Diode Laser–Pumped Solid-State Lasers

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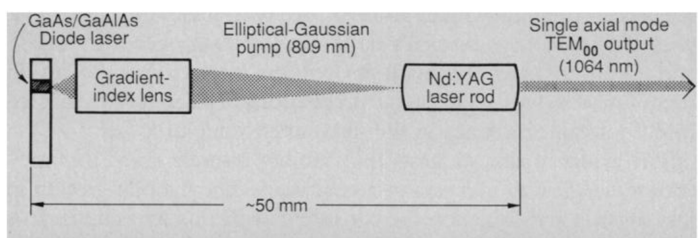
Diode laser–pumped solid-state lasers are efficient, compact, all solid-state sources of coherent optical radiation. Major advances in solid-state laser technology have historically been preceded by advances in pumping technology. The helical flash lamps used to pump early ruby lasers were superseded by the linear flash lamp and arc lamp now used to pump neodymium-doped yttrium-aluminum-garnet lasers. The latest advance in pumping technology is the diode laser. Diode laser–pumped neodymium lasers have operated at greater than 10 percent electrical to optical efficiency in a single spatial mode and with linewidths of less than 10 kilohertz. The high spectral power brightness of these lasers has allowed frequency extension by harmonic generation in nonlinear crystals, which has led to green and blue sources of coherent radiation. Diode laser pumping has also been used with ions other than neodymium to produce wavelengths from 946 to 2010 nanometers. In addition, Q-switched operation with kilowatt peak powers and mode-locked operation with 10-picosecond pulse widths have been demonstrated. Progress in diode lasers and diode laser arrays promises all solid-state lasers in which the flash lamp is replaced by diode lasers for average power levels in excess of tens of watts and at a price that is competitive with flash lamp–pumped laser systems. Power levels exceeding 1 kilowatt appear possible within the next 5 years. Potential applications of diode laser–pumped solid-state lasers include coherent radar, global sensing from satellites, medical uses, micromachining, and miniature visible sources for digital optical storage.

SOLID-STATE LASER DEVELOPMENT HAS BEEN PACED BY THE improvement and discovery of pump sources. The helical lamp, used to pump the first ruby laser, was replaced by the linear flash lamp and discharge arc lamp that are now used to pump virtually every neodymium-doped yttrium-aluminum-garnet (Nd:YAG) and neodymium glass (Nd:glass) laser system in the world. The next advance in solid-state laser technology promises to be improved pumping by means of diode lasers and diode laser arrays (*1*). The recent and rapid advances in the power and efficiency of diode lasers and diode laser arrays and their application to the pumping of solid-state lasers have led to a renaissance in solid-state laser development (*2*). Advanced technology solid-state lasers pumped by diode lasers will make possible such diverse applications as coherent radar for global wind measurements, semiconductor circuit repair, and all solid-state color video projection.

A question often asked is, "Why use the diode laser to pump another solid-state laser instead of using flash lamps or the diode directly?" The diode laser efficiently emits optical radiation into a narrow spectral band. When the emission wavelength of the diode laser lies within the absorption band of the ion-doped solid-state laser medium, diode laser optical pumping can be very efficient with little excess heat generation. Flash lamp pumping efficiency is limited by the broad spectral emission of the lamp and the less efficient absorption of the lamp radiation by the solid-state laser medium. Excess heat and power fluctuations of the lamp also degrade the solid-state laser performance, as does the finite lamp lifetime. The diode laser is essentially a continuous wave (cw) device with low energy storage capability, whereas the solid-state laser can store energy in the long-lived metastable ion levels. The stored energy can be extracted by rapid switching (Q-switching) to provide peak power levels that are orders of magnitude greater than from the diode laser itself. Furthermore, the solid-state laser can collect the output from several diode lasers to provide greater average power than is available from a single diode laser. The diode laser–pumped solid-state laser can operate at a variety of wavelengths not accessible with diode lasers. The diode laser–pumped solid-state laser linewidth is fundamentally orders of magnitude less than that of the



