Two Wavelength Solid-State Laser for Dental Applications

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Since their invention in the early 1960's, lasers have been viewed as tools in search of applications. Today, the situation has been reversed. It is now the application in search of a laser. Presently, there is extreme interest in using lasers as medical and dental tools, largely for their precision and the fact that they are a stand off instrument allowing for contamination free operatory procedures. My work has been to develop an instrument to address several of the medical communities desires in a single, compact instrument. The following details the background of the idea and its initial testing and implications for future development.

The wavelengths of interest to the dental community that I felt I could address were 2.0 microns and 2.8 microns. The 2.0 micron transition has many applications for soft tissue procedures, gum surgeries, pulpectomies, and others. The 2.8 micron wavelength is used for harder surfaces where energy has to be more rapidly deposited. Operation at this wavelength allows for ablation of enamel and dentin, and thus the excavation of dental caries and the removal of previous amalgam fillings. Previously, instruments have been constructed which could perform one or the other operation but not both. By combining both lasers into a single device the price for the user is decreased significantly.

The utility of this instrument is based on its ability to generate two wavelengths that have significant, differing levels of H2O absorption and thus different interactions with the tissues to be treated. This absorption makes these lines very important tools for medical applications. The 2.0 micron laser line is not as strongly absorbed as the 2.8 micron line and this allows it to penetrate and to ablate deeper channels of tissue. This penetration allows the laser to perform as a scalpel and also as a semi- self-cauterizing scalpel. The 2.8 micron line is very strongly absorbed and thus is absorbed almost totally at the surface, allowing it to remove thin layers of tissue at a time, as in skin resurfacing or tattoo removal. Its ultra high absorption allows for ultra precise energy delivery.

A solid-state laser capable of generating two widely spaced wavelengths would also have uses as a Remote Sensing tool. The ability to tune on and off an atmospheric absorption peak makes a single, simple system like the one proposed a good mission candidate if suitable wavelengths can be generated. With the present incarnation such species as Methane (CH_4) and Carbon Dioxide (CO_2) are obvious possibilities. The time oriented pulse generation of this laser also allows for pseudo double pulsing allowing for higher data generation rate.

The reason a two-wavelength system is so desirable is that the two wavelengths experience vastly different water absorptions. The 2.8 micron peak is several orders of magnitude higher than its 2.0 micron counterpart. This depth of absorption translates directly to the rate of heat deposition, which leads to material ablation. The key to this instrument is it will allow, with the touch of a button, the switching of available energy deposition rates, or more directly the depth of cut or enamels penetration. The ability to perform various operatory procedures is directly tied to the unique ability of this laser to switch between two widely seperated discrete wavelengths.

The technology I have pursued is, to my knowledge, the first investigation of its kind. I have used the multiple dopants in a single crystalline material to generate multiple, discrete wavelengths. This is not to be confused with tunable lasing in crystals such as Titanium Sapphire or even line tunability in a material like Neodymium Yttrium Lithium Fluoride. This is a process where different ions are made to lase independently of one another, at vastly different wavelengths, (in our demonstrated case ~600 nanometers separation) and we can switch between them using only electronic means. There are no tuning elements or path switching elements in the laser resonator, so all tuning is performed by changing the pumping rates to the material. The system is further simplified by a new mirror design in which we have specified two regions of reflectivity, which we can specify independently. This allows us to form a single resonator which accommodates both laser transitions, even though they are widely separated in both wavelength and laser cross-section and gain. The design of these mirrors has been tested for the first time by myself and their performance has been as predicted. Coating at wavelengths in the Mid-IR are difficult because of the many layers necessary for adequate reflectivity, but these coatings are durable and have stood up to the incident energy so far. Also, alignment at one wavelength has meant perfect alignment at the other, a crucial element for any low maintenance system. See the picture of the actual system attached. A patent has been filed for the design of these variable reflectivity dual wavelength coatings.

Sample laser rods were obtained from several vendors for evaluation. These rods were uncoated and of various lengths as they were scraps left over from various prior growth runs. These materials are very expensive to grow, so I was very thankful for any pieces, which came even close to my desired concentrations. A list of the donated materials and their gracious suppliers is attached. As these crystals were donations of available materials they were not particularly suitable for a true systematic study. (To do so, I have been informed by A highly respected crystal manufacturer, would entail years and a cost of up to a million dollars for a single family of materials) However, these materials and their testing results have allowed me to draw very valuable conclusions which point me in a much more focused and exciting direction.

The initial idea was to use Erbium and Thulium dopant ions in several crystalline hosts. The Erbium lasing on the $^4I_{11/2}$ to $^4I_{13/2}$ transition with a lifetime of ~ 120 microseconds would generate 2.8 micron radiation and the Thulium operating on a $^3F_4$ to $^3H_6$ transition would lase at 2.02 microns with a lifetime of several milliseconds. I had also hoped that transfer from the Er $^4I_{13/2}$ to the Tm: $^3F_4$ would allow higher population inversions for both transitions.

The first material investigated was a 5.0 by 85 mm Tm:Er:Cr:YAG 0.05:0.30:0.015 rod. The laser rods in all the experiments were housed in a 50 centimeter laser resonator comprised of a 0.90 reflecting flat mirror and a 2 meter Radius of curvature (concave) high reflector >0.99. It lased at 2.700 microns on the first shot and performed admirably for a first attempt. As each shot was generated an audible snap was evident. At first I believed that the noise was the result of optical system damage, but it turned out the noise was caused by the high energy density within the cavity at 2.700 microns which caused the

H_2O aerosol particles in the beam to rapidly heat and expand. After the pulse is gone, the air rapidly cools and contracts and a sonic wave, similiar to thunder follows. The strong absorption at this wavelength really hurts lasing efficiency and is evident in the rolling over of the earliest data curves. Subsequent experiments have taught me how to deal with this absorption thus greatly improving the system efficiency. Some data is attached, however some has been pronounced as proprietary to Lantis Laser Co and has been withheld. Attempts to lase this material at 2.0 microns were unsuccessful and experiments such as optical quality and fluorescence decay were performed.

Fluorescence measurements at 2.0 microns showed a multi exponential decay, but no real detrimental shortening of the lifetime. The measured lifetime was on the order of several milliseconds . Attempts to lase the 2.0 micron transition at pump energies of up to 120 joules per pulse were still unsuccessful so another Er:Tm: rod was tested.

A 4.0 by 85mm Er:Tm:LuAG 0.10:0.06 laser rod was made to operate at 2.944 microns at a slope efficiency of several tenths of a percent. The performance, initially, of this rod was better than the other Erbium transitions. It turns out this result is not necessarily the result of higher gain in this material, but of lower atmospheric absorption at this wavelength. The variability of the output wavelength in these materials is also of great interest as this tends to demonstrate that the desired wavelength can be somewhat tailor made through a process of compositional tuning. The predominant wavelength for my research has been 2.700 microns, still in the highly absorbed region of the spectrum yet low enough to take advantage of a good transmission region in current medical laser fiber delivery systems. This LuAG rod would not generate any energy at 2.0 microns either.

Similar results were obtained for a 5.0 by 85 mm Er:Tm:YAG 0.13:0.0375: rod. It lased at 2.700 microns and exhibited similar efficiency characteristics as the previous two rods. Initial 2.0 micron testing failed, but I constructed a separate test resonator complete with a 0.98 output coupler at 2.04 microns. I was able to obtain lasing at 2.024 microns at a threshold of approximately 115 joules. Previous work on Cr:Tm:YAG performed by Greg Quarles and others at NRL in the early 1990's had shown thresholds near 80 joules for like resonators. It became evident that instead of aiding each other in their respective laser transitions, they were indeed interfering destructively. The Thulium $^3F_4$ to $^3H_6$ transition allows several of the important Erbium manifolds to be quenched, or nonradiatively drained of its inversion. I'll return to this point later. Also, the Tm $^3F_4$ shares its energy with the Er: $^4I_{13/2}$ thus stealing a fair amount of its population (enough to account for the 50% increase in observed threshold.

It became obvious from these findings that Thulium, while successfully lased was not efficient enough to be fielded as part of a useful system. From there, I began to try Holmium added systems. Holmium is the excepted 2.0 micron generating ion due to the fact that it has a stimulated emission cross-section ~ 4 to 5 times that of Thulium. I had originally tried to avoid using the triply doped systems just to lessen the already complex energy transfer dynamics.

