



Diode-pumped solid-state (DPSS) lasers and directly doubled diode (DDD) lasers, are an attractive alternative to air-cooled ion lasers and green helium neon (HeNe) lasers. These lasers combine the beam quality of a gas laser with the small size and efficiency of a diode laser and produce output at discrete wavelengths throughout the visible spectrum. Their excellent output stability, exceptional mode purity, and extremely low power consumption are ideal for both laboratory and OEM applications.

All of the systems described in this section comply with the applicable CDRH standards and IEC directives for stand-alone laser equipment. OEM versions of these lasers, designed specifically for inclusion in other systems, are available.

DPSS LASER CONSTRUCTION

The fundamental design of CVI Melles Griot DPSS laser systems is shown in the accompanying diagram. A semiconductor diode laser is used to pump a doped laser crystal (the lasing medium). One face of the crystal is coated to transmit the pump radiation but reflect the infrared laser radiation generated by the crystal. Visible output is obtained by placing a non-linear doubling crystal inside the laser cavity in close proximity to the laser medium. The output side of this crystal is coated to reflect the infrared fundamental laser frequency (completing the laser cavity) and to transmit the second harmonic generated by the doubling crystal. Finally, beam-conditioning optics collimate the output and filter out any remaining pump-laser or infrared radiation. The overall temperature of the laser cavity and the temperature of the semiconductor diode pump are tightly controlled by thermoelectric coolers (TECs), which provide rock-solid performance and reliability.

