Erbium-Based Edge-Pumped Disk Laser[a]

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ABSTRACT

We report on initial testing of an edge-pumped erbium-based disk laser operating at 1.53 micron. The laser uses a single laser disk having a composite glass construction with erbium-ytterbium co-doped center and undoped perimetral edge designed to channel pump light. Erbium is pumped to a laser transition by 940-nm diode radiation, which is first absorbed by ytterbium with subsequent energy transfer to erbium. This work presents results of initial testing of the laser with resonator optics configured for power extraction with two passes through the disk.

Keywords: Disk laser, solid–state disk laser, laser amplifier, edge-pumping, composite gain medium, amplified spontaneous emission, eye-safe, erbium

1. EYE-SAFER WAVELENGTHS IN THE 1.5-1.8 MICRON RANGE

Wavelengths in the 1.5-1.8 micrometer (µm) range benefit from atmospheric transmission window (**Figure 1**), which is critical to transmission over long-ranges in applications such as communication and lidar. In addition, lasers with emission wavelengths in this range are deemed "eye-safer." Laser injury to the eye can occur both due to overexposure to the retina and due to excessive laser energy absorption in the cornea and/or the lens. As seen in **Figure 2**, the threshold to retinal injury by a pulsed laser operating in the 1.5-1.6-µm band is orders of magnitude higher than at around 1 µm wavelength.

Wavelengths beyond the 1.6 µm continue to be less dangerous to the retina. In addition, light at these longer wavelengths is increasingly more absorbed by the cornea, which further reduces retinal exposure. However, at some wavelengths (namely around 3 µm and around 10 µm) the laser radiation is absorbed very strongly, which results in most of the incident energy being absorbed in a very thin layer of cornea (<100 microns), thereby greatly reducing the threshold for injury.

In view of these considerations, lasers operating in the 1.5-1.8-µm band beneficially offer an overall higher eye safety in combination with good atmospheric transmission.

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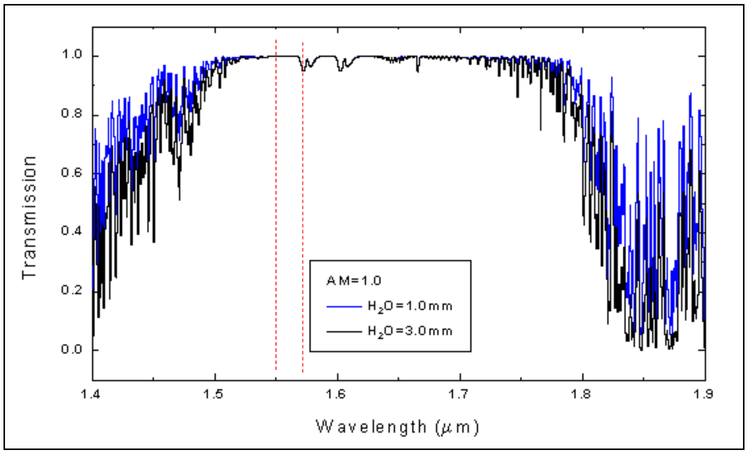


*Figure 1: Atmospheric transmission vs. wavelength showing the 1.5-1.8 μm window (courtesy of NASA [**1**])*

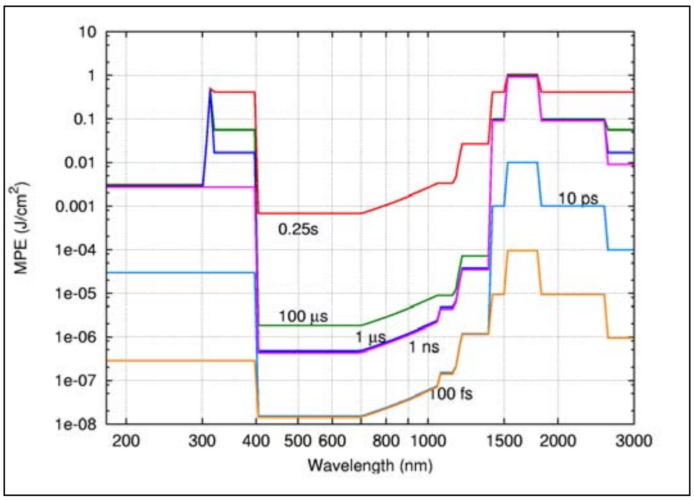


*Figure 2: Pulsed lasers in the 1.5-1.6- μm wavelength range have about three orders of magnitude higher eye-damage threshold than at1- μm wavelength [**2**]*

