Cavity Controlled Semiconductor Lasers

Aram Mooradian, *Member, IEEE*

Invited Paper

I. Introduction

THIS paper is intended to describe some of the early history and more recent trends in the field of cavity-controlled semiconductor lasers and not intended as a comprehensive survey of the field.

The field of semiconductor lasers has progressed dramatically since the first demonstration of a semiconductor diode laser in the 1960s by the group at the General Electric Research Labs followed very closely by the group at the MIT Lincoln Laboratory and the IBM Research Laboratory. These early devices were pulsed and operated as simple p-n junction edge emitters. Many improvements in material technology and device design have made the semiconductor laser the most versatile and commercially useful of all lasers. In the mid 1970s, the concept of confining the injected carriers in a semiconductor heterostructure led to the first CW room temperature operation of GaAs-type devices. By the 1980s, advances in semiconductor material growth provided the ability to "engineer" structures of high-quality semiconductor materials including quantum wells and superlattice structures. The narrow quantum well gain regions were clad with lower optical loss regions into which the laser field extended thereby allowing operation at high efficiency and high-power levels at room temperature. This breakthrough eventually enabled power levels on the order of several watts of multimode power to be produced from devices that were about 100 μm in stripe width.

The general principles of device design and semiconductor properties were continually extended to different materials operating at other wavelengths from the visible/ultraviolet to the infrared. While various pumping schemes were employed including optical and electron beam, electrical current injection remained the dominant practical pumping scheme of choice. In the 1960s and 1970s, semiconductor lasers were extended to vertical cavity or surface-emitting configurations, first using optical pumping and then electrical pumping. This method of design accelerated as Bragg mirrors composed of semiconductor layers grown by MBE and MOCVD techniques were perfected in the 1980s and 1990s. Today, vertically emitting lasers have become a field by themselves, providing highly manufacturable, low-power devices for use in short-range data links and optical interconnect applications. More recently, high-power surface-emitting lasers are being developed with high brightness and properties associated with more conventional solid-state lasers. The marriage between semiconductor laser technology and conventional laser optical control technology using hybrid packaging and assembly techniques will produce a new class of devices with performance levels beyond present diode and conventional laser devices. This latter technology promises to provide a new range of operating characteristics for semiconductor lasers not possible before, thus enabling significant commercial applications. The evolution of this technology has spanned decades and many outstanding researchers have contributed in a seminal way to this field.

II. Early History

Diode lasers operated primarily in the pulsed mode except at cryogenic temperatures during the early years of research. These devices emitted highly multi-mode output beams due to the general lack of mode control. At low temperatures, CW devices could produce a single-frequency output just above threshold of 50–100 mW in a single frequency when a single spatial filament lased. However, multiple modes became predominant as the injection current was increased and power levels could exceed 1-W CW. Despite this multimode tendancy, these devices were used for an early demonstration of their potential utility in spectroscopic applications. Figs. 1 and 2 show an example of such spectroscopic demonstrations. Fig. 1 shows the Raman spectrum of single crystal selenium taken [1] using a CW GaAs diode laser operating at 10°K in a single frequency with a power level of about 50 mW.

Fig. 2 shows the Doppler-limited and pressure-broadened absorption spectra of water vapor This spectrum is representative of the first uses of tunable infrared diode lasers to perform very high-resolution spectroscopy. In this case, the change of injection current of the device produced a thermal tuning of the laser mode over a wavelength range sufficient to resolve several spectral lines of complex molecules. Tunable diode lasers provided a spectroscopic tool with resolution capability far beyond the best available spectrometers and in a relatively compact package. This technology has continued to be developed to the point where commercial laser spectral sensors can monitor low levels of trace species in the atmosphere. High-power diode lasers operating in the near infrared are now being used as efficient, compact, and tunable excitation sources for commercial Raman instrumentation.

