

## Recent advances in hybrid fibre-bulk erbium laser sources

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### Abstract

*Hybrid fibre-bulk solid-state lasers combine the advantages of cladding-pumped fibre lasers and conventional bulk solid-state lasers to offer an attractive route to high laser pulse energies in the eyesafe wavelength regime around  $\sim 1.6\mu\text{m}$  and  $\sim 2\mu\text{m}$ . This paper describes the results of the second stage of a project aimed at developing a hybrid pulsed erbium laser with high pulse energy ( $>100\text{ mJ}$ ) and narrow linewidth output at  $\sim 1.6\mu\text{m}$ .*

Keywords: Fibre lasers, solid-state lasers, erbium lasers, long range sensing

### Introduction

Laser sources operating in the eyesafe wavelength regime around  $1.5\text{-}1.6\mu\text{m}$  continue to attract much interest due to a wealth of applications in areas such as spectroscopy, remote sensing, ranging and free-space communications. For many of these applications, the requirement for high pulse energy is frequently accompanied by the need for good beam quality, high overall efficiency and sometimes a narrow-linewidth output, which are often difficult to achieve simultaneously. The conventional approach for producing laser output in this wavelength regime is via direct diode pumping of erbium-ytterbium co-doped bulk glass or crystal lasers. However, the quantum defect for this scheme is rather high ( $\sim 40\%$ ) and hence a large fraction of the pump power is converted to heat in the bulk laser material. This problem is further exacerbated by energy-transfer-upconversion which increases thermal loading and reduces the effective energy storage time. As a result, the power scaling potential of such sources in both continuous-wave (cw) and pulsed (Q-switched) modes of operation is somewhat limited. This project has the general goal of exploring an alternative

strategy for scaling output power and pulse energy in the  $\sim 1.6\mu\text{m}$  wavelength regime by employing a hybrid laser architecture that combines the advantages of cladding-pumped fibre lasers for high-power cw generation with the energy storage and high pulse energy capabilities of conventional 'bulk' solid-state lasers. The basic idea is to use a high-power cladding-pumped Er,Yb co-doped fibre laser to longitudinally pump a bulk solid-state laser based on Er:YAG directly into the upper laser manifold ( $^4\text{I}_{13/2}$ ) to dramatically reduce the quantum defect heating in the Er:YAG crystal to  $\sim 6\text{-}7\%$ . A further advantage of this approach is that a relatively low  $\text{Er}^{3+}$  ion concentration can be employed (due to the good beam quality of the fibre pump source) with the result that the loss of excitation due to energy-transfer-upconversion can be dramatically reduced opening up the prospect of higher average output power and higher pulse energy. The main aim of this project is to develop a hybrid laser architecture which can be scaled to much higher average power levels ( $>100\text{W}$ ) and much higher pulse energies ( $>100\text{mJ}$ ) in a single-frequency output beam.

Here we report on recent developments and describe the main results obtained

during the second year of this three-year project.

### High-power Er,Yb fibre pump laser

The Er,Yb fibre pump laser is an important element of the hybrid laser system. Efficient operation at high power levels (~100 W) at the required lasing wavelength (1532 nm) for efficient absorption in Er:YAG is essential for practical power scaling via the hybrid laser approach. Last year two high-brightness, multi-bar diode pump modules at 975 nm were developed for efficient pumping Er,Yb ribbon fibres. The pump modules were tested on Er,Yb fibres based on a standard D-shaped double-clad design yielding a maximum output power at 1532 nm of 56 W. Development of the ribbon fibres has been delayed to the final year of the project, so the pump module configuration was modified to allow efficient pumping of the standard D-shaped Er,Yb fibre as a temporary means for further scaling of the fibre laser output power.