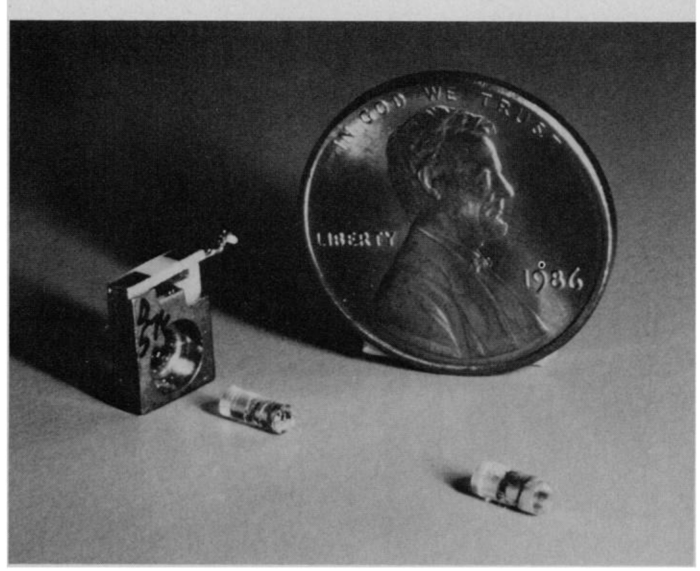


Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

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diode laser source. The solid-state laser source also emits optical radiation in a diffraction-limited spatial beam that is easily focused into a fiber or to a small spot. The result is that the diode laser–pumped solid-state laser provides spectral brightness "amplification" that is essential for many applications that require a high degree of temporal and spatial coherence.

Early Developments

The high efficiency of the diode laser compared to a flash lamp, coupled with the fortuitous overlap of GaAs diode laser emission wavelength with the absorption band of the neodymium ion, has allowed the diode laser source to become a nearly ideal pump source for solid-state lasers. However, it is only with recent improvements in diode laser power and efficiency that the replacement of the flash lamp by the diode laser and diode laser arrays has become a reality.

In 1963, one year after the nearly simultaneous discovery of the diode laser at four laboratories (*3*), Newman (*4*) recognized that the spectral overlap of the GaAs diode laser emission wavelength with the pump absorption band of the neodymium ion could lead to an efficient, compact, all solid-state laser. Keyes and Quist (*5*) successfully tested the idea in 1964 by demonstrating GaAs diode laser pumping of uranium-doped CaF_2 at 4 K. Early progress in diode laser–pumped solid-state lasers was slowed by the need for cryogenic cooling and by the low power levels of the diode lasers. The limited diode laser power led to the investigation of low power threshold intrinsically doped neodymium lasers during the early 1970s (*6*). It was not until 1972, nearly a decade after the pioneering experiment by Keyes and Quist, that Danielmeyer and Ostermeyer (*7*) demonstrated diode laser pumping of Nd:YAG at room temperature.

Recent Progress

The suggestion by Conant and Reno (*8*) in 1974 that diode laser arrays be used for pumping Nd:YAG lay dormant until 1980 when greater powers and efficiencies from the heterojunction GaAlAs diode lasers (*9*) allowed the group led by Rice at McDonnell Douglas to demonstrate a diode laser array–pumped miniature Nd:YAG rod laser (*10*). The work at McDonnell Douglas was motivated by the prospect of developing an efficient, long-lived, solid-state laser transmitter for satellite to satellite communication.

The concept of global wind measurements from a satellite by means of coherent laser radar and the Doppler effect was proposed by Huffaker in 1978 (*11*). Atmospheric wind measurements with CO_2 lasers in ground-based systems had proceeded well. However, for satellite-based global wind measurements the laser transmitter must meet strict weight and size criteria and provide 100 W of average power at 10% electrical efficiency over a 4-year period of operation. These requirements, which seemed impossible to laser technologists only a few years earlier, fit the admonition by Edwin Land, who counseled, "Don't undertake a project unless it is manifestly important and nearly impossible" (*12*).

In 1981, the group at Stanford initiated a study (*13*) of an all solid-state laser system that could meet the challenging requirements for a global remote wind-sensing laser transmitter. In an early laboratory demonstration, Sun and Byer (*14*) showed that a flash lamp–pumped Nd:YAG laser, when properly designed, could operate at the 100-kHz linewidth required for the measurement of wind speed. It was realized, however, that the flash lamp would have to be replaced by a diode laser or diode laser array to meet the efficiency and lifetime requirements of a satellite-based transmitter.

Fig. 2. Output power of the diode laser–pumped Nd:YAG monolithic oscillator versus input diode laser power. The 2.3-mW threshold and 25% slope efficiency are evidence for efficient operation.

