# L A S E R S: The first 25 years

By Anthony J. DeMaria

Since the earliest days of the utilization of the electromagnetic spectrum, there has been a steady drive toward the production and use of coherent electromagnetic energy of higher and higher frequency. This tendency resulted partly from the realization that an increase in transmitted information, directivity, and efficiency were available with increasing carrier frequency and partly as



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a result of crowding and interference between existing frequency bands.

Another important drive toward generating coherent radiation of higher frequency resulted from the fact that researchers were interested in utilizing these waves for probing atoms in solids, liquids, and gases by employing experimental techniques such as nuclear magnetic resonance, paramagnetic resonance, and cyclotron resonance.

As a result of these needs, active electronic devices utilizing the flow of an electron stream in vacuum or the flow of electrons and holes in semiconductor materials have been devised and greatly improved for the generation of higher frequencies. Examples of such devices are: vacuum tubes, transistors, magnetrons, klystrons, traveling wave tubes, parametric amplifiers, and tunnel diodes. With these devices, researchers have generated coherent radiation of frequency in the hundreds of gigahertz, and with the use of harmonic generators, this figure has been extended by approximately an order of magnitude. Almost without exception, as soon as higher frequency devices became available, researchers rushed to utilize them in probing the atomic and molecular domain of liquid, gases, and solids.

#### Natural resonators

The physical dimensions of the resonators used to select the oscillating frequency of conventional oscillators in the higher frequency range are of the order of magnitude of the wavelength of the radiation generated. As a result, the construction of resonators of the small dimensions required at wavelengths shorter than submillimeter becomes extremely difficult. In the late 1940s and early 1950s it became apparent that the old method of scaling down existing devices for higher frequency generation was becoming impossible to apply. In the search for alternate methods, researchers came to realize that the large supply of natural resonators in the form of atomic and molecular systems could be utilized to amplify and even generate coherent electromagnetic energy.

The operation of the ammonia beam (NH<sub>3</sub>) maser by Gordon, Zeiger, and Townes in 1954 ushered in a new breed of active devices.<sup>1</sup> The acronym MASER was formed from *m*icrowave *a*mplification of stimulated *e*mission of *r*adiation. The NH<sub>3</sub> beam maser was the first device to use stimulated emission from population inverted states of quantum mechanical resonances to provide gain for an electromagnetic oscillator. The operation of this quantum mechanical device initiated the field of quantum electronics. In 1984, the field of quantum electronics was 30 years old.

In 1958, A.L. Schawlow and C.H. Townes published a classic paper suggesting the use of the maser principle (with appropriate modification) for the generation of coherent infrared, visible, or ultraviolet radiation.<sup>2</sup> The operation of the first ruby laser by Maiman in the latter part of 1960 made available for the first time a visible light beam having characteristics previously associated only with radio and microwave radiation.<sup>3</sup> The acronym LASER was formed from light amplification of stimulated emission of radiation. This year marks the 25th anniversary of the laser.

Laser action now has been observed in solids (crystalline and noncrystalline insulators and semiconductors), liquids, gases, and plasmas yielding thousands of discrete wavelengths varying from the vacuum ultraviolet to the millimeter wavelength portion of the electromagnetic spectrum. Dve, color centers, and lead salt lasers now provide tunability over the visible, near IR, and IR spectrum. At present, there is an overlap in the abilities of electronic and laser devices for the generation of millimeter and submillimeter wave radiation. Scientists are still driving toward generation of coherent radiation at ever higher frequencies extending to soft and hard x-ray radiation.

Few developments in science have excited the imagination of scientists and engineers as has the laser. The laser made it possible to transport into the optical region all the basic techniques developed for application in the radio and microwave region, such as harmonic generation; parametric amplification; amplitude, frequency, and phase modulation; homodyne and heterodyne detection; chirping and pulse compression. In the 25 vears since its first realization in the form of pulsed coherent emission from a ruby single crystal, the field has grown at a rate rarely experienced in science. The availability of these intense, coherent optical radiation sources has made it possible for scientists to experimentally investigate optically generated plasmas, optical harmonic generation, stimulated scattering effects, photon echoes, self-induced optical transparency, optical adiabatic inversion, picosecond optical pulses, optical pulse compression, holography, optical shocks, self-trapping of optical radiation. optical parametric amplification. optical ranging to the moon, extremely high resolution spectroscopy, refined measurements of many of the basic physical constants (i.e., length, light velocity, etc.), and ultrafast relaxation processes in atoms and molecules.

