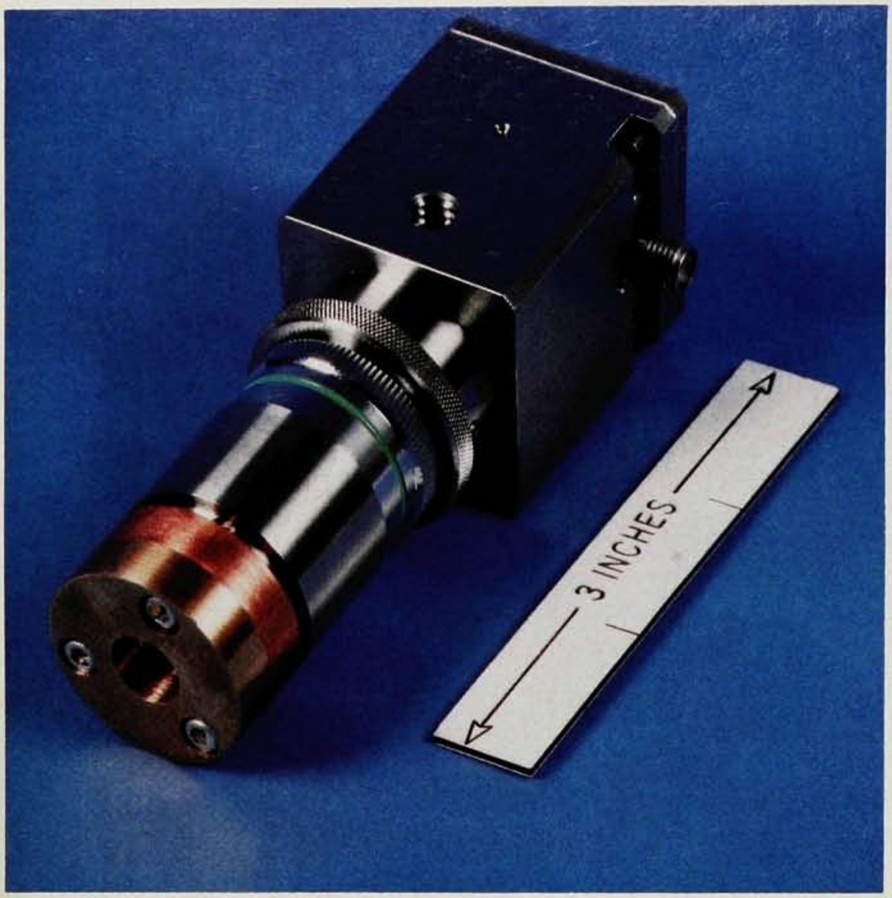
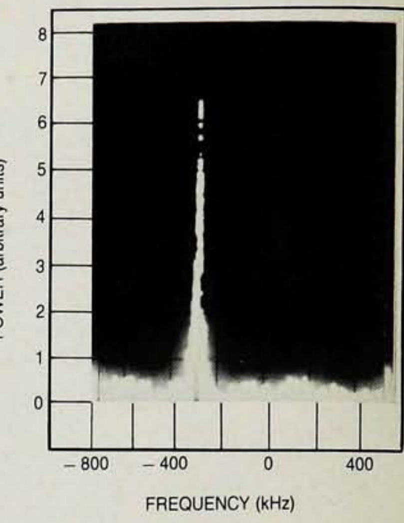
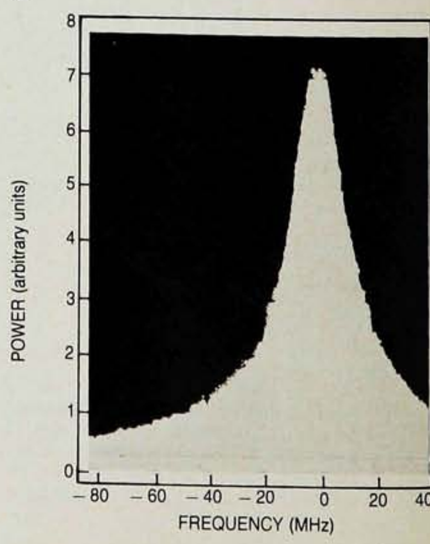




a

Diode lasers: The upper photo **(a)** shows a compact external-cavity diode laser; the adjoining trace shows a heterodyne beat note between two external-cavity diode lasers of a different construction, indicating a linewidth of less than 15 kHz. The lower photo (**b**) shows a semiconductor laser without an external cavity. The adjoining trace shows that the linewidth is much broader. Figure 1

b



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Laser linewidth

Detailed theoretical and experimental study of the quantum effects that limit the spectral purity of lasers has led to semiconductor lasers whose output is highly monochromatic and coherent.

