International Archive of Applied Sciences and Technology, Vol 1 [2] December 2010: 01-12

ISSN 0976- 4828
http:// www.soeagra.com

REVIEW ARTICLE

An Overview of Diode Pumped Solid State (DPSS) Lasers

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ABSTRACT

The primary purpose of text is to explain the mutual influences between the physical and dynamic processes in solids and their lasing properties. It begins with a brief overview of historical developments and the basics of solid state laser materials and design, then describes optical dynamics and energy transfer in solids and analyzes the properties of rare earth and transition metal ion doped crystals, glasses and ceramics. Diode laser pumps for solid state lasers are reviewed with special emphasis on current and future capabilities. The text also outlines the factors that influence the development of new laser materials, and reports on recent developments and technological advances in solid state lasers and photonics that use novel materials and techniques. Included are discussions of pumps for continuous wave or pulsed and side pumping configurations. The use of diode lasers instead of flashlamps as optical pump sources for solid state lasers offers significant advantages such as higher efficiency and longer lifetime. The potential applications of this technology to device singulation for electronic and power generation devices will be described.

KEY WORDS: *Diode pumped, wavelength, lifetime, solid state, optical*

INTRODUCTION

The very rapid progres which has taken place in solid state laser technology over the past few years is due to the culmination of a number of technical innovations covering a wide range of disciplines. The process by which atoms are raised from lower level to upper level is called pumping. Diode pumped lasers are becoming more and more important in laser machining. Diode pumped solid state (DPSS) lasers are solid state lasers made by pumping a solid gain medium, for example, a ruby or a neodymium doped yttrium aluminum garnet (YAG) crystal, with a laser diode. DPSS lasers have advantages in compactness and efficiency over other types, and high power DPSS lasers have replaced ion lasers and flashlamp pumped lasers in many scientific applications, and are now appearing commonly in green and other color laser pointers. Fibre optic waveguides have also been doped with various rare earth ions and pumped by semiconductor lasers. Fibre lasers were realized shortly after the discovery of the laser and were initially transversely pumped by the crude but effective technique of coiling a fibre round a flashlamp [1]. The resulting diode pumped laser has, in general, greatly improved spatial and spectral characteristics than the laser diode itself.

DPSS and diode lasers are two of the most common types of solid state lasers. However, both types have their advantages and disadvantages. Interest has increased in the past few years in using semiconductor diode lasers to excite solid state lasers based on rare earth ion doped transparent solids such as neodymium doped yttrium aluminum garnet (Nd:YAG). Figure 1 shows the absorption spectrum is for 1% doped Nd:YAG. The pulsed flashlamp emits radiation at all wavelengths while the diode laser emits radiation at essentially a single wavelength that can be tuned to a particular absorption line of the Nd:YAG. Traditionally, these solid state lasers are excited by flashlamps that emit broadband radiation. Lamp pumped systems are inefficient, however, with typically 1% electrical to optical efficiency, and the lamps need replacement after approximately 200 hours when operated continuously. Diode laser pump sources allow operation at higher efficiency (10%) and longer life (20.000 hours). DPSS lasers have, over the last ten years, become very important in the laboratory and are beginning to make an impact in the market place. During the last decade the increasing demand for miniaturisation of micro system devices and their associated components has established laser micromachining as the preferred fabrication method in many industrial sectors [2].

The story really became interesting when reliable laser diodes became available in the early 1980s. These laser diodes could be operated either in continuous wave (cw) or pulsed mode at room temperature and had long lifetimes in the region of 100s to 1000s of hours. The use of laser diodes to pump solid state lasers was recognized, with the main applications seen to arise from tasks which require efficient, reliable, long lived optical sources. These tasks could be remote sensing from satellites, space based communications and wind shear sensing from aircraft or at airports. Clearly a satellite based system can not be routinely serviced and must be efficient.

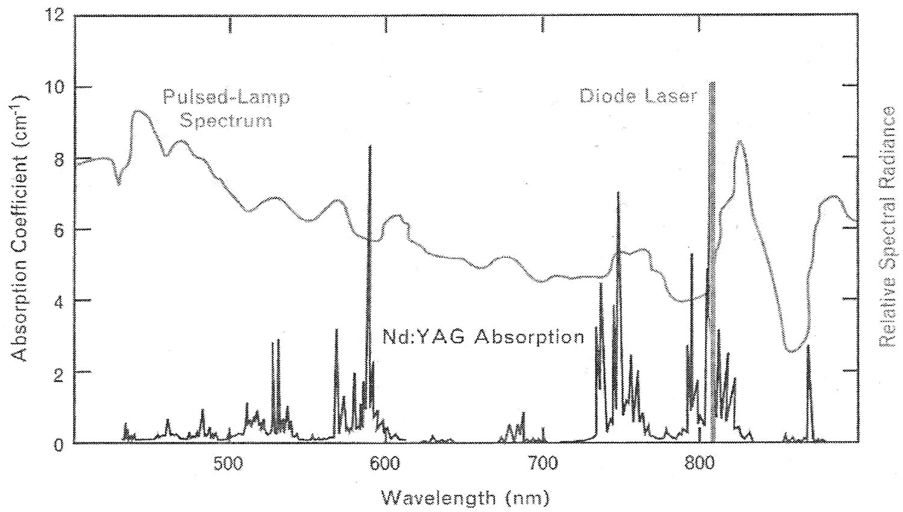

Figure 1. Absorption spectrum of Nd:YAG and the emission spectra of a diode laser and a pulsed flashlamp [3].

