Low-temperature measurement of the fundamental frequency response of a semiconductor laser by active-layer photomixing

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(Received 7 October 1988; accepted for publication 4 December 1988)

We use the active-layer photomixing technique to directly modulate the output of a GaAs semiconductor laser operating at temperatures as low as 4.2 K. The technique produces modulation with nearly perfect immunity to device parasitic effects, revealing the laser diode's intrinsic modulation response. At 4.2 K the parasitic corner frequency is estimated to be 410 MHz, yet the response appears ideal out to 15 GHz. We measure the dynamical parameters governing the response function, the relaxation resonance frequency, and the damping rate, and discuss their low-temperature behavior.

The development of high-speed semiconductor lasers requires an understanding of the fundamental electron-photon dynamics in the active region of the device. The interaction between the lasing mode and the inversion population determines the laser diode's intrinsic modulation response. However, conventional injection current modulation of semiconductor lasers is governed by a response function which is a superposition of the intrinsic response and the parasitic response. The parasitic response function arises from package- and chip-related impedances which divert current from the laser diode's active layer. The intrinsic modulation response is thus obscured, especially at high frequencies.

Recently, we demonstrated an experimental technique, active-layer photomixing, which enabled us to measure the intrinsic modulation response of a GaAs transverse junction stripe (TJS) laser at room temperature.[1] The nature of the photomixing process gives the measurement nearly perfect immunity to parasitic effects.[2] In this letter we employ the active-layer photomixing technique on a TJS laser diode operating at cryogenic temperatures.

Our objective in these low-temperature measurements is twofold. First, to demonstrate that the active-layer photomixing technique is truly immune to parasitic influences. Upon cooling, the laser diode's contact resistance increases due to the freezeout of excess carriers. For this reason, the parasitic response overwhelms the device's intrinsic response, and conventional injection current modulation becomes very inefficient at low temperature. When modulating the laser by active-layer photomixing, however, we see no parasitic influences in the measured modulation response, even at 4.2 K where the device's contact resistance increased by more than a factor of 5 over its room-temperature value. In fact, this experiment represents the first time a semiconductor laser, operating at liquid-helium temperature, has been successfully modulated at microwave rates.

Our second objective is to study the laser diode's intrinsic modulation response at low temperature.[3] From the measured response curves, one can extract dynamical parameters of interest, such as the relaxation resonance frequency and the damping rate. How these parameters change with temperature agrees well with the simple theory discussed below.

The intrinsic frequency response of a semiconductor laser follows from a small-signal analysis of the spatially averaged single mode rate equations for photon density p and carrier density n.

$$\dot{p} = \Gamma g(n,p)p - p/\tau + \theta, \qquad (1a)$$

$$\dot{n} = -g(n,p)p - r(n) + I, \qquad (1b)$$

where Γ is the fill factor, $g(n,p)$ is the optical gain, τ is the photon lifetime, θ is the spontaneous emission rate per unit volume into the optical mode, $r(n)$ is the spontaneous recombination rate per unit volume, and I is the injection level in units of carrier density per second. The resulting response function has the transfer characteristic of a second-order low-pass network, and is given by[4]

$$\hat{p}_m(\Omega)/p_0 = \Gamma g_n \hat{I}_m(\Omega)/(\omega_R^2 - \Omega^2 + i\Omega\gamma), \qquad (2)$$

where p_0 is the steady-state lasing mode photon density, $\hat{p}_m(\Omega)$ is the small-signal amplitude response function, g_n is the derivative of optical gain with respect to carrier density (the differential gain), $\hat{I}_m(\Omega)$ is the injection level amplitude, ω_R is the relaxation oscillation frequency, and γ is the damping rate.

The intrinsic response function has three important features. It is flat at low frequencies, it has a resonance peak near ω_R whose width is governed by γ, and it eventually rolls off at 20 dB/dec beyond the resonance. A 20 dB/dec rolloff in photon density corresponds to a 40 dB/dec rolloff in detected photocurrent. The relaxation resonance frequency ω_R is given by[4]

$$\omega_R^2 = g_n p_0/\tau, \qquad (3)$$

while the other dynamical parameter affecting the shape of the response function, γ, can be expressed as

$$\gamma = \gamma_0 + \tau\omega_R^2(1 + \Gamma|g_p|/g_n), \qquad (4)$$

where γ_0, in general, incorporates the power-independent sources of damping (spontaneous emission, diffusion, etc.) and g_p is the derivative of optical gain with respect to photon density (the nonlinear gain parameter) which has become important in recent work.[5] As shown above, γ is a linear function of ω_R^2 whose slope depends on both the differential gain and the nonlinear gain.