Aram Mooradian

One of the most important properties of laser light is its spectral purity and coherence. This unique quality has been important for the study of many new physical phenomena using laser sources that operate from the vacuum ultraviolet to the far infrared. An understanding of the mechanisms responsible for the broadening of the linewidth is necessary for the development of laser sources with sufficient spectral purity for various applications.

The broadening of the linewidth in lasers is caused by two mechanisms: the so-called "technical" noise due to mechanical vibrations of the laser cavity and other sources of external noise, and the "fundamental" line broadening due to quantum fluctuations. In this article I will discuss the fundamental limits of spectral purity, with particular emphasis on the semiconductor laser. I will also show that one can reduce the fundamental linewidth of a semiconductor laser by coupling it to an external cavity (see figure 1).

The need for spectral purity

A large number of research and technical applications require lasers with a high degree of spectral purity. The linewidth and phase stability of the light source are very important for fiber-optical sensors. The sensors detect changes in the signal phase that are caused by external influences—such as temperature, pressure, or magnetic fields—in a laser signal passing through an optical fiber.

The introduction of tunable lasers with narrow linewidths revolutionized optical spectroscopy. High-resolution spectroscopy using tunable lead-salt diode lasers emitting in the infrared has already proven to be useful. Linear-absorption spectroscopy of Doppler-broadened gases involves linewidths of several tens of megahertz in the infrared to about one gigahertz in the visible region. Nonlinear-absorption spectroscopy requires linewidths that are 100–1000 times narrower. Recent experiments aimed at detecting gravity waves require ultra-narrow-linewidth lasers having widths and stabilities in the subhertz region.[1] Small perturbations of massive Earth-based interferometers could in principle detect the emission of gravitons emitted by large intergalactic objects such as black holes or binary stars. Optical-fiber and line-of-sight laser communication using heterodyne detection require that the spectral width of the laser source usually be less than 1% of the transmitted data rate to achieve a low enough error rate in the information signal. For example, a 1-gigabit data-rate system would require a laser spectral width of less than 10 MHz.

Fundamental linewidth

Two processes contribute to the generation of photons in a laser: stimulated emission, the process responsible for laser amplification in which the radiation emitted by an atom is exactly in phase with the radiation that surrounds the atom; and spontaneous emission due to the transition between upper and lower laser levels caused by the finite lifetime of the upper level.

Because the field from a laser is usually well polarized and nearly monochromatic, we can represent the electric field as the real part of the complex field

$$\mathbf{E}(\mathbf{r}, t) = E(t)\hat{n}e^{i\mathbf{k}\cdot\mathbf{r}}$$

where $\hat{n}$ is the unit polarization vector and $\mathbf{k}$ and ω are the wavevector and frequency of the emitted light. The time variation of the complex amplitude $E(t)$ due to spontaneous emission photons gives rise to the finite linewidth of the radiation. If we plot the values $E(t)$ takes on over a period of time, we get a graph like that shown in figure 2a for a laser. For incoherent light, values of $E(t)$ in the complex plane will take on all the values shown in figure 2b.

In addition to the stimulated emission photons, the spontaneous emission photons that radiate into the laser mode add as a small vector to the laser field vector (see figure 2a) to produce a new laser field vector with field amplitude $E + \Delta E$ and phase angle $\phi + \Delta\phi$. Because spontaneous emission is incoherent, its phase is random; the result-