The largest use of semiconductor lasers is in the area of telecommunications, optical discs, and laser printing. Telecom-

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The author is with Novalux, Inc., Sunnyvale, CA 94086 USA (e-mail: aram@novalux.com).
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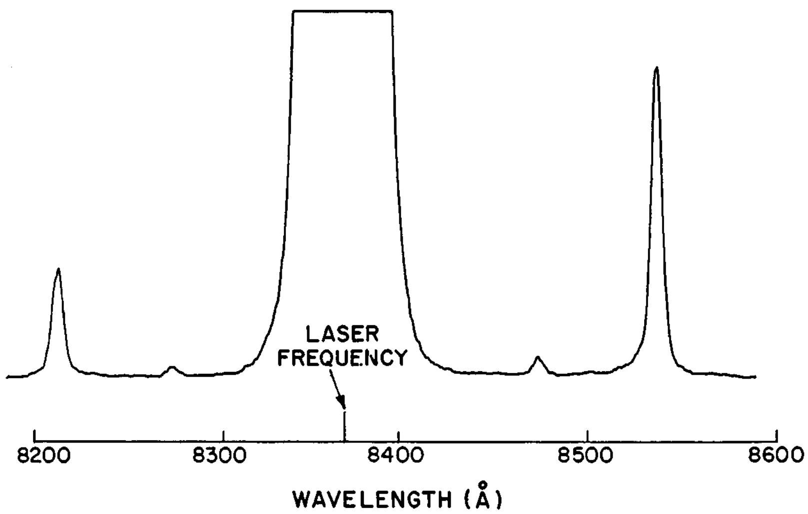


Fig. 1. Raman spectrum of trigonal selenium at room temperature taken using a single-frequency GaAs diode laser operating at 10 K at a wavelength of 837.2 nm. The strong peak around the laser wavelength is scattered spontaneous emission from the diode laser.

