Remembering the Million Hour Laser

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In the late 1960s, Bell Labs had a problem. The nation's demand for long-distance telecommunications services was steadily increasing, but the technologies then in use—coaxial cable and point-to-point microwave transmission through the air—could not keep up with the pace. The major reductions in optical fiber waveguide losses reported in the early 1970s were therefore of great interest. The lowest-loss regions of these fibers were in the 0.8 to 0.9 μm range, which could in principle be accessed by devices built using the GaAs-GaAlAs material system. Thought was given to the possible use of GaAs light-emitting diodes (LEDs), but it was immediately obvious that semiconductor lasers would be much better sources—if they could be developed reliably in commercial quantities. One could easily imagine an efficient GaAs laser that could couple a milliwatt of optical power into a fiber with a core diameter of about 50 μm. Thus was defined the first generation of fiber-optic telecommunication systems.

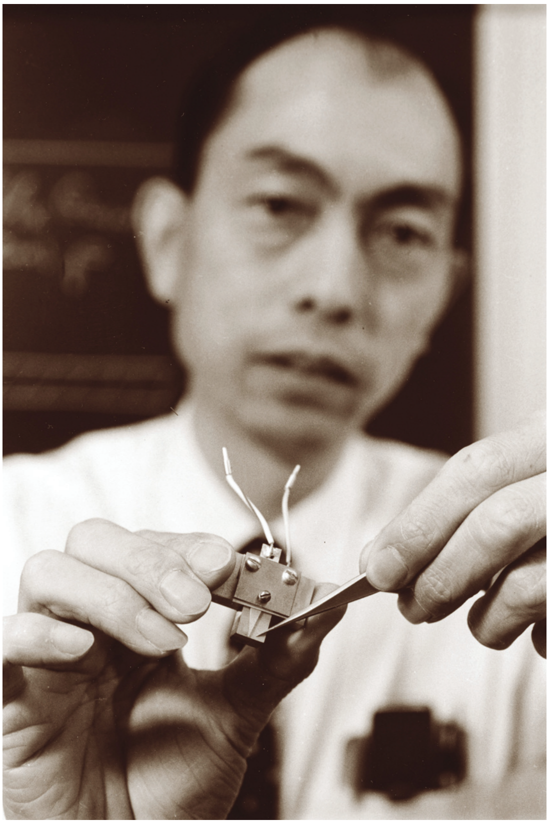
In the late 1960s and early 1970s, the author was a young supervisor working on the development of LEDs for Bell System applications. In that process, he learned quite a bit about the physics, technology, and transfer-to-volume manufacture of III-V semiconductors. One result of this program was the successful implementation of green-emitting GaP LEDs for nighttime dial illumination in the handset of the Dreyfuss-designed Trimline phone. Something like 100 million of these sets were subsequently produced.

In 1973, the author transferred to a small exploratory development group working on semiconductor lasers. The group had benefited from an excellent research effort that happened just down the hall. Most notable was the demonstration in 1970 of a continuously operating room-temperature GaAs-AlGaAs heterostructure semiconductor laser [1] (see Fig. 1). However, these broad-area lasers had high operating currents (around 400 mA) and very short lives (they were sometimes referred to as flashbulbs), but they showed the way forward!

The group's choice of a laser structure for initial development consisted of four planar epitaxial layers grown sequentially by liquid-phase epitaxy (LPE) on a GaAs substrate. We inhibited lateral carrier flow by using proton bombardment to define a "stripe-geometry" wherein only a narrow stripe, 10×250 μm, was electrically pumped (see Fig. 2). These "stripe-geometry lasers" became the workhorses of the early Bell Labs semiconductor laser development. They allowed the sorting out of many reliability and device performance issues. In a typical week, half a dozen or so wafers were processed into some thousands of lasers. Fast turnaround made it possible to quickly and systematically iterate device, processing, and material innovations.

Many of the early stripe-geometry lasers had very erratic properties. Some would lase for a time but would then suddenly become inoperable. Others would die slowly. Still others would not work from the outset. Typical continuous-wave operating lifetimes at room temperature were on the order of minutes to days. Many devices also had other undesirable characteristics, for example, nonlinear light output versus current. It was clear that the group had a very difficult development project on its hands! Some thoughtful observers, including one key Bell Laboratories vice president, opined that success was unattainble.

