

# High power sub 100-fs Kerr-lens mode-locked Yb:YSO laser pumped by single-mode fiber laser

WENLONG TIAN,<sup>1</sup> JIANGFENG ZHU,<sup>1,6</sup> YINGNAN PENG, <sup>1</sup> ZHAOHUA WANG,<sup>2</sup> LIHE ZHENG,<sup>3</sup> LIANGBI SU,<sup>3</sup> JUN XU,<sup>4</sup> AND ZHIYI WEI<sup>2,5,7</sup>

<sup>1</sup>School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China <sup>2</sup>Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

<sup>3</sup>Key Laboratory of Transparent and Opto-functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China

<sup>4</sup>School of Physics Science and Engineering, Institute for Advanced Study, Tongji University, Shanghai 200092, China

<sup>5</sup>School of Physical Science, University of Chinese Academy of Sciences, Beijing, 100049, China jfzhu@xidian.edu.cn

<sup>7</sup>zywei@iphy.ac.cn

**Abstract:** We report on a Kerr-lens mode-locked Yb:YSO lasers for the first time. Pumped by a single-mode fiber laser with high brightness and linear polarization, the Yb:YSO laser can deliver as high as 2 W average power with as short as 95 fs pulse duration at the repetition rate of 137.2 MHz, resulting in the single pulse energy of 14.8 nJ and the peak power of 155.7 kW. This work proves the potential on generation of sub-100 fs pulses with multi-watt level average power with the Yb doped oxyorthosilicates crystals.

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#### **References and links**

- W. Liu, S. H. Chia, H. Y. Chung, R. Greinert, F. X. Kärtner, and G. Chang, "Energetic ultrafast fiber laser sources tunable in 1030-1215 nm for deep tissue multi-photon microscopy," Opt. Express 25(6), 6822–6831 (2017).
- F. Sotier, T. Thomay, T. Hanke, J. Korger, S. Mahapatra, A. Frey, K. Brunner, R. Bratschitsch, and A. Leitenstorfer, "Femtosecond few-fermion dynamics and deterministic single-photon gain in a quantum dot," Nat. Phys. 5(5), 352–356 (2009).
- 3. W. Tian, Z. Wang, X. Meng, N. Zhang, J. Zhu, and Z. Wei, "High-power, widely tunable, green-pumped femtosecond BiB<sub>3</sub>O<sub>6</sub> optical parametric oscillator," Opt. Lett. **41**(21), 4851–4854 (2016).
- F. Emaury, A. Diebold, C. J. Saraceno, and U. Keller, "Compact extreme ultraviolet source at megahertz pulse repetition rate with a low-noise ultrafast thin-disk laser oscillator," Optica 2(11), 980–984 (2015).
- U. Morgner, F. X. Kärtner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, and T. Tschudi, "Sub-two-cycle pulses from a Kerr-lens mode-locked Ti:sapphire laser," Opt. Lett. 24(6), 411–413 (1999).
- O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M. C. Amann, V. L. Kalashnikov, A. Apolonski, and F. Krausz, "High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator," Opt. Lett. 36(24), 4746–4748 (2011).
- S. Ricaud, A. Jaffres, K. Wentsch, A. Suganuma, B. Viana, P. Loiseau, B. Weichelt, M. Abdou-Ahmed, A. Voss, T. Graf, D. Rytz, C. Hönninger, E. Mottay, P. Georges, and F. Druon, "Femtosecond Yb:CaGdAlO<sub>4</sub> thindisk oscillator," Opt. Lett. 37(19), 3984–3986 (2012).
- K. S. Wentsch, L. Zheng, J. Xu, M. A. Ahmed, and T. Graf, "Passively mode-locked Yb<sup>3+</sup>:Sc<sub>2</sub>SiO<sub>5</sub> thin-disk laser," Opt. Lett. **37**(22), 4750–4752 (2012).
- R. Akbari and A. Major, "High-power diode-pumped Kerr-lens mode-locked bulk Yb:KGW laser," Appl. Opt. 56(31), 8838–8844 (2017).
- I. Tomohiro, A. Eilanlou, N. Yasuo, F. Yoshihiko, I. Tomohiro, S. Tetsumi, K. Fumihiko, K. Makoto, and M. Katsumi, "Kerr lens mode-locked Yb:Lu<sub>2</sub>O<sub>3</sub> bulk ceramic oscillator pumped by a multimode laser diode," Jpn. J. Appl. Phys. 54(7), 072703 (2015).
- V. E. Kisel, A. S. Rudenkov, A. A. Pavlyuk, A. A. Kovalyov, V. V. Preobrazhenskii, M. A. Putyato, N. N. Rubtsova, B. R. Semyagin, and N. V. Kuleshov, "High-power, efficient, semiconductor saturable absorber mode-locked Yb:KGW bulk laser," Opt. Lett. 40(12), 2707–2710 (2015).

