1200 nm pumped $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic lasers

ISINSU BAYLAM,¹ SARPER OZHARAR,² AND ALPHAN SENNAROGLU^{1,3,*}

¹Koç University Surface Science and Technology Center (KUYTAM), Rumelifeneri, Istanbul 34450, Turkey

²College of Engineering and Natural Sciences, Bahçeşehir University, Besiktas, Istanbul 34353, Turkey

³Laser Research Laboratory, Departments of Physics and Electrical-Electronics Engineering, Koç University, Istanbul 34450, Turkey

*Corresponding author: asennar@ku.edu.tr

Received 15 September 2017; revised 16 January 2018; accepted 31 January 2018; posted 1 February 2018 (Doc. ID 307276); published 5 March 2018

We report on an experimental demonstration of a 1200-nm pumped $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser. By using a gain-switched, tunable $\text{Cr}^{4+}:\text{forsterite}$ laser, the excitation spectrum was measured, with optimum pumping bands centered near 1198 nm, 1204 nm, and 1211 nm. The highest slope efficiency of 21.5% was obtained at the pump wavelength of 1204 nm. Comparative energy efficiency measurements performed near 1200-nm and 800-nm pumping further showed that nearly 40% improvement was obtained in slope efficiency measured with respect to the incident pump energy for 1200-nm pumping. A transition was further observed from single-wavelength operation at 2066 nm to dual-wavelength operation near 2066 nm and 1967 nm for absorbed pump energies above 50 μJ . In this regime, two consecutive output pulses were observed in the time domain. The shortest temporal duration of the first pulse was 1.1 μs at the incident pulse energy of 105 μJ . The duration and build-up time of the second pulse remained around 5.9 μs and 18.5 μs . We believe that the improved energy efficiency demonstrated for the 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic with 1200-nm pumping can be used as an alternative scheme for the excitation of $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic lasers. © 2018 Optical Society of America

OCIS codes: (140.3580) Lasers, solid-state; (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers; (160.3380) Laser materials.

<https://doi.org/10.1364/AO.57.001772>

1. INTRODUCTION

Tm -doped host materials operating near 2 μm have been utilized as laser sources for ranging, medical, and chemical sensing applications [1–5]. Among Tm -doped gain media, Tm -doped sesquioxides (such as Lu_2O_3 , Y_2O_3 , and Sc_2O_3) have attracted great interest, since they provide extended tunable emission up to 2.1 μm . This enables their use as potential pump sources for ZnGeP_2 [6] and GaAs [7] based optical parametric oscillators. Furthermore, in the particular case of $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$, the high heat conductivity of the host material does not depend on the dopant concentration, making it a promising laser material for power-scaling applications [8,9]. Recently, $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramics have also attracted great interest as a result of the recent developments in the synthesis of ceramic sesquioxides in large volumes and at relatively lower temperatures [10].

To date, $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramics have been shown to operate in continuous-wave (cw), mode-locked, and Q -switched regimes with different pumping configurations [11–16], primarily based on the use of 800-nm pump sources. Pumping near 800 nm excites the $^3\text{H}_6 \rightarrow ^3\text{H}_4$ transition and makes use of the cross-relaxation mechanism, which leads to the generation of two laser photons per pump photon. However, efficient cross relaxation also requires high doping concentrations,

which may degrade the power performance of the laser due to higher re-absorption losses and increased non-radiative decay. Alternatively, the $^3\text{H}_6 \rightarrow ^3\text{H}_5$ transition (pump band near 1200 nm) can also be used to effectively excite the Tm -doped gain media with lower quantum defect [14,17]. In the particular case of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramics, the absorption cross section near 1200 nm is larger than that near 800 nm, as can be seen in Fig. 1, which shows the measured absorbance (calculated in base 10) as a function of wavelength for the 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic [14]. Furthermore, higher peak absorption near 1200 nm enables the use of $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramics with lower doping concentrations, since there is no longer a need to optimize the strength of the cross-relaxation process.