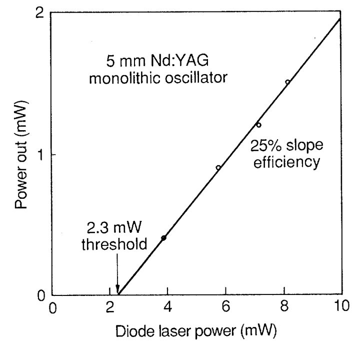
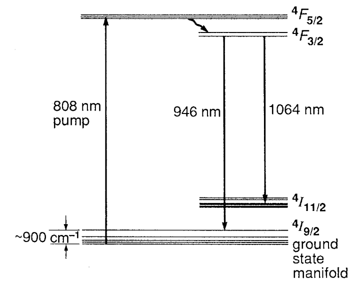


Fig. 3. Energy level diagram for Nd:YAG showing the common four-level 1064-nm transition and the quasi–three-level 946-nm transition. Diode laser pumping occurs at the 808-nm pump band.



Diode Laser–Pumped Neodymium Lasers

In 1982 Zhou *et al.* (*15*) demonstrated a diode laser–pumped miniature Nd:YAG laser with a linewidth of less than 10 kHz. The low threshold and good slope efficiency, together with the potential for long operational life, pointed to the advantages of diode laser pumping for the satellite-based global wind measurement transmitter. The monolithic design, coupled with the small size of the diode laser and focusing optics, meant that the source was rugged and compact. Figure 1 shows a schematic and photograph of the components of the diode laser–pumped, 5 mm long, monolithic Nd:YAG oscillator. Figure 2 shows the Nd:YAG laser output power versus the diode laser pump power for this early device. The 25% slope efficiency along with the 2.2-mW threshold power demonstrated the potential for efficient operation with diode laser pumping.

The Stanford work was soon extended by Sipes (*16*) who reported a diode laser linear array–pumped Nd:YAG laser with 8% wall plug efficiency. Sipes took advantage of the recently introduced commercial diode laser arrays invented and developed at Xerox by Scifres, Burnham, and Streifer (*17*) and commercialized in a joint venture between Xerox and Spectra Physics. The early multistripe diode laser arrays introduced by Spectra Diode were capable of producing in excess of 0.1 W of continuous wave output at 35% electrical to optical efficiency.

The possibility of diode laser pumping of neodymium-doped crystal hosts other than Nd:YAG was also explored. In early work Fan *et al.* (*18*) extended diode laser pumping to neodymium-doped lithium yttrium fluoride (Nd:YLF), which operates at 1047 nm. Nd:YLF is of interest because its long upper-level fluorescence lifetime allows energy storage and thus high pulse peak powers under Q-switched operation. The Stanford group also demonstrated self-Q-switched operation and internal second-harmonic generation by diode laser pumping neodymium doped into the nonlinear and electrooptic crystal $LiNbO_3$ (*19*).

The possibility of diode laser pumping Nd:glass was investigated by Kozlovsky *et al.* (*20*). The lower gain cross section of Nd:glass compared to Nd:YAG led to the expectation that the threshold power for diode pumping would be an order of magnitude higher in Nd:glass than in Nd:YAG. However, since the gain to loss ratio

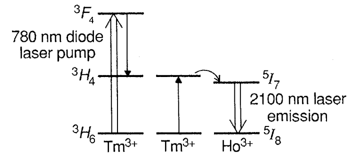


Fig. 4. Energy level diagram of the thulium-sensitized holmium:YAG laser source. The diode laser radiation is absorbed by the thulium ion at 780 nm. The energy is transferred to the holmium ion through a cross relaxation process; the system then exhibits gain and oscillates at 2100 nm. The holmium upper-level fluorescence decay time is 8 msec, which allows energy storage for Q-switched operation.

determines threshold and not the absolute gain cross section, Kozlovsky *et al.* were able to demonstrate experimentally a low 2-mW threshold for diode laser pumping of Nd:glass. Furthermore, the low loss of the Nd:glass medium led to a high 43% slope efficiency. Nd:glass is an interesting medium for diode laser pumping because of its low loss, high optical quality, and broad absorption band at the diode laser pump wavelength.

Three-Level Lasers

The solid-state lasers discussed in the previous section are four-level laser systems. That is, the lower laser level is well above the ground state of the ion and is unpopulated, making inversion and laser operation possible at low pump power levels. Figure 3 shows the energy level scheme for the four-level laser system operating at 1064 nm in Nd:YAG. Also shown is the three-level laser system operating at 946 nm in Nd:YAG. A number of potentially interesting laser systems are three level in nature where the lower level is in the ground-state manifold of the ion and is therefore partially populated at room temperature. Three-level lasers require stronger pumping to overcome the residual population in the ground level, or they require cooling to reduce the lower level population.

