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DIODE-PUMPED IR SOLID-STATE LASERS

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Abstract—The possibilities of construction and applications of laser diode-pumped solid-state lasers are described. The wavelength of the most powerful available diodes is well suited for the excitation of rare earth ions such as Nd^{3+}, Tm^{3+} and Er^{3+} in crystal or glass hosts. The resulting emission of the mid-infrared lasers is suitable for metal machining or for medical applications. The main problem is a suitable beam shaping of the laser diode array in order to achieve a good overlap of pump mode and laser mode. The chosen solution of beam shaping strongly influences the geometry of the solid state laser resonator. Different examples developed at our institute will be described.

I. INTRODUCTION

The laser has seen rapid development over the last 30 years, and an intense research effort continues due to a multitude of applications. Restricting ourselves to solid state lasers there is a strong desire to replace flash lamp pumped systems by laser diode pumped systems with the goal of obtaining highly efficient all solid-state compact lasers. With the replacement of the flash lamp it becomes possible to selectively excite the desired levels of the laser crystal. This can reduce unnecessary phonon transitions in the material which result in undesired heating. A reduction of heating leads to lower thermal lensing or beam distortion. It can therefore be expected that TEM_{00} operation will be possible up to a higher power level than with flash lamp pumping. Also the high efficiency of available laser diodes and the low voltage needed for their operation reduces the size and the cooling requirements of the power supplies. Instead of a power supply with the size of a cupboard including high voltage with its inherent triggering problems and electrical interferences with other equipment, a laser diode-pumped system with comparable output can be operated with a power supply in the size of a personal computer.

II. AVAILABLE DIODES

Suitable diodes are available at a wavelength $\lambda = 780$–870 nm in the case of GaAlAs and at a wavelength of $\lambda = 900$–990 nm in the case of InGaAs. Since the development of the GaAlAs is more advanced with respect to availability, output power and price we will concentrate on continuous laser diode pumping at $\lambda \approx 800$ nm. During the last years the price per Watt of these diodes has been lowered considerably so that today the costs for laser diode-pumping are about comparable to the costs for flash lamp-pumping. It can be expected that the trend to even lower price per Watt will continue. The typical pump diode is a linear array of numerous multistripe emitters with an emission zone of about 1 μm perpendicular to the junction and with an overall length of about 1 cm parallel to the junction. The aperture angle of the emission is about 40° FWHM diffraction limited perpendicular to the junction and about 10° FWHM parallel to the junction. The large angle of 10° is mainly due to a dual lobed emission which is characteristic for coupled multistripe emitters since in phased arrays adjacent stripes tend to emit with a phase shift of π.

III. AVAILABLE RE IONS

The emission around $\lambda = 800$ nm of GaAlAs laser diodes can only be used for pumping those laser materials that have strong absorption bands at this wavelength. In the case of crystals doped with trivalent rare earth ions this condition is especially well fulfilled for Nd^{3+}. Other ions such as Tm^{3+} and Er^{3+} require a somewhat shorter wavelength at about 790 nm.[3] Erbium and a number of ytterbium-sensitized crystals could even better be excited with the emission InGaAs diodes around 970 nm. It can therefore be expected that powerful InGaAs laser diode arrays will soon be available at reasonable prices. With Nd^{3+}, Tm^{3+} or $Tm^{3+}:Ho^{3+}$ and Er^{3+} solid-state laser sources with wavelength of about 1, 2 and 3 μm are available. It can be expected that a laser at 1 μm with a power level of about 100 W in the TEM_{00} mode would be very useful for metal machining. For medical applications the crucial property of the laser radiation is its penetration depth in tissue. Depending on this value different applications can be considered. A laser with 2 μm emission with a penetration depth in the order of 200 μm and with a power of about 10 W can be used in laser surgery for hemostasis, coagulation of tissue as well as tissue welding. A 3 μm laser source with an extremely short penetration in tissue of only about 1 μm and with a power of about 1 W will be used as a knife in surgery or microsurgery. The strong absorption of 3 μm light in tissue leads to immediate partial vaporization. Vaporization is the most effective cooling process in irradiated tissue. This process reduces the heat flow into the tissue that leads to undesired coagulation of the walls of the incision. A reduction of coagulation leads to faster healing. Sometimes this behaviour is in contrast to the desired coagulation for hemostasis so that the surgeon will have to use both wavelengths, 3 μm and 2 μm as well.

IV. PUMP GEOMETRY

The length of the laser array and the large aperture angles of the emission lead to problems in efficiently coupling the diode emission to the mode volume of the crystal laser. In the case of transverse pumping with respect to the laser axis the optical requirements are somewhat relaxed and a simple and efficient pump geometry can be found. Transverse pumping, however, can result in the excitation of laser material lying outside of the TEM_{00} fundamental mode. At high pump power therefore higher transverse modes will also be excited. Higher transverse modes cannot be focused to such a small spot as the fundamental mode. The achievable intensity in the focused beam is therefore reduced with respect to TEM_{00} emission. For this reason longitudinal pumping with a good overlap between pump mode and laser mode is preferred. With crystals in the form of multiple disks[4,5] or a slab[6] multiple pumping is possible and high power can be reached. In this case, however, the requirements for shaping the pump beam are very strict and it becomes rather difficult to find a suitable optical system. In all geometrical pump arrangements high power pumping leads to thermal effects that decrease the beam quality and eventually prevent the laser from oscillating in TEM_{00} mode.[7] Thermal lensing degrades the beam especially in the slab geometry leading to strong astigmatism.