In this study, we demonstrate a gain-switched $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser pumped near 1200 nm [18]. In the experiments, we used a tunable, gain-switched $\text{Cr}^{4+}:\text{forsterite}$ laser as the pump source to determine the excitation spectrum of a 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic between 1194 nm and 1220 nm. Measurements indicated that the optimum bands were centered at 1198 nm, 1204 nm, and 1211 nm. An astigmatically compensated x-cavity was built to investigate the laser efficiency of the 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic. The highest laser efficiency measured with respect to the incident pump energy

Fig. 1. Measured background corrected absorbance of the 3-mm-long, 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic near (a) 800 nm and (b) 1200 nm.

was obtained as 21.5% when the pump wavelength was set to 1204 nm. We further compared the efficiency of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser by using 1200-nm and 800-nm pumping. The results indicated that nearly 40% improvement with respect to the incident pump energy was achieved in the measured slope efficiencies when the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic was pumped near 1200 nm. Similar to Ref. [15], a transition was observed from single-wavelength operation at 2066 nm to dual-wavelength operation at 2066 nm and 1967 nm, as the incident pump energy was increased. We obtained two distinct tuning ranges (1929–1990 nm and 2058–2078 nm) from the gain-switched $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser. Temporal dynamics of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic were further investigated by measuring the pulse durations and pulse build-up times during single- and dual-wavelength operation of the ceramic laser.

2. EXPERIMENTAL SETUP

In the experiments, a tunable, gain-switched $\text{Cr}^{4+}:\text{forsterite}$ laser, excited by a pulsed 1064-nm $\text{Nd}^{3+}:\text{vanadate}$ laser (pulse repetition rate = 1 kHz and pulse duration = 70 ns), was used as the pump source [see Fig. 2(a)]. In order to compare the efficiencies obtained via 1200-nm and 800-nm pumping, we further used a tunable, gain-switched $\text{Ti}^{3+}:\text{sapphire}$ laser that was end-pumped by the frequency-doubled output of the same $\text{Nd}^{3+}:\text{vanadate}$ laser. Both pump lasers were tuned by using a reflective diffraction grating (1500 grooves/mm), positioned at Littrow configuration as one of the end mirrors. As shown in Figs. 2(b) and 2(c), the measured linewidths of the pump lasers were 1.2 nm (1204 nm) and 0.26 nm (796 nm) and remained below 1.5 nm and 0.4 nm, respectively, over the 1194–1220 nm and 760–820 nm wavelength ranges. The M-square parameters of the pump lasers were further determined as 2.85 and 1.5 by using the knife-edge method.

In the lasing experiments, a 3-mm-long, 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic (Konoshima Chemicals Co., Japan, effective Tm^{3+} concentration = $4.2 \times 10^{20} \text{ cm}^{-3}$) was used as the gain medium. The optical characteristics of a similar $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic gain medium can be found in Ref. [19]. An

Fig. 2. (a) Schematic layout of the gain-switched $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser pumped near 1200 nm. Measured linewidths of (b) $\text{Cr}^{4+}:\text{forsterite}$ laser centered at 1204 nm and (c) $\text{Ti}^{3+}:\text{sapphire}$ laser centered at 796 nm.

astigmatically compensated x-cavity was built to investigate the laser efficiency for both pumping wavelengths (1200 nm and 800 nm). The setup for 1200-nm pumping is shown in Fig. 2(a). The tunable output beam of the gain-switched $\text{Cr}^{4+}:\text{forsterite}$ laser was focused to an estimated waist of 30 μm inside the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic by using a converging lens (L1, focal length = 7.5 cm). The $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser consisted of two curved high reflectors (C1 and C2, each with radius of curvature = 7.5 cm), a flat-end high reflector (HR), and a flat output coupler (OC) with 2.8% transmission near the operating wavelength of the laser. To obtain tuning, a quartz birefringent tuning plate (BTP, thickness = 1.5 mm) was further placed in the HR arm of the resonator at Brewster incidence, as shown in Fig. 2(a).