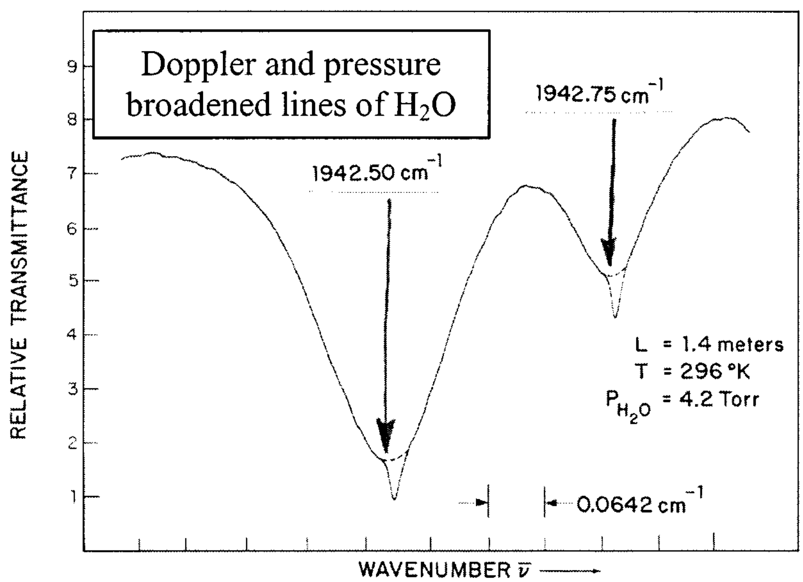


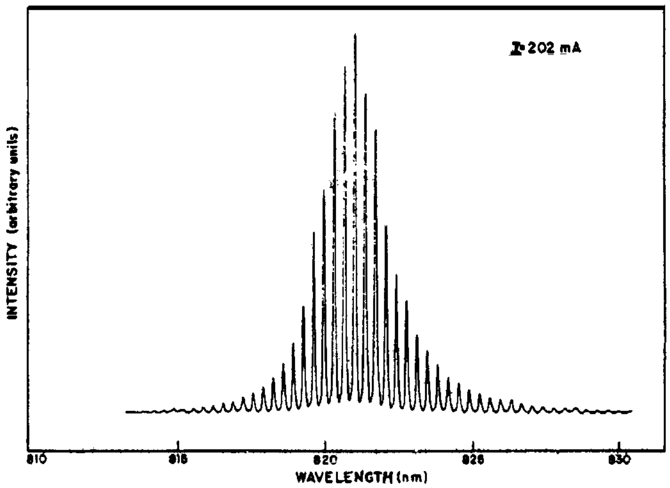
Fig. 2. Absorption spectrum of water vapor in the 5-μm wavelength region taken using a tunable lead salt diode laser using the current tuning of a single longitudinal mode of the device. An optical absorption cell containing low-pressure water vapor was placed in the optical path to overlay the Doppler absorption with the pressure-broadened spectrum. The pressure shift of the molecular transitions can be clearly seen. The spectral resolution of the diode laser was much better than 1 MHz and far greater than the best available Fourier transform instruments. Data taken by R. Eng at MIT Lincoln Laboratory.

munications applications of semiconductor lasers have placed especially stringent demands on the performance of diode lasers with requirements for high brightness and tunability that are a challenge for workers in the field.

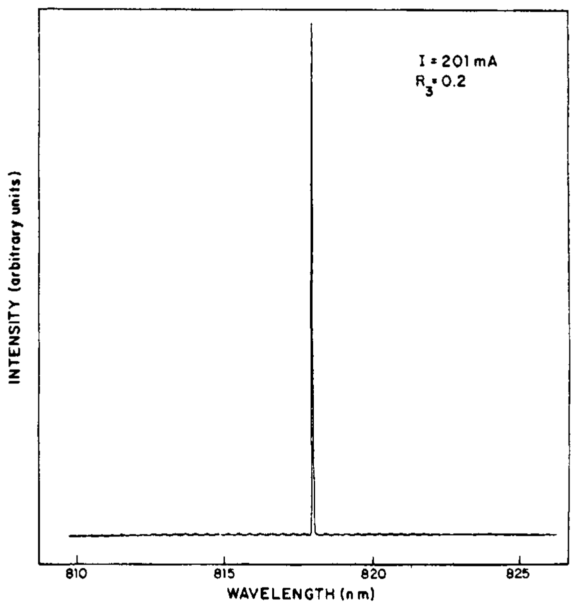
III. Modal Properties

Much of the early work on the spectral properties of semiconductor diode lasers was limited by the inability to control the spectral and spatial mode after the devices were fabricated. A further understanding of the operating physics of these devices was, in part, made possible by the use of external cavity control.

Many researchers studied various aspects of cavity-controlled diode lasers. In the late 1970s and early 1980s, a series of measurements were carried out on cavity controlled diode lasers. In one set of experiments [1], the spectral and spatial mode output of a number of diode lasers (more than 100) with 10–15-μm stripe widths were measured and showed output spectra that demonstrated highly multimode operation. These devices were subsequently antireflection coated on both facets and operated in a highly stabilized external cavity using a super Invar structure contained in a thermally controlled housing. Both a grating and a plane 100% mirror was used as one of the cavity mirrors. Without any intentional spectral mode selection using two plane mirrors for the cavity reflectors, nearly all of the devices produced up to 90% of the original double-ended multimode



(a)



(b)

Fig. 3. (a) Output spectrum of an edge-emitting stripe diode laser at room temperature showing operation in several longitudinal and spatial modes above threshold. The spatial mode frequencies can be just seen as spectrally resolved components of the longitudinal modes. (b) Output spectrum of the same diode laser above operating in an external cavity with a grating as one reflector. Both edges of the diode were antireflection coated. About 90% of the double-ended output of the monolithic diode exited from the output coupler when a 100% reflector was used in place of the grating. Similar single-frequency output was observed without any grating wavelength selecting element in the cavity indicating a predominant lack of spectral and longitudinal spatial hole burning.

