200 W Compact 2.1 µm CTH YAG Laser

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ABSTRACT

For some medical and remote sensing applications, high average power and high pulse energy laser emission is required. In addition to higher output, improved beam quality is also desired. One method to achieve both a higher output and an improved beam quality is to combine the output of multiple resonators. We report on the output of a beam combined resonator with 4 independently operating Chromium, Thulium, Holmium doped YAG (CTH:YAG) or Ho:YAG lasers lasing on the 2.13 µm transition. We have demonstrated an output of 200 W operating at 40 Hz using a novel method of beam combination where a rotating rhomboid prism captures the beam from four separate lasers and translates them to a single optical path. With the stability of a compact package, the laser described herein allows for a simple method of reaching higher peak powers for a single wavelength or of a combination of different wavelengths along a single optical path. Potential applications include urology as well as a pump source for NLO (OPO & OPA) as well as transition metal lasers.

Keywords: Ho:YAG, CTH:YAG, Beam Combining, 2.1 µm, Urology, Solid-State laser, Flashlamp pumped, Holmium

1. BACKGROUND

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. One of the most common solid state laser gain media is CTH:YAG, often referred to as Ho:YAG. High absorption of the sensitizing ions provides for efficient operation due to the high absorption of the flashlamp emission. In typical flashlamp pumped 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 and birefringence. To produce higher repetition rates and/or higher average power systems, laser engineers often combine the outputs of multiple resonators. Temporal multiplexing of pulsed CTH:YAG resonators is commonly utilized to increase repetition rate and average power while maintaining the beam quality of the individual resonators. Laser systems utilizing multiplexed resonators have existed for several decades; however, these systems are bulky and utilize multiple relay reflectors, complicating the optical alignment process.

2. ENABLING TECHNOLOGIES

2.1 QUAD PUMP CHAMBER

The quad pump chamber was designed to minimize spacing between four laser rods. It consists of four independent close coupled diffuse reflector pump chambers integrated into a single housing. Each of the pump chambers are internally equivalent to our single rod pump chamber. With a 4 mm diameter x 130 mm CTH:YAG rods with 35 cm concave ends, the electrical to optical efficiency can exceed 5 percent. For more detailed information, see [1].

2.2 RHOMBOID PRISM

A rhomboid prism, similar to a periscope, is used to combine the beams. The rhomboid prism is rotated about its exit face to combine the output from each individual resonator sequentially. The parallel Total Internal Reflection (TIR) surfaces of the rhomboid prism make it inherently alignment insensitive.

For our experiment, the rhomboid prism was rotated at a constant rotational frequency (f), but the prism could also be stopped or paused on a specific resonator. Since the rhomboid prism is constantly rotating, the beam traces out an arc on the input face which is translated to the output face. The arc length is inversely proportional to the laser pulse duration and the rotational frequency. Ideally, the beam quality of the resultant beam is approximately equal to that of the individual beams.

In our experiment, where each resonator was pulsed sequentially, the combined pulsed repetition frequency (PRF) is the product of the rhomboid prism's rotational frequency and the number of resonators (n).

$$PRF = f * n \tag{1}$$

Since the antireflection (AR) coated rhomboid prism is nearly lossless, the combined average power is the product of combined PRF and the pulse energy (E).

$$P_{avg} = PRF * E \tag{2}$$

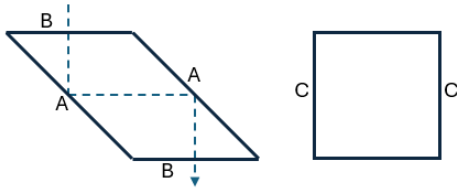

Figure 1 Rhomboid prism for beam combining. Surfaces A are polished TIR surfaces, surfaces B are anti-reflection coated, and surfaces C are ground.

