Optics EXPRESS

High energy (0.8 J) mechanically Q-switched 2.94 µm Er:YAG laser

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Abstract: We report a flashlamp pumped mechanically Q-switched (MQS) 2.94 µm Er:YAG laser based on a spinning mirror with a highest output energy of 805 mJ at a pulse duration of 61 ns and 13 MW of peak power at 1 Hz repetition rate. This record output energy was achieved with the use of 300 mm long MQS Er:YAG laser cavity consisting of a 70% output coupler, 7 × 120 mm AR coated Er(50%):YAG crystal, and 4200 rad/s angular speed of the spinning mirror. The pulse jitter was also measured by using optical triggering and was smaller than 10 ns for 150 ns Q-switched pulses, which could be applicable to many laser applications where precise synchronization of pulses is required.

1. Introduction

Currently, many efforts have been devoted to the development of compact, cost effective, and efficient laser sources operating at 2.94 µm both in free-running and Q-switched regimes because of their numerous scientific, industrial, and medical applications. The 2.94 µm laser wavelength is close to the infrared absorption peaks of water and hydroxyapatite which makes this radiation attractive for biological tissue ablation, laser surgery, and dental treatments [1–4]. To reduce the thermal damage to surrounding tissue, a short laser pulse duration is preferred [3]. The commonly known technique to achieve relatively short and energetic laser pulses is cavity Q-switching. Therefore, for some applications, a Q-switched regime of operation would be preferred to the free running mode. Apart from medical applications, 2.94 µm radiation can also be successfully utilized for pumping Fe doped chalcogenide gain media of middle-infrared amplifiers and tunable lasers (e.g., Fe:ZnSe lasers) [5–7]. Chemical non-chain hydrogen fluoride (HF) and deuterium fluoride (DF) lasers can deliver multi-joule nanosecond pulses for pumping Fe:ZnSe lasers [8]. However, solid-state laser sources (e.g. Er:YAG, $I_{11/2} \rightarrow I_{13/2}$ transition) have advantages over these chemical lasers in terms of convenience, nontoxicity, and simplicity of maintenance.

An Er:YAG laser is a rare-earth, solid-state crystal laser in which up to 50% of the yttrium ions are replaced with Er^{3+} ions. A peculiarity of the $I_{11/2} \rightarrow I_{13/2}$ transition is that it is self-terminating, since the lifetime of the terminal level is longer than that of the upper one. A cooperative up-conversion inside the Er^{3+} system, which is very active at high erbium concentrations, helps to overcome this deficiency and, in result, free running Er:YAG lasers with ≈3-4% efficiency and multi-joule output energies are commercially available and well documented in the literature [9]. However, the generation of short and energetic pulses in Er:YAG lasers is difficult due to several reasons. First, in the Q-switch regime, in contrast to the free-running mode, the energy transfer processes are "frozen" during the giant pulse lasing, access to the stored energy is limited, and the laser efficiency is rather low [10]. Second, the use of highly concentrated and intensively pumped Er:YAG rods is usually accompanied by large thermal depolarization losses that decrease the efficiency of electro-optical and acousto-optical Q-switchers. Finally, all the electro-optical and acousto-optical materials capable of operation at 2.94 µm are expensive and feature low levels of optical damage, limiting Er:YAG pulse energies in Q-switch regime of operation. So far, the

#417301 https://doi.org/10.1364/OE.417301
Journal © 2021 Received 10 Dec 2020; revised 21 Jan 2021; accepted 21 Jan 2021; published 26 Jan 2021

