Optics & Laser Technology 146 (2022) 107548

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Electro optic Tm:YAP/KLTN laser using polarization modulation☆

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ARTICLE INFO

Keywords:
2 μm lasers
Polarization modulation
KLTN
Tm:YAP

ABSTRACT

Electro-optic active Q switched Tm:YAP laser (1940 nm), utilizing a novel switching scheme is presented. The switching is done by a KLTN crystal operated slightly above the ferroelectric phase transition, cut in a trapezoidal shape for reducing acousto-optic oscillations. The novel switching scheme, exploits the emission cross section difference between the main axes in the Tm:YAP, and overcomes the residual oscillations effects even at high repetition rates. The laser exhibited stable operation yielding pulses of 0.95 mJ, and pulse duration of 24 ns at 5 kHz, and pulses of 1.76 mJ and pulse duration of 20 ns at 1 kHz. Increasing the pump diameter from 330 μm to 420 μm has increased the pulse energy at 1 kHz to 2.76 mJ.

1. Introduction

The 2 μm wavelength range is considered as a platform for implementing a wide range of applications. These include in particular LIDARs, remote sensing of gases in the atmosphere, tissue specific microsurgery, and material processing [1,2]. In addition, 2 μm lasers are used as pumps for laser systems and OPOs operating in the MIR spectral range [3].

In this paper we demonstrate unique electro-optic modulation of Thulium based laser with a popular host matrix, Ytterbium Aluminum perovskite (YAP). Tm doped YAP are favored as laser gain medium for number of reasons. The two main emission wavelengths of the Tm:YAP are 1940 and 1990 nm, corresponding to the peak absorption of water and local peak in atmospheric transmission, respectively. In addition, the thermo-mechanical properties of the YAP are comparable to the YAG, and its optical properties are better [4]. These attributes make the Tm:YAP the best choice for most 2 μm applications with the notable challenge of its significant thermal lensing.

High energy short pulses are of main interest in many applications. The main method for generating such pulses is active Q switching (AQS), mostly implemented by acousto-optic modulators (AOM) or electro-optic modulator (EOM). In the 2 μm wavelength range AQS is mainly realized with AOM. As a laser switch the AOM has two main drawbacks, switching time and power consumption. The switching time is bound by the time the sound wave traverses the laser cross section typically longer than 100 ns. Henceforth, the laser performance and pulse duration are impaired in high energy pulses and short cavities. The AOM operation requires constant power supply to the acoustic wave to maintain the accumulated phase. In low power systems, the plug-in efficiency can drop drastically due to the AOM power consumption.

The EOM, which is the other main switching method, is using the electro-optic effect to manipulate the polarization of the laser beam travelling between polarizers. In the 2 μm wavelength range there are few compatible crystals, mainly $LiNbO_3$, RTP and LGS. The standard implementation of the laser cavity consists of a polarizer, an electro-optic crystal, a quarter wave plate (QWP) and the output coupler (OC). The laser beam traversing the polarizer is polarized in specific direction, e.g. p polarization. After traversing the QWP back and forth, the laser polarization is flipped to the s polarization and ejected out of the cavity. By applying appropriate voltage to the electro-optic crystal, it induced phase retardation equal to π, becoming an additional QWP. The additional phase retardation maintains the laser polarization over a full round trip, eliminating the modulator loss. The rise time of the EOM is mainly restricted by the electronic circuit, allowing rise time of few nanoseconds, and the power consumption is negligible for most cases. The main drawback of EOM is the high voltage required. This is especially true in the 2 μm wavelength range, where the voltage required is proportional to wavelength. The required voltage is usually a few kV and the electro-optic crystal length is a few centimeters.

A new and unique electro-optic crystal is the potassium lithium tantalate niobate (KLTN). The KLTN is a derivative of the potassium tantalate niobate (KTN), perovskite crystal with high electro optic co-