2.3 ROTATIONAL STAGE

The rotary stage provides for constant rotation about the axis of the output beam. For the reported configuration, we used a stepper motor powered rotational stage. This stage could rotate at more than 25 Hz, so the resultant laser repetition rate could be more than 100 Hz. [1]

2.4 QUAD DRIVER

We have developed a Quad Driver that can drive up to four flashlamps synchronously, asynchronously, or simultaneously. The PRF for this experiment is 10 Hz for each resonator. When the four resonators are beam combined, the effective operating rate of the laser is 40 Hz. [2]

3. METHODOLOGY

3.1 OPTICAL SIMPLIFICATION

With the high degree of parallelism of laser rods in the pump chamber assembly, all the resonators were able to use a shared output coupler. After the output coupler was aligned with the first resonator, the other three resonators were aligned by adjusting only their high reflectivity (HR) mirrors. The flat, shared output coupler forces all four of the resonators beams to be parallel to each other. For proper operation of the beam combiner, it is necessary the input beams are parallel. Since the rhomboid prism is relatively insensitive to alignment, it can be mounted using only mechanical tolerancing. Fine alignment was not necessary. [3]

3.2 RHOMBOID PRISM BEAM COMBINER

As previously discussed, with a constant rotational speed, the beam translated from the resonator to the output face of the rhomboid prism will trace out an arc. When the rotary rhomboid prism is used as a sequential beam combiner, the timing of each of the resonators is an integer fraction of the period of the prism. Adjusting the timing individually with a small offset for each resonator allows for compensation for some mechanical tolerances in the housing and rod ends. Empirically, we found that an offset of about ± 1 ms significantly improved the beam overlap, reducing the combined beam diameter. For further details, see [1].

4. RESULTS

4.1 BEAM PARAMETERS

The rotary rhomboid prism is designed to combine the output from each individually pulsed resonator sequentially. In testing, we used a Q4X125 pump chamber with a rhomboid prism coated for 2.13 µm operation. The resonators were typical 40 W CTH:YAG operated at 10 Hz. The output energy of the combined beams is approximately equal to that of

the four individual laser resonators, but at four times the repetition rate. There is a slight drop in efficiency due to the extra cooling requirements for the four resonators as our chiller could not maintain the coolant temperature at full power.

The horizontal M^2 was 27. The vertical M^2 was 28. This is typical for a 40 W CTH:YAG single resonator. The M^2 is relatively high due to the thermal effects in the CTH:YAG rod. This M^2 is adequate for launching into a 200 µm fiber optic with a 0.22 NA.

4.2 TEMPORAL ALIGNMENT

Using the rhomboid beam combiner, the timing of the individual pulses can be adjusted to precisely align each resonator to the combined beam axis. Likewise, the pump pulse width of each pulse can be adjusted to tune the resonators for equivalent output energy. We used a pyroelectric camera for our initial alignment tests, but since this is an expensive diagnostic, we developed an alignment method using a simple aperture for sequencing the timing of the resonators. A 4 mm diameter aperture was placed about 10 cm after the rhomboid prism and the delay for each resonator was adjusted over a few milliseconds. The maximum percentage of energy transmitted through the aperture varied from 75 – 82 percent. As shown in Figure 2, the optimum alignment did not occur at exactly 25 ms intervals. The timing was electronically adjusted over a few ms for optimum timing as illustrated in Figure 3. The difference between the energy output of the resonators was likely due to differences in the gain media.

