Compact Laser Beam Combiner

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ABSTRACT

Solid-state laser resonators' operational repetition rate and average output power are often limited by thermal effects including thermally induced lensing in the gain media. Changes in the average pumping power cause changes in the resonator's stability, which results in changes to the output power, divergence and beam quality. To produce higher repetition rates and/or higher average power systems, laser engineers often combine the outputs of multiple resonators.

We report on the development of a compact method of beam combination using a rotating rhomboid prism. The prism is mounted on a motorized rotational stage and sequentially directs the output from multiple parallel resonators into a single beam. Rhomboid prisms are inherently insensitive to misalignment, so the entire system is very compact, stable, and simple to align. The first several iterations were used for combining four Ho:YAG resonators resulting in a system with a 2.13 μm output of over 200 watts at 40 Hz. Although the methodology was initially demonstrated with Ho:YAG resonators, it is flexible and may be used for combining different types of lasers including multiple wavelengths.

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

1. PRIOR ART

Beam combining techniques can be classified into four broad classes: side-by-side, coherent, spectral, and temporal (multiplexing). [1-2] The so-called side by side method of beam combining utilizes a closely spaced cluster of individual beams. While this approach is simple, the resulting Numerical Aperture (NA) of the resultant combined beams is significantly increased. Flashlamp pumped lasers, such as CTH:YAG are often multimode and operate at their peak gain wavelengths, so coherent and spectral beam combining are not possible. Temporal multiplexing of pulsed resonators is commonly utilized to increase repetition rate and average power while maintaining the beam quality of the individual resonators.

Temporal multiplexing usually involves a beam combiner based on a mechanically moving optic, an acousto-optic, or a similar device. 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 [4-11]. An example of a commercially available multiplexed resonator Ho:YAG laser is illustrated in Figure 1. This system has 17 individual optics.

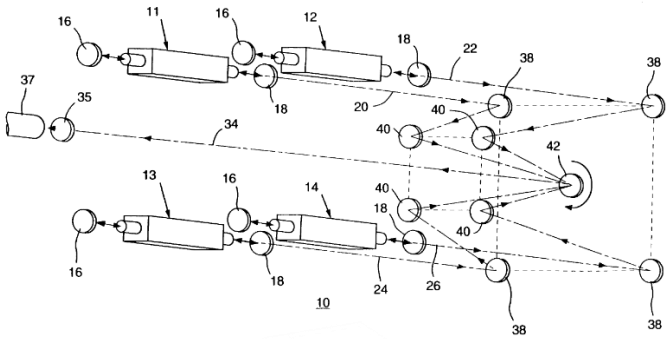

Figure 1 Three-dimensional view of four combined laser resonators

2. DESIGN

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 rod with 35 cm concave ends, the electrical to optical efficiency can exceed 5 percent. The dimensions of the prototype Q4X125 assembly is 40 mm X 57.5 mm X 191 mm. The assembly components were machined on a precision CNC mill, so the parallelism of the rod barrels is better than 3 arc minutes. The operation of each pump chamber is independent; so, the housing can be used with four rods of the same or different gain media with each operating at different parameters (pump energy, repetition rate, pulse duration, wavelength, etc.) The timing of the resonator outputs can be sequentially synchronous, asynchronous, simultaneous, or any combination.

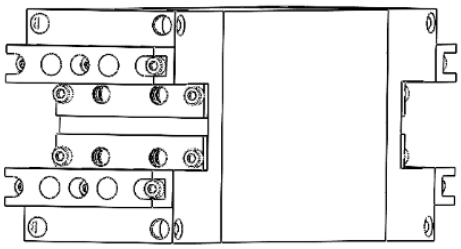

Figure 2 Prototype four chamber laser housing used in experimentation

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 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).

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

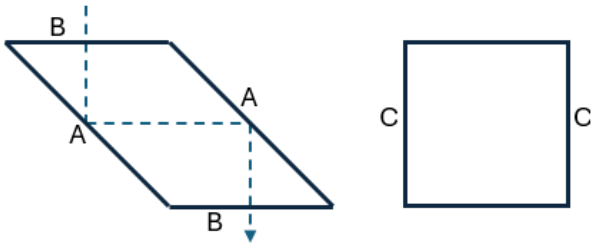

Figure 3 Rhomboid prism for beam combining. Surfaces A are polished TIR surfaces, surfaces B are anti-reflection coated, and surfaces C are ground.

2.3 Rotational Stage

The rotary stage provides for constant rotation about the axis of the output beam. We initially experimented using speed controlled direct current (DC) motors with optical position sensors, but 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. A complete revolution of the rhomboid prism was 64,000 steps, so each step represented about 20 arc seconds. At a rotation rate of 10 Hz, this is about 1.5 µs per step. A step counter was used to determine when the rotational stage was aligned with each resonator.

