A Diode-Pumped, Solid State Nd:YLF Laser for Micro-Machining

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Abstract

We discuss the background, design choices, performance and potential applications for a >10-Watt, diode-pumped Nd:YLF laser, suited for the industrial marketplace.

Introduction

The most common solid state laser used today in industrial applications is based on the crystal Nd:YAG, pumped by either pulsed or cw gas-discharge lamps. The technology of the Nd:YAG laser has not undergone substantial changes since the device was first brought into the commercial market, except for a steady rise in power output made possible by the growth of large, high-quality laser crystals. However, over the next decade or so, this technology is going to become more complex, if not totally changed, because of advances in another key laser technology, high-power semiconductor (diode) lasers. Besides their direct application to industrial processing, high-power diode lasers can also replace lamps as pump sources for solid state lasers. Compared to lamps, diodes have a longer operating life, at least by a factor of ten and perhaps greater in the future. This is especially important for minimizing down-time and maintenance costs in production environments. In addition, because of the reduced level of heating in the laser crystal per unit of average output power, diode-pumped solid state lasers can operate with improved beam quality compared to lamp-pumped lasers with the same output. In nearly all applications, good beam quality is an advantage, but it is especially critical when the laser wavelength is shifted downward by nonlinear conversion in order to more effectively process certain materials. Finally, because of higher efficiency in converting electrical power to laser output, diode-pumped lasers require less electrical power and cooling than lamp-pumped lasers of equivalent power. While this advantage is appreciated most in military and space-based lasers, the reduced electrical and cooling requirements allow greater flexibility of laser location and thus of manufacturing configurations.

Another significant aspect of diode pumping compared to lamp pumping is related to the solid state laser material being pumped. The are many reasons why Nd:YAG is the most common laser crystal, but two of the most important are 1) the material requires a relatively small amount

of power from the lamp to produce laser action and 2) the thermo-mechanical properties of YAG allow generation of high powers without mechanical damage to the material. Other materials provide some advantages over Nd:YAG, such as operating wavelength, but under lamp-pumped conditions either cannot be operated as lasers, require cryogenic cooling or cannot generate high powers without fracturing. Some of these materials, when diode-pumped, work acceptably well, and thus can be considered for a number of applications.

The development of diode-pumped solid state lasers has, not unexpectedly, tracked the development of the diodes themselves. The first "high-power" diodes produced 0.2 Watts (W) of cw power, and the solid state lasers they pumped found applications as single-frequency sources in metrology and for scientific research. These diode-pumped lasers employed a technology called end-pumping, in which the output of the diode laser is focused into the laser material, essentially along the same direction as the output of the solid state laser. This is in contrast to the near-universal side-pumping geometry used in lamp-pumped lasers, where the lamp energy is directed transverse to the output axis, usually into the barrel surface of a long, thin rod of solid state laser material. As higher-power diodes (several W) appeared, diode-pumped lasers, with Q-switching added, found use in the semiconductor industry processing integrated circuits.

Because of fundamental limits in diode lasers, in order to increase the power level from a single device beyond several Watts diode manufacturers were forced to develop linear arrays of diodes on one chip of semiconductor material. The first cw linear arrays generated a total of 5 W of power over a 1-cm-length of array, and the most recent commercial devices have increased this level to 20 W. Pulsed arrays are available with power output as high as 100 W, limited to pulsewidths below 1 msec or so. In order to build high-power, diode-pumped solid state lasers one must employ these arrays, either singly or in multiples. Although the use of sophisticated optics can make it possible for one to use end pumping with linear (or multiple linear) arrays, many of the high-power diode-pumped laser designs have switched to side pumping, and begin to more closely resemble lamp-pumped systems.

In the following we describe a diode-pumped solid state laser (the MPS-1047) now in production that makes efficient use of multiple, cw diode arrays and employs a laser material similar to Nd:YAG, but with some advantages.

MPS-1047: Basic Design Issues

One of the major challenges in the design of solid state lasers, either lamp- or diode-pumped, is dealing with the optical distortion of the laser material created by the optical pumping and lasing cycle, which leaves heat deposited in the material. In the first diode-pumped lasers the level of optical distortion was low, but with the availability of high-power arrays the issue of distortion cannot be ignored in the design of the solid state laser. The optical distortion is due to thermal gradients in the bulk of the laser material and results from two main effects, the change in material refractive index with temperature and the change in index due to the stress in the material created by the gradients. Stress-induced refractive index changes can lead to optical distortion not only of the phasefront of the laser beam passing through the material but also of the polarization properties, since, in general, the stress creates birefringence in the material. The induced birefringence leads to depolarization of linearly polarized light passing through the stressed region. Many implementations or applications of lasers require beams with a high degree of linear polarization and depolarization from the stress-optic effect creates loss in cavities with polarizing elements, thereby reducing laser efficiency.

