200W output power at 10ps from a scalable Z-slab Nd:YAG laser

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ABSTRACT

We demonstrate power scaling of an Nd:YAG picosecond master oscillator power amplifier system to over 200 W. The ‘z-slab’ amplifier design is a power scalable, edge-pumped zigzag slab amplifier architecture, and it is demonstrated here in two alternative multi-stage implementations at 1064 nm using a picosecond seed laser. In a simple design, an average power of 225 W was generated with up to 450 µJ pulse energy at 11 ps pulse duration. In a compact multi-pass design, 150 W was generated with $M^2 < 1.75$.

Keywords: Picosecond, ultrafast, high-power, slab, zigzag, z-slab.

1. INTRODUCTION

There has recently been much interest in high-power ultrashort pulse lasers for use in micromachining. Using high-energy picosecond or femtosecond lasers, ablation dominates over heating, leading to cleaner and more efficient machining[1,2]. Moreover, intense ultrashort lasers facilitate micromachining by the process of electrical breakdown in materials that would otherwise be transparent to the laser light, such as glass. High pulse energy (~100 µJ) and near diffraction limited beam quality are often required for such applications, while increasing average powers are being sought in order to increase processing speed.

The common approach to generating high power picosecond pulses is to use a modelocked oscillator together with a pulse picker and power amplifier. With such short pulse lengths, pulse energy is often limited by the onset of nonlinear effects such as critical self-focusing. This places extra restrictions on the design of the amplifier, which must be designed to keep the B-integral within safe values. Three popular amplifier geometries for low-M^2, high-power scaling are fiber, thin disk and slab. Fiber amplifiers are capable of achieving very high average powers with diffraction limited beam quality, but can suffer from strong nonlinear effects with pulsed lasers due to their small core area and long propagation length. Chirped pulse amplification can overcome these effects to an extent[3], but high energy scaling is limited. Thin disk amplifiers on the other hand have the advantage that the extremely short length of the gain medium coupled with the large beam cross section means that they are less limited by nonlinear damage mechanisms, and capable of reaching over 200 µJ pulse energy with picosecond or subpicosecond pulse durations[4,5]. However, their low gain is not ideally suited to amplification of typically low-power picosecond seed lasers, and they often require regeneration or many passes through the amplifier to achieve the gain levels required.

Although their power scalability is arguably more limited than fiber and thin disk, slab lasers offer potential advantages for picosecond amplification. The gain of slab lasers can be reasonably high, and scaling of ultrashort pulse lasers to the multi-hundred watt level with low M^2 has been demonstrated with the Innoslab design[6,7]. In addition, nonlinear effects are substantially weaker than in fiber lasers, and there is some freedom for adjusting the mode size and propagation distance.

In this paper we present a demonstration of high-power scaling of picosecond lasers using the ‘z-slab’ amplifier design. The z-slab is a modular amplifier based on the established zigzag design, in which the laser beam makes multiple zigzag

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bounces within the slab. By spatially averaging over the slab's thin dimension, the effects of thermal gradients along this axis are strongly suppressed, resulting in high potential for power scaling. Indeed, it has been shown that zigzag lasers can be scaled to multi-hundred watt levels with good beam quality[8-11]. Additionally, the z-slab design is based on well-established solid-state laser technology, making it a good choice for commercial MOPA systems.

Two alternative z-slab amplifier designs are demonstrated here: a long slab used in a single-pass configuration, and a shorter, multi-pass slab. The long slab was optimized as a scalable high-power, high-energy amplifier, whereas the multi-pass shorter slab was designed for improved beam quality and minimization of nonlinear effects.

2. LONG Z-SLAB AMPLIFIER

2.1 Experimental set-up

The long z-slab amplifier, shown in fig. 1, is a high aspect ratio zigzag slab of 1 at.% doped Nd:YAG. The slab was edge pumped through the two long side faces, and cooled through the two large top and bottom faces. The large area of the cooling faces together with the thinness of the slab helped to achieve efficient removal of heat. The laser beam entered and exited through the small end faces, which were Brewster cut, causing the beam to make many bounces on its path through the slab. The slab was pumped at 885 nm by a pair of diode arrays, arranged one on each side in a staggered arrangement as shown in fig. 1. Light from the arrays was focused along the fast axis to create a pump waist size matched to the thickness of the slab. The pump faces were partially coated such that one half of each pump face was antireflective (AR) at 885 nm while the other was highly reflective (HR). Thus the pump light made two passes through the slab. As well as increasing the amount of absorbed power, this helped to ensure a more uniform distribution of gain and heat within the slab.

