

Gas Lasers—The Golden Decades, 1960–1980

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By all rights, gas lasers should have been discovered long before 1961, likely by accident. Einstein's 1917 classic paper derived the relationship among spontaneous emission, stimulated emission, and absorption, but only considered a system in thermodynamic equilibrium (guaranteed *not* to oscillate). It remained only to ask: "What if the system were *not* in thermodynamic equilibrium?" Yet despite countless experiments looking at the absorption of radiation in gas discharge tubes (not in thermodynamic equilibrium), the first gas laser had to wait for Ali Javan of Bell Telephone Laboratories.

First Gas Laser

In 1959 Javan proposed four different ways to make a gas laser:

- (1) A gas discharge in pure neon.
- (2) A gas discharge in pure helium.
- (3) Resonant collisions in between excited krypton and mercury atoms in a discharge exciting the Hg (9^1P) or Hg (6^1F) levels, creating an inversion in the mercury levels.
- (4) Helium atoms in the (2^3S) level in a gas discharge exciting Ne ($2s$) levels to create an inversion in neon levels.

The first three systems do not actually work, but fortunately Javan and his Bell coworkers Bill Bennett and Don Herriott did the fourth experiment. They excited a mixture of helium and neon with a radio-frequency discharge in a gas tube with flat end mirrors coated for maximum reflectivity near 1- μm wavelength, as depicted in Fig. 1. Oscillation of the neon transition $2s_2 \rightarrow 2p_4$ at 1.1523 μm made the first gas laser.

Gas Lasers Using Neutral Atoms

Once the word was out, everybody had to have a helium–neon laser, and a war-surplus night vision 'scope to see the infrared laser output. Hughes Research Laboratories was no exception, and the author found himself in the queue to get one from a mini production line that Hughes had set up. The author had been interested in developing a microwave traveling wave tube (his former professional interest) as a high-frequency photodetector for laser communications and had already done experiments with a pulsed ruby laser. The continuous operation of the He–Ne laser was more attractive for communications, despite the need for a new detector. But fate intervened.

The author had planned to attend the annual Conference on Electron Device Research in late June with his boss, Don Forster, and Hughes Associate Director, Mal Currie. Currie decided they should visit Bell Labs on the way to see what was new and interesting. They were astounded to see a *red* He–Ne laser operating at about 10 mW, in the lab shown in Fig. 2. The three researchers saw the now familiar "red sandpaper" speckle of truly coherent light (which was not very evident in the IR He–Ne laser viewed with a night-vision 'scope). Alan White and J. Dane Rigden had found *another*

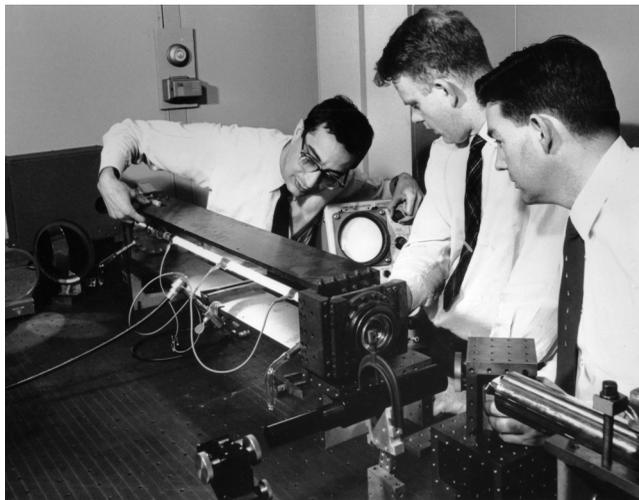
metastable level in helium, the $2s^1S_0$, that collected population from higher-lying helium levels, and was near resonance with the $3s_2$ level in neon. That created a population inversion with the $2p_4$ level on the red laser line at $0.6328\ \mu\text{m}$ and oscillation when red-reflecting mirrors were used for feedback. White and Rigden were in a different Bell technical group from Javan, Bennett, and Herriot, and enjoyed the rivalry. When they announced the red laser the next week at the conference, the rivalry between the two groups was quite evident.

