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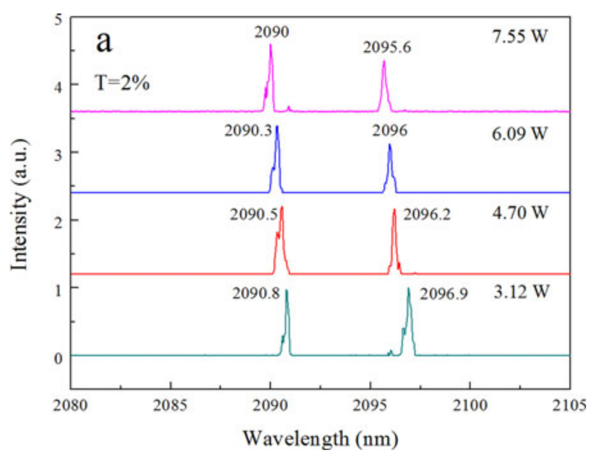

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A Diode-Pumped Dual-Wavelength Tm, Ho: YAG Ceramic Laser

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Abstract: A diode-pumped dual-wavelength CW Tm, Ho: YAG ceramic laser was demonstrated for the first time to our knowledge. A maximum output power of ~1.2 W with a beam quality factor $M^2 = 1.19$ has been generated from the 3at.% Tm, 0.5at.% Ho: YAG ceramic, corresponding to a slope efficiency of 16.7% with respect to the absorbed pump power. This Tm, Ho: YAG ceramic laser operated at dual-wavelengths around 2090 and 2096 nm. With the increase in the absorbed pump power and the output coupler transmittance, blue-shift of the emission wavelength was observed.

Index Terms: Diode-pumped lasers, infrared lasers, solid-state lasers.

1. Introduction

Benefiting from eye-safe nature and high atmospheric transmission, Ho-doped solid-state lasers working in the 2.1 μm spectral region have attracted considerable attention in recent years. It is useful for a number of advanced applications, such as wind shear detection, coherent laser lidar, and remote sensing [1], [2]. As the wavelength of Ho lasers is beneficial to avoid two-photon absorption in non-oxide nonlinear crystals, it is a more preferable pump source for optical parametric oscillators (OPO) to generate mid-infrared lasers [3]. Furthermore, the larger penetration depth of Ho-doped lasers, resulting from the laser wavelengths slightly above 2 μm, leads to different medical applications in comparison with Tm-doped lasers [4].

As a result of the near resonance energy transfer between the $^3F_4$ manifold in Tm ions and the $^5I_7$ manifold in Ho ions, Tm, Ho co-doped laser materials can be directly pumped by commercial ~800 nm AlGaAs diodes, allowing for a simple, compact, low-cost design for 2.1 μm lasers. Tm sensitized Ho lasers have been paid intensive efforts and many kinds of materials were reported to successfully generate lasers near 2.1 μm in recent years. Both schemes of Ti: sapphire pumping and diode pumping have been investigated and reported [5], yielding ~1 W and 300 mW of continuous wave (CW) output. In [6], a comparative study of Tm, Ho: YAP laser in a-cut and b-cut have been reported. A maximum output power of 946 mW at 2013 nm was achieved in b-cut crystal. Using a Ti: sapphire laser as the pump source, the Tm, Ho: $KY(WO_4)_2$ laser was experimentally demonstrated [7], with an output power of 460 mW at 2056 nm. Very recently, tunable operation was realized in the spectral range of 2060-2096 nm in Tm, Ho: $KLu(WO_4)_2$ [8], generating 451 mW of output power at 2081 nm. Tm, Ho co-doped system also have potential to realize the high power output. The dual-crystal Tm, Ho: $GdVO_4$ laser configuration, pumped by two laser diodes, was exploited to generate 20.5 W in CW mode operation with an output wavelength of 2.05 μm [9]. Using two Tm, Ho: YVO_4 rods in a single cavity, an output power of 20.2 W was obtained at 2054.7 nm with an optical to optical conversion efficiency of 32.9% [10].