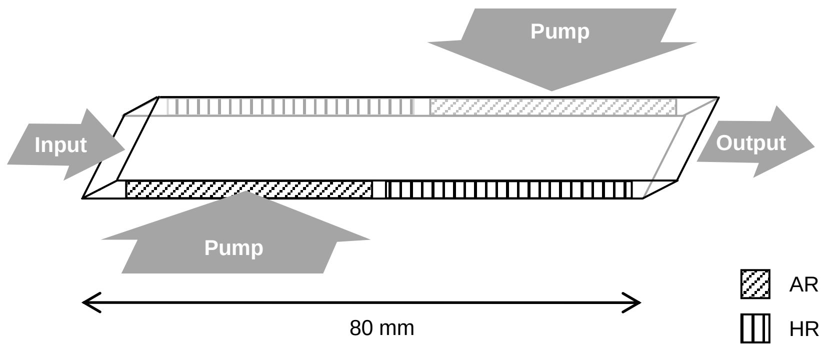

Figure 1. Schematic of long z-slab amplifier.

Three z-slab modules were combined in a linear amplifier chain as shown in fig. 2. The output from the seed laser was re-shaped using cylindrical optics to produce a highly elliptical beam to overlap well with the gain region in the amplifier, and relay optics were used to couple the beam between successive amplifier stages.

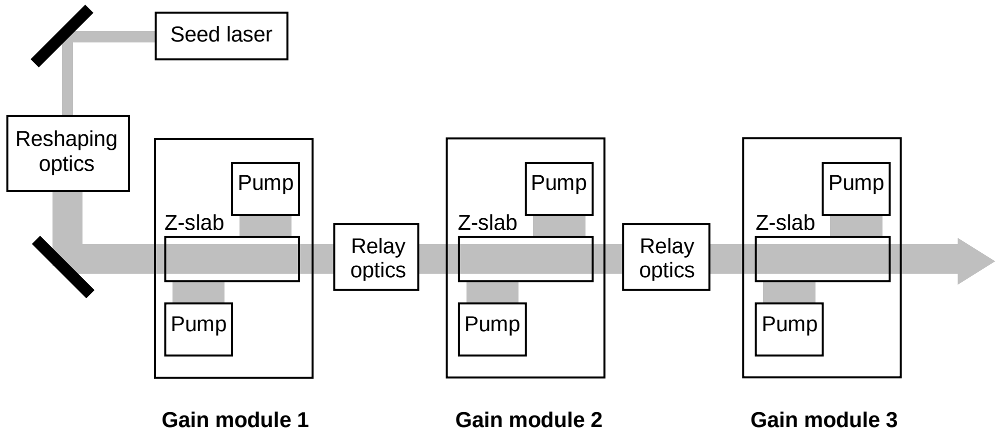

Figure 2. Layout of amplifier chain.

2.2 Results

In this experiment, a 40 W picosecond laser was used as the seed laser. Up to 225 W was obtained from this system, and the output power as a function of total absorbed pump power is shown in fig. 3. The seed laser was operated at a repetition rate of 500 kHz, and the maximum energy achieved was 450 μJ. One reason why this design was able to produce high energy is that the area of the input beam was large, which gave it a relatively high energy damage threshold. The energy was limited to this level by self-focussing in the laser crystal. Under amplification the beam quality was multimode with $M^2 < 5$.