2. ERBIUM LASANT

Trivalent erbium (Er^{3+}) is a traditional ion for lasing in the 1.5-1.6-μm range. Er offers advantageous spectroscopic properties in several host materials. Depending on the host, Er offers bandwidth (BW) of up to about 60 nm, which is critical to its use in ultrashort pulse lasers. In particular, at a 1.55-μm wavelength, a BW of 35 nm is necessary to compress a pulse to 100 fs, **Figure 3**.

Er can be beneficially doped into a variety of glasses, crystals, and ceramics to form a laser gain medium. The choice of the host material may greatly affect the gain medium's spectroscopic and thermal properties, both of which drive the laser performance. Suitable host materials, therefore, should have a favorable spectroscopy, good thermal properties, and are preferably not birefringent. Note that birefringence is often aggravated by waste heat, which is an unavoidable byproduct of operating at high-average power.

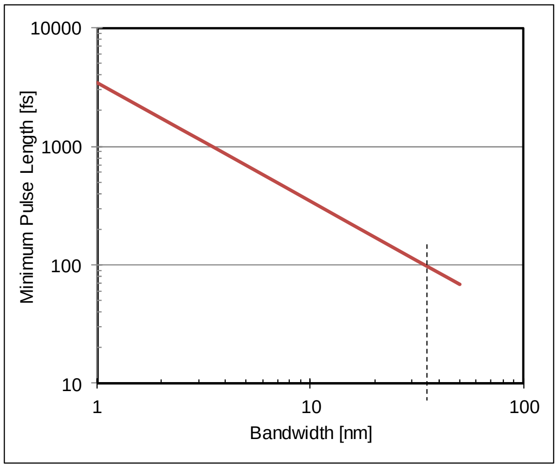


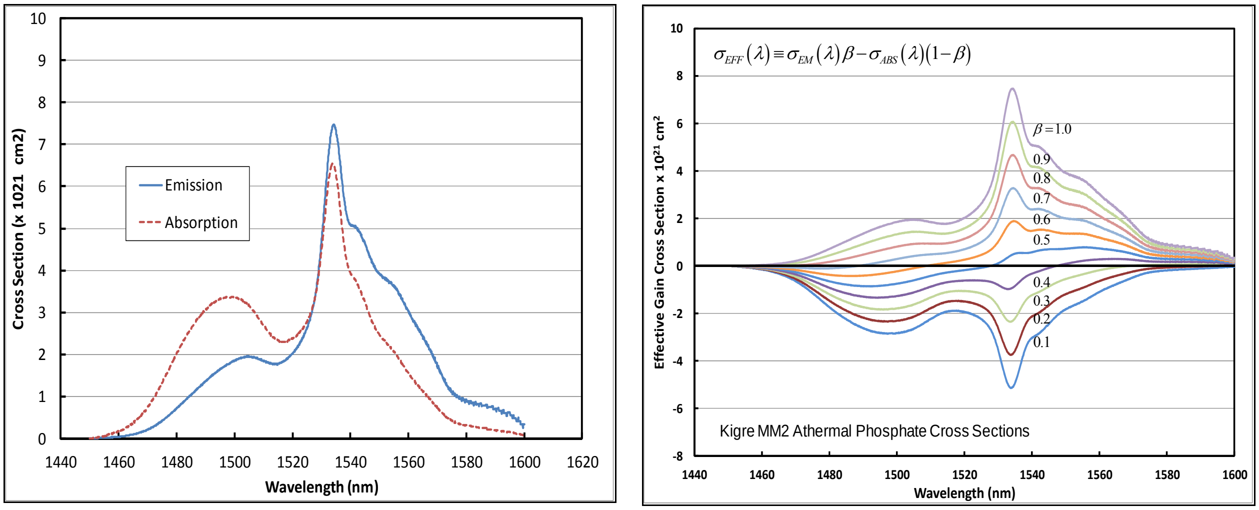
Figure 3: At 1.55 μm wavelength, a BW of 35 nm is required for compression of amplified beam to 100 fs