Much of the early work on DPSS lasers has been reviewed up to the end of 1987 in an article by Fan and Byer [4]. Lincoln laboratory has participated in the development of these lasers since the beginning; the first diode pumped laser was a U^{3+}:CaF_2 laser demonstrated at Lincoln laboratory by Keyes and Quist in 1964 [5]. Subsequent interest has concentrated predominantly on rare earth ions doped into various hosts. The ubiquitous example is of course Nd:YAG which was first laser diode pumped by Ross in 1968 [6], although another rare earth ion, Dy^{2+}, had earlier been pumped by an array of light emitting diodes. The early study on DPSS lasers used a transverse pumping geometry which is convenient when using a number of sources with poor beam quality. Longitudinally or end pumped DPSS lasers were first demonstrated in 1973 [7]. The advantages of this latter approach in minimizing the laser threshold was noted, as was the disadvantage of limited power scaling due to the problem of coupling the output of many laser diode sources into the gain medium.

DIODE PUMPED LASERS

Pumping is usually performed in the following forms: (i) optical pumping uses either cw or pulsed light emitted by a powerful lamp or a laser beam. Optical pumping can be realized by light from powerful incoherent sources. The incoherent light is absorbed by the active medium so that the atoms are pumped to the upper laser level. This method is especially suited for solid state or liquid lasers whose absorption bands are wide enough to absorb sufficient energy from the wide band incident incoherent light sources. (ii) electrical pumping is used for gas and semiconductor lasers. It is realized by allowing a current (continuous direct current, radio frequency current or pulsed current) to flow through a conductive medium, such as an ionized gas or semiconductor. Electrical pumping is usually performed by means of sufficiently intense electrical discharge. Gas lasers commonly use electrical pumping or laser pumping, because their absorption bands are narrower than solid and liquid lasers, wide band lamp light is not efficient enough, much of the lamp energy is dissipated as heat. Electrical pumping is non resonant pumping by electron impact excitation. Electrical pumping is efficient for gases and semiconductors, whose absorption bandwidth is wide enough. Although some optical pumping methods for semiconductor medium have been developed, electrical pumping for semiconductor lasers proved to be more convenient. (iii) chemical pumping, the population inversion is produced directly by exothermic chemical reaction. Chemical pumping usually applies to materials in gas phase, and generally requires highly reactive and often explosive gas mixtures. The exothermic reaction usually generates large amount of energy, if quite a fraction of this available energy is transferred into laser energy, high power and high energy pulses for lasers can be realized. Such lasers are used as directed energy weapons.

There are other pumping processes such as gas dynamic pumping, etc. We refer the reader to books of lasers on the details of pumping processes. Now let's study more about diode laser pumping. Laser pumping has been used since the early days of the development of lasers. Laser pumping has become a very important pumping technique since efficient and high power diode lasers have been developed and widely available in many wavelengths. When we use diode lasers to pump other solid state lasers, we can produce an all solid state laser. Because optical pumping is a resonant process, the wavelengths of the pumping diode lasers must be within the absorption bandwidth of the active medium to be pumped, the nearer to the absorption peak wavelength the better. Figure 2 shows the absorption spectral of Nd:YAG laser, Nd:glass laser, Yb:YAG laser and Yb:Glass laser. Nd:YAG has a peak absorption value at 810 nm, Nd:glass has a peak value at 802 nm, they can be pumped by GaAs/AlGaAs quantum well diode lasers at about 800 nm. While for Yb:YAG laser and Yb:glass laser, the best absorption wavelengths are 960 and 980 nm respectively, we can pump them using InGaSa/GaAs strained quantum well lasers in the 950-980 nm range. We can divide diode laser pumping into four types according to the degree of integration of the diode lasers: single stripe, diode array, diode bar and diode stack. Normally the pumping power increases with the integration degree.

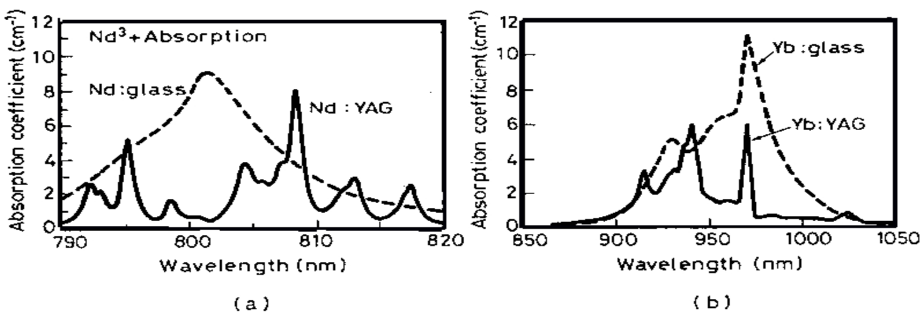

Figure 2. Absorption spectral of (a) Nd:YAG/glass lasers and (b) Yb:YAG/glass lasers [8].

