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Scaling of Solid State Lasers for Satellite Power Beaming Applications

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ABSTRACT

The power requirements for a satellite power beaming laser system depend upon the diameter of the beam director, the performance of the adaptive optics system, and the mission requirements. For an 8 meter beam director and overall Strehl ratio of 50%, a 30 kW laser at 850 nm can deliver an equivalent solar flux to a satellite at geostationary orbit. Advances in Diode Pumped Solid State Lasers (DPSSL) have brought these small, efficient and reliable devices to high average power and they should be considered for satellite power beaming applications. Two solid state systems are described: a diode pumped Alexandrite and diode pumped Thulium doped YAG. Both can deliver high average power at 850 nm in a single aperture.

1. BACKGROUND

In a companion paper[1], a conceptual design for a laser power beaming system for recharging batteries of geostationary satellites was presented. The key feature of the system is the use of modern, large diameter beam directors with an efficient adaptive optics control system to reduce the power requirements of the laser to a manageable level. With these developments, the power level of the laser needed to deliver an equivalent solar flux to geostationary orbit was reduced to the order of 30 kW from the value of 300 kW reported in other studies. At this power level, advanced solid state lasers, which are rapidly being scaled in power, may be used to great advantage for this application.

Solid state lasers have always been a simple, efficient generator of near IR radiation, having few of the difficult technologies usually associated with other lasers. There is no gas discharge (except in the flash lamp pump), no high voltage electron beams, and no toxic, corrosive or flammable gases. By virtue of the fact that the solid state laser medium is already at high density, the physical size of the gain generator is small, especially compared to low density gas lasers or Free Electron Lasers. Liquid dye lasers share this small size feature with solid state lasers, but since they require high flow rates to maintain good medium homogeneity, their pump systems tend to be large. In designs of dye lasers capable of tens of kilowatts from a single aperture, the dye flow approaches sonic velocity and the pump systems become impractical. There are designs for multiple dye lasers at the 30 kW level. These multiple dye lasers could be each tuned a few hundred angstroms apart and still stay at the (broad) peak of the solar cell response curve. Dichroic elements would then combine the beams with no phasing required. At this point, however, this approach appears not to be cost effective.

In comparison with Free Electron Lasers (FEL's), solid state lasers are significantly smaller. For very large powers, of the order of megawatts, the scalability of FEL's may be attractive, but in the intermediary regime of tens of kilowatts, the solid state lasers scale better with regard to cost and size. The primary reason for this is that in order for a FEL to achieve lasing wavelengths less than a micron, the electron beam energy must be large, regardless of the average power level, and this equipment is large and expensive.

Finally, pulse format requirements favor solid state lasers over almost any other type of lasing medium. Solid state lasers with storage times of a hundred microseconds naturally produce long pulses, which at moderate repetition rates, of the order of a kilohertz, have a high duty cycle well suited to efficient solar cell conversion. In fact, it is the use of complex switching mechanisms to produce short pulses needed for many applications which give some solid state lasers a complex nature. Long pulses at high duty cycles are naturally produced by simple solid state lasers.

Two key technical issues have prevented solid state lasers from being considered for power beaming applications; the achievement of a wavelength less than one micron and the attainment of high average power with good beam quality. The development of laser diode arrays capable of scaling to high average power is a crucial factor in overcoming these shortcomings. Two technologies developed at LLNL have made the design of Diode Pumped Solid State Lasers (DPSSL) feasible for a slab laser with 30 kW average power, wavelengths in the 750 nm-850 nm range and with high duty cycle pulse formats. These technologies are the ability to build high density, high average power diode arrays at low cost and a diode pump architecture that uses microlens conditioning and a lens duct to efficiently deliver the outputs of large, two dimensional arrays to the slab lasers.