In these systems, Ho:Tm:Er:LuAG as an example, The Erbium would lase on the same transition as before with the same lifetime, but Thulium would act only as a transfer point for energy to the Ho: $^5I_7$. The Holmium would then transition between the $^5I_7$ and the $^5I_8$ manifold, producing energy at around 2.1 microns.

A 4.0 by 85 mm Er:Tm:Ho:LuAG 0.10:0.06: 0.0326 rod was made to lase successfully at both wavelengths. The rod was not anti reflection coated at 2.8 microns and it was slightly damaged from earlier laser testing. It lased at 2.700 microns at a threshold of near 30 joules. (About twice that of earlier YAG transitions) However, the supply could then be tuned to longer pump pulselengths and several hundred millijoules of 2.1 micron radiation could be generated. Present results show poor slope efficiency but 50 mJ of 2.700 micron and 200mJ have been demonstrated, electronically switchable at this time.

The results from this investigation to date fill a normal size data book, and I can't begin to touch on all that has been learned. However, enough data has been taken to where I feel I can make some further assumptions as to what works and what doesn't. It appears that Thulium does quench the Erbium lasing inversion. Lower Thulium leads to higher slope efficiency and having the Thulium in the lattice appears to push the lasing wavelength to 2.700 microns. Further material growth will limit Tm: concentrations to 1.5 % or lower, or will removed totally if computer modeling leads to the conclusion that it is unnecessary.

Funding has been obtained through the NASA LANGLEY Technology Applications Group to further advance the technology and as stated earlier, the technology has been licensed to an outside company who plan to aid in its development.

A paper has been written and has been accepted for oral presentation by the Optical Society of America OSA at their Advanced Solid-State Laser Conference to be held Feb 13-16 in Davos, Switzerland. I will hopefully be available to attend.

I would like to sincerely thank those who have been a part of this adventure. From start to hopefully, the finish it has been a true joy. It's hard to explain but for me each new laser is a new life, full of equal parts promise and heartache. They give you just enough joy to feed your faith and enough frustration to fuel your curiosity. I do feel truly blessed to have been given the chance to pursue my dream to actually make a difference. I owe a great deal to many people and to them I promise I will do my best, always.

Special Thanks to my Senior Project Advisor Dr. Martin Buoncristiani for his enthusiasm and technical insight.

Special thanks to my FRIENDS at NASA Dr. Lenny McMasters , Anne Overbay , James Barnes and Dr. Carl Gray whose belief in me allowed me to pursue this work, where others would have attempted to squash it as to risky or inconsequential. Thanks to Dr. Brian Walsh for his insight and even more for his ability to keep me grounded in the reality of the results and the fact that success doesn't come overnight.

Extra special thanks to my mentor and friend for many years, Dr. Norman Barnes. If he had not been designated my mentor for these past few years he would have done it anyway, on his own time and out of a sincere wish to see me succeed. His willingness to teach me began over 12 years ago when I'm sure I was much more of a burden than a help, yet he has remained patient and open to suggestion to this day. It has been an honor to tackle the technical hills we have faced together and I feel I am a much better scientist and person because of him.

I would like to thank the three most precious people in my life, my beautiful wife Christy, my son Dylan and my future son Tyler. You are truly the reason I try to do anything with my life and you are the reason I'd like to see a better tomorrow. You have allowed me to dream again and to see a world teeming with possibilities. You are the first things I think about every morning and the last things I think about every night and the source of my strength throughout these years.

God Bless!

Two Wavelength Solid-State Laser

for

DENTAL APPLICATIONS

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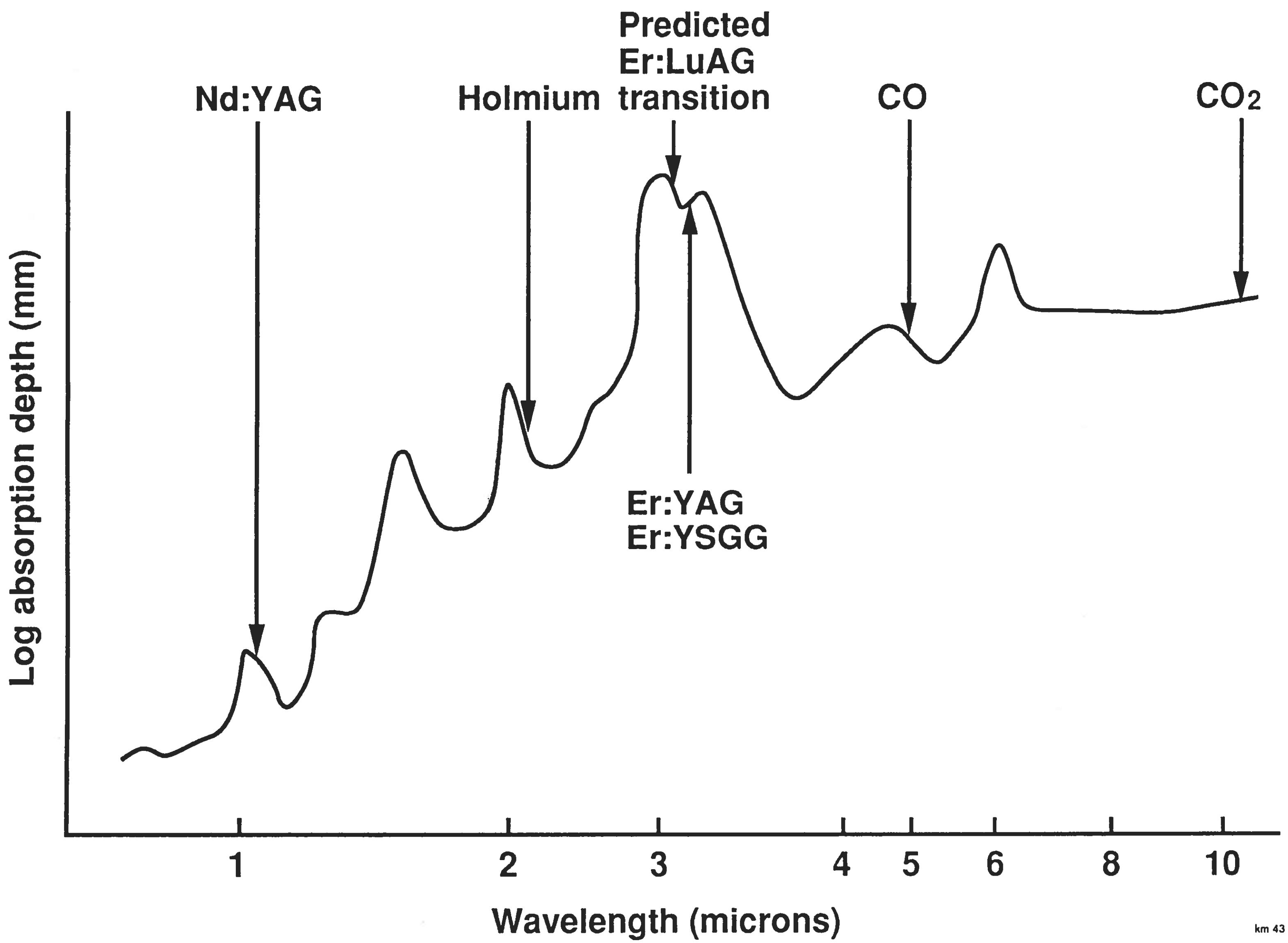
Tissue Absorption Vs Laser Wavelength