In addition to the inherent attraction of exploring, characterizing, extending, and exploiting a new physical phenomenon, research in lasers was stimulated by the early experimental verification that coherent radiation could be generated in crystalline systems different from ruby and in other optical transparent media such as gases, glasses, semiconductors, and liquids. Thus, a large research effort in materials research was joined to the extensive phenomenological investigations.

## A multidisciplinary field

The laser device field today encompasses numerous disciplines including solid state, molecular and atomic physics, spectroscopy, optics, acoustics, electronics, semiconductor technology, plasma physics, vacuum technology, organic and inorganic chemistry, molecular and atomic kinetics, thinfilm technology, glass working technology, crystallography, and more recently, e-beams, x-rays, fluid dynamics, aerodynamics, and combustion physics. In sum, even without considering applications, the field has grown so fast and proliferated so broadly that the tendency for scientists to specialize within it is a virtual necessity. As a result, probably no individual today would profess to be authoritative over the whole field of laser devices, or even knowledgeable of most of the significant literature.

For approximately the first 15 years, 1954 to 1969, the field of quantum electronics was in the 'technology birth' phase. This phase was characterized by numerous scientific discoveries and inventions, as well as widely believed visions and predictions of numerous medical, industrial, commercial, scientific, and military applications. A shift in emphasis from maser to laser devices occurred after the operation of the ruby laser in 1960. During this phase, numerous laser devices were discovered from a large variety of gases and liquids, as well as both amorphous and crystalline dielectrics and semiconductor solid state materials.

Relatively few business opportunities existed during this phase except to sell components, materials, and devices to researchers concerned with developing the technology base of lasers. Some opportunities existed in selling relatively newly discovered laser sources to researchers interested in probing the linear and nonlinear electromagnetic behavior of atoms and molecules in liquids, solids, and gases. Large corporations were funding in-house research efforts in the technology as well as capturing significant government research and development contracts, which were directed toward determining the feasibility of numerous military applications during this early development cycle of the technology.

For approximately the next 15 years, laser technology entered the "engineering development" phase. This phase was characterized by a very noticeable decrease in scientific breakthroughs and a perceived impatience with the progress the technology was making in finding applications which addressed large market opportunities. This was the period when the statement. "the laser was a solution in search of a problem," was often heard. Many companies with marginal interest in laser technology dropped out of the field during this period. During this phase, entrepreneurs invested considerable effort in searching for and prioritizing perceived markets having large growth potentials. During these first two periods, the military market was larger than the commercial/industrial markets.

Laser technology has now firmly entered the "manufacturing technology" phase. Sizable markets have now been identified. There is now a strong system and subsystem development effort where laser devices provide either significant lower cost or higher performance leverage over older, more mature technologies. Consequently, product developments have now intensified and many new start-up companies are being created. In addition, well-established large corporations are marketing products aimed at markets that laser technology can uniquely address. These markets are in telecommunications, data processing and storage, entertainment, printing, material working, and medical applications. The commercial/industrial markets are now larger than the military market.

The home consumer is also beginning to experience laser technology directly by means of video and audio disks, laser printers for small computers, bar code readers at checkout counters, fiber-optics telecommunications, and various medical treatments. There is evidence that consolidation is beginning to occur among numerous small companies dedicated toward markets that utilize laser technology.

## Next: 'mature' technology

At some time in the future, laser technology will enter the "mature technology" phase, which will be characterized by cost and volume (i.e., economy of scale) driven markets requiring capital intensive manufacturing plants. Eventually a few large companies will address the most important markets, and chances are good that the surviving manufacturers will not be recognized as the laser manufactures known to us today.

It has been reported that the dollar value of the 1984 worldwide laser market in the commercial and government/military sector was approximately \$2.855 billion and \$1.305 billion, respectively,<sup>4</sup> for a total of approximately \$4.16 billion. Figure 1 compares the 1983 and the 1984 market dollar values. Of the commercial market, ap-



FIGURE 1. Laser industry world markets. Source: Spectra-Physics, 1983 and 1984 annual reports.

proximately \$2.502 billion was reported to be in systems and addons, while laser devices themselves amounted to approximately \$353 million of the 1984 world commercial market. From these estimates, an entrepreneur would rightfully conclude that business opportunities are more plentiful if one adds systems and add-ons to his laser device products.