3. RESULTS AND DISCUSSION

Figure 3(a) shows the excitation spectrum of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic gain medium, determined by measuring the output pulse energy of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser near 2 μm as a function of the input pump wavelength. Also shown in Fig. 3(a) is the measured variation of the incident pump energy as a function of wavelength. From the measured excitation spectrum, the optimum pumping bands were determined to be 1198 nm, 1204 nm, and 1211 nm. The corresponding small-signal absorption (η_a) was measured to be 52.7%, 67.6%, and 57.6%, respectively, at these wavelengths. In the case of the $\text{Ti}^{3+}:\text{sapphire}$ pump source, the optimum pumping bands were 774 nm, 796 nm, and 811 nm with measured small-signal absorption of 41.6%, 42.4%, and 36.8%. Energy efficiency measurements were performed with respect to the incident pump energies for all six pumping wavelengths, as shown in Figs. 3(b) and 3(c). For 1200-nm (800-nm) pumping, the highest slope efficiency of 21.5% (15.8%) was obtained at the pump wavelength of 1204 nm (796 nm),

Fig. 3. (a) Measured excitation spectrum of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser as a function of the input pump wavelength. Measured energy efficiency curves of the gain-switched $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser pumped near (b) 1200 nm and (c) 800 nm.

showing the advantage of 1200-nm pumping for the 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser, as discussed above.

At all pumping wavelengths, the ceramic laser operated near 2066 nm close to lasing threshold. As the incident pulse energy was increased, a transition from single-wavelength operation (2066 nm) to dual-wavelength operation (2066 nm and 1967 nm) occurred at all pumping wavelengths except 1198 nm. Dual-wavelength operation was not observed at the pumping wavelength of 1198 nm for two reasons. First, note that as the pump laser was tuned from 1210 nm to 1198 nm, its total output energy incident on the ceramic gain medium decreased from 127 μJ to 87 μJ [see Fig. 3(a)]. Second, the total absorption of the ceramic gain medium measured at 1198 nm (52.7%) was lower than those at 1204 nm (67.6%) and 1211 nm (57.6%), yielding a maximum available absorbed pump energy of 46 μJ at 1198 nm. This was lower than the absorbed pump energies at 1204 nm (57.5 μJ) and 1211 nm (51 μJ) needed to observe dual-wavelength operation.

The transition from single- to dual-wavelength operation was due to an increase in the gain at shorter wavelengths with increasing inversion factor, as was discussed in Ref. [15]. The average passive loss (L) of the resonator at 2066 nm was further estimated as 1.7% by using the lasing threshold data obtained from the 796-nm pumped $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser. The expected slope efficiencies of the ceramic laser excited at the selected pumping wavelengths were estimated by using

$$\eta_{\text{exp.}} = \eta_{\text{CR}} \eta_o \eta_a \frac{\lambda_p}{\lambda_L} \frac{T}{T + L}, \quad (1)$$

where λ_p is the pump wavelength, λ_L is the laser wavelength, T is the output coupler transmission, L is the round-trip passive loss of the resonator, η_o is the overlap factor for the pump and the laser beams, and η_a is the small-signal absorption of the ceramic at the given pump wavelength. η_o was determined by using the estimated root-mean-squared spot sizes of the pump and the laser beams inside the gain medium and came to 0.97 and 0.95 for 1204 nm and 796 nm pumping [20]. The parameter η_{CR} in Eq. (1) provides information about the strength of the cross-relaxation process during laser operation, with $\eta_{\text{CR}} = 1$ and $\eta_{\text{CR}} = 2$ corresponding to cases of no cross relaxation and fully effective cross relaxation, respectively. In the case of 1204 nm pumping, η_{CR} was taken as 1 for the $^3\text{H}_6 \rightarrow ^3\text{H}_5$ transition. The expected energy efficiency for 1204-nm pumping came to 23.7% in reasonable agreement with the measured value of 21.5%. By using Eq. (1) and the measured efficiency for 796-nm pumping, η_{CR} was further estimated to be 1.86 ± 0.28 . This indicates that cross relaxation is already highly effective for the 1.5% $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic and increases the laser efficiency by 86%.

