# Laser Development at Lincoln Laboratory

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**Since the early 1960s Lincoln Laboratory has been a major contributor to the science and technology of lasers. Key accomplishments include semiconductor lasers for fiber communications and spectroscopy, wavelength-tunable ionic solid state lasers, and techniques for achieving spectral purity and frequency stability in semiconductor lasers as well as gas lasers. Coupled to this work on laser technology have been numerous fundamental studies in quantum electronics and materials on the one hand and applications in communications and radar on the other.**

Laser research at Lincoln Laboratory began in 1962, soon after the invention of the laser, and has continued to be a major component of several programs for nearly three decades. The initial work was on semiconductor lasers, and a strong effort has continued in that area, with the use of various materials to develop lasers spanning a broad wavelength range from 0.3 $\mu$m in the ultraviolet to 30 $\mu$m in the infrared. The numerous applications of these lasers have included spectroscopy, pollution monitoring, radars, and communications. A particularly important contribution was made in the area of fiber communications with the development of quaternary InGaAsP diode lasers for the low-fiber-loss wavelength range of 1.3 to 1.5 $\mu$m. Through publications, direct contacts, and spin-offs, much of this technology has found its way into the commercial arena. Taking advantage of the technologies developed in Lincoln Laboratory's Solid State Division, laboratory staff formed Laser Analytics (now part of Laser Photonics) in 1974 for the commercialization of spectroscopic and pollution-monitoring devices, and established Lasertron in 1980 for the manufacturing of fiber-communications components.

In addition to research on semiconductor lasers, Lincoln Laboratory undertook work on ionic solid state lasers in the 1970s with an emphasis on the development of broadly wavelength-tunable sources. A highlight of this work was the invention and development of the titanium sapphire ($Ti:Al_2O_3$) laser. Tunable from 0.65 to 1.12 $\mu$m, $Ti:Al_2O_3$ lasers are very versatile devices whose applications range from agile-beam laser radars to laser medicine. $Ti:Al_2O_3$ lasers are now manufactured by a number of organizations, including Schwartz Electro-Optics, where ex–Lincoln Laboratory staff played a key role in the lasers' commercialization. Closely linked to the solid-state-laser research has been the use of nonlinear optical materials for frequency mixing or doubling to produce sources at new wavelengths.

In the area of gas lasers, research that began in 1963 focused on achieving a new level of frequency stability with applications in coherent laser radar and high-precision spectroscopy. These ultrastable devices enabled the demonstration of $CO_2$ laser radars at the Firepond site in Westford, Mass., starting in the late 1960s. For the submillimeter portion of the spectrum, gas lasers that provided a large number of wavelengths in the range from 58 to 755 $\mu$m were developed for use in spectroscopy and as sources for testing submillimeter-wavelength detectors.

Besides developing laser technology, Lincoln Laboratory has made important contributions to laser physics and to the science of laser materials. Fundamental studies were carried out on the band structure of semiconductor laser materials, nonlinear optics, light-scattering phenomena, and high-resolution spectroscopy of gas molecules. In the materials area, the development of semiconductor epitaxial growth techniques and the growth and study of ionic solid state crystals provided the technology base for advances in laser technology. Indeed, the numerous scientific and technological

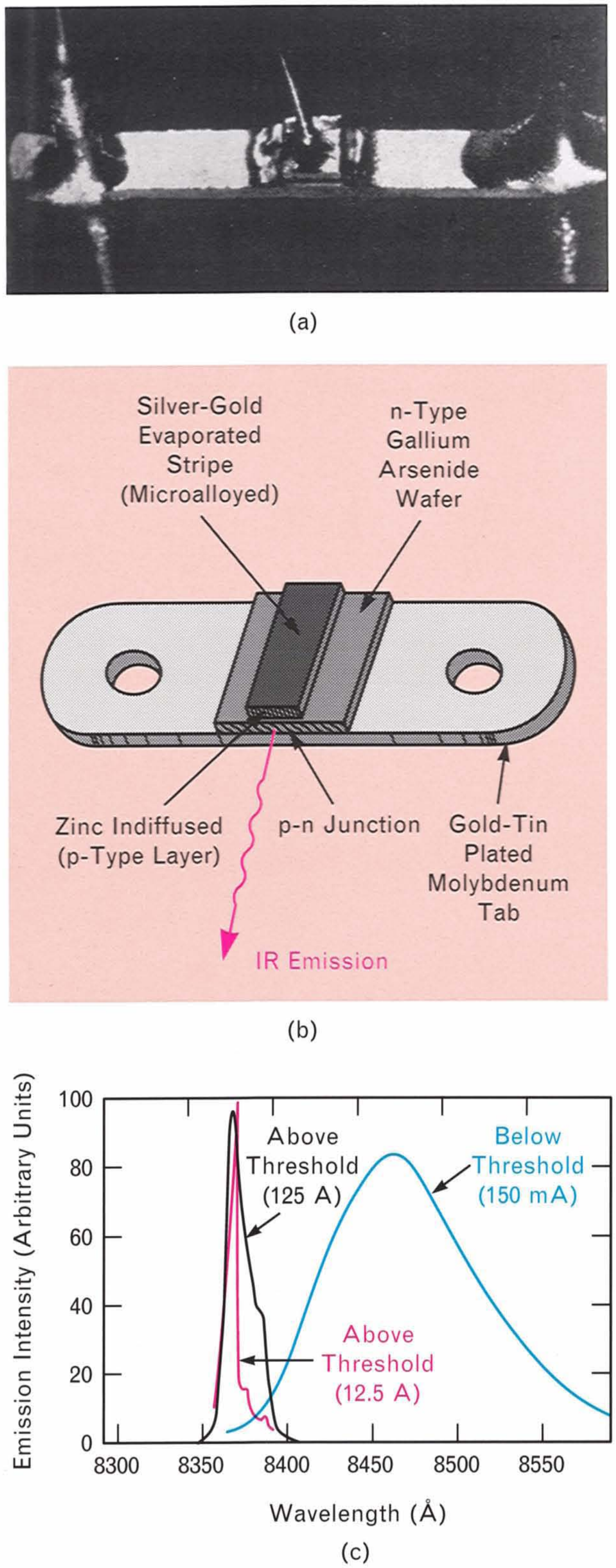



**FIGURE 1.** One of the first GaAs diode lasers fabricated at Lincoln Laboratory: (a) photograph, (b) schematic representation, and (c) spectra of emission below and above the laser threshold at 4.2 K. (Note: The laser also operated at 77 K.)

achievements have resulted from a close collaboration of physicists, materials scientists, and device engineers.

Additional details on Lincoln Laboratory's development of lasers and their applications appear in two earlier review articles [1, 2].