It is important to note in Fig. 1 that the size of the military market was smaller than the commercial market in 1983 and 1984. This trend is expected to continue in the future. A 1983 forecast predicted that the laser worldwide market would grow at a 23% annual rate,<sup>4</sup> with well over 75 laser companies significantly addressing these world markets. This remarkably high growth rate is comparable to that experienced by the microelec-



COMMERCIAL 44% SYSTEMS & ADD-ON 47% LASER DEVICES 26% **GOVERNMENT & MILITARY** 6% TOTAL MARKET 29% 0 10 20 30 40 50 % GROWTH



FIGURE 3. Commercial laser industry world market. Source: Spectra-Physics, 1983 and 1984 annual reports.

tronic and information processing market.

Figure 2 compares the 1984 and 1983 growth of the laser markets. Note that the total market grew by 29% in 1984 when compared with the 1983 sales. Military sales experienced only a 6% increase in this same period, while the commercial market grew by a phenomenally large 44%.

A more detailed look at the 1983 and 1984 laser commercial world market reveals that approximately 63% and 50%, respectively, of these two years' commercial markets (i.e., \$1.25 billion and \$1.44 billion, respectively) were attributed to the area of printing and graphics associated with information and data processing (See Fig. 3). Since Spectra-Physics does not have a product line in the entertainment or computer field, data on semiconductor lasers and subsystems associated with the video and audio disks and data storage markets was not included in its annual report,<sup>4</sup> and thus not included in the data illustrated by Fig. 3. The audio and video disk entertainment market is bringing laser technology directly into the home. Fortune forecasted that "music lovers in the U.S. will gobble up 15 million disks . . . vs. 5.8 million in 1984."5 Fortune also forecasted that "this year, worldwide sales of players and disks are expected to reach \$1.3 billion."

The second largest segment of the world's laser commercial market is laser material working, which accounted for approximately 11% in 1983 (i.e., \$210 million) and 10% in 1984 (i.e., \$285 million) of the total market, while the third largest market segment was communication, which accounted for approximately 8% in 1983 and 1984 (i.e., \$150 million and \$225 million, respectively). The medical market is the fourth largest segment, with \$105 million in 1983 and \$150 million in 1984, capturing just over 5% in each of these

two years. The metrology, industrial inspection, and scientific laser market was just under 5% in 1983 and 1984 (i.e., \$90 million and \$135 million, respectively) of the total market, and it ranks fifth in size after the medical market. The data capture (bar code readers. etc.) sector of the market is the sixth largest in size, with 1983 and 1984 market percentages of just under 4% (i.e., \$75 million and \$110 million, respectively). The smallest segment was the alignment market, with 1983 and 1984 sales of \$70 million and \$85 million, respectively, and market percentages of just under 4% in 1983 and just under 3% in 1984. In the 1983 numbers, a \$35 million miscellaneous category is included which is not shown as a bar plot in Fig. 3, but included in the \$1,985 million total.<sup>4</sup>

sers in the medical field is a source of great pleasure to laser researchers. One of the earliest medical applications of lasers was in retina operations. Lasers are now either being used or investigated in cataract surgery, bleeding ulcers treatment, opening of blocked windpipes, reconnection of severed nerves, removal of tumors, and cleaning the plaque that clogs blood vessels. Lasers are also starting to play a role in dermatology, plastic surgery, gynecology, and podiatry. It is no wonder that the market for laser systems for medical applications is expected to double in each of the next several years. It is an embryonic but exploding market.

Figure 4 compares 1984 sales growth with 1983 sales for the market segments identified in Fig. 3. The communication and the metrology/industrial inspection mar-

The expanding applications of la-



FIGURE 4. Commercial laser industry growth, 1983-1984.



FIGURE 5. Fiber optics market: fibers, cables, transceivers, components. Source: Business Week, May 21, 1984.



FIGURE 6. Applications of semiconductor lasers.

kets had an astonishing 50% growth in this two-year period. The data capture and the medical section of the market had outstanding increases of 47% and 43%, respectively. The growth of 36% achieved by the material working market and 21% for the alignment market would be the envy of most high technology industries. The printing and graphic section of the laser market had the smallest growth—15%—of the identified market.

