Compensation of Thermal Lensing in Solid-State Laser Gain Media using Phantom Pulses

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ABSTRACT

Phantom pulses are low energy, high repetition rate pulses used to induce controlled thermal lensing in the laser rod for purposes of achieving full output energy at single shot operation and/or at a broad range of repetition rates. The energy of the phantom pulses is below the lasing threshold and the repetition rate is low enough so that there is minimal stored energy left in the gain media when the lasing pulse occurs. The method of using phantom pulses to increase performance benefits resonators that perform better at a higher average power. Additionally phantom pulses can be used to control divergence over a resonator's operational range.

Keywords: Phantom Pulses, Solid-State Lasers, Thermal Lensing, Pulsed Lasers, CTH:YAG, Thermal Loading, Flashlamp Pumped, High Power, Er:YAG

1. INTRODUCTION

In simple solid-state laser resonators, the operational repetition rate is often limited by thermally induced lensing in the gain media. Changes in the average pumping power affect the resonator's stability, which results in changes to the laser beam's divergence and beam quality. A typical flashlamp pumped solid-state laser resonator is shown in Figure 1. The flashlamp (2) will pulse at specified parameters, optically exciting the ions in the laser gain media (3). Although many solid-state lasers are now optically pumped with semiconductor lasers, flashlamp pumped solid-state lasers can economically produce high peak power and high energy pulses. Typical flashlamp lifetime is in the range of 10 – 100 million shots. Many laser systems, such as medical laser devices often only require a few flashlamp changes during their lifetime.

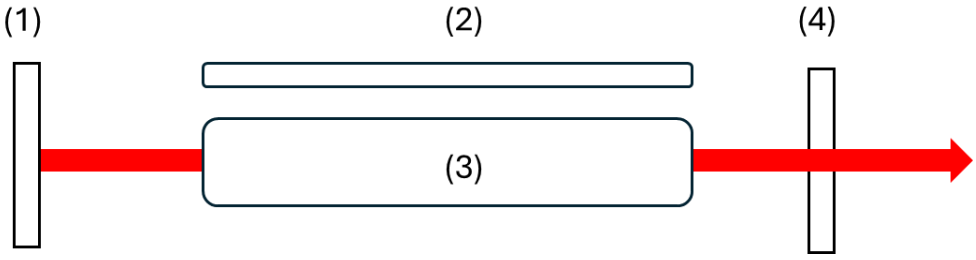

Figure 1. Example of a flashlamp pumped solid-state laser resonator where elements are 1. High reflective mirror, 2. Flashlamp, 3. Laser gain media, 4. Output coupler. Note that 2 and 3 are typically mounted inside a pump chamber

Two of the most common solid-state laser gain media are Ho:YAG and Er:YAG. Ho:YAG and Er:YAG have very different lasing properties due to their different rare earth dopants. Flashlamp pumped Ho:YAG laser gain media is typically co-doped with Chromium (Cr^{3+}) and Thulium (Th^{3+}) [1] sensitizing ions and is commonly referred to as CTH:YAG. The high absorption of the sensitizing ions provides for efficient operation due to the high absorption of the flashlamp emission. When used with flashlamp pumping, Er:YAG is typically richly doped with Er^{3+}. Er^{3+} substitutes for 50 percent of the Yttrium (Yt^{3+}) ions. [2] Similar to CTH:YAG, the high doping concentration of Er:YAG provides for efficient operation due to high absorption of the flashlamp emission.

1. 1 CTH:YAG

A depiction of the energy transfer is shown in Figure 2. A large portion of the flashlamp energy is absorbed by the Cr^{3+} ions. After a nonradiative decay, the excitation is transferred into the Th^{3+} ion via dipole-dipole interactions. The Th^{3+} ion then interacts with the ground state Th^{3+} ion which gives rise to two Th^{3+} ions which transfer energy to the Ho^{3+} ions to lase on the 2.13 μm transition. [1] In typical CTH:YAG resonators, the electrical-optical efficiency may exceed five percent. However, the high optical absorption causes severe thermal effects including thermally induced thermal lensing, photo-elastic effects and birefringence.

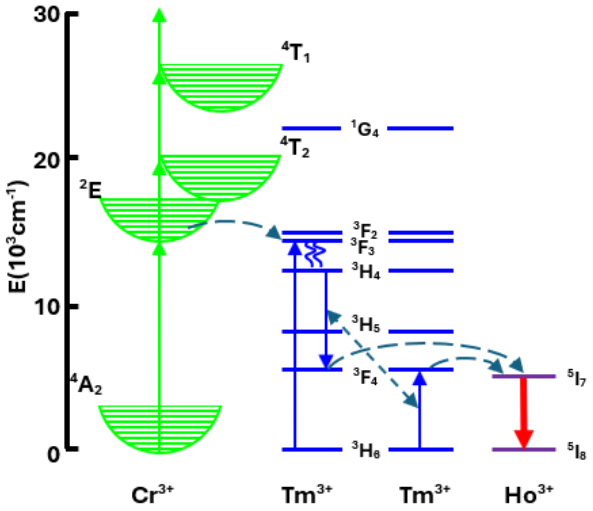

Figure 2. Transition of energy between co-dopants in a CTH:YAG laser, adapted from [1]