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#### Research Article

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- F. Pirzio, S. Cafiso, M. Kemnitzer, F. Kienle, A. Guandalini, J. A. der Au, and A. Agnesi, "65-fs Yb:CaF<sub>2</sub> laser mode-locked by semiconductor saturable absorber mirror," J. Opt. Soc. Am. B 32(11), 2321–2325 (2015).
- G. Machinet, P. Sevillano, F. Guichard, R. Dubrasquet, P. Camy, J. L. Doualan, R. Moncorgé, P. Georges, F. Druon, D. Descamps, and E. Cormier, "High-brightness fiber laser-pumped 68 fs-2.3 W Kerr-lens mode-locked Yb:CaF<sub>2</sub> oscillator," Opt. Lett. 38(20), 4008–4010 (2013).
- P. Sévillano, G. Machinet, R. Dubrasquet, P. Camy, J. Doualan, R. Moncorge, P. Georges, F. Druon, D. Descamps, E. Cormier, and P. Moulton, "Sub-50 fs, Kerr-lens mode-locked Yb:CaF2 laser oscillator delivering up to 2.7 W," in *Advanced Solid-State Lasers Congress* (Optical Society of America, 2013), paper AF3A.6.
- A. Greborio, A. Guandalini, and J. A. der Au, "Sub-100 fs pulses with 12.5-W from Yb: CALGO based oscillators," in SPIE LASE (International Society for Optics and Photonics, 2012), paper 823511.
- P. Sévillano, P. Georges, F. Druon, D. Descamps, and E. Cormier, "32-fs Kerr-lens mode-locked Yb:CaGdAlO<sub>4</sub> oscillator optically pumped by a bright fiber laser," Opt. Lett. 39(20), 6001–6004 (2014).
- S. Manjooran and A. Major, "Generation of sub-50 fs pulses with >1.5 MW of peak power from a diodepumped Yb:CALGO laser oscillator," in *Conference on Lasers and Electro-Optics* (CLEO) (2016), paper JTu5A.82.
- W. Tian, Y. Peng, Z. Zhang, Z. Yu, J. Zhu, X. Xu, and Z. Wei, "Diode-pumped power scalable Kerr-lens modelocked Yb:CYA laser," Photon. Res. 6(2), 127–131 (2018).
- H. Zhao and A. Major, "Powerful 67 fs Kerr-lens mode-locked prismless Yb:KGW oscillator," Opt. Express 21(26), 31846–31851 (2013).
- H. Zhao and A. Major, "Megawatt peak power level sub-100 fs Yb:KGW oscillators," Opt. Express 22(25), 30425–30431 (2014).
- R. Akbari, H. Zhao, K. A. Fedorova, E. U. Rafailov, and A. Major, "Quantum-dot saturable absorber and Kerrlens mode-locked Yb:KGW laser with 450 kW of peak power," Opt. Lett. 41(16), 3771–3774 (2016).
- F. Bain, A. Lagatsky, C. Brown, and W. Sibbett, "High-power Kerr-lens mode-locked ytterbium lasers," Proc. SPIE 6871, 68712L (2008).
- M. Tokurakawa, A. Shirakawa, K. Ueda, R. Peters, S. T. Fredrich-Thornton, K. Petermann, and G. Huber, "Ultrashort pulse generation from diode pumped mode-locked Yb<sup>3+</sup>:sesquioxide single crystal lasers," Opt. Express 19(4), 2904–2909 (2011).
- S. Kitajima, H. Nakao, A. Shirakawa, H. Yagi, and T. Yanagitani, "Kerr-lens mode-locked Yb<sup>3+</sup>-doped Lu<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> ceramic laser," Opt. Lett. 41(19), 4570–4573 (2016).
- 25. L. Zheng, L. Su, and J. Xu, "Growth and Characterization of Ytterbium Doped Silicate Crystals for Ultra-Fast Laser Applications," in *Modern Aspects of Bulk Crystal and Thin Film Preparation*, N. Kolesnikov, ed. (2012).
