Kerr-lens mode-locked Tm^{3+}:Sc_2O_3 single crystal laser in-band pumped by an Er:Yb fiber MOPA at 1611 nm

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We demonstrate a Kerr-lens mode-locked Tm^{3+}:Sc_2O_3 single crystal laser in-band pumped by an Er^{3+}:Yb^{3+} fiber MOPA at 1611 nm. Pulses as short as 166 fs with an average output power of 440 mW are obtained. The spectral bandwidth and center wavelength are 29.3 nm and 2124 nm, respectively. At a longer pulse duration of 298 fs we obtain 1 W of average output power. The repetition rate is 95 MHz and the conversion efficiency against the absorbed pump power is as high as 47%. To the best of our knowledge, this is the first Kerr-lens mode-locked Tm^{3+} doped solid state laser. © 2017 Optical Society of America

OCIS codes: *(140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers.*

http://dx.doi.org/10.1364/OL.99.099999

Tm^{3+} doped materials are recognized as most promising for highly efficient high power lasers in the 2 μm wavelength range. They have a variety of applications such as material processing (silicon, organic, polymer materials) [1,2], LIDAR [3] and as a pump source for generating coherent light at even longer wavelengths, such as Ho^{3+} lasers around 2.1 μm [4], Cr^{2+} lasers around 2.2-2.9 μm [5], mid-infrared OPOs for wavelengths up to 12 μm [6,7], or mid-infrared supercontinuum generation [8]. Nowadays, mode-locked Tm^{3+} doped solid state lasers were reported based on various kinds of gain media and saturable absorbers e.g. Tm^{3+}:Lu_2O_3 with single wall carbon nanotubes [9], Tm^{3+}:KYW with semiconductor saturable absorber [10], and Tm^{3+}:CLNGG with graphene [11]. Among Tm^{3+} doped materials, Tm^{3+} doped sesquioxides (Tm^{3+}:Re_2O_3, Re=Sc, Lu or Y) are the most attractive gain materials as they possess superior thermal and mechanical properties as well as a broad gain bandwidth above 1980 nm where less water vapor absorption and Tm^{3+} reabsorption exist. In addition, the influence of Stark splitting on Tm^{3+} doped materials is larger than that of Ho^{3+} doped materials so that one of the gain peaks of Tm^{3+}:Sc_2O_3 is shifted to a wavelength of 2150 nm (Fig.1a) which is longer than typical peak gain positions of Ho^{3+} doped materials. The Re_2O_3 have high nonlinear refractive induces (about twice as high as YAG [12]) that increase self-phase modulation effect in mode-locked operation. Although the available crystal size is limited due to the high melting points of Tm^{3+}:Re_2O_3 so far and their small absorption cross sections around 800 nm require thick gain media, pulses as short as 175 fs, 218 fs, and 148 fs were obtained by Ti^{3+}:sapphire laser pumped mode-locked Tm^{3+}:Lu_2O_3 [9], Tm^{3+}:Sc_2O_3 [13] and Tm^{3+}:$LuScO_3$ [14] lasers, respectively. Promising results have also been obtained with mode-locked Tm^{3+}:Lu_2O_3 under direct laser diode (LD) pumping [15]. In prior mode-locked Tm^{3+} solid state lasers, Ti^{3+}:Al_2O_3 lasers or LDs emitting at ~800 nm were used as pump sources, because thanks to a fortuitous two-for-one cross-relaxation process ($^3H_6 \Rightarrow {}^3H_4 \Rightarrow 2 \times {}^3F_4$), Tm^{3+} lasers at 2 μm can be highly efficient despite the large energetic difference between the pump and the laser photons (Fig. 1b). This process, however, requires high Tm^{3+} doping levels which may cause thermal problems or detrimental reverse cross relaxation processes at high inversion levels [16]. In addition, the available pump power and efficiency of Ti^{3+}:Al_2O_3 pump sources as well as the brightness of direct LD pump sources are strongly restricted so far. Direct in-band pumping from the ground state $^3H_6$ into the upper laser level $^3F_4$ (Fig.1b) at wavelengths around 1.6 μm is another very attractive scheme for Tm^{3+} lasers that would mitigate the restrictions mentioned above and allow for an