output power in a linearly polarized, single longitudinal mode from the output coupler end of the cavity. The linear polarization was selected by the diode waveguide. Fig. 3 shows the before and after spectra for a representative device [2]. As this external cavity laser slowly drifted with time, a second longitudinal mode slowly appeared whose frequency was determined by the wavelength of the slight residual transmission peak associated with the Fabry–Perot resonance of the diode. Only one frequency, however, was operating at any time and power was partitioned between these two frequencies. With thermal control of the entire cavity structure, the device operated stably in one single frequency. These devices had sufficiently low-reflectivity coatings on both ends of the device (<0.2%/facet) so as to reduce the complicating effects of a laser cavity with mode than two mirrors. This result was an indication of the effective lack of spectral and longitudinal spatial hole burning in these devices. Thus, such diode lasers would only oscillate in a single frequency when the device was constrained to operate in a single spatial mode. It is interesting to note that many experiments that were carried out on external cavity controlled lasers showed the presence of a significant number of spectral modes in the output. Most of these experiments were carried out using optical mounts that were not completely stable and the mechanical vibrations due to ambient acoustic noise usually produced partition mode noise in the device. While only one mode would be oscillating at one time, most of the spectral measurements were taken using a relatively slow scanning technique and thereby averaged over the partition mode spectrum to show several frequencies oscillating despite the use of a very low noise power supply to drive the diode laser.

Subsequent work carried out at the Sony Research Laboratories demonstrated that when an edge-emitting GaAs/GaAlAs diode laser was fabricated with a stripe width of about 3 μm the laser operated in a fundamental transverse mode and the laser output occurred in a single frequency well above threshold, further demonstrating the lack of spectral and spatial hole burning. Wider stripe widths allowed the onset of additional spatial and therefore spectral modes. Such mode switching produced kinks in the light output versus current characteristics as well as modal noise.

Operation of such large stripe width devices in a fundamental spatial mode can produce a near Gaussian shaped beam across the width of the diode facet without the hot spots usually associated with high power, monolithic wide stripe diode lasers. These cavity-controlled devices could be driven to higher output power levels because of the lack of such hot spots and the presence of the antireflection coating before the onset of catastrophic degradation of the facet. External cavity devices could be tuned over their useful gain bandwidth by the use of a cavity-tuning element such as a grating. Tuning ranges of 10–100 nm have been demonstrated for devices operating in the near infrared and this technology has been successfully commercialized. The high optical gain associated with edge-emitting diode lasers requires that very low reflective coatings be used to prevent these lasers from oscillating on their own at the high drive current levels. Longer devices that produce higher output power have such high gain that a residual, single-ended reflectivity of better than 0.1% is usually required to prevent the devices from oscillating by themselves and to provide broad tuning ranges without significant effects of residual facet reflectivity. The complex nature of the facet modal index provides a challenge to achieving the required reflectivity. One particularly useful scheme to achieve such a high-quality coating that is used by a number of workers is to monitor the derivative of the current voltage curve of the device during the coating process to observe the increase of threshold current and follow it as the device cools in the coating chamber to calibrate where the coating process should be stopped.

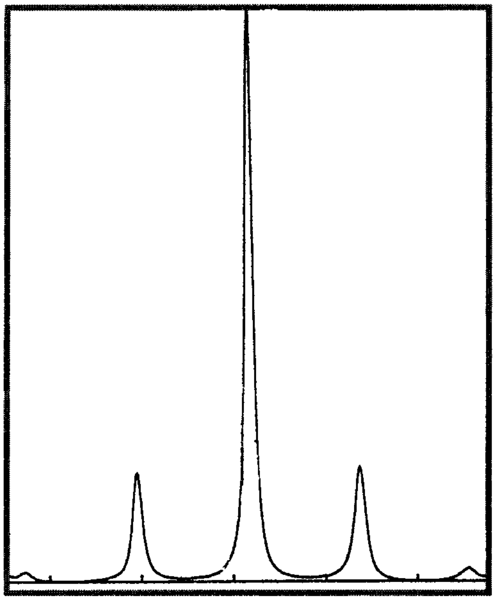


Fig. 4. Scanning Fabry–Perot trace of the output from a single-frequency GaAlAs diode laser operating at room temperature is shown on a linear scale. Two upper and lower relaxation–oscillation sidebands can be seen separated by about 2 and 4 GHz from the main line, respectively, that arise from damped relaxation oscillations of the laser field intensity driven by spontaneous emission noise. These sidebands intensities are inversely proportional to the power in the central laser line as expected from theory.