That night on the drive back from Bell in New Jersey to our hotel in New York, the group discussed the new red laser. Currie (who was driving) ended by saying “We have to have one!” The author sensed that he had just received a battlefield promotion to “Gas Laser Researcher.”

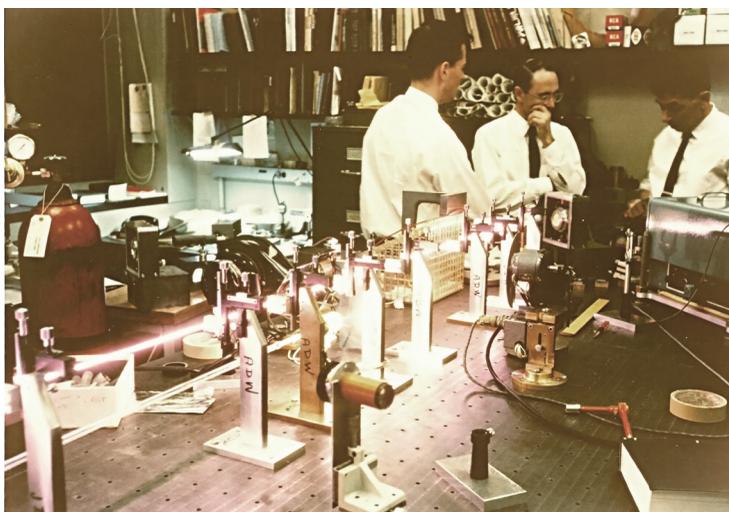
Helium–neon gas mixtures turn out to have several infrared lines from $2s$ levels to $2p$ levels, and several lines from green to deep red between the $3s_2$ level and $2p$ levels. In addition, several infrared lines in the $3\text{-}\mu\text{m}$ range have so much gain that they can easily suppress the red laser line. Arnold Bloom, Earl Bell, and Bob Rempel of Spectra-Physics found that they could prevent $3\text{-}\mu\text{m}$ emission by adding an intracavity prism.

Other researchers rushed to extend these results. Another Bell Labs group built a 10-m discharge tube to obtain oscillation on many more infrared lines to wavelengths beyond $100\ \mu\text{m}$ in various noble-gas mixtures. This early burst of research showed that oscillation was possible in pure noble gas discharges, without adding helium. That led to a burst of research on the noble gases, which are easy to investigate because they do not interact with the discharge tube walls or electrodes.

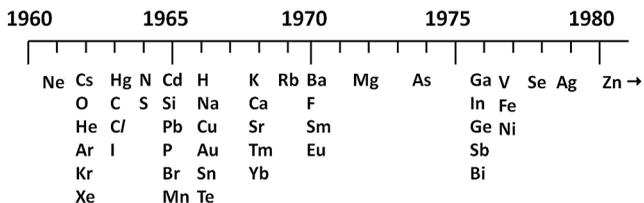
Interest soon turned to other materials, starting with the permanent gases such as oxygen, nitrogen, and chlorine, which dissociate into atoms in a discharge, and expanding to easily vaporized elements such as mercury, iodine, and sulfur. Reports of new lasers multiplied, and it seemed that almost *anything* that you could vaporize and put in a gas discharge would lase. Figure 3 shows how the ranks of lasing elements grew during the first two decades, the “golden age” of gas laser research. The author



▲ Fig. 1. Ali Javan, W. Bennett, and D. Herriott with the first He–Ne laser at Bell Laboratories. (Reprinted with permission of Alcatel-Lucent USA Inc., courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)



► Fig. 2. J. D. Rigden, A. D. White, and W. W. Rigrod with the first red He–Ne laser at Bell Laboratories. (Courtesy of Alan White.)



▲ Fig. 3. Timeline for the discovery of laser oscillation in neutral atoms during “the golden age” of gas laser research, 1962 to the 1980s.



▲ Fig. 4. A simple helium–neon gas laser typical of those in supermarket optical scanners. The cavity mirrors are attached directly to the ends of the small diameter discharge tube. An aluminum cold cathode surrounds the discharge tube. Tubes like this sold for about \$100, and typically lasted for over 10,000 hours.