Q-switched operation of Er:YAG lasers was demonstrated both by using active (electro-optics [11], acousto-optics [12], mechanical [7]) and passive [13] methods. Among these methods, electro- and acousto-optical Q-switching techniques are the most advanced methods that exhibit high stability, fast switching and effective controllability. So far in short pulse regime, the highest output energy from 2.94 µm Er:YAG laser was demonstrated with the use of $LiNbO_3$ electro-optical Q-switch [11]. The highest output energy achieved was 226 mJ with 62 ns pulse duration at a 3 Hz repetition rate. However, at the 2.94 µm wavelength range, it is difficult to find good and affordable electro- and acousto-optic Q-switchers because of their low optical quality, low-optical damage threshold, and limited dimensions, which limits their practical applications. In contrast, mechanical Q-switch (MQS) techniques are simple, cost-effective and not sensitive to the wavelength. So far, several mechanical Q-switchers, not sensitive to the wavelength, have been developed. The radiation of 2.79 µm Er:YSGG laser with a Q-switch based on frustrated total internal reflection (FTIR) was reported in [14] and demonstrated 35 mJ of output energy in a single pulse. The major drawbacks of these Q-switches are high operation voltage, relatively large switching times, and difficulty in controlling the beam quality. On the other hand, MQS methods based on spinning mirrors do not have these limitations. MQS 2.94 µm Er:YAG lasers based on spinning mirrors are well known and have been reported in multiple articles [15,16]. Recently, the MQS Er:YAG laser based on a spinning mirror with the highest output energy of 260 mJ with a pulse duration of 150 ns was developed [17].

In this paper, we revisited the concept of mechanical Q-switching as nowadays the only pathway for designing sub-Joule level Q-switched 2.94 µm Er:YAG laser. The objective of this study is to design and develop a cost effective, high output energy MQS Er:YAG laser source operating at 2.94 µm with small timing jitter. These MQS Er:YAG laser sources have the potential to be attractive for many practical applications.

2. Experimental results and discussion

The schematic diagram of the flashlamp pumped mechanically Q-switched Er:YAG laser is shown in Fig. 1. In this experiment, we used Er:YAG rods with sizes from ϕ4 × 100 mm to ϕ7 × 120 mm and 50 at.% doping concentration of Er^{3+}. The two facets of the rods had AR-coatings at 2.94 µm. A xenon flashlamp with 250 µs pulse duration was used to pump Er:YAG gain media. We used a non-selective linear cavity containing a 70% flat output coupler (OC), an Er:YAG rod, and a flat spinning high reflecting (HR) mirror as shown in Fig. 1.

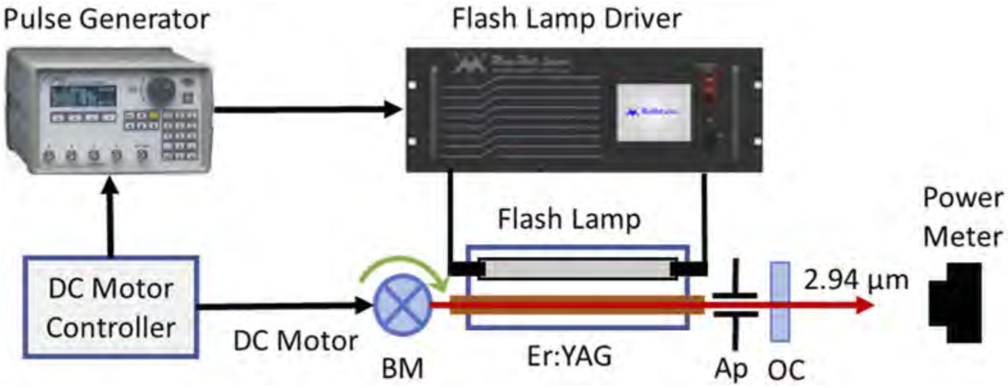


Fig. 1. Schematic diagram of mechanically Q-switched Er:YAG laser; OC - output coupler; BM - back spinning mirror, Ap - Aperture.

The MQS was realized with the use of a spinning back mirror. The spinning mirror was positioned in a homemade mount and rotated by means of a DC motor at a ~40,000 rpm rate.