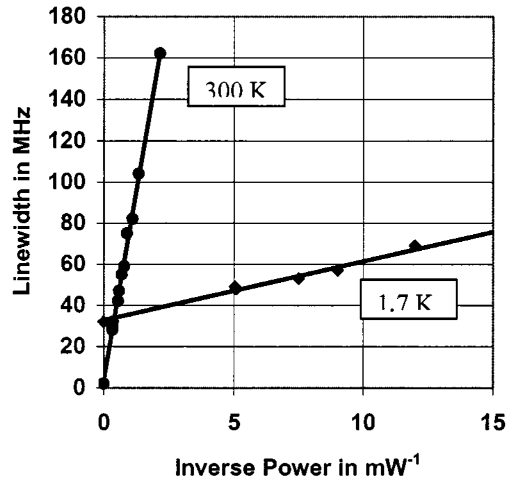


Fig. 5. Shows measurement of the linewidth (full width at half maximum) of a single-frequency GaAlAs diode laser as a function of inverse power taken at 300 and 1.7 K. The zero crossing was determined from a linear fit and is 1.9 MHz at 300 K and 35 MHz at 1.7 K. Data for the same device that is not shown has zero intercepts of 5.2 MHz at 195 K and 8.4 MHz at 77 K, respectively, with decreasing values of slope.

IV. Spectral Linewidth

As diode laser technology advanced to the point where monolithic and external cavity devices could be made to operate in a single longitudinal mode, the issue of spectral lineshape was further investigated. The spectrum of a single-frequency edge-emitting GaAlAs diode laser operating around 800 nm is shown in Fig. 4. The data was taken using a high-resolution scanning Fabry–Perot interferometer and shows a Lorentzian linewidth of many tens of megahertz together with upper and lower side-band peaks (as many as three such side-band peaks have been observed) shifted from the center peak by relaxation frequency of the device. The linewidth of such lasers has been the subject of extensive study by many workers and it was determined quite early that the spectral linewidth was significantly greater than what was predicted by the conventional Schawlow–Townes theory.

Fig. 5 shows the inverse power dependence of diode laser linewidth at room temperature and superfluid helium temperature. This data is representative of many linewidth measurements carried out for GaAlAs devices operating near 800 nm that were fabricated in somewhat different ways. Measurements of a large number of lasers showed consistently linear dependence of linewidth on inverse power when the lasers continued to operate in a single fundamental longitudinal mode. When devices did begin to operate in more than one mode or spatial filaments at higher power levels, the linewidths increased significantly and was believed due to additional partition mode noise in these imperfect devices.

Fig. 6 shows a diagram of the laser field intensity and phase together with many spontaneous emission events that alter the amplitude and phase. Each spontaneous emission event with its random phase causes a change in amplitude and phase of the laser field that subsequently undergoes a random walk around the circumference of the average field intensity. The time rate of change in phase results in the spectral linewidth. In addition, the change in laser amplitude is restored to its average value by undergoing damped relaxation oscillations for each random event. This results in generation of the spectral sidebands shown in Fig. 4. Measurement of the sideband frequency shift and amplitude relative to the laser power clearly showed the expected square root dependence of the cavity relaxation frequency as well as the sideband intensity with laser power. As the gain or population density becomes clamped above threshold, the number of spontaneous emission events per unit time becomes fixed while the field amplitude continues to increase. From simple geometry, the linewidth can be intuitively seen to be inversely dependent upon power. An additional contribution to the linewidth that is independent of power is due to Raman scattering from free carriers in the gain region. This effect would only become significant at high-power levels, but is likely overcome by the power independent linewidth due to carrier density fluctuations described below. The measurement of linewidth in single-frequency diode lasers clearly showed that linewidth did not follow the simple Schawlow–Townes theory.