There are several approaches to reducing the deleterious effects of optical distortion. One well-known way to essentially eliminate loss from stress-induced birefringence is to employ a non-isotropic, birefringent laser material, where the inherent natural birefringence of the material is much larger than any stress-induced birefringence. As long as the laser mode is polarized along one of the principal axes of the material, the loss from stress-induced birefringence is negligible[1].

With regard to the problem of phasefront distortion in the bulk, it is well known that some classes of materials have greatly reduced thermal distortion compared to others. Fluoride materials, such as $LiYF_4$ (YLF) are one such class, and the low distortion is presumed to result from the negative change in refractive index with increasing temperature, which tends to cancel the positive change from increasing stress[2]. Experimental data[3] on thermal distortion in lamp-pumped laser rods of Nd:YLF show that thermal lensing, a simple measure of distortion, is considerably less (about one-fifth as large) than in Nd:YAG. YLF has the additional advantage of being naturally birefringent.

One potential problem area with YLF, especially compared to the more common host YAG, is caused by the relatively poor thermo-mechanical properties of the material. Table 1 lists selected thermal and mechanical properties of the crystals YAG and YLF.

Table 1. Properties of YAG and YLF

Property	**YAG**	**YLF**
Thermal expansion (10^{-6}/C)	7.8	13, 8 (a,c)
Thermal conductivity (W/m-C)	13	6
Young's modulus (kg/mm^2)	31725	7650
Yield strength (kg/mm^2)	20	3.4

Table 1 shows that the thermal expansion in YLF is comparable to YAG along one axis (c) and much higher along the other; the thermal conductivity is lower. Also, the deformation of YLF under stress (related to the inverse of Young's modulus) is four times higher than in YAG and the yield strength of YLF, the point at which stress may permanently damage the crystal, is nearly six times lower. In combination, these properties predict that, compared to YAG, YLF will undergo a greater deformation of its dimensions for a given level of pump power dissipation per unit volume and will fracture at lower powers.

Thus, in designing our high-power diode-pumped laser we were faced with a choice between one crystal (YLF) that would have low phasefront and polarization distortion and another (YAG) that would have high mechanical strength. We had earlier, favorable experiences with YLF in operating at high powers without fracture and we chose that material for our high-power, diode-pumped system.

MPS-1047: Laser Head

A five-pass Nd:YLF gain element, with segmented dielectric coatings (AR/HR) deposited directly on the end facets, is at the heart of the MPS-1047 laser head. The 3-cm-long Nd:YLF crystal is transversely pumped by a pair of 1-cm-long, 20-W diode-laser bars. The diode-laser bars are coupled to the gain element through a single fiber lens attached directly to each bar package. These lenses minimize the divergence of the pump light in the plane perpendicular to the linear emitter. The bars are offset on opposite sides of the Nd:YLF crystal to create a sheet of gain in the crystal. The pump faces of the crystal have segmented dielectric coatings (AR/HR) to allow double-pass pump absorption. The pump geometry is a central feature of the design in that it yields a laser that is relatively insensitive to the alignments, spectra and temperatures of the diode-laser bars. This is in contrast to some of the complex, multi-element imaging schema that have been developed for similar purposes, and benefits both the reliability and cost of the technology. Certain aspects of the laser head design are the subject of a patent application.

The laser resonator (shown schematically in Fig. 1), includes a cylindrical end mirror, a spherical mirror and a flat output coupler, and is designed to produce a near-diffraction-limited ($M^2 < 1.2$) beam over a wide range of operating points up to the maximum pump power (Fig. 2). (The commercial resonator layout includes a fourth, flat mirror for packaging purposes.) The combination of mirrors is a simple means of compensating for the weak phasefront distortion in the laser crystal, which can be approximated as a cylindrical lens. The essentially power-independent beam properties of the laser are an indication that phase-front distortion is not an important factor in the operation of the laser. The output was measured to be linearly polarized with power in the orthogonal polarization less than 1% of the total output at full pump power. The average slope of the input-output curve in Fig. 2 is approximately 42%. If all the incident pump power was converted to laser output power the expected slope would be 77%, and thus the design extracts, in the TEM_{00} mode, 55% of the maximum possible power . The output powers observed both in near-diffraction-limited operation and multimode (>16 W) are, to our knowledge, the highest powers reported to date for cw, diode-pumped Nd:YLF lasers.