There are basically two types of pump geometry, longitudinal pumping (pump beam enters the laser medium along the resonator axis) and transverse pumping (pump beam incident on the active medium from transverse directions to the resonator axis). For longitudinal pumping, the beam needs to be concentrated to a small and circular spot (Figure 3 and 4). The simplest, if not least costly way to double the pump power is to obtain a higher power pump diode. However, this normally means that the emitting area (stripe width) also increases so that all other factors being equal, the spot or mode size in the laser crystal also increases. One way to double the pump power without increasing the spot size is to optically combine two similar pump diodes. Since these types of edge emitting laser diodes are polarized, a pair of them can be combining using a polarizing beam splitter producing a result that is very nearly double the output power of a single diode, but is non polarized.

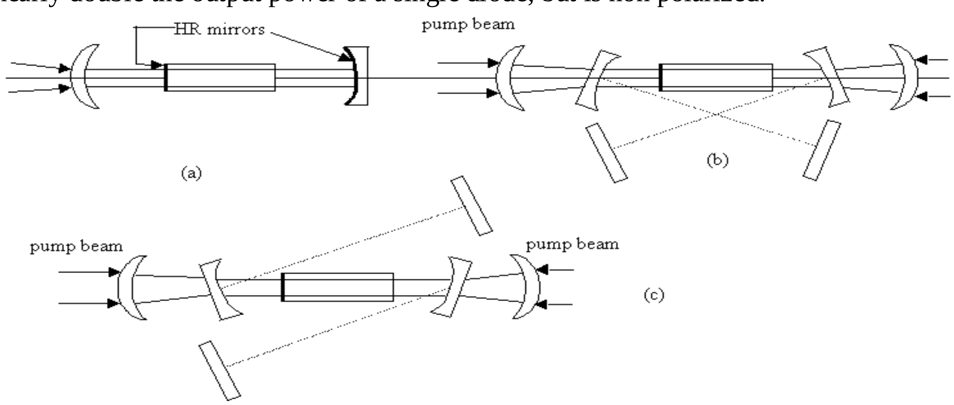

Figure 3. Longitudinal diode laser pumping.

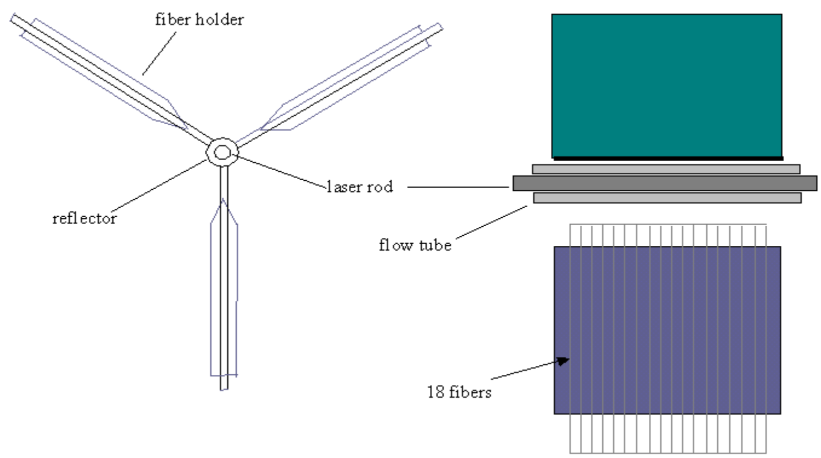

Figure 4. Transverse diode laser pumping.

Combining optics consists of:
1. Fast axis correction (optional, cylindrical microlens).
2. Beam collimation (spherical positive lens).
3. Slow axis correction (anamorphic prism pair).
4. Turning mirror or other means for aligning the two beams.
5. Polarizing beam splitter used as beam combiner (PBS cube).
6. Focusing lens(es) if required.

Items 2, 4, and 6 will need to either be adjustable using precision mounts, or be glued in place once positioned properly. The optics and beam splitter must be coated for the desired wavelength.

DPSS lasers offer several advantages over the broadband pumping schemes that use cw or pulsed pump sources. The growth in the utilization of diode lasers such as diode arrays or bars to pump solid state lasers results directly from a large volume production of diode lasers and arrays, which have reduced the cost of delivered power from semiconductor laser diode. Also, diode laser characteristics such as wavelength stability, overall efficiency, and operational lifetime (10.000 hours or more) have been significantly improved during the last decade.

Advantages of diode pumping

Summarizes some of the typical characteristics of DPSS lasers:

1. Optical efficiency: DPSS lasers are highly efficient because of the direct excitation of the pump beam into the useful absorption band of the lasing ion. Direct excitation minimizes the unwanted losses in the lasing crystal with optical to optical efficiency of up to 70%. Selecting the composition of the host material enables laser diodes to be constructed with wavelengths between 600 nm and approximately 30 µm in the infrared. Over much of this region the output power and lifetime of laser diodes is remarkably poor. Only in wavelength regions where strong commercial or military interest is present have sufficient resources been deployed to develop an efficient and long lived device. Notable examples of this process have occurred at 1.5 µm and 1.3 µm, which are important telecommunications wavelengths, and near 800 nm which is important for communications, entertainment and medical applications. Only in the vicinity of 800 nm have high powered devices been built. The driving force has been military applications including pumping Nd doped solid state lasers [9].