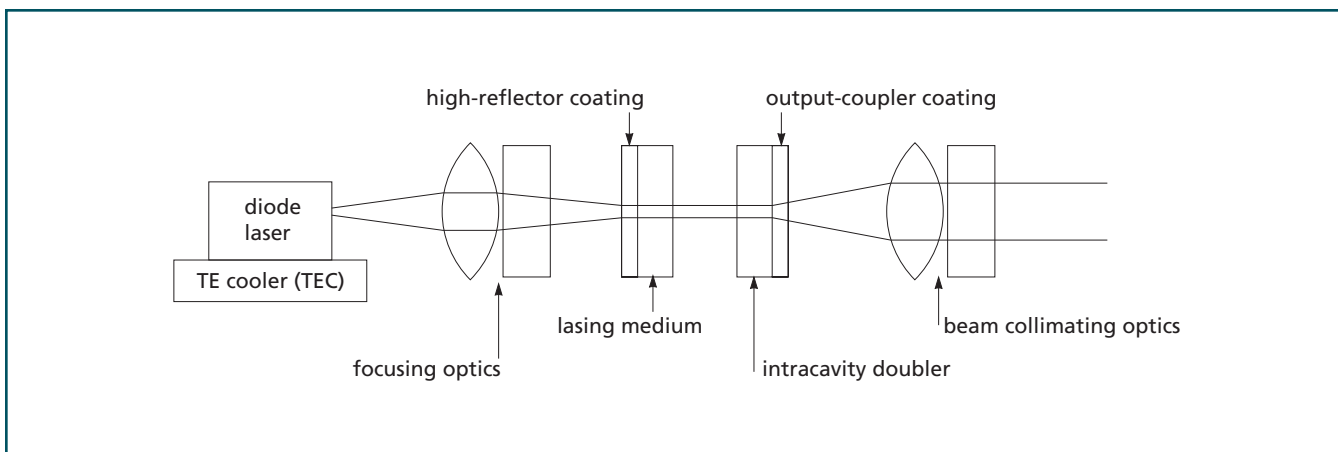
Introduction to Solid-State Lasers

DDD LASER CONSTRUCTION

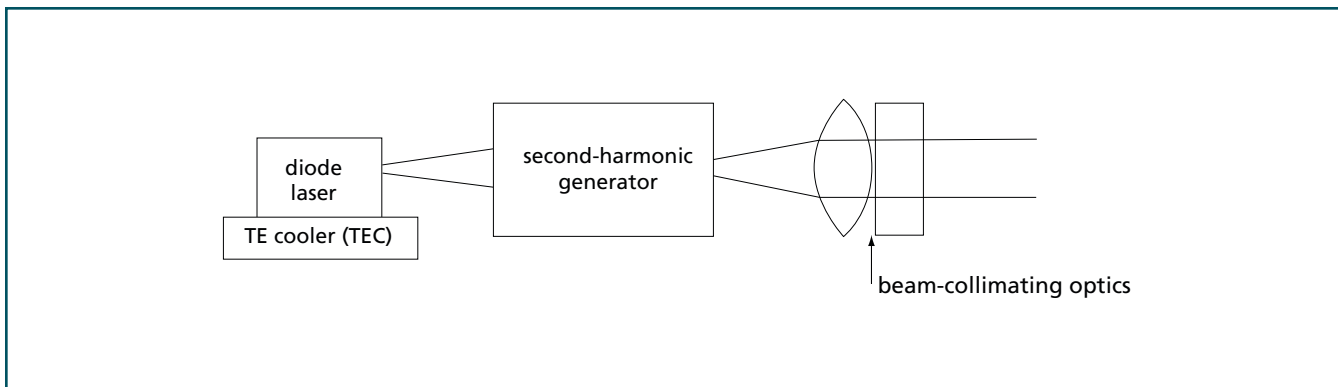
The directly doubled diode laser is an elegant solution for applications requiring low to moderate output power at 488 nm, because it uses far fewer parts, surfaces, and coatings than competing solid-state designs. The basic construction is shown in the figure on the next page. A Telcordia-qualified 976-nm telecom diode is coupled into a second harmonic generator, which converts the output to 488 nm. Beam-conditioning optics collimate the output. The diode laser temperature is tightly controlled by a TEC to maintain a wavelength tolerance of better than ± 0.5 nm.

CVI Melles Griot DPSS and DDD Lasers

Wavelength (nm)	cw Output Power (mW)	Description	Laser Series
457	100–300	DPSS Direct Beam	85 BLS
473	5–15	DPSS Direct Beam	85 BCA
488	10–50	DDD Direct Beam	85 BCD
488	10–30	DDD Fiber Coupled	85 BCF
532	5–20	DPSS Direct Beam	85 GCA
532	5–20	DPSS Direct Beam	85 GCB
532	2000–3000	DPSS Direct Beam	85 GHS
561	5–35	DPSS Fiber Coupled	85 YCF
561	10–75	DPSS Direct Beam	85 YCA



Optical schematic of a CVI Melles Griot DPSS laser



Optical schematic of a CVI Melles Griot DDD laser

About Diode-Pumped and Solid-State Lasers

The DPSS laser revolution

The optical difficulties encountered with diode lasers—difficulty in coupling to the high divergence light, poor mode quality in the slow axis of wide-stripe lasers, low output power from single-transverse-mode lasers—led to a new philosophy about how best to use these efficient, long-lived, compact light sources. This concept, championed in the 1980s by a group at Stanford University headed by Prof. Bob Byer, has been termed the diode-pumped solid state (DPSS) laser revolution.

The logic is simple. The primary light source (the diode laser) pumps another laser (an infrared crystal laser) to convert to a good mode, the beam of which is wavelength converted (by nonlinear optics techniques) to a visible output. The diode laser source replaces the discharge lamp for optically pumping the gain crystal in a traditional, high-efficiency, infrared laser. The infrared beam is generated in that independent resonator with a good mode, and consequently it can be efficiently converted with an intracavity nonlinear crystal to a visible beam with a good mode. Though power is lost at each step, the result is still a single-mode visible beam generated with a total electrical-to-optical conversion efficiency of several percent. These DPSS lasers are replacing the older visible gas lasers whose conversion efficiencies rarely reach 0.1 percent.

End- and Side-Pumping Geometries

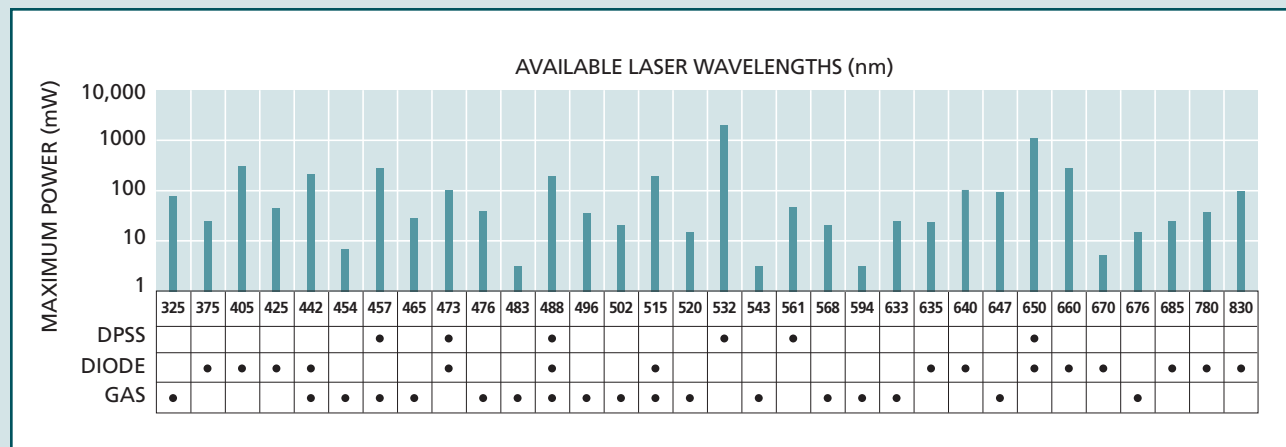
The first DPSS lasers were made by focusing the diode light from a single laser diode emitter through the high-reflector coating (at 1.06 μm)

