# Measurement of the fundamental modulation response of a semiconductor laser to millimeter wave frequencies by active-layer photomixing

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The room-temperature modulation response of a GaAs/GaAlAs semiconductor laser (relaxation resonance frequency, $\nu_R = 6.5$ GHz) is measured to 37 GHz using the active-layer photomixing technique. The measured response function agrees with the theoretical ideal, and there is no indication of device parasitic effects. An ultrahigh-finesse Fabry–Perot interferometer is used to detect the optical modulation, which appears as sidebands in the laser field spectrum. With a moderately faster laser diode (i.e., $\nu_R \sim 10$ GHz), the modulation response should be measurable beyond 100 GHz.

High-frequency modulation of semiconductor lasers is governed by a superposition of two independent response functions, the intrinsic response and the parasitic response. The intrinsic response defines the maximum attainable modulation rate of a laser diode and also provides insight into the physics of lasing action in semiconductors. However, high-frequency injection current modulation in semiconductor lasers is limited by parasitic elements in the device which shunt carriers around the active layer. The intrinsic modulation response is thus obscured at high frequencies. Recently, however, we demonstrated a new technique, active-layer photomixing, which generates parasitic-free modulation at all frequencies.[1-3] In this letter we use the active-layer photomixing technique to measure the room-temperature modulation response of a GaAs/GaAlAs laser diode to the millimeter wave frequency of 37 GHz. The modulation sidebands in the field spectrum are detected with an ultrahigh-finesse ($\sim$40 000) Fabry–Perot interferometer, and the measured response agrees with the theoretical response function presented below. We note that wide-band millimeter wave modulation (to 38 GHz) has been reported for a cooled InGaAsP laser with a 31 GHz corner frequency.[4] In our experiment, the laser diode's relaxation resonance frequency is only 6.5 GHz. With a moderately faster laser diode (i.e., resonance frequency $\sim$10 GHz), it should be possible to directly measure the modulation response beyond 100 GHz.

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 and carrier density in the active region. A cosinusoidally varying photon density is assumed:

$$p(t) = p_0 + \hat{p}_m \cos \omega_m t \tag{1}$$

and the resulting response function for the small-signal photon density amplitude is given by[5]

$$\hat{p}_m(\omega_m) = \Gamma g_n \hat{I}_m(\omega_m) p_0 / [(\omega_R^2 - \omega_m^2)^2 + (\gamma\omega_m)^2]^{1/2}, \tag{2}$$

where $\omega_m$ is the modulation frequency, $\Gamma$ is the confinement factor, $g_n$ is the derivative of optical gain with respect to carrier density (the differential gain), $\hat{I}_m$ is the small-signal injection current amplitude, $p_0$ is the steady-state lasing mode photon density, $\omega_R$ is the relaxation oscillation frequency (Ref. 5), and $\gamma$ is the damping rate. The intrinsic response function $\hat{p}_m$ is flat at low frequencies, has a resonance near $\omega_R$, and eventually rolls off at 20 dB/dec beyond the resonance.

To measure the laser diode's modulation response, one normally detects the modulated light with a fast *p-i-n* photodiode connected to an electronic microwave spectrum analyzer. The detection bandwidth of commercially available near-infrared photodetectors, however, is limited to about 20 GHz. In addition, the photocurrent signal must compete with a noise floor in the spectrum analyzer which typically starts at $-110$ dBm near dc and climbs at a rate of 1.7 dB/GHz.[6] A much larger detection bandwidth can be obtained by measuring the modulation signal with an optical spectrum analyzer, a scanning Fabry–Perot interferometer (FPI). The modulation signal then appears as sidebands in the laser field spectrum. However, the ability to observe modulation sidebands at high frequencies depends critically on the finesse of the FPI, which should be as high as possible. For this experiment, the FPI (Newport SR-240) has a fin-