The effective emission cross section (σ_e) of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic was estimated by using the measured small-signal absorption and lasing threshold data as described in Ref. [21]. For the three selected pump wavelengths of 1198 nm, 1204 nm, and 1211 nm, σ_e at 2066 nm came to be $(4.58 \pm 0.26) \times 10^{-21} \text{ cm}^2$. During the gain-switched operation of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser pumped at 1204 nm, we further obtained two distinct tuning bands over the 1929–1990 nm and 2058–2078 nm wavelength ranges (see Fig. 4) by using the BTP. In the tuning experiments, the incident pump energy was 105 μJ .

Fig. 4. Measured tuning curve of the dual-wavelength, gain-switched $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser pumped with an incident energy of 105 μJ at 1204 nm.

Fig. 5. Measured (a) spectral and (b) temporal profiles of the gain-switched, dual-wavelength $Tm^{3+}:Lu_2O_3$ ceramic laser at the incident pump energy of 105 μJ . Measured pulsewidths and pulse build-up times for the pulses (c) P_1 and (d) P_2 as a function of the incident pulse energy.

Dual-wavelength operation and temporal dynamics of the gain-switched $Tm^{3+}:Lu_2O_3$ ceramic laser were further investigated by measuring the spectral output, pulse duration, and pulse build-up times as a function of the incident pulse energy at 1204 nm. In these experiments, the BTP was not included in the cavity. The gain-switched $Tm^{3+}:Lu_2O_3$ ceramic laser produced two emission peaks at 2066 nm and 1967 nm with two output pulses when the absorbed pulse energy was set above 50 μJ [see Fig. 5(a)]. Similar multi-pulse behavior was also observed when the $Tm^{3+}:Lu_2O_3$ ceramic laser was pumped near 800 nm with the Ti^{3+} :sapphire laser.

During the temporal characterization experiments, the pulse duration of the gain-switched Cr^{4+} :forsterite pump laser remained below 53 ns, which was much shorter than the fluorescence lifetime of the ceramic gain medium. For absorbed pump energies below 50 μJ , the $Tm^{3+}:Lu_2O_3$ ceramic laser operated only at 2066 nm with a single-pulse output.

For absorbed pump energies above 50 μJ , the laser produced two pulses (P_1 and P_2) and dual-wavelength operation was observed, as shown in Figs. 5(a) and 5(b). Energy-dependent durations and build-up times of both pulses were further measured with respect to the Cr^{4+} :forsterite pump pulse. Results summarized in Figs. 5(c) and 5(d) demonstrate that the pulse duration and the pulse build-up time both decreased with increasing incident pump energy for the first pulse (P_1) as expected for gain-switched operation [22]. In particular, the pulse duration and build-up time decreased from 14 μs to 1.1 μs and from 61.2 μs to 6 μs as the incident pump energy was increased from 43 μJ to 105 μJ . In the case of the second pulse (P_2), the duration and pulse build-up time did not vary significantly with the incident pump energy and remained near 5.9 μs and 18.5 μs , respectively.

4. CONCLUSIONS

In conclusion, we reported the experimental demonstration of a gain-switched $Tm^{3+}:Lu_2O_3$ ceramic laser pumped near 1200 nm. By using a tunable, gain-switched Cr^{4+} :forsterite laser as the pump source, the optimum pumping wavelengths were first determined to be 1198 nm, 1204 nm, and 1211 nm. Energy efficiency measurements indicated that the highest slope efficiency of 21.5% was obtained at the pump wavelength of 1204 nm. We also compared the energy efficiency of the 1.5% $Tm^{3+}:Lu_2O_3$ ceramic laser at the pumping wavelengths near 1200 nm and 800 nm. The energy efficiency analysis showed that for the case of 800-nm pumping, cross relaxation improved the slope efficiency by 86%. Higher absorption as well as smaller quantum defect for 1204-nm pumping resulted in approximately 40% higher slope efficiency with respect to the incident pump power in comparison with 796-nm pumping. Note that if one compares the slope efficiencies with respect to the absorbed pump energies for 1204-nm (31.8%) and 796-nm (37.3%) pumping, 796-nm pumping appears to be advantageous. However, from a practical perspective, what determines the extractable output energy of a laser is ultimately related to the maximum available incident pump energy. Hence, for the same total incident pump energy, 1200-nm pumping proves to be more effective in comparison with 800-nm pumping, since the $Tm^{3+}:Lu_2O_3$ ceramic has higher absorption and lower quantum defect.