- M. Jacquemet, C. Jacquemet, N. Janel, F. Druon, F. Balembois, P. Georges, J. Petit, B. Viana, D. Vivien, and B. Ferrand, "Efficient laser action of Yb: LSO and Yb: YSO oxyorthosilicates crystals under high-power diode-pumping," Appl. Phys. B 80(2), 171–176 (2005).
- F. Thibault, D. Pelenc, F. Druon, Y. Zaouter, M. Jacquemet, and P. Georges, "Efficient diode-pumped Yb<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub> and Yb<sup>3+</sup>:Lu<sub>2</sub>SiO<sub>5</sub> high-power femtosecond laser operation," Opt. Lett. **31**(10), 1555–1557 (2006).
- W. Tian, Z. Wang, J. Zhu, L. Zheng, J. Xu, and Z. Wei, "Highly efficient and high-power diode-pumped femtosecond Yb:LYSO laser," Laser Phys. Lett. 14(4), 045802 (2017).
- 29. W. Li, Q. Hao, H. Zhai, H. Zeng, W. Lu, G. Zhao, L. Zheng, L. Su, and J. Xu, "Diode-pumped Yb:GSO femtosecond laser," Opt. Express **15**(5), 2354–2359 (2007).
- J. Liu, J. Yang, W. Wang, L. Zheng, L. Su, and J. Xu, "Passive picosecond and femtosecond mode-locking laser action of Yb<sup>3+</sup>: LuYSiO<sub>5</sub>," Laser Phys. 21(4), 659–662 (2011).
- J. Zhu, W. Tian, J. Wang, Z. Wang, Z. Wei, L. Zheng, L. Su, and J. Xu, "Diode-pumped passively mode-locked Yb:GYSO laser generating 324 fs pulses at 1091 nm," Opt. Lett. 37(24), 5190–5192 (2012).
- B. Zhou, Z. Wei, Y. Zhang, X. Zhong, H. Teng, L. Zheng, L. Su, and J. Xu, "Generation of 210 fs laser pulses at 1093 nm by a self-starting mode-locked Yb:GYSO laser," Opt. Lett. 34(1), 31–33 (2009).
- W. Tian, Z. Wang, J. Liu, J. Zhu, L. Zheng, X. Xu, J. Xu, and Z. Wei, "Dissipative soliton and synchronously dual-wavelength mode-locking Yb:YSO lasers," Opt. Express 23(7), 8731–8739 (2015).
- W. Tian, Z. Wang, J. Zhu, Z. Wei, L. Zheng, X. Xu, and J. Xu, "Generation of 54 fs laser pulses from a diode pumpedkerr-lens mode-locked Yb:LSO Laser," Chin. Phys. Lett. 32(2), 024206 (2015).
- 35. J. Zhu, Z. Gao, W. Tian, J. Wang, Z. Wang, Z. Wei, L. Zheng, L. Su, and J. Xu, "Kerr-Lens Mode-Locked Femtosecond Yb:GdYSiO<sub>5</sub> Laser Directly Pumped by a Laser Diode," Appl. Sci. 5(4), 817–824 (2015).
- W. Tian, Z. Wang, L. Wei, Y. Peng, J. Zhang, Z. Zhu, J. Zhu, H. Han, Y. Jia, L. Zheng, J. Xu, and Z. Wei, "Diode-pumped Kerr-lens mode-locked Yb:LYSO laser with 61fs pulse duration," Opt. Express 22(16), 19040– 19046 (2014).
- 37. C. Xu, D. Tang, J. Zhang, H. Zhu, X. Xu, L. Zheng, L. Su, and J. Xu, "Sub-100 fs pulse generation in a diode pumped Yb:Sc<sub>2</sub>SiO<sub>5</sub> laser," Opt. Commun. **294**, 237–240 (2013).
- W. Tian, Z. Wang, J. Zhu, L. Zheng, X. Xu, J. Xu, and Z. Wei, "Diode-pumped Kerr-lens mode-locked Yb: GSO laser generating 72 fs pulses," Opt. Laser Technol. 79, 137–140 (2016).
- 39. P. Haumesser, R. Gaumé, B. Viana, and D. Vivien, "Determination of laser parameters of ytterbium-doped oxide crystalline materials," J. Opt. Soc. Am. B **19**(10), 2365–2375 (2002).