In the automated offices of tomorrow, it has been widely forecasted that video screens will some day displace ink and paper. Today, however, office automation is producing more paper, not less. The printers that help computers create much of this paper have become a \$2.4 billion industry, with the promise that printer sales will more than double before the decade ends.<sup>6</sup> Semiconductor laser printer technology is expected to become the major competitor against ink jet printers in the future computer printer market. One or both of these technologies is expected to displace the impact of the typewriter technology extensively used today.

Much of the laser communication market-that is, the fiber-optics telecommunication marketsis held by large, vertically integrated corporations such as AT&T. NT&T, and IT&T, and is thus not available to other manufacturers. Undoubtedly, this fact is responsible for the relatively small fraction of the total commercial laser industry world market attributable to the laser communication market as illustrated by Fig. 3. By 1990, it is forecast that the fiber-optics world market will exceed \$4.5 billion per year while the U.S. market will be approximately \$2 billion per year (Fig. 5). Business Week predicted that the end of conventional copper wire in the telecommunications industry could come as early as the turn of the century; more-

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over, semiconductor lasers coupled with fiber-optics technology will make ground and undersea cable communication so inexpensive that few commercial communication satellites will be launched in the 1990s.<sup>7</sup> There were 250,000 miles of optical telecommunication fibers installed within the U.S.A. in 1983. Northern Business Information Inc. has forecasted that approximately  $1.3 \times 10^6$  miles of telecommunication fiber will be installed within the U.S. in 1986. This installation is expected to increase to  $4.5 \times 10^6$  miles in 1990.<sup>7</sup>

Over the last 20 years, three areas of laser technology that have received continuous and extensive R&D support are laser weapons, controlled fusion, and semiconductor laser development. By most estimates, the first two are still believed to be 20 years away from making a national impact. Because of their importance to national security and economical well-being, they have received extensive government R&D support in many countries. The semiconductor laser, on the other hand, has been developed primarily by industrial R&D funds and spawned many new sectors of major industries such as telecommunication, printing, video and audio disks, data recording, and bar code reading, as depicted in Fig. 6. As another example of the large markets spawned by the semiconductor laser, Electronics Week forecasted that the data storage optical disks market will reach \$7.3 billion by  $1990.^{8}$ 

Optical disks can offer more than 20 times the information density of current magnetic storage devices at a lower cost per byte. Consequently, they are envisioned as generating the next revolution in mass storage. The technologies for write-once and read-only optical disks have been well in hand for some time. They use a modulated laser beam to permanently engrave a submicron-sized bubble or pit in the active layer of a medium. Intensive research has been focused on erasable optical disks utilizing a semiconductor laser that causes either a phase-change or magnetooptical change in a media. At present, 40 megabyte magneto-optical disks and drive systems for mass storage are about to enter the market.

# Quantum electronics vs. electronics

From the standpoint of the time required to commercialize the field of quantum electronics so that it represents a sizable market, all indications are that its development has not been that different from the development of the electronics field, which was initiated by the invention of the vacuum tube at the turn of this century. The heart of electronic technology is the device that controls the flow of an electron stream (electrical current) either a vacuum tube or a transistor. Since the laser controls the flow of a photon stream (light), the laser can be considered to be the heart of quantum electronics technology. Some have carried this analogy one step further and called the quantum electronics field "photonics." One should not jump to the conclusion that electronics and photonics technologies will compete against each other: Instead of competing, these two fields complement one another.

Most will agree that after only 25 years in existence, the laser field is young and robust, with a highly promising and exciting future. It is now spawning new products and opening up major new segments of basic industries which will insure its growth well into the next century. The fields of fiber-optics telecommunications; optical audio and video disks; optical data storage; opto-electronics: lasers for material working (cutting, welding, heat treating, hole drilling, scribing, etc.): medical laser applications: laser instrumentation; and military applications are still in a state of infancy so that considerable growth is yet to come.

The most serious challenge laser technology faces is the continuing shortage of electro-optical engineers required (1) to develop the numerous new and rapidly evolving products the technology is generating and (2) to continually advance the state-of-the-art technology required to meet new product needs. To work in the field as an engineer, one needs a background in optics and electronics as well as in quantum electronics; however, most engineers working in the field are either physicists who have learned some electronics or electronic engineers who have learned some optics. The offering of a formal undergraduate engineering curriculum in electro-optical (or photonic) engineering would be a big boost to this emerging technology giant.

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