☆ This document is the results of the research project funded by The Israel Innovation Authority.
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https://doi.org/10.1016/j.optlastec.2021.107548
Received 22 June 2021; Received in revised form 25 August 2021; Accepted 19 September 2021
Available online 4 October 2021

efficient. The KTN has a cubic lattice above its ferroelectric phase transition. When approaching the phase transition the niobate atoms form clusters, decreasing the KTN transmittance. The addition of the lithium ions prevents the cluster formation while maintain the large electro optic coefficient [5]. In the KLTN deep para electric phase the dielectric constant follow curie law, increasing with the KLTN temperate decreasing. This has significant impact on the electro-optic effect. As the refractive index differential is proportional to the dielectric constant square [6]. At the proximity of the phase transition the dielectric constant is diverge from the curie law and is even larger than predicted by it [7]. The centrosymmetry of the KLTN at the para electric phase is nullify the linear electro-optic coefficient. Henceforth, the KLTN electro-optic effect is quadratic. This is beneficial to avoid optical damage. As other electro-optical crystal, the KLTN can suffer from optical damage through photo conductivity that create internal electric field. When using the KLTN, the quadratic nature of the electro-optic effect allows the use of bipolar driving voltage, mitigating the onset of optical damage [8]. This allows the implementation of KLTN crystal only few millimeters long with driving voltage lower than 1 kV even at a wavelength of 2 μm.

AQS Tm:YAP lasers have been demonstrated several times. In 2008 Cai S., Kong J., Wu B. et al. reported a pulsed laser based on AOM with repetition rate up to 10 kHz. At 1 kHz the pulse energy was 1.57 mJ and pulse duration of 80 ns [9]. In 2010 Li G., Yao B.Q., Meng P.B. et al. published AOM based laser with repetition rate of 10 kHz. Pulse energy was1.25 mJ with 126 ns pulse duration [10]. Tm:YAP based on EOM are very rare. In 2020 Yaling Y. et al. have presented a Tm:YAP laser based on LGS crystal with a driving voltage of 2.4 kV. The repetition rate was 200 Hz with pulse energy of 3.15 mJ and pulse duration of 17 ns[11]. Y. Wen et al. published in 2020 Tm:YAP based on RTP crystal. The modulator consisted of 2 RTP crystals with 2x2x12 mm^3. Despite the small cross section and the length, the driving voltage was 1.1 kV. The repetition rate was 10 kHz with pulse energy of 2.2 mJ and pulse duration of 20.64 ns [12].

In 2018 we reported a Tm:YLF laser based on KLTN crystal at the deep paraelectric phase. Due to strong piezoelectric ringing the repetition rate was limited 340 Hz [13,14]. To reduce the piezoelectric ringing the KLTN sample was cut in trapezoidal shape. The different length of the crystal support different acoustic wavelengths that destructively interfere with each other [15]. The decrease in the piezoelectric ringing slightly improved the performance, but the laser did not operate above 500 Hz.

Recently in Photonics West 2020 [16] we introduced a novel electro-optic switching method, polarization modulation. The new switching method was designed to drastically reduced the piezoelectric ringing on the laser performance. The standard EOM modulates the intensity transmitted through it, inserting high loss to the laser cavity. The fluctuations in the modulation caused by the piezoelectric ringing are translated to a time dependent change in the laser round trip gain. In the polarization modulation method, the electro-optic crystal state determinate the polarization state at the gain crystal. When applied to anisotropic crystals this translates to gain modulation as the gain in the crystal can differs greatly between different polarization. Unlike intensity modulation this method does not relay on polarizing element. The modulator consists only from a QWP and the electro-optic crystal. The QWP is tilted with respect to the gain crystal main axes. Laser beam polarized parallel to one of the main axes will rotates its polarization by double passing through the QWP, unable to maintain a high gain polarization state. By applying electrical field across the electro-optic crystal, the polarization state is maintained over the full round trip, allowing efficient lasing. Using this method, the threshold difference between the 'off' and 'on' state is relatively small. The small effect of the full phase retardation on the round trip gain, also implies that the piezoelectric ringing has small effect on the laser performance. On the other hand, the threshold for pre-pulse lasing is low and the maximum pulse energy is capped. The maximum energy is correlated to the 'off' state population inversion density threshold and increases with the effective mode diameter. This method was successfully demonstrated in Tm:YLF/KLTN laser, exploiting the gain difference between the π and σ polarization and expanded the repetition rate range up to 5 kHz. The Tm:YAP is a promising candidate for this switching method with three distinct gain curves. At 1940 nm polarization parallel to the a and c axes will have similar gain, but polarization parallel to the b axis will have around four times less gain, a more significant gap than the one existing in the YLF. This makes a and c cut YAP a perfect host for the polarization modulation method [17].

In this paper we demonstrate for the first time a Tm:YAP laser with KLTN as an electro-optic crystal. The switching was based on polarization modulation. The laser was operated at 330 and 420 μm pump spot diameter in the gain crystal. At 330 μm the pulse energy was 1.76 mJ and 20 ns pulse duration at 1 kHz. Increasing the pump diameter increased the pulse energy limit to 2.76 mJ. The laser operated up to 5 kHz at both pump diameters.