Efficient solid state lasers generally produce wavelengths larger than one micron, which are inappropriate for efficient solar cell conversion. This is certainly true for GaAs solar cells which have a long wavelength cutoff at about 0.9 microns. For silicon solar cells, radiation damage, which normally occurs after many years in orbit, also shortens the long wavelength to less than one micron. Hence, solid state lasers, which efficiently operate at 1.06 microns, are not useful for the battery charging application which normally would be used for satellites after many years in orbit. For a longer term application, however, megawatt class solid state lasers at 1.06 micron might be well suited to orbital transfers scenarios. In this application, the satellites are new, the solar cells have not been radiation damaged to any great extent, and such a wavelength might be acceptable. Designs for solid state lasers for weapon applications have been developed in the multimegawatt range, but these designs will not be discussed here. In the meanwhile, two designs for a DPSSL at 30 kW in the wavelength range of 750 nm-850 nm will be described.

It will be necessary that the laser deliver its beam power with a phase front and irradiance distribution which is close to the diffraction limit. There are several common approaches to achieve this. Lasers with high gain can support the losses intrinsic to the effective (transverse) mode discrimination property of high magnification unstable resonators. For the two lasers discussed here, Alexandrite and Th:YAG, neither appear to have the gain necessary to support this approach effectively and an easier method for these lower gain systems is the Master Oscillator-Power Amplifier (MOPA) scheme. In this scheme, an oscillator small enough to deliver good beam quality is amplified through subsequent stages until the desired output power is reached. The MOPA approach allows for intermediate stages of beam quality control and is a safe, albeit less elegant way, of achieving good quality beams. Finally, there are approaches which incorporate phase conjugation to restore the phase quality of a low power input beam after it has passed through an amplifier. The average power scaling of this approach, especially at low peak powers, is still being investigated at a fundamental level. If successful, interesting ways of combining the MOPA and the power oscillator approach to achieve excellent beam quality at high average power, could be envisioned.

LLNL has developed a laser amplifier technology coupled with phase conjugation which allows generation of near diffraction limited output at high average power. This was first developed using Stimulated Brillouin Scattering (SBS) for short pulse (~10 ns) solid state lasers where 25 J pulses with 1.25x diffraction limited beam quality were generated.[2] The technique was later extended to longer pulse higher average power systems. Pulses of 40 J and 1 μs can now be generated with the same beam quality. More recently LLNL, jointly with Russian researchers from the Applied Physics Institute, have developed a Stimulated Thermal Scattering (STS) technique which will provide extension of the phase conjugation to very low excitation thresholds. With this ultra low threshold capability, very long, nearly CW pulses can be phase conjugated, allowing high average power, near diffraction limited beam quality.

2. LASER TECHNOLOGY

2.1. Laser Diode Arrays

The technology of high average power laser diode arrays which has been developed at LLNL is well documented in the literature[3] and only the salient features as they apply to the present application will be discussed here. The present technology includes the fabrication of AlGaAs diodes in a two dimensional array formed by "racking" individual diodes in a line to form a module which has been operated at 100 watts CW per linear centimeter. These modules are then "stacked" one on top of each other to form an array. Although the height of the stack is arbitrary since the cooling for each module is self-contained and therefore each module is independent, stacks as high as 150 have been made. At present, the modules are stacked with a pitch of 10 modules per centimeter so that the power density for CW operations is 1 kW/cm^2. This power density is a critical number for the design of DPSSL's because it determines whether or not focusing of the pump light is required for efficient solid state laser operation. The laser quantities which directly affect the required pump intensity are the saturation flux of the pump transition and the extraction efficiency of the lasing process. These vary widely from one solid state laser system to another.

The efficiency of laser diodes can be as high as 60% where efficiency is defined here as the ratio of diode light produced to electrical power input. Even at this high value of efficiency, significant waste heat per unit volume is produced in the module and must be removed with little change in diode temperature if the frequency and efficiency are to remain stable. At the module level, the waste heat load is of the order of 1 kW/cm^2 which severely stress the state-of-the-art for heat removal by water systems. A unique heat exchanger system using laminar flow concepts has been developed[3] which has demonstrated the capability to remove such high heat loads and this concept has been extensively developed for LLNL's laser diode arrays. In order to control the thermal boundary layer to enable kilowatt/cm^2 heat removal, the water flow channel dimensions must be kept extremely small, of the order of 15 microns. Fabrication of such small channels is accomplished by lithographic/chemical etching methods similar to those developed for the solid state chip industry. Inlet and exhaust manifolds are fabricated so that stacking modules under compression produces adequate water seals and the entire process is entirely modular. Diode stacks of arbitrary height and 1 cm width can be placed adjacent to each other to form large two dimensional arrays.