## 1. Introduction

The generation of high power femtosecond pulses directly from a laser oscillator is currently one of the frontiers of ultrafast optics, as their extensive applications range from nonlinear microscopy [1] to ultrafast spectroscopy [2] as well as from frequency conversion [3] to high-field science [4]. Femtosecond Ti:sapphire oscillator is currently mature in generating tunable femtosecond pulses from 700 nm to 1000 nm as well as down to sub-5 fs pulses [5]. However, the power scalability is limited to about 4 W, due to not only the costly green pump source but also its moderate quantum efficiency. On the other hand, Yb doped gain media with several merits including more than 90% quantum efficiency, allowing direct diode pumping, broad emission spectrum as well as long excited state lifetime are well known as optimal alternatives in high power femtosecond pulse generation with reduced heat deposition and thermal loading. Although a variety of Yb-doped materials have been managed to deliver high power femtosecond pulses by means of either thin-disk technology [6–8] or simple bulk geometry [9–11], it is still challenging to directly extract sub-100 fs pulses with watt level average power from a Yb solid-state laser. Because such a laser demands the Yb-doped gain medium with not only a flat emission spectrum of sufficiently broad bandwidth but also excellent thermal conductivity to suppress the thermal lensing. Currently, Yb-based femtosecond lasers delivering watt-level sub-100 fs pulses have been reported only in a few kinds of crystals such as Yb:CaF<sub>2</sub> [12-14], Yb:CGA [15-17], Yb:CYA [18], Yb:KGW [19–21], Yb:KYW [22], Yb:YVO<sub>4</sub> [22], and Yb:Lu<sub>2</sub>O<sub>3</sub> [23] as well as Yb:LuAG ceramic [24]. Apart these materials, the family of Yb doped oxyorthosilicates [25] (including Yb:GSO, Yb:LSO, Yb:YSO, Yb:GYSO and Yb:LYSO crystals) are also promising candidates for producing sub-100 fs pulses with watt level average power, due to their broad emission spectra as well as excellent thermal conductivities as summarized in Fig. 1. The large ground states and excited state energy splitting of Yb<sup>3+</sup> ions in Yb-doped oxyorthosilicates not only lead to quasi-four level operation but also result in broad fluorescence spectra, such as 48 nm in Yb:YSO and 73 nm in Yb:LSO, both of which support generating transform limited pulses down to sub-50 fs. In addition, all the thermal conductivities of Yb doped oxyorthosilicates beside Yb:GSO crystal are large than that of Yb:KGW, implying the potential in high power operation. Thus, an increasing attention has been paid to this family of gain media since last decade. Laser performances on both continuous wave (CW) and mode-locking have been demonstrated. In 2005, M. Jacquemet et. al. reported on the efficient laser actions of Yb:LSO and Yb:YSO oxyorthosilicates crystals with high CW optical conversions of more than 50% for the first time [26]. In 2006, F. Thibault et. al. reported on the high-power semiconductor-saturable-absorber-mirror (SESAM) mode-locked operation based on Yb:YSO and Yb:LSO crystals, providing more than 2.6W average output power with 198 fs and 260 fs pulse durations, respectively [27]. Recently, as high as 3.07 W average output power was directly generated from the SESAM mode-locked Yb:LYSO laser, while the pulse duration was 297 fs [28].



