Q-switched diode pumped Nd:YAG rod laser with output power of 420W at 532nm and 160W at 355nm

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ABSTRACT

Intra-cavity harmonic generation in diode-pumped Q-switched Nd:YAG rod lasers is a preferred architecture to generate high output power at 532nm and 355nm in multimode operation. We have developed a side-pumped, dual rod Nd:YAG laser with intra-cavity second harmonic generation using Type II LBO in a double-pass configuration. A maximum 532nm output power of 420 W was achieved at 10 kHz with an M^2 of about 24. The pulse duration was 70 ns with a pulse energy stability of less than 0.7% rms. By incorporating a novel birefringence compensation technique and adding a Type II LBO sum frequency generator, we attained 160W of 355nm output at a repetition rate of 8 kHz with an M^2 of 18 and a pulse duration of 45 ns.

Keywords: Diode-pumped Nd:YAG laser, Q-switching, harmonic generation, intra-cavity doubling, intra-cavity tripling

1. INTRODUCTION

Over the last ten years, the output power of Q-switched DPSSLs emitting in the green (514 - 532 nm) and in the ultraviolet spectral range (343 - 355 nm) has increased by more than one order of magnitude due to the advent of reliable high power diode bars, the improvement in the quality of nonlinear crystals (LBO) and the decrease of thermal effects in the gain media. Average output powers in excess of 400W at 532nm [1] and 125W at 355nm [2,3] have been reported in transverse multimode operation at repetition rates around 10 kHz. In TEM_{00} mode operation, output powers of greater 130W [4] and 80W [6] at 532nm and 355nm, respectively, have been generated.

Commercial diode-pumped TEM_{00} mode solid state lasers emitting at green and UV wavelengths have found numerous uses in a variety of industrial applications such as via-hole drilling, wafer scribing and dicing, IC package singulation, memory repair, solar cell manufacturing (Table 1). Most of these applications require Q-switched operation with pulse energies of 50 to 200 µJ and repetition rates between 10 and 200 kHz. Early industrial applications of UV lasers were limited to those requiring low power (<500mW) or low pulse energy (<50 µJ); such as stereo-lithography and small hole drilling in dielectric materials.

Wavelength	Application	Average Power	Beam Quality M^2	Repetition Rates	Pulse Duration
355nm	memory repair	0.4 - 1.0 W	< 1.3	100 - 200 kHz	< 10 ns
355nm	stereolithography, wafer marking	0.5 - 5 W	< 1.3	30 - 70 kHz	6 - 25 ns
355nm	flex circuit via drilling	8 - 12 W	< 1.3	20 - 40 kHz	40 - 80 ns
355nm	flex circuit via drilling	15 - 28 W	< 1.3	80 - 120 kHz	25 - 40 ns
355nm	PCB via hole drilling	10 - 28 W	< 1.3	80 - 120 kHz	25 - 55 ns
355nm	wafer scribing/dicing	2 - 8 W	< 1.3	250 - 300 kHz	< 90 ns
355nm	thin film pattering, lithography	100 W	< 20	10 - 25 kHz	> 50 ns
532nm	solar cell scribing	5 - 10 W	< 1.3	30 - 80 kHz	40 - 80 ns
532nm	IC package singulation	30 - 45 W	< 1.3	100 - 150 kHz	50 - 100 ns
514nm	silicon annealing	> 80 W	< 5	5 -15 kHz	200 - 600 ns
532nm	silicon annealing	> 100 W	< 30	5- 10 kHz	> 150 ns
532nm	silicon drilling	> 100W	< 30	5-10 kHz	< 100 ns
532nm	Ti:sapphire pumping	30 - 90 W	< 30	1 - 10 kHz	< 200 ns

Table 1 Applications of diode-pumped Q-switched solid state laser in the green and UV spectral range.

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In recent years, applications in wafer dicing and scribing have emerged that require high repetition rate operation (>200kHz) with pulse energies of greater 20µJ, a power specification that requires utilization of UV lasers that would be capable of generating greater 20W of UV power at lower repetition rates (~100 kHz). There is also an emerging interest in high power multimode UV lasers to potentially replace excimer lasers in lithography. Figures 1 and 2 show the evolution of average power for Q-switched UV and green DPSSLs over the last decade. In the green wavelength range (514-532nm), TEM_{00} mode output powers have exceeded 70W [14] and 130W with MOPA configurations with one or more amplifiers, respectively. In multimode operation, 100W for side-pumped Nd:YLF, 150W for Yb:YAG disk lasers, and 200W for side pumped Nd:YAG lasers have been achieved, with all of these system using intra-cavity frequency doubling in LBO. Industrial applications of these multimode green lasers are semiconductor annealing, thin film removal, and more recently solar cell manufacturing.