During the measurement, the rotation rate of the back mirror was varied and optimized to generate a single Q-switched pulse with a maximum output energy. The pulses from the DC motor controller were used to trigger the pulse generator. The pulse generator decreased the repetition rate of the triggering pulse to 1-10 Hz and provided an adjustable delay for triggering of the flashlamp driver as shown in Fig. 1. We used a Megawatt Lasers' flashlamp driver KALD 20-10 capable of providing up to 120 J pulses with a 250 µs pulse duration to drive the flashlamp. Efficient cooling of the laser rod and the flashlamp was accomplished with the use of a Termotek chiller P300. The following sections describe various optimizations of the MQS Er:YAG laser cavity that were performed to obtain the maximum output energy in a single pulse with the highest possible beam quality.

At the first stage of our experiment, we used Big Sky's ϕ4 × 100 mm Er:YAG crystal and measured the output-input characteristics of the laser. To control the output beam quality, we also installed an intracavity aperture near the output coupler. From this stage, as reported in [7], we obtained up to 17 mJ of output energy in a single pulse of 150 ns duration with a beam quality close to Gaussian and a small beam divergence of ~10 mrad ($M^2 \approx 2$). The maximum output energy was limited by multi-pulsing.

At the second stage, our objective was to resolve the multi-pulsing issue which occurred in our preliminary stage and limited the maximum output energy achievable in a single pulse. Generally, the multi-pulsing issue occurs if the switching time of the modulator (spinning mirror) is too long. In this case, the first laser pulse may not be able to extract the full energy stored in the gain medium. This problem can be resolved by increasing the rotational speed of the back mirror (fast switching time). For this experiment, we used Megawatt Lasers's ϕ4 × 105 mm Er:YAG crystal (300 mm cavity length) and measured the temporal profiles and output energies of the MQS Er:YAG laser at different pump energies and two different rotational rates of the back mirror at a 10 Hz repetition rate as depicted in Fig. 2. As one can see from Fig. 2, at 460 and 670 Hz rotational rates of the back mirror, the maximum achieved output energies in a single pulse were 91 mJ (200 ns) and 121 mJ (120 ns), respectively. Further increase of pump energies resulted in multi-pulsing. We also performed our experiment at a low rotational rate of the back mirror (240 Hz) and obtained a maximum single pulse output energy of only 23 mJ. These results signify that the increase of the rotational rate of the back mirror mitigates the multi-pulsing problem and enables a higher single pulse output energy. Since we obtained maximum output energy in a single pulse with the use of the highest rotational rate of the spinning mirror, further experiments were conducted at the maximum rotational rate, which was 670 Hz.

At the third stage, we compared the performance of two different Er(50%)YAG crystals in terms of maximum output energy in a single pulse at 10 Hz repetition rate resulting in the following:

(1) ϕ4 × 105 mm: $E_0 = 121$ mJ (FWHM = 124 ns),

(2) ϕ7 × 120 mm: $E_0 = 137$ mJ (FWHM = 200 ns).

After the comparison, we observed that the larger output energy was achieved with the use of a longer crystal (ϕ7 × 120 mm), which was used in the following measurements. Further increase of the pump energy is accompanied not only by the multi-pulsing problem but also by the optical damage of cavity mirrors due to a strong thermal lensing effect inside the laser cavity.

At the fourth stage, we mainly focused on the suppression of the thermal lensing effect to obtain higher output energy without any optical damage. The thermal lensing effect is very common in solid state lasers, especially operating at higher pump energies and repetition rates. This effect limits the achievable output energy as well as the laser beam quality. Therefore, the mitigation of thermal lensing effect is essential for energy scaling without damaging the optics. Positive thermal lensing can be commonly compensated by lowering the repetition rate, using concave facets of the rod, and using negative lens inside the cavity. In this experiment, we used a

