Long-Wavelength Diode-Pumped Solid-State Lasers as Inertial Fusion Energy (IFE) Drivers

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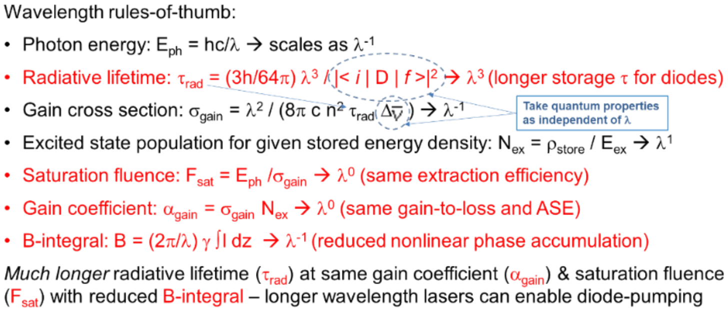
Summary: We consider the IFE prospects of solid-state lasers that operate at wavelengths considerably longer than typical 1 µm lasers[1] like the Nd:glass "workhorse" lasers[2] that are in ubiquitous use today. This concept offers substantial potential benefits as well as new challenges. The well-known Er, Tm, and Ho lasers operate between 1.6-2.1 µm, and therefore would likely need to be at least frequency quadrupled to the 4th harmonic (0.4-0.5 µm). The crucial advantage is that the emission (i.e., storage) lifetimes of the upper laser levels are more than an order of magnitude longer than Nd:glass, thereby reducing the diode cost by similar factor.[3] Herein, we suggest analyzing the potential performance of long-wavelength solid-state fusion lasers in detail, including the basics physics and many practical issues, along with a laser system-level cost estimate. In this way, we will develop an understanding of the benefits and risks associated with this approach to fusion laser design.

Narrative: The commercial viability of IFE depends strongly on the capital costs and wall-plug efficiency of the laser driver. Overall IFE power plant capital costs associated with the drive laser are primarily driven by the laser diode pump sources that convert electrical energy into optical energy to be stored in the laser gain medium. Two examples of system-level 1 µm laser studies are in Ref. 4, where overall and diode costs, final optic radiation-hardness, gas-cooling design, and system optimization are addressed, among many other issues and technologies. The overall efficiency of the laser driver depends on both intrinsic spectroscopic properties of the chosen gain medium, and the engineering and materials science that enables optical energy extraction in an efficient regime (i.e., with the extraction fluence at or above the saturation fluence). New technologies that enable more efficient optical energy storage and/or extraction, or advances in laser design that have the potential to dramatically impact laser driver capital costs therefore have strong leverage in the long-term success of IFE in achieving the grand vision of providing clean, reliable, and accessible base-load power for the world's future electricity needs.



Wavelength rules-of-thumb:

- Photon energy: $E_{ph} = hc/\lambda \rightarrow$ scales as λ^{-1}
- Radiative lifetime: $\tau_{rad} = (3h/64\pi)\,\lambda^3 / |<i\,|\,D\,|\,f>|^2 \rightarrow \lambda^3$ (longer storage τ for diodes)
- Gain cross section: $\sigma_{gain} = \lambda^2 / (8\pi\, c\, n^2\, \tau_{rad}\, \Delta\bar{\nu}) \rightarrow \lambda^{-1}$
- Excited state population for given stored energy density: $N_{ex} = \rho_{store} / E_{ex} \rightarrow \lambda^1$
- Saturation fluence: $F_{sat} = E_{ph} / \sigma_{gain} \rightarrow \lambda^0$ (same extraction efficiency)
- Gain coefficient: $\alpha_{gain} = \sigma_{gain} N_{ex} \rightarrow \lambda^0$ (same gain-to-loss and ASE)
- B-integral: $B = (2\pi/\lambda)\, \gamma \int I\, dz \rightarrow \lambda^{-1}$ (reduced nonlinear phase accumulation)

Take quantum properties as independent of λ

Much longer radiative lifetime (τ_{rad}) at same gain coefficient (α_{gain}) & saturation fluence (F_{sat}) with reduced B-integral – longer wavelength lasers can enable diode-pumping

Fig. 1: Wavelength power laws for critical parameters of laser operation.