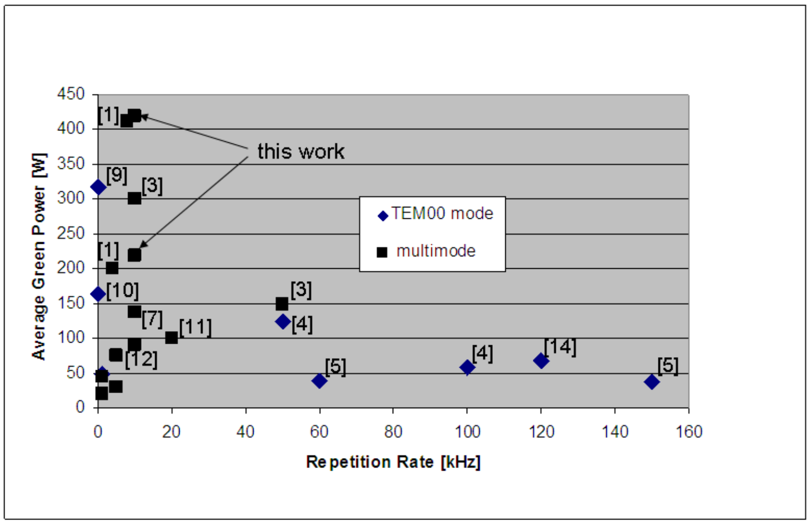


Fig. 1. Reported average power of Q-switched green DPSSLs in TEM_{00} mode and in multimode operation. See list of references.

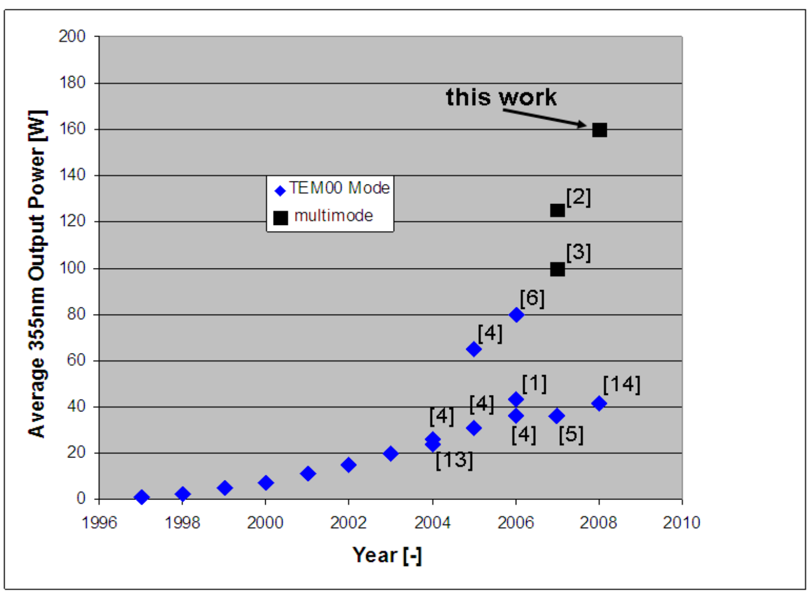


Fig. 2. Reported average power of Q-switched UV DPSSLs in TEM00 mode and in multimode operation. See list of references.

2. DUAL ND:YAG ROD LASER

We have developed a side-pumped Q-switched, dual rod Nd:YAG laser system to address the growing need for high power infrared, green and UV power for flat panel and solar-cell processing as well as for lithography. Each gain module consists of a 169 mm long Nd:YAG rod, that is pumped by six linear arrays with 5 bars each. The six arrays are arranged in a six-fold symmetry, similar to the pump architecture reported in [15]. The bars are soldered to a water-cooled copper heat sink which enables utilization of distilled cooling water. This is a major advantage compared to micro-channel cooled bars which require PH-controlled, DI cooling water and small-particle filters. The rod dimensions and doping concentration as well as the pumping geometry was optimized to generate a flat-top transverse gain profile and low thermal lensing. The specified optical pump power per gain module is 1.35kW. Figure 3 shows the measured output power and emission wavelength as a function of operating time for ten arrays at the specified output of 225W. The long lifetime of these arrays ensures operation of the gain modules for several years. Each gain module was characterized in cw operation in a short flat-flat resonator with a cavity length of 0.3m and an output coupling transmission of 50%. A maximum output power of 550W was achieved at a pump power of 1.4kW, with a slope efficiency of 53%.

