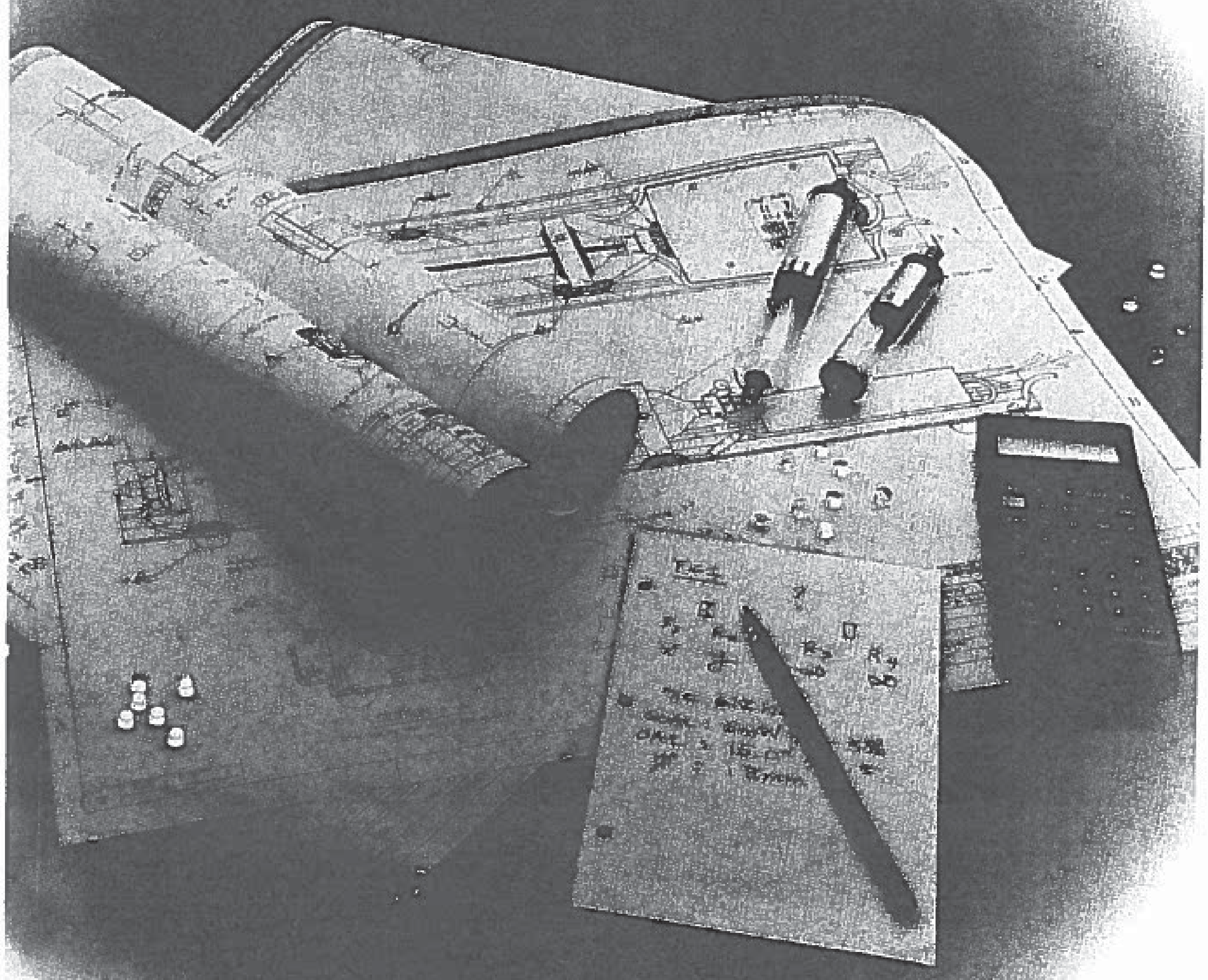
LASER ENGINEERING



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10

Conventional Solid-State Lasers

Objectives

- To summarize the sequence of historical events leading to the development of the modern commercial conventional solid-state laser.
- To summarize the commercial applications of conventional solid-state lasers.
- To describe the major laser host materials for conventional solid-state lasers.
- To describe the various energy states of the Nd:YAG laser and to summarize how these states interact with each other.
- To compare and contrast noble gas discharge lamp pumping versus semiconductor diode laser pumping for conventional solid-state lasers.
- To describe the design and construction of noble gas discharge lamp pumped conventional solid-state lasers. This includes the details of the noble gas discharge lamps, the power supplies, and the pump cavities.
- To describe the construction of a modern noble gas discharge lamp pumped Nd:YAG laser.
- To describe the design and construction of semiconductor diode laser pumped conventional solid-state lasers. This includes the details of the semiconductor pump lasers, the power supplies, and the pump cavities.
- To describe the construction of a modern semiconductor laser-pumped Nd:YAG laser.

10.1 HISTORY

One application that has driven a great deal of laser development is the idea of a directed beam weapon. From Buck Rogers to Captain Janeway, the concept of aiming a beam of energy at a target and vaporizing it has been very compelling to the military. In 1960, soon after the invention of the ruby laser, the Department of Defense (DOD) spent approximately $1.5 million on laser development. In 1961 the DOD spent $4 million on laser-related research, increasing to $12 million in 1962 and $19 to 24 million in 1963.[1] From 1960 to roughly 1980, the majority of academic research and much of industrial research was funded (directly or indirectly) by the military community.[2]