2.2. Optical Compression

For laser system designs which require higher pumping fluxes than is produced by the diode arrays themselves, some form of focusing or optical compression is required. Situations requiring compression can be (1) transverse pumping geometries where the saturation flux is higher than the diode pump flux and (2) end pumping geometries where the size of the diode arrays is much larger than the cross section of the laser medium. The simplest focusing concept is a cylindrical lens in front of each diode bar to focus the output beam. Such "microlens" have been developed at LLNL[5] and provide compression factors of up to 100 with high efficiency. To concentrate the entire diode array, another form of "lens-duct" has been developed at LLNL[6]. The lens-duct is fabricated from a transparent optical material, such as glass or fused silica, and is a tapered structure with cross sectional area starting at the diode array and ending at the slab area, either the side area for transverse pumping or the end area for longitudinal pumping geometries. It is useful to consider the operation of this optical device as an immersion lens with its output face located at its focus, i.e., its length, l, radius R and index of refraction, n, being related by the following relation:

$$l = Rn/(n-1)$$

In practice, the output face would be located somewhat before the focus, at the circle of least confusion, because operation in this manner improves the transfer efficiency of the device. The purpose of the tapered planar faces (total internal reflection surfaces) is to deliver the pump light (to the slab) which would ordinarily fall outside the input aperture of the slab if an ordinary lens were to be used to focus the diode array on the slab. Devices with similar aspect ratios as those required for the satellite power beaming application have been successfully demonstrated, although at a smaller geometric scale[5], in several laser systems at LLNL.

3. SOLID STATE LASER CANDIDATES

3.1. Alexandrite

With the two technologies described above, high average power diode laser arrays and efficient compression optical transport systems, high average power DPSSL can be considered. However, due to the wavelength constraint, standard Nd:YAG lasers are inappropriate with the exception of the orbital transfer application, and other solid state systems must be considered. The first system is the Alexandrite laser which has a nominal lasing wavelength of 750 nm with a pump band centered at 680 nm. Alexandrite is chromium doped beryl, $Cr:BeAl_2O_4$, and its spectroscopy and kinetics are well known.[7] The nominal doping concentration is sufficient for the short absorption length necessary for efficient transverse pumping in thin slabs. The absorption bands are wide so that control of the diode laser wavelength (usually by careful temperature control) is unnecessary. The critical value of thermal shock expressed as a power gradient is large, 2.5 time larger than that of YAG, so that high power operation is feasible. The thermal shock parameter is so large that the surface heat fluxes allowed by stress considerations alone can lead to nucleate boiling of the coolant at the surface. For example, for a 5 mm thick slab, the surface heat flux based solely on thermal shock is 150 W/cm^2, which is well above the surface boiling limit, and the coolant must be pressurized to accommodate this heat removal. This is not a significant problem and pressurization has been included in the following designs.

The major problem with Alexandrite is the high value of saturation flux, $I_{sat} = 150\ kW/cm^2$, which is approximately 60 times larger than that of Nd:YAG. This means that to reach sufficient gain to keep the gain/loss ratio large and hence result in high extraction efficiency, high pump power densities must be developed. High pump power densities will result in large waste heat loads and concepts such as pressurized coolant systems, which can take full advantage of the large thermal shock parameter, must be used. Even with these considerations, the gain and therefore extraction efficiency of Alexandrite lasers will be low unless long crystals can be manufactured. With these concepts in mind, three cases were developed. The first uses present state-of-the-art crystals and is limited to a few kilowatts. The second uses a crystal scaling technique recently demonstrated which increases the height of the crystals and results in average powers roughly twice that needed for the satellite battery recharging application. The third case extends the length of the crystals beyond the present state-of-the-art to a length which is feasible according to other crystal growing techniques but which will require significant funds to realize. The power level for this case is in the several hundred kilowatt regime.

3.1.1. Case 1. Average power = 3.8 kW.

The geometry of the transverse diode pumped, Alexandrite laser is illustrated in Fig. 1.