2.4 Quad Driver

A multiple resonator laser driver was created where the single AC power circuit, HV DC power circuit, safety interlock circuit, microcontroller, diagnostic circuit and energy storage circuit are shared among multiple laser driver outputs, eliminating redundancy. The method of using a single high power HV charging module allows for reduced size, weight, and cost and improves reliability and dependability. Using shared, integrated components improves timing accuracy as external cabling and discrete interface hardware are eliminated. This approach also allows for increased timing control for the multiple resonators used in testing. [12]

3. METHODS

3.1 Rhomboid Prism Beam Centration

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. For the resultant combined beam diameter to be similar to the individual resonator's beam diameters, the arc must be minimized. For a pulse duration (τ), and a rotational velocity (ω), the prism will rotate:

$$\theta = \omega\tau \tag{3}$$

Assuming small angles, the diameter of the combined laser beam, d, is:

$$d = \emptyset + x sin\theta \tag{4}$$

Where $\emptyset$ represents the diameter of the individual laser resonator beams and x is the displacement of the rhomboid prism. We used a laser beam diameter 4 mm, an electrical pulse width of 500 µs, and a rotation rate of 10 Hz (resulting in a combined 40 Hz output). The resultant beam diameter is approximately 4.3 mm.

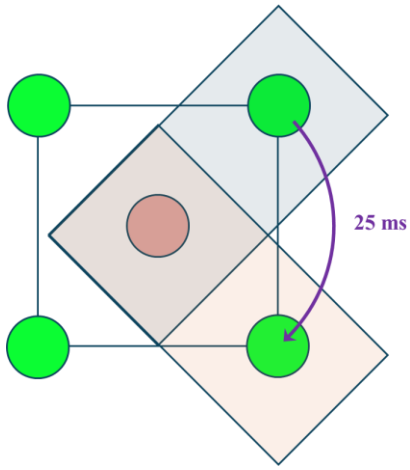

Figure 4 Depiction of rhomboid prism rotating where the green circles represent the gain media, the red circle is the axis of the combined beam. The blue rectangle is the original location of the prism, and the orange rectangle is the translated position of the prism for the subsequent resonator.

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. For example, if the prism is rotating at 10 revolutions per second, and there are four resonators, the timing between each adjacent resonator would be 25 ms. 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.

4. RESULTS

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. As is seen by the graph in Figure 5, 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.

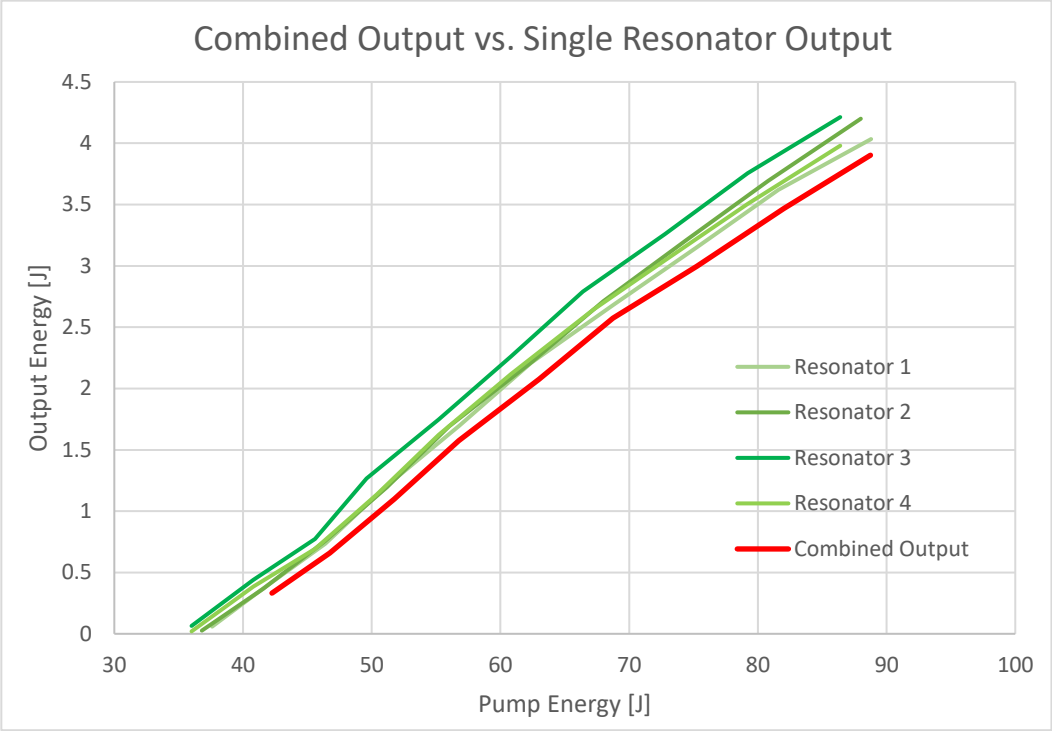

Figure 5 Plot of combined beam output and single resonator output as a function of electrical pump energy

A beam profiler was used to capture the M^2 of the combined beam using a 250 mm lens. The horizontal M^2 was 27. The vertical M^2 was 28. This is typical for 40 W CTH:YAG.

5. CONCLUSION

In conclusion, the compact laser beam combiner is a new method which eases the optical, electronic and mechanical design of a high power and repetition rate laser system. This methodology can be scaled to combine a larger number of laser resonators. The beam quality and energy are approximately that of a single laser resonator. Additional experimentation with shared optics is planned.

ACKNOWLEDGEMENTS

We would like to acknowledge the help we received from Dr. Ramesh Shori for his insights and help with experimentation.

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