## Semiconductor Lasers

Soon after demonstration of the first laser at Hughes Research Laboratory in 1961 with lamp-pumped ruby [3], a number of researchers began to speculate about the possibility of laser emission in other media, including semiconductors. Because of its leading role in semiconductor research, Lincoln Laboratory was in a good position to investigate such materials as potential laser sources.

Early in 1962 researchers in the Solid State Division observed very high efficiencies (quantum efficiencies of 85%) in the spontaneous emission from GaAs diodes at 0.84 $\mu$m [4]. This observation set the stage for laser development that several organizations undertook, including Lincoln Laboratory. In the fall of 1962 diode lasers were demonstrated independently at General Electric [5, 6], IBM [7], and Lincoln Laboratory [8]. Figure 1 contains a photograph, a schematic diagram, and spectra of one of the first GaAs diode lasers. At the same time, researchers at Lincoln Laboratory also developed a theoretical semiconductor-laser model that identified some of the unique characteristics of these devices [9].

In the following years, work in the Solid State Division concentrated on developing lasers in other semiconductor materials to cover different parts of the wavelength spectrum. Although the motivation for this work during the early stage was primarily scientific, lasers fabricated from the different materials subsequently formed the basis for numerous applications, in such areas as spectroscopy and fiber communications. Several milestones are worth noting. Laser emission was observed at 3.1 $\mu$m in InAs diodes in 1963 [10] and later in other III-V compounds: the ternary InGaAs at 1.8 and 2.1 $\mu$m [11], and InSb at 5.1 $\mu$m [12]. In 1964, lasers were also fabricated in the IV-VI lead salts: PbTe at 6.4 $\mu$m [13] and PbSe at 8.3 $\mu$m [14].

In all of the initial diode lasers the current was injected in a direction normal to light emission. Later, a longitudinal pumping configuration was realized in InSb [15] by using the structure shown in Figure 2. Such a struc-

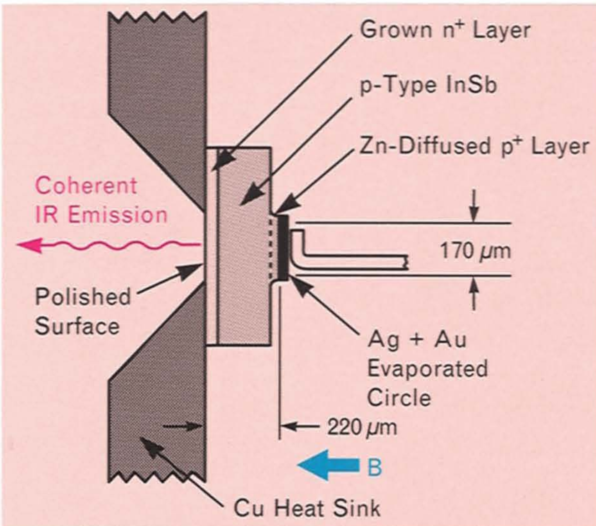



**FIGURE 2.** InSb diode laser with cavity designed for emission parallel to the injection current.

ture has several advantages, in particular a smaller beam divergence. The difficulty in fabricating high-performance devices of this type, however, prevented their development in other materials until the 1980s, when researchers first in Japan and later in the United States made significant progress in this area. As a result, the advanced fabrication techniques now available have enabled the production of good-performance arrays of longitudinally pumped lasers in GaAs and in InGaAsP. Arrays of this type are of particular interest for optical signal processing and optical interconnects.

During the late 1960s the semiconductor laser work at Lincoln Laboratory included the wavelength tuning of diode lasers by means of applied pressure and optical as well as electron-beam pumping. In a collaborative effort between Harvard University [16] and Lincoln Laboratory, the application of hydrostatic pressure to PbSe lasers tuned their emission from 8 to 22 $\mu$m (Figure 3). Electron-beam pumping was of special interest because it enabled extension to wavelengths into the visible and UV spectra through the use of wide-energy-gap semiconductors for which p-n junctions could not be produced. Thus laser emission was obtained for the first time in CdSSe, which covers the range from 490 to 690 nm as the ratio of S to Se is changed [17], and high efficiencies as well as high powers were obtained in CdS at 490 nm (26% power efficiency, 350 W peak) [18] and ZnS at 330 nm (6.5%, 1.7 W) [19]. Optical pumping with a GaAs diode laser source proved useful for semiconductors that emitted in the infrared (>1 $\mu$m) range, e.g., HgCdTe in which emission was observed near 4 $\mu$m [20]. Later, in the 1970s in a collaborative effort between Lincoln Laboratory and MIT, HgCdTe lasers were also demonstrated at shorter wavelengths (1.2 to 2 $\mu$m) through optical pumping with Nd:YAG lasers at 1.06 $\mu$m [21].

Increased research in the development of lead-salt lasers commenced in the late 1960s after the discovery that in the ternary alloys PbSnTe and PbSnSe the energy gap decreases with increasing Sn content, reaches zero at a certain composition, and then increases because the energy bands cross [22], as shown in Figure 4 for PbSnSe. This effect allows coverage of a broad wavelength spectrum from 6.4 $\mu$m in PbTe and 8.3 $\mu$m in PbSe to greater than 30 $\mu$m in both materials.

Clear evidence of the band crossing was provided by the magnetic field dependence of laser emission in $Pb_{1-x}Sn_xSe$ diodes (Figures 5[a] and [b]) [23]. As indicated in the insets of Figures 5(a) and (b), conduction- and valence-band energy levels in a magnetic field are quantized into magnetic levels, called Landau levels. Consistent with the band-crossing model, the energy of the lowest Landau-level transition increases on one side of the transition (for $x < 0.15$) and decreases on the other