2. Wavelength: The wavelength at which laser diodes operate is dictated by the size of the band gap, since the light arises from the recombination of electrons and holes in a pn junction. The band gap may be tuned in size by two main processes: (i) Altering the composition of the host material. (ii) Changing the temperature of the host material. Other physical effects such as the application of pressure may also change the band gap but they tend to produce too small an effect to be useful [7]. The output wavelength of diode lasers varies from diode to diode because of small differences in fabrication and the wavelength changes with temperature. The variation in output wavelength leads to increased cost because only diode lasers in a small wavelength range are usable. The change in wavelength resulting from temperature variation requires that the diodes must be temperature controlled.

3. Operational lifetime: The operational lifetime of laser diodes or arrays is much larger than that of conventional arc or filament lamps. A typical laser diode array can operate without significant degradation for more than 10.000 hours, but usually up to $3x10^4$ hours, while a cw lamp must be replaced after 200-400 hours of operation (or 10^7 shots in the case of pulsed pumping). The performance of a diode laser degrades exponentially with time. Initially, the failure rate is low, but it increases exponentially with the operating time. Failure mechanisms of laser diodes are divided into two main classes:
1. User induced damage (such as mechanical, thermal or electrical shock or electrostatic discharge).
2. Intrinsic damage, which results from three main sources: (i) degradation of laser mirrors or facets because of high current densities or current spikes. This will increase internal losses and lead to catastrophic failure. (ii) damage resulting from crystal defects within the active region, which will lead to an increase in absorption losses within laser diode. Such defects are common in AlGaAs laser diodes because of the oxidation and migration of the aluminum. At present efficient aluminum free laser diodes replace the aluminum containing lasers. (iii) resistive losses and heating because of increases in the resistance of electrical contacts to the laser.
4. Temperature: Since the diode laser is narrow bandwidth pumping source, it pumps only the useful absorption bands relevant to laser action, reducing the thermal load in the crystal. This thermal load results from the quantum gap between the pump and the leasing photons. Thermal effects such as thermal lensing, thermally induced birefringence, and thermal damage to the lasing to the crystal are reduced significantly. Fine tuning the temperature of the laser diode causes a change in wavelength. For GaAlAs devices the wavelength tunes at an approximate rate of +0.25 nm $ºC^{-1}$ mainly due to the change in band gap with temperature. This feature is used to tune the laser diode into coincidence with the absorption bands of rare earth ions. Normally the lasers will be cooled down, since this gives a longer lifetime for the laser diode. It is usual to specify the room temperature wavelength of the laser diode some 5 nm longer than the rare earth absorption feature that will be pumped. Simple Peltier coolers can provide a temperature change of about 40 ºC corresponding to a wavelength shift of 10 nm. The Nd:YAG absorption linewidth is ~2 nm so the diode temperature has to be set to better than ±4 ºC, which is not too demanding in the laboratory. The influence of temperature on the wavelength of the laser diode causes problems of packaging the DPSS laser. Pulsed laser diodes suffer from a transient thermal wavelength shift. Since the current is pulsed through the laser diode, the temperature is never in equilibrium and a transient wavelength shift occurs. The wavelength increases during the optical pulse. Measurements of this effect have revealed shifts of ~5 nm. Shifts of this magnitude are larger than the absorption linewidth of many solid state laser materials [10, 11]. Account has to be taken of this effect when predicting the efficiency of pulsed DPSS lasers. The diode lasers are normally cooled by thermoelectric cooler for low power systems, and by liquid cooling for high powers. Cooling can stabilize the diode laser frequency.
5. Beam quality: Although the beam quality of a laser diode or diode array is not good, the use of coupling optics makes it possible to obtain a good TEM_{00} beam mode form a DPSS laser. The coupling optics circularize the output beam emanating from the laser diode array or bar, and then couple the beam into the solid state laser crystal either by direct coupling or an optical fiber [12]. The cylindrical fast axis collimating lens can reduce the beam divergence of diode laser stacks to a value of lens than 10 mrad. The solid state laser can be pumped longitudinally or transversely. This subject is technologically well established and will be discussed in the next section. The laser crystal host can be in the form of a crystal, waveguide or optical fiber [7].
Since the absorption length of the diode laser beam focused inside the solid state laser crystal is short, the pump mode volume is smaller than the laser cavity mode volume and one expects a good spatial beam quality. The laser cavity itself is short and therefore the output power of the DPSS laser is a single longitudinal mode. The best transverse mode quality is obtained from single stripe devices. The low ellipticity of a source with dimensions of 3x1 μm ensures that the output power may be efficiently coupled into optical fibre or into solid state laser materials. Single laser diodes may provide up to 150 mW in a single transverse mode. The shape of the output beam from a single strip device is shown in Figure 5.