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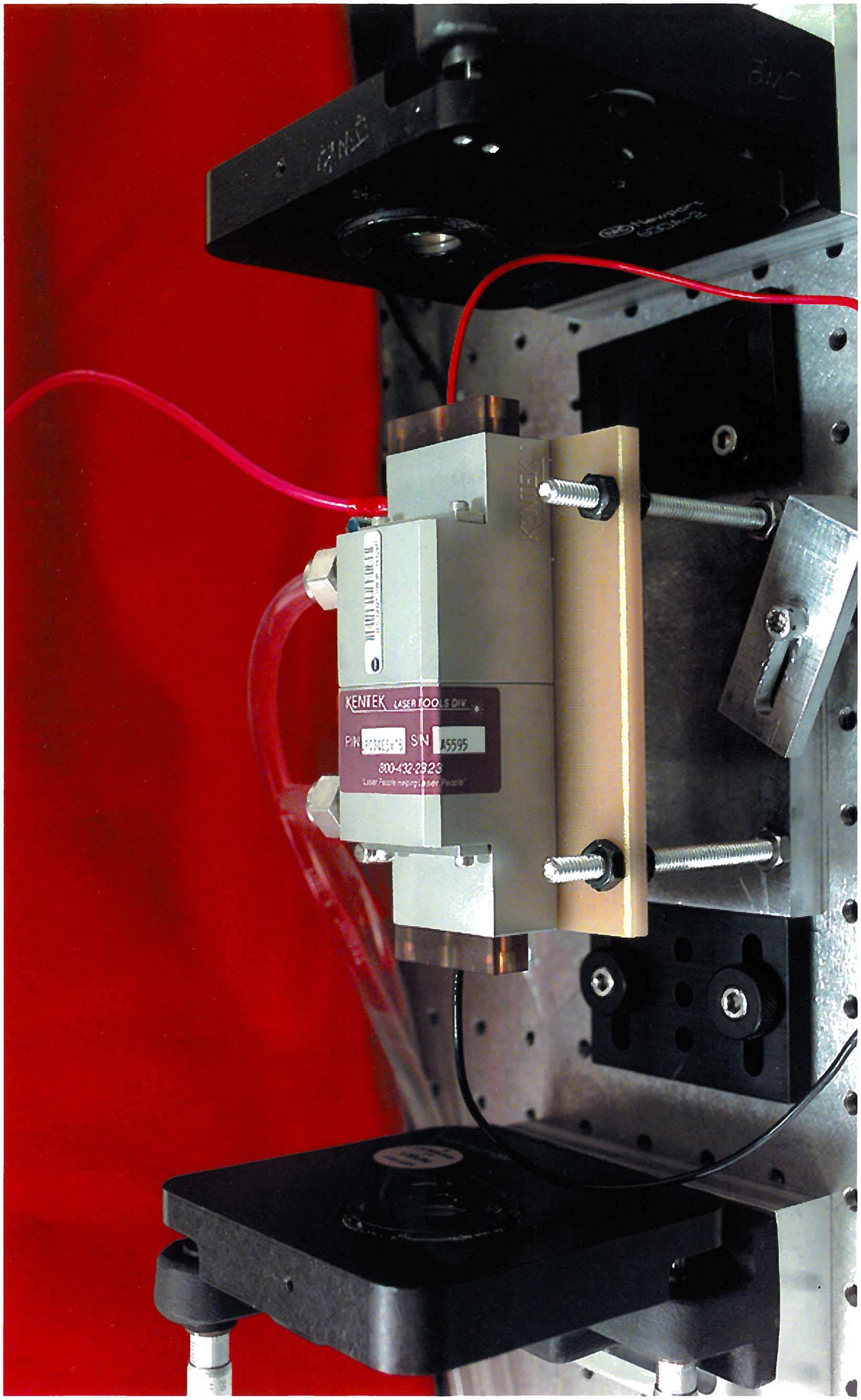
TECHNOLOGY OF THE TWO WAVELENGTH SOLID STATE LASER

- Single laser produces both discreet wavelengths
- Produced by separate ions
- Pumping rate dependent wavelength selection
- Energy transfer dependent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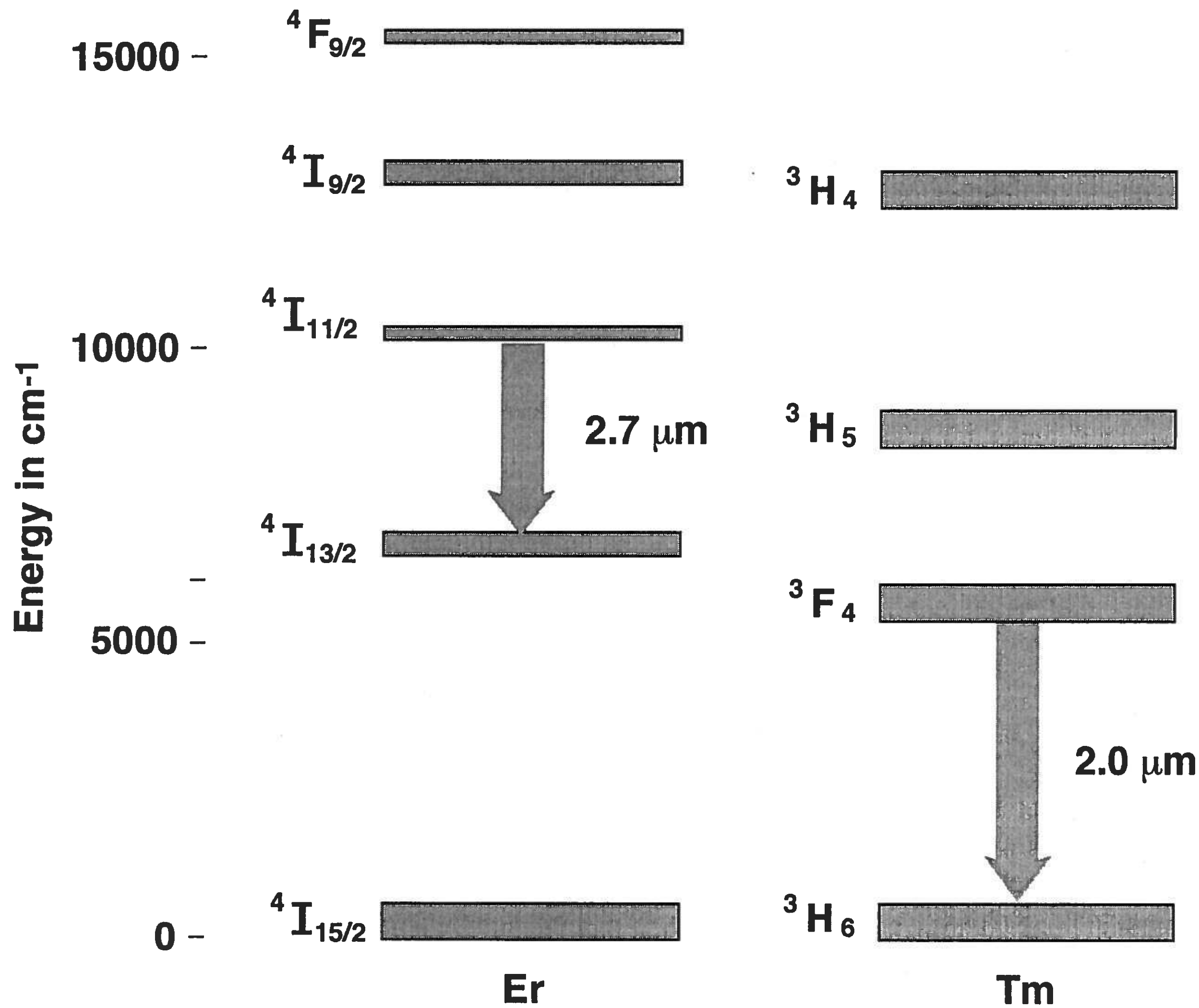
MATERIALS FOR EVALUATION

Material	*Concentration*	*Source*
Er: Tm: Cr YAG	30%, 5%, 1.5%	Union Carbide / Bicron
Er: Tm: YAG	13%, 3.75%	Union Carbide / Bicron
Er: Tm: LuAG	10%, 6%	Scientific Materials
Er: Tm: Ho LuAG	10%, 6%, .36%	Scientific Materials
Er: Tm: Ho YLF	30%, 6%, .50%	Lightning Optical Corp.