Fig. 1. Thermal conductivity and emission bandwidth of the Yb-doped crystals for high-power femtosecond generation.

general, passively mode-locked femtosecond lasers based on Yb-doped In oxyorthosilicates using SESAM produce comparatively longer pulses on the order of several hundred femtoseconds [27, 29–32], which is mainly due to the multiple spectral peaks in their fluorescence spectra. The advantage in gain of the peaks over the valleys limits the spectral broadening of the mode-locked pulses. In addition, the multiple peaks structure will also enable the dual-wavelength synchronously mode-locking operation [33]. In contrast, the Kerr-lens mode-locking (KLM) technology is more feasible for sub-100 fs pulses generation from a Yb doped oxyothosilicates laser. With multi-mode laser diode (LD) as the pump source, previous studies demonstrated as short as 54 fs, 55 fs, 61 fs, 71 fs and 72 fs from the KLM solid-state lasers based on Yb:LSO [34], Yb:GYSO [35], Yb:LYSO [36], Yb:SSO [37] and Yb:GSO [38] crystals, respectively. In order to enhance the Kerr-lens effect for generating sub-100 fs pulses, tight focusing cavities were implemented in the above lasers, which is incompatible with the large pump spot of a multi-mode LD, resulting in bad mode matching and then low efficiency. Therefore, all the KLM Yb-doped oxyothosilicates lasers suffered from the limited output power on the order of several tens milliwatts, which severely limits their applications. Employing a high-power single-mode fiber laser, which has very high brightness as well as excellent linear-polarization property, as the pump source is an effective method to cope this issue and improve the output power to watt level by providing much better mode matching for higher efficiency.

In this paper, we firstly report on a single-mode fiber laser pumped KLM Yb:YSO laser. Upon the incident pump power of 7.5 W, 95 fs pulses centered at 1040 nm with as high as 2.03 W average output power were obtained at the repetition rate of 137.2 MHz. The resulted single pulse energy and peak power are 14.8 nJ and 155.7 kW, respectively.

#### 2. Experimental setup

The pump source is a commercial single mode fiber laser (ALS-IR-75, Azur Light Systems) emitting at 976 nm with up to 10 W output power. Compared with the common pump source of laser diode, such single mode fiber laser has some evident advantages including very high brightness (linewidth is only about 50 kHz), excellent beam quality with  $M^2 < 1.1$ , distinct linear polarization characteristic as well as much lower noise. With a lens of 60 mm focal length, the pump beam was focused into the center of an Yb:YSO crystal (from Prof. Jun Xu's group) with 26.5 µm spot radius and as long as 4.5 mm confocal parameter. The resulted maximum pump intensity was up to 0.9 MW/cm<sup>2</sup>. The 3-mm long gain medium was wrapped with an indium foil and mounted tightly in a water-cooled copper heat sink maintained at 14°C. The crystal was 5 at.% Yb<sup>3+</sup> doped and anti-reflective coating around 980-1100 nm. Since the absorption cross section is strongly polarization dependent in



Yb:YSO crystal [39], a half-wave-plate (HWP) was used to adjust the polarization of the incident pump for optimal absorption.



Fig. 2. Experimental setup of the Kerr-lens mode-locked Yb:YSO laser. HWP: half wave plate; L: lens; C1, C2 and C3: concave mirrors; OC: output coupler; GTI1 and GTI2: Gires-Tournois Interferometer mirrors; HR: flat mirror with high reflectivity.