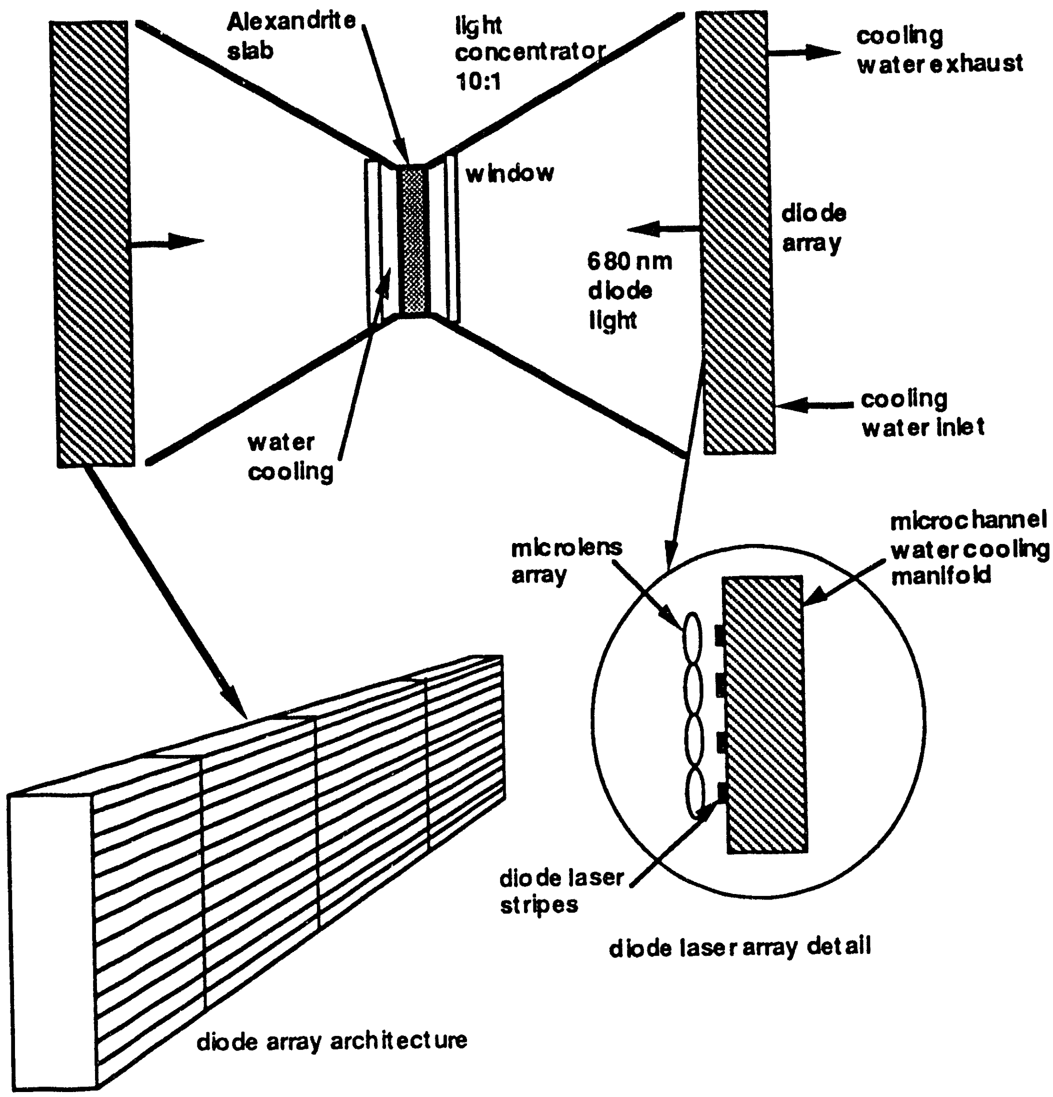

Figure 1. Alexandrite laser concept.