Important clues to improvements came in early 1973 from an experiment in which "windows" were fabricated on the substrate side of stripe-geometry lasers in such a way that spontaneous emission (and scattered stimulated emission if present) from the stripe region of the laser could be observed with an infrared optical microscope. Dark-line defects (DLDs), which



▲ **Fig. 1.** Izuo Hayashi, holding a heat absorbing device, points to the location of a broad-area semiconductor laser designed by Bell Laboratories scientists. (Bell Laboratories/Alcatel-Lucent USA Inc., courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)

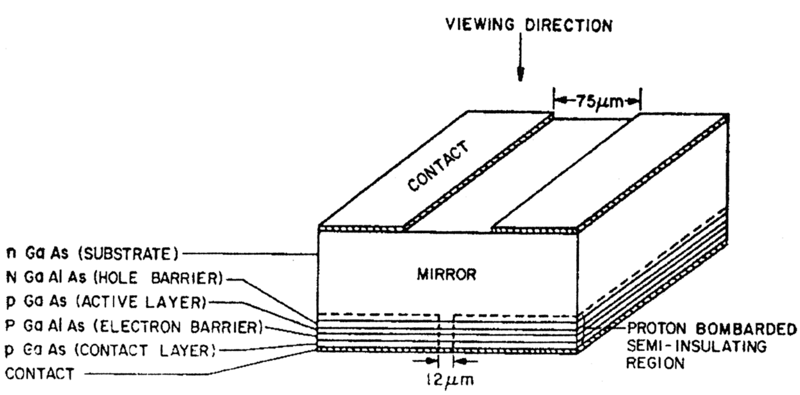
grew in a laser's active region during operation, were observed and were determined to be the principal failure mechanism in devices that stopped working in the first 100 hours or so [2].

This paper correctly stated that "the combination of low-strain processes and extreme cleanliness in materials growth should provide a dramatic increase in laser life." It galvanized a large technical community such that it seemed that everyone in the world with an electron microscope then decided to investigate this area. A picture was, in this case, worth many thousand words!

The Bell group subsequently worked hard to understand and eliminate localized modes of degradation, including those associated with DLDs in the long narrow-lasing region of the laser and those associated with mirror surfaces. Subsequent experiments showed that DLDs identical to those seen in lasers could be generated by optical pumping of undoped and unprocessed laser material, thus confirming that DLD initiation and growth could result from properties of laser material that were not associated with proton bombardment, *p-n* junction dopants, or contact metallization technology.

Many improvements in LPE growth technology and its automation were also made during this period. Fundamental difficulties with this "batch" process made it stubbornly difficult to reproducibly control, but it was greatly improved in the skilled hands of the Bell group's crystal growers.

By late 1974, with continuing work on many technology fronts, the reliability situation had improved considerably, and selected lasers had been operating continuously for more than a year at room temperature (typically 30°C). On the basis of the data obtained, the group was able to conclude that "continuous room-temperature operation of these devices as lasers with power outputs exceeding 1 mW per laser face for times in excess of 100,000 h is possible." This was an important feasibility demonstration. However, it served to reinforce the urgency of finding ways to confidently "accelerate" diode aging so that lasers tested for short periods could be installed in the field with the expectation that they would last for decades.



◀ **Fig. 2.** Schematic diagram of a proton-bombardment-delineated stripe geometry GaAs/GaAlAs semiconductor laser with a "window" on the substrate side. Note the four epitaxial layers of different composition grown by liquid-phase epitaxy [B. C. De Loach, Jr., B. W. Hakki, R. L. Hartman, and L. A. D'Asaro, Proc. IEEE **61**, 1042 (1973)].

By early 1977, with continued work on growth and process improvements, screening techniques, and protocols for accelerated aging, it was felt that, for a set of randomly selected lasers, it was possible to confidently predict a median lifetime at 22°C at 34 years and a mean time to failure at 22°C at 1.3 million hours (>100 years). The so-called "million hour paper," which was published in 1977 [3], demonstrated that it was possible to construct semiconductor laser devices with very long lifetimes.

Soon after these results were published, the author attended a conference in England on the general subject of light emission from semiconductors. During the Q&A, the head of the laser development program at the Standard Telecommunications Laboratory asked, publicly and rather pointedly, "Dick, would you please tell us the secret of your reliability success?" The author puzzled for a moment and then blurted into the microphone, "We do everything very carefully." This brought a good deal of laughter from the audience, but it was not intended as a joke. It took some years to convince skeptics that the success of the Bell group's development program required the solution of hundreds of problems, innovation by scores of outstanding well-motivated people, millions of dollars, systematic iteration, and a good deal of time. Perhaps its key achievement was the "proof of principle" that semiconductor lasers with long lifetimes were possible—a little like Roger Bannister's four-minute mile. In years since, it has appeared that most business and political leaders, as well as scientists who have not been involved in difficult high-tech development programs, do not appreciate what it takes to succeed with these types of endeavors.