The excess linewidth over the linewidth predicted by the Schawlow–Townes theory was explained by C. H. Henry [3] in terms of an additional, delayed change in phase associated with the change in laser field intensity. There are numerous references that describe the derivation of the Schawlow–Townes phase noise laser linewidth. The additional line broadening due to a delayed phase change of the laser field produces a linewidth for a semiconductor laser given by

$$\boldsymbol{\Delta\nu} = \boldsymbol{\Delta\nu}_{ST}(1+\boldsymbol{\alpha}^2) \tag{1}$$

where $\boldsymbol{\Delta\nu}_{ST}$ is the original Schawlow–Townes linewidth and α is the so-called linewidth enhancement factor which is the ratio of the change in refractive index to the change in gain for

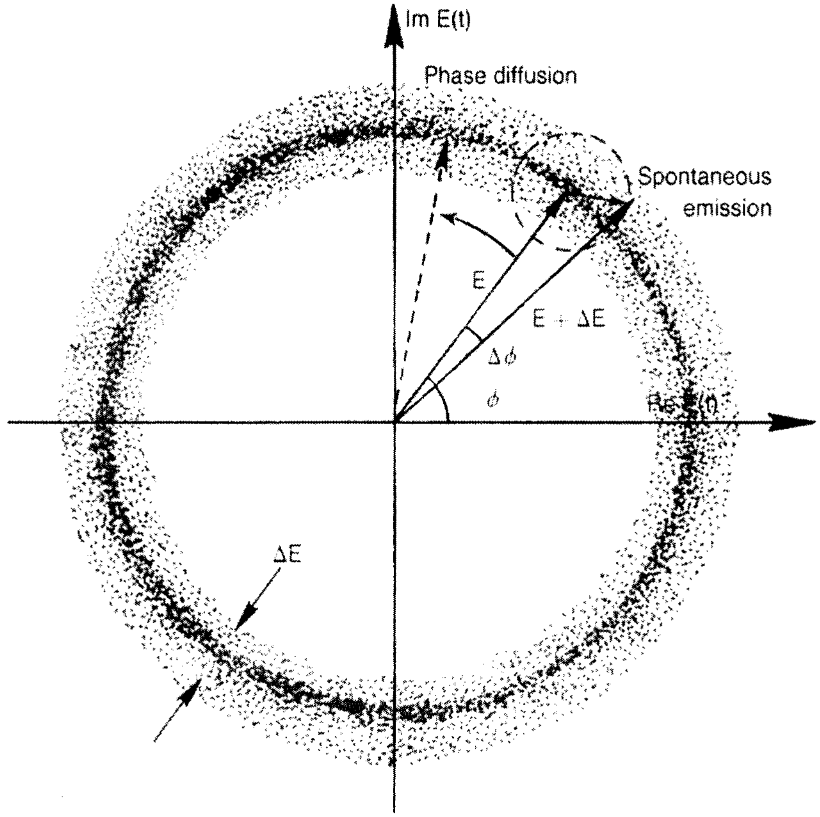


Fig. 6. Phasor diagram of the laser field intensity and phase angle. Each dot on the circle represents a position of the laser field amplitude and phase as altered by a spontaneous emission event. The phase of the laser field undergoes a random walk around the circumference of the circle while the field amplitude is restored to a clamped valued by undergoing damped relaxation oscillations. These damped relaxation oscillations produce sidebands on the main laser intensity as seen in Fig. 4.

a given change in carrier density. This enhancement factor can vary in various semiconductor laser devices from just over one to almost ten, depending on temperature, material system, and wavelength. In addition to the power dependent linewidth, several workers have observed a power independent component to the linewidth that is described below.