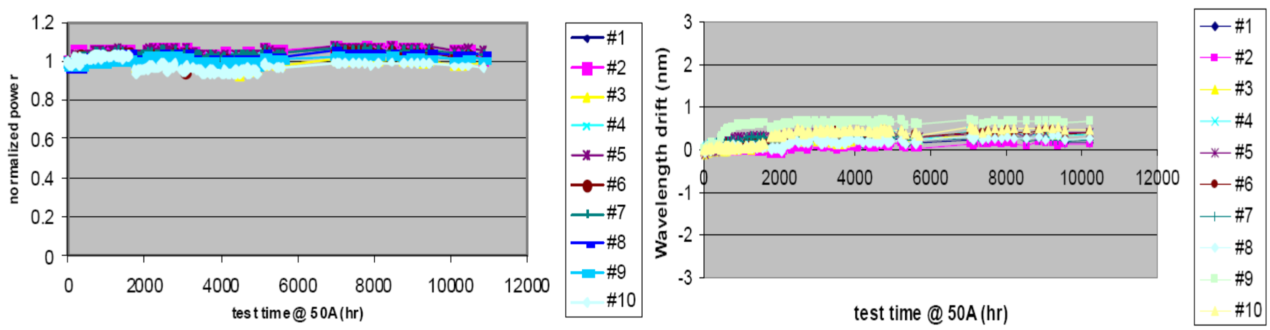


Fig. 3. Measured output power and peak emission wavelength of ten linear arrays over a time period of 10,000 hours.

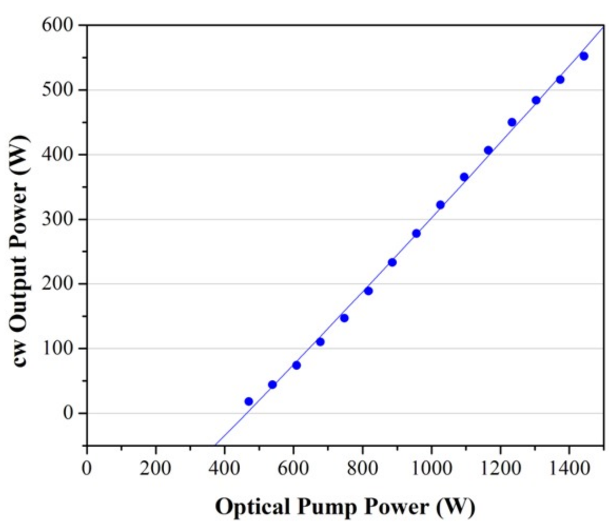


Fig. 4. Measured output power in cw operation of one gain-module in a short flat-flat resonator as a function of optical pump power (50% output coupling).

The two gain modules were arranged in a symmetric flat-flat resonator with two dual-channel AOMs and a 50% output coupler (Fig.5). The geometrical resonator length of 1.5m was chosen to generate a beam quality of well below M^2=20 at the highest pump power. At 10 kHz and a pump power of 1.29kW per gain module, a maximum, non-polarized, output power of 630W was measured with a pulse duration of 70 ns and a pulse energy stability of 0.4% rms.