Glass provided either in a bulk or in a fiber form is the most commonly used host for Er. Because glass can be alloyed with most elements in a wide range of proportions, there is essentially an infinite number of glass compositions. Glass compositions suitable for hosting laser ions belong primarily to the families known as silicate, phosphate, fluorophosphate, germinate, boro-fluoride, and bismuth-lead. Er:glass has broader and smoother absorption and emission features than Er doped into crystals. These spectral properties offer relaxed temperature control for pump diodes, improved laser tunability, and broader BW.

Optical quality of glass can be made superior to that of crystals and ceramics, which translates to lower scattering losses. In addition, optical glass can be made athermal, which means that the coefficient of thermal expansion is balanced by a negative dn/dt to make the coefficient of optical path essentially invariant with temperature. This translates to greatly reduced susceptibility to thermally induced optical path difference (OPD). Glass gain elements can be reliably made in large sizes and with composite features. The key drawback of glass is its low thermal conductivity; typically an order of magnitude lower than crystals. However, unlike in crystals, thermal conductivity of glass is not degraded by doping or by elevated temperature. This may be contrasted with some crystals, where even a few percent doping by laser ions may nearly halve the thermal conductivity of the material.

While Er doped into silicate glass (and its variants) are a popular choice for fiber lasers, this material has rather low lasing cross-sections, which makes it less attractive for bulk laser gain medium. In contrast, Er emission cross-section in Kigre's MM2 phosphate glass (**Figure 4a**) is almost 2-times higher than the cross-section in silicate glass. **Figure 4b** shows the effective gain cross-section in the same material for different levels of inverted fraction (β). Certain novel fluorophosphate laser glasses [**3**] exhibit even higher emission cross-sections.

Crystals, namely YAG, Y_2O_3, Sc_2O_3, and Lu_2O_3 also offer advantageous hosts for Er, especially in the area of much improved thermal conductivity. Corresponding ceramic materials are now commercially available. Spectroscopic properties of these Er-doped crystals have been recently described in detail at both ambient and cryogenic temperatures by Merkle et al. [**4**].



a) Absorption and emission cross-sections *b) Effective gain cross-section at various β*

Figure 4: Cross-section for Er doped into Kigre MM2 phosphate glass (courtesy of Kigre, Inc.)

3. PUMP ARCHITECTURE

Lasing performance of the Er laser is also strongly influenced by the mechanism by which energy is delivered into the upper energy state of the ion. Traditionally, Er lasers have been operated by energy transfer from a co-doped Yb sensitizer pumped by flashlamps or, more recently, by laser diodes, **Figure 5a.** One advantage of pumping via Yb sensitizer is that the pumping and lasing phenomenologies can be substantially decoupled. In particular, one can independently optimize Yb doping for desired absorption level and/or uniformity, and Er doping for optimum lasing. The Yb sensitizer can be conveniently pumped by laser diodes at around 940 or 980 nm. Such diodes are beneficially very efficient, widely commercially available, and inexpensive. The absorption feature at 940 nm is at least 10-nm wide in most materials. However, in some materials (notably in YAG), the very advantageous absorption feature at around 980 nm is too narrow (~2 nm) to be pumped by conventional diodes and narrow band diodes must be used.