The linewidth dependence on power shown in Fig. 5 at various temperatures [4] for a GaAlAs laser clearly shows a power independent component that increases at lower temperature to become the dominant effect at 1.7 K. This power independent component of the linewidth has been attributed to a change in the refractive index of the loaded laser cavity due to carrier density fluctuations [5]. A phenomenological model describing this spectral contribution to the laser linewidth has shown good agreement as a function of laser threshold with temperature. The dominant power independent line broadening is determined by this effect at 1.7 K, where the threshold current levels are as much as 100 times less than what they were at room temperature for the same device. Consistent results depended upon devices that did not freeze out carriers at low temperature and that maintained their output in a stable single mode at all power levels. Monolithic diode lasers with variations in the fabrication or with defects could produce inconsistent results, however, significant numbers of high-quality devices were used to provide repeatable results. Low-noise power supplies were required to measure these lineshapes to avoid contributing to the laser frequency jitter. It would be interesting to consider the linewidth

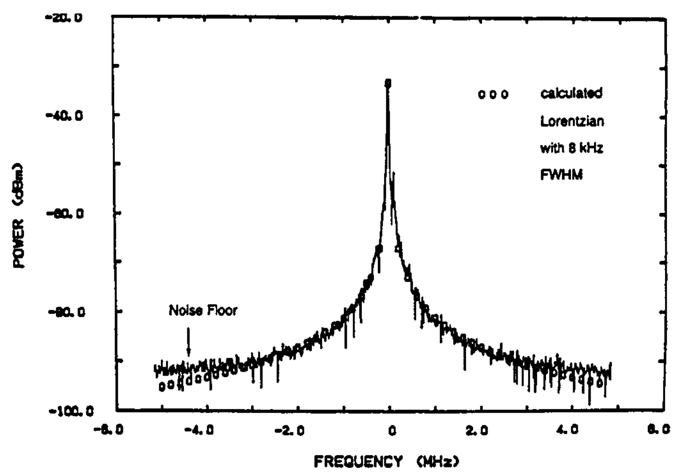


Fig. 7. Heterodyne spectrum of two free-running GaAlAs external cavity diode lasers, each operating at about 10-mW CW. The fast scan on a decibel scale allows a fit to a Lorentzian lineshape to determine a single device linewidth of 8 kHz.

characteristics of very small volume quantum wire or dot lasers at very low temperatures where there are much fewer carriers in the gain region above threshold.

When these edge-emitting diode lasers were operated in an external cavity, a significant reduction in the laser linewidth was observed. Fig. 7 shows a heterodyne beat spectrum taken between two free-running, stable, external cavity GaAlAs diode

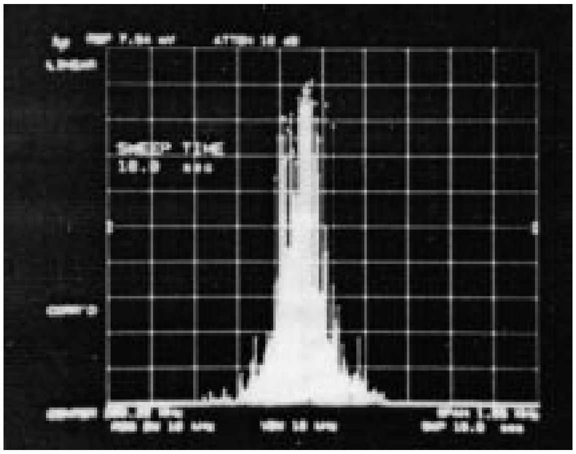


Fig. 8. Heterodyne beat spectrum between two free-running external cavity GaAlAs diode lasers of Fig. 7. Scale is 100 kHz/division with a 10-kHz resolution bandwidth and a 10-s scan. The Gaussian envelope of the beat spectrum is indicative of the "technical" noise. The average jitter bandwidth for each laser is about 50 kHz/s. In addition to the short-term jitter, there is a long-term drift between the two devices not seen in this trace.