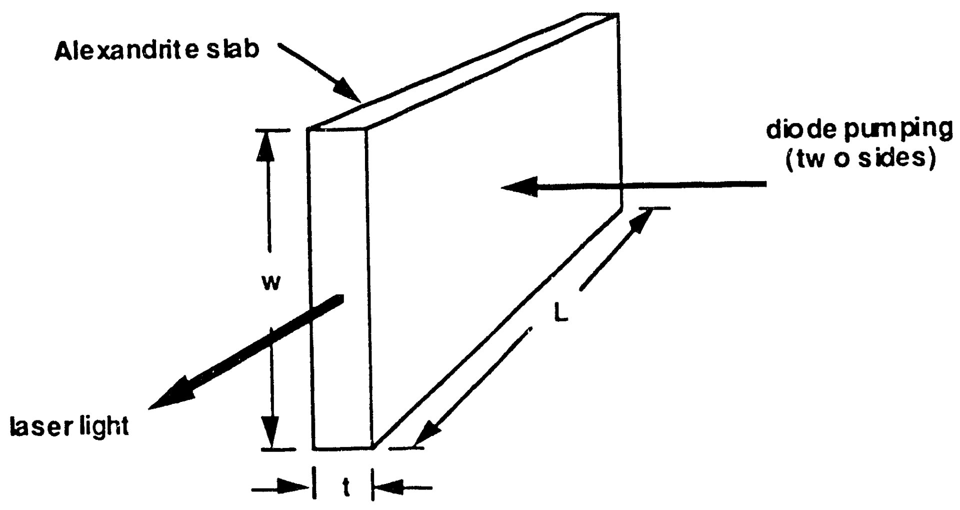

Figure 2. Alexandrite slab dimensions.

The Alexandrite slab configuration is shown in Fig. 2. Two diode laser pump arrays are formed by stacking the one centimeter wide modules to a height of 10 times the slab height, and then arranging additional diode arrays side by side to be slightly larger than the length of the slab. The diode arrays are fitted with microlens arrays and lens-ducts for optical compression. The pump band of Alexandrite of 680 nm cannot be accessed by standard AlGaAs diodes. Instead, a diode consisting of the quaternary material, AlGaInP, is used. This material lases in the 680 nm band[7] and its construction is applicable to the techniques developed at LLNL for AlGaAs diodes. These diodes emit a third less photons than AlGaAs in the same area for an output flux of about 300 W/cm^2 and it is for this reason that the 10x lens-duct is needed in this transverse pumping concept. The Alexandrite slab is face cooled by pressurized water flow with a cooling rate of 75 W/cm^2 in order to stay below the local boiling limit. The details of the window seal for the water cooling and the efficient transmission of the pump light through the cooling liquid has been demonstrated at LLNL on various Nd:YAG lasers.

For the 3.8 kW case, the crystal dimensions are:

$$t = 4 \text{ mm},\ w = 1.5 \text{ cm and } L = 10 \text{ cm}$$

The duty cycle of the laser is 25% corresponding to pulses of 260 microseconds in duration spaced one kilohertz apart. The peak loading on the output face of the crystal is 55 kW/cm^2 based upon the output power, duty cycle, and fill factor of 37%. The fill factor is adjusted to exclude top and bottom portions of the crystal equal to a crystal thickness in order to avoid thermal end effects. The efficiency of the AlGaInP diodes is about 15% based upon the ratio of light at 680 nm to electrical input power. The efficiency of optical pumping the Alexandrite crystal with 680 nm light is about 20% giving an overall laser efficiency of 3%.

It is important to note that the surface heat dissipation factor of 75 W/cm^2 integrated over the two sides of the crystal accounts for only a portion of the input optical power to the crystal. In solid state lasers such as these, the major portion of the input power which must be removed as heat is that portion corresponding to the quantum defect of the lasing process. That is to say, the energy difference between a lasing photon at 750 nm and a pump photon at 680 nm appears as heat in the crystal and must be removed by the coolant. The remainder of the energy deposited in the crystal, other than that which appears as laser energy, is transported out of the crystal in the form of fluorescence and does not significantly contribute to the heating of the crystal. Since it is only the waste heat which can degrade the crystal and contribute to poor beam quality, these solid state lasers can produce good beam quality if properly cooled and thermal optical distortions are controlled.

Crystals of this size can be grown at present and diodes of this type can be produced using the same technology developed at LLNL for other programs. Therefore, this 3.8 kW laser represents a near term device which could serve as a power beaming source for a near term demonstration of power beaming to low earth orbit as outlined in the companion paper.