on the end of the Nd:YAG rod. This “end-pumping” geometry provide good overlap between the pumped volume and the lasing volume, but it limited the pump power to that available from single-mode diode emitters.

In order to increase laser output and reduce cost (diode lasers suitable for end pumping are twice as expensive as diode laser arrays), diode arrays were mounted along the length of the laser rod. However, because of poor overlap of the pump beam with the 1.06 μm beam, the efficiency of this “side-pumping” technique was only half that of end-pumping geometries. No pump diode cost savings resulted.

Then in the late 1980s two advances were made. First, a variety of new laser rod materials, better tailored to take advantage of diode laser pumps, were introduced. Nd:YVO₄ crystals have five times the gain cross section of Nd:YAG, and the Nd can be doped into this crystal at much higher concentrations. This decreases the absorption depths in the crystal from cm to mm, easing the collimation or focusing quality required of the pump beam. This crystal had been known, but could be grown only to small dimensions, which is acceptable for diode-pumped crystals. Another crystal introduced was Yb:YAG, pumped at 980 nm and lasing at 1.03 μm —leaving very little residual heat in the crystal per optical pumping cycle and allowing small chips of this material to be pumped at high levels.

Second, means were devised to make micro-cylindrical lenses (focal lengths less than a mm) with the correct surfaces (one type is a hyperbolic profile) for collimating or reducing the fast-axis divergence of



Technology and spectral offering

the diode laser output. With good tooling and beam characterization these are correctly positioned in the diode beam and bonded in place to the diode housing. This allows more conventional lenses, of smaller numerical aperture, to be used in subsequent pump light manipulations.

End-Pumping with Bars

With these two new degrees of freedom, laser designers realized they could create optical trains that would give them end-pumping system efficiencies (achieve good overlap between pump and lasing modes) with diode arrays as pump sources to obtain a lower diode cost per watt in their systems. This produced an explosion of unique DPSS laser designs generically described as “end-pumping with bars.”

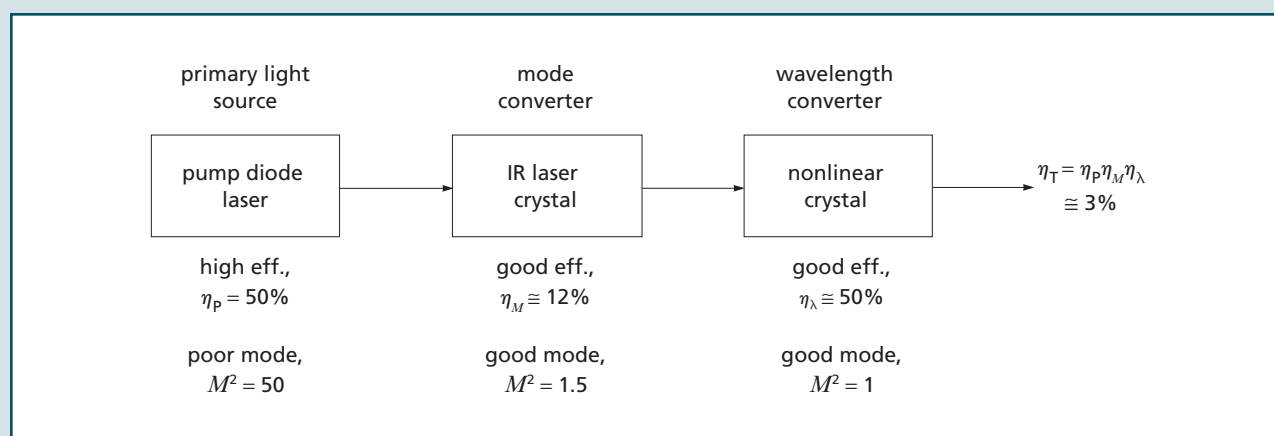
The figure following shows the example previously mentioned, delivering the array light through a fiber bundle, with the fibers at one end spread out to butt align with the linear stripes of an array, and the other end of the bundle gathered to an approximately circular spot. Although the circular spot is large, its focal image, formed with high numerical aperture (NA) optics, is small enough to satisfactorily overlap the IR cavity laser mode. The small depth of focus, from the high NA optics, is inconsequential here because of the short absorption depth in the Nd:YVO₄ laser crystal. The laser head can be disconnected from the diode modules at the fiber coupler without loss of alignment.