Energy Level Diagram



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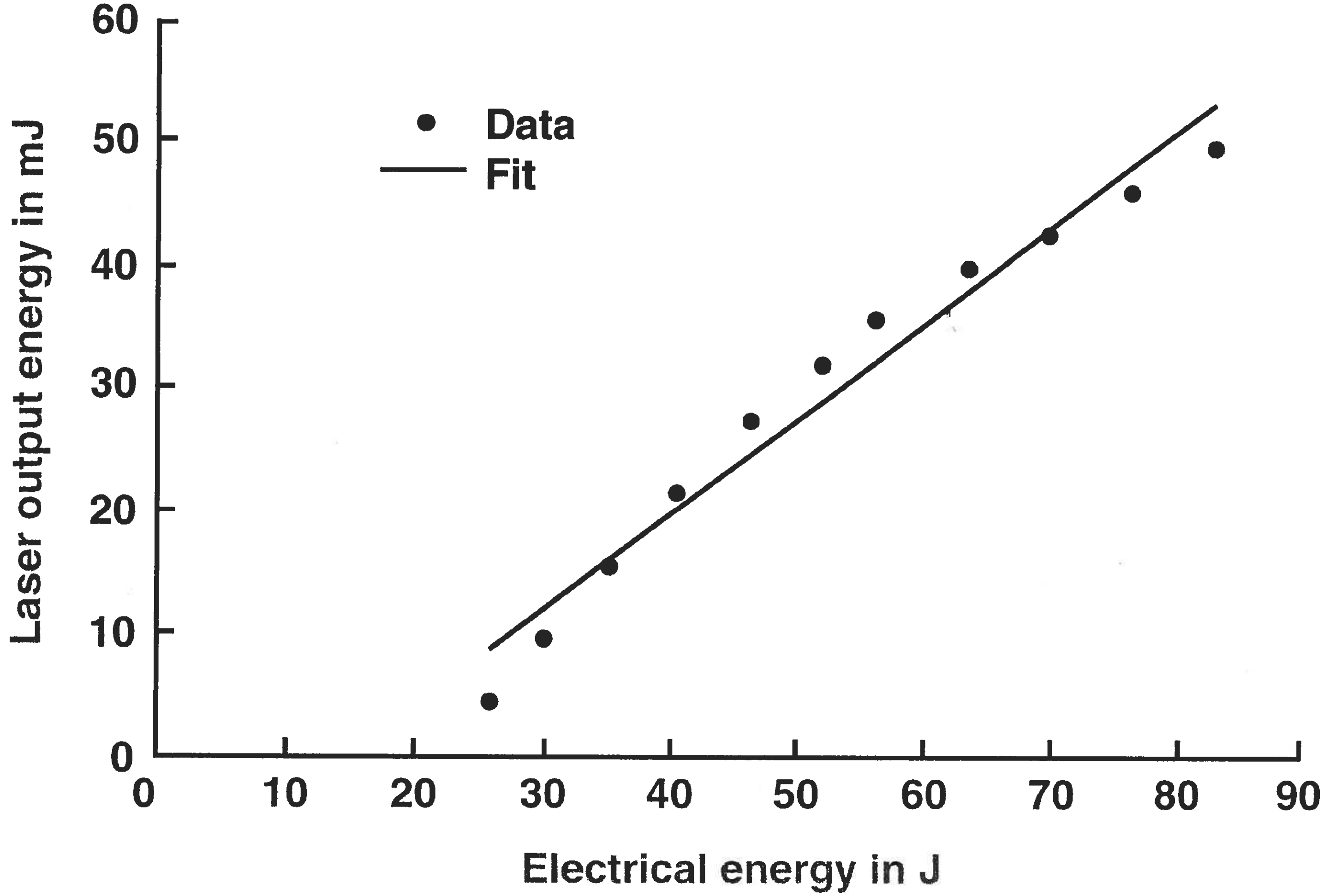
Tm:Er:Cr:YAG Laser Output Energy at 2.7 Micrometers

Tm:Er:Cr 0.05:0.30:0.015, 5.0 by 85 mm, 0.90 reflecting and 2.0 m RC



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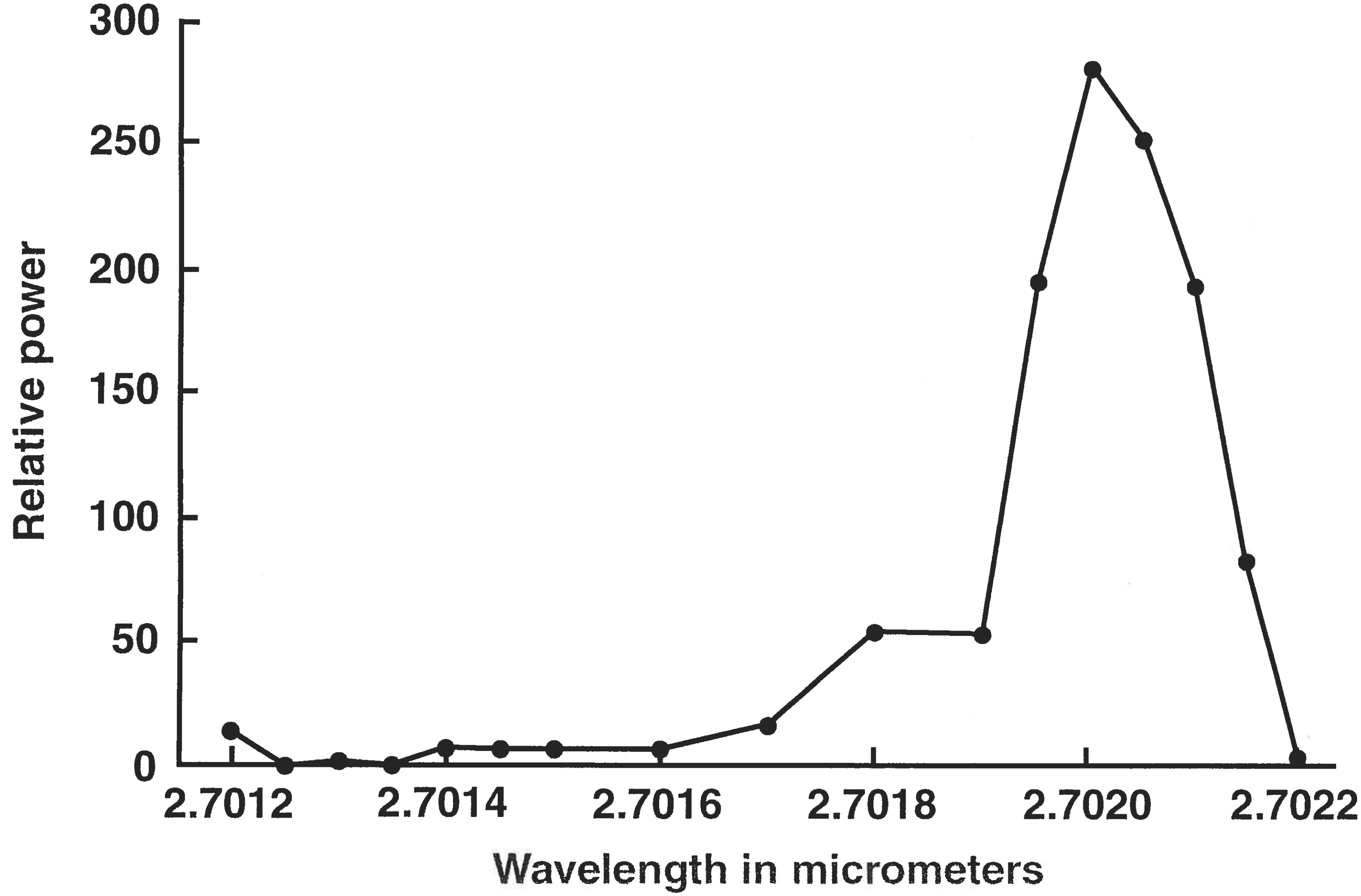
Tm:Er:Cr:YAG Lasing Wavelength