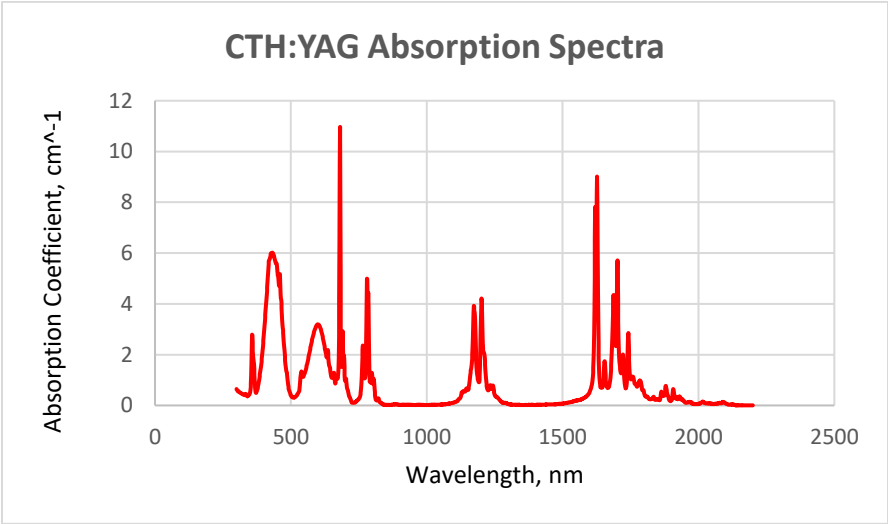

Figure 3. CTH:YAG Absorption Spectra [3]

One of the most common applications for solid-state lasers is urology, specifically lithotripsy. Typically, flashlamp pumped CTH:YAG lasers are used, and these lasers are operated with an output of up to 4 J with a pulse duration of 250 – 800 μs and a repetition rate range of 1 to 30 Hz.

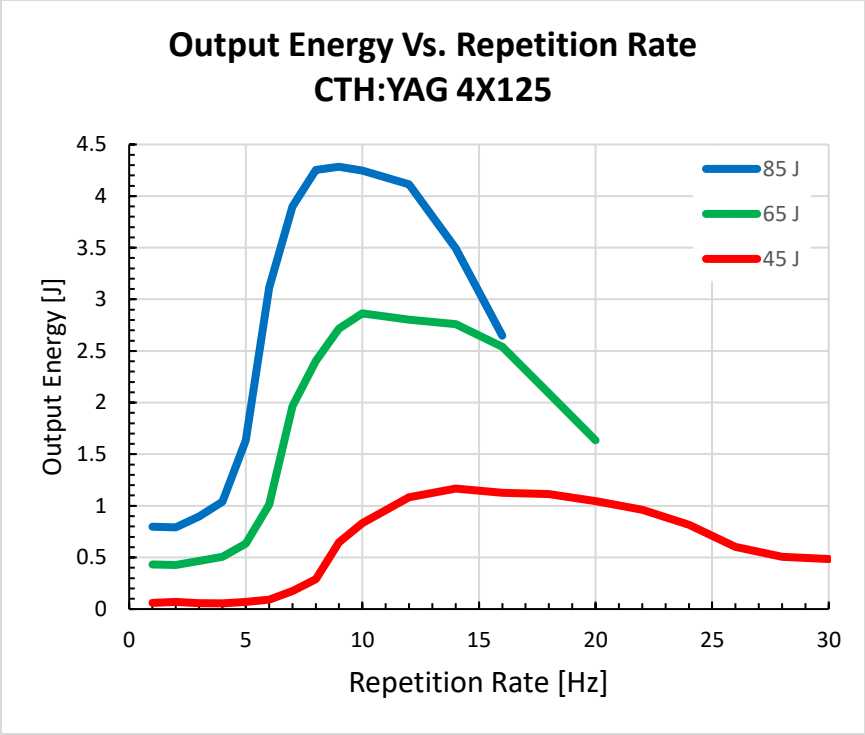

Figure 4. Output energy as a function of repetition rate for a 4 mm diameter by 125 mm diameter CTH:YAG rod with 35 cm concave ends and flat resonator optics at 45, 65, and 85 J pump energies

CTH:YAG has high optical absorption, as seen in Figure 3, and exhibits severe thermally induced lensing and birefringence. A method commonly used to partially compensate for thermally induced lensing is to introduce negative lensing in the gain media with the use of 10 - 100 cm concave radii on the rod ends. [4] This method compensates for thermally induced lensing at a single average pump power. In a simple resonator comprised of a bi-concave rod and flat mirrors, the resonator is stable when operated above the compensation average pump power and unstable when operated below. Thus, this resonator configuration will perform better at a moderate average pump power and will perform poorly or not at all at lower average pump power.

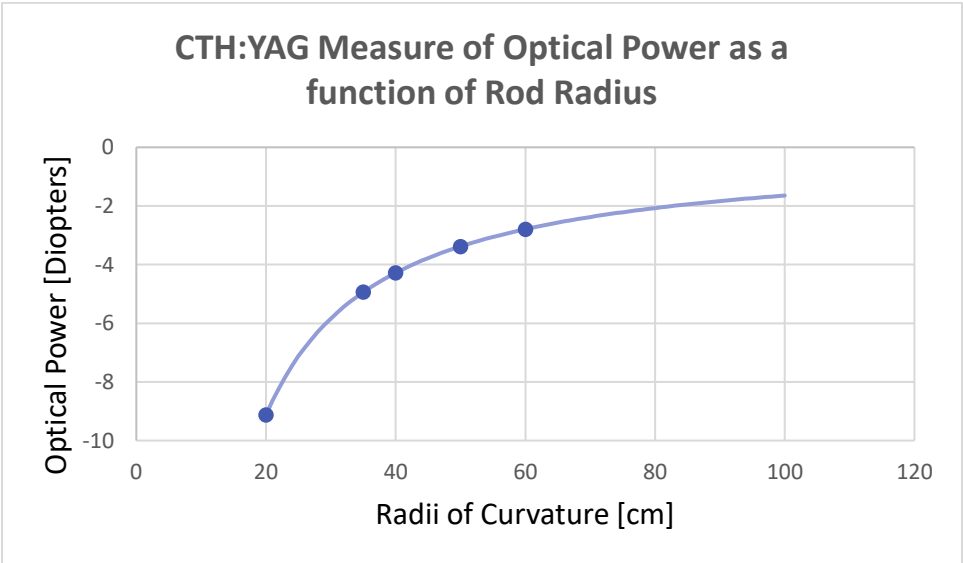

Figure 5. Effect of radius of curvature on optical power for a 125 mm long biconcave CTH:YAG rod

As shown in Figure 5, as the radii of the rod faces increases, so does the optical power. With longer radii, the maximum repetition rate is approximately 10-20 Hz for a 4 mm diameter by 130 mm CTH:YAG rod. Note that as the radius increases, the beam divergence increases significantly.