In the case of 1200-nm pumping, at absorbed pump energies above 50 μJ , dual-wavelength operation was observed at 2066 nm and 1967 nm with two output pulses. Temporal measurements indicated that the duration and build-up time of the first pulse monotonically decreased with increasing pulse energy. The shortest temporal duration for the first pulse was

measured to be 1.1 μs at the incident pulse energy of 105 μJ . The duration and build-up time of the second pulse remained around 5.9 μs and 18.5 μs .

Various semiconductor laser architectures operating near the 1200-nm pumping band of the $\text{Tm}^{3+}:\text{Lu}_2\text{O}_3$ ceramic gain media have been recently reported [23–25]. We foresee that the improved energy efficiency demonstrated in this work for 1200-nm pumping has the potential to pave the way for the development and widespread use of 1200-nm diode-pumped Tm-doped lasers.

Funding. Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TÜBİTAK) (114F185).

REFERENCES

1. T. Bilici, S. Mutlu, H. Kalaycioglu, A. Kurt, A. Sennaroglu, and M. Gulsoy, "Development of a thulium (Tm:YAP) laser system for brain tissue ablation," *Laser Med. Sci.* **26**, 699–706 (2011).
2. R. Rasier, M. Ozeren, O. Artunay, H. Bahcecioglu, I. Seckin, H. Kalaycioglu, A. Kurt, A. Sennaroglu, and M. Gulsoy, "Corneal tissue welding with infrared laser irradiation after clear corneal incision," *Cornea* **29**, 985–990 (2010).
3. K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, "2 μm laser sources and their possible applications," in *Frontiers in Guided Wave Optics and Optoelectronics*, B. Pal, ed. (InTech, 2010).
4. T. Day, M. Pushkarsky, M. Weida, D. Arnone, and R. Pritchett, "Miniaturized tunable, external cavity quantum cascade lasers," in *8th International Conference on Mid-Infrared Optoelectronics* (2007).
5. S. W. Henderson, C. P. Hale, J. R. Magee, M. J. Kavaya, and A. V. Huffaker, "Eye-safe coherent laser-radar system at 2.1- μm using Tm, Ho:YAG lasers," *Opt. Lett.* **16**, 773–775 (1991).
6. P. A. Budni, L. A. Pomeranz, M. L. Lemons, C. A. Miller, J. R. Mosto, and E. P. Chicklis, "Efficient mid-infrared laser using 1.9- μm pumped Ho:YAG and ZnGeP₂ optical parametric oscillators," *J. Opt. Soc. Am. B* **17**, 723–728 (2000).
7. N. Leindecker, A. Marandi, R. L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann, "Octave-spanning ultrafast OPO with 2.6–6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser," *Opt. Express* **20**, 7046–7053 (2012).
8. J. Sanghera, J. Frantz, W. Kim, G. Villalobos, C. Baker, B. Shaw, B. Sadowski, M. Hunt, F. Miklos, A. Lutz, and I. Aggarwal, "10% $\text{Yb}^{3+}:\text{Lu}_2\text{O}_3$ ceramic laser with 74% efficiency," *Opt. Lett.* **36**, 576–578 (2011).
9. C. Krankel, "Rare-earth-doped sesquioxides for diode-pumped high-power lasers in the 1-, 2-, and 3- μm spectral range," *IEEE J. Sel. Top. Quantum Electron.* **21**, 1602013 (2015).
10. K. Ueda, J. F. Bisson, H. Yagi, K. Takaichi, A. Shirakawa, T. Yanagitani, and A. A. Kaminskii, "Scalable ceramic lasers," *Laser Phys.* **15**, 927–938 (2005).