The modified pumping arrangement is shown schematically in figure 1. The pump modules were polarisation-combined to produce a single beam with  $M^2$  parameters of ~340 (in the plane of figure 1) and ~60 (in the orthogonal plane) and then spatially divided into two beams with  $M^2$  parameters of ~170 and ~60 in orthogonal planes using a knife edge mirror to produce beams with beam parameters compatible with efficient launching into the 400  $\mu\text{m}$  diameter (0.5 NA) inner-cladding of the Er,Yb fibre. Pumping the fibre from both ends is also beneficial in that the thermal loading is reduced compared to the previous single-ended pumping configuration. The Er,Yb fibre used in these experiments had a pure silica inner-cladding and an Er,Yb co-doped phospho-silicate core of diameter 30  $\mu\text{m}$ . Pump light was launched into the fibre (via the scheme shown in figure 1) with a launch efficiency of ~90%. Precise wavelength selection of the Er,Yb fibre laser to the absorption peak in Er:YAG at 1532 nm was

provided by an external cavity comprising a diffraction grating (600 lines/mm) in the Littrow configuration. Both end sections of the fibre were carefully mounted in a water-

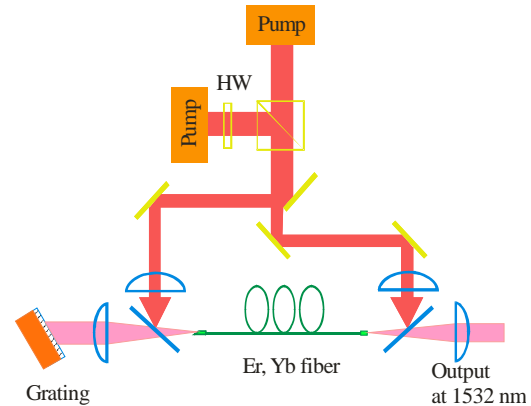


Fig. 1. Tunable Er,Yb fibre laser.

cooled V-groove heat-sinks to prevent thermally-induced damage to the fibre's outer-coating due to heat generated in the core via quantum defect heating. We investigated two different methods for cooling the remaining section of fibre. The first method was simply to passively cool the fibre by immersing it in a water bath, and the second method was to air-cool the fibre using an electrically-operated fan.

Fig. 2 shows the output power at 1532 nm as a function of launched pump power for the two cooling methods. We obtained

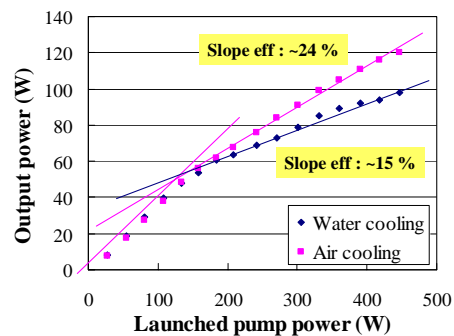


Figure 2: Fibre laser output power at 1532 nm

the highest output power of 120 W in a beam with  $M^2 < 5$  at 440 W launched pump power using fan-assisted cooling. By comparison, direct water-cooling yielded a

maximum output power of 98 W, which was 18% lower than for air-cooling. This difference suggests that the energy transfer efficiency from Yb ions to Er ions is improved at elevated temperatures. However, we also noted that the fibre was very vulnerable to the thermal-induced damage at the highest pump power and hence the proposed ribbon fibre geometry still offers the most promising route to high output power.

### Continuous-wave Er:YAG lasers

Er:YAG has strong emission peaks at 1617 nm and 1645 nm. Laser operation at 1645 nm is generally easier to achieve owing to the less pronounced three-level character and hence lower re-absorption loss at this wavelength. However, there are a number of methane lines in the region of 1645 nm, so operation at 1617 nm may be more desirable for some sensing applications. We have investigated operation at both wavelengths to determine the upper limits on lasing efficiency for this hybrid erbium laser scheme and the requirements for efficient operation at either wavelength.

#### (a) Operation at 1645 nm

To evaluate the cw laser performance we employed a simple four-mirror folded resonator (as shown in figure 3) comprising a plane input coupler mirror with high reflectivity ( $HR > 99.8\%$ ) at the lasing wavelength (1600-1700 nm) and high transmission ( $HT > 95\%$ ) at the pump wavelength (1532 nm), concave mirrors (R1 and R2) of 100 mm radius of curvature (ROC) with high reflectivity ( $>99.8\%$ ) at both the lasing and the pump wavelengths and a plane output coupler with transmission (T)  $\sim 20\%$  at the lasing wavelength. To investigate the impact of  $Er^{3+}$  doping concentration on laser performance, we employed crystals with 0.25 at.% and 0.5 at.% doping levels. In

both cases the crystal lengths (i.e. 58 mm and 29 mm respectively) were selected to have the same pump absorption efficiency and hence the same re-absorption loss at the lasing wavelength. Both faces of each crystal were antireflection coated in the 1.5  $\sim$  1.7  $\mu\text{m}$  wavelength range. The pump absorption efficiency at low pump powers