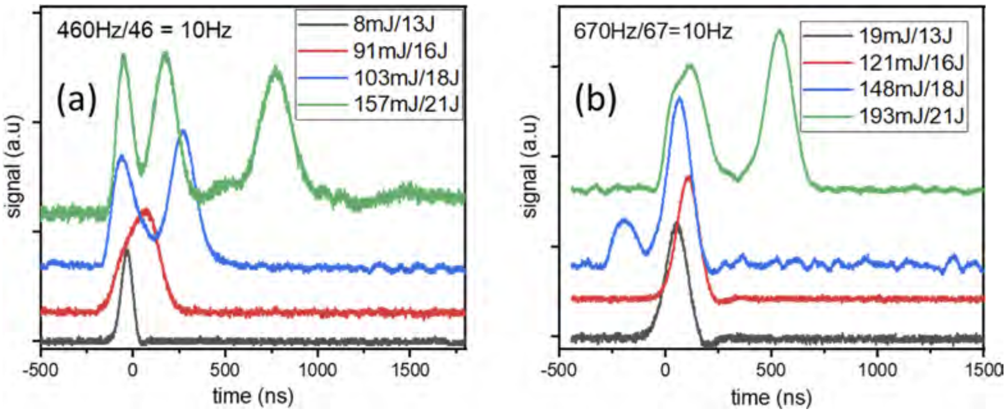


Fig. 2. Temporal profiles of the MQS Er:YAG laser at four different pump energies (13 J, 16 J, 18 J, and 21 J) and respective output pulse energies (pulse widths) (a) 8 mJ (80 ns), 91 mJ (200 ns), 103 mJ, and 157 mJ; (b) 19 mJ (115 ns), 121 mJ (120 ns), 148 mJ, and 193 mJ measured for two different rotational rates of the spinning mirror (a) 460 Hz; (b) 670 Hz.

longer 120 mm Er:YAG crystal (for higher gain) and cooled it to 17^0C, just above the dew point of water, which is 16^0C. To study the dependence of the thermal lensing effect on the repetition rate, we measured the output-input characteristics of the laser at different repetition rates at a fixed 670 Hz rotational rate of the spinning mirror, as shown in Fig. 3(a). As one can see from Fig. 3(a), the decrease in repetition rate results in an increase of the laser threshold; however, it allows for a higher single pulse output energy. At 10, 5, 3, 2.5, and 2 Hz, we obtained 153 mJ (400 ns), 257 mJ (330 ns), 375 mJ (175 ns), 400 mJ (110 ns), and 520 mJ (75 ns) single pulse output energies, respectively. From this experiment, we observed that the decrease in repetition rate enables smaller pulse durations of the output laser pulses. These results show a significant improvement in our results in comparison to previous experiments [7,17]. These results signify that the decrease in repetition rate significantly decreases the thermal lensing effect, hence, enabling a higher output energy in a single pulse without any optical damage. Further increase of the pump energy resulted in multi-pulsing.

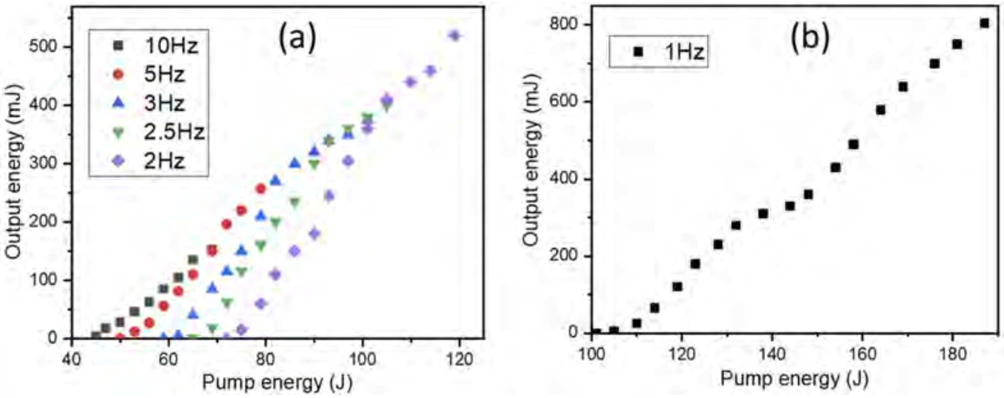


Fig. 3. Input output characteristics of MQS Er:YAG laser at (a) 2 to 10 Hz; (b) 1 Hz repetition rates.

