2.1 µm Compact Laser with Fiber Launched Output for Urological Applications

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ABSTRACT

For some urological applications such as lithotripsy and Benign Prostatic Hyperplasia (BPH) treatment, high average power and high pulse energy laser emission in the 2 µm spectral region is required. Often, this requires the usage of multiple laser resonators combined to overcome the thermal effects of the CTH:YAG gain media. Beam combining methods can be complicated and difficult to align. Our novel beam combining method, with the use of several enabling technologies, results in a physically and optically compact design capable of reaching high average power. We report on the output of a beam combined laser with 4 independently operating CTH:YAG resonators lasing on the 2.13 µm transition. Each resonator produced approximately 4 J at a repetition rate of 10 Hz, resulting in a combined output of more than 4 J at 40 Hz. We have demonstrated the output of beam combined resonators resulting in an output greater than 120 W through a 600 µm fiber at a 40 Hz repetition rate. We have also demonstrated the ability to launch a laser beam with output power of approximately 60 W through a 200 µm fiber.

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

1. INTRODUCTION

One of the most common solid state laser gain media is CTH:YAG, often referred to as Ho:YAG. 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. A depiction of the energy transfer is shown in Figure 1. A large portion of the flashlamp energy is absorbed by the Cr^{3+} ion. 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. [2] 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, photo-elastic effects and birefringence.

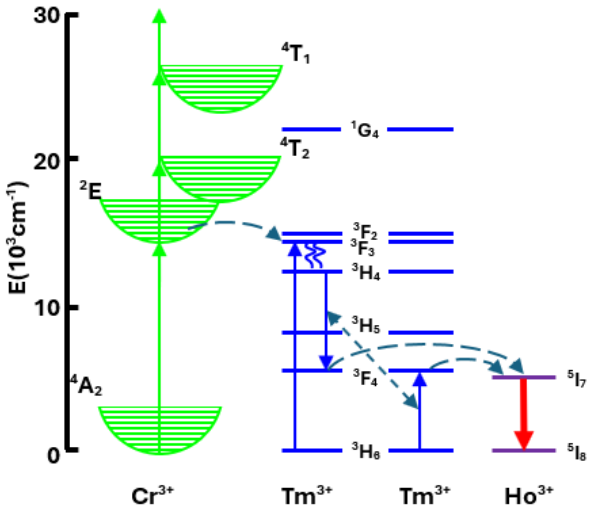

Figure 1. Transition of energy between co-dopants in a CTH:YAG laser, adapted from [1]

Urology is one of the most common applications for solid state lasers. Often, flashlamp pumped CTH:YAG resonators are used, and these resonators are operated with an output energy of up to 4 J with a pulse duration of 250 – 2,000 μs and a repetition rate range of 1 to 30 Hz. CTH:YAG resonators lasing on the 2.13 μm transition have been used for urological applications dating back to the 1990's. [3] As is shown in Figure 2, CTH:YAG has a relatively high optical absorption in water. [4] Since tissue is mainly composed of water, much of the energy produced from the Ho:YAG laser is absorbed superficially, resulting in a controlled method of tissue and stone ablation. [3]

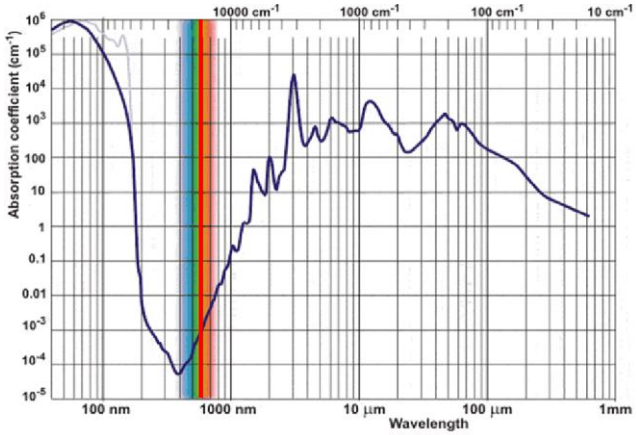

Figure 2 Absorption spectrum of water adapted from [4]

Although CTH:YAG resonators are relatively efficient due to the high absorption of the flashlamp pumping, they suffer from severe thermal effects and are limited in both repetition rate and average power. To produce higher repetition rates and/or higher average power systems, laser engineers often combine the outputs of multiple resonators. Flashlamp pumped CTH:YAG lasers are usually 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. [5-12] An example of a commercially available multiplexed resonator Ho:YAG laser is illustrated in Figure 3. This system has 17 individual optics.