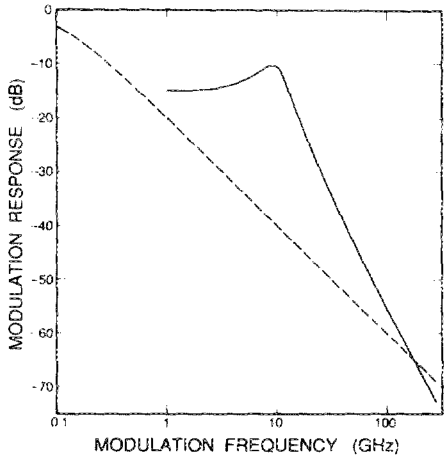


FIG. 1. Graphical evaluation of modulation sideband detection using a Fabry–Perot interferometer. At frequencies where the response function lies above the background Lorentzian (dashed curve), the modulation sidebands are observable.



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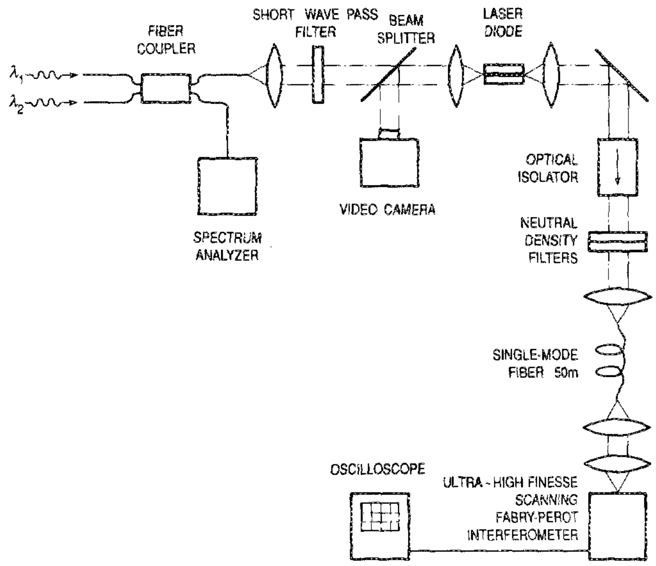


FIG. 2. Schematic diagram of the experimental arrangement. The high-frequency modulation is generated in the laser diode by active-layer photomixing and detected with an ultrahigh-finesse Fabry–Perot.

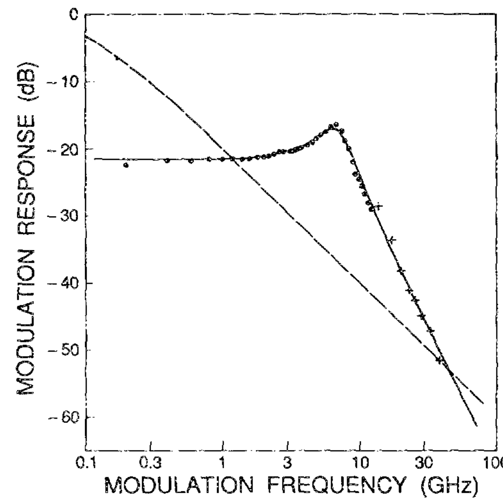


FIG. 3. Modulation response to millimeter wave frequencies. The high-frequency data ( + ) were measured with a Fabry–Perot and the low-frequency data (●) were recorded with a *p-i-n* photodiode. The background Lorentzian (dashed curve) is also shown.

esse of 40 000, a free-spectral range of 8 THz, and an instrumental resolution of 200 MHz at 800 nm.