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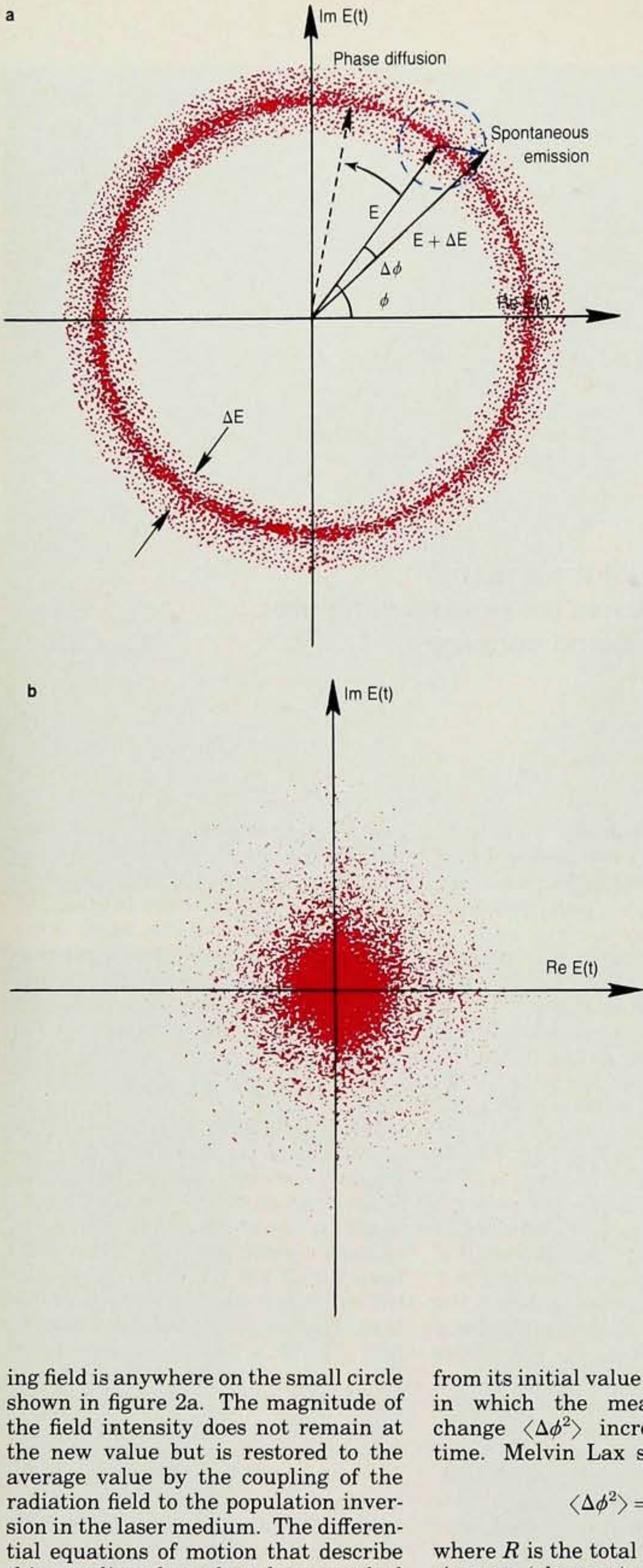


Complex representation of the field intensity. Each dot represents the random tip of the field vector. In **a** we show the field intensity of laser light as it is modified by spontaneous emission photons. The average spread of radial field intensity is ΔE, while the laser-field phase angle undergoes a diffusion from its initial value at time $t = 0$. For comparison, the distribution of the complex amplitude of incoherent light is shown in **b**. There $E(t)$ takes on a set of random values distributed around the origin. Figure 2

ing field is anywhere on the small circle shown in figure 2a. The magnitude of the field intensity does not remain at the new value but is restored to the average value by the coupling of the radiation field to the population inversion in the laser medium. The differential equations of motion that describe this coupling show that the perturbed field amplitude returns to its equilibrium value by undergoing damped oscillations, as shown in figure 3.

The phase angle, however, does not have a force that restores it to the original phase. The repeated occurrence of spontaneous emission events thus causes the phase angle to diffuse from its initial value in a random walk, in which the mean square phase change $\langle \Delta\phi^2 \rangle$ increases linearly in time. Melvin Lax showed[2] that

$$\langle \Delta\phi^2 \rangle = \frac{R}{2I}\,t \qquad (1)$$

where R is the total spontaneous emission rate (photons/sec) and I is the total number of photons—or the optical intensity—in the mode. As shown in figure 2a, the laser field at time t has an uncertainty in its phase compared with the value at $t = 0$. Each dot near the circumference of the circle represents the possible position of the field vector after the spontaneous emission of a large number of photons. A convenient way of describing[2] the phase diffusion, which is equivalent to a linear Brownian motion, is by the correlation of the field at time t with the field at time zero: $\langle E^*(t)E(0)\rangle$. It can be shown that the changes in ϕ have a Gaussian distribution. In this case,

$$\langle E^*(t)E(0)\rangle \approx E(0)^2 e^{i\omega t - \langle \Delta\phi^2 \rangle/2} \qquad (2)$$