The interest in three-level laser systems motivated Fan and Byer (*21*) to investigate theoretically the possibility of diode laser pumping three-level laser transitions. The theory and subsequent experiments showed that diode laser pumping of three-level lasers was possible at room temperature. The first three-level laser system investigated was the 946-nm transition of Nd:YAG. Diode laser pumping of this laser transition was successful at room temperature with a 10-mW threshold power and a 34% slope efficiency (*22*). This laser transition is of interest because of its potential for frequency doubling, which would generate blue radiation at 473 nm. Frequency doubling has been demonstrated recently and is discussed below.

In recent work Duczynski *et al.* (*23*) demonstrated cw krypton ion laser–pumped operation of a thulium-sensitized holmium-doped YAG (Tm-Ho:YAG) laser at 2100 nm. This work was extended to diode laser pumping in a joint effort between the Hamburg University group (under the direction of Huber) and the Stanford group. The work demonstrated diode laser pumping and cw room temperature operation of the Tm-Ho:YAG laser system (*24*). The 2100-nm laser source operates in the eye-safe region of the spectrum and is thus of interest for coherent radar applications including global wind sensing. It also oscillates at a wavelength that is strongly absorbed by liquid water and, for this reason, may be of interest for medical applications.

The Tm-Ho:YAG laser operates through an energy transfer process in which the pump radiation absorbed by the thulium ion is transferred by a cross relaxation process to the holmium ion as shown in Fig. 4. The cross relaxation–sensitized pumping process for this system offers the unique possibility of a laser with a quantum efficiency of 2. That is, for every pump photon absorbed by the thulium ion at the 780-nm band, two inverted holium ions are created. This allows the laser to operate at high efficiency with the diode lasers and diode laser arrays already developed for pumping the Nd:YAG laser at 805 nm. The Tm-Ho:YAG laser system is more complex than Nd:YAG and requires further study. However, the early results at room temperature of 4-mW threshold pump power with a 19% slope efficiency are promising. In addition, the long 8-msec upper-level lifetime offers the potential for high peak power output under Q-switched operation.

Q-Switched and Mode-Locked Operation

The long upper-level energy storage times in solid-state lasers allow optical energy to be extracted in high peak power pulses under Q-switched operation. In the diode laser–pumped Nd:YAG and Nd:YLF lasers, peak output power levels of 2.8 kW in 10-nsec pulses and repetition rates of 1 to 3 kHz have been reported (*25*). These kilowatt peak power, microjoule energy lasers are useful for semiconductor processing and micromachining applications. They offer the advantages of compact size, long operational lifetimes, and high efficiency compared to traditional water-cooled, flash lamp–pumped laser sources.

The diode laser pumping of Nd:glass was extended by Basu and Byer (*26*) who reported a diode laser–pumped mode-locked Nd:glass oscillator. The Nd:glass laser oscillated when cw-pumped with a 30-mW diode laser. When acousto-optically mode-locked, the laser produced a continuous train of pulses with pulse widths of less than 10 psec in duration. Even shorter pulse widths are possible by frequency chirping the output in a single-mode glass fiber followed by pulse compression with a grating pair (*27*). Applications for this all solid-state mode-locked source include optical sampling of GaAs circuits with the recently developed electrooptic sampling method introduced independently by Mourou (*28*) and by Bloom (*29*).

Single-Frequency Operation: The Monolithic Nonplanar Ring Oscillator

The requirement for a stable single-frequency local oscillator source for coherent radar and for global wind measurements led Kane and Byer (*30*) to invent the monolithic nonplanar ring

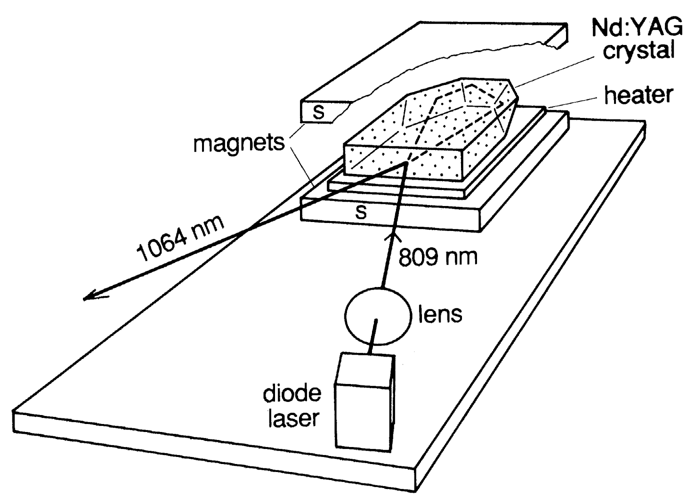


Fig. 5. Schematic of the diode laser–pumped, nonplanar ring oscillator that incorporates the elements of an optical diode to force oscillation in a single direction. The nonplanar ring oscillator operates in a single direction at a single frequency output and is insensitive to feedback.