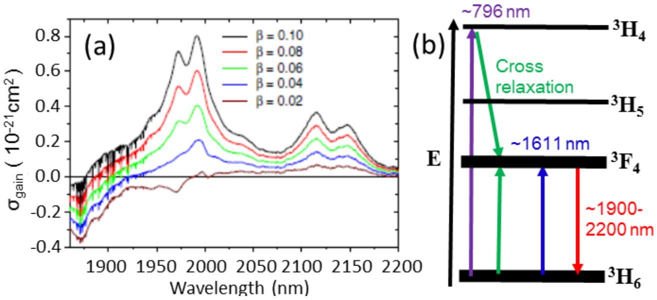

Fig. 1. (a) Gain spectra of Tm^{3+}:Sc_2O_3 for a different inversion fraction, β [12, 15]). (b) Energy level of Tm^{3+}:Sc_2O_3. Two-for-one cross-relaxation pumping process and in-band pumping process are shown.

improved performance of Tm^{3+} lasers. This concept has previously been applied to a Tm^{3+} fiber laser operating at very short emission wavelengths between 1650 nm and 1750 nm. Direct in-band pumping by an Er^{3+} fiber laser allowed for more than 60% of efficiency at more than 10 W of output power [17]. Moreover, a slope efficiency in excess of 90% could be demonstrated from a Tm^{3+} fiber laser emitting at 2005 nm in- band pumped by another Tm fiber laser at 1908 nm [18]. In-band pumped Tm^{3+} solid state lasers such as LD pumped Tm^{3+}:KYW [19], Er^{3+} solid state laser pumped Tm^{3+}:YAG [20], Raman fiber laser pumped Tm^{3+}:CGA [21] and Tm^{3+}:Lu$_2$O$_3$ [22] lasers were also demonstrated. We also have already reported Tm^{3+}:KYW [23] and Tm^{3+}:Sc$_2$O$_3$ [24] lasers in-band pumped by fiber lasers in continuous wave (CW) operation mode. To achieve shortest pulse durations, mode-locked lasers based on the Kerr-lens mode locking (KLM) technique possess many advantages [25, 26]. KLM in the mid-IR wavelength range, however, is challenging as the magnitude of the Kerr-lens effect is proportional to w^4 where w is the cavity mode radius which is proportional to square root of the laser wavelength. KLM in mid-IR wavelength range has previously been successfully demonstrated only with the semiconductor materials Cr^{2+}:ZnSe and Cr^{2+}:ZnS, both exhibiting an order of magnitude larger nonlinear refractive indices [26] than that of typical insulator laser crystals used in the IR wavelength region. Very recently, KLM at 2.1 μm was obtained with a Ho:YAG thin-disk laser with an additional Kerr medium inside the cavity [27]. KLM of any Tm^{3+} doped solid state laser has not been reported so far.

Here, we demonstrate the first Kerr-lens mode-locked Tm^{3+} laser to the best of our knowledge. The Tm^{3+}:Sc$_2$O$_3$ laser was in-band pumped by an Er^{3+}:Yb^{3+} fiber MOPA at 1611 nm and generated pulses as short as 166 fs and 298 fs at 440 mW and 1 W of average output power, respectively.

The schematic setup of the KLM laser cavity is depicted in Fig. 2. We used a standard Z-shaped cavity consisting of an end mirror, two folding mirrors, an IR grade fused silica prism pair for dispersion compensation, and an output coupler. The pump source was a home-built 1611 nm Er^{3+}:Yb^{3+} fiber MOPA (linearly polarized, ~30 MHz narrow linewidth, ~8 W maximum power [28]).