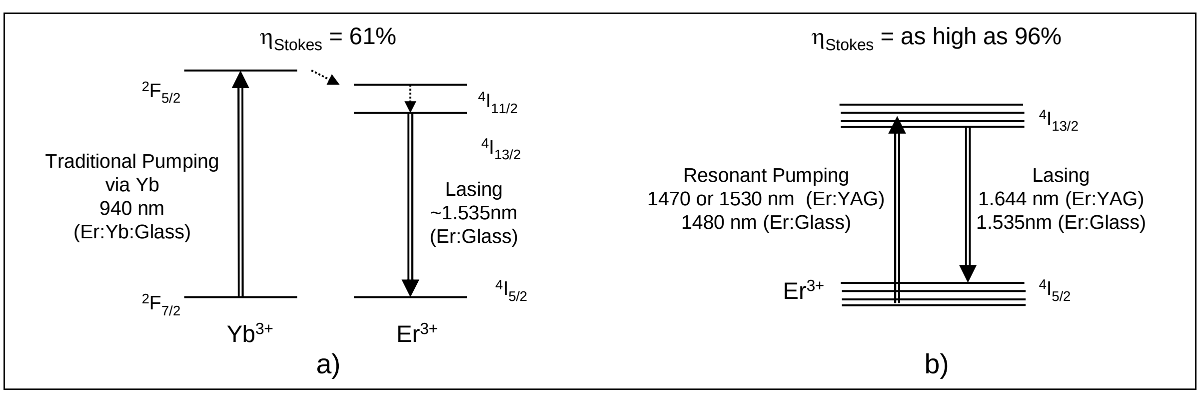


Figure 5: Pumping of Er: a) traditional enery transfer via Yb, and b) resonant pumping

An obvious drawback of pumping Er via Yb sensitizer is the low Stokes efficiency (~60%) and high waste heat fraction (~40%). The waste heat is deposited into the gain medium and limits the output. This thermal effect significantly detracts from the otherwise very attractive pumping via Yb sensitizer.

In the last decade, high-power semiconductor laser diodes emitting near 1.5 μm became robust, and commercially available. This new technology offers resonant (direct) pumping of the Er^{3+} ion by delivering the excitation energy directly into the upper state, **Figure 5b**. Key motivation for resonant pumping is greatly improved Stokes efficiency (up to 96%) and a corresponding reduction of waste heat deposited into the gain medium. As a result, resonantly-pumped Er-doped gain medium can be operated at much higher average power than with Yb sensitizer. Resonant pumping was demonstrated in 2005 [**5**] in Er:YAG and in 2012 in silicate glass fiber [**6**]. **Figure 6** illustrates the resonant pumping process in Er doped into silicate glass. The graph plots the effective (net) cross-section of Er versus wavelength for different values of inversion (β).

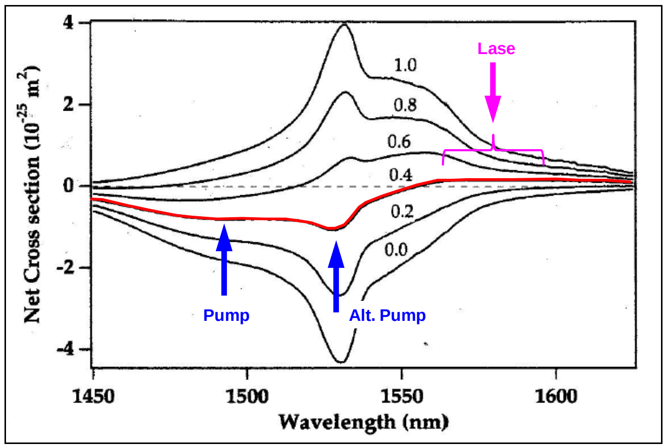


*Figure 6: Resonant pumping process in Er doped into silicate glass (after [**7**])*

Note that resonant pumping, while beneficial for reducing the heat load to the gain medium, does not necessarily improve the electro-optical efficiency of the laser. The process for pumping via Yb sensitizer seen in **Figure 7** uses very efficient 940- or 980-nm laser diodes while the gain medium process has a limited efficiency. In resonant pumping, the laser diodes emitting at around 1.5-μm wavelength are rather inefficient, but the gain medium energy transfer process is very efficient. One may view resonant pumping as a means for shifting the waste heat from the gain medium into the diodes. In the end, the electro-optical efficiency of the laser is very nearly same [**6**].