Recent interest and new results in long wavelength IR lasers hints that there may be significant advantages in required pump diode peak power and costs associated with these new material systems that warrant significant further attention. The basics of the fundamental physics of long wavelength lasers is outlined in Fig. 1, where simple scaling laws are expressed. If we take the quantum transition moments to be similar for the rare earth laser ions under consideration, then we recognize that the radiative lifetime scales with λ^3 which translates into a λ^{-3} advantage in the diode cost, owing the increased storage time. In contrast, the gain cross section and gain coefficient scale mildly as $1/\lambda$ and λ^0, respectively, and the B-integral captures a useful $1/\lambda$ advantage.

In Fig. 2 below, we present survey information[5] for representative rare-earth doped crystals for the energy levels (top left); gain cross sections and emission lifetimes (bottom left); and the absorption and emission spectra of Ho:YLF (right-hand side) as a promising candidate. The lifetimes are in the 6-18 msec range, far greater than 0.4 msec for Nd:glass. The increase in the upper state lifetime serves to dramatically lower the diode cost – the primary cost in high-energy lasers – as the diode cost is primarily dictated by the peak power (and not the pulse length). The gain cross sections at the laser wavelength vary substantially from 0.3 to 1.8×10^{-20} cm^2, where values on the order 1.0×10^{-20} cm^2 are deemed to be workable. The plots on the right serve as the means to explain the nature of a "quasi-four level laser", where it is noted that there is absorption at the laser wavelength of 2.1 µm. By the principle of reciprocity, the emission spectra can be precisely calculated from the absorption spectrum as shown. Owing to this quasi-four level nature, a certain pump power is therefore required to achieve gain beyond the absorption at the laser wavelength. The physics of quasi-four level lasers is well-understood and can be modeled.

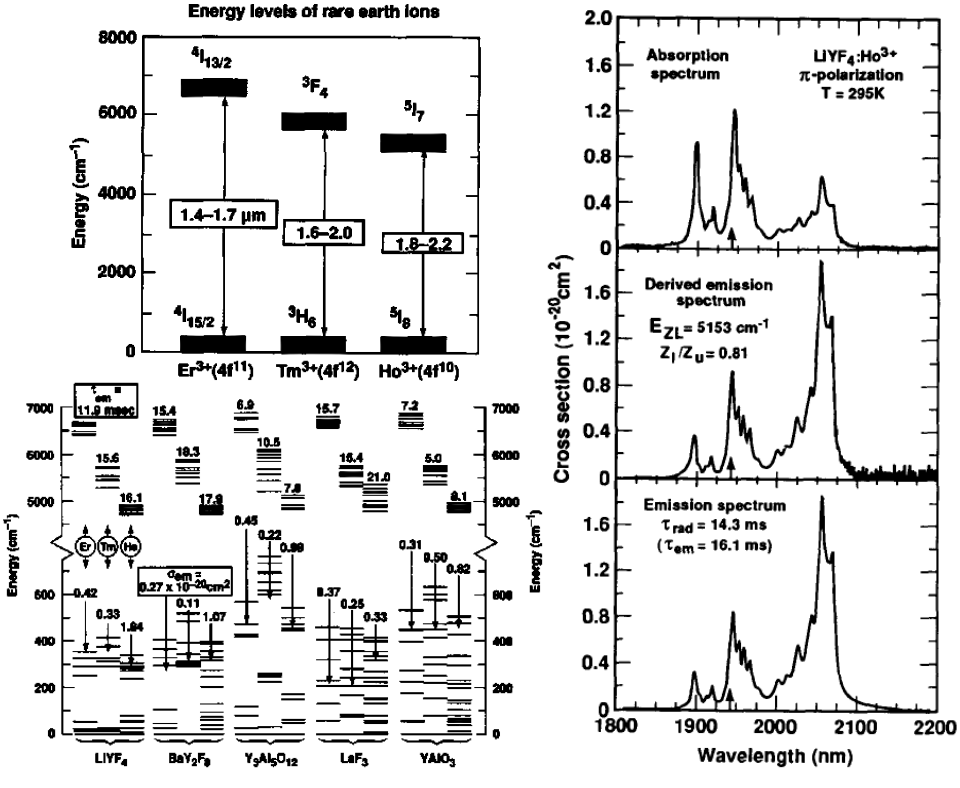


Fig. 2: (Top Left) Energy levels for Er, Tm, and Ho; (Bottom Left) Illustrative gain cross sections and emission lifetimes for a few standard gain medium hosts and dopants; (Right) Absorption and emission spectra of Ho:YLF, a case with a desirable gain cross section, also representing the basic understanding of a quasi-four level system.