Due to its excellent physical and chemical properties, as well as the high thermal conductivity, Tm, Ho: YAG has long been a promising candidate for generating laser near 2.1 μm. Spectroscopy and diode-pumped operation of Tm, Ho: YAG crystals have been reported with a maximum of 50 mW CW output power [11], [12]. More recently, a diode-pumped Tm, Ho: YAG laser with a maximum output power of 391 mW and a slope efficiency of 9.91% in free running mode was demonstrated [13]. In [14], a compact high power Tm, Ho: YAG laser was presented based on intracavity LD side pumped Tm: YAG and Tm, Ho: YAG laser modules, yielding 37.34 W of CW output power under the temperature of 6 °C.

Transparent laser ceramics have been proven to be a promising laser material. Benefiting from the progressing manufacturing technology, laser ceramics having similar optical and thermal properties with single crystals are available now. The advantages of short fabrication period lower cost, the mass production capability, as well as the convenience to prepare multifunctional and multilayer samples, have guaranteed ceramics wide applications as a laser material. A diode-side-pumped and Q-Switched rod-type Tm, Ho: YAG ceramic laser operating at a low repetition rate of 10 Hz was demonstrated and used as the pump source for OPO [15]. Spectroscopy of Tm, Ho: YAG ceramic and crystal at the same doping level was demonstrated hardly have any difference in [16]. Then laser experiment was carried out using Gradient doped rod-type Tm, Ho: YAG ceramic and by further improving the pumping chamber, 930 mJ of pulse energy was obtained at repetition rate of 10 Hz [17]. However, to the best of our knowledge, the CW laser performance of Tm, Ho: YAG ceramic laser has not been reported. The thermal accumulation in CW laser operation could significantly influence the energy transfer and up-conversion processes in Tm, Ho co-doped system and the laser performance would be different from that in Q-switched operation.

In this paper, a diode-pumped dual-wavelength CW Tm, Ho: YAG ceramic laser was reported. The laser performance of Tm, Ho: YAG as function of the Tm, Ho doping ratio was analyzed and the output coupler transmittance was optimized. A maximum output power of $\sim$1.2 W with a beam quality factor $M^2 = 1.19$ has been generated, corresponding to a slope efficiency of 16.7% with respect to the absorbed pump power. The transmission spectrum, the fluorescence spectrum and the spectral characteristic of the 3at.% Tm, 0.5at.% Ho: YAG ceramic were investigated in detail. This Tm, Ho: YAG ceramic laser operated at dual-wavelengths around 2090 nm and 2096 nm. With the increase in the absorbed pump power and the output coupler transmittance, obvious blue-shift of the emission wavelength was observed. To the best of our knowledge, this is the first demonstration of the Tm, Ho: YAG ceramic laser operating at CW mode.

2. Transmission Spectrum and Fluorescence Spectrum

The sample used for transmission and fluorescence spectrum measurements is a Tm, Ho: YAG ceramic co-doped with 3at.% Tm and 0.5at.% Ho. The dimension of the ceramic sample is 16 mm in diameter and 3.05 mm in thickness with both end surfaces optically polished. The transmission spectrum of Tm, Ho: YAG ceramic over the wavelength range of 200-2000 nm at room temperature was measured by a UV-VIS-NIR spectrophotometer (Lambda 950; Perkin-Elmer, Waltham, MA) and the result is shown in Fig. 1. In the non-absorption regions the sample presents an optical transmittance of $\sim$85%. The ceramic sample exhibits several absorption peaks around 358, 683, 781, 1205, and 1626 nm. Among them, the absorption peak of 781 nm, corresponding to the transition of $^3H_6 \rightarrow {}^3H_4$ in Tm^{3+}, matches the emission wavelength of commercially available AlGaAs laser diode well and can be used to achieve efficient pumping.

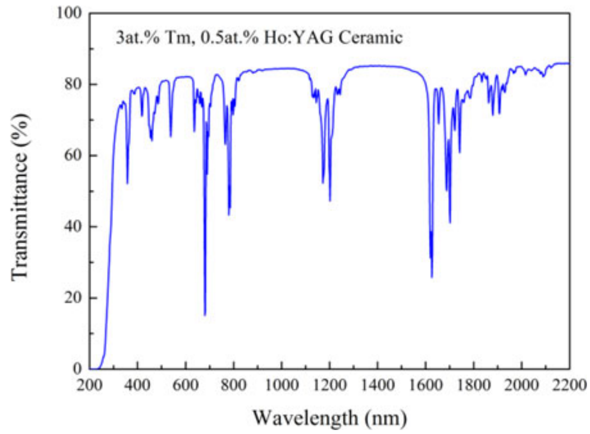

Fig. 1. Transmission spectrum of Tm, Ho: YAG ceramic.