100 microsecond pump pulselength



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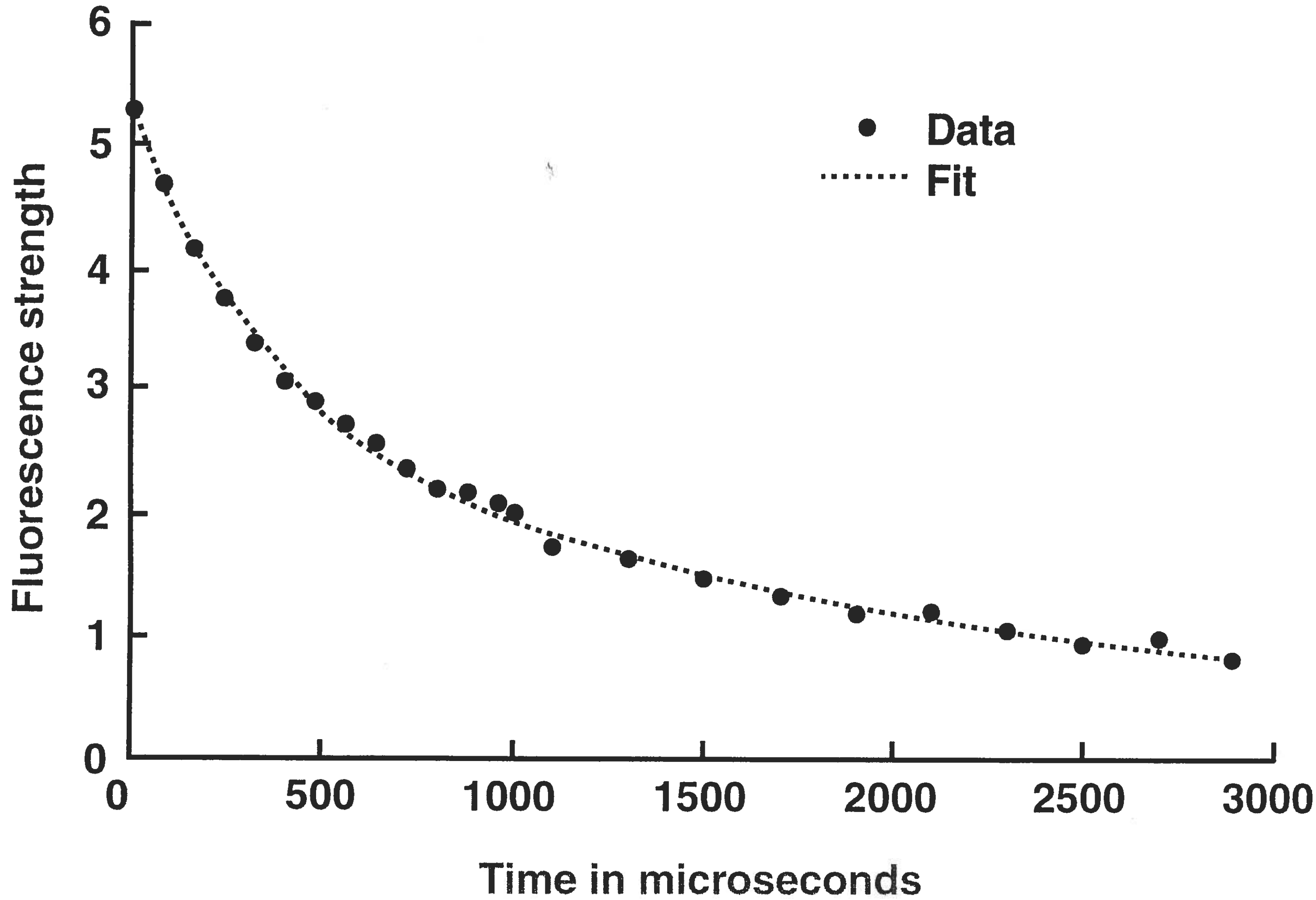
Tm Fluorescence in Tm:Er:Cr:YAG Sample

Fluorescence at 2.0 micrometers



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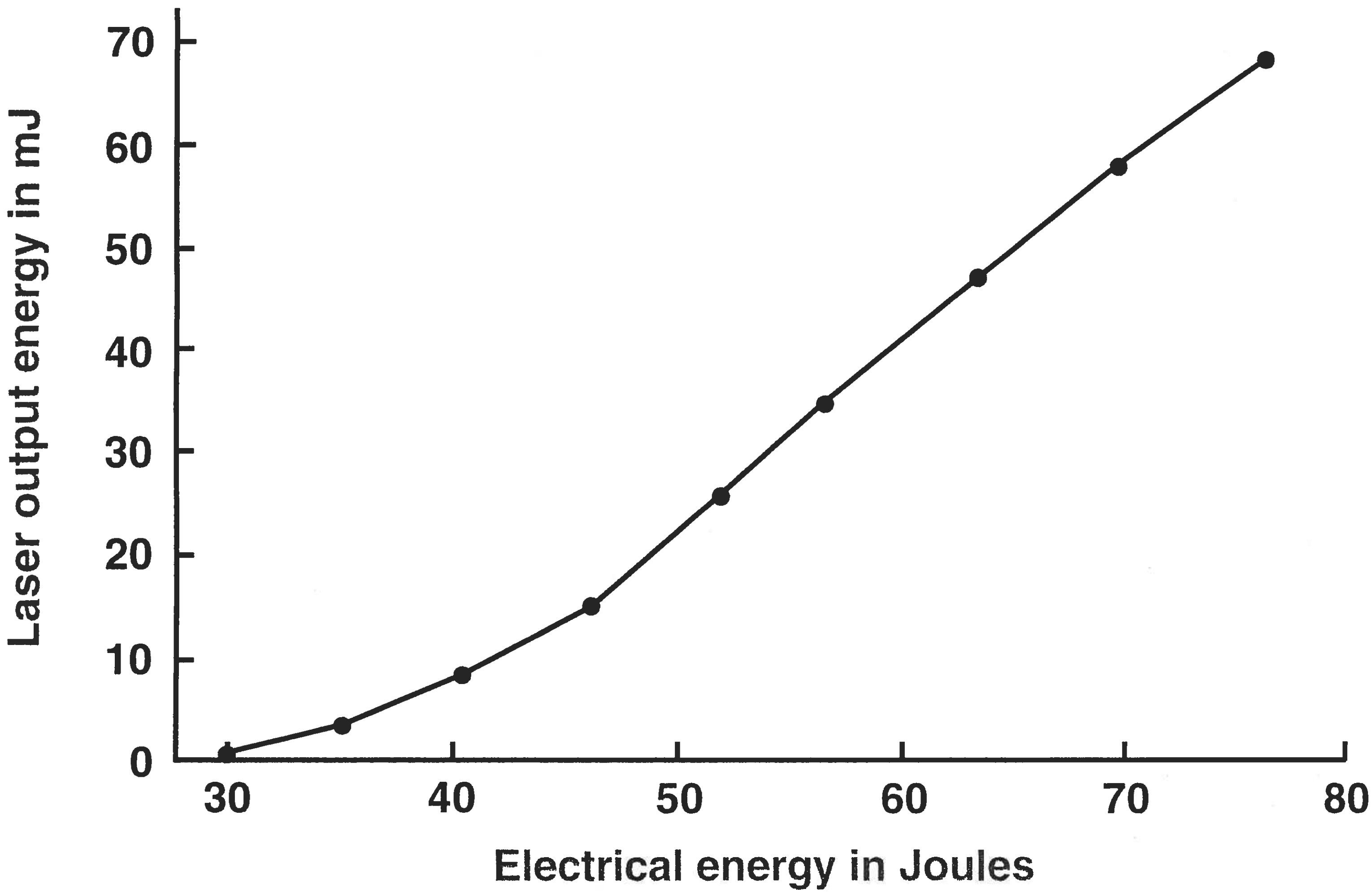
Er:Tm:LuAG Lasing at 2.944 microns