While the biconcave rod is beneficial for higher repetition rates, it does not allow for operation at lower repetition rates as the resonator is unstable. For some medical procedures, both low as well as higher repetition rates may be necessary. Currently, this is achieved by multiplexing multiple resonators with flat rod faces. This can be both bulky and expensive and is not always practical.

1.2 Er:YAG

Er:YAG is also a common flashlamp pumped solid-state laser media. When doped at high concentrations, the dominate laser line is due to the $^4I_{9/2} - {}^4I_{11/2}$ trasmission at 2.936 µm. Similar to CTH:YAG, the high doping concetration of Er^{3+} allows for high absorption of the flashlamp light, resulting in reasonable pumping efficiency. The high absorption; however, causes strong thermal induced lensing and birefringence. The 2.936 µm wavelength is useful for medical and atmospheric research applications because of high water absorption,. Er:YAG has a low emission cross-section, so resonator stability is important for efficient operation. It is interesting that Er:YAG resonators with flat rod faces and flat resonator optics tpically perform better at higer repetition rates where the resonator is stabilized by thermal lensing. A resonator utilizing a 4 mm diameter by 100 mm long Er:YAG rod produces less than 100 mJ in a single shot and over 3 J at 10 Hz with the same pump energy. As reported in this paper,by using phantom pulses we were able to obtain the same energy at repetition rates from single shot to over 10 Hz.

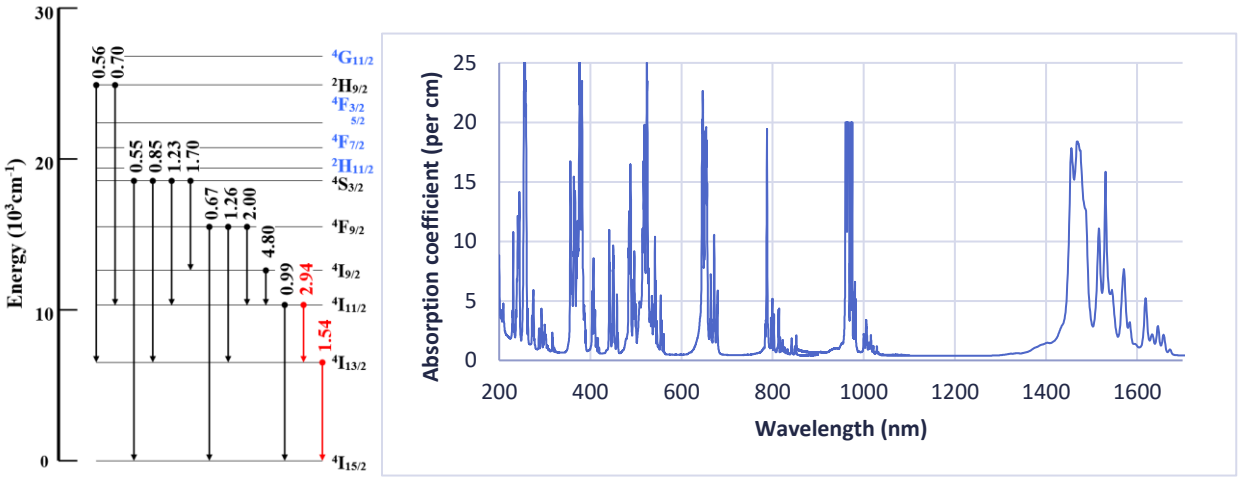

Figure 6. Energy Levels and absorption spectra of 50% Er:YAG [5]