In another example, an even higher-NA optic (comprising a cylinder lens and a molded aspheric lens) was used to directly focus the 1-cm width of a micro-lensed array bar onto the end of a Nd:YVO₄ gain crystal. This produced an oblong pump spot, but good overlap with the IR cavity mode was achieved by altering the infrared cavity (inserting two intracavity beam expansion prisms in that arm) to produce a 5:1 elliptical

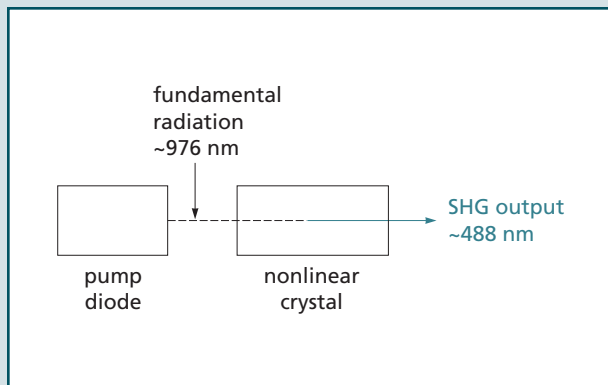
cavity mode in the gain crystal. Another design used a nonimaging pyramidal “lens duct” to bring in the pump light from a diode laser stack to the end of a gain crystal. Yet another brought light from several arrays into a lasing rod centered in a diffuse-reflecting cavity by means of several planar (glass-slide) waveguides, each piercing a different sector of the reflector sidewall. These are but a few of the design approaches that have been successfully taken.

488 nm Solid-State Lasers

A variety of solid-state approaches are used to achieve 488 nm output, a popular wavelength used for excitation of fluorophores in biotech applications. One approach, optically pumped semiconductor lasers (OPSL), utilizes a diode to pump a solid state gain chip atop a Bragg reflector which then passes through an external non linear crystal to double the 976 nm fundamental radiation down to 488 nm. The OPSL approach typically requires a large number of components and more complex fabrication, coating and assembly compared to other approaches that follow. True DPSS approaches utilize a pump diode, two gain mediums and a frequency mixing of 914 and 1064 nm radiation along with a single frequency generator to produce 491 nm, a wavelength close, but not quite optimum for the narrow bandwidth filters and fluorophores used in these applications. Directly doubled diodes (DDD) offer the best of both worlds by generating both the optimum 488 nm wavelength and a minimal number of components to achieve it (see figure below). DDD's use a pump diode at 976 nm and unlike other doubled diode laser approaches which use external cavity components, an integrated non-linear crystal/cavity. This approach results in a laser that is highly efficient, robust and volume manufacturable.



The logic for DPSS lasers



Directly doubled diodes

Microchip Lasers

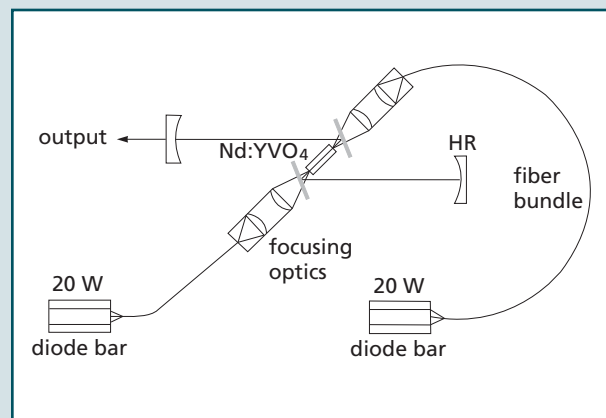
Another procedure that can be used to make available potentially inexpensive, mass produced, low power, visible output DPSS lasers is mimicking semiconductor chip processing methods. In the late 1980s, MIT Lincoln Labs took this approach and created the "microchip" laser. A thin Nd:YVO₄ plate is polished flat and then diced into ~2-mm-square chips. Each of these chips is then optically contacted to similar, flat, diced KTP doubling crystal plates to make a cube. Prior to dicing, the surfaces that will become the outer cube surfaces are coated for high reflectivity at 1.06 μm . When single-mode diode laser pump light is focused through one mirrored end of the cube, the heat produced makes a thermally-induced waveguide that creates a stable cavity for IR lasing. Since the KTP crystal is within this cavity, the IR lasing is converted to a 532 nm (green) output beam with 10's of milliwatts of output. The diode temperature must be controlled to maintain a stable pump wavelength and thermal waveguide. In addition, the cube temperature should be stabilized. Because of the short cavity, the IR laser operates at a single longitudinal mode, and the cavity length must be thermally tuned to keep the mode at the peak of the gain curve. Laser operation in a single frequency suppresses "green noise," discussed next.