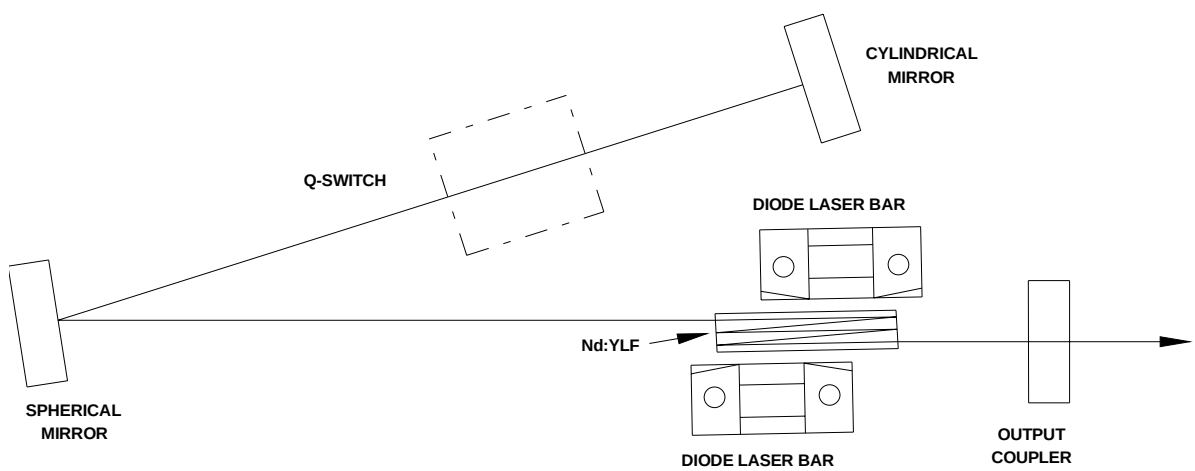

Figure 1. MPS-1047 resonator schematic.

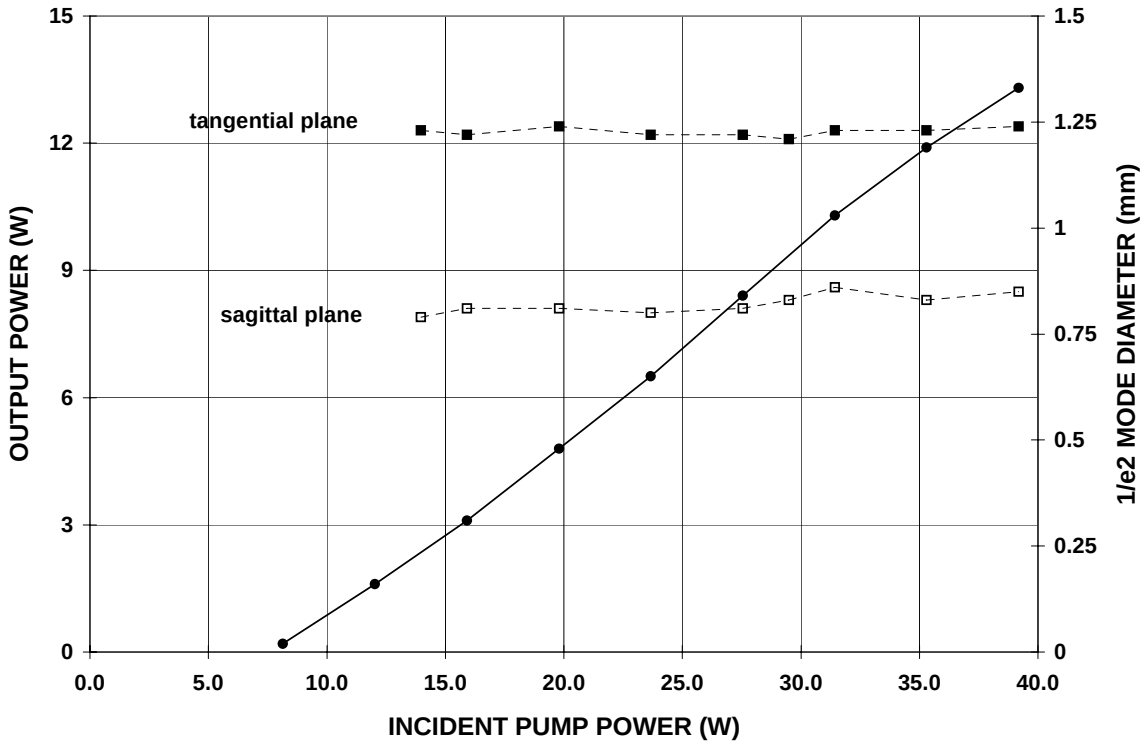

Figure 2. Near-diffraction-limited power output (solid curve) and beam dimensions (dotted curves) of MPS-1047 laser as a function of diode-laser pump power.