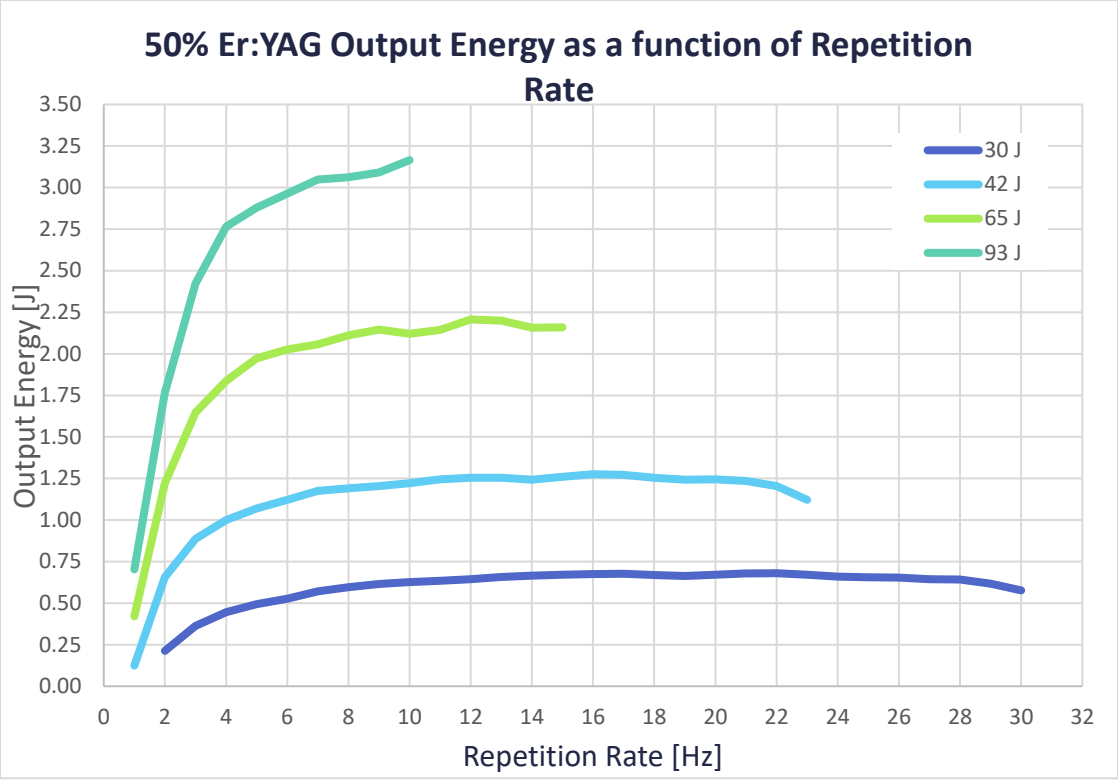

Figure 7. Output energy as a function of repetition rate for a 4 mm diameter by 100 mm long Er:YAG rod with flat ends and flat resonator optics at 30, 42, 65, and 93 J pump energies.

One common method which allows for low repetition rate and/or single pulse(s) is to allow the laser to reach thermal equilibrium before emitting pulse(s). The lower repetition rate or single shots are then gated by a fast shutter.

1.3 Balance of thermal and mechanical optical power

In solid-state lasers, the gain media absorbs pump energy volumetrically. In the form of a cooled cylinder, the gain media's refractive index and the photo-elastic effect have a quadratic variation with radius. Ignoring the end effects of the laser rod, the first order thermal effect is spherical lensing. [6] With the use of phantom pulses, we can balance the biconcave and thermal lensing effects to create a resonator which is able to operate from low to high repetition rates. If one treats the laser rod as a thick lens, then the effective focal length of the laser rod having concave radii ends can be defined as [6]:

$$\frac{1}{f_{thick\ lens}} = (n_0 - 1)\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{l(n_0-1)}{R_1 R_2}\right) \quad (1)$$

where R_1 and R_2 are the radii of the rod ends, l is the rod length, and n_0 is the refractive index of the laser rod. The thermally induced focal length of the laser rod at a given pump power is defined to be [6]:

$$\frac{1}{f_{thermal}} = \left(\frac{P_h}{KA}\right)\left(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\emptyset} n_0^3 + \frac{\alpha r_0 (n_0-1)}{l}\right) \quad (2)$$

where P_h is the pump heat dissipated in the rod, K is a constant dependent upon material properties and the cooling configuration, and A is the cross-sectional area of the rod. In YAG, the temperature-dependent variation of the refractive index (1/2 dn/dt) is responsible for ~74% of the thermal lensing. The stress-dependent variation of the refractive index ($\alpha C_{r,\emptyset} n_0^3$) is responsible for ~20% of the thermal lensing. Where α is the coefficient of thermal expansion, $C_{r,\emptyset}$ are the radial and tangential elasto-coefficients of YAG. The end-face curvature caused by thermal expansion $\frac{\alpha r_0 (n_0-1)}{l}$) where l is rod length, is responsible for less than 6% of the thermal effects. As Koechner points out, to the first order, thermal

lensing is independent of the rod length and laser engineers have little control over the rod's focal length at a given pump power. Addition of equations 1 and 2 leads to the effective focal length combining contributions due to the thermal effects of the laser material with the biconcave effects of the rod itself (Eq. 3).

$$P_{opt} = \frac{1}{f} = (\frac{P_h}{KA})(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\emptyset} n_0^3 + \frac{\alpha r_0 (n_0 - 1)}{l}) + (n_0 - 1)(\frac{1}{R_1} + \frac{1}{R_2} + \frac{l(n_0 - 1)}{R_1 R_2}). \quad (3)$$

Many of the values in equation 3 are constant with respect to the laser geometry and material. Therefore, the parameters which influence the focal length are the power dissipated through the laser rod due to the heat (P_h) and the biconcave nature of the rod. We can simplify equation 3 to equation 4 where the values of C_1 and C_2 are constants. By applying the method of phantom pulses, we can control the residual heat in the laser rod and therefore control the thermal lensing.

$$P_{opt} = \frac{1}{f} = (P_h * C_1) + C_2 \quad (4)$$

Table 1 Constants used in Equations 1-4. [7] [8] [9]. Note similarities in values are thought to be due to the YAG host crystal

Constant	Description	Value CTH:YAG	Value Er:YAG
K	Thermal Conductivity	11.2 W/m/K	11.2 W/m/K
A	Rod cross-sectional area	For testing we used a 2 mm radius rod	For testing we used a 2 mm radius rod
$\frac{dn}{dT}$	Change in the refractive index due to thermal strain	7.8*10^-6 /℃	7.8*10^-6 /℃
α	Coefficient of thermal expansion	6.14*10^-6 /℃	6.14*10^-6 /℃
$C_{r,\emptyset}$	Photo-elastic coefficient	.022	.022
n_0	Refractive Index	1.83	1.83
r_0	Radius of the rod	For testing we used a 2 mm radius rod	For testing we used a 2 mm radius rod
R_1	Radius of Curvature of the rod face 1	For testing, we used -35 cm	0
R_2	Radius of Curvature of the rod face 2	For testing, we used -35 cm	0
l	Length of the rod	For testing, we used 13 cm	For testing, we used 10 cm

2. ELECTRICAL METHODOLOGY

2.1 Explanation of Phantom Pulses

Phantom pulses are relatively low energy, high repetition rate pulses of short duration that add power to the laser rod without generating laser output. The phantom pulses are fired into the flashlamp by the laser driver and can be tuned as needed for the laser material and application. To generate the phantom pulses, a modified pulse routine was utilized. As noted, no additional hardware is required. The 500 µs laser pulse and the phantom pulses were synchronized by their rising edge. Figure 8 shows an example of the timing for the phantom pulses interleaved with the laser pulses.