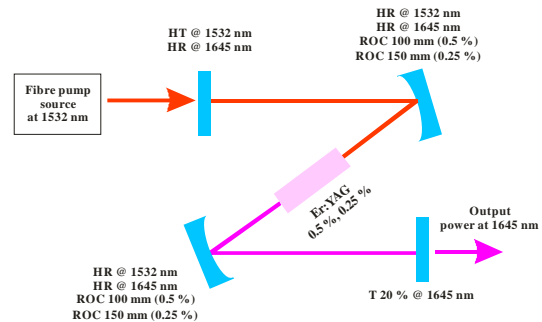


Fig. 3. Experimental set-up for Er:YAG laser

was measured to be  $> 98\%$  for both crystals, but decreased at high pump powers due to ground-state bleaching. The Er:YAG rods were mounted in water-cooled aluminum heat-sinks maintained at a temperature of 17  $^{\circ}\text{C}$  and positioned between the two curved mirrors (R1 and R2). For the 0.5 at.% crystal, the physical length of the resonator arm between the curved mirrors was  $\sim 125$  mm and the total physical length of the resonator was  $\sim 365$  mm resulting in a calculated  $TEM_{00}$  waist radius of  $\sim 80$   $\mu\text{m}$  in the Er:YAG crystal. The Er, Yb fibre laser output was collimated and then focused to a beam radius of  $\sim 75$   $\mu\text{m}$  with the aid of curved mirror R1. A slightly modified cavity design was used for the 0.25 at.% crystal with mirrors R1 and R2 both having a radius of curvature of 150 mm. In this case, the physical length between the curved mirrors, R1 and R2, was increased to  $\sim 180$  mm and the total physical length of the resonator was  $\sim 540$  mm resulting in the calculated  $TEM_{00}$  waist radius of  $\sim 100$   $\mu\text{m}$  in the Er:YAG crystal.

Figure 4 shows the output power of both Er:YAG lasers at 1645 nm as a function of pump power. For the 0.5 at.% crystal, the threshold pump power was  $\sim 3.6$  W and the slope efficiency with respect to incident pump power was  $\sim 86\%$ . The maximum optical conversion efficiency was 71%, which is close to the theoretical limit when threshold pump power and cavity losses are taken into account. There was no roll-over

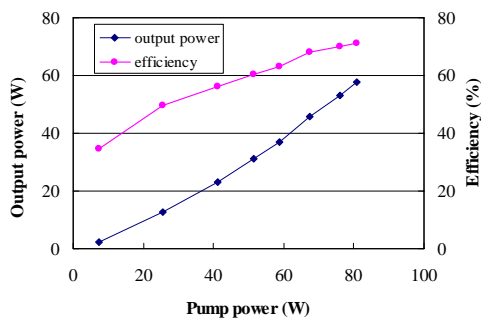


Fig 4(a). Output power versus pump power for 0.5 at.% doping level

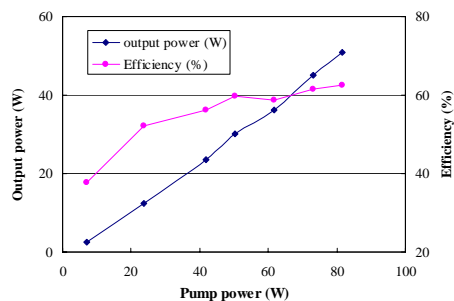


Fig 4(b). Output power versus pump power for 0.25 at.% doping level

up to the maximum pump power and the laser produced a maximum output power of 57.6 W at 1645 nm for 82 W of incident pump power. By comparison, the laser incorporating the 0.25 at.% Er:YAG crystal reached threshold at a slightly lower pump power of  $\sim 2.8$  W and had a slope efficiency with respect to incident pump power of  $\sim 74\%$ . The maximum output power was 51 W for 82 W of incident pump power. The slightly lower output power for the 0.25

at.% doping level was attributed to poorer spatial overlap with the pumped region.