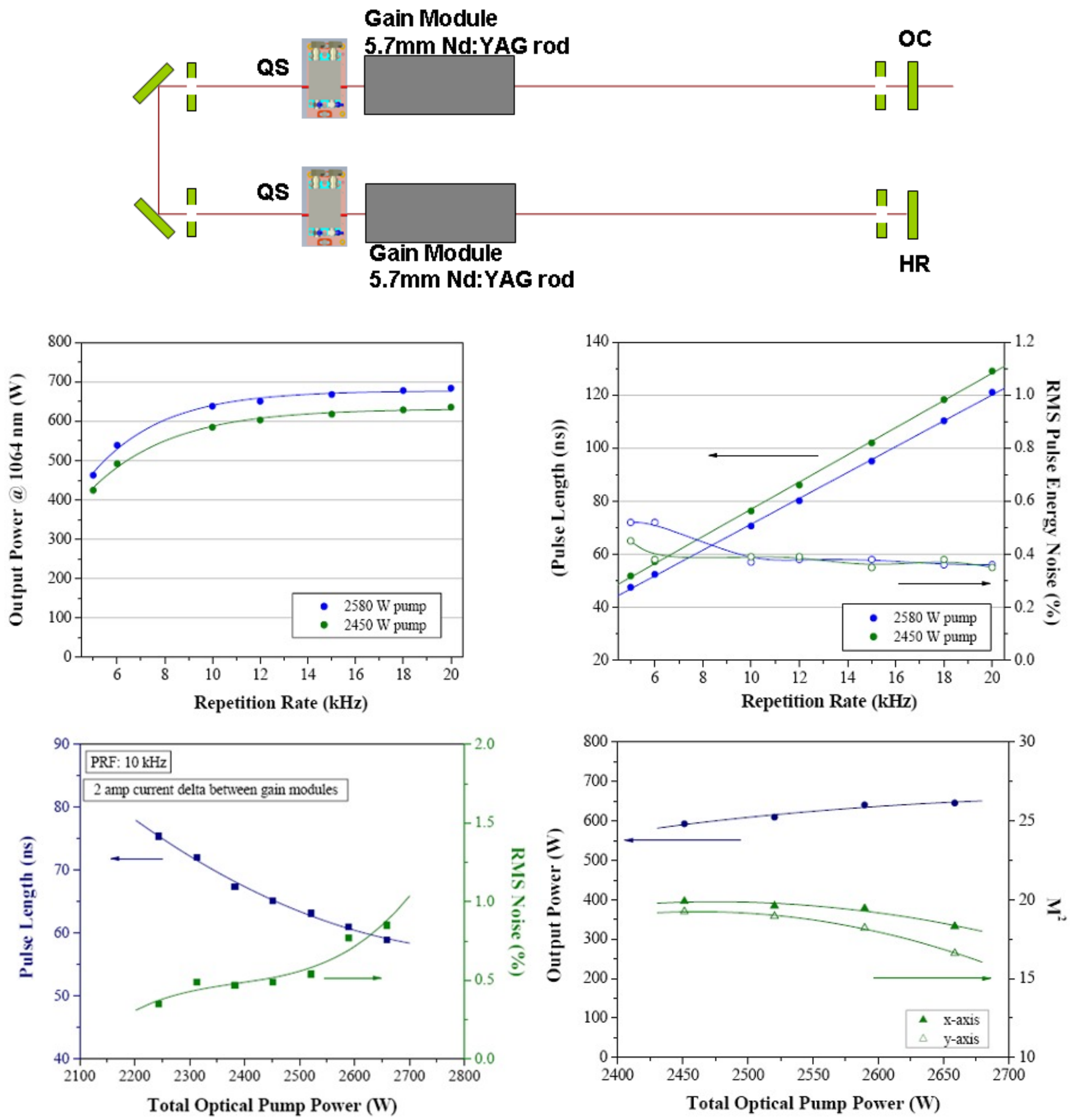
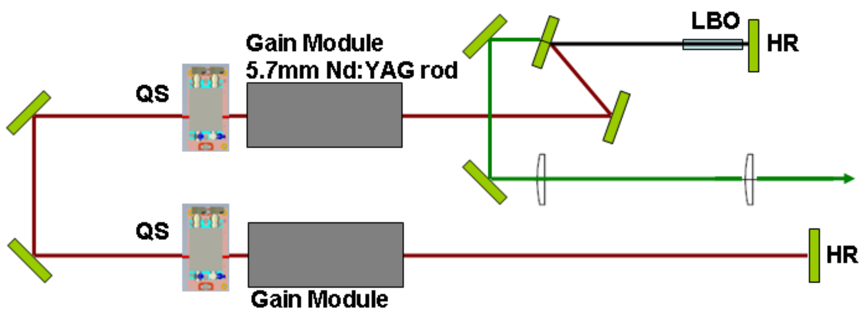


Fig. 5. Measured output power, pulse duration and energy rms noise in Q-switched operation as a function of the repetition rate (top). Measured pulse duration, rms pulse energy noise and M^2 values versus the optical pump power is shown at the bottom for 10 kHz operation. The cavity layout is shown at the top.