3.1.2. Case 2. Average Power = 60 kW.

The physics of this configuration remain the same as the previous case but it is assumed that the size of the crystal has been increased substantially to the following dimensions:

$$t = 8 \text{ mm},\ w = 6 \text{ cm and } L = 24 \text{ cm}$$

Several innovations contribute to the larger crystal dimensions. First, it is assumed that several crystals can be bonded in the lengthwise dimension, as shown in Fig. 3. Such crystal bonding has been successfully demonstrated in the case of garnet hosts and beryl hosts should be similar. For a wider crystal, the thickness can be increased to 8 mm and still stay within the stress limit set by the thermal shock parameter. Finally, it is assumed that with modest gains in crystal growing technology, the length of the crystal can be increased by a factor of 2.5 without significant difficulty. Assuming other diode parameters are scaled in a similar manner, the output power of this configuration is about 60 kW.

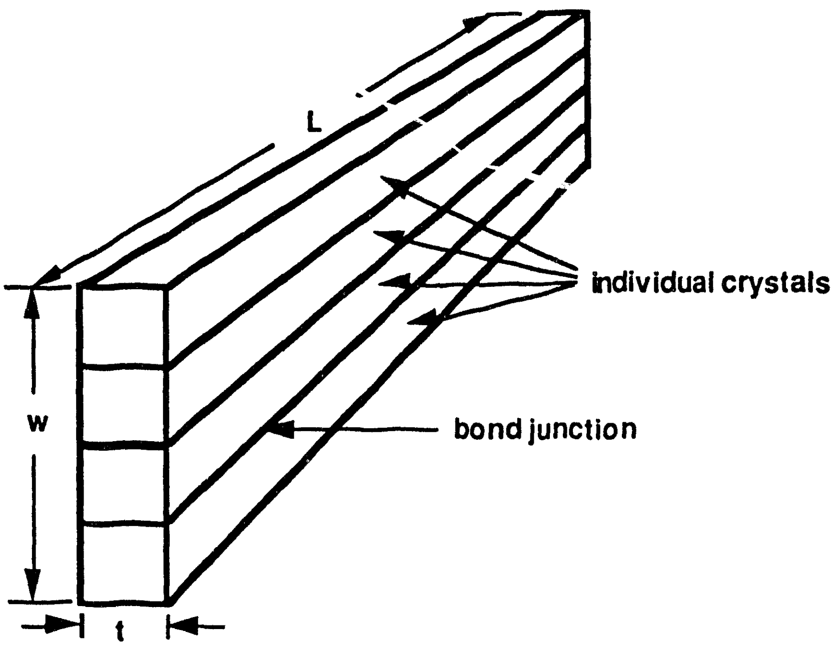

Figure 3. Crystal bonding to increase size.

3.1.3. Case 3. Average Power = 325 kW.

For this case, the transverse dimensions of the crystal remain the same but the length has been increased by a factor of 4 to 96 cm. Clearly, this represents a breakthrough in the technology of crystal growing and no estimate of the time or funds to achieve this is intended. It is clear that crystal growing technology is the key to very high average power DPSSL and that this is an important area for consideration in the future.

3.2. Thulium Doped YAG

3.2.1. Spectroscopy

Thulium doped YAG has been demonstrated in several small scale experiments[8] lasing at 1.92 microns and there is considerable interest in this material for the near IR range. According to the spectroscopic scheme shown in Fig. 4, a transition at 825 nm is also possible when pumped by standard AlGaAs diode arrays at 780 nm. Several spectroscopic issues of Tm^{3+} drive the design and also highlight the risk factors associated with the concept. As indicated in the figure, the Tm^{3+} ion is pumped at 780 nm between the ground $^3H_6$ and the excited $^3H_4$ manifolds and lased between the same manifolds at 825 nm. The small value of the laser emission cross section at 825 nm of $3x10^{-21}$ cm^2 necessitates operating the laser with a very high intracavity intensity to efficiently extract the stored energy. The key technical issue here is the development of reliable coatings on the slab at the average intensity loadings which are required.

