$) with change in carrier density using

$$\Delta n' = (n_0/\lambda)\Delta\lambda, \tag{3}$$

where n_0 is the nonresonant refractive index and λ is the laser wavelength. The imaginary part of the refractive index change can be related to gain changes (Δg) as a function of carrier density using

$$\Delta n'' = (c/4\pi\nu)\Delta g. \tag{4}$$

The power-independent or residual linewidth has been studied at 273, 195, and 77 K for TJS devices with values for this contribution of 1.9, 5.2, and 8.4 MHz, respectively.[3] The origin of this effect was described by a phenomenological model[3] involving the statistical fluctuation in the number of conduction electrons in the small active volume of the de-