2. Experimental setup

The Tm:YAP laser setup is shown in Fig. 1. The pumping source is a fiber-coupled laser diode with 105 μm diameter and N.A. of 0.22. The pump diode laser was temperature adjusted to maintain its emission wavelength at 793 nm. The pump beam was focused on the laser crystal, using a pair of bi-convex lenses, anti-reflection (AR) coated at 650–1050 nm. The pump was arranged for spot diameters of 330 and 420 μm inside the Tm:YAP crystal. A 10 mm long and 3x3 mm cross-section, c cut Tm:YAP crystal, having 3 at.% Tm doping concentration was used as the gain medium. The Tm:YAP crystal was AR coated at the laser and pump wavelengths. The crystal was wrapped using an indium foil and fastened into an aluminum holder, which was water cooled to 18 °C. An end-pumped architecture was realized for the Tm:YAP cavity. A plano-concave mirror with a 200 mm radius of curvature (ROC) was used as a rear cavity mirror, having an AR coating at the pump wavelength, and a high reflectance (HR) coating at 1850–2000 nm. A plano-concave mirror with a 100 mm ROC was used as an output coupler (OC). The OC was partially reflecting (PR) coated with 55% reflectance for the 1850–2000 nm. The cavity length was 150 mm. the cavity length and rear mirror was empirically chosen to minimize pulse damage inside the cavity considering thermal lensing. The switching apparatus consisted of a 2 mm long KLTN crystal combined with an achromatic QWP that was placed at 45° with respect to the KLTN and the Tm:YAP crystals axes. The KLTN crystal was grown by the top seeded solution growth method [18]. A trapezoidal prism was cut from the grown boule and polished to optical grade, with clear aperture of 3x3 mm^2. Its facets that were perpendicular to the optical axis of the resonator were coated with antireflective coating for 1880 nm. Aluminum electrodes were deposited on the opposing side-facets of the trapezoidal prism. The crystal length through which the beam propagated was 2 mm. The KLTN crystal was installed in a temperature-controlled holder, that maintained its temperature at $T = T_c + 6°C = 24°C$.

The energy of the generated optical pulses was measured using an energy meter (Ophir, PE50-C). Temporal pulse characterization was done using 12.5 GHz extended InGaAs photodetectors (EOT, ET-5000) and a 100 MHz oscilloscope (Tektronix, AFG3102C). The output power was measured, after filtering the residual pump power, using Ophir power meter (model No. L50(150) A-35).

3. Results

The laser was operated with two different focusing lens, resulting in two distinct diameters for the pump laser spot on the gain crystal. The focal length of the focusing lens was change from 75 to 100 mm, resulting in spot diameter increase from 330 μm to 420 μm. The CW performance of the Tm:YAP at both setups is shown in Fig. 2. As expected, the laser threshold has increased significantly when increasing the pump diameter. On the other hand, the better overlap between the

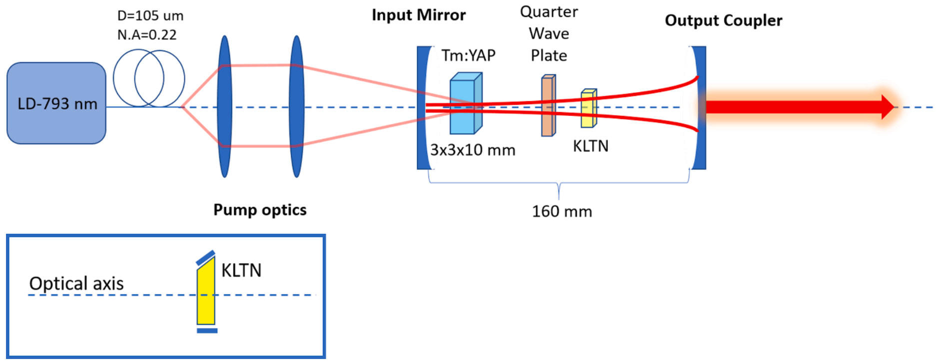

Fig. 1. Experimental setup schematic of the Tm:YAP laser. The KLTN shape is shown in the inset, the electrodes are highlighted.