3. DUAL ND:YAG ROD LASER WITH HARMONIC GENERATION

We decided against using birefringence compensation with a quartz rotator to generate linearly-polarized light, because even with imaging of the rods we observed a decrease of the output power by more than 10 percent. Instead we used a Type II LBO for frequency doubling, whose phase matching angle and nonlinear coefficient are high enough for intra-cavity doubling in a Q-switched multimode infrared laser. By using a 20mm Type II LBO in an intra-cavity double-pass configuration with an infrared beam diameter of 2mm inside the crystal, a maximum 532nm output power of 420 W was measured at a repetition rate of 10 kHz and a total optical pump power of 2.6 kW. The pulse duration was 70 ns with a pulse energy stability of less than 0.7% rms. At the maximum output power, the beam quality at 532 nm was measured to be M^2=24 in the x- and the y-direction. We found the beam quality at 532nm was typically 30% lower as compared to the infrared beam, a behavior that seems to be caused by saturation in the LBO. By lowering the pump power, we observed that the relative beam quality difference decreases gradually until no difference in beam quality is observed at green power levels of less than 50W. A lifetest has been running for 6,500 hours at 360W of output power and no degradation of the LBO has been observed. However, in order to guarantee service-free operation for at least 2 years, we have implemented a motorized LBO-shifter that allows automated access to different LBO spots, if required.

Some annealing applications require a homogenous line beam with line widths of less than 20 microns with line lengths of greater 100mm. For this application, it is necessary to generate a low-M^2 output beam in one direction, while a high M2 is maintained in the perpendicular direction. By using a modified resonator configuration, we were able to generate an asymmetric, low-M^2 output beam with M^2 of 22 in the horizontal direction and an M^2 of less than 10 in the vertical direction. The maximum 532nm output power of the asymmetric beam was 220 W at 10 kHz.



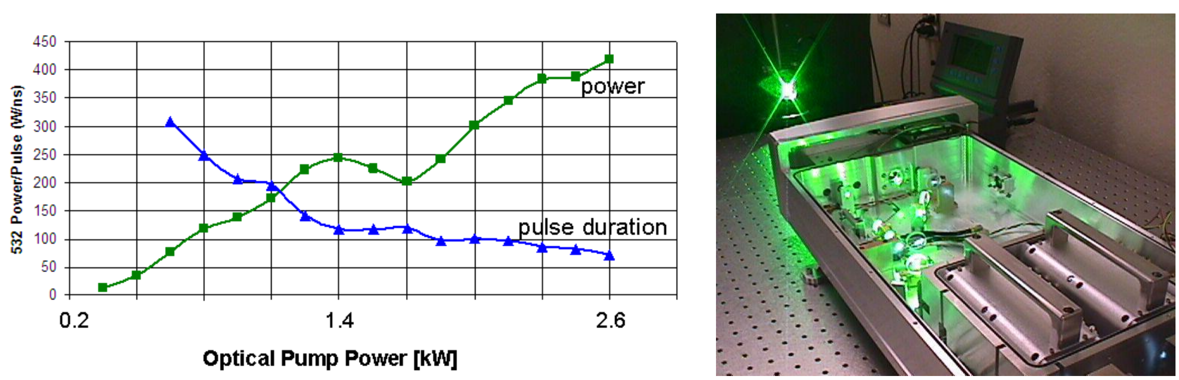


Fig. 6. Measured 532nm output power and pulse duration at 10 kHz as a function of pump power. Measured beam quality at 420 W output power is $M^2 \sim 24$. The photograph shows the opened laser head of a prototype unit with the two field-replaceable gain modules visible.