From equations 1 and 2 we see that the correlation function decays exponentially

$$\langle E^*(t)E(0)\rangle = E(0)^2 e^{i\omega t - t/\tau_c} \qquad (3)$$

where $\tau_c = 4I/R$ is the laser coherence time (a measure of the average time it takes for the laser phase to become uncorrelated from its initial value), ω is the laser frequency and the brackets denote a statistical average. The Fourier transform of equation 2 leads to a Lorentzian line shape with a spectral linewidth given by:

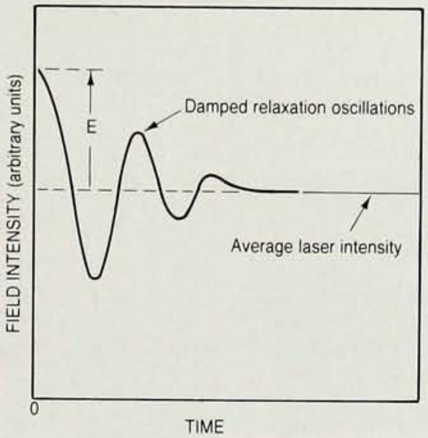
$$\Delta\nu = \frac{R}{4\pi I} \qquad (4)$$

An alternative way of expressing equation 4 in terms of experimentally measurable parameters is

$$\Delta\nu = \frac{\pi h\nu\Gamma^2}{P} \qquad (5)$$

where P is the power in the laser mode and Γ is the "cold cavity" Q of the laser, that is, the linewidth of the passive cavity resonator. In their first paper on the laser, Arthur L. Schawlow and Charles H. Townes derived[3] a value for the linewidth that is twice that given in equation 5. Later, Lax showed that the Schawlow–Townes analysis only applies to lasers operating below threshold. Above threshold, the lasing action stabilizes the field-amplitude fluctuations, reducing the predicted linewidth by a factor of two and leading to the field distribution shown in figure 2. The change in linewidth in going from below threshold to above threshold was calculated[4,5] and verified[6] experimentally in a herculean experiment. Equation 5 is the well-known modified Schawlow–Townes linewidth[2] that had been accepted for many years as describing the laser linewidth. The treatment I have given here is similar in many respects to that developed, even before the laser, for electronic oscillators driven by electrical noise. In a laser oscillator above threshold, the population inversion reaches a stable level, and any increase in the excitation rate shows up as increased laser power. Because the amount of spontaneous emission is proportional to the population in the upper level, the spontaneous emission rate also becomes stabilized above threshold. Figure 2a shows that the magnitude of phase-angle fluctuation $\Delta\phi$ decreases linearly with field amplitude, providing a physical argument for the inverse power dependence of $\langle\Delta\phi^2\rangle$ and the laser linewidth.

Most of the early work in the study of linewidth was on gas lasers. The parameter values for, say, a typical helium–neon gas laser will, according to equation 5, lead to linewidths of about a hundredth of a hertz. In practice, such linewidths are difficult to measure and even more difficult to achieve. For such lasers, the observed linewidth is dominated by technical noise. Most laser systems require exceptional efforts to stabilize and reduce the effects of technical noise to approach more closely the fundamental linewidth. At present, the best results for laser-frequency control have been obtained with a dye laser locked to an acoustically isolated solid-quartz Fabry–Perot etalon. Two such independent lasers, when heterodyned together, showed a beat frequency stable to a few hertz.[7]



Laser-field intensity fluctuations following an impulse of spontaneous emission that produces an impulse change of field intensity of ΔE. The field-intensity scale is exaggerated. Figure 3

Semiconductor laser linewidth

The modified Schawlow–Townes description of the fundamental laser linewidth remained the established view for many years. For gas lasers under most operating conditions, this was indeed an adequate description. The first measurements[8] of the fundamental linewidth of semiconductor lasers were performed on a lead-salt diode laser operating near a wavelength of 10 microns. By heterodyning the output of the diode laser with a stable carbon-dioxide laser whose linewidth had already been demonstrated to be less than a few hundred hertz, the lineshape of the diode laser was shown to be Lorentzian with a width predicted by equation 5. The demonstration of the first continuously operating diode lasers at room temperature, using crystals of the alloy GaAlAs, resulted in widespread interest in the practical use of such devices and accelerated the development of high-quality, low-cost lasers. The use of precision microelectronic fabrication techniques produced lasers that operated reliably in a single frequency, allowing careful measurements of the fundamental linewidth. Our measurements[9] showed the line-broadening mechanisms for GaAlAs and later GaInAsP diode lasers to be more complex than predicted by equation 5.