oscillator. A schematic of a diode laser–pumped nonplanar ring laser is shown in Fig. 5. This device combines the elements of an optical diode into a monolithic ring structure to achieve single axial mode, unidirectional oscillation. In recent work (*31*) the linewidth of the diode laser–pumped nonplanar ring oscillator has been determined by performing beat note measurements between two independent laser oscillators. The observed 10-kHz linewidth, shown in Fig. 6, is not the fundamental linewidth of the device that is governed by the Schawlow-Townes equation (*32*)

$$\Delta \nu = h\nu/(2\pi\delta^2 P) \qquad (1)$$

where $\Delta\nu$ is the linewidth in hertz, δ is the decay time of the resonator, P the output power of the device, and $h\nu$ is the photon energy. This equation, first published in the 1958 paper that proposed the optical maser, shows that the experimentally observed 10-kHz linewidth of present nonplanar ring oscillators is well above the expected quantum-limited linewidth of 1 Hz for 1 mW of output power predicted by Eq. 1. Work is in progress to reduce the linewidth to that determined ultimately by the quantum noise limit.

In the future, the monolithic nonplanar ring oscillator may play a role similar to the highly stable quartz crystal oscillator introduced for frequency stabilization of radio-frequency electronic circuits. When fully engineered, the monolithic ring oscillator should operate at the quantum noise–limited linewidth. This will allow the development of quantum noise–limited optical sensors on the basis of the measurement of induced optical frequency shifts. For example, the Nd:YAG ring oscillator is known to tune with temperature at 3 GHz/°C, with magnetic field at 16 MHz/T, and with strain at 1 MHz per gram force. The ring also senses rotation at 1 hour^{-1} $(\text{Hz})^{-1/2}$, thus opening the possibility of an all solid-state laser gyro. The operation of the nonplanar ring oscillator has been extended to the 1324-nm line of Nd:YAG by Trutna (*33*) for use in coherent optical fiber measurement instrumentation.

Visible Radiation by Harmonic Generation

Diode lasers can be frequency-doubled directly as demonstrated by Gunter, who used $KNbO_3$ (*34*), and recently by Taniuchi and Yamamoto (*35*), who used a planar guided wave interaction in $LiNbO_3$. However, efficient harmonic generation of diode lasers has not been demonstrated because of the low power and nonideal spectral and spatial mode characteristics of the diode laser. The improved spatial and spectral characteristics of the diode laser–pumped miniature solid-state laser source do allow efficient harmonic generation.

In early work at Stanford, the nonlinear crystal $MgO{:}LiNbO_3$ was used to frequency-double a diode laser–pumped Nd:YLF laser source (*18*). The $MgO{:}LiNbO_3$ doubling crystal (*36*) was placed inside of the laser resonator to take advantage of the high circulating power levels. Figure 7 shows a schematic of the internal second-harmonic generation experiment in which a 30-mW diode laser–pumped Nd:YLF laser crystal was frequency doubled to yield 0.3 mW of cw green output power.

Harmonic generation was reported nearly simultaneously by Baer (*37*) who demonstrated efficient internal second-harmonic generation (SHG) with the nonlinear crystal potassium titanium phosphate (KTP) in a diode laser–pumped Nd:YLF laser. Baer discovered that the sum-frequency generation that occurred as a result of the multifrequency operation of the laser led to temporal instabilities in the harmonic output.

The instabilities inherent in internal SHG shown by Baer can be avoided by external resonant harmonic generation, first proposed and demonstrated in the late 1960s by Ashkin, Boyd, and Dziedzic

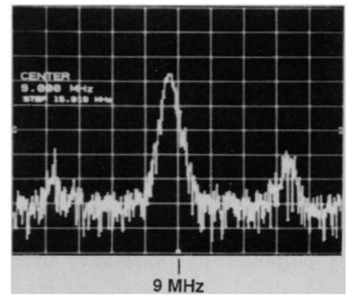


Fig. 6. Optical spectrum generated by beating two independent laser oscillators. The less than 15-kHz width of the beat frequency spectrum is mainly the result of technical noise and is well above the expected 1-Hz quantum noise limited linewidth of the nonplanar ring oscillator. Vertical scale: 10 dB per division. Horizontal scale: 20 kHz per division.