As is shown below, beyond the resonance frequency the modulation sidebands asymptotically approach a 40 dB/dec rolloff. Clearly there exists some high-frequency limit beyond which the sideband signal is not measurable. However, in contrast to the electronic spectrum analyzer, the background, or noise floor, arising from the FPI is a decreasing function of frequency. This background results from the presence of the lasing mode (i.e., the optical carrier) which appears as a Lorentzian with the linewidth of the FPI assuming the FPI linewidth is much greater than the lasing mode linewidth. The tails of this Lorentzian roll off at 20 dB/dec, eventually obscuring the sideband signals. As Fig. 1 shows, however, this point of intersection can be at ultrahigh frequencies, far into the millimeter wave regime ($\geqslant$30 GHz). The figure shows, in a log-log plot, a typical modulation response function $[(\hat{p}_m)^2]$ of a laser diode with a 10 GHz resonance frequency and relative sideband intensity, at the resonance, of 10%. Also shown is the background from the optical carrier, assuming a corner frequency of 100 MHz, corresponding to a 200 MHz linewidth for the Lorentzian. At frequencies where the modulation response function lies above the Lorentzian, the modulation sidebands are, in principle, detectable. For this example the high-frequency detection limit can be over 150 GHz. As is evident from the figure, the intersection point depends sensitively on the resonance frequency and modulation depth of the laser diode, and on the linewidth (inverse finesse) of the FPI. In practice, the background level may be raised somewhat by spontaneous emission from the laser diode, but this did not affect our measurement.

The FPI used in this experiment has a 20 $\mu$m cavity and 30 cm radius of curvature mirrors. In this near-planar resonator, higher order transverse modes spaced 27.6 GHz apart may be excited by a single-frequency optical input.[7] These modes can potentially interfere with the detection of the modulation sidebands whenever the modulation frequency is near a multiple of 27.6 GHz. However, the higher order transverse modes appear only on the high-frequency side of the fundamental, whereas the modulation sidebands appear symmetrically on both sides of the fundamental. The low-frequency modulation sideband can thus be tracked more readily as a function of modulation frequency. Careful matching of the optical input to the fundamental transverse mode is still required, however, because weakly lasing longitudinal modes of the semiconductor laser, spaced 140 GHz apart, can excite their own set of higher order transverse modes in the FPI. In our experiment, optimum mode matching suppresses the higher order transverse modes by at least 26 dB compared with the fundamental.

We now examine how the intrinsic response function $\hat{p}_m$ relates to the laser field spectrum, which is what one observes at the output of a FPI. Direct modulation of a semiconductor laser, by active-layer photomixing or injection current modulation, affects the amplitude and also the phase of the laser field due to the dependence of refractive index on carrier density. The time-dependent field may then be taken as

$$E(t) = (E_0 + \hat{E}_m \cos \omega_m t)\exp[i(\omega_0 t + \hat{\phi}_m \cos \omega_m t)], \tag{3}$$

where $\omega_0$ is the cw oscillation frequency and $\hat{E}_m$ is the small-signal field amplitude, given by

$$\hat{E}_m / E_0 = \tfrac{1}{2}(\hat{p}_m / p_0), \tag{4}$$

i.e., the field amplitude is proportional to the photon density amplitude when they are small-signal quantities. In Eq. (3), $\hat{\phi}_m$ is the response function of the phase deviation given by[8]

$$\hat{\phi}_m = \tfrac{1}{2}\alpha(\hat{p}_m / p_0), \tag{5}$$

where $\alpha$ is the linewidth enhancement factor. Although $\hat{p}_m$, $\hat{E}_m$, and $\hat{\phi}_m$ are, in general, complex functions, we treat them as real for our purposes since their relative phases become zero at high frequencies.[9] The field spectrum resulting from



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Eq. (3) consists of the center line at $\omega_0$, and AM and FM induced sidebands at $\omega_0 \pm n\omega_m$, where $n$ is an integer. For modulation frequencies greater than the relaxation oscillation frequency, only the first sidebands are observable. The intensity of these first sidebands is equal to

$$A(\omega_0 \pm \omega_m) = [E_0 J_1(\hat{\phi}_m)]^2 + \{\tfrac{1}{2}\hat{E}_m [J_0(\hat{\phi}_m) - J_2(\hat{\phi}_m)]\}^2, \quad (6)$$

where $J_n$ is the Bessel function of order $n$. For small-signal modulation we may use the approximation:

$$J_n(x) \approx x^n/2^n n!, \quad x \ll 1, \quad (7)$$

and so obtain

$$A(\omega_0 \pm \omega_m) = \tfrac{1}{4}(E_0^2 \hat{\phi}_m^2 + \hat{E}_m^2) \propto (\hat{p}_m)^2, \quad (8)$$

where Eqs. (4) and (5) were used to get the final proportionality relation. The intensity of the first-order modulation sidebands, as a function of $\omega_m$, is therefore directly proportional to the square of the intrinsic response function [Eq. (2)].