The schematic of the experimental setup is shown in Fig. 2. A modified X-folded prismless cavity with seven mirrors was employed in the experiment. C1 and C2 were dichroic concave mirrors with 100 mm radium of curvature (ROC), coated with high reflectivity over 1020-1100 nm (R>99.9%), and high transmittance around 800-1000 nm (R<5%). Thus, it promises us to record the unabsorbed pump power directly behind the concave mirror C2 with laser effect. GTI1 and GTI2 (from LAYERTEC GmbH) were Gires-Tournois Interferometer mirrors for intra-cavity dispersion compensation, with  $-550 \text{ fs}^2$  and  $-800 \text{ fs}^2$  group delay dispersion (GDD) per bounce respectively. C3 was a concave mirror with 300 mm radium of curvature (ROC), coated with high reflectively in the region of 1020-1100 nm (R>99.9%). The cavity was ended by a flat mirror (HR) with highly reflectivity over 1020-1100 nm and a wedged output coupler (OC) with 10% transmittance mounted on a translation stage, respectively. The slight wedge of the OC was helpful to avoid disturbing to the mode locking from the back reflection. The beam waist radius in CW operation (ignoring the Kerr-lens effect) in the center of the Yb:YSO crystal was calculated to be 31x36 µm  $(1/e^2)$  based on the ABCD matrix, which is larger than that of the focused pump beam. Thus, a soft aperture was readily formed to enable the KLM. The total cavity length was about 1093 mm, corresponding to a repetition rate of 137.2 MHz.

#### 3. Results and discussion

At first, we characterized the CW operation properties of the Yb:YSO laser. When the polarization of incident pump was perpendicular to the X axis of the Yb:YSO crystal, only 1.03 W output power was produced with as high as 5.21 W unabsorbed pump power for the maximum pump power of 10 W. The absorption efficiency and the corresponding opticaloptical efficiency were only 47.9% and 21.5%, respectively. When adjusting the polarization to be parallel to the X axis, the maximum output power raised to 3.6 W and the unabsorbed pump power dropped to 1.78 W, corresponding to an optical-optical efficiency of 43.8% and an absorption efficiency of 72.2%. In this condition, we recorded the output power as a function of the incident pump power as shown in Fig. 3(a). the threshold for laser operation was 750 mW and the slope efficiency above 5 W incident pump power was about 48.7%. The change in slope around 5 W in Fig. 3(a) is caused by the increasing of the absorption efficiency for Yb: YSO crystal. The spatial distribution of the output laser was measured with a commercial multiple-axis knife edge scanning laser beam profiler (Beam Analyzer USB, Duma Optronics Ltd.) as presented in Fig. 3(b), where the diagonal lines labeled V and W are the axes along which the measurements are made and displayed. As shown in Fig. 3(b), the laser beam has an elliptical profile which was contributed to the astigmatism caused by the two folded concave mirrors. Besides, the spot size in both horizontal and vertical directions are 625  $\mu$ m and 1340  $\mu$ m (1/e<sup>2</sup> level), respectively.



Fig. 3. (a) CW output power versus the pump power. (b) Spatial distrubution of the CW output.

In order to realize the KLM operation, the cavity was detuned close to the edge of the stability domain by translating the C2 mirror, where the CW output power decreased from 2.4 W to 1.92 W under 7.5 W incident pump power. Reproducible mode-locking operation could be achieved only if a weak perturbation was introduced such as taping the mirrors or pushing the translation stage. When locked, the Yb:YSO oscillator delivers a stable pulse train at 137 MHz repetition rate with the output power increased to 2.03 W for 7.5 W pumping power. Using a commercial optical spectrum analyzer (AvaSpec-ULS2048, Avantes), we measured the mode-locked optical spectrum as shown in Fig. 4(a). The full width at half maximum (FWHM) of the spectrum was 11 nm with the central wavelength at 1040 nm, which supported a transform limited pulse duration of 85.4 fs assuming a sech<sup>2</sup> pulse shape. The corresponding intensity autocorrelation trace was measured by a commercial intensity auto-correlator (APE PulseCheck USB), as shown in Fig. 4(b). The FWHM bandwidth of the autocorrelation trace was about 147 fs, corresponding to 95 fs pulse duration if a sech<sup>2</sup> pulse shape was assumed, which was close to the Fourier limited pulse duration.



Fig. 4. (a) Optical spectrum of the Kerr-lens mode-locked laser. (b) The corresponding intensity autocorrelation trace. The experimental data and the sech<sup>2</sup>-fitting curve are described by the solid magenta curve and the dashed black curve, respectively.