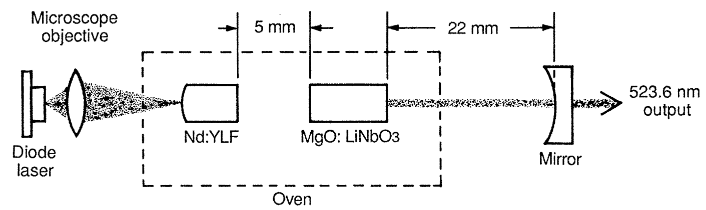


Fig. 7. Schematic of internal second-harmonic generation of a diode laser–pumped Nd:YLF laser using a $MgO{:}LiNbO_3$ nonlinear crystal to generate 0.3 mW of cw green. The output mirror is highly reflecting at 1047 nm and has a radius of curvature of 2.5 cm.

at Bell Laboratories (*38*). The harmonic conversion efficiency is increased by generating high circulating powers in an external cavity that can be resonant at either the second harmonic or at the fundamental wavelength.

In an elegant experiment that combined the advantages of the single-frequency nonplanar ring oscillator with the stability of a monolithic resonator fabricated onto a lithium niobate nonlinear crystal, Kozlovsky *et al.* (*39*) demonstrated efficient externally resonant harmonic generation. The single-frequency radiation was focused into a monolithic $LiNbO_3$ cavity resonant at 1064 nm. The increased circulating power at the fundamental led to 2 mW of second-harmonic power at 532 nm for only 15 mW of incident 1064-nm radiation. This approach, shown schematically in Fig. 8, offers the advantages of keeping optical elements out of the laser oscillator, independently optimizing the harmonic generation process, and yielding stable, single-frequency second-harmonic output. In the above experiment, iodine vapor strongly fluoresced when illuminated by the narrow linewidth, single-frequency green radiation. This opens the possibility of stabilizing the optical frequency of the diode laser–pumped Nd:YAG nonplanar ring oscillator by locking onto a hyperfine component of the iodine absorption spectrum (*40*) by means of sub-Doppler saturation spectroscopy. Recently, external resonant second-harmonic generation in a ring $LiNbO_3$ resonator achieved 56% conversion efficiency to yield 30 mW of cw green radiation.

As mentioned above, the operation of Nd:YAG on the three-level transition at 946 nm is of interest because of the possibility of generating blue output at 473 nm by harmonic generation. The successful generation of 3 mW of blue radiation was reported by Dixon *et al.* (*41*). Other nonlinear materials that are suitable for harmonic generation of the 946-nm transition have been evaluated by Fan and Byer (*22*). In a recent experiment, Bjorklund *et al.* (*42*) demonstrated efficient blue output by summing a diode laser–pumped Nd:YAG 1064-nm source with the output of the diode laser at 810 nm in KTP. The possibility also exists of modifying $LiNbO_3$ by periodically changing the sign of the nonlinear optical coefficient in step with the phase slip of the harmonic process to quasi-phasematch for efficient harmonic generation to the blue. Recent progress in the growth and periodic poling of the ferroelectric domains in $LiNbO_3$ show that this approach is feasible (*43*). Blue radiation is of interest for reading optical disks and as a source of radiation for fluorescence studies of biological systems.

Array-Pumped Solid-State Lasers

The rapid progress in diode laser technology has led to the development of diode laser arrays as a replacement for flash lamps for pumping high peak and average power solid-state laser sources. The group at McDonnell Douglas pioneered the design and demonstration of diode laser array–pumped Nd:YAG laser sources (*44*). The effort has involved the development of two-dimensional diode laser arrays assembled from bars of diode laser emitters that are stacked between copper plates for electrical contact and conduction cooling. At the Conference on Lasers and ElectroOptics held in Baltimore in April 1987, the McDonnell Douglas group and, independently, the group from Spectra Diode Laboratories described the performance of two-dimensional laser diode arrays formed from stacked bar emitters (*1*). The arrays described were operated at 200-μsec pulse widths at 10% duty factor with peak output power levels that exceeded 1000 W/cm^2. Furthermore, the overall efficiency of the two-dimensional arrays was greater than 45% and the arrays had projected lifetimes of over 1000 hours.