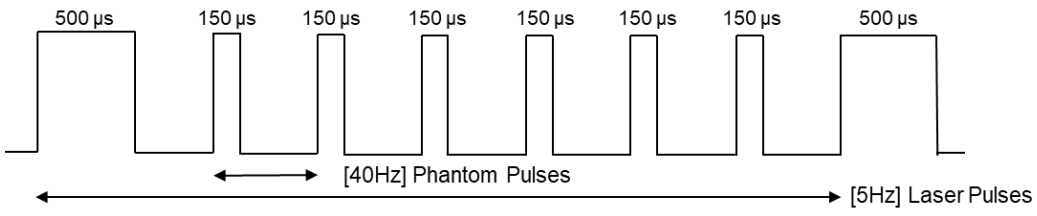

Figure 8 Timeline of 5 Hz, 500 µs laser pulses with 40 Hz, 150 µs phantom pulses (not to scale)

2.2 Phantom Pulse Parameters

As shown in equation 5, the total power dissipated in the laser rod is the sum of the residual heat of the laser and the phantom pump pulses. To calculate the power needed for the phantom pulses to reach the optimal laser output power, the value of P_{total} was set to be the value at the optimal laser pulse repetition rate. For example, if a laser resonator operates at an average pump power of 760 W for an optimal repetition rate of 10 Hz, then to operate at 1 Hz the average laser pulse power will be 76 W and the average power of the phantom pulses, to compensate for the thermal loading, will be 684 W. The power of the phantom pulses may be modified by either pulse width or repetition rate of the phantom pulses depending on the application.

$$P_{total} = P_{laser\ pulses} + P_{phantom\ pulses} \tag{5}$$

As shown in [4], we have measured the thermal induced optical power in the laser rod is about 25% greater when not lasing. However, empirically we have found that ignoring this difference is close enough to optimal and is a good starting point.

3. RESULTS

3.1 CTH:YAG Output

Figure 9 illustrates various repetition rates both with and without phantom pulses. For this test, the laser rod had 35 cm concave radiused faces and the alignment had been optimized for 500 μs at 10 Hz operation at full power. The resonator length between HR and OC mirrors is 220mm, which is typical for a 40 W CTH:YAG Lithotripsy laser. This illustrates the benefit of the phantom pulses where the energy output at lower repetition rates can equal or even outperform that of 10 Hz.

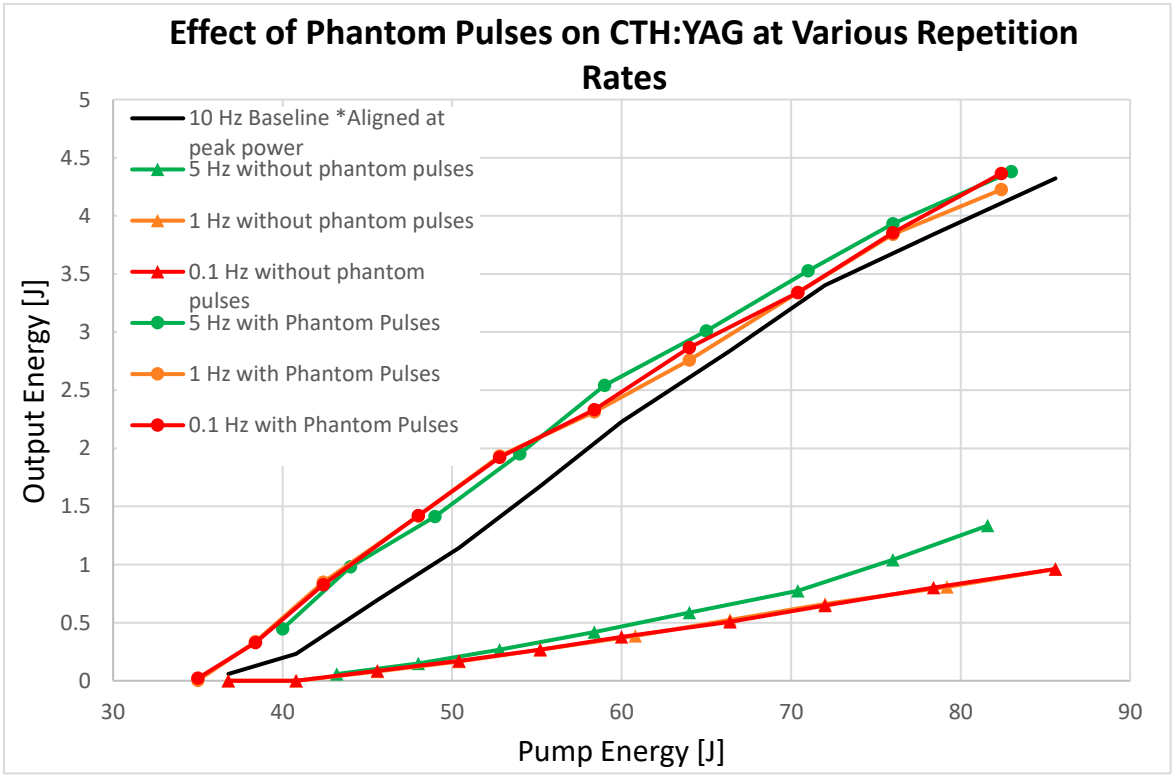

Figure 9 Representation of phantom pulses increasing the laser energy output for a CTH:YAG Resonator

3.2 Er:YAG Output

Like the output of the CTH:YAG, the Er:YAG resonator performance was significantly improved at lower repetition rates using phantom pulses. Er:YAG is a low gain laser media, so when used with flat rod faces and flat resonator mirrors, the resonator stability is achieved by thermal lensing of the laser rod. Without phantom pulses, at lower repetition rates, the output energy is significantly decreased as shown in Figure 7.