In any case, after the group's considerable reliability achievements, the hard parts of the laser development program still lay ahead. The words of the great statesman Winston Churchill, referring to much more serious issues than ours, provided some encouragement: "Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

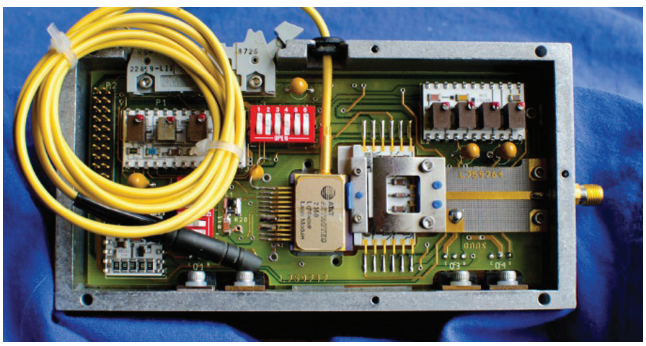
As the Bell group became better able to fabricate and age lasers, the testing of device characteristics and the ability to analytically model these devices were also refined. These developments greatly aided the early identification of lasers with deficiencies and also pointed the way to eliminating those problems.

The first applications of these lasers in the Bell System were in system experiments that were not intended to carry commercial traffic. These used 50-μm-core multimode fiber and data rates of 45 and 90 Mb/s. After that, they were tried in short-distance trials carrying live traffic, including a successful May 1977 installation in which fibers were used to connect three telephone central offices in downtown Chicago. The small physical size and large capacity of the fiber system helped to relieve crowding in the underground (and sometimes underwater) ducts that connected the offices. Then the trials became ambitious: In February 1980 at the Winter Olympics at Lake Placid, New York, the television feed was carried over an experimental optical fiber system and broadcast around the world. Fingers were crossed! In the end, it was fabulous to see the "Miracle on Ice" performance of the U.S. men's ice hockey team via the superior television picture made possible by our fiber system (see Fig. 3). These first-generation lasers were subsequently used in the fiber systems for the Northeast corridor and many other terrestrial trunk applications. Technology "proof of principle" had become "technology of choice!"

The second-generation lasers were designed for use in the 1.3-μm window of the improved, single-mode, 5-μm-core diameter fibers. Their buried-heterostructure design made use of two epitaxial growth sequences with an etching step in between. Figure 4 shows a 1.7-Gb/s transmitter developed by Optical Society Fellow Richard G. Smith and his group that made system implementation possible.

The complex fabrication process ultimately produced very high-yield, high-performance, high-reliability buried-heterostructure lasers that stayed in volume production from about 1984 to 1997. These multimode lasers could be used at data rates up to about 2 Gb/s. They were the mainstay of the Bell System's 417-Mb/s applications and, later, its FT series G 1.7-Gb/s applications providing the first high-speed 1.7-Gb interconnects among some 200 major U.S. cities. These and subsequent lasers came to possess such high reliability and could be applied in terrestrial trunk and undersea applications because the Bell System group became increasingly able to screen out lasers that had non-fundamental modes of degradation. Short-duration high-stress testing, specific to the individual laser design in the laser certification process, was used.

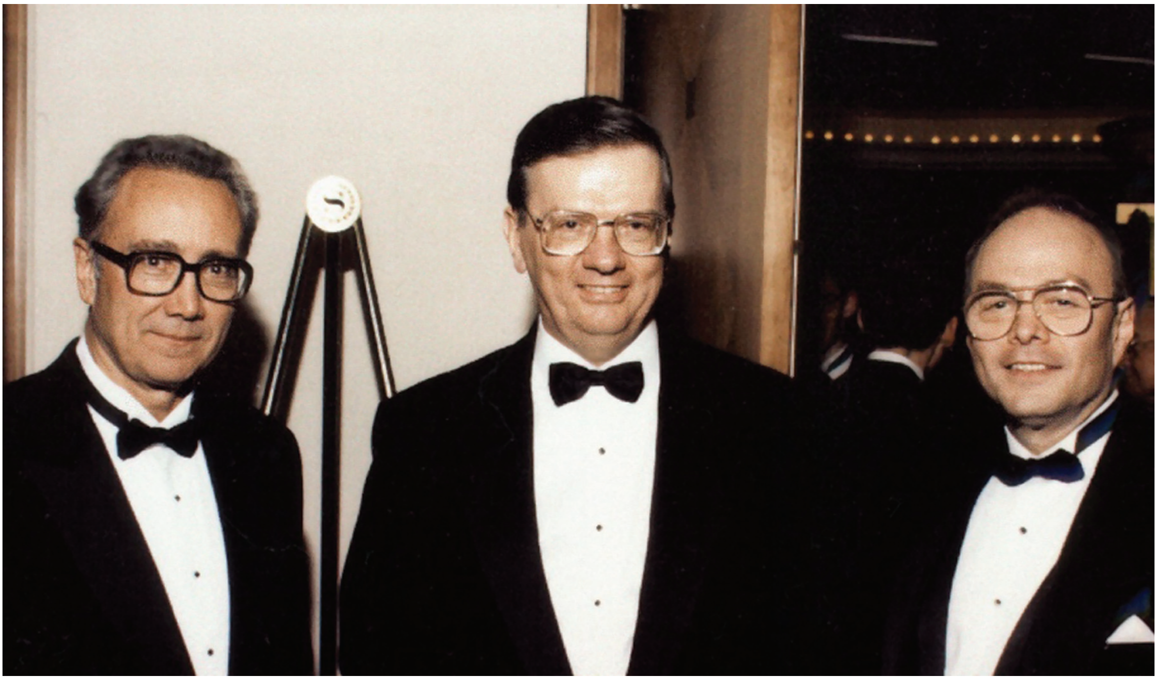
▲ **Fig. 3.** The televised feed for the 1980 Olympic Ice Hockey matches (like the one between Canada and the Netherlands shown here), including the famous "Miracle on Ice" game, was carried over an experimental fiber optic system.