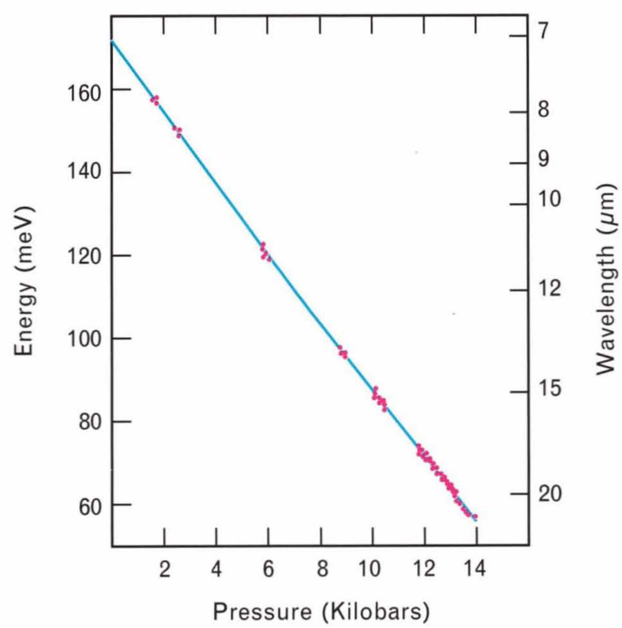



**FIGURE 3.** Wavelength tuning of a PbSe diode laser operated at 77 K by means of hydrostatic pressure.

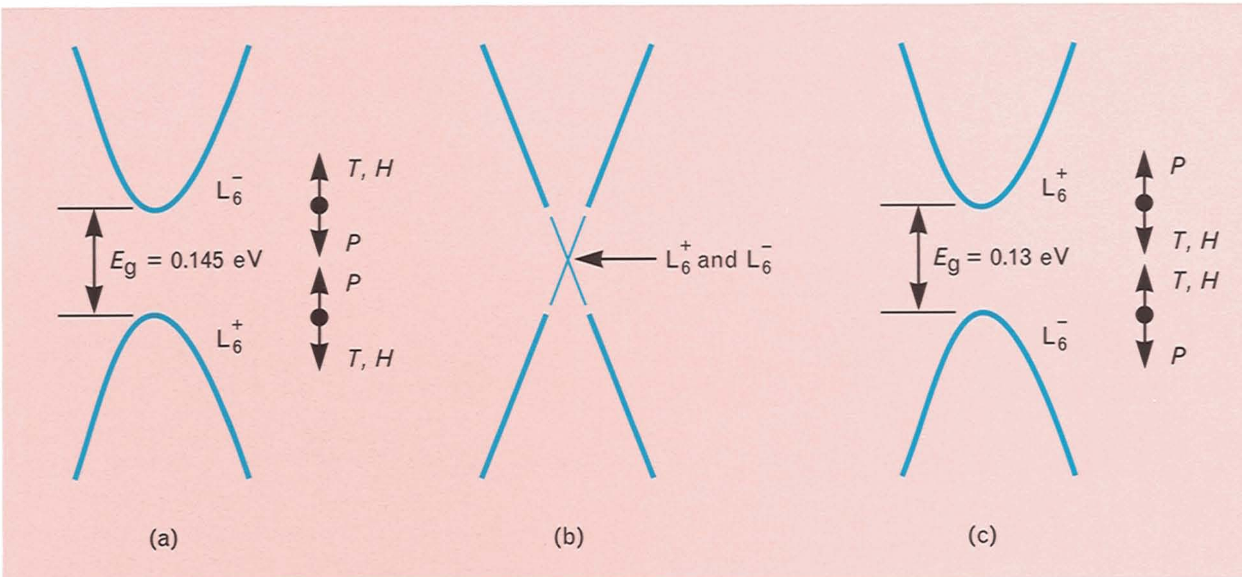



**FIGURE 4.** Schematic representation of the valence and conduction bands at 12 K for (a) PbSe, (b) $Pb_{0.85}Sn_{0.15}Se$, the composition at which the energy gap $E_g$ is approximately equal to zero, and (c) $Pb_{0.7}Sn_{0.3}Se$. The effects of applying pressure $P$ and magnetic field $H$, and increasing temperature $T$ are indicated.

side (for $x > 0.15$). In PbSnTe diodes, emission was observed at wavelengths as long as 31.2 $\mu$m. During the 1970s considerably more sophistication was introduced in lead-salt lasers through the use of double heterostructures to increase the temperature of operation [24] and distributed feedback to achieve single-frequency operation [25].

Also in the late 1960s, heterodyne measurements made with 10.5-$\mu$m lead-salt lasers showed that their linewidths are determined by phase fluctuations that are due to the spontaneous emission of photons [26]. Linewidths as narrow as 54 kHz were observed (Figure 6). These results were the first experimental verification of the theory of quantum-phase noise of A.L. Schawlow and C.H. Townes [27]. The narrow linewidths, the ability to produce devices at any required wavelength to match molecular absorption lines, and the capability of short-range tuning through variation of the injection current opened up semiconductor-laser applications in high-resolution spectroscopy and air-pollution monitoring. These applications provided the impetus for the creation in 1974 of the first spin-off in the laser area—Laser Analytics. This initial work on lead-salt alloy materials also led to their exploration as infrared detectors, with emphasis on wavelengths in the 8-to-12-$\mu$m atmospheric window [28].

Perhaps the most visible accomplishment of Lincoln Laboratory's laser effort is in the area of laser sources for fiber telecommunications. In the early 1970s the advent of low-loss optical fibers prompted numerous laboratories to search for appropriate semiconductor lasers to use as transmitters. For silica fibers the wavelength range of 1.3 to 1.6 $\mu$m was of special interest because both minimum absorption losses and minimum frequency dispersion occur in this range.

A number of ternary III-V semiconductor alloy systems including InGaAs [29] and GaAsSb [30] had been investigated elsewhere, but researchers could not develop high-performance, long-lifetime lasers of those materials. The lack of success was attributed to a mismatch in the crystal lattice spacing between the active region of the laser and the substrate material on which the laser structure was epitaxially grown. Such a mismatch produced a high density of defects that inhibited efficient laser operation and led to rapid degradation.

Figure 7 is a plot of energy gap (wavelength) as a function of lattice constant for selected III-V compounds. In the figure, lines that connect the binary compounds represent ternary alloys (e.g., AlGaAs), and areas bounded by the lines represent quaternaries (e.g., InGaAsP, which is shown shaded). The good lattice match of the ternary alloy AlGaAs to GaAs, which is used as a substrate, is recognized as the reason for the successful development of diode lasers in this system in the wavelength range of

0.68 to 0.86 $\mu$m. Unfortunately, no ternary lattice-matched system exists for the wavelength region from 1.3 to 1.6 $\mu$m. However, as shown in Figure 7, the additional degree of freedom introduced by adding a fourth element permits lattice matching of the quaternary InGaAsP to InP over the wavelength range of 0.92 to 1.7 $\mu$m.