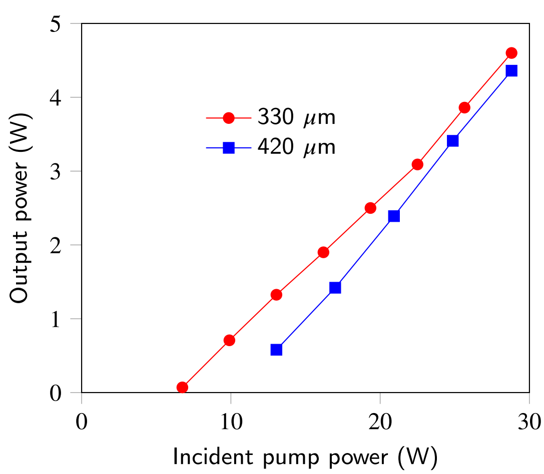

Fig. 2. CW output power at both pump configurations.

pump radius and the laser mode improved the slope efficiency, reaching almost the same maximum output. The laser was adjusted to pulsed operation by rotating the QWP 45° with respect to the crystals axes. Applying DC voltage on the KLTN crystal shifted the laser toward the open state, increasing the output power. The laser CW operation vs. the voltage applied across the KLTN crystal is shown in Fig. 3. Optimal operation of the laser was obtained with applied voltage of 700 V.

The laser operated up to 5 kHz at both pump configurations. The laser pulse energy and pulse duration (FWHM) at different repetition rates are shown in Fig. 4 and the pulse energy standard deviation is

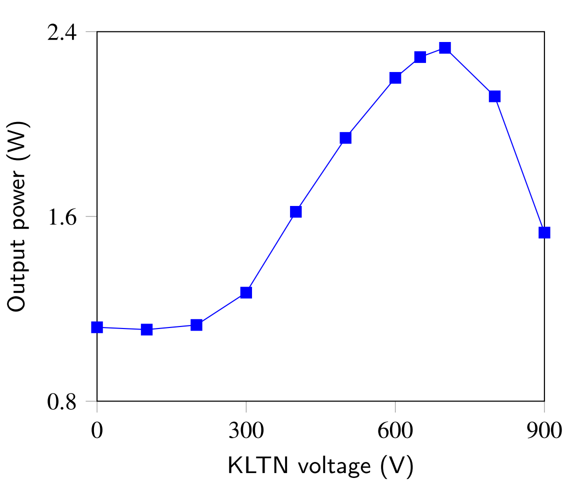

Fig. 3. Output power vs DC voltage on the KLTN crystal.

shown in Fig. 5. At repetition rate of 1 kHz, the maximum pulse energy with 330 um was 1.76 mJ, at pump power of 16 W. Increasing the pump power further initiate prelasing and did not increase the pulse energy. Increasing the pump diameter to 420 μm delay the prelasing to pump power of 24 W and maximum pulse energy of 2.76 mJ. The pulse duration has stabled around 20 ns for both configuration at maximum energy, however for the same energy the pulse duration is longer with 420 μm due to the lower energy density. At the higher repetition rates the pulse energies at maximum pump power is lower than the energy cap at both configurations. The pulse energy graph at 3 kHz resembles the CW graph with the higher threshold and slope efficiency with the larger pump diameter.

The pulse energy deviation is similar for all the laser configurations. The energy fluctuations are very high for low energy pulses and decrease significantly at high energies. It is plausible that low energies pulses are more effected by the piezoelectric ringing. The lower the pulse energy the longer the pulse build up time is. Henceforth, the pulse is influenced by more fluctuations in the laser gain, and a slight deviation in the initial population inversion is amplified by the temporal gain fluctuations.

Another notable phenomenon is the minimum pulse energy for stable lasing. At low pump power the laser repetition rate was lower than the voltage repetition rate. This phenomenon can be attributed to detection limits, as the pulse energy fluctuation at low energy is significant, as shown in Fig. 5, the simultaneous detection of all the pulses is elusive. Another consequence of the energy fluctuation that can affect the repetition rate is the pulse build time. At the low end of the pulse energy the build time is significantly elongate even with small energy difference. The long build time is affected by more of the piezoelectric ringing, and is elongated even more. This long build time may drive the pulse build beyond the duration of the voltage pulse, 10 us, closing the cavity and preventing the pulse formation. The stabilization energy is higher at the configuration with large pump diameter due to the lower gain for the same output energy.

The pulse temporal shape is shown in Fig. 6, average over 128 pulses to reduce noise. The M^2 factor was measured to be less than 1.1 as shown in Fig. 7. The laser beam diameter was measured with a 150 μm diameter circular pinhole.