▲ **Fig. 4.** 1.7-Gb/s transmitter.

Subsequently, more-sophisticated InP-based lasers, including designs with distributed feedback gratings to produce a single, stabilized wavelength [4] were designed, developed, and manufactured by the group. An electro-absorption modulator was later incorporated, on the same chip, into this design. Descendants of these devices—operating at data rates as high as 40 Gb/s, but more typically at 10 Gb/s—are useful for wavelength-division-multiplexing applications and remain in volume production in the United States, Japan, and other parts of the world. They make use of the "ultimate" low-loss 1.5–1.6-μm region in modern single-mode fibers. Metal organic chemical vapor deposition technology has now substantially replaced LPE in diode laser manufacture.

During these long, difficult years, the author sometimes pondered the meaning of Wolfgang Pauli's characterization of condensed-matter physics as "Schmutzphysik." Did he mean simply that it was complex and therefore hard? Did he mean that it was difficult literally because impurities (dirt) at unheard-of small concentrations affect everything? Or did he simply mean that any elegant physics involved was hidden in an opaque matrix of mud? At times, the author thought of the group's researchers as the "mudders." Fortunately, they ended up finding gold. Bob Rediker, a professor at MIT and MIT Lincoln Labs, expressed his view of the work leading to long-lived diode lasers as follows: "In the 1980s and early 1990s, I mounted a campaign with



▲ **Fig. 5.** B. C. DeLoach, R. W. Dixon, and R. L. Hartman receiving the IEEE Gold Medal for Engineering Excellence in 1993.

others to insist that those who by much hard work made inventions practical be honored. In particular, I wanted recognition for the team at Bell Telephone Laboratory. They had increased the mean time to failure at room temperature of the double-heterostructure GaAs-based laser from several minutes in 1970 to an extrapolated 8 million hours in 1978." Rediker's efforts along with others led to B. C. DeLoach, R. W. Dixon, and R. L. Hartman receiving the IEEE Gold Medal for Engineering Excellence in 1993 for this work (see Fig. 5).

The group's efforts in the 1970s, 1980s, and 1990s were aimed at Bell System applications in long-distance, high-volume voice, data and video transmission—both on land and undersea. Today, essentially all terrestrial and undersea telecommunications, data, and television traffic above the local distribution level is carried in fiber using lasers as sources. The Internet would not be possible without these laser devices. Undersea cables with long repeaterless spans (approaching 10,000 km) now often have the high-performance lasers that encode digital information only at the land ends. Much simpler continuously operating lasers, which carry no signal information, are used to pump fiber amplifiers that are periodically spaced under the sea. Data rates in a single fiber, using very-high-speed modulation and wavelength division multiplexing, in high-volume applications, can approach 1 Tb/s—20,000 times higher than the group's initial 45-Mb/s rates!

The program also supported what was then called "fiber-to-the-home," or colloquially "the last mile." This application took longer to become a reality because of the breakup of the Bell System and the high costs of serving individual customers. It was pleasing, and a little nostalgic, when about five years ago Verizon brought their laser-based FiOS product to the author's home. On the consumer products side, it has been extremely satisfying to witness the unexpectedly fast and widespread application of lasers in products such as printers and CD/DVD players and/or the dramatic price reductions made possible by these high-volume applications. Through the efforts of thousands of scientists and engineers throughout the world, both the programs the author worked on and their subsequent applications have succeeded beyond his wildest dreams.

The author is grateful to each one of the scores of professional scientists, technologists, and many others who contributed to the success of the Bell Laboratories semiconductor laser development program during the last decades of the twentieth century. It was fun being along for the ride.

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