From their previous work on avalanche photodiodes [31] in the early 1970s, researchers at Lincoln Laboratory were aware of the defect problems in the mismatched

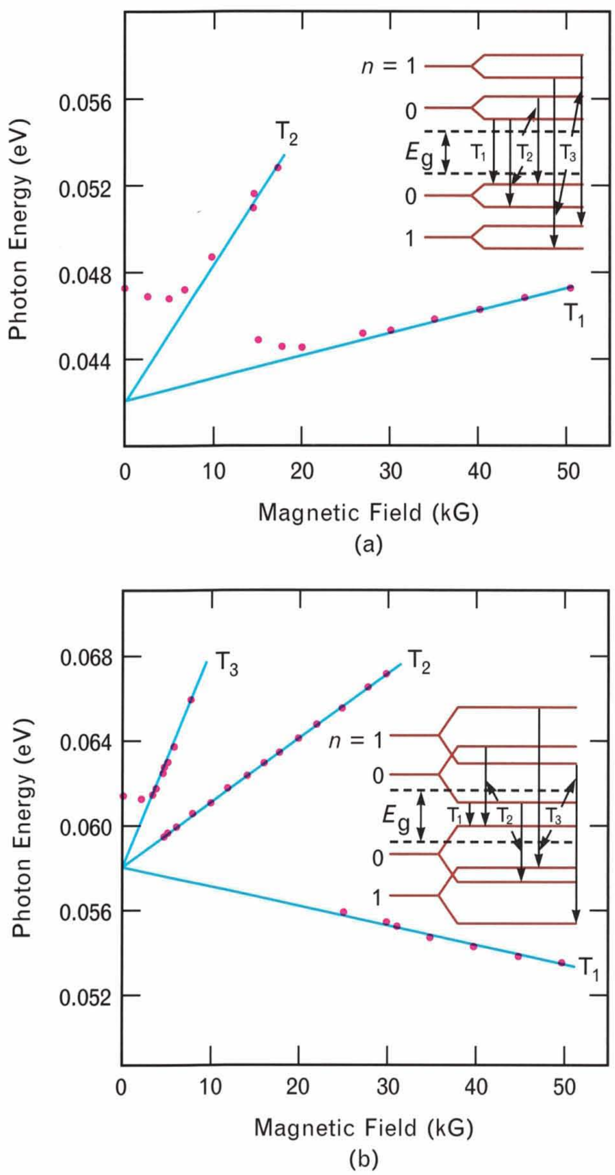



**FIGURE 5.** Magnetic field dependence of laser emission in $Pb_{1-x}Sn_xSe$ for (a) $x$ = 0.10 and (b) $x$ = 0.22. The figures show the reversal of slope for the lowest Landau-level transition ($T_1$) due to the band crossing.

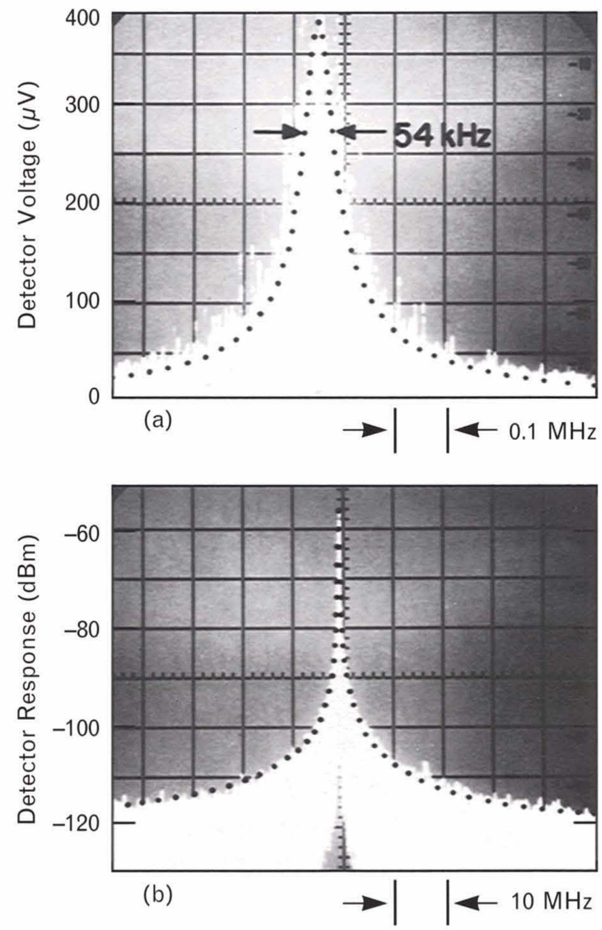



**FIGURE 6.** Spectrum-analyzer display of beat note between a 240-$\mu$W single-frequency $Pb_{0.88}Sn_{0.12}Te$ diode laser (well above threshold) and the P(14) transition of a $CO_2$ gas laser. The IF bandwidth is 10 kHz. Sweep rates and exposure times are respectively (a) 0.2 sec/division and 2 sec, and (b) 0.002 sec/division and 0.5 sec.

InGaAs/GaAs system. Partly on the basis of this experience, the InGaAsP/InP system was chosen for 1.3-to-1.6-$\mu$m lasers and detectors. Earlier work on InGaAsP photoemission devices [32] and diode lasers operating at 77 K [33] supported the choice. In the mid-1970s Lincoln Laboratory researchers, using InGaAsP/InP, quickly demonstrated CW operation at room temperature [34] and several-thousand-hour lifetimes [35]. The system was almost immediately adopted by laboratories in Japan and later in the United States. Today InGaAsP/InP is the main system used for transmitter sources and detectors in fiber communications.

During the late 1970s and the 1980s numerous contributions were made in laying the foundation for the materials and device technology of the InGaAsP

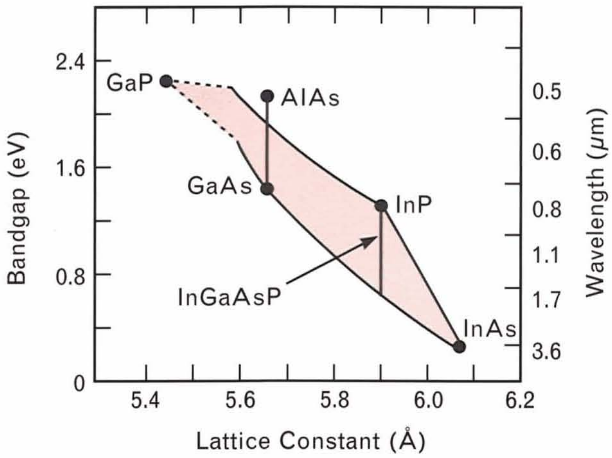



**FIGURE 7.** Energy gap and wavelength as a function of lattice constant for selected III-V compounds and the corresponding ternary and quaternary systems at 300 K. Note the good lattice match between AlGaAs and GaAs, and between InGaAsP and InP.

system. Detailed studies were performed of the conditions for lattice matching in the liquid-phase epitaxial growth of InGaAsP on InP substrates [36] and, more recently, a mass-transport technique [37] was developed for the fabrication of buried-heterostructure lasers and laser arrays. To take advantage of the growing need for fiber-communications transmitters and receivers, Lincoln Laboratory staff founded Lasertron in 1980.

Without special cavity designs, semiconductor lasers generally operate in multiple spectral and spatial modes; because of a low-$Q$ cavity, the linewidth of semiconductor lasers is broad compared to that of gas lasers. Following earlier outside work in the use of external cavities [38], researchers at Lincoln Laboratory demonstrated in the early 1970s that single-mode narrow linewidths and wavelength tuning at high power levels could be obtained by introducing a grating in the external cavity [39]. More recently, very stable external resonators have been used with both AlGaAs and InGaAsP diode lasers, and linewidths as small as 5 kHz have been achieved [40, 41]. A stability better than 15 Hz was observed [41] (Figure 8) by phase-locking two external-cavity lasers.