Er:Tm: .10; .06 4 by 85 mm rod .90 reflecting and 2.0 m RC



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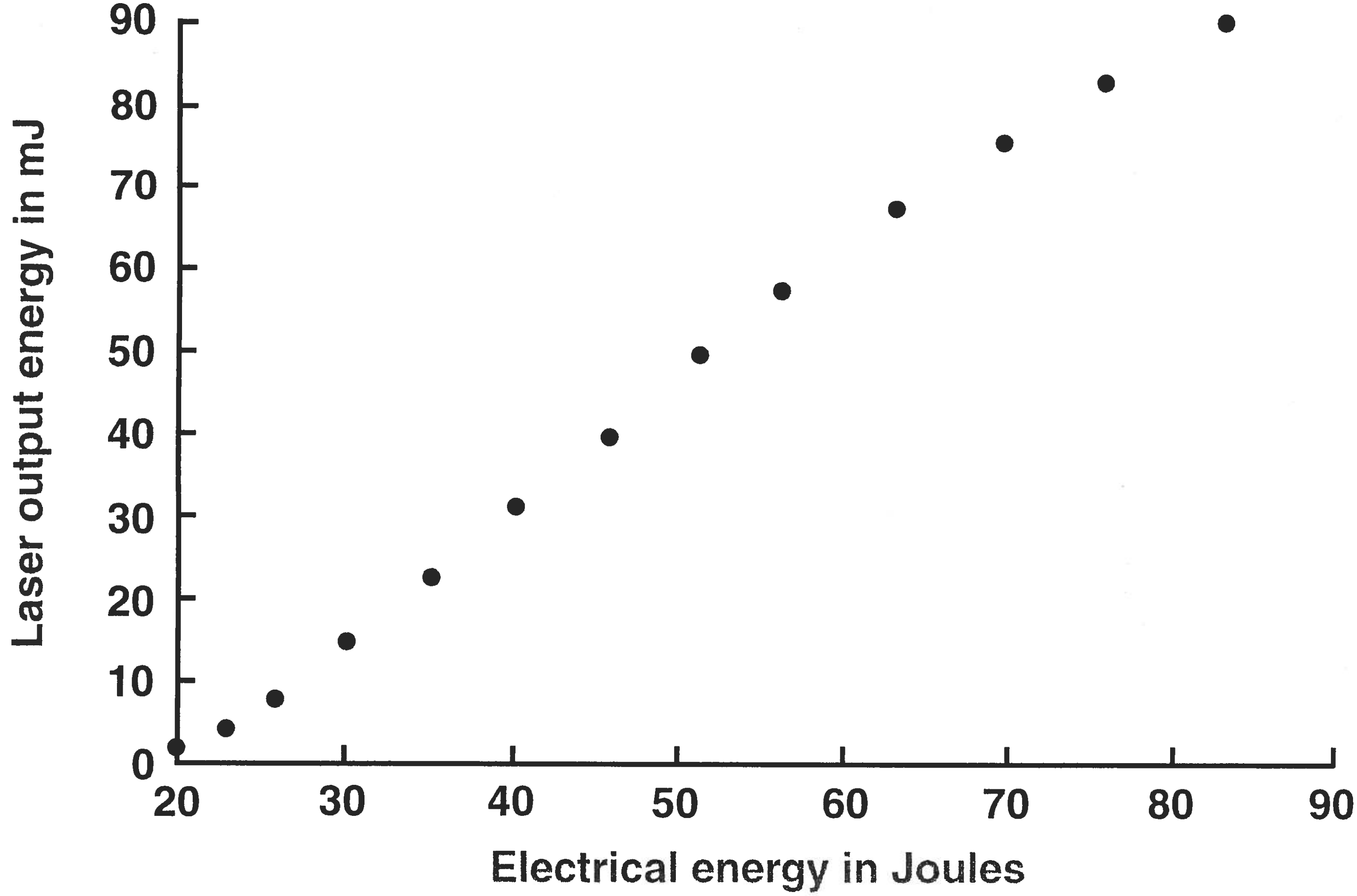
Er:Tm:YAG Lasing at 2.7 Microns

Er:Tm .13; .0375 5.0 by 85 mm rods



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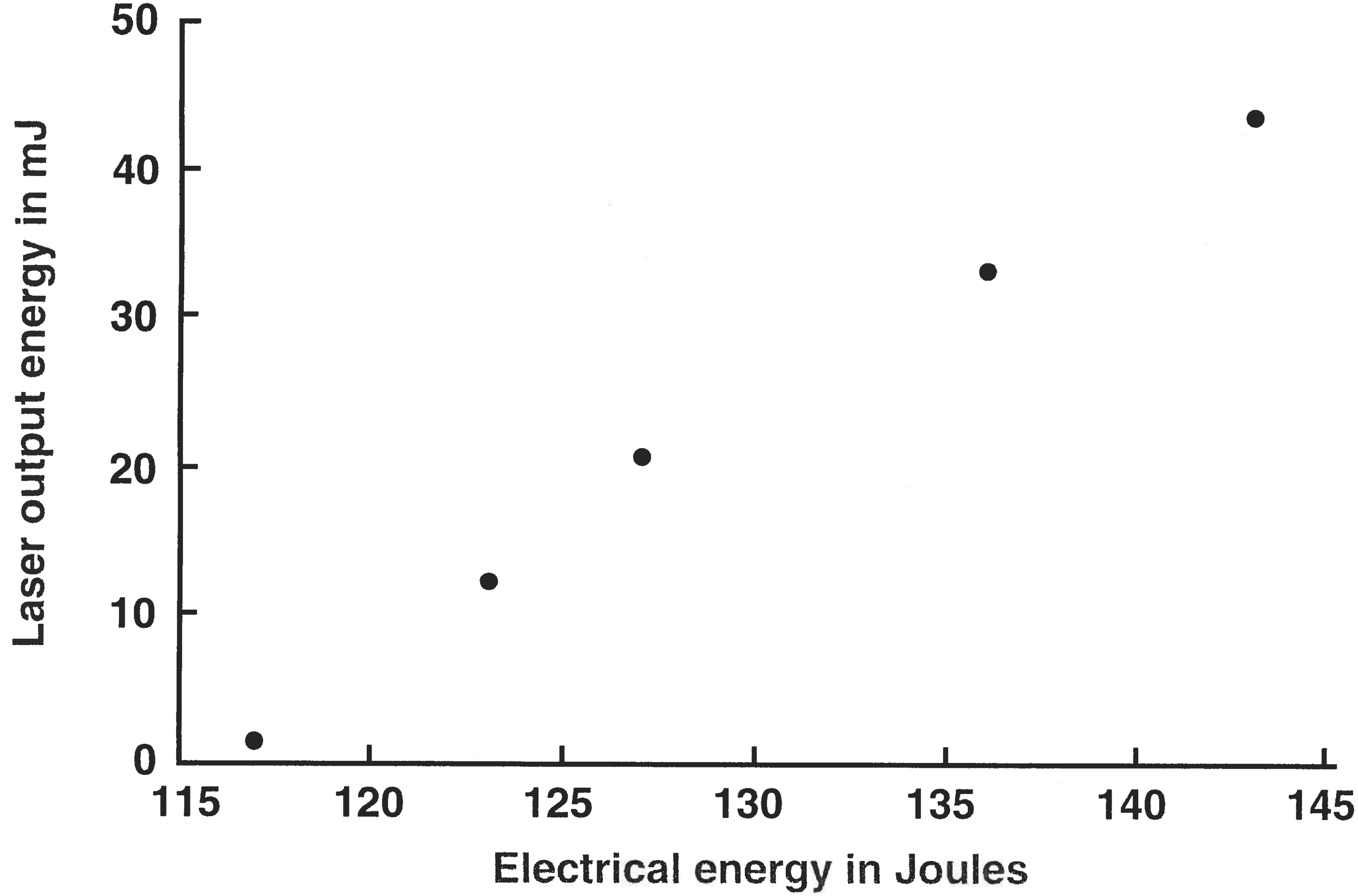
Er:Tm:YAG Lasing at 2.02 Microns