The first commercial He–Ne lasers sold for about \$20,000, but the prices quickly dropped as commercial manufacturers learned the tricks, and large-scale applications developed. By 1970, the 2-mW-output lasers of the type shown in Fig. 4 that were used in early supermarket checkout scanners sold for about \$100 (plus power supply). The mirrors were sealed directly on the ends of the glass envelope with a low-melting-temperature glass frit. Millions of such He–Ne lasers were manufactured, but now this application has all but been taken over by red diode lasers, and He–Ne lasers will soon become collector’s items.

Ionized Gas Lasers

In the course of investigating new gas lasers in 1963, W. Earl Bell and Arnold Bloom of Spectra-Physics discovered the first gas laser that oscillated on energy levels of ions while testing mixtures of helium and mercury. Like the early He–Ne laser, they used a simple glass discharge tube, a few millimeters in diameter and about a meter long. The key difference was using high current pulses of a few tens of amperes, rather than a constant current of few mA. This produced laser pulses with peak power of a few watts at wavelengths of 0.5677 and 0.6150 μm in the green and orange—an important milestone because the green line at the time was the shortest visible wavelength yet produced by a laser. Figure 5 shows Bell in his laboratory at Spectra-Physics with an early pulsed He–Hg⁺ laser.

The excitation mechanisms behind the He–Hg⁺ laser were unclear at the time, and at least four groups tried to pin it down, including Bloom and Bell; Rigden (who had moved to Perkin-Elmer); G. Convert, M. Armand, and P. Martinot-Lagarde at CSF in France; and the author at Hughes. Independent experiments by Rigden and the author showed that a neon–mercury discharge could also produce the orange mercury-ion line, ruling out simple charge exchange as the mechanism.

personally had no doubt that you could make a gas laser from such hard to vaporize elements as tungsten, osmium, rhenium, and iridium if you could put a discharge through them in vapor form, but the technical community so far has not felt it was worth the effort.

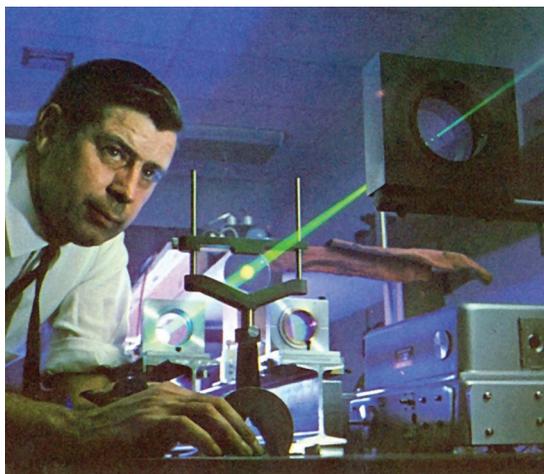
The technology for He–Ne lasers is actually pretty simple; think “neon sign.” A simple glass tube, 2 to 10 mm in diameter and 100 to 2000 mm in length, was commonly used. A DC discharge of 2 to 10 mA is typically required. (A radio-frequency discharge at 27 MHz was used in the first He–Ne laser, but DC is simpler.) The gain of a typical red He–Ne laser is quite low, only a few percent per meter. But the optical gain of a 3.39- μm He–Ne laser can be tens of decibels per meter, so a meter-long discharge tube might well oscillate with the feedback from the first surface reflection of an uncoated glass window perpendicular to the optical path. A simple discharge tube in pure xenon may easily exhibit 20-dB gain at 3.508 μm . This is the author’s argument that the gas laser should have been discovered by accident long ago (but no one records such an event).

To put an extra nail in the coffin of charge exchange, the author tried an argon–mercury discharge. (Argon has an ionization potential well below that of neon.) This initially did not produce the orange and green Hg II laser lines, so the mixture was pumped out. After the tube was refilled with a helium–mercury mixture, the discharge again produced the orange and green Hg II laser lines—plus a turquoise blue laser output, which turned out to be ionized argon, shown in Fig. 6. The blue pulse coincided with the electron current, not the discharge afterglow, suggesting that electron collision was the mechanism behind the argon-ion oscillation. That system, similar to the one shown with the author in Fig. 6, opened up a new chapter. It was Valentine’s Day, 14 February 1964.

