# DIODE LASER PUMPED SOLID STATE LASERS

Diode lasers are fast becoming an ideal source for pumping solid state lasers, due of their high electrical to optical power conversion efficiency, narrow spectral output, long operating lifetime and the small size. These sources have not only replaced arc lamp pumped systems in many applications, they have often provided new capabilities such as much more stable single frequency emission and much shorter q-switched and mode locked pulses.

Diode lasers are being used in both 'end' and 'side' pumping geometries. Diode pumped solid state lasers with diffraction limited output beams that utilise end pumping are generally more efficient than those where side pumping is employed. In an end pumping scheme, with proper mode matching, high efficiencies even close to the quantum limit are possible. Diode pumped infared $Nd^{3+}$ lasers and intracavity frequency doubled green lasers are turning out to be efficient laser sources which are useful for a variety of applications ranging from medical diagnostics to optical data storage.

Much work has concentrated on the evaluation of the laser performance of various neodymium doped matrices under diode pumping. All $Nd^{3+}$ laser materials can be divided into two groups. The first group consists of YAG, YLF, $GdVO_4$, $YVO_4$ and pure GGG. In these materials the fluorescence lines are nearly homogeneously broadened at room temperature. The second group consists of LNA, ASN, and GGG (Ca,Cr) and GGG (Ca, Zr, Mg) which are also called sub-GGG. For these materials, the inhomogeneous broadening of the fluorescence bands has to be taken into account to explain the surprising variations of their slope efficiencies with the output mirror transmission. In most of the above mentioned materials, the absorption band of $Nd^{3+}$ is quite narrow while the emission wave length of the AlGaAs laser diodes varies with its junction temperature at a rate of $\cong 0.3$ nm/°C, and thus a few degrees change scans the whole 800 nm absorption band of most $Nd^{3+}$ doped laser materials. For this reason, and also to prolong the junction life time, laser diodes are often equipped with a thermoelectric cooler which is highly energy consuming. This reduces the overall electrical to optical efficiency of the laser. It is then a major goal to find a laser material with absorption bands wide enough to support a certain variation of the pump wavelength, thus giving the possibility to eliminate the diode temperature regulation device.

Measurements of the optical efficiency (IR output versus incident pump power) as a function of the diode junction temperature up to of about 300°C, shows that $YVO_4$, $GdVO_4$, Sub-GGG and LNA are broadband materials that could be pumped by a laser diode without thermal regulation. Reported laser characteristics measurements show that both $YVO_4$ and $GdVO_4$ combine good laser efficiency with low sensitivity to diode temperature fluctuations; thus they would be certainly the best materials if the energy consumption of the thermoelectric cooler is also considered. Nd:$YVO_4$ and Nd:$GdVO_4$ show similar spectroscopic properties. The task of achieving high optical quality Nd:$YVO_4$ crystal is beset by a number of technological problems while the development of Nd:$GdVO_4$ crystal presents fewer technical problems.

Gadolinium vanadate belongs to the group of oxide compounds crystallizing in a $ZrSIO_4$ structure with tetragonal space group. The four fold symmetry axis is the crystallographic c axis. Perpendicular to this axis are the two indistinguishable a and b axis. The lattice parameters of $GdVO_4$ are $a = 7.211$ and $c = 6.350$. The uniaxial crystal Nd:$GdVO_4$ shows strong polarization dependent absorption transitions due to the anisotropic crystal field. At 808.4 nm the peak absorption coefficient in $\pi$ polarization is 78 $cm^{-1}$ for a 1.2% neodymium doping level, resulting in an effective absorption cross section of $5.2 \times 10^{-19}$ $cm^2$. The half width of the absorption at 808.4 nm is 1.6 nm. Nd:$GdVO_4$ shows strong fluorescence at 1064 nm wavelength when it is excited by 808 nm laser diode beam. This fluorescence is dependent on the polarization of the pump beam.

The overriding objective in a diode pumped laser is to efficiently convert the pump light to laser output. To achieve this goal it is required that each of the intermediate steps in the process viz transfer of the pump light to the active media, the absorption of the pump light and the extraction of deposited power from the active media be efficient. Efficient transfer of the diode power to the active media mode volume is difficult. This is a result of the high divergence of laser diode in the perpendicular direction. The high divergence requires the use of very fast collimating optics.