To claim the stability of the mode-locking operation, the radio frequency (RF) spectrum was also measured via a photo detector with a 3-dB bandwidth of 1 GHz and a commercial RF spectrum analyzer (R&S FSVA40). The signal was recorded for both a frequency window of 500 kHz with 1 kHz resolution bandwidth (RBW) and a 1 GHz with 100 kHz RBW as described in Fig. 5. The distinct signal to noise ratio of the fundamental beat note at 137.25 MHz was 80 dBc. Stable mode locking operation was illustrated by the clean RF





Fig. 5. The RF power spectrum of the Kerr-lens mode-locked laser in the frequency span of 500 kHz (a) and 1 GHz (b), respectively.

In addition, further characterizations including the beam profile and mode-locking performances at different pump power were presented. As shown in Fig. 6(a), the Yb:YSO oscillator could maintain single-pulse mode-locking operation when the pump power was from 6 W to 7.5 W. It turned to multi-pulses region when higher pump power was employed and failed to mode lock with lower than 6 W pump power. For temporal features, the pulse duration shortened from 106 fs to 91 fs when the incident pump power increased from 6 W to 7 W and raised to 95 fs afterward. The shortest pulses of 91 fs were obtained under 7 W incident pump power with 1.85 W output power, which shows the balance between the net intracavity GDD and the self-phase-modulation. Figure 6(b) depicted the near field beam profiles in the mode-locked operations recorded with an optical beam analyzer (Beam Analyzer USB, Duma Optronics Ltd.). The transverse beam distribution gets more circular than that in CW operation. And, the KLM laser beam has a spot size of 536  $\mu$ m x 1095  $\mu$ m in the horizontal and vertical directions, respectively.



Fig. 6. (a)The output power and pulse duration of the mode-locked pulses as a fuction of the incident pump power. (b) The spatial distrubution of the mode-locking pulse with 2.03 W output power.



Fig. 7. Summary of the state-of-art results from Yb-based bulk lasers in generating sub-100 fs pulses with watt level output power [12–24].

A summary of the sub-100 fs mode-locked lasers based on bulk Yb-ion-doped crystals with watt level average output power is shown in Fig. 7. Previously, Yb-based bulk lasers delivering watt-level sub-100 fs pulses have been reported only with a few kinds of gain media, such as Yb:CaF<sub>2</sub> [12–14], Yb:CGA [15–17], Yb:CYA [18], Yb:KGW [19–21], Yb:KYW [22], Yb:YVO<sub>4</sub> [22] and Yb:Lu<sub>2</sub>O<sub>3</sub> [23] crystals as well as Yb:LuAG ceramic [24]. Among them, sub-50 fs pulses with watt level average power were only generated from Yb:CGA as well as Yb:CaF<sub>2</sub> crystals, due to their broad emission spectra combining with excellent thermal conductivities. In this work, pumped by a high-power single-mode fiber laser, Yb:YSO crystal is proved to be capable in generating sub-100 fs pulses with over 2 W average power. Taking into account of that other Yb-doped orthosilicates crystals such as Yb:LSO, Yb:SSO, and Yb:LYSO has broader emission spectra and higher thermal conductivities than Yb:YSO crystal does (see Fig. 1), it is possible to generate sub-50 fs pulses with watt level average power from these Yb-doped orthosilicates crystals in the fiber pumping geometry.

## 4. Conclusion

In conclusion, we have reported on a high power KLM Yb:YSO oscillator pumped by a single-mode fiber laser emitting at 976 nm. With 10% output coupler, the CW thershold was only 750 mW, and the optical-optical efficiency as well as an absorption efficiency were 43.8% and 72.2%, respectively. By finely tuning the cavity, stable pulses with as high as 2.03 W average power and 95 fs pulse duration were obtained. The pulses had 14.8 nJ pulse energy and a record peak power of 155.7 kW. This work is not only the first demonstration of KLM operation in the Yb:YSO oscillator, but also the first time to demonstrate a watt level Yb-doped orthosilicate lasers delivering sub 100 fs pulses. It is believed that higher power with even shorter pulses could be obtained from Yb-doped orthosilicates crystals in this fiber pumping geometry.

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