At the final stage, our objective was to optimize all the laser parameters to obtain a higher output energy in a single pulse with a higher beam quality. We used the same 120 mm long crystal which was used at the fourth stage for higher gain and worked at a 670 Hz rotational rate of the back mirror with the coolant temperature set to 17^0C. Since we could not further increase the rotational rate of the mirror to resolve the multi-pulsing issue at the fourth stage, we instead decreased the repetition rate to 1 Hz. Then we measured the output-input characteristics of MQS Er:YAG laser at a 1 Hz repetition rate as shown in Fig. 3(b). The maximum single pulse output energy achieved was 805 mJ at a 61 ns pulse duration corresponding to 13 MW peak power. Further increase of the pump energy resulted in optical damage to the AR coating of the Er:YAG crystal. To our knowledge, this is the highest output energy of a Q-switched 2.94 µm Er:YAG laser documented in the literature. We believe that further compensation for thermal lensing and further optimization of the gain element could enable ≈1 J single pulse output energy from a MQS Er:YAG laser.

Figure 4 shows the temporal and spatial beam profiles of the MQS Er:YAG laser pulses at (a) 180 mJ and (b) 805 mJ output energies under 123 J and 187 J pumping, respectively, measured at a 1 Hz repetition rate. The temporal profiles of the laser pulses were measured with a fast Boston Electronics PEMI series HgCdTe detector with a response time of ~1.2 ns and the typical spatial beam profiles were measured by a Spiricon PyroCam III. At the intermediate 180 mJ output energy we were able to obtain a short pulse with a 35 ns duration and a high beam quality ($M^2 \approx 2$). The spatial beam profile did not feature any hot spots and was very close to a Gaussian profile as shown in the insert of Fig. 4(a), which is applicable to many medical and scientific applications that require energetic nanosecond pulsed radiation with a high beam quality. At the highest output energy, 805 mJ, we obtained single pulse lasing with a 61 ns pulse duration as shown in Fig. 4(b). The insert of Fig. 4(b) shows a few hot spots in the spatial beam profile. We believe that these hot spots caused optical damage of the AR coating of the Er:YAG crystal facets.

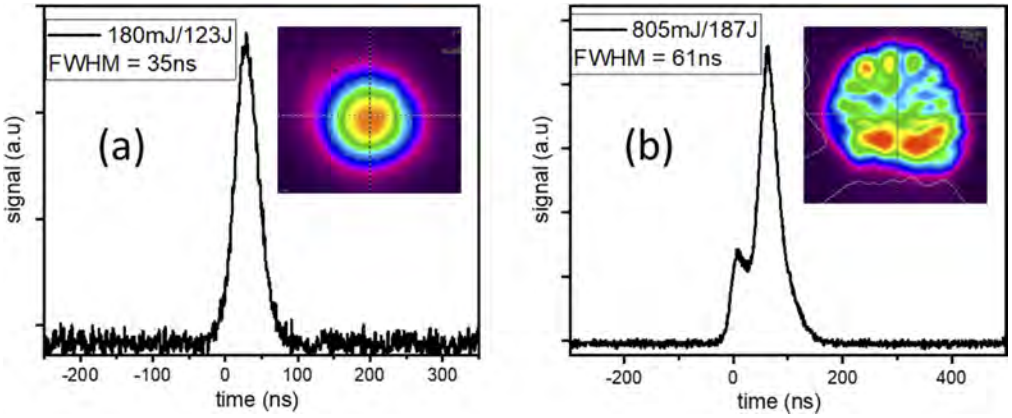


Fig. 4. Temporal and spatial beam profiles of MQS Er:YAG laser at (a) 180 mJ; (b) 805 mJ output energies measured at 123 J and 187 J pump energies, respectively.