The testing apparatus utilized a standard 30 W Er:YAG laser resonator with a length of 195 mm. Figure 10 shows the impact of the phantom pulses on output energy for a variety of lower repetition rates. Use of phantom pulses increased the output energy by over 15 percent at 5 Hz and almost 20 times at 1 Hz.

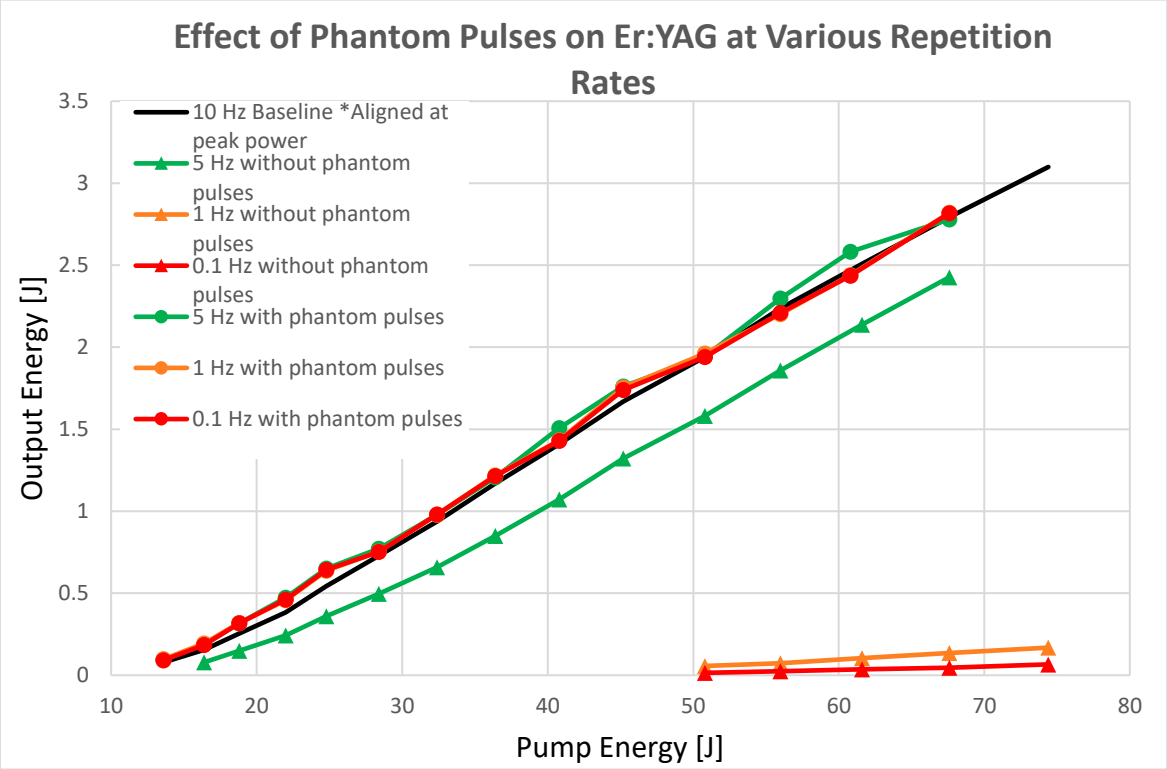

Figure 10 Demonstration of phantom pulses increasing the laser energy output for a Er:YAG Resonator. The three sets of data with the phantom pulses are essentially equal.

3.3 Cold Start and Burst Applications

Repetitively pulsed solid-state lasers require several seconds of operation before they reach thermal equilibrium. The first pulses are typically a different pulse energy, and the resonator has a different divergence than after it has reached equilibrium. As shown in Figure 12, for a resonator with a 4 mm diameter x 100 mm Er:YAG rod, the output energy rises from nearly zero to full power in about a second. In many cases, it is desirable to have "instant on" full power or to output a burst of pulses of equal energy. In some cases, it is necessary to emit a burst of only one pulse or single shot operation at full energy. By utilizing phantom pulses, we have demonstrated that we are able to control the first pulse, as well as all subsequent pulses through thermal loading of the laser rod, as is demonstrated in Figure 13.

To demonstrate the utility of phantom pulses, we developed a timing scheme to switch between "standby" mode and the "operational" mode, as is shown in Figure 11. In standby mode, only phantom pulses are used to maintain the thermal loading in the rod. When the lasing output is desired, the triggering circuit switches to operational mode, i.e. the laser pulses. At the end of the burst of pulses in operational mode, the triggering circuit switches back to standby mode with only phantom pulses, and lasing ceases.

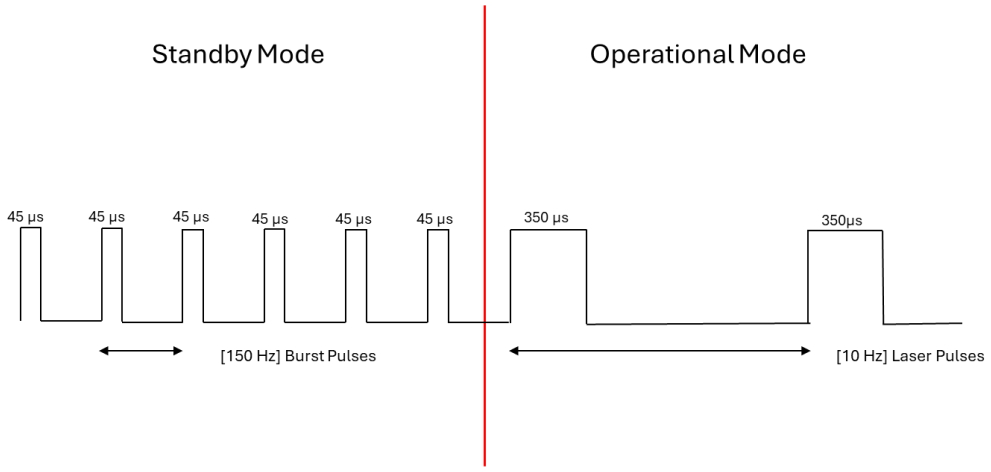

Figure 11 Cold Start Test for Er:YAG with 150 Hz phantom pulses in standby mode and 10 Hz operation in operational mode