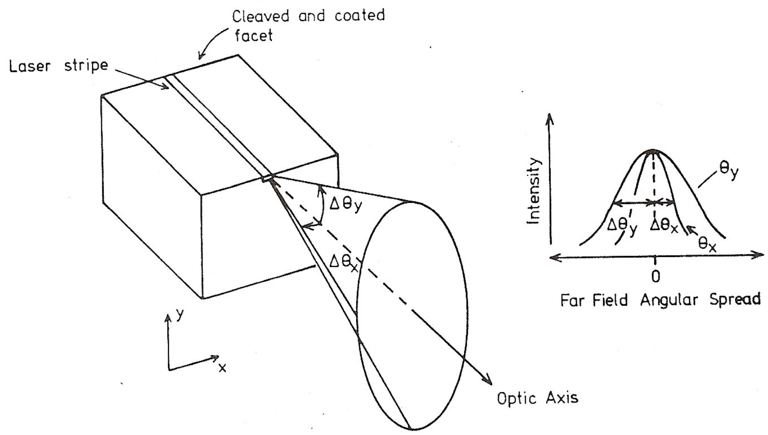

Figure 5. The elliptic beam shape arising from the transverse dimensions of a single laser diode stripe [7].

To date the most extensively used pumping geometry is longitudinal pumping. The output from the diode laser is collimated and beam shaped to achieve a circular profile before being focused down to form a pump spot on the laser rod. This technique allows good matching between the lasing spot size of the solid state laser cavity and the pump spot size in the gain medium. This spatial overlap between pump and lasing modes, known as mode matching, is critical to the efficiency of the diode pumping process.

Frequently, DPSS lasers are pumped by laser diode arrays in order to achieve high output powers. As has been noted, the simplest way to increase the output power from a single laser diode is to increase the width of the emitting region either by fabricating a number of laser diode stripes in close proximity so that there is a series of emitting regions, or by enlarging the width of the electrically pumped region. The output of arrays lies in the region of 200 mW to 3 W cw output at present. True arrays of laser diode stripes tend to be partially coherent and may exhibit the two lobe structure in the far field characteristic of the phase changes due to evanescent coupling between adjacent stripes. This feature appears less obvious as the output power and number of stripes increase due to reduced coherence across the array. The broad stripe arrays are multi transverse mode devices and the beam quality depends on how hard they are driven [7]. Applications of high power fiber delivery from diode lasers include pumping either bulk or fiber lasers, machining and marking, soldering, and power transmitting. High power fiber coupled diode laser sources could lead to the creation of compact high power diode pumped lasers. Similar systems that have been demonstrated either have relatively low power because they were limited to only one or two sources focused into a fiber, or because they consist of a fiber bundle in which one or two sources were focused into a fiber and then many fibers were brought together to form the pump source [13, 14]. A single fiber to carry all the power, as opposed to a fiber bundle, is desirable because it is less bulky and it maintains a greater degree of pump beam brightness, which allows improved performance from diode pumped lasers.

COMMON DPSS PROCESSES

The most common DPSS laser in use is the 532 nm wavelength green laser pointer. A powerful (>200 mW) 808 nm wavelength infrared GaAlAs laser diode pumps a neodymium doped Nd:YAG or a neodymium doped yttrium orthovanadate (Nd:YVO_4) crystal which produces 1064 nm wavelength light from the main spectral transition of neodymium ion. This light is then frequency doubled using a nonlinear optical process in a potassium titanyl phosphate ($KTiOPO_4$, KTP) crystal, producing 532 nm light. Green DPSS lasers are usually around 20% efficient, although some lasers can reach up to 35% efficiency. In other words, a green DPSS laser using a 2.5 W pump diode would be expected to output around 500-900 mW of 532 nm light. In optimal conditions, Nd:YVO_4 has a conversion efficiency of 60% [15], while KTP has a conversion efficiency of 80% [16]. In other words, a green DPSS laser can theoretically have an overall efficiency of 48%. In the realm of very high output powers, the KTP crystal becomes susceptible to optical damage. Thus, high power DPSS lasers generally have a larger beam diameter, as the 1064 nm laser is expended before it reaches the KTP crystal, reducing the irradiance from the infrared light. In order to maintain a lower beam diameter, a crystal with a higher damage threshold, such as lithium triborate (LBO), is used instead. Much of the excitement in nonlinear optics has been caused by a new generation of nonlinear materials. These new materials are non hygroscopic, have high damage threshold and good phase matching characteristics. Materials which are now widely available include KTP, LBO potassium niobate (KNB) and beta barium borate (BBO).

Blue DPSS lasers use a nearly identical process, except that the 808 nm light is being converted by an Nd:YAG crystal to 946 nm light (selecting this non principal spectral line of neodymium in the same Nd doped crystals), which is then frequency doubled to 473 nm by a BBO or LBO crystal. Because of the lower gain for the materials, blue lasers are relatively weak, and are only around 3-5% efficient. In the late 2000s, it was discovered that bismuth triborate (BiBO) crystals were more efficient than BBO and LBO and do not have the disadvantage of being hygroscopic, which degrades the crystal if it is exposed to moisture [17].