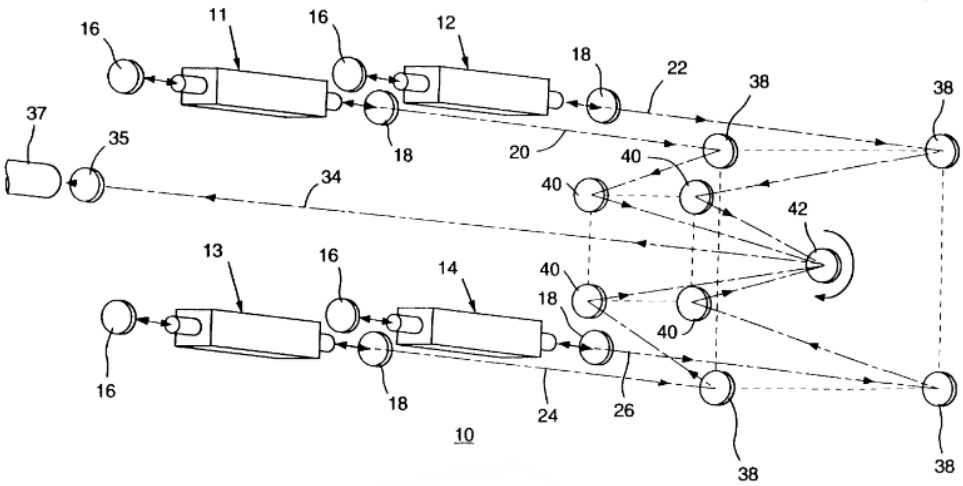

Figure 3 Three-dimensional view of four combined laser resonators

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 [13].

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).

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

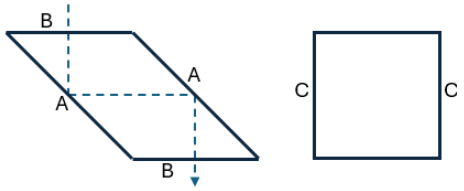

Figure 4 Rhomboid prism for beam combining. Surfaces A are polished TIR surfaces, surfaces B are anti-reflection coated, and surfaces C are ground.

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. [13]

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. [14]

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.

We also attempted to use a shared high reflector. The concentricity of the commercial laser rods was not adequate for the resonators to use both a shared output coupler mirror and shared high reflective mirror. The output of two of the resonators was about 90 percent of each other, but the other two were only about 50 percent. We plan to try a shared high reflectivity mirror again with improved or handpicked laser rods.

Since the rhomboid prism is relatively insensitive to alignment, it can be mounted using only mechanical tolerancing. Fine alignment was not necessary. Figure 5 shows an example setup of a laser resonator with a single shared output coupler.

Figure 5 Multi-pump laser gain media entering a shared output coupler

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. 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 rhomboid 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 ∅ 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.

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 rhomboid 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.[13]

3.3 APERTURE METHOD OF 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. A 4 mm diameter aperture was placed at the position of where the focusing lens will be for launching into the fiber. The timing was adjusted over a few ms to find the optimum timing. [15]

4. RESULTS

4.1 BEAM PARAMETERS

The rotary rhomboid prism is designed to combine the output from each individually pulsed resonator sequentially. 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. This method was tested up to 200 W, but for fiber launching, we limited the output to 160 W. [13]

The horizontal M^2 was 27. The vertical M^2 was 28 (not shown). This is typical for a 40 W CTH:YAG single resonator. Assuming an average of the empirically measured horizontal and vertical M^2, we can use equation 5 (adapted from [17]) to calculate the

maximum allowed beam waist ω at the proximal end of a 0.22 numerical aperture (NA) fiber to be about 85 µm. The beam waist is a radius so the beam diameter, or spot size, at the proximal end of the fiber is approximately 170 µm.

$$\omega = \frac{\lambda \cdot M^2}{\pi \cdot NA} \tag{5}$$

4.2 FIBER OPTIC TESTS

Using a biconvex lens with an Effective Focal Length (EFL) of 15.4 mm, we translated the proximal end of fiber optics with core diameters of 365 and 550 µm across the focused spot and measured the transmitted energy. The beam diameter on the lens was approximately 5 mm, so the NA was approximately 0.16. The beam waist calculated by equation 5 should be approximately 115 µm. Empirically, we found the beam waist to be between 100 and 110 µm as shown in Figures 6 and 7, which is in good agreement with the calculation.