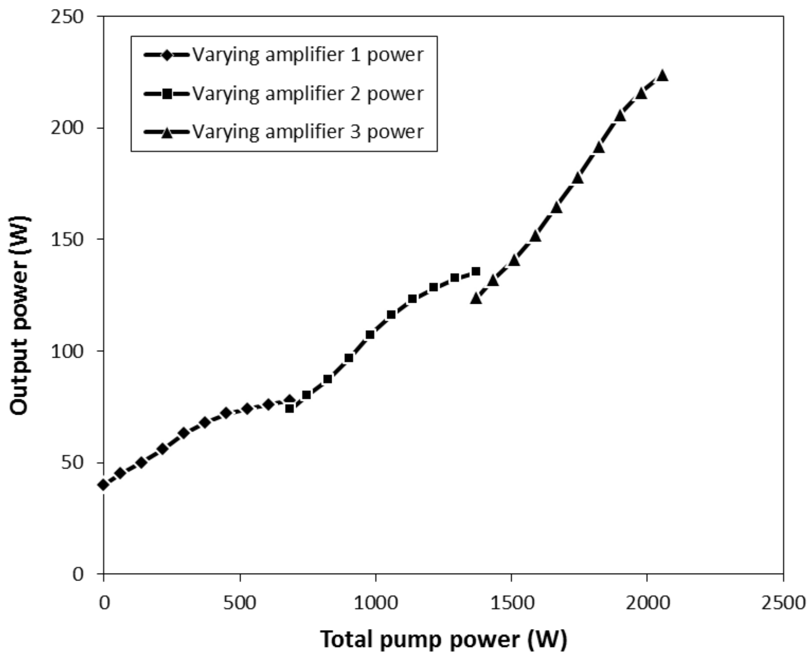

Figure 3. Output power vs. total absorbed pump power for three-stage picosecond amplifier system using long single-pass z-slab amplifier. The amplifiers were turned on in sequence, with previous stages left at full power. The graph shows the power measured at the output of each successive amplifier stage.

The pulse duration was measured with an autocorrelator, and the autocorrelation plot is shown in fig. 4. Under amplification, the pulse duration was found to be 10.7 ps, compared with 9.8 ps for the seed laser alone, indicating a small amount of pulse stretching in the amplifiers.

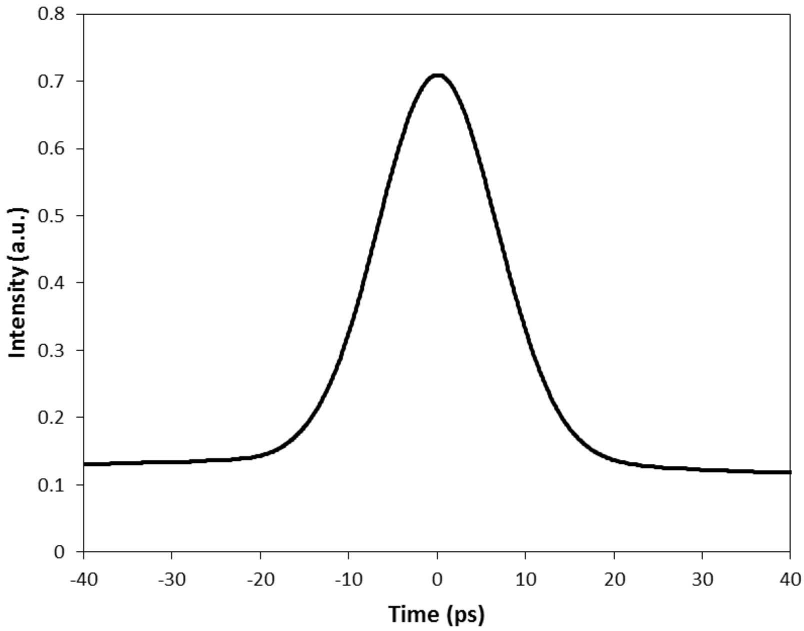

Figure 4. Autocorrelation plot at an output power of 225 W. From these data the pulse duration was calculated to be 10.7 ps.