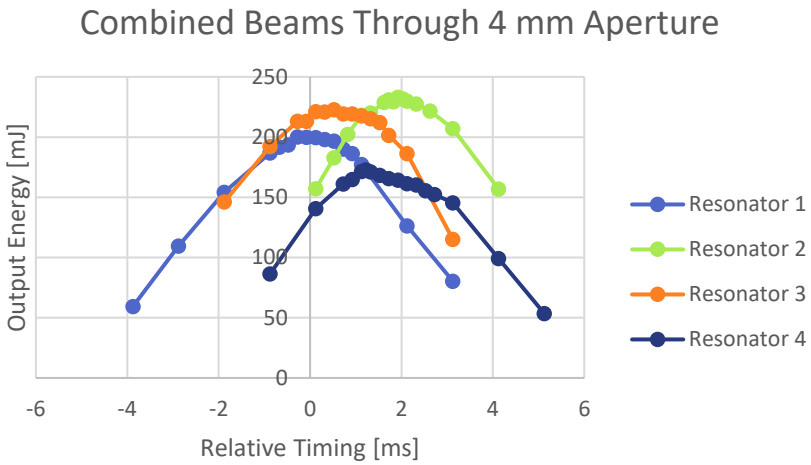

Figure 2 Transmission through the aperture non-adjusted timing(i.e. Resonator 1 at 0 ms, Resonator 2 at 25 ms, Resonator 3 at 50 ms, Resonator 4 at 75 ms).

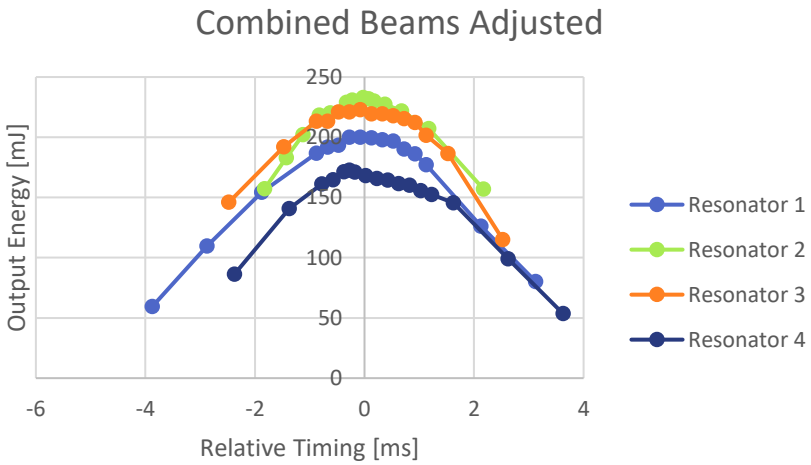

Figure 3 Transmission through the aperture as a function of optimized timing

Timing optimized using the aperture method at low power was almost identical to the optimized timing with the pyroelectric camera at full power. This method of timing optimization is simple and could be used both in the initial setup and during field servicing.

4.3 COMBINED CURVES AT DIFFERENT REPETITION RATES

Once the validation of the beam combining setup as well as the alignment and beam quality of the combined laser output were confirmed, we tested the system at a combined PRF of 40 Hz at 4.5 kW total pump power. At these test parameters, the laser operation was able to reach 200 W with an average output pulse energy of 5 J.

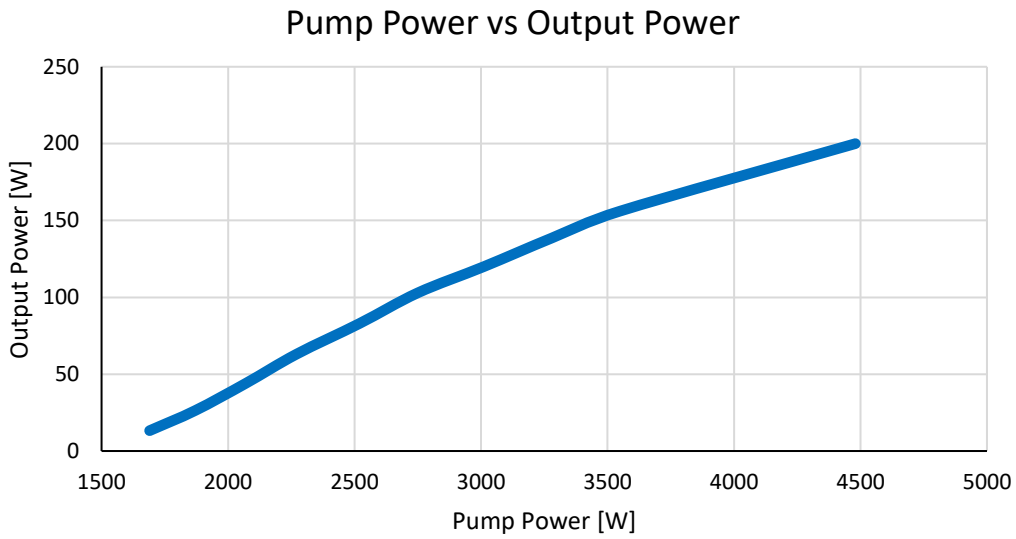

Figure 4 System output power as a function of pump power at 40 Hz.