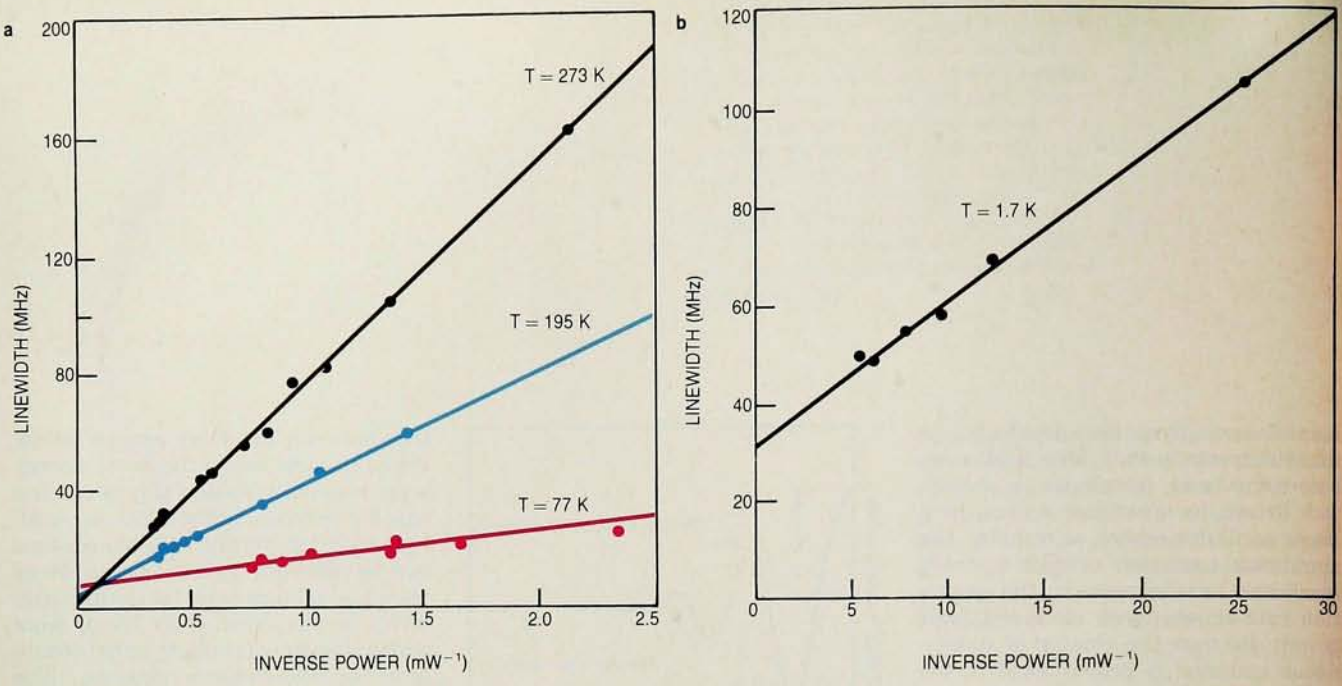
The first precision measurements[9] of the linewidth of a GaAlAs diode laser at room temperature showed that the width increased linearly with increasing reciprocal output power (see figure 4a) as expected, but with a magnitude some 50 times greater than that predicted by equation 5.