### (b) Operation at 1617 nm

To investigate laser operation at 1617 nm, we employed a similar cavity design but with the option of including an etalon plate of 100  $\mu\text{m}$  thickness near the output coupler to provide additional wavelength discrimination as required. Figure 5(a) shows the output power as a function of incident pump power for the 0.5 at.%

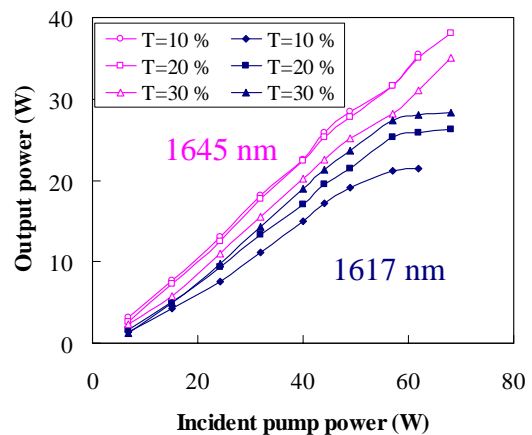


Fig 5(a). Output power versus pump power for 0.5 at.% doping level

Er:YAG crystal laser with 10%, 20% and 30% transmitting output couplers at 1645 nm and 1617 nm. In all cases, the etalon was required to force lasing at 1617 nm. The results show somewhat better performance at 1645 nm and a very pronounced roll-over in output power at 1617 nm. We attribute this to the stronger three level character of the 1617 nm line and the increase in re-absorption loss with temperature as pump power is increased. When an output coupler with a transmission of 50% was used, the Er:YAG laser operated at 1617 nm without the need of the etalon (see figure 5(b)). Thus, raising the excitation density required for threshold can also be an effective method for ensuring operation at 1617 nm. However, this does have the disadvantage that the loss due to energy transfer upconversion increases

leading to additional heat loading and even more pronounced three-level character. The threshold pump power at 1617 nm for a 50 % transmittance output coupler was ~5.2 W and the slope efficiency with respect to incident pump power was ~42 %. From figure 5(b) it can be seen that there is a very

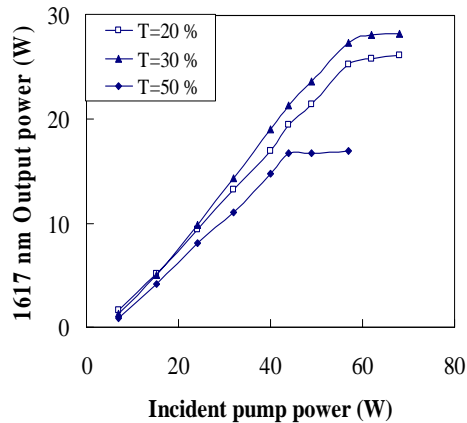


Fig 5(b). Output power at 1617 nm for different output coupler transmissions

marked roll-over in the laser output due to increased three-level character.

Figure 6(a) shows the impact of changing the Er:YAG doping level on laser performance at 1617 nm. Reducing the doping level to 0.25 at.% results in a significant improvement in performance

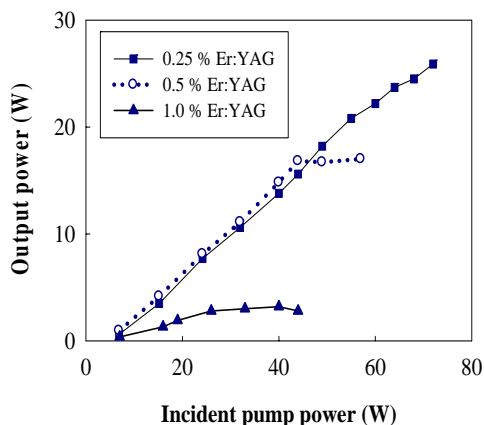


Fig 6(a). Output power at 1617 nm for different doping levels

that can be attributed to a much lower thermal loading density. In contrast, increasing the doping level to 1 at.% leads

to a dramatic reduction in efficiency and the roll-over in power occurs at a much lower pump power than for the Er:YAG crystal with a 0.5 at.% doping level.

Figure 6(b) shows the performance at 1617 nm for an optimised resonator containing the 0.25 at.% crystal. The laser produced a maximum output power of 31 W in a beam with  $M^2 \approx 2.2$  for 72 W incident pump power. The threshold pump power was ~4.1 W and the slope efficiency with respect to incident pump power was ~47 %. There was no evidence of a roll-over in output power even at the maximum available pump power.