V. BEAM SHAPING

Different methods to solve the problem of pump beam shaping have been investigated. Solutions include pig tailing with fibres,[8,9] the use of refractive[10] or reflective optics as well as the use of diffracting optics.[11–13] As an example for pig tailing with an efficient line to bundle converter Fig. 1 shows a fibre-optical solution to concentrate the diode laser emission to a small spot.

Stacking the fibres at the output side leads to a quadratic light source 279 μm wide by 225 μm high. Due to mode mixing even in a short piece of 10 cm fiber length the output divergence is symmetric with about 22° FWHM. Adjustment tolerances and coupling efficiencies are described in Ref. (8). The converter is designed for a 15 W laser diode bar with 10 phased arrays each 200 μm

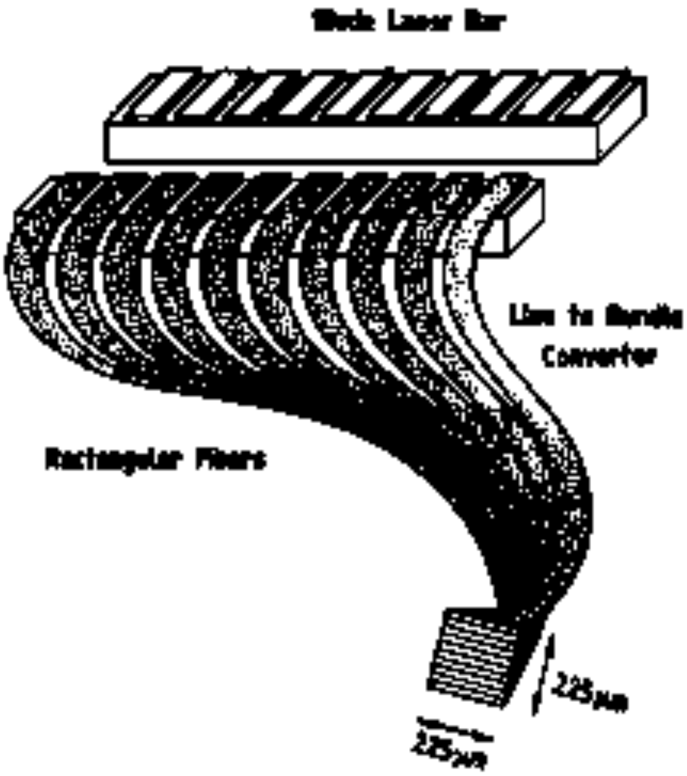

Fig. 1. A fibreoptic line to bundle converter.

wide and 1 μm high. Each of the ten fibres is composed from ten quadratic fibrelets of about 22.5 μm × 22.5 μm. The thickness of the cladding is only about 2 μm leading to a core-to-cladding fill factor of 85%. The refractive index of the quadratic core is as high as 1.62 with respect to 1.49 of the cladding resulting in a numerical aperture of 0.66 that allows acceptance of >98% of the divergence of the laser beam.

VI. EXAMPLES

Depending on the optical system, a large number of different geometrical arrangements has been tested in our Institute. Diode pumped lasers have been realized in Nd^{3+}, $Tm^{3+}:Ho^{3+}$ or Er^{3+} doped glass fibres at wavelengths of 1.06, 2.05 and 2.76 μm, respectively. In this case a fibre geometry can be found that allows efficient multimode pumping of single mode lasers. Depending on the dopant, output powers in the 1 W range can be reached with such fibres. With crystals numerous experiments have been performed with laser diode pumped Nd^{3+}:YAG lasers.[9]

Transversal pumping of Nd^{3+}:YAG was performed in a parabolic pump cavity as shown in Fig. 2. This geometry with a pump cavity made from BK-7 glass has the advantage that up to four of these units can be combined to pump a crystal of 2 cm length.[10,11] As yet experimental data are available for a system of two pump cavities with a total of eight pump diodes (10 W high power laser diodes from Jenoptik Laser Diode GmbH). With a 2 cm Nd:YAG rod with 4 mm dia pumped in a 10 cm resonator with the mirrors of $R = 0.98$ and $R = 0.95$ with a pump power of 70 W a maximum output power of 13.5 W at $\lambda = 1.06$ μm has been achieved with a slope efficiency of 24.6%. 5 W have been reached in TEM_{00} mode.