MPS-1047: Q-Switched Performance

Many of the applications of cw-pumped solid state lasers involve the use of Q-switching, which converts the output of the laser into a series of short pulses, suitable for ablative materials processing or the excitation of nonlinear processes such as harmonic generation. The Q-switch is a fast optical shutter inserted in the laser resonator to alternately turn on and turn off laser action. In solid state lasers there is sufficient energy storage in the laser medium to generate a short, energetic pulse when the laser is turned on. An interesting feature of Nd:YLF compared to Nd:YAG is the approximately 2x-longer storage time, which leads at low pulse rates to 2x more energetic Q-switched pulses.

The physical layout of the MPS-1047 resonator facilitates inclusion of an acousto-optic modulator for Q-switching, as shown by the dotted lines in Fig. 1. The performance with the modulator in the resonator is plotted in Fig. 3, which shows Q-switched peak power and pulsewidth as a function of pulse rate. Above a pulse rate of 10 kHz, the average power of the laser is essentially constant, close to the cw level, and the pulse energy decreases inversely with pulse rate. In other work we have operated the laser with pulse rates over 100 kHz. The higher gain and shorter total resonator path lead to shorter pulsewidths, higher maximum pulse rates and higher peak powers compared to lamp-pumped lasers with the same average power level.

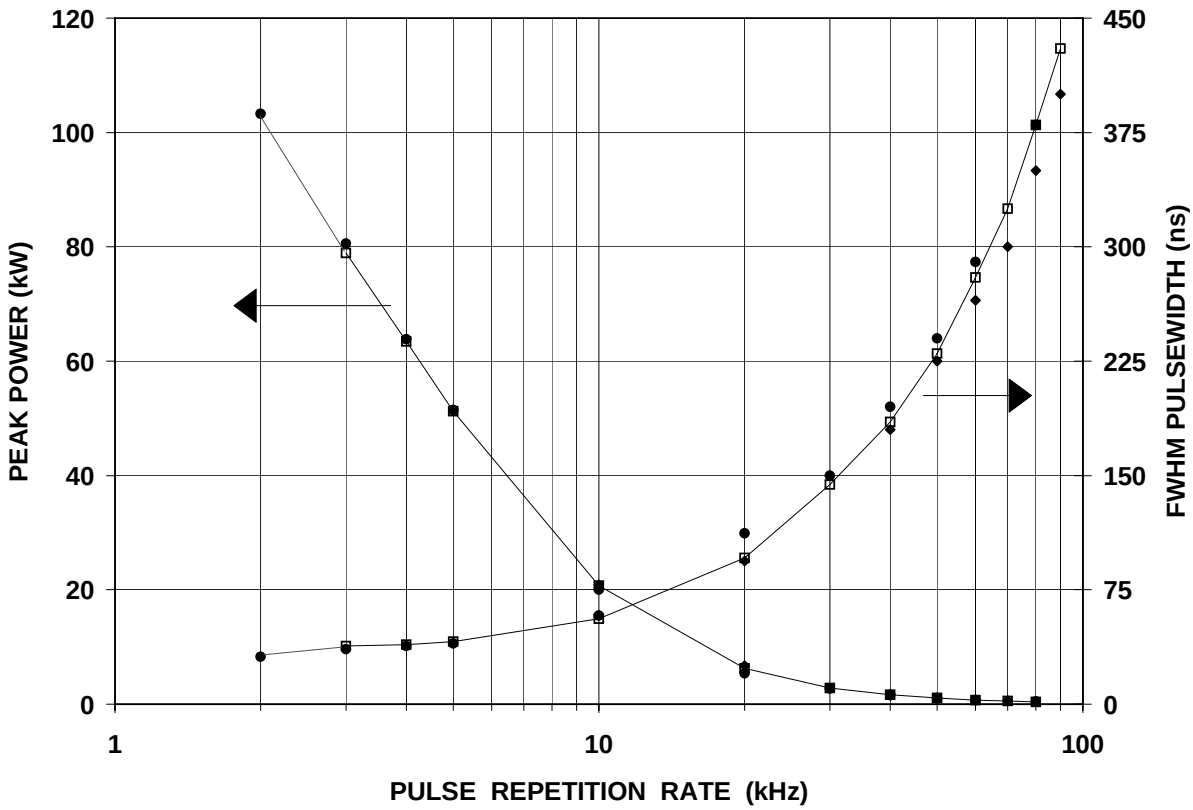

Figure 3. MPS-1047 Q-switched peak power and pulsewidth as a function of pulse rate at full output power.