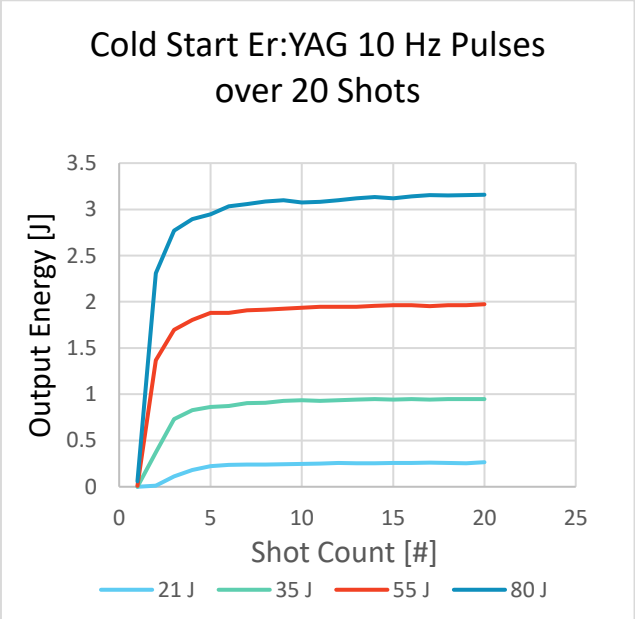

Figure 12 (left) Representation of cold start without phantom pulses for an Er:YAG resonator at 10 Hz laser repetition rate

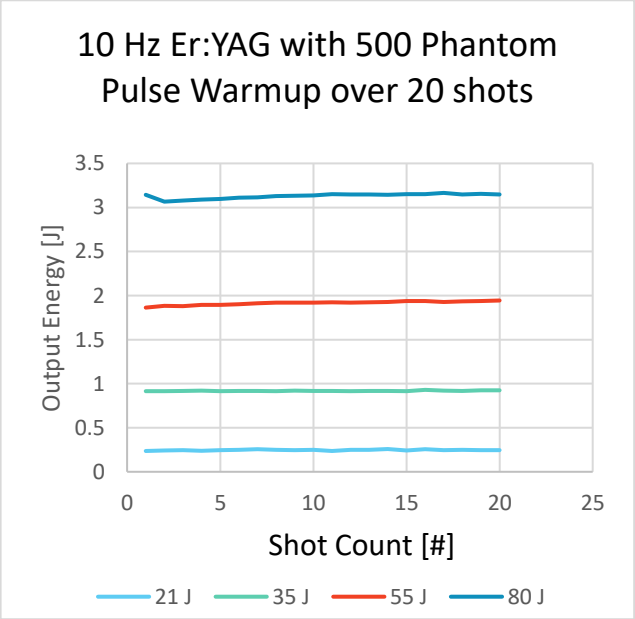

Figure 13 (right) Representation of cold start with phantom pulses for an Er:YAG resonator at 10 Hz laser repetition rate

To investigate how long the pulse train of phantom pulses were required before full energy output on the first pulse, we varied the number of phantom pulses from turn on from 0 to 750. As shown in Figure 14, for 5 J flashlamp phantom pulses at 150 Hz, full 3 J output energy was achieved after approximately 150 pulses or about 1 second.

For our application, where a 3 J single shot pulse was required, we increased the laser energy from 116 mJ to 3 J with phantom pulses. This is an improvement of over 25 times!