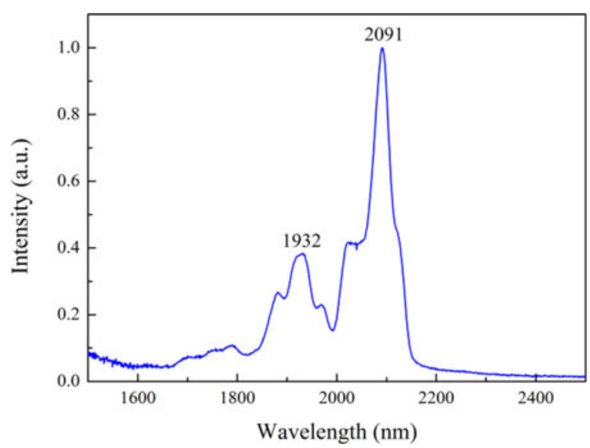

Fig. 2. Fluorescence spectrum of Tm, Ho: YAG ceramic.

Fig. 2 shows the fluorescence spectrum of the Tm, Ho: YAG ceramic from 1500 nm to 2500 nm at room temperature, which was monitored by an infrared spectrometer (FLS 980). A non-smooth multiple-spire structure can be observed in the spectrum and two major emission peaks located at 1932 nm and 2091 nm. However, taking the strong reabsorption effect around 1.9 μm into consideration, it is difficult to obtain the emission wavelength at 1932 nm in such a quasi-three level laser system.

3. Experimental Setup

A schematic drawing of the laser setup used in these experiments is shown in Fig. 3. The Tm, Ho: YAG ceramic sample was pumped by a fiber-coupled laser diode (CLH 2050, DILAS) emitting around 785 nm with a maximum power of 45.6 W. In order to match the absorption peak of the ceramic, the center wavelength of LD is tuned by changing the temperature of the cooling system and 32 °C was used in our experiment. The output-coupling fiber of the laser diodes had a core diameter of 400 μm and a numerical aperture of 0.22. The laser beam of the pump was reimaged into the ceramic with a spot radius of 100 μm by a lens assembly (F1 and F2) having 1: 0.5 imaging ratio. A plano-concave stable resonator was employed to investigate the laser performance of the Tm, Ho: YAG ceramic. The rear mirror M1 was antireflection (AR)-coated at the pump wavelength

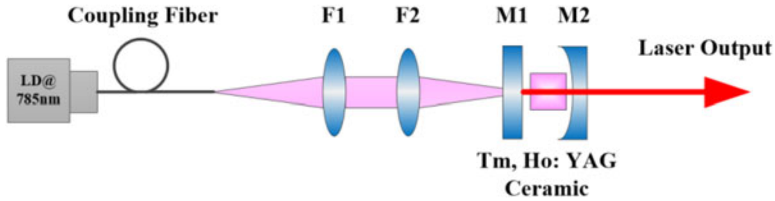

Fig. 3. Schematic diagram of the Tm, Ho: YAG ceramic laser.

TABLE I
Summary of the Concentration Comparison Experiment Results

Ceramic	Single-pass absorption	Output Power	Slope efficiency
3at.% Tm, 0.5at.% Ho	28.3%	1164 mw	16.7%
3at.% Tm, 0.3at.% Ho	27.6%	880 mw	12.5%
2at.% Tm, 0.5at.% Ho	19.7%	855 mw	13.2%
2at.% Tm, 0.3at.% Ho	19.1%	903 mw	13.4%

and high reflection (HR)-coated at the laser wavelength, and three different output couplers (M2) having transmissivities of 2%, 5%, 10% at the laser wavelength were used for optimization. The total physical cavity length was about 6 mm. In order to optimize the resonator configuration, the laser performance of four output couplers with different radii of curvatures (inf, 100 mm, 200 mm, 300 mm of 2% transmission) were investigated and finally we selected a curvature radius of 200 mm as the output coupler according to our experimental results. All the Tm, Ho: YAG ceramic samples used in the following experiments have a dimension of 3.05 mm $\times$ 2.85 mm $\times$ 3.05 mm. Both end surfaces of the ceramics (3.05 mm $\times$ 2.85 mm) were polished to laser quality and AR-coated in the range of 760–810 nm and 2000–2200 nm. To eliminate the heat generated during the laser experiment, the ceramics were wrapped in an indium foil layer of 100 μm in thickness and then mounted in a water-cooled copper heat-sink. The temperature of the cooling water was maintained at 15 °C.