Progress in epitaxial growth techniques and the use of quantum-well active regions—thin (~100 Å thick) layers sandwiched between other layers of materials with wider energy gaps and smaller indexes of refraction—have in recent years produced dramatic improvements in the performance of diode lasers. Current thresholds as low as 50 A/cm$^2$ and power efficiencies exceeding 50% are now commonplace for AlGaAs lasers. Because each diode laser element can produce only a limited amount of power, arrays of lasers are needed for high-power applications, such as laser radars. Consequently, a major portion of the diode laser research at Lincoln Laboratory since the 1980s has been devoted to the development of arrays. To date, these arrays have been used primarily as pump sources for solid state lasers [42].

A remaining major challenge in the diode laser field is the achievement of coherence among elements of large (≥1 cm$^2$) high-power multielement arrays. Such coherent combining could produce near-diffraction-limited beams at high (≥100 W) power levels and thereby greatly expand the scope of both military and civilian applications of lasers. Research at Lincoln Laboratory that could help realize this goal includes the development of monolithic diode laser arrays in which individual elements are fabricated on a wafer by lithography and etching. Arrays of this kind are candidates for establishing coherence when they are used in external-cavity configurations in conjunction with matched

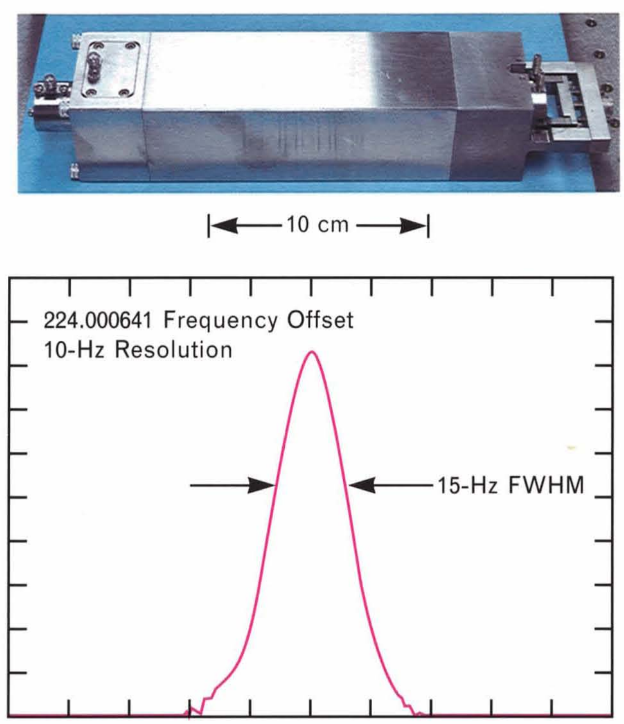



**FIGURE 8.** (top) Exterior view of external-cavity GaAlAs diode laser and (bottom) heterodyne spectrum of two phase-locked external-cavity GaAlAs diode lasers. The horizontal scale is 10 Hz/division and the vertical scale is linear.

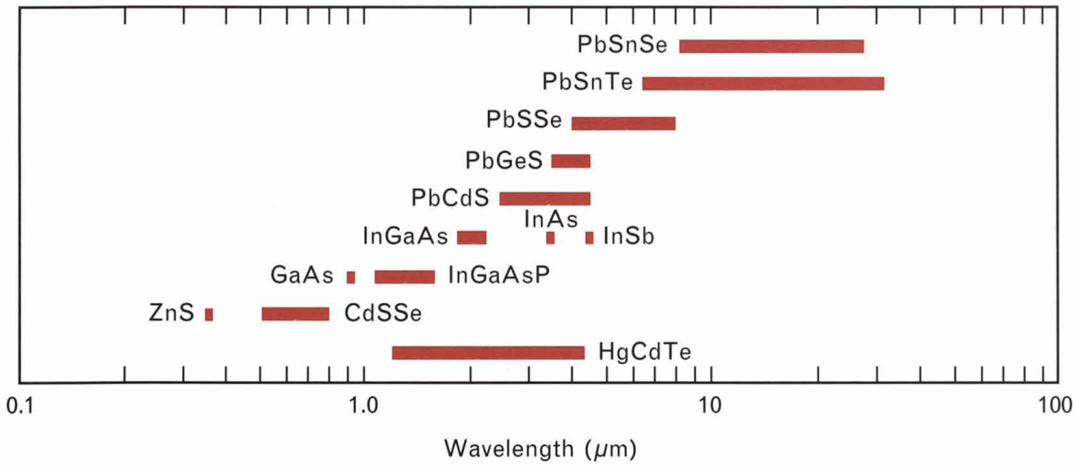



**FIGURE 9.** Wavelengths of semiconductor lasers that were first developed at Lincoln Laboratory.

arrays of microlenses [43].

Significant initial demonstrations in the coherent combining of diode lasers in small arrays have been performed in Lincoln Laboratory's Optics Division. A near-diffraction-limited beam was obtained with binary optics techniques and the so-called Talbot effect, which involves the diffraction from periodic objects [44].

Another direction of current research is toward the development of high-performance lasers for room-temperature operation in the 2-to-5-μm wavelength range. Sources in this range are of interest for laser radars, for the detection of atmospheric pollutants, and for communications with low-loss $CaF_2$ fibers that are under development at other laboratories. Using GaInAsSb as the active material, Lincoln Laboratory researchers have recently developed lasers at 2.3 μm with good performance at room temperature [45].

Figure 9 summarizes the semiconductor lasers that were first demonstrated at Lincoln Laboratory. Two are particularly notable. The first is the GaAs laser, which researchers demonstrated at GE and IBM simultaneously but independently. The second is the quaternary InGaAsP laser, which Soviet researchers initially demonstrated in low-temperature operation but which Lincoln Laboratory staff first developed for room-temperature operation with long lifetimes.