MQS Er:YAG lasers with variable pulse durations may have applications in optical sensing, telecommunication, metrology, microscopy, medical (laser surgery), and scientific (effective pump source for Fe:ZnSe laser) areas [18]. To obtain the minimum and maximum values of the pulse duration from our laser system, we performed our experiment at different pump repetition rates and rotational rates of the spinning mirror. We fixed the rotational rate of the back mirror to 670 Hz where we obtained our best results. The minimum and maximum values of the pulse durations were measured to be 35 ns (180 mJ) and 1.2 µs (25 mJ) at 1 Hz and 15 Hz repetition rates, respectively, as shown in Fig. 5. These results indicate that the developed MQS Er:YAG laser system features a ~35 folds variation of pulse durations from tens of nanoseconds to the microsecond range.

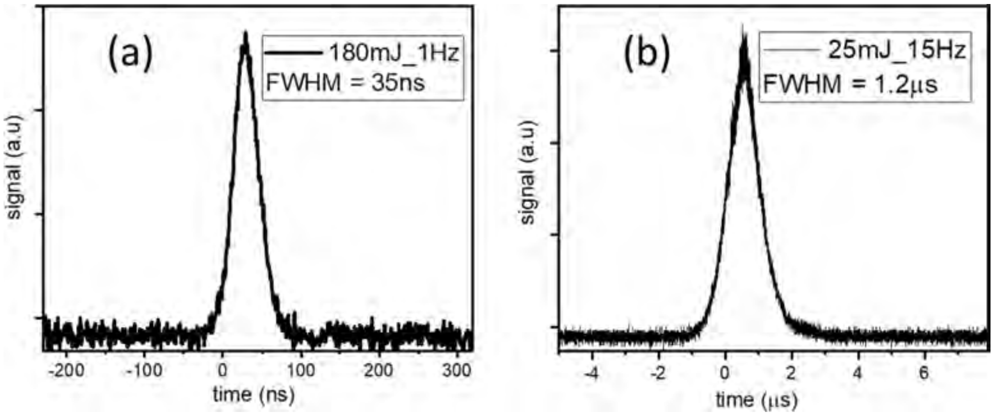
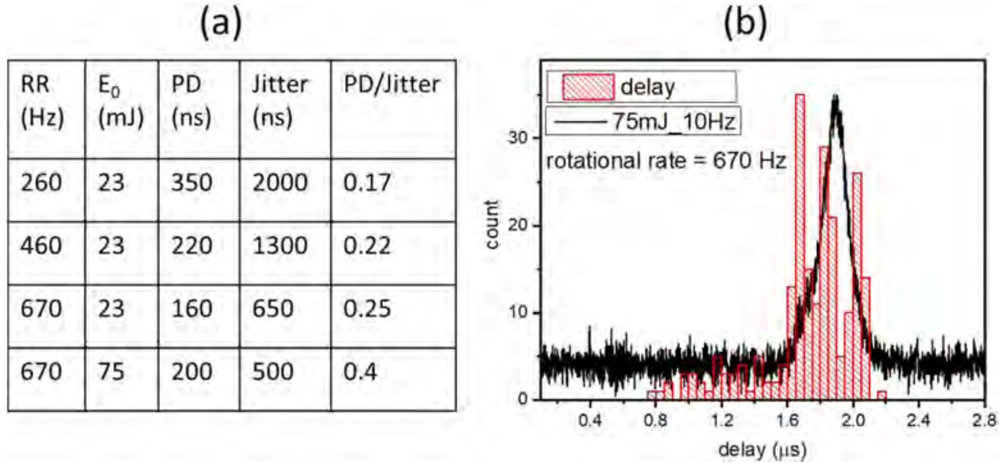


Fig. 5. Temporal profiles of MQS Er:YAG laser at (a) 1 Hz; (b) 15 Hz repetition rates.