An additional broadening mechanism that modifies equation 5 comes from the incomplete population inversion between the laser energy levels. While in most lasers the lower energy level is usually empty, this is not the case for semiconductor lasers, especially at room temperature. Laser photons can be absorbed by exciting electrons from the valence band (or an impurity level) to the conduction band, from which they may reradiate either stimulated or spontaneous photons. The additional spontaneous photons thus created increase the fluctuations in field intensity. The linewidth given by equation 5 is increased by a factor n_s, the spontaneous emission factor, which is the ratio of the spontaneous emission rate per mode to the stimulated emission rate per laser photon. This factor is about 2.5 at room temperature and becomes unity by 77 K for GaAlAs lasers. The remaining discrepancy factor of 20 was explained[7] by Charles Henry; it is due to spontaneous emission events that alter the field amplitude as shown in figure 2a. The discrepancy had been considered[2] earlier for gas lasers in which the cavity mode is detuned from the atomic transitions, but it had not been observed experimentally.

In semiconductors, laser action takes place at energies below the strong interband absorption edge, and this discrepancy effect is dominant. When the field intensity changes, it returns to the steady-state average value by undergoing damped relaxation oscillations, as shown in figure 3. During this time (a few nanoseconds), both the real and imaginary part of the refractive index change as the electron population density also changes in response to the field. The imaginary index change provides changes in gain that restore the steady-state amplitude. The change in the real part of the refractive index produces a phase change that adds an additional broadening to the laser linewidth, which can be significantly larger than the broadening produced by the instantaneous phase changes. The expression for the power-dependent linewidth is given by

$$\Delta\nu = \Delta\nu_{ST}(1 + \alpha^2)n_s \qquad (6)$$

where $\Delta\nu_{ST}$ is the modified Schawlow–



Linewidth of a single-frequency GaAlAs diode laser as a function of reciprocal output power at temperatures of 273, 195, 77 (**a**) and 1.7 K (**b**). The straight lines are least-square fits to the data. Figure 4

Townes linewidth given by equation 4 or 5 and α is the ratio of the change of the real part to the change in the imaginary part of the refractive index. We verified[11,12] experimentally that equation 6 accounts for the observed power-dependent linewidths to within 10–15% at four temperatures between 273 and 1.7 K for GaAlAs diode lasers. The experimental results are shown in figure 4.

Additional phenomena contribute to the laser lineshape. The Fabry–Perot scan of the output from a GaAlAs diode laser (see figure 5) shows the presence of sidebands separated by about two gigahertz from the main laser line. These sidebands come from the damped relaxation oscillations that occur every time the laser-field intensity is perturbed by the spontaneous emission noise.[13,14] The relaxation oscillations cause $\langle \Delta\phi^2(t) \rangle$ to undergo damped sinusoidal oscillations at short times.[15,16] The temporal behavior of these intensity fluctuations was already shown in figure 3. The integrated intensity of these sidebands relative to the integrated intensity of the main peak increases linearly with increasing reciprocal output power. For typical GaAlAs diode lasers, this fractional value is a few tenths of a percent at output power levels of about ten milliwatts. The presence of these sidebands can interfere with many applications requiring a high degree of spectral purity.

An additional source of broadening is evident in figure 4. The linewidth intercept is nonzero and the magnitude of the intercept becomes significantly larger at low temperature. This is equivalent to the presence of a non-power-dependent line broadening,[17] which adds to the power-dependent effects already discussed above. The nonzero intercept may be explained by the very small actual size of these semiconductor lasers. The region in which population inversion occurs is on the order of $0.1\times2\times200$ microns or 4×10^{-11} cm^3. The absolute number N of conduction electrons is also relatively small, ranging from about 10^8 at room temperature down to about 10^6 at 1.7 K for typical lasers. If one assumes that the number of these conduction electrons fluctuates statistically so that the root-mean-square fluctuation in the electron number is $\sqrt{N}$ we can construct a phenomenological model for the fluctuation of the laser frequency that involves the fluctuation of the Fabry–Perot resonant frequency of the laser cavity. The cavity-mode frequency fluctuations are related to changes in the refractive index n via the phenomenological relation

$$\delta\nu = (\nu/n)(\mathrm{d}n/\mathrm{d}N)\sqrt{N} \qquad (7)$$

where $\mathrm{d}n/\mathrm{d}N$ is evaluated at the laser frequency ν. The parameters in this equation, evaluated[17,12] at four temperatures, lead to a remarkably close agreement between the observed and calculated power-independent linewidths.