## Ionic Solid State Lasers

Research on ionic solid state lasers at Lincoln Laboratory has been aimed at the development of efficient, compact sources with an emphasis on broad wavelength tunability, which greatly extends the range of both military and civilian applications. Development of wavelength-tunable transition-metal lasers was undertaken in the 1970s. By improving the quality of the laser crystals and by using another laser as a pump source, researchers in the Solid State Division greatly enhanced the performance of these lasers, which had first been demonstrated by lamp pumping at Bell Laboratories in the mid-1960s. An example is the $Co:MgF_2$ laser [46], which operated in the CW mode when pumped with a 1.06-μm Nd:YAG ($Nd_x$-doped $Y_{3-x}Al_5O_{12}$) laser, and was tuned from 1.63 to 2.08 μm (Figure 10). The first UV laser was demonstrated in 1979 with Ce:YLF (Ce-

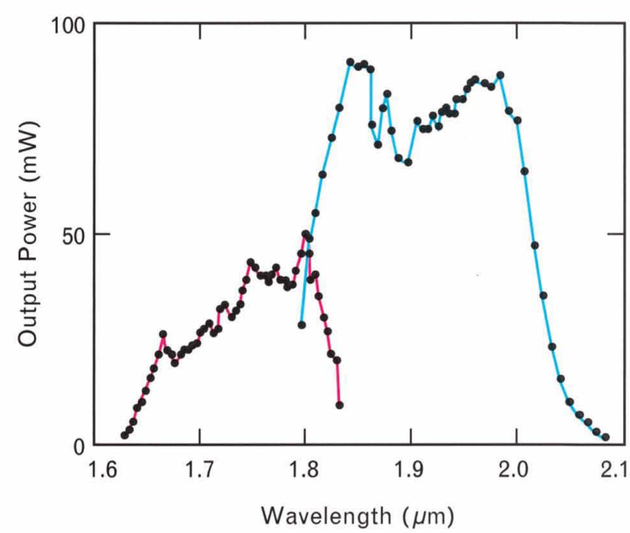
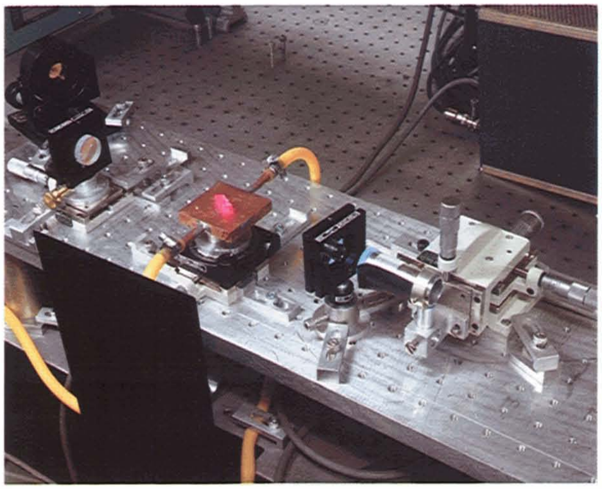
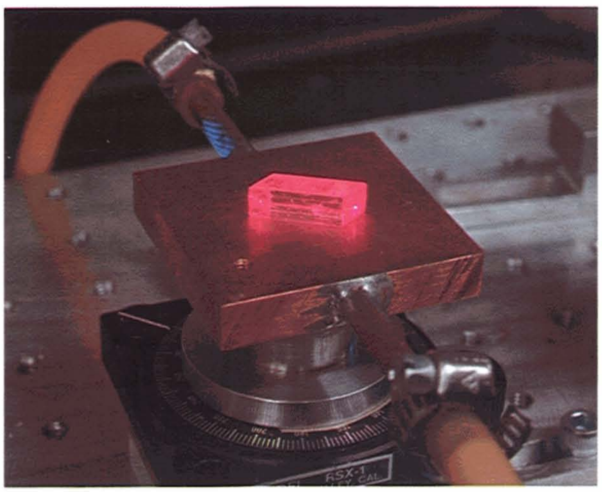



**FIGURE 10.** Tuning curves for $Co:MgF_2$ laser. Two sets of mirrors were required to tune the laser over the wavelength range from 1.63 to 2.08 μm, hence the two overlapping curves. The absorbed power was 1.2 W and the temperature was 80 K.



(a)



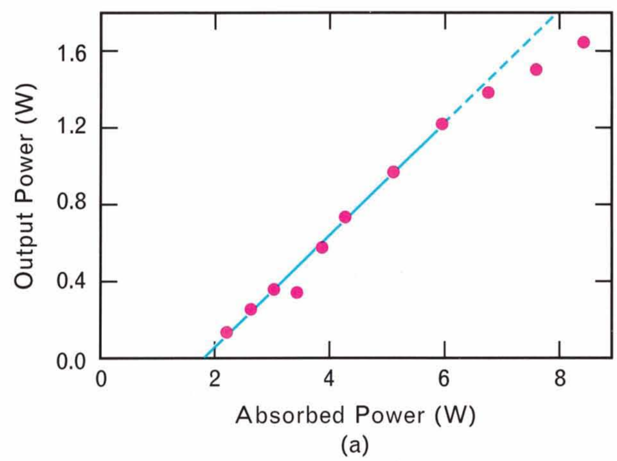
(b)

**FIGURE 11.** $Ti{:}Al_2O_3$ laser, which Lincoln Laboratory invented and developed. Tunable from 0.65 to 1.12 $\mu$m, $Ti{:}Al_2O_3$ lasers are very versatile devices with potential applications in high-resolution spectroscopy, agile-beam laser radars, spatial illuminators, and laser surgery.

doped $YLiF_4$) [47], which is tunable from 300 to 325 nm. Later, emission at 286 nm was obtained from $Ce{:}LaF_3$ [48]. These were also the first observations of laser emission that resulted from 5d-4f transitions in trivalent rare earths.

A major contribution was the initial demonstration and subsequent development of the $Ti{:}Al_2O_3$ laser, which is broadly tunable from 0.65 to 1.12 $\mu$m and can be designed for very efficient and stable operation at room temperature [49, 50]. Fundamental materials studies carried out in the 1980s identified and reduced the parasitic defects in $Ti{:}Al_2O_3$ crystals. As a result, CW operation was achieved at room temperature and slope quantum efficiencies of 86% were measured with a frequency-doubled (0.53 $\mu$m) Nd:YAG laser as a pump source. Figure 11 shows a longitudinally pumped $Ti{:}Al_2O_3$ crystal and Figure 12 shows the operation at 300 K. The wide gain bandwidth of this laser also permits the generation of ultrashort light pulses. In mode-locked operation, pulses as short as 200 fsec were recently demonstrated in a joint effort between the MIT campus and Lincoln Laboratory [51]. Various types of $Ti{:}Al_2O_3$ lasers are already commercially available with potential uses in high-resolution spectroscopy, agile-beam laser radars, spatial illuminators, and laser surgery.