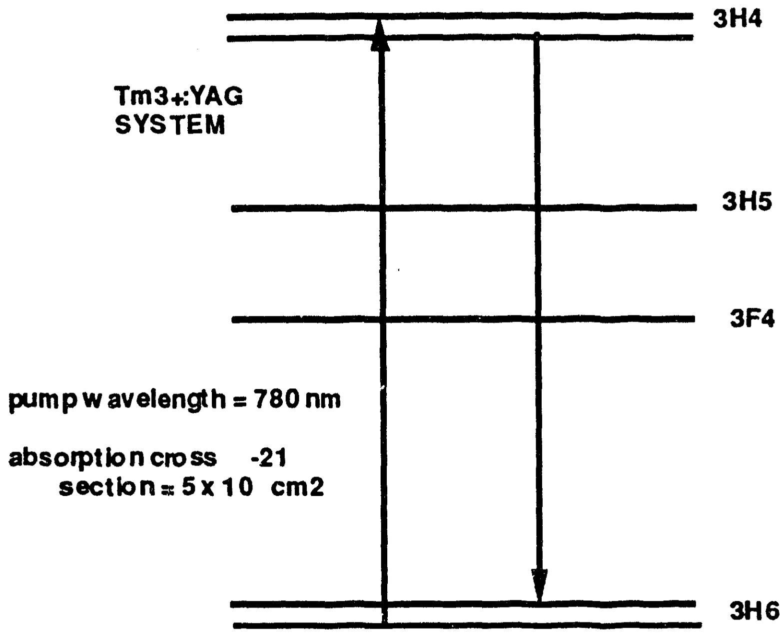

Figure 4. Spectroscopy of thulium doped YAG under ground state depletion conditions.

The presence of ground state absorption at the desired laser emission wavelength of 825 nm necessitates very hard pumping of the Tm^{3+} ions to elevate the gain of the system to sufficient levels to overcome this ground state absorption of the laser radiation. The need for intense pumping suggests a longitudinal pumped geometry as the preferred configuration. This spectroscopic scheme, incorporating ground state depletion for its operation, was successfully demonstrated in Nd:Y_2SiO_5 (yttrium orthosilicate) by producing a lasing transition at 911 nm.[8] The scheme here is similar and the specific values of the cross sections lead to the same operating scenario.

The intense pumping also leads to the use of a slab geometry. The longitudinally pumped slab configuration allows the intense pump radiation to be efficiently absorbed over a long enough path length to adequately distribute the generated thermal power in the slab to acceptable levels. In this context, "acceptable" levels means that the ability to conduct the waste heat out the surface of the slab without fracturing the slab.

Figure 5 is a sketch of the proposed laser system. For the satellite battery charging application, the average power level is 30 kW with a pure CW format. The pump array consists of microchannel cooled and microlens/lens-duct conditioned laser diode arrays emitting at 780 nm. The required pump power is 160 kW CW. The pump array is constructed using the standard LLNL technology with laser diode modules carrying a 1 cm long bar of AlGaAs laser diode material. Using the demonstrated value of 100 W/module, the array is comprised of 1600 modules which occupies a height of 1.6 m based upon the present stacking pitch of 10 modules per centimeter.