At first sight it is not entirely clear why the conduction-electron density should fluctuate at all according to the equations of motion, except at the relaxation frequency, and this only leads to the relaxation frequency sidebands discussed above. A number of experimenters, however, have observed[18,19] that both the amplitude and frequency of the laser fluctuate with a power spectrum that depends inversely on the frequency. The presence of $1/f$ noise in semiconductor electronic devices is well known and can stem from carrier traps that exist in the material. Carrier trapping,[20] or any other mechanism that could influence the electron number density or temperature[21] without being affected by the laser field, could in principle contribute to the power-independent linewidth. More work needs to be done to understand this phenomenon completely.

All of the line-broadening mechanisms I have described above are for monolithic diode lasers where the natural reflectivity of the cleaved ends of the diode provides the mirrors that define the cavity. The fundamental spectral width is substantially larger than most other types of lasers and inadequate for a number of applications requiring greater spectral purity. One of the ways to overcome all of the fundamental broadening is by coupling the laser to an external resonator to increase the cavity Q. By increasing the total length of the laser so that most of the cavity consists of air or vacuum, the fractional contribution to

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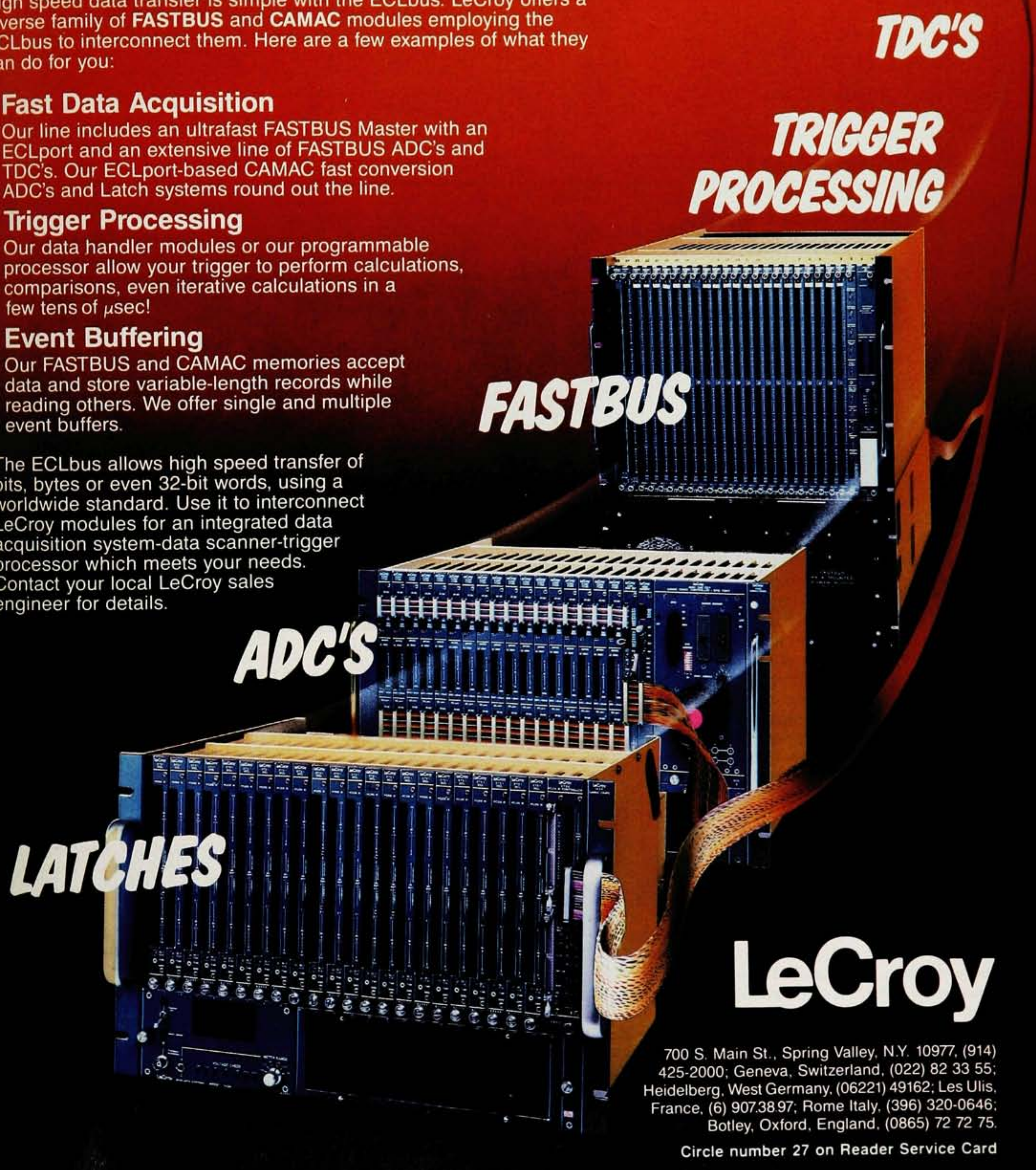