11. O. L. Antipov, A. A. Novikov, N. G. Zakharov, and A. P. Zinoviev, "Optical properties and efficient laser oscillation at 2066 nm of novel Tm:Lu₂O₃ ceramics," *Opt. Mater. Express* **2**, 183–189 (2012).
12. A. A. Lagatsky, O. L. Antipov, and W. Sibbett, "Broadly tunable femtosecond Tm:Lu₂O₃ ceramic laser operating around 2070 nm," *Opt. Express* **20**, 19349–19354 (2012).
13. A. A. Lagatsky, Z. Sun, T. S. Kulmala, R. S. Sundaram, S. Milana, F. Torrisi, O. L. Antipov, Y. Lee, J. H. Ahn, C. T. A. Brown, W. Sibbett, and A. C. Ferrari, "2 μm solid-state laser mode-locked by single-layer graphene," *Appl. Phys. Lett.* **102**, 013113 (2013).
14. E. J. Saarinen, E. Vasileva, O. Antipov, J. P. Penttinen, M. Tavast, T. Leinonen, and O. G. Okhotnikov, "2 μm Tm:Lu₂O₃ ceramic disk laser intracavity-pumped by a semiconductor disk laser," *Opt. Express* **21**, 23844–23850 (2013).
15. O. Antipov, A. Novikov, S. Larin, and I. Obronov, "Highly efficient 2 μm CW and Q-switched Tm³⁺:Lu₂O₃ ceramics lasers in-band pumped by a Raman-shifted erbium fiber laser at 1670 nm," *Opt. Lett.* **41**, 2298–2301 (2016).
16. A. A. Lagatsky and J. M. Hopkins, "Diode-pumped femtosecond Tm-doped Lu₂O₃ ceramic laser," in *Laser Congress (ASSL, LAC)*, OSA Technical Digest (Optical Society of America, 2016), paper JTu2A.5.
17. F. Fusari, S. Vetter, A. A. Lagatsky, B. Richards, S. Calvez, A. Jha, M. D. Dawson, W. Sibbett, and C. T. A. Brown, "Tunable laser operation of a Tm³⁺-doped tellurite glass laser near 2 μm pumped by a 1211 nm semiconductor disk laser," *Opt. Mater.* **32**, 1007–1010 (2010).
18. I. Baylam, S. Ozharar, and A. Sennaroglu, "Tm³⁺:Lu₂O₃ ceramic lasers pumped near 1200 nm," in *Laser Congress (ASSL, LAC)*, OSA Technical Digest (Optical Society of America, 2017), paper JTh2A.13.
19. O. L. Antipov, S. Y. Golovkin, O. N. Gorshkov, N. G. Zakharov, A. P. Zinov'ev, A. P. Kasatkin, M. V. Kruglova, M. O. Marychev, A. A. Novikov, N. V. Sakharov, and E. V. Chuprunov, "Structural, optical, and spectroscopic properties and efficient two-micron lasing of new Tm³⁺:Lu₂O₃ ceramics," *Quantum Electron.* **41**, 863–868 (2011).
20. A. Sennaroglu, *Photonics and Laser Engineering: Principles, Devices, and Applications* (McGraw-Hill, 2010).
21. P. F. Moulton, "An investigation of the Co:MgF₂ laser system," *IEEE J. Quantum Electron.* **21**, 1582–1595 (1985).
22. A. Sennaroglu, U. Demirbas, A. Kurt, and M. Somer, "Concentration dependence of fluorescence and lasing efficiency in Cr²⁺:ZnSe lasers," *Opt. Mater.* **29**, 703–708 (2007).
23. A. Rantamaki, J. Rautiainen, L. Toikkanen, I. Krestnikov, M. Butkus, E. U. Rafailov, and O. Okhotnikov, "Flip chip quantum-dot semiconductor disk laser at 1200 nm," *IEEE Photon. Technol. Lett.* **24**, 1292–1294 (2012).
24. T. D. Germann, A. Strittmatter, J. Pohl, U. W. Pohl, D. Bimberg, J. Rautiainen, M. Guina, and O. G. Okhotnikov, "Temperature-stable operation of a quantum dot semiconductor disk laser," *Appl. Phys. Lett.* **93**, 051104 (2008).
25. S. L. Vetter, J. E. Hastie, V. M. Korpijarvi, J. Puustinen, M. Guina, O. Okhotnikov, S. Calvez, and M. D. Dawson, "Short-wavelength GaInNAs/GaAs semiconductor disk lasers," *Electron. Lett.* **44**, 1069–1070 (2008).