Active-layer photomixing is the mixing of two single frequency laser sources with a small frequency difference in the active region of a semiconductor laser. The energies of

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the two beams are chosen to fall within the band gap of the laser diode's cladding layers, but well above the band gap of the active layer, so that the two beams are selectively absorbed in the active layer. The absorption process generates a population of electrons and holes whose density is modulated at the beat frequency of the sources. These carriers relax to the bottom of their respective bands at subpicosecond time scales, resulting in modulation of the optical gain. We bias the semiconductor laser to an operating point above threshold using a dc bias current, and modulate the light output about this point using active-layer photomixing. By scanning the frequency of one of the single frequency sources one can tune the modulation frequency across the microwave spectrum.

The experimental arrangement for the low-temperature measurements is shown in Fig. 1. The details of the basic experimental arrangement are described in a previous letter,[1] but there are two significant modifications in this low-temperature experiment. First, to allow for the band-gap increase at low temperature, the mixing light is at a wavelength of 676.4 nm, as opposed to 752.5 nm in the room-temperature measurements. The GaAs active layer is absorbing at this shorter wavelength from room temperature to 4.2 K, while the AlGaAs cladding layer remains transparent. Second, the laser diode is mounted on a copper heat sink in a continuous flow cryostat. A pair of quartz windows positioned at right angles on the chamber provides access to the top surface and front facet of the laser diode. Because efficient coupling into the active region of the device requires submicron mechanical stability, one must allow sufficient time for any thermal stresses in the mount to equilibrate. For this reason our measurements are performed at 293, 77, and 4.2 K. In addition, all measurements were made on a single laser diode, so that statements about the device's temperature-dependent behavior are meaningful.

When a semiconductor laser is cooled, several things happen: threshold current decreases, contact resistance increases, lasing wavelength shifts to shorter wavelengths, and differential gain increases. To demonstrate that the TJS laser is behaving normally at low temperature we plot light output versus current curves for the device in Fig. 2, where, for example, the threshold current decreases to 0.63 mA at 4.2 K. The laser diode's contact resistance, given by the asymptote of the differential resistance at forward bias condition, increases substantially from 7 Ω at 293 K to 17 and 39 Ω at 77 and 4.2 K, respectively.

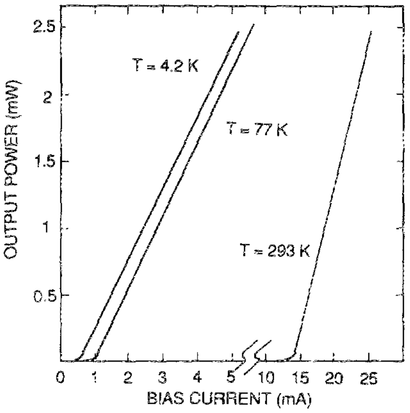

FIG. 2. Output power vs bias current at three temperatures.

Typical response curves at each temperature are shown in Fig. 3. The bias levels are adjusted so that each curve corresponds to an output power of approximately 2 mW per facet. We see that the resonances are clearly defined, and that the laser diode speeds considerably as the temperature is lowered. In addition, the room-temperature response curve eventually rolls off at the theoretical 40 dB/dec rate. The high-frequency cutoff in the data results from the limited photodetector bandwidth and noise floor of the microwave spectrum analyzer. We note that the parasitic *RC* corner frequency is 410 MHz for a typical 10 pF capacitance at 4.2 K, yet there is no effect on the response curve, with the data appearing to be ideal out to 15 GHz.

A plot of the square of the relaxation resonance frequency versus output power appears in Fig. 4. The theoretical linear behavior given by Eq. (3) is seen at all three temperatures. The slope of this line increases by a factor of 7.0 and 13.6 at 77 and 4.2 K, respectively, over its room-temperature

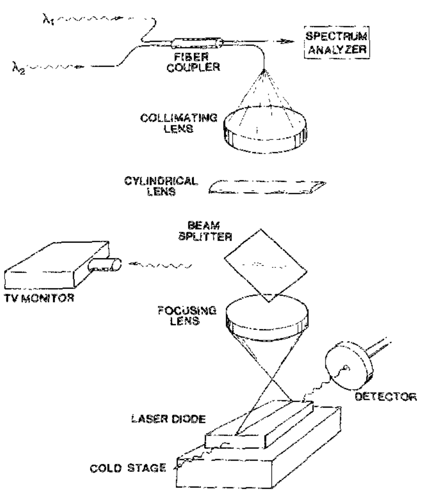

FIG. 1. Schematic diagram of the experimental arrangement.