In order to generate UV radiation via intra-cavity frequency mixing Type II LBO, it is necessary to have linearly polarized light entering the harmonic leg of the cavity. The standard method to enforce linear polarization in a dual rod Nd:YAG laser is to insert a 90 degree quartz rotator between the rods and relay image the principal planes of the rods onto one another [16]. However, by using this technique with a thin-film polarizer near the output coupler, we found that the linearly polarized IR output power was reduced by more than 10% as compared to the unpolarized output. This is due to the non-perfect relay-imaging of the rods in combination with differences in the stress distributions inside the two rods. We added a proprietary, additional compensator in the output leg of the resonator (Fig.7), which reflects the polarization that is perpendicular to the polarization of the output beam back through the gain modules. By using this 'residual birefringence' compensator, the measured linearly polarized output power at the maximum pump power was the same as compared to the unpolarized laser output (Fig.8). The intra-cavity green radiation was generated using a non-critically phase matched, 20mm long Type I LBO. Subsequent frequency mixing in a 20mm Type II LBO and harmonic beam separation using an intra-cavity Brewster prism resulted in a UV output power of 160 W at 8 kHz and a pump power of 2.7 kW (Fig. 9). The measured M^2 of the elliptical UV beam was 16 x 18 at 10 kHz (Fig.10).

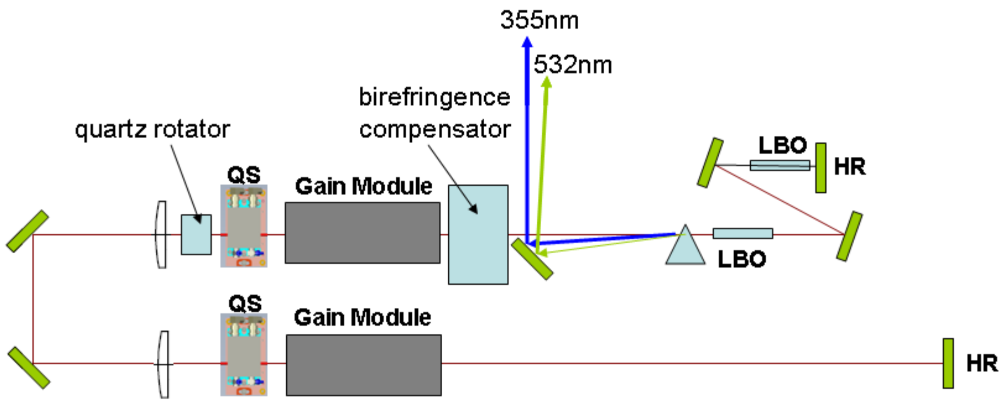


Fig. 7. Cavity layout for intra-cavity tripling of the dual rod Q-switched Nd:YAG laser. Total geometrical resonator length is 1.8m. In addition to birefringence compensation using a quartz rotator and relay-imaging of the rods, a proprietary 'residual birefringence compensator' was added to generate linearly polarized output power with virtually no depolarization losses.

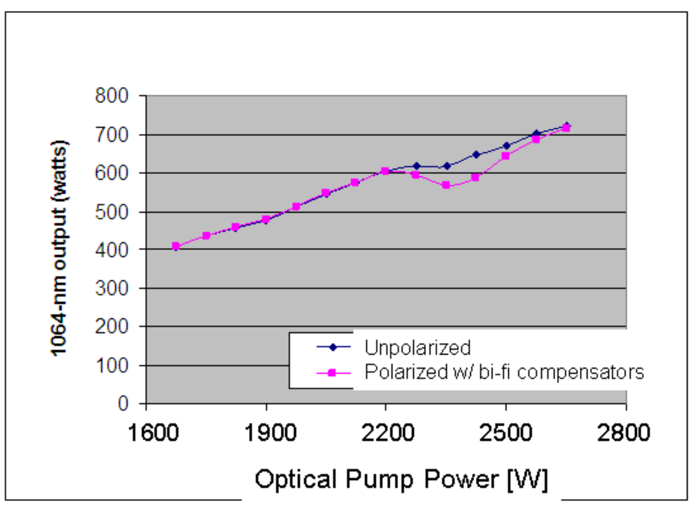


Fig. 8. Measured cw output power at 1064nm without and with birefringence compensation using a quartz rotator, relay-imaging and a proprietary, residual birefringence compensator. At the maximum pump power, the polarized output power was virtually identical to the unpolarized output power. The power dip of the polarized output is due to the resonator passing the confocal point in the equivalent g-diagram.