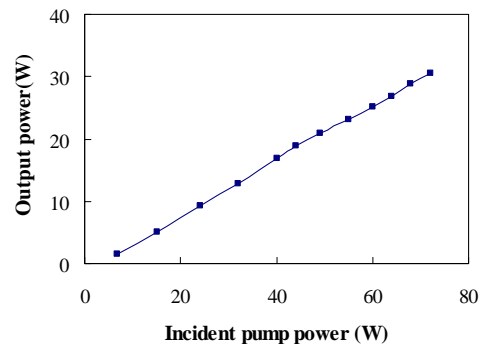


Fig 6(b). Output power at 1617 nm for an optimised resonator

### Determination of the upconversion parameter in Er:YAG

Energy-transfer-upconversion can have dramatic effect on the performance of in-band pumped Er:YAG lasers, so a knowledge of the upconversion parameter and how it varies with  $\text{Er}^{3+}$  doping level is essential for optimising the laser design. Recently we have developed an alternative and simpler technique for determining the upconversion parameter in four-level lasers based on measuring laser threshold pump power as a function of resonator loss [1]. This approach exploits the fact that upconversion loss is increased for higher excitation densities and that the excitation density in a laser can be increased by simply increasing the resonator loss. We

successfully applied our analytical model to determine the ETU parameter of Nd:YVO<sub>4</sub>. We have now extended our analysis to include quasi-three-level lasers. The experimental procedure employs a simple end-pumped two-mirror resonator configuration with adjustable resonator loss (see figure 7). The resonator loss was varied by rotating the angle of an undoped YAG plate in the cavity. The Er,Yb fibre

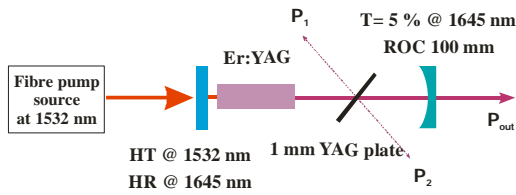


Fig. 7. Experimental set-up for measuring the upconversion parameter.

laser was collimated and then focused to a beam radius of  $\sim 200 \mu\text{m}$  at the centre of the Er:YAG crystal under investigation so that the pump beam size does not vary significantly along the gain material. The resonator consisted of a plane mirror with high reflectivity ( $>99.8\%$ ) at the lasing wavelength of  $1.645 \mu\text{m}$  and high transmission ( $>98.0\%$ ) at the pump wavelength of  $1.532 \mu\text{m}$  and a concave mirror with reflectivity of  $95\%$  at  $1.645 \mu\text{m}$  and  $100 \text{ mm}$  radius of curvature to minimise the impact of thermal lensing. The cavity length was  $\sim 50 \text{ mm}$  resulting in a calculated TEM<sub>00</sub> waist size of  $\sim 110 \mu\text{m}$  at the surface of the plane mirror. Two separate Er:YAG rods were studied, a  $15 \text{ mm}$  long  $1.0\%$  Er:YAG crystal and a  $29 \text{ mm}$  long  $0.5\%$  Er:YAG. Both were mounted in water-cooled aluminium heat-sinks maintained a temperature of  $17^\circ\text{C}$  and positioned close to the plane mirror.

From the results for threshold pump power as a function of resonator loss we determined upconversion parameters to be  $6.1 \times 10^{-18} \text{ cm}^3/\text{s}$  and  $1.2 \times 10^{-18} \text{ cm}^3/\text{s}$  for the  $1.0 \text{ at.}\%$  and  $0.5 \text{ at.}\%$  Er:YAG crystals respectively (see figure 8). The value for the  $1 \text{ at.}\%$  doped crystal is in good

agreement with value reported in the literature and measured using a much more complicated technique. Our model therefore offers an alternative and simpler method for measuring the upconversion parameter in quasi-three-level lasers.

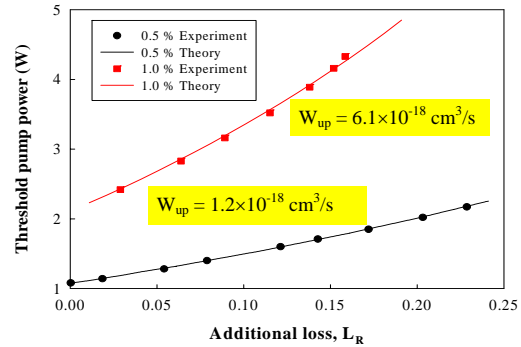


Fig. 8. Threshold pump power as a function of resonator loss.