Longitudinal pumping of Nd^{3+}:YAG was performed with a commercial pump module (Fisba DL-50). This system delivers 50 W pump power with a beam of NA = 0.3 (with 50 mm focal length) or with NA = 0.15 (with 100 mm focal length). With the 100 mm focal length the measured size

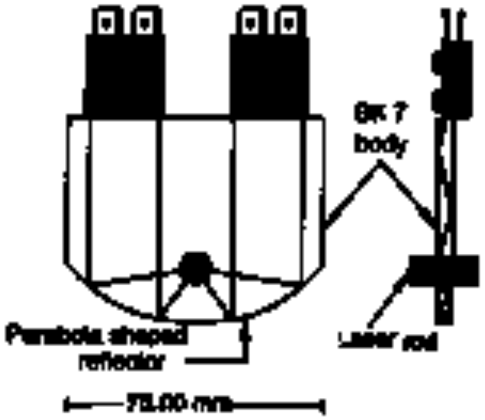

Fig. 2. A parabolic pump cavity.

of the elliptical spot is about 0.55 mm diameter by 0.4 mm diameter FWHM. Such a pump beam is well suited for longitudinal pumping since it can easily be matched with the laser mode. Preliminary results with a 2 cm rod of 5 mm diameter in a resonator of 60 mm length with two flat mirrors of $R = 1$ and $R = 0.9$ led to a multimode output of up to 20 W.

In a number of other experiments for simplicity the diode emission was simulated with a Ti:sapphire laser because no laser diodes were available with an emission wavelength below 800 nm. Examples are Tm:Ho:YAG,(14) Tm:Ho:GdVO$_4$,(15) Er:YLF(16) and Er:YSGG.(17) The Tm:Ho: experiments have been performed in active mirror mode, an experimental arrangement using longitudinal pumping. The set-up is shown in Fig. 3. This arrangement is extremely suitable for highly absorbing crystals with short rod lengths. The rear mirror is highly reflecting for the laser wavelength and also for the pump wavelength. It is further in close thermal contact with the laser crystal, so that cooling can be achieved longitudinally through the back window instead of radially as in a conventional system. The reflected pump light leads to a homogeneous distribution of pump light as it is desired when losses such as reabsorption in a quasi three level laser or quadratic losses due to upconversion can occur.(18) With short crystals such as 0.4 mm in the case of Tm:Ho:GdVO$_4$(15) a very efficient cooling of the crystal is achieved and it is expected that influences of thermal lensing will be minimized in such an arrangement. It is interesting to note that this concept is also used with very thin crystal discs for a multi 100 W Yb:YAG laser with reduced thermal distortion.(19) In such an arrangement the pump light of the diodes can be strongly focused. The resulting large aperture does not lead to low pump density if the pump light is absorbed with a fraction of a mm.

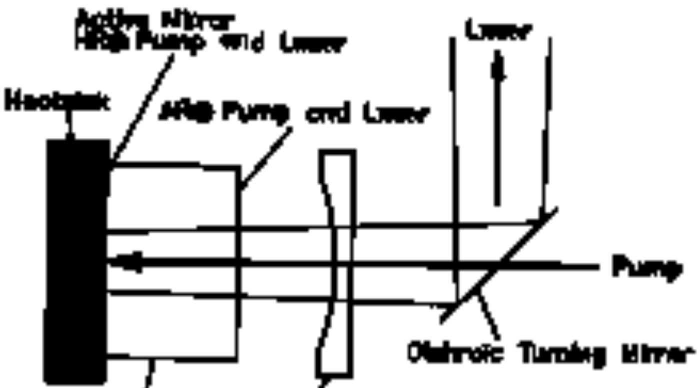

Fig. 3. Experimental arrangement in active mirror mode.

VII. CRYSTALS

Depending on beam shaping technique and resulting pump geometry also the properties of the crystals have to be optimized. In the case of Nd^{3+}, and $Tm^{3+}:Ho^{3+}$ lasers conventional crystals such as YAG have proven to give excellent results.[16-18] In the case of Er^{3+} excited with pump diodes at 790 nm wavelength the situation is somewhat more complicated due to the complex spectral behaviour of Er^{3+}. A thorough simulation of the laser process including all the relevant levels, excited state absorption processes and cross-relaxation processes shows that most oxide crystals are not very suitable for 3 μm lasing in CW mode. The most promising candidates are currently fluorides such as $Er:LiYF_4$ or $Er:BaY_2F_8$. There is, however, a very strong effort to investigate also new crystals such as $Cs_3RE_2X_9$ ($X = Cl, Br, I$) with excellent properties in view of low phonon energy, long fluorescence lifetimes and strong cross-relaxation coefficients.[21-23]

VIII. SUMMARY

In summary we have shown that diode laser pumping of rare-earth doped crystals is especially suitable for Nd^{3+}, Tm^{3+} or $Tm^{3+}:Ho^{3+}$ as well as for Er^{3+}. These rare-earth ions allow laser transitions around 1, 2 and 3 μm, respectively. 1 μm laser emission is suitable for metal machining if power levels in the order of 100 W are reached. 2 μm and 3 μm emission is suitable for medical applications such as coagulation or tissue welding with 2 μm laser radiation or cutting of tissue with minimum thermal damage with 3 μm emission. The problems arising from the emission properties of diode arrays can be solved in numerous ways and with a suitable pump geometry, especially in active mirror mode with very thin crystals very high pump densities can be reached and thermal distortions can be minimized.

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