Violet DPSS lasers at 404 nm have been produced which directly double the output of a 1.000 mW 808 nm GaAlAs pump diode, for a violet light output of 120 mW (12% efficiency). These lasers out perform 50 mW gallium nitride (GaN) direct 405 nm Blu ray diode lasers, but the frequency doubled violet lasers also have a considerable infrared component in the beam, resulting from the pump diode.

Yellow DPSS lasers use an even more complicated process: A 808 nm pump diode is used to generate 1,064 nm and 1,342 nm light, which is summed to become 593.5 nm. Due to their complexity, most yellow DPSS lasers are only around 1% efficient, and usually more expensive per unit of power. In addition to optical fibre waveguides, waveguide lasers have been fabricated in bulk glasses and in a variety of crystals.

EXAMPLES OF DPSS LASERS

In this section we consider the performance of a range of specific DPSS lasers. We begin by considering in some detail the laser diode pumped Nd:YAG laser, which is certainly the best studied laser diode pumped system. We will then consider the performance of the laser diode pumped Nd:X laser, where X is any one of a number of host materials and also laser diode pumped stoichimetric materials. The stimulus for the research into these materials is essentially to reduce the size of DPSS lasers.

Nd doped DPSS lasers

The trivalent neodymium ion was the first of the rare earth ions to be used in a laser and it is the dopant which has received most attention in the field of DPSS lasers. The Nd^{3+} ion has a strong absorption at 0.81 μm, which coincides with the emission wavelength of commercially available GaAs and GaAlAs laser diodes. Most of the research reported on laser diode pumped Nd doped lasers has concentrated on the four level high gain $^4F_{3/2}$ - $^4I_{11/2}$ transition which corresponds to a laser output in the region of 1.06 μm. However, work has also been reported on the 1.3 μm $^4F_{3/2}$ - $^4I_{13/2}$ transition, and on the three level 0.946 μm $^4F_{3/2}$ - $^4I_{9/2}$ transition. In this paper, all Nd doped laser results refer to the 1.06 μm transition unless otherwise stated (Figure 6). Figure 7 shows a simplified energy level diagram for Nd and several other important rare earth ions.

The upper state lifetime is another important parameter for energy storage which can vary significantly with the choice of host medium. The problem which effects Nd^{3+} doped laser materials is that of concentration quenching of the upper state lifetime, where the lifetime decreases with increasing Nd^{3+} concentration. This leads to an increase in pump threshold. However, high doping is often desirable in DPSS lasers so that the pump radiation can be absorbed in a smaller volume, yielding a lower pump power threshold. One class of material in which this problem may be over come is that of stoichiometric materials, where the Nd^{3+} is a constituent component of the material, rather than a dopant [7].

Laser diode pumped Nd:YAG laser

The Nd:YAG laser has become the most common DPSS laser for a variety of reasons. The advantages of the Nd^{3+} ion as a dopant have been mentioned previously. The level of neodymium doping in YAG is limited to about 1.5% due to concentration quenching of the upper state lifetime. The YAG host is hardness, high thermal conductivity and good optical quality.

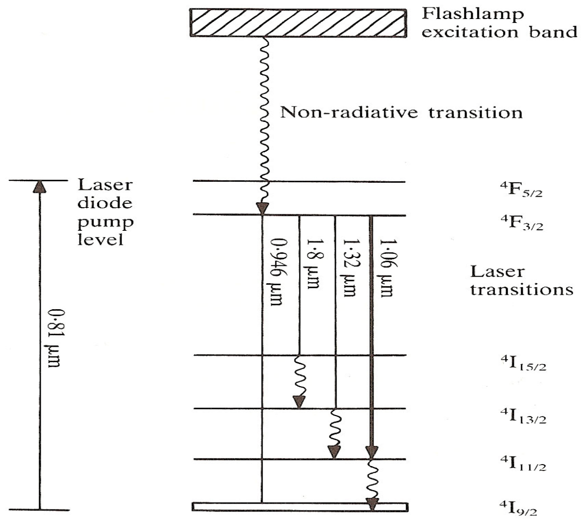

Figure 6. Enegy level diagram for Nd:YAG, illustrating process of diode laser excitation and Nd:YAG laser transitions.

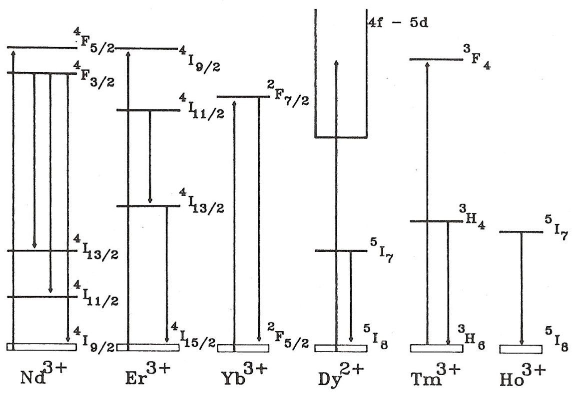

Figure 7. Simplified energy level diagrams for some of the most important rare earth ions [7].