### Q-switched Er:YAG laser

A preliminary study into scaling the pulse energy from a Q-switched Er:YAG laser was conducted using a simple two-mirror (multimode resonator) incorporating a rubidium titanyl phosphate Pockels cell and a multi-plate polariser composed of two undoped YAG plates at Brewster's angle (as shown in figure 9). At high pump powers, a significant reduction in lasing

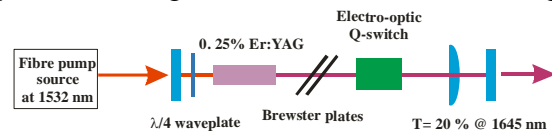


Fig. 9. Set-up for Q-switched Er:YAG laser

efficiency was observed due to thermally-induced birefringence in the Er:YAG crystal. To remedy this problem a quarter-wave plate was inserted in the resonator between the laser rod and high reflectivity plane mirror. Figure 10 shows the performance of the Er:YAG laser in cw mode with and without the quarter-wave plate. A relatively large pump beam size ( $\sim 1.7 \text{ mm}$  in diameter) was used in our experiments to reduce the risk of damage to

mirror dielectric coatings when operating in Q-switched mode.

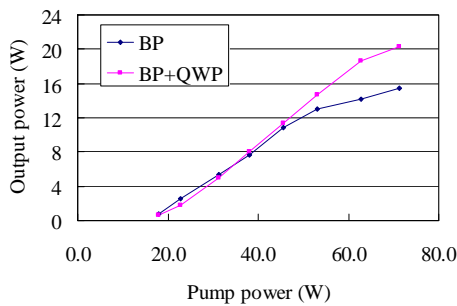


Fig. 10. Cw performance of Er:YAG laser (QWP: Quarter-wave plate, BP: Brewster plate)

Preliminary results for Q-switched operation are summarised in figure 11, which shows the dependence of pulse energy on repetition rate for an incident pump power of 48 W. The maximum pulse energy was 23.3 mJ with pulse duration of less than 100 ns at 30 Hz repetition rate, corresponding to a peak power of >233 kW. The highest pulse energy obtained in our experiment was 30 mJ with pulse duration of less than 20 ns at 20 Hz repetition ratio, corresponding to a peak power of >1.5 MW for 55 W of pump power. However, the damage threshold of the input coupler's coating was less than 100 MW/cm<sup>2</sup>, which was much lower than the expected (>200 MW/cm<sup>2</sup>) and hence the mirror was susceptible to damage at high pulse energies. Further improvement in performance should be possible by using higher damage threshold mirror coatings.

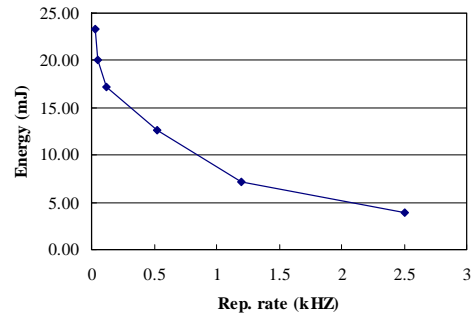


Fig. 11. Q-switched pulse energy as a function of the repetition rate.

## Conclusion

During the second year of this project we have successfully increased the output power from the Er,Yb fibre laser pump source at 1532 nm to 120 W using a modified pump coupling scheme and fibre laser resonator design. With the aid of this pump source we have demonstrated in-band pumped Er:YAG lasers with output powers up to ~58 W at 1645 nm and ~31 W at 1617 nm in cw mode, and pulse energy up to 30 mJ in Q-switched mode. Q-switched performance is currently limited by the mirror damage and thus by using mirrors with a higher damage threshold in conjunction with an optimised cavity design, we believe that much higher pulse energies should be attainable. A simple method for determining the upconversion parameter in Er:YAG has also been developed. An accurate knowledge of the upconversion parameter is essential for further optimisation of the Er:YAG laser design, especially when operating in Q-switched mode at low repetition rates.

## References

1. I. O. Musgrave, M. J. Yarrow, J. W. Kim, W. A. Clarkson, To be submitted to IEEE Journal of Quantum Electronics.

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