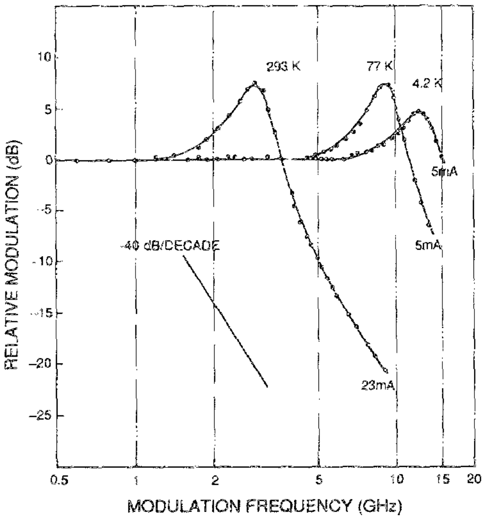

FIG. 3. Measured modulation response at three temperatures.

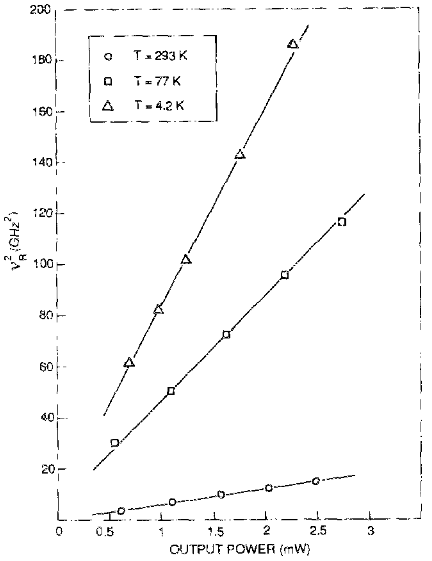

FIG. 4. Square of resonance frequency vs output power.

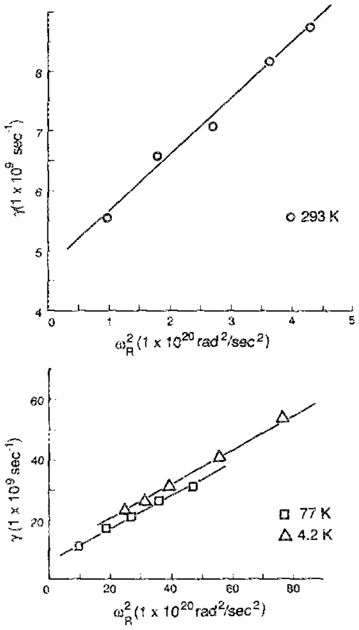

FIG. 5. Damping rate γ vs square of resonance frequency.

value. We attribute most of this increase to the increase in g_n [Eq. (3)] caused by the narrower gain spectrum at low temperature. In Fig. 5 the damping rate γ is plotted as function of ω_R^2. For each temperature the linear relationship predicted by Eq. (4) is observed. The slope of this line decreases from 9.3 ps at 293 K to 5.6 ps at 77 and 4.2 K. This decrease in slope, from room temperature to liquid-nitrogen temperature, is consistent with the simple theory which incorporates the nonlinear gain [Eq. (4)] and the measured increase in the differential gain at low temperature. The apparent saturation in the slope as the temperature is lowered from 77 to 4.2 K indicates that the increase in g_n is offset by an increase in g_p. Although we do not speculate here on the origins of the nonlinear gain, further low-temperature experiments could help decide among possible mechanisms.

In summary, we have used the active-layer photomixing technique to directly modulate the output of a semiconductor laser operating at cryogenic temperature. The technique produces parasitic-free modulation, enabling a measurement of the laser diode's intrinsic modulation response. Even at 4.2 K where the parasitic corner frequency is estimated to be 410 MHz, the response appears ideal out to 15 GHz. From the measured response curves we find values for the relaxation resonance frequency and the damping rate. Their low-temperature behavior agrees with the simple theory incorporating the nonlinear gain.

This work is supported by the National Science Foundation, the Powell Foundation, and ATT Corporation. One of us (MAN) is grateful for financial support from IBM Corporation.

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