4. Conclusion

We demonstrate for the first time an electro-optic Tm:YAP laser switched by polarization modulation. The switching method allows the use of the KLTN crystal at high repetition rate, exploiting its strong electro-optic effect for low switching voltage and short cavity length. The laser operation was based on the Tm:YAP anisotropic gain at 1940 nm. The high gain difference allows maximum pulse energies of 1.76 mJ at tight pump configuration. Increasing the pump diameter has increased the pulse maximum energy to 2.76 mJ. At high repetition rate the laser stabilized only at high fluence especially at the wider pump diameter. The reason for these phenomena is unclear yet and needed to

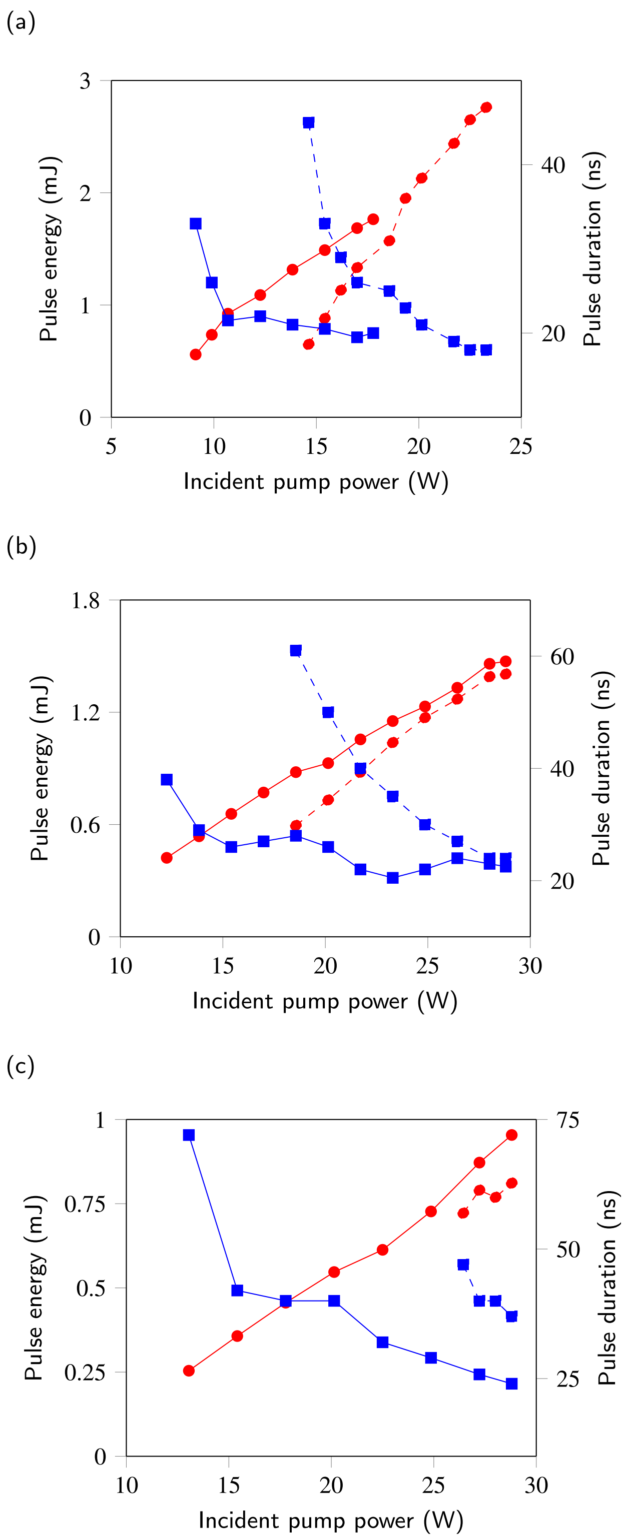

Fig. 4. Pulse energy (Circle, left axis) and pulse duration (Square, right axis) of Tm:YAP at (a) 1 kHz (b) 3 kHz and (c) 5 kHz. Both 420 μm pump diameter (dashed) and 330 μm pump diameter (solid) presented.