Researchers at Lincoln Laboratory were the first to demonstrate the use of diode lasers as pump sources for



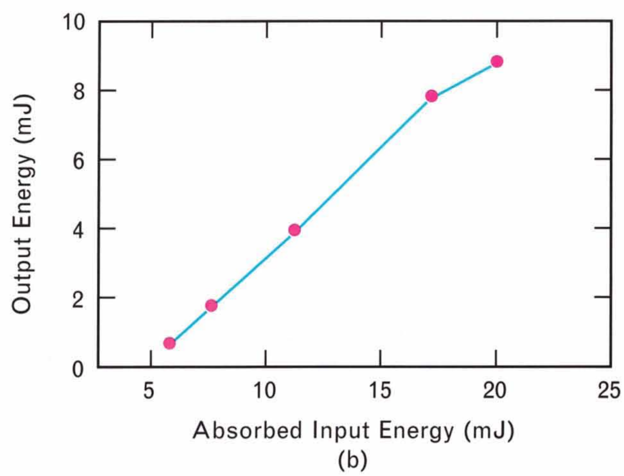




**FIGURE 12.** $Ti{:}Al_2O_3$ laser at 300 K: (a) CW operation and (b) pulsed operation. The reflectivity of the output mirror was 70%, the laser was pumped at 535 nm, and the slope quantum efficiency was 86%.

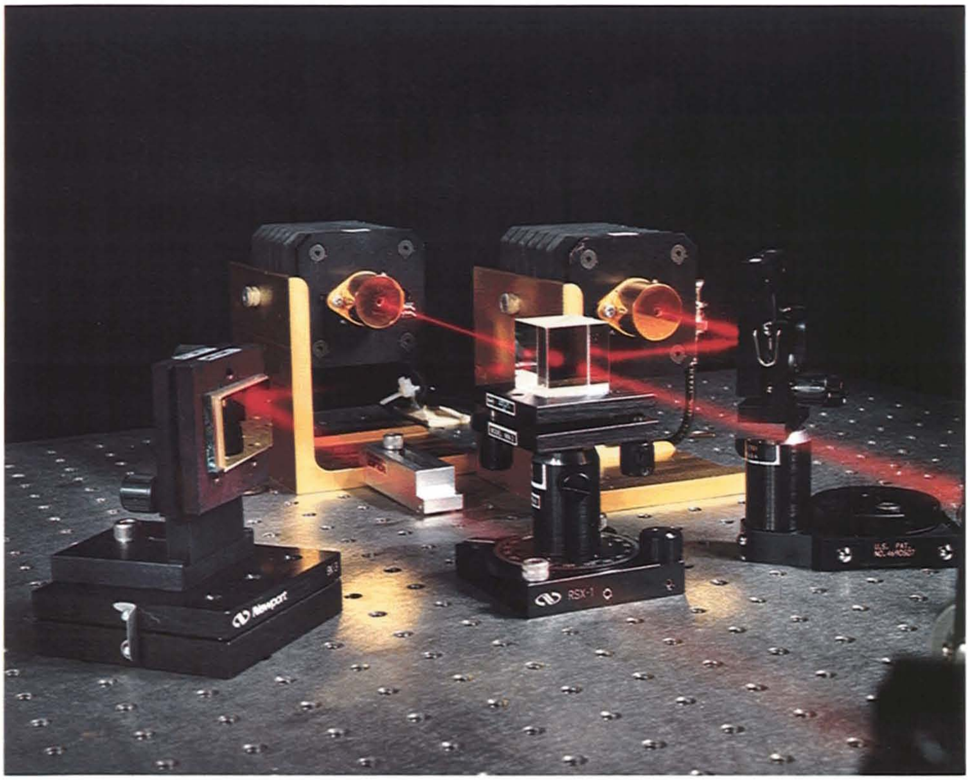


**FIGURE 13.** Two microchip lasers in a heterodyne experiment. (Note: The holes on the work table are 1 inch on center.)

ionic solid state lasers in 1964 by using a bank of GaAs diodes to pump a $U^{3+}$:$CaF_2$ laser rod [52]. However, extensive employment of this technique did not take place until two decades later, when diode lasers had achieved the adequate wavelength control, high efficiency, room-temperature operation, and long lifetimes that made such pumping advantageous over lamp pumping. The present effort in this area includes tiny diode-pumped microchip lasers [53] (Figure 13) for applications as stable narrow-line sources in communications and fiber gyros and as efficient high-power transmitters for laser radars [54]. As an example of the latter application, the Solid State Division has developed a 10-W-average-power diode-pumped Nd:YAG laser that is currently being used at the Firepond site in laser radar experiments for range measurements and for tracking space objects.

## Gas Lasers

Applications in laser radar and high-precision spectroscopy have driven most of the gas-laser development at Lincoln Laboratory. Starting in the mid-1960s, the Optics Division designed and built sealed-off $CO_2$ lasers for ultrastable operation in the $TEM_{00}$ mode for use as local oscillators and master oscillators in coherent 10.6-$\mu$m radars [55, 56]. Single-frequency output powers up to 45 W and a yet-to-be-surpassed short-term frequency stability of $\Delta f/f \leq 1.5 \times 10^{-13}$ over 0.1 sec were obtained. Figure 14 is a photograph of one of the first sealed-off $CO_2$ lasers, which was built with four invar rods to reduce the cavity-length variation with temperature. To achieve absolute frequency stabilization, a technique that makes use of saturation resonance on the 4.3-$\mu$m wavelength fluorescence of $CO_2$ was invented [57]. The technique enables absolute frequency reproducibilities to within 3 kHz in nine $CO_2$ isotopic species. Thus secondary frequency standards in the 8.9-to-12.3-$\mu$m wavelength range could be created with the Cs atomic clock used as a primary standard.

For applications in compact imaging radars, a modified ultrastable $CO_2$ laser that can be operated either in a CW or electronically Q-switched mode was built [58]. Miniature transverse-electric atmospheric-pressure lasers with 10-W average powers (20 mJ at 500 Hz) were designed and built for lidar measurement of atmospheric constituents [59]. In 1970 Lincoln Laboratory was also the first to achieve the sealed-off operation of CO lasers, which were used in various spectroscopic applications and in the optical pumping of spin-flip Raman lasers (discussed in the following section).

In the early 1970s a team in the Solid State Division made important contributions in the area of submillimeter-wavelength lasers. A $CO_2$ laser was used as a source for pumping gas molecules at frequencies far removed from the vibrational transitions [60], in contrast to the resonant pumping used by other researchers. Nonresonant pumping greatly increased the number of gases that could be used for submillimeter lasers (which thus greatly extended the number of possible wavelengths) and allowed significant wavelength tuning by the application of an electric field. Laser emission at numerous lines in the range from 58 to 755 $\mu$m was obtained with methane ($NH_3$) and other gases. These lasers were instrumental in greatly expanding the applications of submillimeter spectroscopy, including the study of impurity levels in semiconductors such as GaAs [61].