It turned out that the groups at Spectra-Physics, CSF, and Hughes had independently discovered the Ar II 0.4879- μm laser. So had W. R. Bennett, Jr., J. W. Knutson, Jr., G. N. Mercer, and J. L. Detch at Yale University, who had not been studying mercury-ion lasers but were trying to make an argon-ion laser! It was clearly an idea whose time had come. Another group at Bell Laboratories, E. I. Gordon, E. F. Labuda, and R. C. Miller, found that the argon-ion laser could emit continuously, unlike the mercury-ion laser. In a matter of months, water-cooled discharge tubes were emitting more than 2 W continuously. The efficiency was below 0.1%, so several kilowatts of input was needed, requiring major improvements in discharge tubes.

Other noble-gas ion lasers followed quickly. More than two dozen laser lines in krypton and xenon ions were discovered within a week of the argon laser. Neon oscillation followed in a couple of months, the time needed to obtain cavity mirrors at the right wavelengths. Spectrographic plates recorded laser oscillation on lines of oxygen, nitrogen, and carbon left as impurities in the discharge tubes. Further spectroscopic research discovered laser emission from multiply ionized species at higher peak currents.

Watts of continuous-wave blue laser light opened the possibility of new applications. Among the first was improving coagulation to repair detached retinas, which had been done with high-power xenon lamps and later ruby lasers. Krypton-ion lasers, able to emit red, yellow, green, and blue light simultaneously, were quickly adopted for light shows. Their use at rock concerts introduced new types of customers to laser companies that were used to scientists; one customer arrived at Spectra-Physics with a wad of hundred-dollar bills to buy a krypton laser, put the laser in his station wagon, and drove off to a show that night. By far the largest application for ion lasers became high-power pumps for dye lasers, making ion lasers the “power supply” for much science.



▲ Fig. 5. W. E. Bell in his laboratory at Spectra-Physics with an early pulsed helium–mercury ion laser. (AIP Emilio Segre Visual Archives, gift of W. Earl Bell.)



▲ Fig. 6. Photograph of the author with a pulsed argon-ion laser in his laboratory in February 1964: an air-cooled fused silica discharge tube with Brewster’s angle windows and external mirrors. Pulse lengths of a few microseconds with a simple capacitor discharge and rates of a few hundred per second were used.

Molecular Gas Lasers

Nobel Laureate and former Optical Society President Arthur Schawlow once said, “A diatomic molecule is a molecule with one atom too many.” However, for molecular lasers this author would say instead, “If one atom is good, then several must be better.” Molecules have more degrees of freedom than atoms or ions, including the number and kind of atoms, the molecular structure, the nature of energy levels, and type of pumping, leading to the demonstration of thousands of molecular lasers. The first was carbon monoxide, which L. E. S. Mathias and J. T. Parker made oscillate on electronic transitions in a pulsed discharge at 0.8 to 1.2 μm . Close behind it was the 0.337- μm N_2 laser demonstrated by H. G. Heard. The third molecular laser would be the charm—and most successful—the 9- to 11- μm CO_2 laser, discovered at Bell by C. K. N. Patel, W. L. Faust, and R. A. McFarlane.