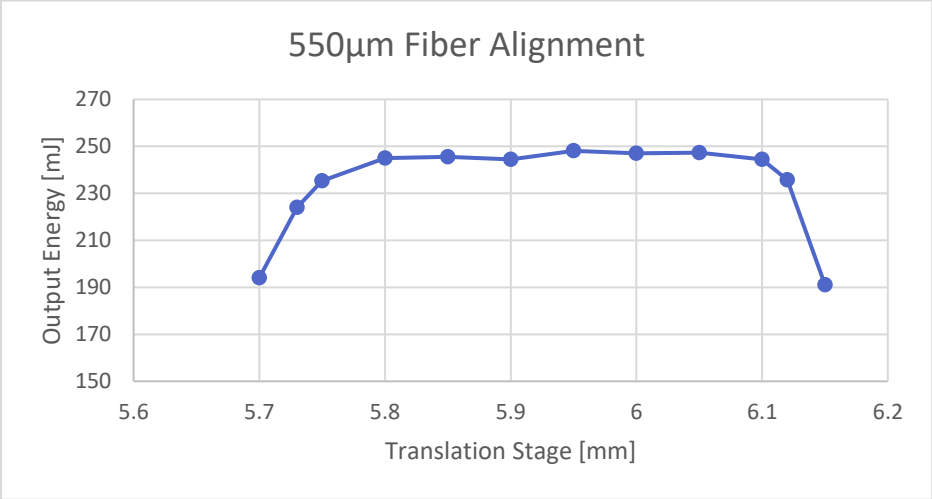

Figure 6 Fiber alignment through a translated 550 µm fiber. Resultant spot diameter is approximately 200 µm

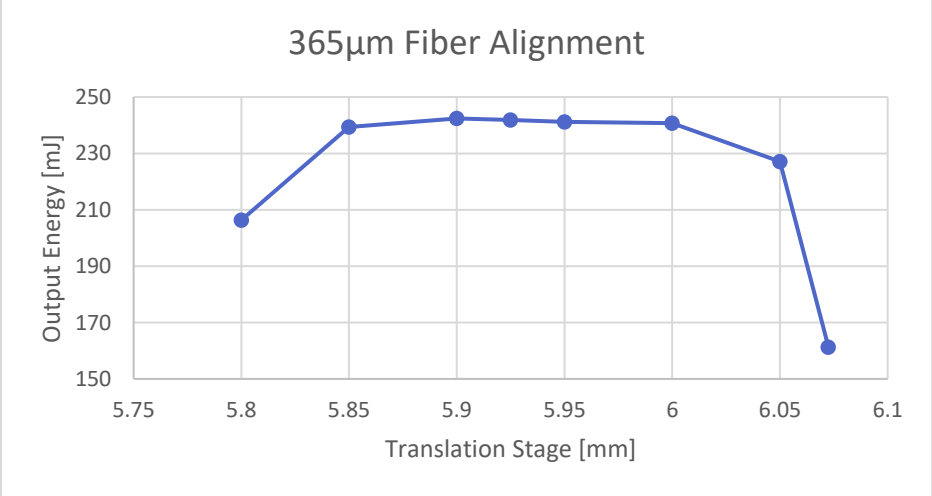

Figure 7 Fiber alignment through a translated 365 µm fiber. Resultant spot diameter is approximately 215 µm

4.3 FIBER LAUNCHING

As seen in [13], the combined beam energy is approximately equal to that of a single resonator, but at four times the repetition rate. As calculated in Equation 4, the resultant beam diameter on the output face of the rhomboid prism was approximately 4.3 mm. The beam diameter on the 15.4 mm EFL lens was approximately 5 mm, so the NA was approximately 0.16.

For the first test, we utilized a 600 µm core diameter fiber. As shown in Figure 8, we were able to transmit 120 Watts without issue. We then switched to a 200 µm core diameter fiber. As shown in Figure 9, we were able to transmit a little over 60 Watts. This was at the thermal limit of the SMA fiberoptic connector. We believe that with a better heat sink, we could easily exceed 60 Watts with the 200 µm fiber. Note that the output through the 200 µm fiberoptic and the 600 µm fiberoptic were the same (61.5 Watts) at a pump power of 2.36 kW.