Some applications require higher PRF's than 40 Hz. To test the beam combiner at repetition rates up to 100 Hz, the rotary stage was modified to rotate at greater than 1500 rpm. The optimum PRF of the individual resonators with the 4 mm diameter x 130 mm rod with 35 cm concave ends is 8 – 15 Hz. At higher repetition rates, the thermal loading caused by the approximately 35 J threshold energy causes extreme thermal lensing and overwhelms the overall efficiency. Nonetheless, we also tested the system at a combined PRF 80 and 100 Hz as shown in Figure 5.

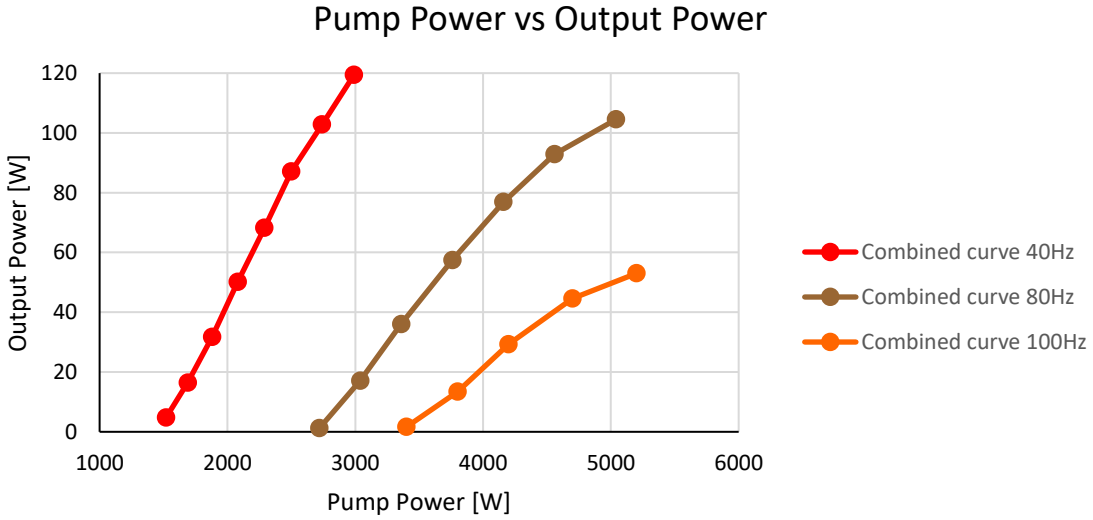

Figure 5 System output power as a function of pump power at 40, 80, and 100 Hz

CONCLUSIONS

In conclusion, we have developed a compact CTH:YAG laser system that has exceeded 200 W of average power at 40 Hz with a peak power of over 10 kW. We have also demonstrated PRFs up to 100 Hz. Enabling technology includes the compact four chamber pump module, the rhomboid prism beam combiner, shared output coupler, the high-speed rotary stage with very accurate positioning, and a four channel flashlamp driver. The entire system utilizes only six optics including 4 high reflectivity mirrors, 1 output coupler, and the rhomboid prism beam combiner. This system eases the optical, electronic and mechanical design of high power and high repetition rate laser systems. This methodology can be scaled to combine a larger number of laser resonators. The combined beam quality and energy are essentially the same as a single laser resonator at a repetition rate four times higher. We believe that this technology will be beneficial for urology as well as many other applications. Future tests include operation at other wavelengths and a multi-wavelength test.

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