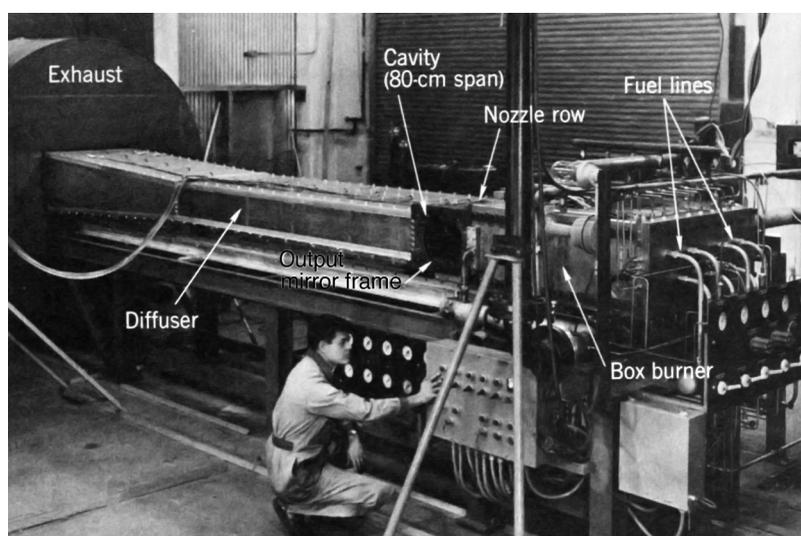
The diatomic noble gases, noble-gas halides, and noble-gas oxides in the list exist only in an electronically excited state, called an “excimer.” The population inversion occurs because the molecule quickly falls apart into atoms when it drops to the ground state. The rare gas-halide excimers have become commercially important because they produce powerful pulses in the vacuum ultraviolet. The 193-nm argon-fluoride laser is used in laser ablation of the cornea to correct vision defects and in high-resolution lithography to make silicon integrated circuits.

Larger and more complex gas molecules also have been made to oscillate, mostly by optical pumping with the 9- to 11- μm light from CO_2 lasers. These larger molecules have hundreds of rotational/vibrational transitions in the far-infrared region, and to make matters more complicated, the wavelengths depend on the hydrogen, carbon, nitrogen, and oxygen isotopes in the molecule.

The most important molecular gas laser, CO_2 , like the He-Ne laser, depends on energy transfer from a more abundant species to the light emitter, so it might better be called the nitrogen- CO_2 laser. Typically a discharge excites a gas mixture of ten parts N_2 and one part CO_2 , with most energy going to excite N_2 molecules to their lowest vibrational level, which is metastable so it cannot radiate. However, they can transfer energy by colliding with CO_2 molecules, which have a near-resonant energy level that produces a vibrational population inversion. CO_2 oscillation occurs on rotational sublevels of the inverted vibrational level, which can be selected by tuning the cavity.

Carbon dioxide lasers can have efficiency of 10% or more, among the highest of any gas laser, and a factor of 100 higher than most atomic or ionic lasers. That makes CO_2 the gas laser of choice when power is important. Applications including burning date codes or other identification on plastic bottles, cutting sheet metal, or even cutting the special glass used in cell phone displays.

In the mid-1960s, the AVCO Everett Research Laboratory produced record continuous CO_2 output of 50 kW, shown in Fig. 7. This “gas-dynamic laser” burned fuel at high temperature



◀ Fig. 7. An experimental gas-dynamic CO_2 laser developed by AVCO Corporation circa 1968. The output was over 50 kW.

(2000°F) and pressure (20 atm.) and then exhausted the mixture of 89% nitrogen, 10% CO₂ and 1% water vapor through a supersonic expansion nozzle. This produced a CO₂ population inversion downstream, which could oscillate when passed through an optical cavity. The black circle above and to the right of the technician's head was the beam output. The combustion chamber is at the right of the device, and the exhaust to the atmosphere is to the left of the picture. (The combustion exhaust was relatively harmless to the environment, but the highly poisonous cyanogen C₂N₂ was used as fuel to keep the exhaust low in hydrogen, so extreme care was needed to make the fuel burn properly.) Later, a 400-kW version was installed in the Airborne Laser Laboratory, a laser-weapon testbed built in the 1970s.

Hydrogen–fluoride (HF) chemical lasers, which burn hydrogen and fluorine to produce HF gas that lases in a system similar to the gas-dynamic laser, have reached megawatt-class powers in demonstrations on the ground. These are described by Jeff Hecht in his chapter on laser weapons.

Summary

The two decades ending in the 1980s were the heyday of gas laser development. Today, the world of gas lasers is much quieter, with only a few types remaining, with mostly carbon dioxide in the factory and some excimers and argon ion lasers in ophthalmologists' offices.

A list of literature citations for the thousands of gas lasers implied by this chapter would be longer than the chapter itself. The interested reader is referred to guides to that literature, such as [1].

Reference

1. R. J. Pressley, ed., *Handbook of Lasers* (CRC Press, 1971 and subsequent editions).