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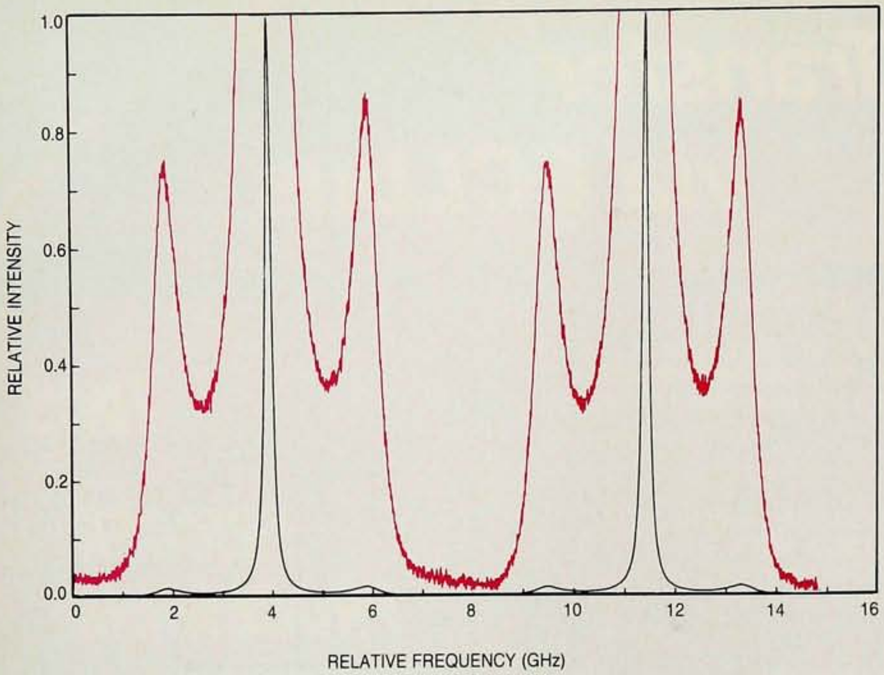

Fabry–Perot spectral scan of the output of a single-frequency GaAlAs diode laser at room temperature over a range of two free spectral scans. Sidebands separated by about 2 GHz are due to relaxation oscillations that are driven by the spontaneous emission noise in the device. An amplification of the trace by a factor 50 is shown in red. Figure 5

the fundamental linewidth can be reduced by several orders of magnitude. This follows immediately from equations 4 and 5. Increasing the cavity size without increasing the amount of active material increases the total optical intensity I (the total number of photons in the mode) while leaving the spontaneous emission rate R unchanged. Figure 1a shows an external-cavity laser structure together with a heterodyne-beat signal between two external-cavity GaAlAs diode lasers of a somewhat different design. For comparison, the output of a monolithic diode laser without such a cavity is shown in figure 1b. Linewidths for external-cavity diode lasers have been shown to be less than 15 kHz and governed by only the technical noise. These devices can be made very stable by the incorporation of active control techniques such as locking to stable passive cavities or to microwave standards[22] to reach sub-hertz stabilities. The cost of such lasers could be much lower than other laser sources, and experiments requiring multiple lasers could be carried out more readily. A semiconductor laser such as GaAlAs of a given alloy composition can be continuously tuned over a broad emission bandwidth of about 10 nm. Diode lasers of different materials and alloy compositions have operated in the range from 0.6 to 35 microns and are a useful source of high-resolution tunable radiation.

Ultra-stable diode lasers locked to narrow atomic transitions or radio-frequency standards could be useful sources as secondary frequency standards. A number of efforts are currently underway to improve microwave frequency standards by using GaAlAs diode lasers for optical pumping of cesium.[23]

Because of their small size, high efficiency and low cost, as well as the high spectral purity and stability they achieve, these semiconductor diode laser devices will find many applications in industry and research.

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