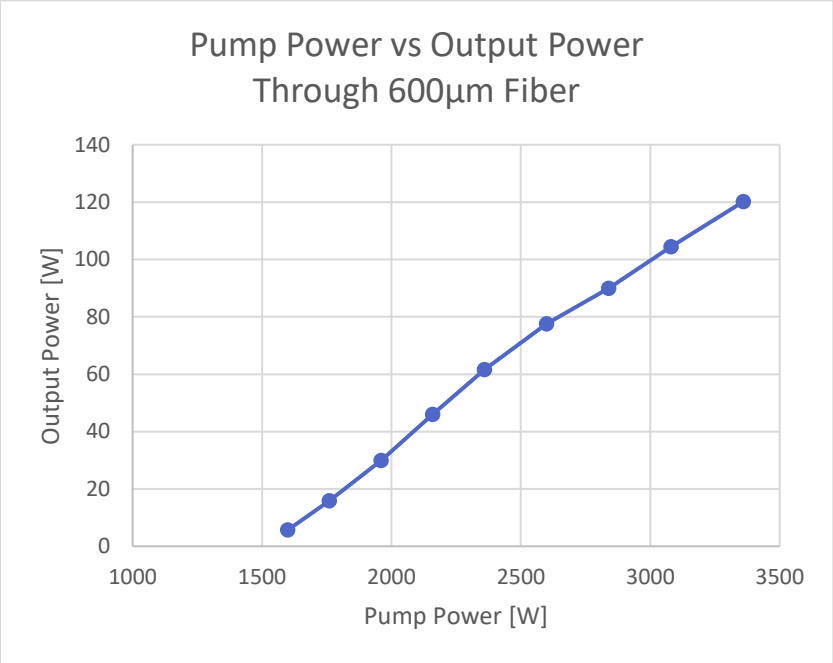

Figure 8 CTH:YAG 2.13 µm Laser power transmitted through a 600 µm core diameter fiberoptic

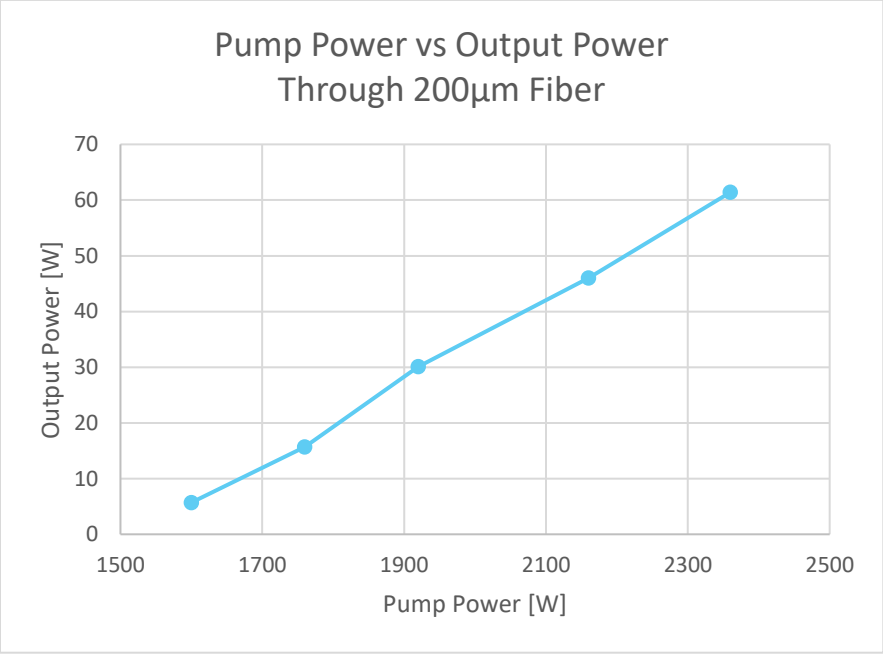

Figure 9 CTH:YAG 2.13 µm Laser power transmitted through a 200 µm core diameter fiberoptic

5. CONCLUSIONS

In conclusion, the compact laser beam combiner is a new method which eases the optical, electronic and mechanical design of a high power and high repetition rate laser systems. 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 at higher repetition rates. Fiber alignment with this method is relatively simple and with minimal losses. We believe that this technology will be beneficial for urology as well as other applications. Future tests include operation at other wavelengths and a multi-wavelength test.