3. MULTI-PASS Z-SLAB AMPLIFIER

3.1 Experimental set-up

The compact multi-pass z-slab, shown in fig. 5, was designed as an alternative to the amplifier described in the previous section. As above, the slab was made of 1 at.% doped Nd:YAG with Brewster cut end faces, but it was significantly shorter and thicker. The beam path was folded by two mirrors placed close to the slab such that the beam made multiple spatially-separated passes through the amplifier. Thus, instead of the beam being elliptically shaped to match the gain region, the beam was simply passed multiple times through the slab in order to fill it. Although this led to a less perfect spatial overlap with the gain, it did not require the beam to be highly elliptical. The smaller beam cross section also decreased the power required to saturate the amplifier, which made it more efficient to use with low power seed lasers. The shorter, thicker dimensions helped to keep the B-integral low despite the smaller beam cross-section.

Moreover, the folded beam introduced a spatial averaging effect along the width of the slab. One of the issues with edge-pumped zigzag slab lasers of this type is that the exponential absorption of the pump creates gradients in the gain and thermal profiles perpendicular to the zigzag plane, which the zigzag path cannot eliminate[11]. In this design, spatial averaging occurs along both transverse axes, with the intended effect of substantially reducing overall beam degradation.

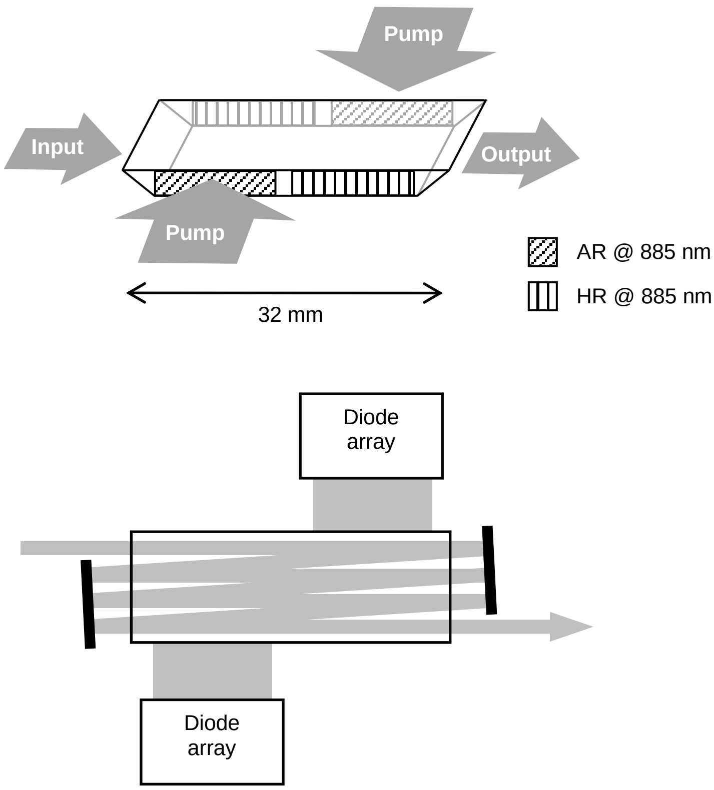

Figure 5. Schematic of compact multi-pass z-slab amplifier, showing pumping scheme and multi-pass configuration.

The amplifier chain consisted of three amplifiers. In the first two amplifiers the laser beam made seven passes through the amplifier and in the third amplifier it made five passes. The output from the seed laser was re-shaped using a simple telescope to give a beam size of 800 x 800 μm at the input to the first two amplifiers, and 800 x 1200 μm in the third. More passes were used in the first two amplifiers in order to keep the beam size smaller and reduce the effective saturation power, thus improving the efficiency when used with a low-power seed laser. The number of passes was in practice limited by the expansion of the laser beam due to divergence (which the short length of the slab helped to minimize). More passes could be achieved with a more complex optical setup.

A seed laser with an average power of 4.5 W was used for this experiment. As with the system in section 2, the pulse duration of the seed laser was 10 ps.

3.2 Results

Up to 150 W average power was obtained from this system. Figure 6 shows the output power as a function of the total absorbed pump power. It can clearly be seen that the amplifiers became more efficient as the power increased. The amplifiers were added in sequence, so the discontinuities in the curve represent a 10-15% transmission loss caused by passing through each additional stage. This loss was partly caused by imperfect optical coatings on the folding mirrors, as well as some slight clipping in the vertical axis. The total optical-to-optical efficiency of the system was 17%. This will be improved by making use of a high power seed laser as well as optimized beam shapes and more passes in the amplifiers.