## Nonlinear Optics and Frequency Conversion

The advent of lasers provided a unique tool for fundamental studies in nonlinear optics and light scattering. These phenomena could in turn be used to convert and/or tune a laser's wavelength, thus greatly broadening the scope of applications. Examples of such early work at Lincoln Laboratory were studies of phase-matched stimulated Raman scattering and measurements of lattice and band-electron spontaneous light scattering in semiconductors [62, 63]. The studies included the effect of an external electric field on the electron distribution [64]. The above work, which was carried out in the late 1960s, led to experiments that used applied magnetic fields to investigate spin-flip and Landau-level light scattering in semiconductors. In 1970, researchers at Bell Laboratories were the first to demonstrate a spin-flip Raman laser in InSb by using a 10.6-$\mu$m $CO_2$ laser. (A spin-flip Raman laser is based on scattering of light in which the spin of electrons in magnetic-field-induced energy levels in a semiconductor is reversed.) Shortly after, Lincoln Laboratory staff demonstrated the first CW Raman laser by using a 5-$\mu$m CO laser that took advantage of resonant excitation near the bandgap of InSb [65]. Output powers of 2 W with a 90% conversion efficiency were obtained with broad wavelength tunability in the 5-$\mu$m wavelength range, and frequency-

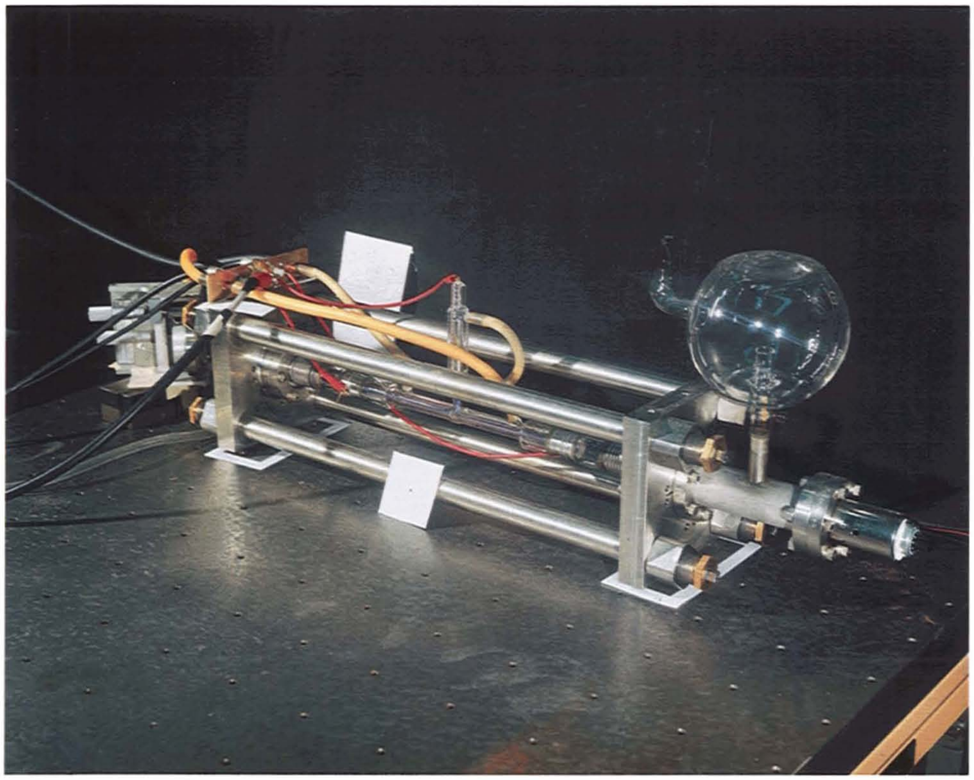


**FIGURE 14.** Photograph of one of the first ultrastable sealed-off $CO_2$ lasers built at Lincoln Laboratory.

stabilization and mode-control techniques were applied to develop a tool for laser spectroscopy. In addition, the self-focusing effects of laser beams in gases as well as in solids were studied both experimentally and theoretically. This research included collaborative efforts between Lincoln Laboratory, the University of California at Berkeley, and IBM [66, 67].

Other topics of investigation in the 1970s were harmonic generation and frequency mixing in nonlinear optical materials. High-quality crystals of the calcopyrites $CdGeH_2$ and HgGaSe were grown and used to frequency-double the 10.6-$\mu$m $CO_2$ emission. A conversion efficiency of nearly 30% was obtained for lidar experiments in the remote sensing of atmospheric constituents [68]. An extremely useful application of frequency conversion has resulted from the observation that the frequency sum of two Nd:YAG emission lines—one at 1.06 $\mu$m and the other at 1.32 $\mu$m—exactly match the sodium line at 0.59 $\mu$m. The cover photograph for this issue shows the yellow (0.59 $\mu$m) light beam formed by the sum-frequency mixing of the two wavelengths of a Nd:YAG laser in a nonlinear crystal. The precise wavelength match to the sodium resonance permits the probing of the earth's mesospheric atomic sodium layer in this experiment.

## In This Issue

The articles in this issue provide a detailed description of some of Lincoln Laboratory's accomplishments in the laser field during the past several years, including recent work in progress.

In the diode laser area, J.P. Donnelly discusses the development of incoherent high-power arrays for use as pump sources. The technologies for collimating the output of array elements by means of microlenses and some initial attempts at establishing coherence among the elements are described by Z.L. Liau, V. Diadiuk, and J.N. Walpole. H.K. Choi, C.A. Wang, and S.J. Eglash discuss two very recent advances in diode laser technology: the achievement of record low thresholds in strained-layer InGaAs lasers, and the development of efficient room-temperature 2.3-$\mu$m GaInAsSb lasers.

Two articles are devoted to the use of diode lasers as pump sources for ionic solid state lasers. T.Y. Fan's article primarily covers high-power devices, and J.J. Zayhowski's article describes the microchip laser, a low-power device that achieves stable single-frequency operation in a simple and inexpensive structure.

In the area of broadly tunable solid state lasers, an article by K.F. Wall and A. Sanchez deals with the invention and development of the $Ti:Al_2O_3$ laser. Finally, techniques for stabilizing and controlling laser output spectra for applications in laser radars are covered by P.A. Schulz and C. Freed. Schulz's article describes the frequency control and wavelength tuning of solid state lasers and Freed's article deals with the development of ultrastable $CO_2$ lasers.

## Acknowledgments

The contributions made by Lincoln Laboratory during the past 28 years to the science and technology of lasers constitute the work of a large number of staff members whose names are found in the references. The writing of this historical review was facilitated by the existence of two earlier review articles by P.L. Kelley [1] and R.H. Rediker et al. [2] and by valuable editorial comments and suggestions from Alan McWhorter and Aram Mooradian.

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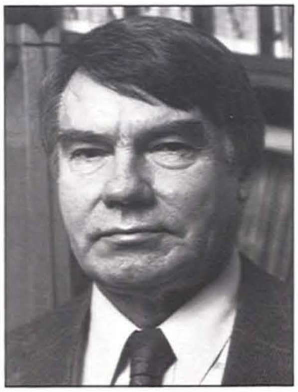

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