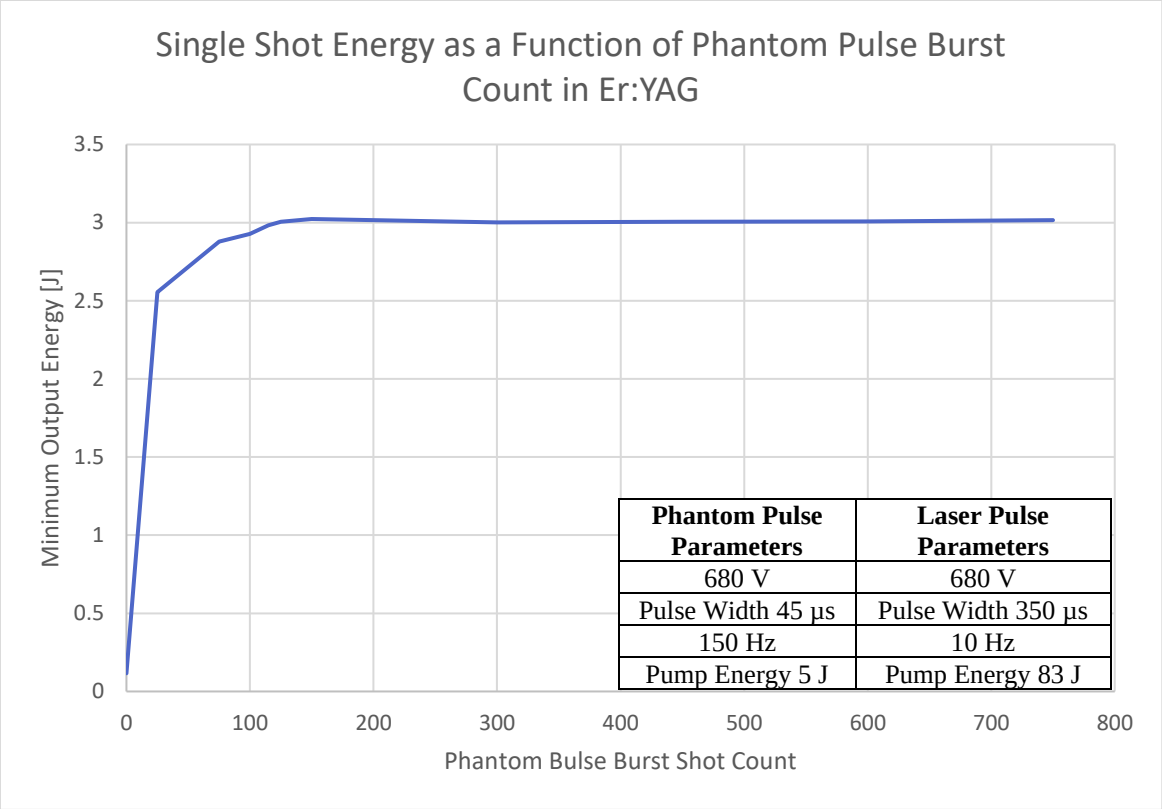

Figure 14. Cold start testing showing the impact of phantom pulses in standby mode on the initial shot energy

An important note is that at 10 Hz operation, phantom pulses are not necessary to boost the performance of the laser resonator. If a lower laser pulse repetition rate were chosen for the operational mode, the first shot is thermally compensated by the phantom pulses and would be at full energy. Subsequent pulses would decrease to the performance level without phantom pulses. For example, if a 1 Hz Er:YAG laser pulse repetition rate was used after switching from standby mode to the operational mode, the energy output would drop from 3 J to the thermal equilibrium of about 150 mJ within the first couple of seconds. This is because the phantom pulses would no longer be maintaining the thermal equilibrium. Therefore, a more complex pulse method would be required. For future work, a timing diagram similar to Figure 15 with the standby mode phantom pulses as well as an interleaved phantom and lasing pulses operational mode would be required. The power of the phantom pulses during the operational mode would be less than the power of the phantom pulses during standby mode and may be adjusted by changing either the repetition rate or the pulse width.

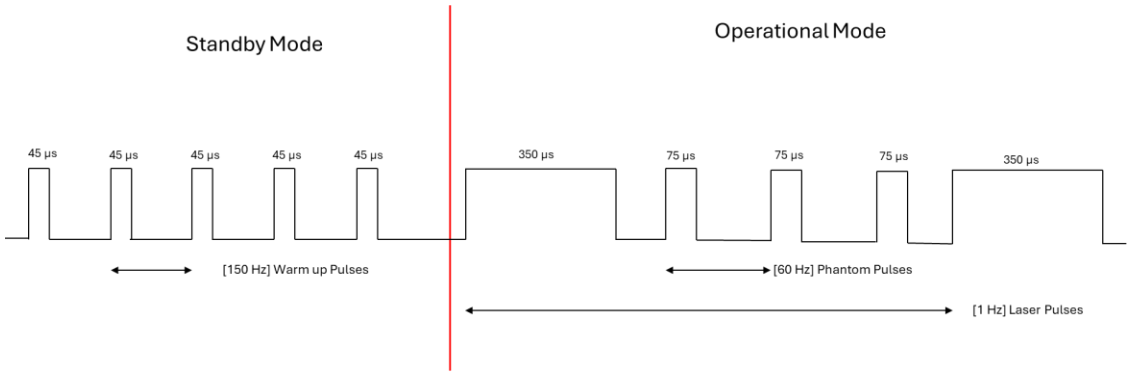

Figure 15. Burst operation of Er:YAG with 150 Hz phantom pulses in standby mode and 75 Hz phantom pulses in operational mode and 1 Hz laser pulses in operational mode (not to scale)

4. CONCLUSIONS

Improved repetition rate and output

In conclusion, phantom pulses provide a reliable method of increasing performance of solid-state laser materials at a low repetition rate without altering the geometry of the laser rod. This method allows for a single resonator system which can perform over a large range of repetition rates, including single shot. In the case of CTH:YAG, phantom pulses can compensate or overcompensate for the negative lensing from a biconcave rod even at low repetition rates.

In the case of materials, such as Er:YAG, where thermal induced lensing is required for resonator stability and efficient operation, phantom pulses are also able to significantly increase the performance of the resonator at low repetition rates. The output of a simple Er:YAG resonator was improved by 20 times at 1 Hz or less.

Burst or single shot operation

We have demonstrated that phantom pulses are useful for resonators that need to operate at full energy on the first pulse or for all pulses in a burst mode.

Operation at single voltage with a single power supply and capacitor bank

We have demonstrated that we can power both the phantom pulses and lasing pulses from the same power supply and capacitor bank. We have also demonstrated that we can power the phantom pulses and the lasing pulses from independent drivers with a single flashlamp.

There are some drawbacks to the use of phantom pulses such as lower wall plug efficiency. Given that the laser driver is supplying both the pulses for the phantom pulses and the laser pulses, a higher overall drive power is needed for low average power operation.

5. FUTURE WORK

1. Operation at duty cycles or burst, where the resonator would switch between standby and operation and back.
2. Test our theory that we can maintain the resonator divergence over all operating conditions.
3. Improving our modeling to include both radial and tangential Photo-elastic coefficients.
4. Develop an algorithm to predict the best phantom pulse energy and pulse duration.
5. Additional empirical testing to determine what effect the phantom pulses have upon the flashlamp, if any.

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