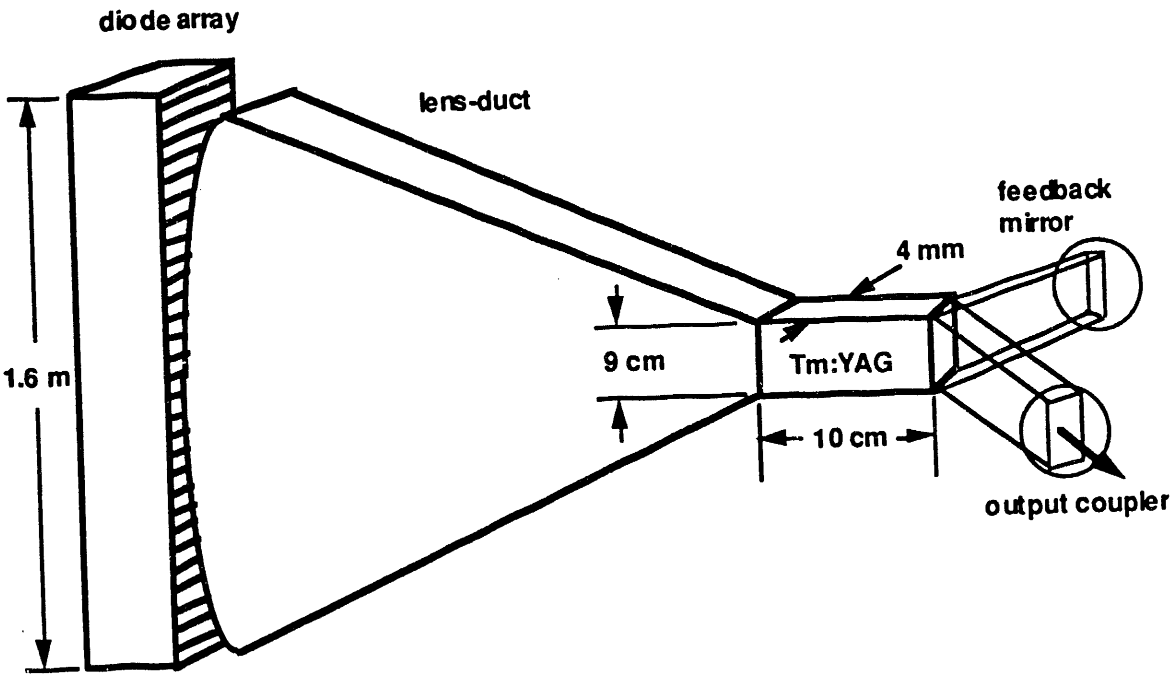

Figure 5. Thulium doped YAG laser concept.

The dimensions of the Tm:YAG slab are 9 cm high x 10 cm long x 4 mm thick and the Tm doping density is very light, approximately 0.22%, corresponding to an ion density of $3 \times 10^{19}/cm^3$. A slab of these dimensions can be harvested from a boule grown with a flat interface as fabricated by the bonding technique shown in Fig. 3. The pump input surface of the slab would be optically coated to be a high reflector at the laser wavelength of 825 nm and a high transmitter at the pump wavelength of 780 nm. The face on the opposite end of the slab would have the conjugate of this optical coating applied, i.e., it would be AR coated at the laser wavelength and HR coated at the pump wavelength. This coating configuration effectively allows the pump beam to be double passed down the length of the slab which gives better coupling of the pump to the slab than if only a single pass geometry were used.

To efficiently deliver the pump radiation to the slab, a microlens array and lens-duct is used as in the Alexandrite example. The optical path in the square tipped slab is the same as that used in the diode pumped kilowatt laser recently demonstrated at LLNL. The energetics of the system have been modeled using a code developed at LLNL. The results of the code indicate that the 30 kW is achieved under optimum conditions with an output coupling of 85%. The pump input end of the slab is calculated to be at 32% of the fracture limit. If this value is found to be unreliable in terms of fracture, it is reasonable to go to lower doped, longer slabs. At LLNL, slabs of Nd:YAG have been fabricated with length in excess of 20 cm so that the crystal growing technology is not the constraining factor. The average thermal power that must be conducted away from the slab is 32 W/cm^2. Again, the assumption which has been made to calculate this thermal value is that the only source of heat in the slab is the quantum defect between the pump photon energy and the laser emission photon energy. It is assumed that all other waste energy is radiated out of the slab in fluorescence. Finally, the intracavity laser intensity in the slab is approximately 250 kW/cm^2 which stresses the reliability of the optical coatings.

5. CONCLUSIONS

Diode pumped solid state lasers have been demonstrated at LLNL as a result of technology developments in the areas of high power diode arrays and optical delivery systems. Although most work has been in the one micron range with Nd:YAG, the two concepts presented here can extend the wavelength down to the 750 nm-850 nm range with the same high average power capabilities. There are technical issues associated with crystal growth, diode array fabrication and optical delivery systems, however, the economic payoffs are staggering. The projected efficiencies, low fabrication and operating costs can make satellite power beaming a viable industry with a large revenue stream. Both designs are capable of kilowatt operation with little development in the near term which is important for rapid, proof of principal, demonstrations. With development, the 30 kW versions should be ready in the 1996 time frame when several large, 8 meter class telescopes should come on line.

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