98% output coupler at 2.0 microns input energy estimated



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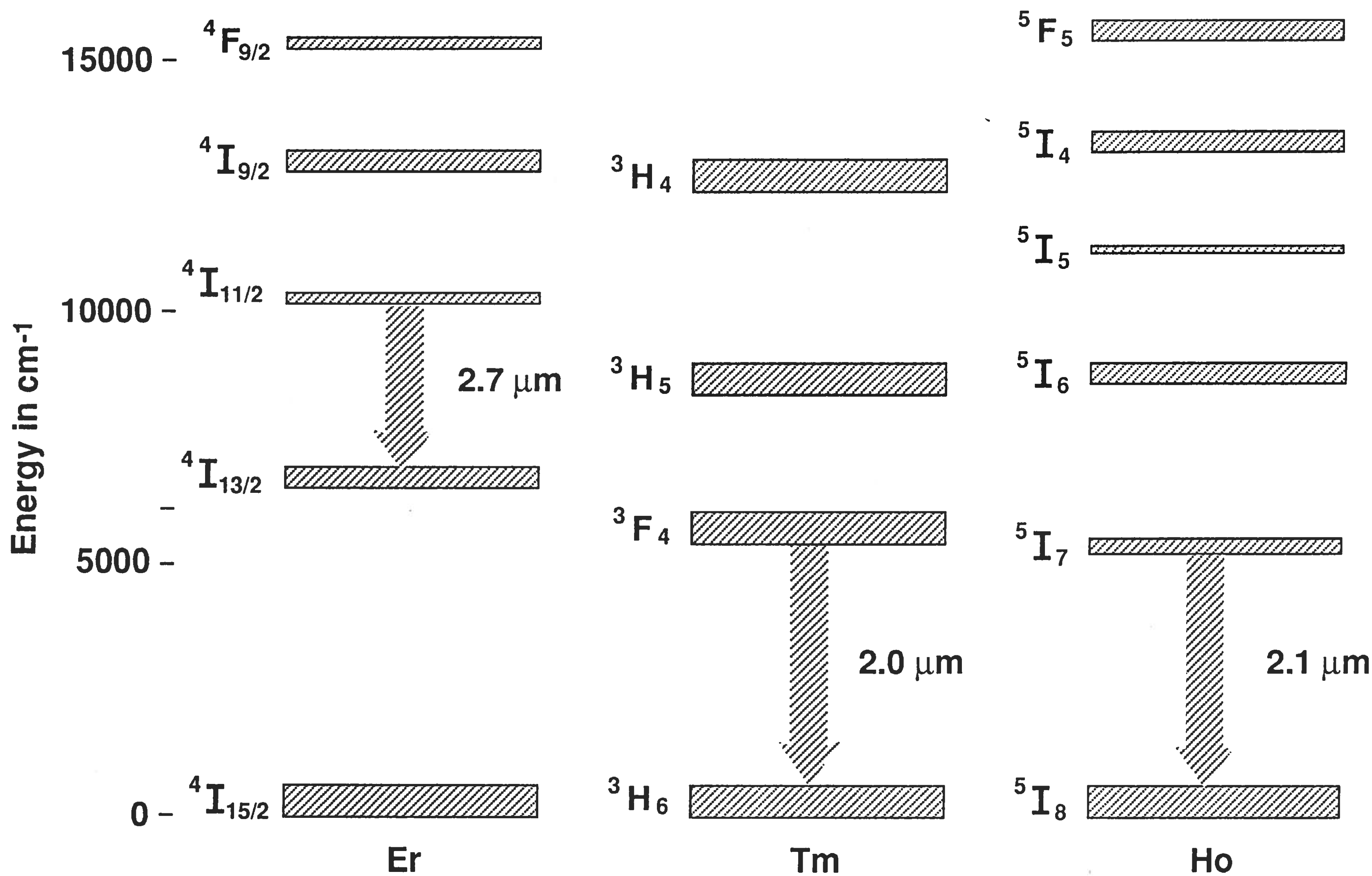
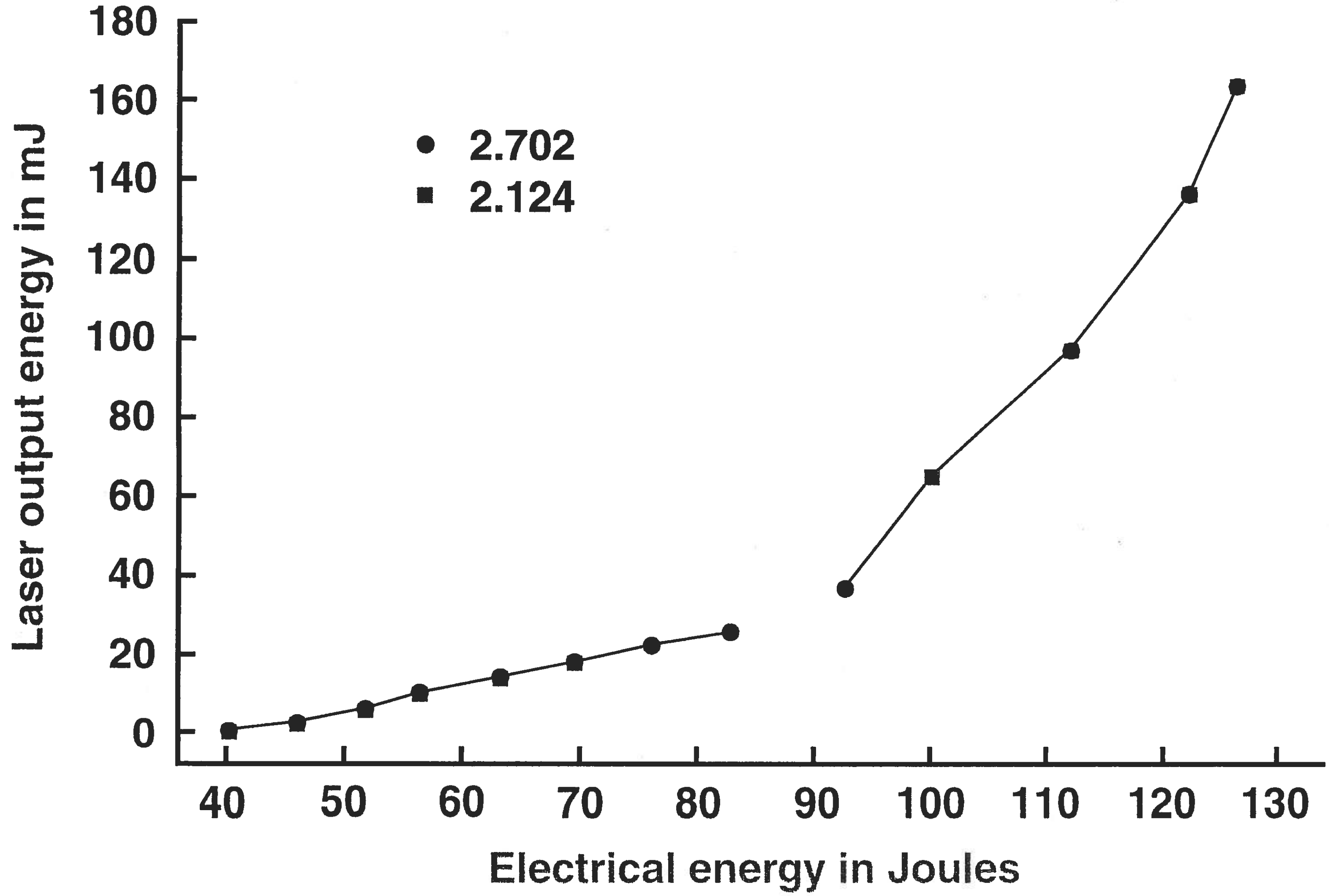
Energy Level Diagram



Two Wavelength Lasing in Er:Tm:Ho:LuAG

Er:Tm:Ho: .10; .06; .00326 rod end slightly damaged .90 R 2m OC and .99 flat



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Accomplishments to Date

1. Multiwavelength concept proven

    - electronic switching, hands off operation
    - complex physics, simple system
    - desired wavelengths generated
    - energy increased 5x

2. Funding obtained through Technology Applications Group

    - to further advance development
    - commercial interest expressed

3. Oral presentation accepted at Advanced Solid State Laser Conference   Feb. 13-16   Davos, Switzerland

CONCLUSIONS

- Multiwavelength lasing is a reality
- Efficiency can be optimized through concentration
  - chromium aids efficiency
  - high thulium tends to quench erbium lasing
  - energy transfer dynamics are complex
    - multiexponential decays evident
- Wavelength can be compositionally tuned
  - Er:YAG 2.700 micrometers
  - Er:LuAG 2.944 micrometers

MULTIWAVELENGTH LASER FOR MEDICAL APPLICATIONS AND THE IMPLICATIONS OF ATMOSPHERIC LENSING

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Abstract

Lasing at two medically important wavelengths, 2.124 microns and 2.700 microns, has been achieved from a single multiply doped laser rod in a simple resonator. Effects of atmospheric absorption and lensing were explored.