The highest overall efficiencies are generally obtained from the longitudinally or end pumped geometry, due to the excellent matching that can be obtained between the solid state laser TEM_{00} mode. The first highly efficient laser diode end pumped Nd:YAG laser was reported by Sipes [18], who obtained an output of 80 mW at an overall (electrical to optical) efficiency of 8%. The limitations imposed on efficient coupling using end pumping mean that to obtain higher powers it is necessary to use a scheme whereby a laser rod or slab is pumped using a transverse pumping geometry. A disadvantage of the transverse pumped geometry tend to be much lower than for the end pumped case due to poor mode matching. Several authors have published results for pulsed systems. Optical slope efficiencies of 23% for slabs [19] and 54% for rods [20] have been obtained.

Transversely pumped cw Nd:YAG lasers have also been reported [13, 21]. Burnham and Hays [21] used four cw laser diodes to pump a Nd:YAG rod transversely. 3.3 W of multimode output were obtained, at an overall efficiency of 3.5%. As expected, the efficiency of TEM_{00} operation was lower at 2%.

Laser diode pumped Nd:YLF laser

The Nd:YLF laser has several properties very different from those of the Nd:YAG laser. The fact that it is a uniaxial material means that, simply by using an intracavity polarizer, one can select one of two different wavelengths for each transition. For the $^4F_{3/2}$ – $^4I_{11/2}$ transition these wavelengths are 1.047 µm, and 1.053 µm, with the 1.047 µm polarization exhibiting the higher gain. The natural birefringence of Nd:YLF swamps the effect of thermally induced birefringence observed in materials such as Nd:YAG.

The fluorescence lifetime of Nd:YLF is approximately twice as long as that of Nd:YAG. Furthermore, a large amount of energy can be stored in the medium gain 1.053 μm transition before the onset of amplified spontaneous emission. These facts make the laser diode pumped Nd:YLF laser an attractive medium for the generation of high power Q switched pulses [22-25]. The results show that approximately twice the pulse energy can be obtained from a Q switched Nd:YLF laser than from a Q switched Nd:YAG laser, due to the difference in the fluorescence lifetime for these media. The highest peak power that has been obtained to date from the laser diode pumped Nd: YLF laser is 70 kW, in a pulse of duration <10 ns [25].

Q switching was demonstrated in light emitting diodes pumped Nd:YAG and Nd doped potassium gadolinium tungstenate (Nd:PDT) [26]. A number of different techniques for Q switching were used including electrooptic, acoustooptic, saturable absorber, and cavity dumping. Pulse lengths as short as 4 ns using cavity dumping were obtained, with the highest peak power being 170 W in a 65 ns pulse in Nd:PGT by acoustooptic mode locking.

Laser diode pumped Nd:glass laser

Nd:glass is an ideal candidate for laser diode pumping due to its wide absorption spectrum in the region of 800 nm. Unlike, for example, the YAG host, the concentration of active ions can be very high before the onset of concentration quenching (approximately 7% Nd_2O_3 in phosphate glasses). The main disadvantage of glass as a host medium is its low thermal conductivity (0.6 W $m^{-1}K^{-1}$ for Schott LG760 phosphate glass as opposed to 11 W $m^{-1}K^{-1}$ for Nd:YAG). This makes the Nd:glass laser particularly susceptible to thermal effects, such as thermal lensing, thermally induced birefringence and thermal damage. The first reported operation of an laser diode pumped Nd:glass laser was by Kozlovsky et al. [27]. A pump power threshold of 2 mW and a slope efficiency of 42% was obtained from a monolithic device, when pumped with a low power single stripe laser diode.

The highest output power obtained from an laser diode pumped Nd:glass laser was reported by Fan [3]. Using a spinning glass disc as the gain medium to overcome thermal problems, an output power of 550 mW was obtained for an absorbed power of 2 W. Basu and Byer [16] carried out an analysis of the scalability of laser diode pumped Nd:glass lasers in the zig zag slab and rotating disc geometries. They predicted that for the rotating disc laser, up to 20 kW of average output power should be achievable.

Diode pumped stoichiometric lasers

We consider the work carried out to date on stoichiometric laser materials. The stimulus for the research into these materials is essentially to reduce the size of DPSS lasers. Stoichiometric materials are compounds which contain the lasing species, rather than hosts into which the species is doped. Due to this, the concentration of active ions can be much larger in stoichiometric materials, resulting in a shorter absorption length for the pump radiation.

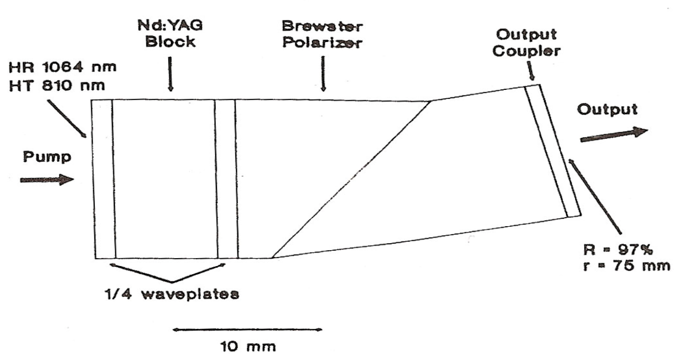

Figure 8. Schematic diagram of the monolithic twisted mode cavity Nd:YAG laser (adapted [7]).