The "Green Noise" Problem

As the early DPSS laser designs giving visible-output beams were being introduced, it became apparent that there was a problem unique to this architecture. The visible output power, 532 nm in the green spectrum, could break into high-frequency chaotic oscillations of nearly 100-percent peak-to-peak amplitude. This was named the "green problem" by Tom Baer (then at Spectra-Physics), who in 1986 showed the

effect to be due to the dominance of sum-frequency-mixing (SFM) terms coupling different longitudinal modes over second-harmonic-generation (SHG) terms, in the nonlinear conversion step from IR to visible output. Several (all met by the new laser designs) lead to this effect: (1) the IR laser cavity is short (~10 cm or less) with only a few longitudinal modes oscillating, (2) nonlinear conversion efficiencies are high (20% or more), and (3) nonlinear phase-matching bandwidths span several longitudinal mode spacings (true of the commonly used KTP doubling crystal). Then the sum frequency mixing output losses couple the longitudinal modes in relaxation oscillations where the turn on of one mode turns off another.

Two early solutions to this problem emerged. The first is to make the IR cavity long enough to give hundreds of oscillating modes, so that the noise terms average to insignificance as in a long gas laser. The second is to make the IR oscillation run on a single longitudinal mode so that there are no SFM terms. This can be done by using intracavity frequency control elements such as an etalon, or by using a ring cavity (with a Faraday-effect biasing element to maintain the direction of light travel around the ring). Ring cavities eliminate the standing-wave interference effect of linear cavities, termed "spatial hole burning," and the laser runs single frequency when this is done. As more experience was gained with DPSS laser design, other clever solutions to the "green problem" were found, tailored to each particular device and often held as trade secrets. It can be surmised that these involve precise control of wavelength, spatial hole burning, beam polarization, and cavity-element optical path differences to reduce the strength of longitudinal mode SFM terms.



Schematic of an "end-pumping with bars" geometry using fiber bundle delivery, one of many variants on the DPSS laser theme

Uniqueness of DPSS Laser Designs and Laser Reliability

Unlike the gas lasers they replace, no universal approach is applied in the details of different DPSS laser designs and laser models. There is a large variety of solutions to the major problems, many solutions are unique, and many are held as proprietary. Major design differences are found in:

- the means for optically coupling the pumping light into the gain medium,
- the management of the thermal lens produced by absorption of the pump light in the cavity,
- the control of green noise,
- the strain-free mounting, heat sinking, and placement of the small lasing and nonlinear crystals in the laser cavity, and
- the hermetic sealing of the laser cavity to protect the often delicate crystals and critical alignments of component

Note that because the intracavity space must be hermetically sealed there usually is no field repair, maintenance, or adjustment of a DPSS laser head. If it fails, it is returned to the manufacturer. It is evident that DPSS lasers are a lot less generic than the gas lasers they replace. For a problem with a particular laser model, there may be no standard solution available in the technical literature. With so many variables, there often are surprises when new designs are first manufactured and introduced. Under these circumstances, the user is advised to pick a supplier with a record of years of consistent manufacture, who has over time dealt with his own unique set of component and assembly problems. If this advice is followed, then the expectation with current products is that a new DPSS laser will operate reliably for 10,000 hours or more.

561 nm DPSS Laser

The newest addition to the CVI Melles Griot laser product line is a DPSS laser with yellow output at 561 nm, an ideal excitation wavelength for biomedical fluorescence.

This 16.5-cm-long laser head delivers up to 75 mW of output power, and consumes less than 10 W of wall plug power at 25 mW and less than 18 W at 75 mW. The laser is pumped by a single stripe diode laser. Frequency-selective elements in the cavity limit IR oscillation to the 1.123 μm Nd line (one of the weaker lines in the 1.064 μm manifold) and constrain this oscillation to a single longitudinal mode. The output is low noise (0.5 percent rms) with excellent mode quality ($M^2 < 1.2$). Polarization is vertical with respect to the mounting surface with an extinction ratio of $>100:1$.



561 nm yellow diode pumped solid-state laser