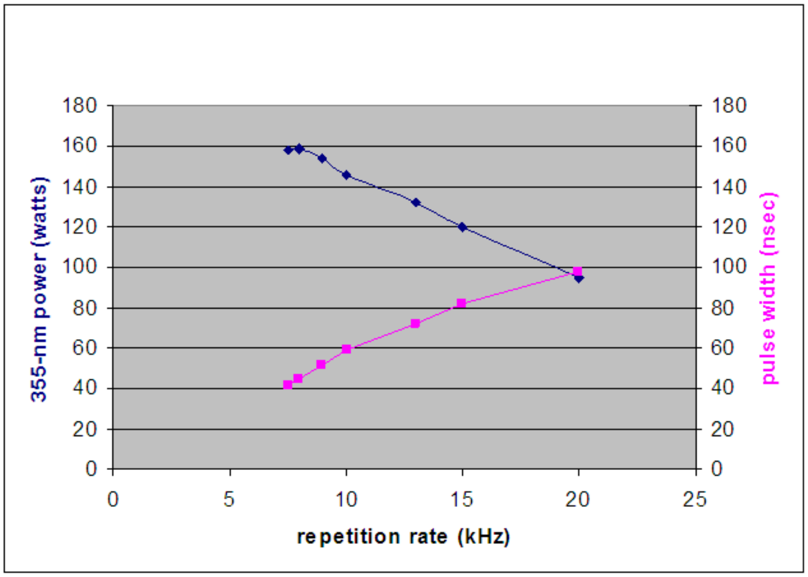


Fig. 9. Measured output power and pulse duration at 355nm as a function of repetition rate for the resonator shown in Fig.7.

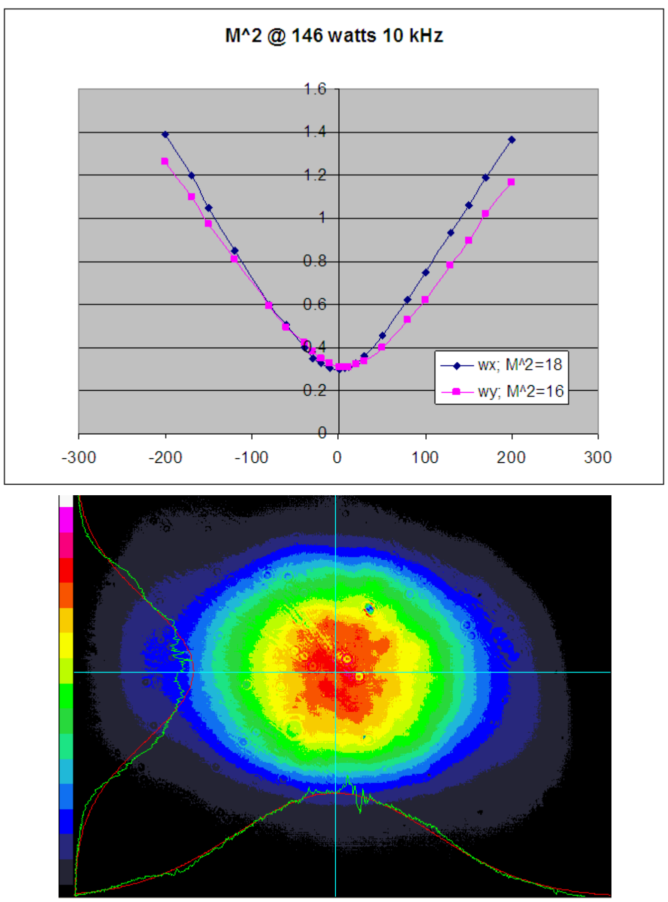


Fig. 10. Measured beam quality and near-field intensity profile of the 355nm output beam at 10 kHz.

4. SUMMARY

We have developed a Q-switched, side-pumped dual rod Nd:YAG laser which generates 420W of green output power at 10 kHz and 160W of UV power at 8 kHz using intra-cavity harmonic generation in LBO. Optical efficiencies were 16% and 6%, with beam quality factor M^2 of 24 and 18, respectively. To the best of our knowledge, these are the highest reported output powers to date for both wavelengths. By using an asymmetric resonator, the M^2 of the green output beam could be reduced to less than 10 with an output power of 220W at 10 kHz. A novel birefringence compensation technique was applied to enforce linear polarization without depolarization loss. The maximum infrared output power of this system was 690W at a repetition rate of 20 kHz and an optical pump power of 2.6 kW. High power Q-switched multimode lasers in the green spectral range are already being used in semiconductor annealing, and will find applications in solar cell processing and to some extent in Ti:Sapphire amplifier pumping. High power Q-switched UV Nd:YAG lasers may replace high power excimer lasers in lithography, provided that the output power can be further increased to greater 300W.

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