Very early in the development of lasers, it was recognized that noble gas lasers were far too inefficient for any possibility of a directed energy weapon. Three-state ruby lasers were not much better. However, in 1961 Johnson and Nassau demonstrated laser action using trivalent neodymium in calcium tungstate.[3] This was a significant development, as it opened the class of efficient four-state trivalent rare earth laser dopants. Later in 1961, Elias Snitzer succeeded in obtaining laser action from trivalent neodymium (Nd) doped in barium crown glass.[4] This development showed that laser action could be obtained in a material that could be fabricated in large sizes (see Figure 10.1 for a photograph of the very large NOVA glass laser).

In the period following the experiments of Johnson, Nassau, and Snitzer, solid-state laser research exploded into a flurry of experiments demonstrating laser action from a wide variety of di- and trivalent rare earth dopants in an incredible variety of laser hosts. More details on this history can be found in the review papers of the era by Kiss and Pressley[5] and by Young.[6] For a modern list of di- and trivalent rare earth dopants (and their hosts), see Weber.[7] (Laser dopants and their hosts are discussed in Section 10.3.)

Hundreds of important research results were obtained during this prolific period. Of special interest is the demonstration of laser action in Nd-doped yttrium aluminum garnet (YAG) by Joseph Geusic et al. at Bell Laboratories[8] and the demonstration of laser action from the trivalent dopants thulium, holmium, ytterbium, and erbium in YAG by Johnson et al., also at Bell.[9] Other Nd:YAG milestones are the first demonstration of

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[1] Joan L. Bromberg, *The Laser in America, 1950–1970* (Cambridge, MA: The MIT Press, 1991), p. 102.

[2] Arthur Schalow has said, "I often joked that no matter what you told the press about lasers, it always came out as a 'death ray' or a cure for cancer—or both!" Quoted in Jeff Hecht, *Laser Pioneers*, revised ed. (Boston, MA: Academic Press, 1992), p. 92.

[3] L. F. Johnson and K. Nassau, *Proc. IRE* (Correspondence) 49:1704 (1961); L. F. Johnson, G. D. Boyd, K. Nassau, and R. R. Soden, *Phys. Rev.* 126:1406 (1962); and L. F. Johnson, G. D. Boyd, K. Nassau, and R. R. Soden, *Proc. IRE* (Correspondence) 50:213 (1962).

[4] E. Snitzer, *Phys. Rev. Lett.* 7:444 (1961).

[5] Z. J. Kiss and R. J. Pressley, *Proc. IEEE* 54:1236 (1966).

[6] C. Gilbert Young, *Proc. IEEE* 57:1267 (1969).