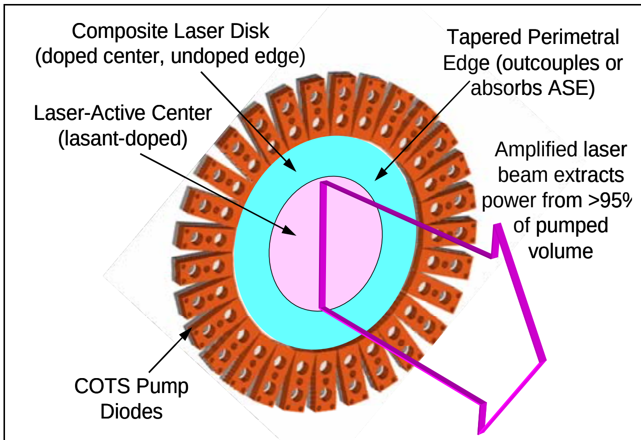
Er Laser Pump Architecture	Pump Diode Efficiency (%)	Stokes efficiency (%)	Overall Electro-Optical Efficiency (%)
Pumped via Yb Sensitizer	55	60	33
Resonantly Pumped	35	95	33

Figure 7: Electro-optical efficiencies of a traditional and a resonantly pumped Er laser

While resonant pumping beneficially reduces the quantum defect (=1-Stokes efficiency), the proportionate amount of waste heat (also known as heat fraction) deposited into the gain medium may not be always reduced by the same amount. Studies done by Condon et al. [**8**] indicate that under resonant excitation the heat fraction in certain Er-doped fluoro-phosphate glasses came close to the quantum defect level, while in phosphate glasses remained at 17-19% (about 3-4 times the quantum defect level).

4. EDGE-PUMPED DISK LASER

We have previously reported on a disk laser with an edge-pumped configuration [**9**] (**Figure 8**). The edge-pumped disk laser (EPDL) uses a composite laser disk having undoped material attached to the peripheral edges of a doped center, **Figure 9** [**10**]. This construction improves coupling between the pump diodes and the gain medium, aids concentration of pump radiation, provides cooling to the doped disk edge, and helps to suppress parasitic oscillations by trapping or outcoupling ASE [**11**]. Pump diode arrays are arranged around the circumference of the composite disk and generally point toward its center. Diode emitters are placed close to the perimetral edge to ensure good coupling efficiency into the material. Pump radiation is first concentrated in the tapered portion of the undoped edge, followed by injection into the doped disk where it is channeled between the disk faces and gradually absorbed.



- COTS diode arrays (multiple vendors)
- Diode–to–gain medium coupling efficiency >95%
- Pump absorption efficiency >90%
- Gain uniformity >90%
- Extraction from > 95% of pumped volume
- ASE absorption / outcoupling via tapered disk edge
- Round aperture for good mode matching
- Excellent optical quality ⇒ adaptive optics not necessary
- Disk can be either gas or liquid–cooled
- Very simple, compact, and lightweight packaging

Figure 8: Edge–pumped disk laser uses diodes closely coupled to the disk edge for high efficiency, uniform gain, and compact packaging

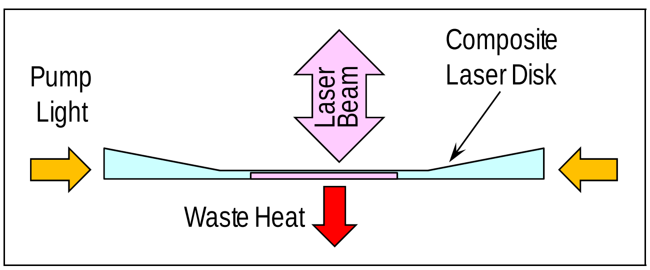


Figure 9: Edge–pumped disk laser concept

Edge-pumping beneficially provides a long absorption path for the pump. Such a long path allows for reduced disk doping and makes it more practical to use laser ions with low absorption cross–sections. Reduced doping also permits quasi-three-level ions (e.g., Er) to overcome ground state absorption (GSA) at laser wavelength at much lower pump densities, thus reducing the lasing threshold. In general, EPDL can be operated at lower volumetric pump densities than a comparable face-pumped device. Reduced pump density translates to a proportional decrease in waste heat and thermo-optical distortions, **Figure 10**. In addition, a thicker disk may be constructed, thus offering higher gain. Moreover, edge-pumping uniquely enables tailoring of gain profile by varying the arrangement of pump diodes [**12**]. We previously reported on lasing a Yb-based EPDL at 1 μm [**13**].