By limiting the repetition rate and hence the energy of the seed laser, the energy of the amplified beam was intentionally limited to 100 μJ as a precaution to avoid damage due to nonlinear effects. No damage was observed in any of the amplifier crystals up to this pulse energy.

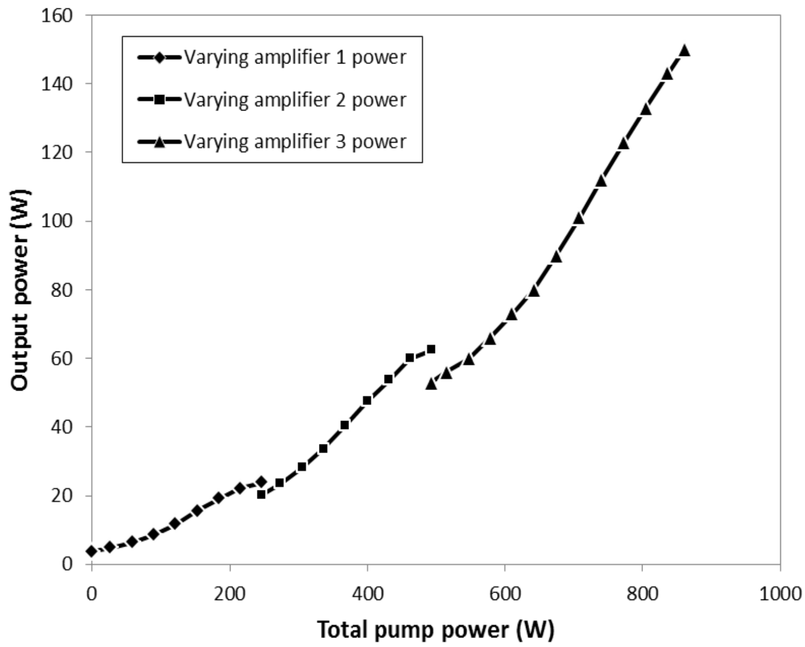

Figure 6. Output power vs. total absorbed pump power for three-stage picosecond amplifier system using short multi-pass z-slab amplifier. The amplifiers were turned on in sequence, with previous stages left at full power. The graph shows the power measured at the output of each successive amplifier stage.

The M^2 at 150 W output power was measured to be $M^2 < 1.75$, which demonstrates the improvement in beam quality caused by spatial averaging in the multi-pass arrangement. By spatially averaging along both axes transverse to the propagation direction, the multi-pass z-slab represents an advance over some other edge-pumped architectures, which usually suffer beam degradation along at least one transverse axis. By further optimization of the coupling optics and number of passes though the slab, we believe that improvement of the beam quality and further scaling of the power are possible with this amplifier design.

4. CONCLUSION

We demonstrated power scaling to the multi-hundred watt level with an Nd:YAG picosecond master oscillator power amplifier system. The ‘z-slab’ modular amplifier design, based on an edge-pumped zigzag slab architecture, was introduced, and was demonstrated in two different multi-amplifier set-ups.

In the first implementation a long, high aspect ratio z-slab amplifier was demonstrated, producing up to 225 W from a 40 W picosecond seed laser. A maximum energy of 450 μJ was demonstrated in the system, showing the potential of the z-slab design to produce high power, high energy picosecond pulses.

The second implementation made use of a more compact slab in a folded set-up, whereby the laser beam made multiple spatially-separated passes through the amplifier. Up to 150 W was obtained with this design from a 4.5 W seed laser with $M^2 < 1.75$. By spatially averaging the beam in both the horizontal and vertical axes, the multi-pass z-slab overcame one of the drawbacks of edge pumping, without requiring the use of a complex pump delivery scheme.

The z-slab design was shown to be a promising candidate for high power scaling of picosecond lasers. Based on well-established Nd:YAG solid state laser technology, it is straightforward to implement. No hard limit has yet been reached in terms of average power, and with further optimization it is believed that kW class powers with a good beam quality are achievable.

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