Tm^{3+}:Sc$_2$O$_3$ has an absorption cross section of 0.82 × 10^{-20} cm^2 at 1611.5 nm which is twice as high as the absorption around 800 nm [15] so that the material thickness can be reduced for in-band pumping. In addition, the MOPA pump source provides single transverse mode output which is favorable for KLM. The gain medium was a Tm^{3+}(1%):Sc$_2$O$_3$ crystal with a thickness of 2.7 mm and a circular aperture of 7 mm mounted in a water cooled copper heat sink and placed between the folding mirrors at Brewster's angle. The folding mirrors had a high reflection (HR, >99.8%) coating for the wavelength range between 1850 nm and 2200 nm and a radius of curvature of 100 mm. The pump light was imaged into the gain medium by an aspherical lens (f = 18.4 mm) and a spherical lens (f = 75 mm) through one of the folding mirror, which provided a transmission of 90% for the pump wavelength and were HR coated for the range of expected laser wavelengths. The estimated diameters of the pump laser mode and the cavity mode at the position of the gain medium were 47 × 47 μm and 55 × 57 μm (sagittal × tangential), respectively. The end mirror has HR a coating for wavelengths above 2050 nm, a high transmission below 1950nm, and some residual transmission around 1980 mm. These transmission characteristics shifted the operation wavelength to the longer wavelength, broader gain peak around 2120 nm instead of the peak around 1980 nm with somewhat higher gain (cf. Fig. 1a) [9]. The prism pair had a tip-to-tip separation of 7.5 cm corresponding to a total GDD of ~-2400 fs^2 per roundtrip. We utilized two different plane output couplers (OC) with a wedge of 30' and transmissions of 1% or 2.5% between 2000 nm and 2300 nm. While the 1% OC was utilized to obtain shortest pulse durations, the 2.5% OC allowed for the higher average output powers. Initially we tried SESAM mode locking, where the SESAM was placed in the cavity arm without the prism pair and the 1% OC was placed after the prism pair (see Fig. 2). Due to the high losses of the available SESAM and the absence of the end mirror we could not suppress lasing at ~1980 nm and did not obtain mode locking with fs-pulses. Thus, we replaced the SESAM by a plane HR mirror and obtained KLM after some careful alignment of the distance between M1 and M2. However, in the subsequent experiments we placed the 2.5 % OC in the other arm of the cavity in order to avoid spatial dispersion effects occurring in the prism-arm which could be problem in further pulse shortening. In none of the experiments we utilized a hard aperture inside the cavity so that the self-starting KLM would be induced by the soft aperture effect in all cases.

The laser characteristics of the KLM Tm^{3+}:Sc$_2$O$_3$ laser with the 1% OC are shown in Fig. 3a. The KLM laser operation was self-starting while increasing the pump power. With the onset of KLM, the output power increased significantly by about 100 mW from 220 mW to 320 mW. At an output power of 320 mW a pulse duration of 247 fs was obtained under an incident pump power of 1.4 W. The pulse train of the KLM is shown in Fig. 3b and Fig. 3c. The repetition rate was 95 MHz. The KLM was stable for several hours and self-recovering after interrupting the resonator.

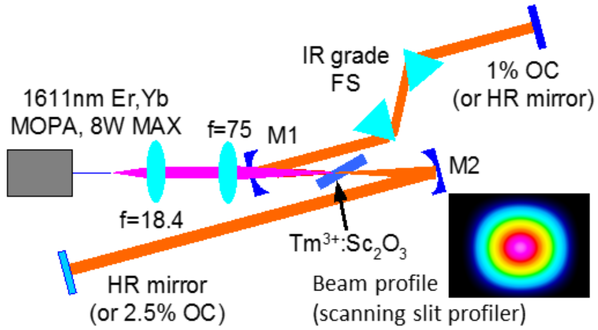

Fig. 2. Schematic picture of the KLM laser

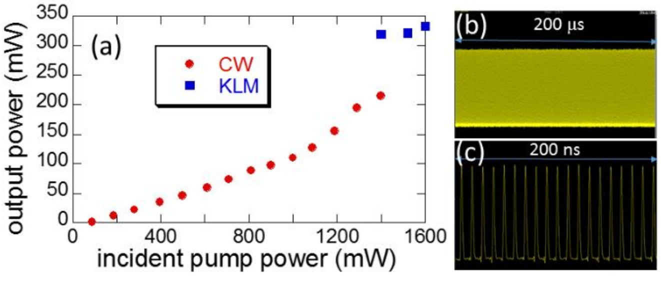

Fig. 3. (a) Laser characteristics of the KLM Tm^{3+}:Sc$_2$O$_3$ laser with 1% OC. (b) Pulse train for the period of 200 μs (c) Pulse train for the period of 200 ns.