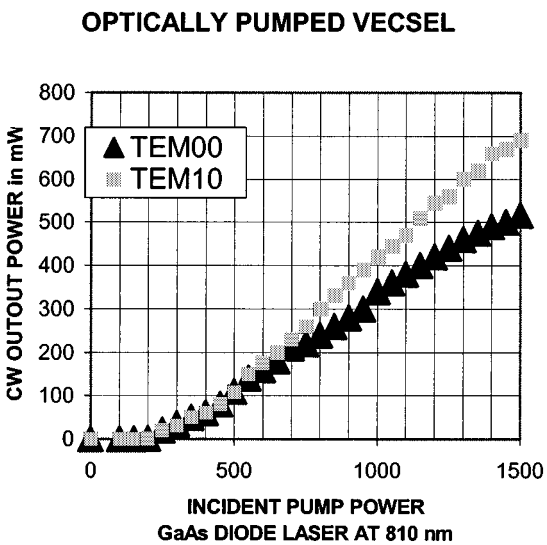


Fig. 9. Laser output power from a vertical external cavity GaInAs semiconductor laser as a function of incident pump power. A CW GaAlAs diode laser operating at 810 nm was used as the excitation source. Data is from [9].

lasers operating near 800 nm with a power of about 10-mW CW each. Fitting the of the beat spectrum gave a single-laser linewidth of less than 1 kHz. Fig. 8 shows the beat spectrum of the same two lasers taken on a linear scale. The measurement time was one minute, which was long enough to show the Gaussian envelope of the "technical noise" contribution to the spectral shape. This short-term technical noise was due primarily to ambient acoustic fluctuations while a longer term relative drift noise component was due to slow temperature and power supply drift. Further increases in the spectral stability or reduction of the laser linewidth require active feedback control to a reference such as a Lamb dip absorption line, a super cavity, or a stable secondary reference source. With present high-power semiconductor laser sources, it is possible to achieve a linewidth of less than 1 Hz. The effects of kT thermal fluctuations in the resonator structure have to be taken into account for high-power external cavity lasers when the fundamental linewidth is less than a few tens of hertz. All of these results are for a predominantly two-mirror cavity. When there is some significant degree of residual reflectivity of facets or compound resonators, more complicated phase relationships occur that under certain conditions can lead to less stable operating conditions [6]. In particular, the multiple phase relationships can cause modal instability that can be driven by all of the noise sources described above.

V. Surface-Emitting Lasers

In the 1960s and 1970s, work was carried out using laser [7] and electron beam pumping of semiconductor laser platelets. These were the first experiments on surface-emitting lasers. Later, electrically pumped operation of a surface-emitting laser was demonstrated [8]. Today, vertical-cavity surface-emitting lasers (VCSELs) have become a maturing technology that has been successfully commercialized. Until recently, VCSELs have been relatively low-power devices, operating with a few milliwatts of single-mode output and tens of milliwatts of multimode output. Early work on cavity-controlled surface-emitting lasers was carried out on optically pumped devices operating at cryogenic temperatures [9]. More recent work has been carried out [10] on high-power diode-pumped vertical external cavity semiconductor lasers with more than 500-mW CW being produced in the fundamental TEM_{00} mode. Fig. 9 shows the output from this optically pumped device. A fundamental difference between such a cavity-controlled device and an edge-emitting laser is that the edge-emitting diode laser beam is contained in a waveguide while the above device has a freely propagating Gaussian mode much like conventional solid state or gas lasers. In contrast to edge emitter, for example, the beam in the laser cavity can have a nearly flat wavefront that would allow efficient frequency conversion. The relatively large emitting areas as compared to edge-emitting diode lasers for similar output power levels have about two orders of magnitude less laser field intensity incident on the surface of the device.

The linewidth characteristics of surface-emitting semiconductor lasers (VCSELs) have also been studied [11] by several workers. Monolithic devices exhibited inverse power linewidth slopes of about 305 kHz·mW that indicates a linewidth enhancement factor, α, of about 1.7 that is significantly lower that other devices. Interestingly enough, there is also observed a residual linewidth of 2.6 MHz that may be due to the same carrier density fluctuations described for edge emitters. The very small gain volumes in these devices would provide only a few times 10^5 electrons at threshold. Low-temperature measurements would provide further insight into this effect.

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Aram Mooradian (M'99), photograph and biography not available at the time of publication.