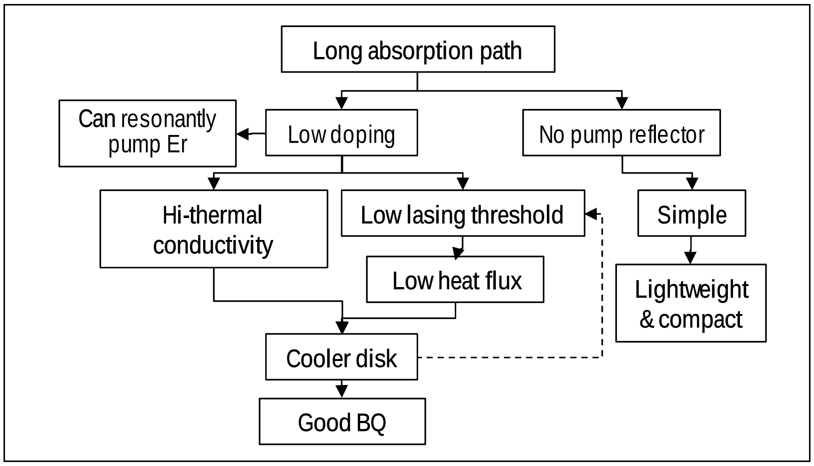


Figure 10: Benefits of long absorption path in EPDL

5. ERBIUM-YTTERBIUM GLASS LASER DISK

We constructed a composite laser disk test article using Kigre's QX phosphate glass as a host material, **Figure 11**. The central portion of the disk is co-doped with Er and Yb ions. The density of Yb ions was chosen so that the power density of absorbed 940-nm pump radiation would be highly uniform. The perimetral portion of the disk was undoped. The front surface of the laser disk was equipped with antireflective coating while the back surface was equipped with a highly reflective coating. The laser disk was pumped with diodes arranged as shown in **Figure 12**. Pump energy absorbed by Yb ions was then transferred to Er and a positive gain at 1532 nm was induced.

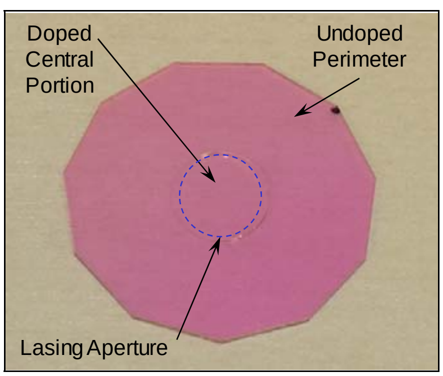


Figure 11: Construction of the composite laser disk

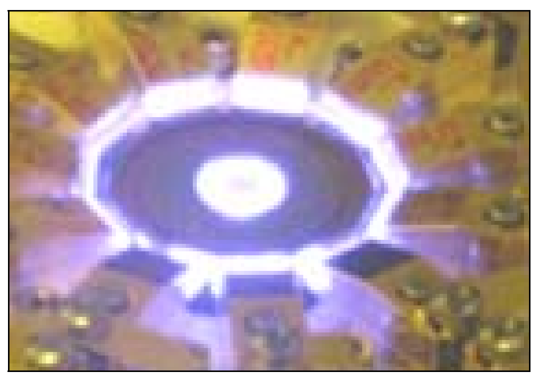


Figure 12: Laser disk being pumped by 940-nm diodes

Lasing tests of the Er/Yb:glass laser disk were conducted in a stable resonator cavity configured to pass the beam through the disk two (2) times per round trip (**Figure 13**). Pump was applied in 3-ms long pulses. Green upconversion light was noticeable but it was very rather weak, **Figure 14**. Quasi-cw lasing was readily achieved, **Figure 15**. **Figure 16** shows laser power and pulse energies obtained with outcoupling mirrors having 1, 2, 4, and 6% transmission.