[7] Marvin J. Weber, ed, *Handbook of Laser Science and Technology, Vol. I, Lasers and Masers* (Boca Raton, FL: CRC Press, Inc., 1982); and the more recent supplement: Marvin J. Weber, ed, *Handbook of Laser Science and Technology, Sup. I, Lasers* (Boca Raton, FL: CRC Press, Inc., 1991).

[8] J. E. Geusic, H. M. Marcos, and L. G. Van Uitert, *Appl. Phys. Lett.* 4:182 (1964).

[9] L. F. Johnson, J. E. Geusic, and L. G. Van Uitert, *Appl. Phys. Lett.* 7:127 (1965).

Q-switched Nd:YAG operation by Geusic et al.,[10] and the first mode-locking of Nd:YAG by DiDomenico et al.[11] (Q-switching is discussed in Section 6.2 and mode-locking in Section 6.4.)

Another important pattern began to emerge during the solid-state laser development period of the 1960s. Unlike gas laser development, solid-state laser development was driven by the available materials technology. This pattern was certainly apparent during the early days of Nd:YAG laser development. When Geusic had originally identified YAG as a possible laser host, there were no high optical quality YAG crystals available. Geusic worked with LeGrand G. Van Uitert (of the Chemistry Research Department at Bell Laboratories) to develop a Czochralski crystal-growth process specifically for making high optical quality Nd:YAG crystals. This growth process was then handed off to Union Carbide. The laser developments in Nd:YAG precisely paralleled the continuing improvements in the crystal-growth technology.[12]

During this developmental period, Nd:YAG began to emerge as the leading solid-state material for commercial solid-state laser development. YAG is a mechanically robust and high optical quality material with good thermal properties. Neodymium is a four-state laser ion and (when doped into YAG) yields a laser system whose pump bands match well with standard commercial light sources. The combination of the two led to the introduction of the lamp-pumped Nd:YAG laser as a standard commercial laser source (see Section 10.4).

Nd:glass was another laser material to achieve prominence during this period. Glass is a less robust material than YAG and has significantly poorer thermal conductivity. However, the isotropic nature of glass permits higher doping concentrations for the laser ion and glass can be manufactured in very large sizes. Thus, Nd:glass became a favorite laser material for large laser systems. The crown jewels of these efforts are the huge glass lasers built by Lawrence Livermore National Laboratories for inertial confinement fusion (see Figure 10.1). These lasers began with Janus (1974; with an output energy on the order of 80 joules), and proceeded through Cyclops (1975), Argus (1976), Shiva (1977), and Nova (1984); gaining roughly an order of magnitude energy during each development cycle. An overview of the LLNL laser program is given by Emmett et al.[13] and Lawrence Livermore National Laboratory publishes a detailed annual report.

Another important thread in solid-state laser systems is development of semiconductor diode pumping of solid-state lasers (see Section 10.5.5). It was recognized extremely early that the light from semiconductor junctions could efficiently pump solid-state lasers. The first proposal of this concept was by Newman in 1963, and the experimental demonstration consisted of using 880 nm radiation from an LED-like source to excite fluorescence in $Nd:CaWO_4$.[14] Ochs and Pankove in 1964 used an array of LEDs in a transverse geometry to pump a $Dy^{2+}:CaF_2$ laser.[15] The first semiconductor diode laser pumped solid-state laser

[10] J. E. Geusic, M. L. Hensel, and R. G. Smith, *Appl. Phys. Lett.* 6:175 (1965).

[11] M. DiDomenico, J. E. Geusic, H. M. Marcos and R. G. Smith, *Appl. Phys. Lett.* 8:180 (1966).

[12] Joan L. Bromberg, *The Laser in America, 1950–1970* (Cambridge, MA: The MIT Press, 1991), pp. 176–7.

[13] J. L. Emmett, William F. Krupke, and J. I. Davis, *IEEE J. of Quantum Electron.* QE-20:591 (1984).

[14] R. Newman, *J. Appl. Phys.* 34:437 (1963).

[15] S. A. Ochs and J. I. Pankove, *Proc. IEEE* 52:713 (1964).

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