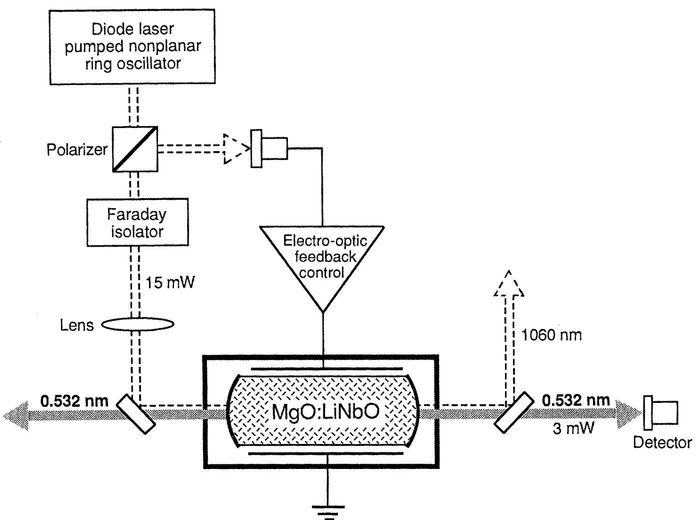


Fig. 8. Schematic of external resonant second-harmonic generation in a nonlinear crystal of MgO:$LiNbO_3$ onto which a resonator has been fabricated; 3-mW of cw green radiation was generated for 15 mW of incident 1064-nm power from the diode laser–pumped nonplanar ring oscillator. The electronic feedback loop acting through the electrooptic coefficient of the nonlinear crystal stabilized the external cavity at resonance.

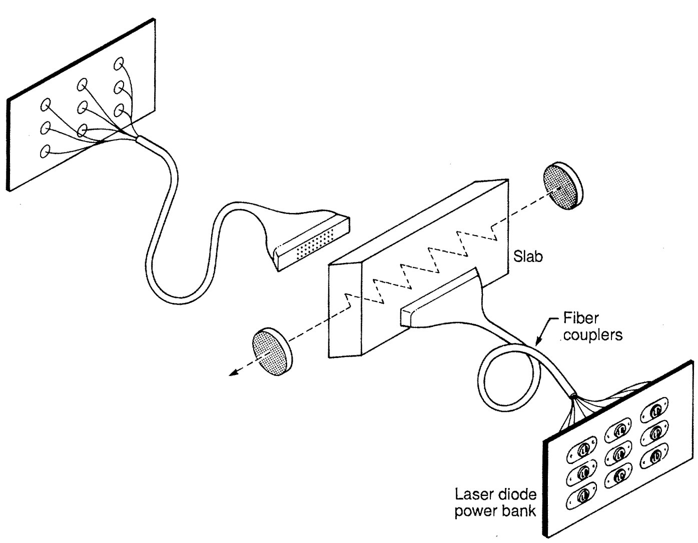


Fig. 9. Schematic of a proposed high average power slab laser oscillator pumped by an array of diode lasers. The use of many individual diode lasers with optical fiber coupling offers the advantages of lower cost, ease of power scaling, and long-term reliability.

Berger *et al.* (*45*) of Spectra Diode Laboratories presented results of an experiment in which a miniature Nd:YAG rod geometry oscillator operated at 10% overall electrical efficiency when pumped by a laser diode array. The group at McDonnell Douglas reported the use of a two-dimensional diode laser array to pump a Nd:YAG slab geometry laser. They reported 0.3 J of output energy from the Nd:YAG laser when pumped by 0.9 J of input energy from the diode laser arrays. The slope efficiency of the Nd:YAG laser was 33% in both long pulse and Q-switched operation. In recent work, Reed *et al.* (*46*) used a diode laser array to pump miniature Nd:YAG and Nd:glass slab laser oscillators. In this experiment, a 10-mm-long slab of either Nd:YAG or Nd:glass was placed adjacent to a 10 mm by 4 mm area diode laser array. The average output power obtained for the diode array–pumped Nd:YAG slab laser was 0.56 W at 42% storage efficiency.

Future Directions

These early diode laser–pumped solid-state laser experiments are promising and support further efforts toward the development of high average power diode laser arrays. A major hurdle to wider use of diode lasers and diode laser arrays is cost. One approach being pursued to reduce the cost is to develop face-emitting diode laser arrays that avoid the cleaving and reassembled steps necessary for the production of diode laser arrays from bar emitters. Approaches for directing the laser radiation generated in the plane of the GaAs wafer out of the plane include anisotropic etching of reflecting facets onto the wafer and preparation of second-order Bragg grating reflectors on the surface of the wafer (*47*). An alternate approach is to prepare lasers that emit normal to the wafer surface with built in normal reflectors and gain in the direction normal to the wafer surface (*48*).