Fig. 3 includes data on a high-energy diode-pumped Tm:YLF amplifier, which is of interest because of the very long emission life (see Fig. 2). Using a total of up to 20 kW from two diode arrays, 50J has been extracted in pulsed mode. This is an encouraging result with the highest energy reported to date but which is still far from the performance that would be required for an IFE driver.

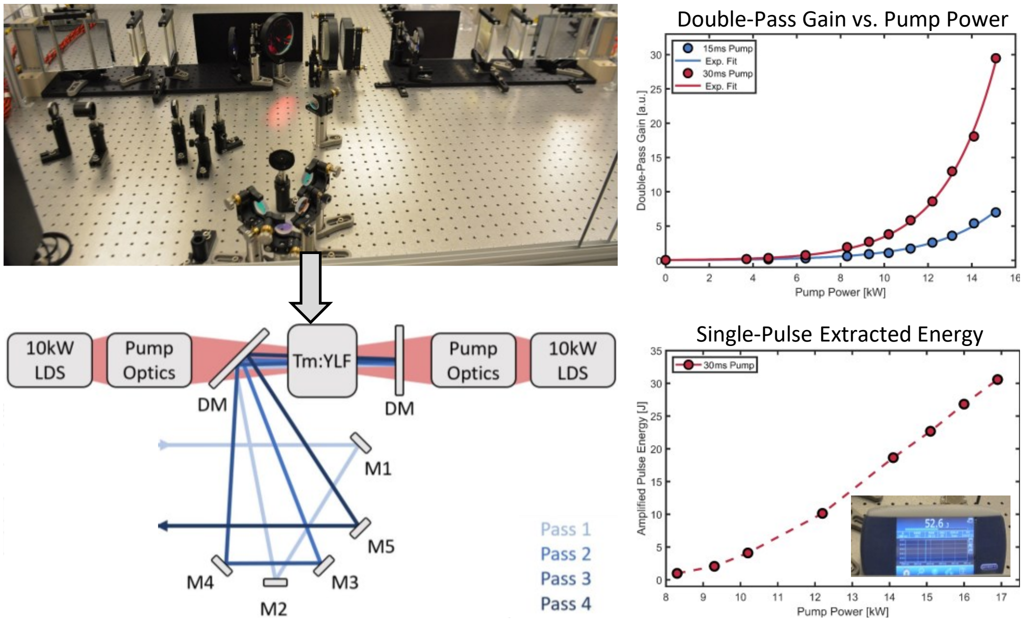
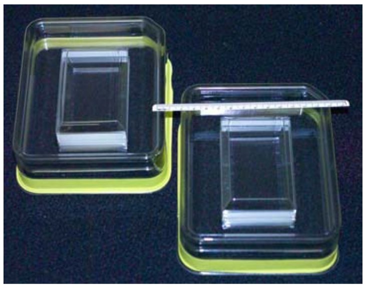


Fig. 3: Example[6] *of (Top left) a very high energy diode-pumped Tm:YLF laser amplifier and (bottom left) it's associated optical layout. (Top right) The measured double-pass small-signal gain and (bottom right) the single-pulse extracted energy demonstration. >50J was extracted from the amplifier, to our knowledge significantly higher than any other 2µm single-pulse laser source.*

Currently, Ho-doped crystals appear to have the most desirable gain extraction cross sections generally (for efficient extraction that is more readily achieved and maintained), although we reserve judgment as to the most efficacious gain medium at this time. However, there are several over-riding issues to be considered and addressed:

- **Pumping**: Long-wavelength laser diodes are generally less efficient (~50% of laser diode efficiency in the near IR) and are presently only available at lower power (~50W versus >200W per bar); moreover, the low efficiency appears to be due to the fundamental Auger loss mechanism in laser diodes[7]. On the other hand, in sufficiently high doping densities, Tm ions pumped at 0.8 µm with conventional high-performing diodes experience a unique and well-known 2-for-1 cross relaxation process, producing two excited Tm ions per pump photon, with only a minor quantum defect energy loss. Lasing back to the ground state of the Tm ions can occur, but the quasi-three-level nature of lasing on that transition incurs a moderate efficiency penalty. There is a possibility that the Tm/Ho co-doped pair may also be enabling[8], where the excited Tm ions transfer their stored energy to the Ho laser ions, though there is an efficiency loss associated with this step (no worse than 50%); kinetic analysis would be needed to render a judgment for this pumping strategy. As mentioned above, the Tm can also be directly diode-pumped at 1.6 µm – also with the energy transfer step to Ho – which is a substantial advantage (in both pumping cases) in terms of managing the quasi-four-level nature of the Ho gain transition. Finally, the architecture could involve diode-pumped multi-mode efficient Tm-lasers (with many millisecond-pulses) that are deployed to pump the Ho-laser. There are many potential advantages of this scenario in terms of pump brightness. Careful analysis is needed to optimize each pumping architecture and to identify the most favorable pumping scheme.



- **Frequency Conversion**: To utilize long-wavelength DPSSLs as IFE drivers with characteristics comparable to existing facilities, an additional frequency conversion stage would be needed to frequency convert the ~2 µm light to the 1.0 µm wavelength of more conventional sources. This can be accomplished with several popular and mature nonlinear crystals (BBO, LBO, YCOB, etc.), albeit with an additional efficiency penalty. Both LBO and YCOB have been demonstrated to be eminently “growable” crystals. While the pictures of 5.5×8.5 cm^2 YCOB crystals on the right[9] are a very hopeful manifestation of what may be possible, neither the growth of YCOB nor LBO to IFE-relevant apertures (>20 cm) has been demonstrated. YCOB has excellent basic optical properties, being characterized by a very large temperature bandwidth (40 °C-cm), very low absorption near 2 µm (<1%/cm), and a large d_{eff} nonlinear coefficient (3-5× of KDP), making efficient frequency conversion more achievable and cost effective through the reduction in material growth volume. Ref. 10 describes the operational performance for the “inverse” process of 1 µm → 2 µm conversion, which fundamentally is the same as second harmonic conversion. Based on available information, >80% second harmonic conversion efficiency should be readily achievable for a square pulse. The above discourse is based on a thorough survey of known nonlinear media.
- **Cooling**: At this juncture, the helium gas-cooling methodology has been demonstrated by LLNL[11] (Mercury and HAPLS Lasers) and Rutherford Appleton Laboratory[12], so the technical risk is now relatively low, though scaling to IFE-relevant apertures has not yet been demonstrated. It may be advantageous to operate modestly below ambient temperature, which turns out to entail a complex assessment of required pump brightness and the temperature-dependent level of ground state depletion.

Overall, the system-level analysis of these long-wavelength lasers is complex and would require a complete and thorough analysis of the many physics issues that come into play, such as amplified spontaneous emission, pulse distortion, gain narrowing (with respect to bandwidth requirements), pump efficiency, nonlinear ripple growth, and the quasi-four level nature of the laser transition. Codes are presently available to expeditiously perform this work, although there are many possible architectures that would be designed and studied. The crystals potentially deployed in the laser would need to be assessed in terms of the possibility of large-size growth at reasonable cost. Achieving high optical damage threshold for optics and coatings is another crucial aspect of high peak power lasers, and operation at ~2 µm is much less developed than for 1 µm lasers. Also, the proposed work on long-wavelength lasers would directly offer fractional spectral bandwidths comparable to that of current 1 µm systems.

Recommendation: Long-wavelength IR lasers exhibit spectroscopic properties that are favorable when compared with traditional 1 µm laser sources, enabling reductions in required laser diode power for comparable delivered laser energy, thus potentially dramatically reducing IFE power plant capital costs. We recommend that a program be established to investigate these long-wavelength lasers and associated components/technologies (including optical coating development, active and passive beam control technologies, diagnostics, etc.) for IFE driver systems and to optimize the laser driver designs for direct comparisons with other potential driver candidates.

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