Dixon et al. [28] have used an interesting technique to couple the pump radiation into the LNP ($LiNdP_4O_{12}$) laser mode where the crystal is placed in very close proximity to the laser diode output facet. Due the very short absorption length of the LNP crystal, there is no need for collimating and focusing optics to be used, as is normally the case for DPSS lasers. Using a separate output coupler, laser operation was obtained at both 1047 nm (slope efficiency 33%) and 1317 nm (slope efficiency 10%). The maximum output powers obtained were 73.5 mW and 24 mW, respectively. Using a monolithic device (Figure 8), 28 mW output was obtained at 1317 nm. The authors believe that the slope efficiencies reported will increase as crystal growth and fabrication techniques are improved [7]. If the axes of the wave plates are properly adjusted, a standing wave with an axially uniform energy density can be created. Spatial hole burning is thus eliminated.

Diode pumped waveguide lasers

In addition to bulk lasers, there is much interest in the use of laser diodes to pump waveguide lasers. The use of guided wave structures instead of bulk devices is also of interest for diode pumping. One reason is the compatibility of guided wave devices with optical fiber systems. Another reason is that by guiding both the pump wave and the laser mode, higher pump densities and therefore gain compared to bulk devices can be achieved. The first report of a guided wave device was end pumped a multimode, Nd doped, silica based, glass fiber laser. The cavity was provided by either depositing reflector coating directly onto the end of the fiber or by external mirrors.

Waveguiding structures were also considered for a transverse pump geometry [29]. Such a device may offer advantages such as small resonator construction and good transverse mode stability. Design calculations were performed for an light emitting diode array pumped, rectangular cross section waveguide fabricated of a number of Nd laser materials including Nd:YAG, and LNP. Such a device made of an LNP gain medium with a glass cladding was demonstrated using Ar^+ laser pumping [30, 31].

CONCLUSION

DPSS lasers generally have a higher beam quality and can reach very high powers while maintaining a relatively good beam quality. Because the crystal pumped by the diode acts as its own laser, the quality of the output beam is independent of that of the input beam. In comparison, diode lasers can only reach a few hundred milliwatts unless they operate in multiple transverse mode. Such multi mode lasers have larger a beam diameter and a greater divergence, which makes them less desirable. In fact, single mode operation is essential in some applications, such as optical drives.

On the other hand, diode lasers are cheaper and more energy efficient. As DPSS crystals are not 100% efficient, some power is lost when the frequency is converted. DPSS lasers are also more sensitive to temperature and can only operate optimally within a small range. Otherwise, the laser would suffer from stability issues, such as hopping between modes and large fluctuations in the output power. DPSS lasers also require a more complex construction. Diode lasers can also be precisely modulated with a greater frequency than DPSS lasers.

Neodymium doped materials other than YAG and stoichiometrics have been used. Other materials have different spectroscopic properties which have advantages over YAG and stoichiometrics. Three important properties are upper state lifetime, absorption spectra, and output wavelength. To obtain larger energy storage, it is desirable to use materials with longer upper state lifetimes. In a pulsed mode, the maximum pulse energy is proportional to the upper state lifetime for a fixed value of cw pump power. The absorption features in the diode laser wavelength band should be wide so that control of the diode laser wavelength is less critical. In addition, it is shown later that the strength of the absorption is a key parameter for these devices. The exact output wavelength of the diode pumped solid state laser is important in some applications. For example, the 1.064 μm output of Nd:YAG does not match the peak gain of Nd doped phosphate glass systems.

The current generation of diode laser used for pumping solid state materials yields efficiencies of around 30%, resulting in DPSS lasers with overall electrical to optical efficiency of around 15%. New tecnologies in semiconductor diode laser fabrication have demonstrated devices with 50% conversion from electrical to optical power. Such improvements in the basic diode pump will in future lead to even greater efficiencies being produced by DPSS lasers [32]. The progress in device physics has now made a jump ahead of the applications. In the next few years we are likely to see a broadening of the range of applications to which this exciting new technology is applied.

Higher average powers can presently be obtained from lamp pumped systems. However, scaling to higher average powers for diode pumped systems appears feasible due to rapid advances in diode laser array technology. The field of diode laser dumped solid state lasers is moving rapidly. These devices have already been shown to be excellent sources due to their compactness, high efficiency, good frequency stability, and simple design and should find a wide variety of applications. DPSS lasers are now widely used in place of argon and helium cadmium lasers for high performance stereolithography systems due to their superior efficiency, reduced operating costs and compact size. Because of the high speed scanning process used in stereolithography, the laser must be quasi cw on the time scale of the scanning system. The fast growing fields of bio science are now taking advantage of the latest developments in DPSS laser technology. Laser transitions which offer the possibility for diode laser pumping are presented. It is clear that diode pumped solid state lasers offer the possibility of greatly improved performance over lamp pumped solid state lasers and other sources and will be important devices in the future.

ACKNOWLEDGEMENTS
I would like to thank Professor Dr. Andrew SUCIU (Materials Science and Engineering Division Laser Technology, Politehnica University of Bucharest, Bucharest-Romania) is also gratefully discussed for DPSS lasers.

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