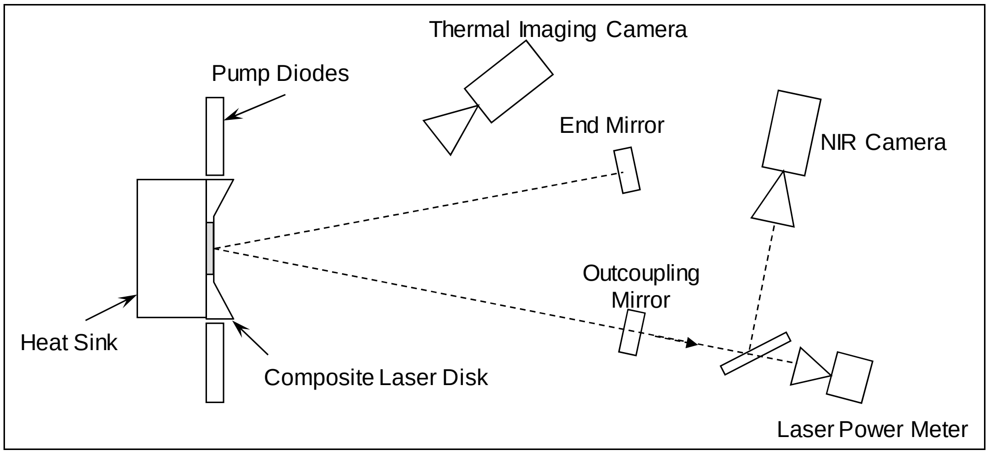


Figure 13: Lasing setup

Figure 14: Green upconversion light in the disk

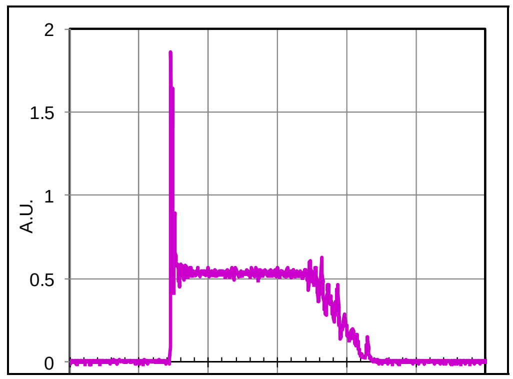


Figure 15: Laser disk being pumped by 940-nm diodes

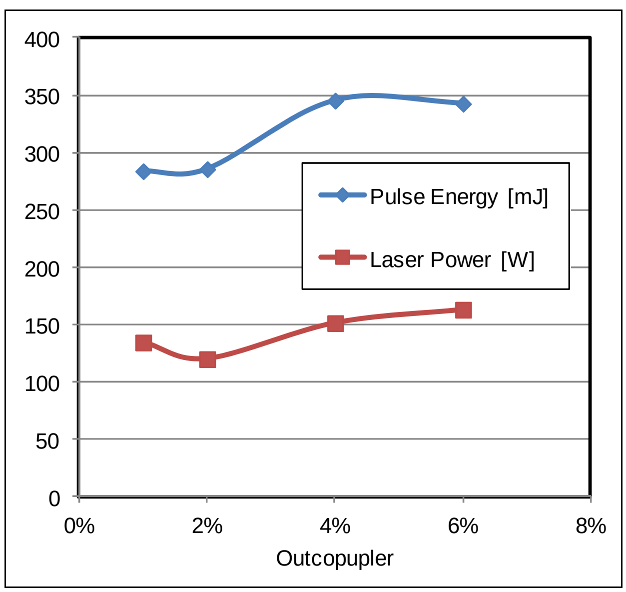


Figure 16: Laser power and pulse energies measured for several values of outcoupling mirror transmission values

5. CONCLUSION

We presented results from initial testing of a Er/Yb:glass EPDL. The composite laser disk was fabricated from Kigre's QX phosphate glass. The disk was edge-pumped by 940-nm diodes operated in pulse mode. The Er/Yb:glass disk was lased in a stable resonator using double-pass configuration. Stable lasing at 1535 nm was readily attained. This wavelength is within the 1.5-1.8 mm transmission window while offering reduced eye hazards. Lasing bandwidth in the Er:QX glass approaches 60 nm, which makes it a suitable gain medium for amplification of pulses for later compression to under 100 fs.

The Er-based EPDL is suitable for applications where high-average laser power and/or high-pulse energy with near-diffraction-limited beam quality are required, especially if large bandwidth is also desirable. One such demanding application is laser acceleration of charged particles in nuclear particle research.

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