The requirement of precise synchronization of nanosecond pulses from different laser sources, essential for many laser applications, stimulated us to study the pulse jitter of MQS Er:YAG laser system. Generally, electro and acousto-optically Q-switched laser devices are the most advanced and possess the smallest time jitters because of fast switching of the quality factor of the cavity [19]. However, the high cost and low optical damage threshold of electro-optical and acousto-optical materials capable of operating at the 3 μm spectral range hampers their practical applications. On the other hand, MQS lasers do not have these limitations but possess higher jitter times mainly because of the variation in angular speed and slow switching of the cavity Q-factor with respect to the pulse build-up time. Here we describe simple and cost-effective techniques for reducing the timing jitter of the MQS Er:YAG laser system, which can be of interest for many laser applications where precise synchronization of pulses is required.

To study the MQS Er:YAG laser pulse timing jitter, we used a 120 mm crystal and measured the pulse jitter at three different rotational rates of the spinning mirror in a 300 mm linear cavity at a 10 Hz pump repetition rate. The summarized results are depicted in Fig. 6. At first, we kept the output energy at the 23 mJ level and worked at three different rotational rates of the back mirror. As one can see from table in Fig. 6(a), the increase in rotational rate from 260 to 670 Hz results in a significant decrease of the pulse jitter (~ 3 times). Then we kept the rotational rate at 670 Hz and worked at 75 mJ level of output energy. We observed that the increase in output energy to 75 mJ resulted in the decrease of the pulse jitter to 500 ns. Figure 6(b) shows the pulse jitter at 75 mJ of output energy with a 200 ns pulse duration and 500 ns jitter. These results indicate that working at higher output energies of the laser and higher rotational speeds of the spinning mirror could significantly decrease the pulse jitter of MQS Er:YAG laser. Further jitter reduction is possible with the use of higher laser output energies and higher rotational rates of the back mirror, as well as with the use of a folded cavity and an intracavity aperture for the elimination of pulse jitter associated with a multi-mode regime of operation.

The dynamics of a giant-pulse build up in the cavities of mechanically and passively Q-switched lasers is very similar and in both cases laser oscillation starts with a low Q factor [20]. This results in the formation of a long initial buildup time. In passively QS lasers, this initial stage of the pulse build-up time could be as long as 100 μs. Our idea here was to utilize this long initial build-up time from MQS Er:YAG laser to trigger other system components using sensitive detector. We believe that this technique will significantly decrease the MQS laser pulse jitter. This technique depends on the two parameters: (a) maximum achieved pre-pulse delay and (b) jitter associated with optical triggering. The use of sensitive detector for triggering could significantly improve these parameters. For this measurement, we used a Boston Electronics



RR (Hz)	E_0 (mJ)	PD (ns)	Jitter (ns)	PD/Jitter
260	23	350	2000	0.17
460	23	220	1300	0.22
670	23	160	650	0.25
670	75	200	500	0.4

Fig. 6. (a) Table of pulse jitter values measured at three different rotational rates of back mirror and two different output energies where RR – rotational rate and PD – pulse duration; (b) temporal profile of 75 mJ output pulse and jitter of MQS Er:YAG laser.

HgCdTe sensitive detector with a ∼ 90 ns rise time to trigger the detection system. Figure 7(a) shows the typical example of one of our measurements with a 150 ns pulse. First, we triggered our system at 0 ns (from where the optical signal started) and then observed the delay to the pulse maximum which was measured to be 375 ns. The measured signal at zero delay was significantly smaller than that at 375 ns delay, however it was sufficient for stable triggering. A maximum delay of $\Delta t \approx$ -500 ns to a pulse maximum was demonstrated for a pulse with FWHM = 130 ns. We believe that the use of a detector with a faster rise time and higher sensitivity will enable the development of a controller with a maximum pre-pulse delay up to ∼1 μs with a small optical jitter.