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REFERENCES

[1] G. J. Quarles, A. Rosenbaum, C. L. Marquardt, L. Esterowitz *High Efficiency 2.09/Ltm Flashlamp-Pumped Laser* Appl. Phys. Lett., Vol. 55, No. 11, pp. 1062-64, 11 September 1989

[2] Lei Wang, Chunqing Gao, Mingwei Gao, and Yan Li, *Resonantly pumped monolithic nonplanar Ho:YAG ring laser with high-power single-frequency laser output at 2122 nm*, Opt. Express 21, 9541-9546 (2013)

[3] Sandhu AS, Srivastava A, Madhusoodanan P, Sinha T, Gupta SK, Kumar A, Sethi GS, Khanna R. *Holmium : YAG Laser for Intra Corporeal Lithotripsy*. Med J Armed Forces India. 2007 Jan;63(1):48-51. doi: 10.1016/S0377-1237(07)80109-2. Epub 2011 Jul 21. PMID: 27407938; PMCID: PMC4921716.

[4] Chaplin, M. (n.d.). *The vibrational spectrum of water. London South Bank Universi*ty. Retrieved January 2, 2025, from https://water.lsbu.ac.uk/water/water_vibrational_spectrum.html

[5] Barr, O. C., *Optical Combined/Distributor Using V-Shaped Mirror Assembly*. (1979). U.S. Patent No. 4,154,507. U.S. Patent and Trademark Office. https://patents.google.com/patent/US4154507

[6] Weis, J. (1981). *Beam Combiner*. (U.S. Patent No. 4,283,116). U.S. Patent and Trademark Office. https://patents.google.com/patent/US4283116

[7] Verdeyen, J. T., & Toliver, G. A. (1975). *Method and apparatus for sequentially combining pulsed beams of radiation* (U.S. Patent No. 3,924,937). U.S. Patent and Trademark Office. https://patents.google.com/patent/US3924937

[8] Chen, S., Yang, P., Wang, Z., Wu, Y., Feng, G., Yan, Y., Wu, J., & Xie, X. (2021). *Rotating shaft reflection type pulse laser beam combiner and pulse beam combining laser system* (China Patent No. CN109212743B). Chinese Patent Office. https://patents.google.com/patent/CN109212743B

[9] Saadatmanesh, V., & Loeb, M. P. (1995). *Multi-head laser assembly* (U.S. Patent No. 5,387,211). U.S. Patent and Trademark Office. https://patents.google.com/patent/US5387211

[10] Bowers, P. L., & Levin, M. L. (1991). *Gatling gun laser pulse amplifier using rotating mirrors* (U.S. Patent No. 4,998,259). U.S. Patent and Trademark Office. https://patents.google.com/patent/US4998259

[11] Burkhalter, J. H. (1967). *Sequentially firing array of laser units* (U.S. Patent No. 3,310,753). U.S. Patent and Trademark Office. https://patents.google.com/patent/US3310753

[12] Hodson D/ R., Massie N. A.,*Rotating Mirror Beam Combiner or Splitter.* (1981). GB Patent No. 2074341A. British Patent Office. https://patents.google.com/patent/GB2074341A

[13] Hamlin, S. J., Hart, B., Charpentier, A., Hardy, C., Likins, A. (2025). *Compact Laser Beam Combiner* (Paper No. 13341-61). In Proceedings of SPIE Photonics West Conference 13341, San Francisco, CA.

[14] Hamlin, S. J., Hardy, C., Younis, W., & Charpentier, A. (2025). *Quad flashlamp driver* (Paper No. 13341-62). In Proceedings of SPIE Photonics West Conference 13341, San Francisco, CA.

[15] Hamlin, S. J., Hart, B., Charpentier, A., Hardy, C., Likins, A. (2025). *200 W compact 2.1 um CTH:YAG laser* (Paper No. 13341-9). In Proceedings of SPIE Photonics West Conference 13341, San Francisco, CA.

[16] Paschotta, R. (2013, November 12). *Beam quality limit for multimode fibers*. Retrieved January 16, 2025, from https://www.rp-photonics.com/spotlight_2013_11_12.html

[17] W. Koechner, *Solid State Laser Engineering*, 6th Edition, Springer, New York, 2006.