The experimental arrangement appears in Fig. 2. The laser diode used in this experiment is a GaAs/GaAlAs buried-heterostructure device with a 23 mA threshold current and lasing wavelength of 786 nm. The laser, at room temperature, is biased above threshold by a dc injection current and the output is small-signal modulated by the active-layer photomixing technique. Briefly, active-layer photomixing is the mixing of two single-frequency laser sources with a tunable frequency difference in the active region of a semiconductor laser. The technique generates parasitic-free modulation at the beat frequency of the sources, and its principles are described in previous letters.[1-3] For the photomixing sources we use a single-mode krypton laser operating at 676.4 nm and a dye laser running DCM dye at the same wavelength. These sources are collimated from the output of a 50/50 fiber coupler and focused onto the rear facet of the laser diode, which is mounted on a narrow (300 μm) stub so that both facets may be accessed. A short-wave pass filter prevents feedback to the rear facet. The incident optical power is 2.5 mW. The emission from the modulated semiconductor laser is focused into a 50-m-long single-mode optical fiber. An optical isolator with 40 dB isolation suppresses feedback to the front facet, and a narrow bandpass filter rejects any scattered pumping light. Coupling into the fiber serves the dual purpose of spatially filtering the lasing mode and rejecting a significant amount of spontaneous emission. Approximately 5 cm of the fiber jacket is removed at the input end and the exposed cladding is immersed in glycerine to strip the cladding modes propagating in the fiber. The output from the fiber is mode matched into the FPI through a 10 cm focusing lens, and a photomultiplier tube (PMT) detects the light transmitted through the FPI. The PMT photocurrent is converted to a voltage signal which is amplified and displayed on an oscilloscope whose sweep is synchronized with the FPI. The PMT gain is set to a high value and the input light intensity is adjusted with calibrated neutral density filters.

Figure 3 shows the modulation response of the laser diode running at a bias current of 40.5 mA. The high-frequency data (12 GHz $< \omega_m/2\pi < 37$ GHz) were obtained by measuring the modulation sideband relative intensity, as discussed above. At resonance, the relative intensity (sideband/carrier) is 2%. For completeness, the low-frequency response ($\omega_m/2\pi < 12$ GHz) is also shown. These data were recorded with a photodiode and microwave spectrum analyzer, because at low frequencies higher order sidebands complicate the spectrum observed on the FPI.[10,11] From the low-frequency data we can determine the resonance frequency (6.5 GHz) and damping rate (4.7 GHz). A theoretical response curve [$(\hat{p}_m)^2$, see Eq. (2)], based on these parameters, also appears in the figure. The high-frequency data agree reasonably well (no device parasitic effects are observable) with the theoretical curve to the highest measured frequency of 37 GHz. Notice that the modulation sideband signal is lost approximately where the response curve and background Lorentzian intersect. We mention that a slightly faster laser ($\omega_R/2\pi \sim 7.5$ GHz) was modulated to 44 GHz before the sideband signal was lost in the background. Unfortunately, it catastrophically failed before a complete response curve could be mapped out.

In conclusion, we have measured the intrinsic modulation response of a GaAs/GaAlAs semiconductor laser to the millimeter wave frequency of 37 GHz. The optical modulation is generated, parasitic-free, by the active-layer photomixing technique. An ultrahigh-finesse Fabry–Perot interferometer detects the modulation sidebands created by the photomixing, and the measured response agrees with the theoretical response function. By performing this experiment on a moderately faster semiconductor laser (i.e., resonance frequency ~ 10 GHz) than that used in this measurement, it should be possible to measure the response beyond 100 GHz.

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