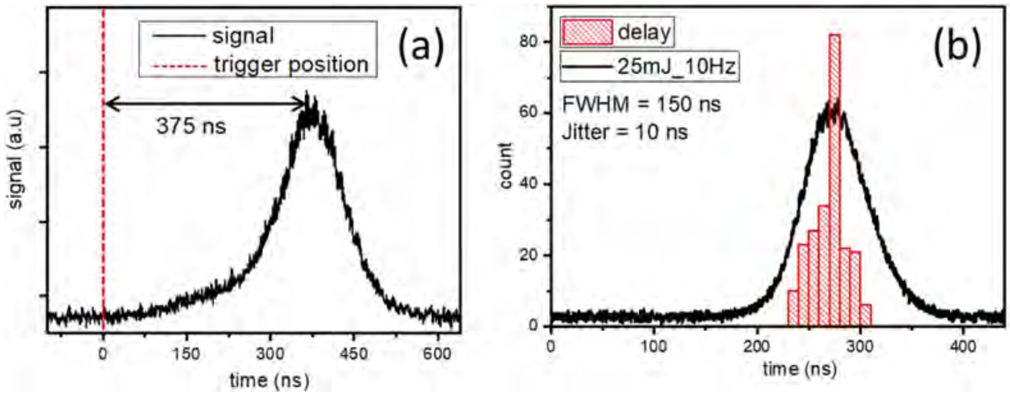


Fig. 7. (a) Temporal profile with triggering position; (b) pulse jitter measurement of MQS Er:YAG laser from optical triggering.

Figure 7(b) shows the pulse jitter of the MQS Er:YAG laser measured with optical triggering. From this measurement, we obtained a ∼10 ns pulse jitter, which is ∼15 times smaller than the pulse duration. A laser with such a small jitter could be of interest for many laser applications requiring precise synchronization between the pulses. In multi-stage high energy chirp-pulse and regenerative amplifiers, precise pulse triggering is usually locked to the clock based on an 80-100 MHz fs-master oscillator. An additional external pulse delay generator allows for a decrease in repetition rate to typical rates of 10 Hz-1 kHz and for setting required delays for other components of the amplifier. In the case of a regenerative amplifier pumped by a MQS laser, the repetition rate could be synchronized with an optical trigger from the MQS laser while the final delay could still be synchronized with a clock based on an 80-100 MHz fs-master oscillator. In this case, the expected time jitter will be equal to a round trip time of the fs laser (~10 ns) and will be significantly smaller than the pulse duration of the MQS laser.

3. Conclusions

In summary, we report a flashlamp pumped 2.94 µm radiation of MQS Er:YAG with a world record 805 mJ output energy with a 61 ns pulse duration and 13 MW peak power at a 1 Hz repetition rate. The maximum output energy was limited by damage to the AR coating of Er:YAG gain element. We believe that further compensation for the thermal lensing effect could enable >1 J output energy in a single pulse from a MQS Er:YAG laser.

We have also demonstrated the pulse duration variability of MQS Er:YAG laser over tens of nanoseconds to the microsecond range. It was also shown that optical triggering of the MQS laser enables a fine synchronization of the pulses with a ~10 ns jitter, which could be of interest for many laser applications where precise synchronization of pulses is required.

Funding. National Institute of Environmental Health Sciences (P42ES027723); U.S. Department of Energy (DE-SC0018378); Air Force Office of Scientific Research (FA9550-13-1-0234).

Disclosures. The work reported here partially involves intellectual property developed at the University of Alabama at Birmingham (UAB). This intellectual property has been licensed to the IPG Photonics Corporation. Dr. Fedorov, Dr. Martyshkin and Dr. Mirov declare competing financial interests.

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