The average power ultimately available from two-dimensional diode laser arrays will be determined by the ability to remove heat. In 1982 Tuckerman and Pease (*49*) suggested a method for heat removal from integrated circuits that employed a high efficiency finned microchannel cooler. The Tuckerman and Pease finned cooler, when fabricated in silicon, is capable of removing 1000 W/cm^2 of heat by conduction. Diode laser efficiencies have increased rapidly until at this time internal quantum efficiencies of 60% have been demonstrated (*50*). This has led to overall laser electrical efficiencies at room temperature of greater than 50%. Thus, half of the electrical input power is removed as coherent optical radiation and half is removed as heat. In the future, the coupling of the microfinned cooler with face-emitting diode laser arrays promises to yield a source of coherent optical radiation that approaches 300 W/cm^2 average optical output power. Today, average optical output power levels of 75 W/cm^2 have been achieved with stacked-bar emitters (*1*). If the individual diode laser emitters were phase coherent then the array could be electrooptically swept in angle or focused for applications to materials processing. At this time, the diode laser array radiation is only partially coherent. The emitted radiation is suitable for pumping solid-state lasers from which optical power can be extracted in a diffraction-limited spatial mode in either cw or Q-switched format. The overall electrical to optical output efficiency of a diode laser array–pumped solid-state laser is expected to exceed 15%.

The high cost of assembling two-dimensional diode laser arrays suggests an alternate approach to achieving high average output power levels through diode laser pumping. The report of a 0.75-W average power diode laser source with 25% efficiency (*51*) suggests the use of many individual diode lasers and optical fibers to route the power into a slab geometry solid-state laser oscillator. Previous work with flash lamp–pumped solid-state lasers has demonstrated the advantages of the slab geometry for high average power applications (*52*). The present cost of diode lasers in unit quantities reflects the research cost and not the production cost in quantity. Volume production leads to a cost reduction of 10 for every order of magnitude increase in production volume. This suggests constructing high average power solid-state lasers with a large number of 1-W diode lasers as an alternative to constructing more expensive diode laser arrays. One approach shown schematically in Fig. 9 is to couple the diode laser power to the solid-state slab laser medium through optical fibers. The diode lasers can be mounted remotely from the solid-state laser to facilitate electrical driver design and cooling. One advantage of this approach is the ability to service the system without disturbing the optical alignment of the solid-state laser. A second advantage is the ability to increase the output power in stages by adding more pumping diode lasers as needed. This design also exhibits a soft failure mode as opposed to a catastrophic failure mode because individual pump diode lasers fail independently. This controlled failure mode is advantageous for industrial applications and for space applications where long-term reliability is important.

Studies of past diode laser cost and performance show that the cost per unit output power has been falling a factor of 20 every 4 years. The cost projections are based on information from the diode laser manufacturers in Europe, the United States, and Japan. This rapid decrease in cost per watt of output power is consistent with historical pricing of silicon-based semiconductor devices. The decreasing cost with time suggests that diode laser–pumped solid-state lasers will be competitive with lamp-pumped lasers at the 1-W power level by 1989, at the 10- to 100-W level by 1992, and at power levels exceeding 1kW by 1994.

Conclusion

The rapid progress in diode laser development offers the potential for achieving efficient, compact, long-lived, all solid-state laser sources. Diode-pumped solid-state lasers will meet a growing number of scientific, medical, and industrial applications that require the combination of compact size, efficiency, and high optical power. Applications that stem from the coherence of the solid-state laser source include coherent Doppler radar for clear air turbulence monitoring from aircraft, earth observing, and perhaps global wind sensing from a satellite platform. Future scientific applications include coherent astronomy and possibly gravity wave astronomy. Medical applications appear promising because of the small size, efficiency, and choice of wavelengths of diode laser–pumped solid-state lasers, especially at the 2100-nm region where the radiation is absorbed in less than 100 μm of liquid water. Industrial applications are being initiated with the currently available microjoule Q-switched laser sources for micromachining and semiconductor circuit repair and modification. The use of diode laser–pumped solid-state lasers will extend to materials processing as the average power levels increase to beyond the kilowatt level.

However, if history is a guide, these compact efficient sources of coherent radiation will find widest application in the area of entertainment. Laser light shows and compact disks are already a reality. It is interesting to note that the Nd:YAG laser wavelengths at 946 nm, 1064 nm, 1121 nm, and 1320 nm can be frequency-doubled to generate output at blue, green, yellow, and red wavelengths. In the future diode-pumped solid-state lasers coupled with nonlinear optical processes may provide an all solid-state laser capable of generating the primary colors required for the projection of color video images.

REFERENCES AND NOTES

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