It is the beam quality of the laser diode which dominates the design of the high power end pumped laser. For applications which do not require diffraction limited beam quality in the perpendicular direction, a simple rod lens effectively collects and collimates the light. Aspheric cylindrical lenses can efficiently collect the light while maintaining the good beam quality. Most end pumped lasers do not require aspheric elements in the pump optics, since the mode size is limited by the low beam quality of the

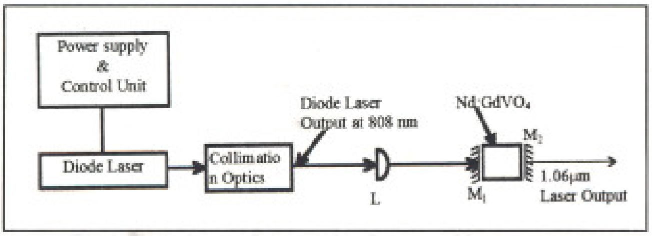


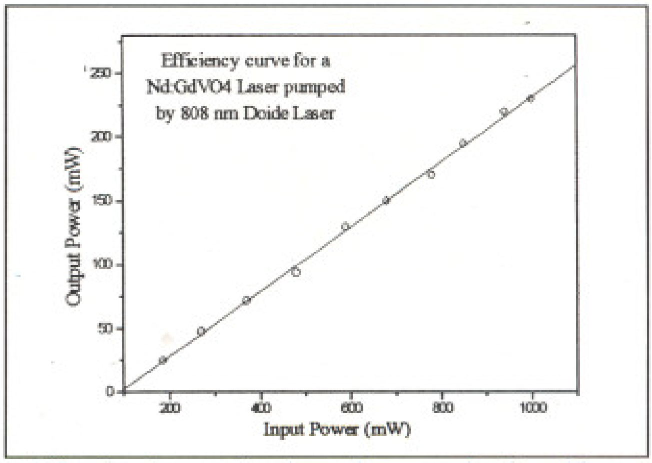
**Fig. 1 Experimental setup of end-pumped laser system.**

pump in parallel direction. The pump spot size within the lasing material will be larger than the calculated value since the beam diverges while being absorbed. The focusing optics can cause additional aberrations. Thus the low beam quality demands the use of short focal length optics, limits the pump intensity and requires large mode volume resonators for efficient pumping.

Efficient absorption of the pump light is inherent to the end pump geometry due to the increased absorption length. End pumping schemes offer the advantages of high pump efficiency and good mode selection for single mode operation of solid state lasers. This form of pumping allows the pump energy to be deposited in to the central region of the gain medium, thus exciting the lowest order transverse mode. As a consequence of this pump nonuniformity, the transverse heat distribution, which results from the quantum inefficiencies, is also nonuniform. Nonuniform heating distributions tend to produce parabolic temperature and phase error profiles. Heating of the crystal also leads to beam depolarization effects as a consequence of thermal stress induced birefringence. The most fundamental limitation on power scaling is the possibility of thermal fracture. It is more difficult to reduce thermal stresses in an end pumped geometry than in side pumped geometry, where the axial dimensions of the rod may be scaled linearly (for fixed pump power) to achieve linear reduction in thermal stresses.

For efficient extraction of laser power the pump spot should be approximately the same size as the fundamental mode. This can be achieved by the proper design of the laser cavity.

We have chosen Nd:GdVO4 as the gain medium for the development of diode pumped solid state laser in our laboratory. Laser experiments at 1.06 $\mu$m were performed with a 2.5 mm thick Nd:GdVO4 crystal sample. The crystal has been oriented with the c-axis parallel to the polarization direction of the diode laser. In our experiment an FTI make diode laser of 1W output power was used. The divergence of the output beam from the diode was 5.8° and 1.3° in the perpendicular and parallel direction respectively and was collimated with the help of a collimator optics of focal length of 8.0 mm. The collimated beam was then focused on to the gain medium by a lens of 50.0 mm focal length. The power supply to operate the diode laser and the control unit for the thermoelectric cooler were developed in our laboratory. We used two types of resonator configurations, plane-plane geometry and plano-concave geometry.



The plane-plane resonator is formed by optical coating on the end surfaces of the crystal (fig 1). The end facing the diode laser has a high reflection coating whereas the other end has a partial transmission (5%) at 1064 nm. Both the surfaces were AR coated at 808 nm. The thermal lens produced by the pump beam inside the crystal makes the cavity stable for laser operation. The crystal was mounted on a copper plate to reduce the thermal stress developed inside the crystal. The output power of the laser at 1064 nm was 225 mW, for a pump power of 1000 mW, giving a slope efficiency of 22.5% as shown in figure above.