MPS-1047: Cooling System and Power Supply

The wavelength of a diode laser shifts with operating temperature, requiring some temperature regulation of the pump diodes to insure a stable power output from the Nd:YLF laser head. We chose to use water cooling for the diodes and for the laser crystal as well. The heat from the diodes and laser crystal is initially removed via conduction cooling to copper heat sinks, and the heat sinks are in turn water cooled, with water brought into the laser head via tubing contained in an umbilical cable. A combination cooling and power supply unit (SSC-40) contains a pump and a heat exchanger employing multiple, single-stage, air-cooled Peltier elements. The latter provide precise and smooth temperature control while avoiding the vibration and reliability problems associated with mechanical refrigerators.

Power for the diode lasers is delivered to the head by the umbilical as well, and converted from the AC line input with an efficient, switching mode power supply. Another switching supply provides DC for the coolers, pump and control electronics. The use of switching supplies allows the laser to run on universal power (90-240 VAC), simplifying setup in different countries.

MPS-1047: Nonlinear Conversion

The MPS-1047 combination of high Q-switched peak power and excellent beam quality is well suited for driving nonlinear processes. As an initial demonstration of second harmonic generation at a 10-kHz pulse rate, we obtained 6.8 W of average power at 523.5 nm with 11.2 W incident on a 15-mm-long, noncritically phase-matched LBO crystal. To achieve the desired phase-matching, we maintained the LBO temperature at 172°C. Calculations show that an average power of 1 W at the fourth harmonic, 261.8 nm, can be generated in the material BBO, and experiments are planned to verify this.

MPS-1047: Applications

Although the title of the paper mentions the use of the laser for micro-machining, there are a number of other applications for which the MPS-1047 is well suited. In the area of industrial lasers, the device has the advantage of operation with regular line power (a 15A circuit suffices) and no external cooling water. The diode lasers are warranted for 5000 hours of operation, an industry standard that is expected to improve over time. The laser head is compact, about 15 inches long and 4 inches square and can be mounted in any position. Table 2 lists some of the applications that have been considered for the device.

Table 2. Possible MPS-1047 applications

General Area	Mode
Microcutting / Hole drilling	Q-switched
Micromachining -gold	Q-switched, second harmonic
Micromachining - ceramics, plastics	Q-switched, third and fourth harmonics
Hybrid circuits trimming	Q-switched
Diamond processing	Q-switched
Marking/engraving	Q-switched
Graphics - plate exposure	CW

A photograph of the entire laser system appears as Fig. 4 on the next page and includes the laser head, SSC-40 cooling and power-supply unit and a remote-control box. Also available with the system is control via a RS-232 interface.

Figure 4. Photograph of MPS-1047 laser head (bottom left), SSC-40 cooler and power supply (top) and remote control box (bottom right).

References

1. G.A. Massey, **Applied Physics Letters** 17, 213, 1970.
2. B.W. Woods *et al.*, **Journal of the Optical Society of America** B8, 970, 1991.
3. J.E. Murray, **IEEE Journal of Quantum Electronics** QE-19, 488, 1983.

Meet the Authors

William C. Schwartz is the CEO of SEO, a Florida Corporation engaged in the research, development and production of lasers and laser-based systems. Dr. Schwartz did his undergraduate work at the University of Chicago and graduate studies in Mathematics at the University of Missouri. After working for North American Aviation and Martin Marietta, he founded International Lasers Systems in Orlando, FL, where the major product was lamp-pumped Nd:YAG lasers for airborne rangefinders and target designators. In 1983 Dr. Schwartz started the company that bears his name, was later involved in the establishment of CREOL at the University of Central Florida and served as LIA President for the year 1995.

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Peter F. Moulton is a Vice-President of SEO and General Manager of the SEO Research Division in Concord, MA. Dr. Moulton studied Physics as an undergraduate of Harvard and in 1975 received his Ph.D. from M.I.T in Electrical Engineering, having done his research work at the M.I.T. Lincoln Laboratory. He remained at Lincoln for a decade, where he investigated new types of solid state lasers and invented the Ti:sapphire tunable laser. Joining SEO in 1985, he continued solid state laser research and development work, including diode-pumped single-frequency and high-power lasers, lamp- and diode-pumped mid-infrared devices, diode-pumped tunable lasers and optical parametric oscillators. In addition, he has been involved in developing new laser applications related to medicine and remote sensing. Dr. Moulton is a Fellow of the OSA.