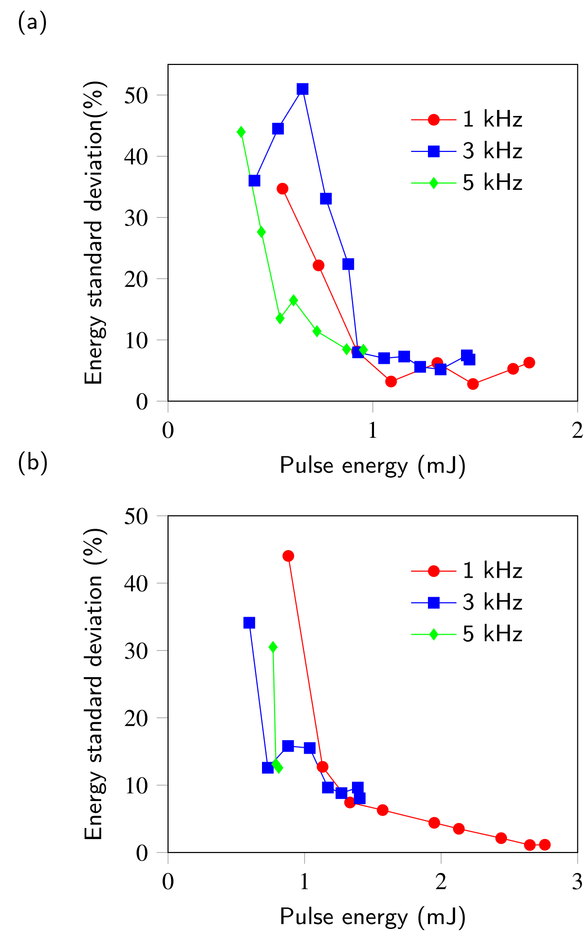

Fig. 5. Pulse energy standard deviation of the Tm:YAP laser at different repetition rates in both configuration ((a) 330 μm and (b) 420 μm).

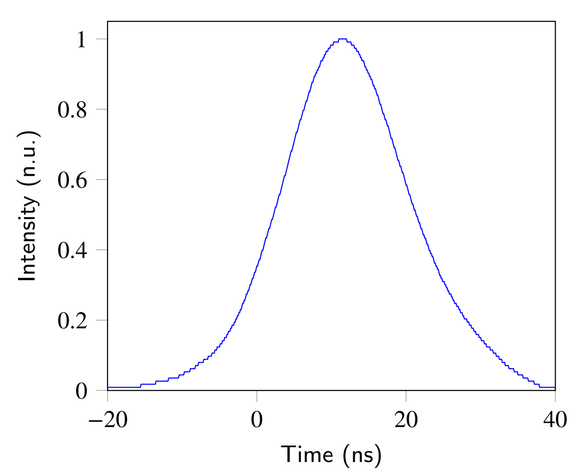

Fig. 6. Laser temporal pulse characteristics.

be investigated in the future.

These results show the great potential of the KLTN as an electro-optic crystal for long wavelength. The combination of the KLTN low driving voltage with the acoustic wave mitigation through cavity and crystal design allows for simpler high repetition rate laser at 2 μm. The polarization modulation method can be applied to most of the anisotropic laser crystals. Applying this method can be beneficial at obviating the need for interactivity polarizer and reducing acoustic effect at certain repetition rates [14].

The polarization modulation method has been demonstrated with Tm doped lasers. These lasers has wide gain curve, with large overlap between different polarizations. The relative high gain at the weaker polarization implies lower cap on the pulse energy. Applying this method to narrow gain ions, such as Nd:YLF, has a potential for much higher maximum pulse energy.

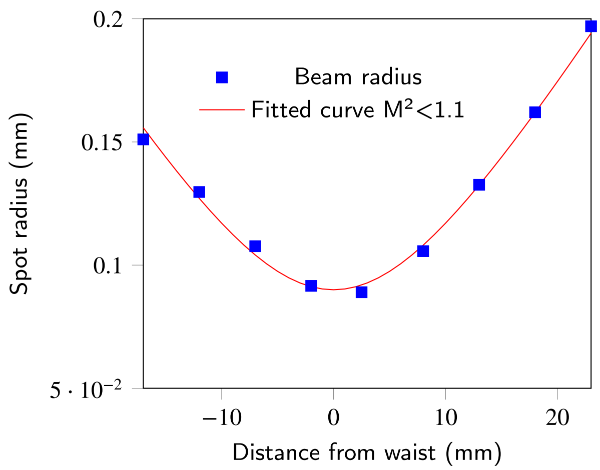

Fig. 7. Spot diameter measured with circular pinhole. Fitted curve with $M^2 < 1.1$.

The authors thanks Professor Agranat from the Hebrew University of Jerusalem for the KLTN crystal and the bipolar driver.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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