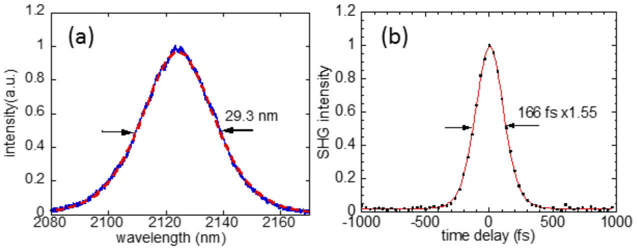

Fig. 4. (a) Measured spectrum (blue solid curve) and its sech^2 fitting (red dashed curve). (b) Autocorrelation trace at the output power of 440 mW. Measured data (black circles) and Sech^2 fitting (red curve).

After the optimization of the cavity for short pulse duration, i.e. alignment of the insertion depth of the prisms, the position of the gain medium along the optical axis, the distance between the folding mirrors as well as the pump power, pulses as short as 166 fs (assuming sech^2 pulses) with a spectral bandwidth of 29.3 nm at a center wavelength of 2124 nm were obtained (Fig. 4a and Fig. 4b). The optical spectrum was measured by an OSA205 (Thorlabs Inc.) and the pulse duration was measured by a home-built autocorrelator with a 300 μm thick type 2 KTP nonlinear crystal. The pulses were close to Fourier limited with a time bandwidth product of 0.32. At the shortest pulse duration the output power was 440 mW at a pump power of 3.15 W. The corresponding pulse energy and peak power were 4.6 nJ and 28 kW, respectively. The intracavity peak power would be as high as 2.8 MW. During the experiment, we observed a red shift of the peak emission wavelength when the laser was aligned for shorter pulse durations (Fig. 5a). The shortest peak wavelength was 2116 nm and it continuously shifted to 2128 nm during the alignment and finally switched to 2139 nm. This switch is explained by the multi-peak gain structure of Tm^{3+}:Sc$_2$O$_3$ (Fig. 1a). The pulse duration at the sub-peak around 2140 nm was 214 fs (Fig. 5b) at a center wavelength of 2142 nm and a spectral bandwidth of 24.0 nm. The corresponding time bandwidth product was 0.34. In this operation regime, the KLM was very sensitive and CW breakthrough peaks were observed in the spectrum e.g. when increasing the pump power. Under some alignment conditions, we observed a random switching of the center wavelength between the peaks at ~2128 nm and ~2140 nm or between KLM and CW operation mode, which ultimately limited the available shortest pulse duration. We thus believe that by utilizing optimized mirror coatings and/or improved cavity design with respect to the modulation depth of the KLM, it should be feasible to address the total 3dB gain bandwidth of the double-peak gain structure of Tm^{3+}:Sc$_2$O$_3$ around 2.1 μm of 50 nm or even more, depending on the inversion level (see Fig. 1a). In this way, sub-100 fs pulse durations should be possible. It should, however, be noted that an estimation of the modulation depth of the current KLM cavity from the increasing of the output power with the onset of KLM (cf. Fig. 3a) is not straight forward. This is because unlike hard aperture KLM based solely on a loss modulation, the soft aperture KLM process is based on an effective gain modulation via changing the mode matching between the laser mode and the pump mode [29].

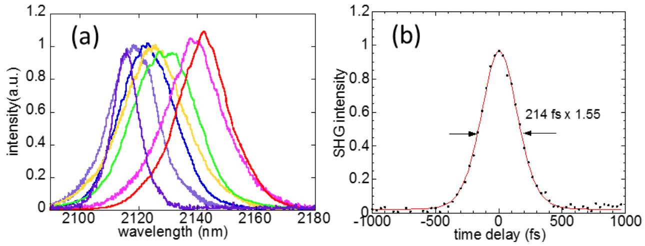

Fig. 5. (a) Measured spectra with different pulse spectral bandwidth. The shift and broadening of the emission peak to longer wavelengths went along with a pulse shortening. The pulse shortening was not observed after the switch of peak emission to ~2140 nm. (b) Autocorrelation trace of the center wavelength of 2142 nm.