In plano-concave geometry the crystal is mounted on a copper plate near a plane HR mirror. The output coupler has a 80 mm radius of curvature and 5% transmission at 1.06$\mu$m. The laser cavity is nearly hemispherical. This plano concave cavity has a waist of $\omega_c = 80\,\mu$m. The single mode operation was confirmed. The crystal absorbed 97% of the diode laser pump light. With the 5% output coupler we obtained 160 mW output power with a slope efficiency of 16%. The reason for the lower slope efficiency of the laser performance in this configuration may be due to the improper matching of the cavity waist with the focused pump spot.

Second harmonic generation (SHG) in a diode pumped miniature Nd:GdVO4 laser was achieved by placing a non linear optical crystal KTiOPO4 (KTP) within the laser resonator to take advantage of the high circulating field. The phase matching range covered by a KTP crystal with respect to temperature acceptance or angular acceptance is large. In our laser arrangement one face of the KTP crystal has HR coating for 1064 nm and HT coating for 532 nm while the other face was AR coated for 1064 nm. This AR coated face was attached with the crystal surface while the other face of the crystal was in touch with a plane mirror which was HR for both 1064 nm & 532 nm and thus ensuring plane-plane geometry. The crystal operates in type-II phase matching condition. 1mW output green light was observed.

The small size and simple structure of the diode laser enables a direct coupling of the pumping radiation to the laser without any complex optics. But to obtain good overall electrical efficiency, the thermoelectric cooling, which is necessary to stabilise the operating wavelength of the laser diode, must be considered as well. It is of major importance to check the performance of these laser crystals as a function of the diode wavelength.

In our laser experiments, only end pumping was employed, but side pumping is necessary for scaling to higher powers. This allows pumping by arrays of diode lasers. It remains to be seen whether the efficiency of side-pumped devices can approach that of end-pumped devices, with near diffraction limited output beams. One possible approach to pump with diode arrays in a small volume is to couple the pump power from each individual diodes to the gain medium through optical fibers. It is very difficult to produce consistent and reliable intracavity frequency doubled lasers due to their intrinsic complexity. Solid state lasers have nonlinear cross saturation properties because of standing wave effects in the laser cavity. Combining this with a nonlinear output coupling gives a system with two coupled nonlinearities. As the strength of these couplings are varied they lead to bistability, oscillation and ultimately chaotic amplitude fluctuations.

Despite these problems, recent developments in diode pumps solid state lasers have not only made these lasers efficient alternatives to flash lamps pumped solid state lasers but they are also going to replace gas and ion lasers in several applications.

Rakesh Kapoor

# We Interview . . . .

**Dr R Chidambaram, Chairman, Atomic Energy Commission & Secretary, Department of Atomic Energy visited CAT during February 1996. He saw the booster synchrotron in operation and also visited various labs. Following is an excerpt from his interview with the Newsletter editorial board:**

Q. CAT is about to complete 10 years. What do you think of the progress made till now?

Since the ten years of its inception CAT has made excellent progress under the dynamic leadership of Dr Bhawalkar. A very significant advantage in CAT is the low average age of the scientists working here, compared to other units. Therefore, they still have a lot of potential to achieve higher goals. The balance between science and technology maintained in laser programme is an ideal mix. The working atmosphere is very open. Both things together means scope is there for everyone.

Q. In your opinion, what should be the future goals of CAT now?

CAT should be working in the forefront of laser science for example developing new kinds of lasers. In this context, one should not worry too much about technology (buy it wherever possible or develop an alternative). On the technological development side, we have to note that after liberalisation the multinationals are looking to India as a big market. So they also have a vested interest in preventing us from developing technology on our own. To this end, tricks like labeling technologies strategic to prevent us from buying them, are used. But once the same thing is developed here the sanctions are removed. Therefore, we have to develop capability for making every component so as to be able to bargain from a strong position. In this context the development of synchrotron radiation source at CAT is an important step.

Q. Since the R&D work done in labs like CAT does affect the market, what should be the level of interaction between institutions like this centre and the Indian industry?

We should work in the frontline research areas because that governs the development of new technology. The responsibility of making industry aware of this fact rests with R&D labs. They have to reach out to industry, not vice versa. A good example of this kind of interaction are the chemical and drug industries in India. R&D centres should contribute their knowledge to bring our industry up to internationally competitive standards. Once the technology is available to them, the cheaper labour and good management practices in India would ensure economic competitiveness. We also have a big advantage in the excellent software expertise available in the country. What we have to ensure is that before transferring the technology to industry from R & D centres, it should be brought up to a level where it can compete with established brands in quality. In this context, the development of laser fluorimeter, medical lasers and $CO_2$ laser at CAT is a step in the right direction.

Q. A lot of resources are invested in national facilities.