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Work has been performed to develop a multiwavelength solid state laser to address medical and dental applications. A single laser operating at 2.124 μm and 2.700 μm has been demonstrated. Lasing can be achieved either individually or simultaneously by controlling the pumping rate. The effects of water vapor absorption on increased loss and atmospheric lensing were explored.

Lasers operating at ~ 2.8 μm experience strong H_2O absorption and are thus highly absorbed by living cells. Systems operating around 2.1 μm have also been recognized for their use as operatory tools due to their water absorption characteristics. Lower H_2O absorption at 2.1 μm allows the beam to penetrate and make deeper incisions. Its use as a laser scalpel has been pursued . It also has utility as a dental instrument for gum, pulp, and other soft tissue procedures. Erbium lasers have found acceptance in the dental community for their ability to ablate enamel and dentin and allow for the efficient removal of dental caries. The high absorption has also found interest in the medical community as a tool for skin resurfacing.

In our attempt to develop a single laser to generate both useful wavelengths we have investigated 5 different multiply doped laser materials. In all cases the dopant chosen to generate the ~2.8 micron wavelength was Erbium lasing on the $^4I_{11/2}$ to $^4I_{13/2}$ transition. The other codopants were chosen for their potential lasing ability at ~2.0 microns and their possibility of aiding the Erbium transition through energy transfer processes. Both Thulium only , lasing on the $^3F_4$ to $^3H_6$ transition, and Thulium Holmium, lasing on the $^5I_7$ to $^5I_8$ transition, codopants were tried.

Special Dual band reflective mirrors were designed and fabricated to allow lasing at both wavelengths in a single resonator . A 0.90 reflective output coupling flat mirror, and a 2 meter concave high dual band reflector formed the resonator, the length of which was varied. Previously two sets of mirrors would have been needed, but the new mirrors allow exceptional coalignment of both transitions and eliminates a great deal of the system complexity and cost.[1] All testing was performed at room temperature, 15.3° C and at a repetition rate of 1 Hertz.

A 5.0 by 85.0 mm Cr:Tm:Er:YAG rod, 0.015:0.05:0.30, was evaluated in a 76 mm close coupled flooded ellipse cavity and demonstrated a threshold of 17.6 Joules and a slope efficiency of .2%. This slope efficiency was hampered by atmospheric H_2O absorption even in the short resonator path, which presented itself in the form of an audible snap as the water molecules in the beam were flash heated. Subsequent testing showed that operation under nitrogen purge to minimize water vapor absorption increased laser output energy on the order of 30%. The laser operated at 2.700 μm as measured by a ½ meter Spex monochromator. No lasing was achieved on the Thulium $^3F_4$ to $^3H_6$ transition for pump energies nearing 140 J at a pump pulse duration of 400 microseconds. Cr:Tm:YAG lasing has been demonstrated by Quarles et al.[2] At threshold energies near 70 joules for a 0.98 output coupling. Energy sharing between the the Er: $^4I_{13/2}$ and the Tm: $^3F_4$ would lower the upper laser level population and force a higher threshold. All other Er:Tm: samples also suffered from this energy sharing.

A 5.0 by 85mm Er:Tm:YAG rod, 0.13:0.0375 , was lased at 2.700 μm demonstrating a threshold of 19 J and a slope efficiency of .14% . It was lased at 2.019 μm with a .98 output coupler with a threshold of 115 J and a slope efficiency of .01%.

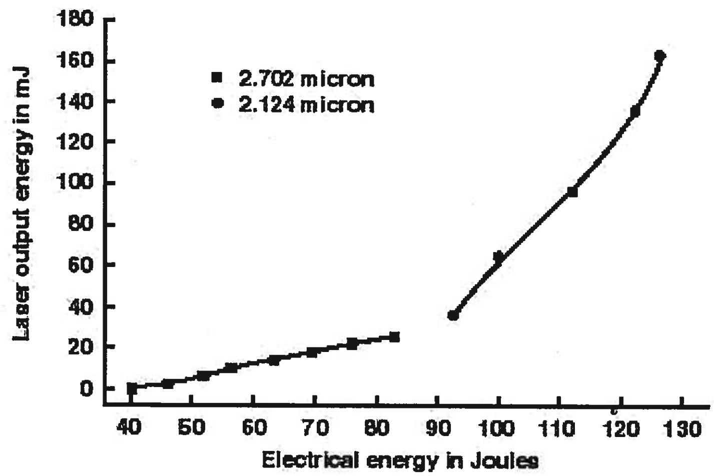
A 4.0 by 85mm Er:Tm:LuAG rod , 0.10:0.06:, was evaluated to lase at 2.944 μm with a threshold of 33.5 joules and a slope efficiency of .15%. No lasing was observed at ~ 2.0 microns.

Two Er:Tm:Ho: combinations successfully operated at both wavelengths. A 4.0 by 85mm Er:Tm:Ho:LuAG rod, 0.10:0.06:0.003:, lased at 2.700 μm with a threshold of 39 joules and a slope efficiency of .08%. Fig.1 It also lased at 2.124 μm on the Ho $^5I_7$ to $^5I_8$ transition utilizing a 600 microsecond pump pulse, having a threshold of 82 joules and a slope of 0.3%. Another sample, a 5.0 by 80mm Cr:Er:Tm:Ho:YAG rod, 0.005:0.40:0.06:0.0038: , lased at 2.700 μm with a threshold of 30.5 joules and a slope efficiency of .05%. Lasing was also achieved at 2.124 μm with a threshold of ~70 joules and a slope efficiency of 0.42%.

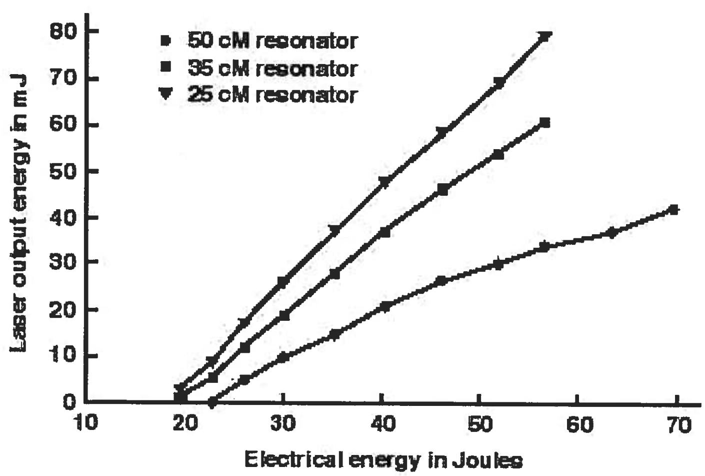
Atmospheric absorption of the laser radiation is deleterious in two ways, both as a loss and as a thermally induced perturbation of the laser resonator. Atmospheric absorption constants, even in between the absorption peaks can be large at 2.7 μm, >0.02 m^{-1} . An absorption coefficient this large can cause a thermal lensing effect [3] which can lead to increased diffraction losses. To test this, the laser output was sampled twice, one sample being focused onto a 200 μm pinhole and detector and the other sample impinging on a similiar detector. Measurements of the ratio demonstrated that the fraction of the beam going through the pinhole decreades during the pulse, supporting the atmospheric perturbation hypothesis.

Lasing at two medically important wavelengths has been achieved from a single multiply doped solid state laser rod in a simple resonator. To achieve sufficient laser energy at the nominal 2.1 micron line, Tm:Ho: codopants must be utilized, taking advantage of the much higher Holmium cross-section and gain. The lower than expected slope efficiencies tends to infer quenching of the Erbium $^4S_{3/2}$ and $^4I_{9/2}$ levels by the Thulium $^3F_4$. The data lends support as the two rods with the highest Thulium concentrations also demonstrate the highest thresholds and the lowest slope efficiencies. Lasing at the nominal 2.8 micron line is not only hampered by the H_2O absorption in the atmosphere but also by the fact that the heating in the beam path sets up an atmospheric lens which moves the resonator toward instability. Work to scale the energies to current medical specifications is underway along with an effort to quantify the thermal perturbations.

Two Wavelength Lasing in Er:Tm:Ho:LuAG



Effect of Resonator Length on 2.7 Micrometer Lasing



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