As previously mentioned, we also performed experiments with the 2.5% OC targeting higher average output powers. Indeed we could increase the average output power to a value as high as 1 W at a pulse duration of 298 fs (Fig. 6a and Fig. 6b), a pump power of 3.7 W, and a somewhat larger tip-to-tip prism separation of 8.5 cm. As expected due to the higher inversion needed to overcome the larger losses in this configuration, the center wavelength of 2115 nm was somewhat shorter than for the best results obtained with the 1% OC. The spectral bandwidth of 15.5 nm yielded a time bandwidth product of 0.31, corresponding (within the error) to Fourier limited sech^2 pulses. The pulse energy and the peak power were 10.5 nJ and 35.2 KW, respectively. It should be noted that the absorption efficiency of the laser crystal was estimated to be only 56% by measuring the residual pump powers. The resulting absorbed pump power of 2.1 W corresponds thus to a conversion efficiency vs. the absorbed pump power as high as 47%. The KLM at the similar output power level was also obtained without the water cooling The beam profile measured with a scanning beam profiler shown in Fig.1 (with the 2.5% OC) indicates the expected high beam quality of the KLM laser. In fact, KLM could hardly be achieved with poor beam quality and corresponding larger mode diameters.

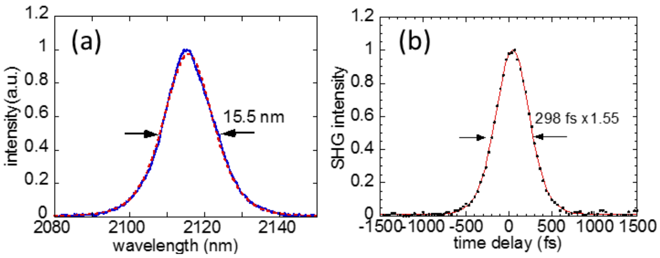

Fig. 6. (a) Measured spectrum (blue solid curve) and its Sech^2 fitting (red dashed curve). (b) Autocorrelation trace of pulses at the output power of 1W and the center wavelength of 2115 nm.

In conclusion, we have demonstrated the first Kerr-lens mode-locked operation of a Tm^{3+} doped solid state laser in the 2 μm wavelength range. We employed an Er^{3+}:Yb^{3+} fiber MOPA pump source at 1611 nm for in-band pumping of Tm^{3+}:Sc$_2$O$_3$. Pulses as short as 166 fs with an average output power of 440 mW were obtained. The center wavelength was 2124 nm and the spectral bandwidth was 29.3 nm. In a configuration optimized for high output power, 1 W was obtained in 298-fs-pulses. This is the first mode-locked operation with a fiber laser in-band pumping scheme for Tm^{3+} and the first watt-level output power mode-locked oscillator in this wavelength range, too. The results were limited by the onset of mode locking instabilities and CW breakthroughs, but neither by the available pump power nor by thermal problems so far. Thus further increasing of the output power with the similar pulse duration seems feasible by increasing the total GDD of the cavity. Further pulse shortening could also be possible by using a hard aperture inside the cavity. The new in-band pumped short pulse Tm^{3+} solid state laser scheme could also be useful for high power amplifier systems in the 2 μm wavelength range, even though the total efficiency and further power scaling of them is currently limited by the available pump sources. Highly efficient high power operation could be enabled utilizing by more powerful LDs or cascaded Raman laser in-band pump sources in future.

Funding. We acknowledge financial support from JSPS KAKENHI Grant-in-Aid for Young Scientists (B) Grant Number JP16K17526, The Amada Foundation, and the Photon Frontier Network Program of the Ministry of Education, Culture, Sports, Science and Technology, Japan. This work has also been supported by the excellence cluster 'The Hamburg Centre for Ultrafast Imaging - Structure, Dynamics and Control of Matter at the Atomic Scale' of the Deutsche Forschungsgemeinschaft.

Acknowledgment. We thank Dr. Philipp Koopmann for the growth of the Tm^{3+}:Sc_2O_3 single crystal used in the experiments and valuable prior works on this gain material [16].

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