4. Experimental Results

Four ceramic samples with different doping concentrations were used in our experiment and the doping concentrations were listed in Table I. The laser performances were investigated in detail using 2% transmission output coupler of 200 mm radius of curvature. Fig. 4 shows the output powers as functions of the absorbed pump powers for the four laser ceramic samples, and the detailed information was presented in Table I.

For a Tm, Ho co-doped ceramic laser system, the strong absorption of Tm^{3+} at about 781 nm and the following cross-relaxation process provided a high pump quantum efficiency. Then the subsequent energy transfer from $^3F_4$ of Tm to $^5I_7$ of Ho led to the excitation of the upper laser level of Ho and finally the laser was emitted through the $^5I_7 \rightarrow ^5 I_8$ transition. Both the absorption efficiency and the quantum efficiency of the cross-relaxation process were affected by the doping concentration of Tm. While the doping concentration of Ho ions had great influences on the emission coefficient and the up-conversion process [18]. Besides, the energy transfer efficiency between them was also greatly affected by the doping concentrations of both Tm and Ho and the final slope efficiency was affected in this way [19]. A better concentration ratio of Tm^{3+} and Ho^{3+} would lead

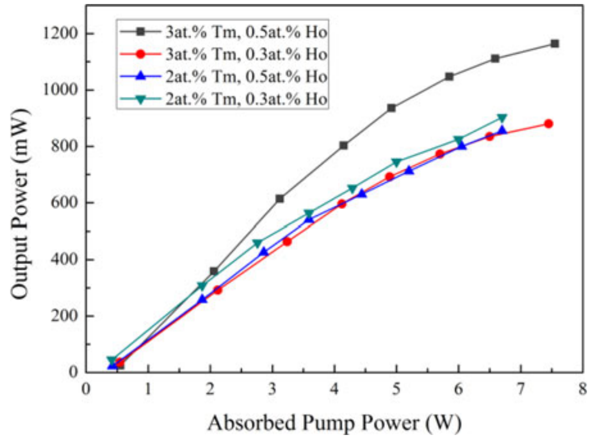

Fig. 4. Laser performance for different co-doping ratio of the Tm, Ho: YAG ceramics.

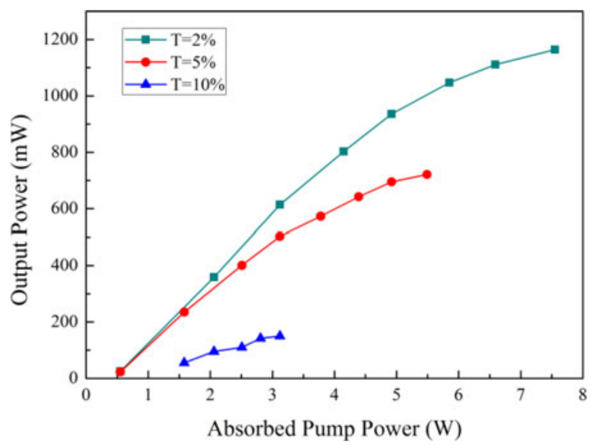

Fig. 5. Laser performances for output couplers of different transmissions.

to a better laser performance. In our experiments, the best laser performance was achieved with the 3at.% Tm, 0.5at.% Ho: YAG. The maximum output power was ~1.2 W and the corresponding slope efficiency was 16.7% with respect to the absorbed pump power. By further optimizing the concentration ratio between Tm^{3+} and Ho^{3+}, higher efficiency and higher output power could be achieved.

Further research was carried out on the basis of the 3at.% Tm, 0.5at.% Ho: YAG ceramic sample. Three output couplers having different transmissions of 2%, 5% and 10% (R = 200 mm) were used for comparison and the results are shown in Fig. 5. From Fig. 5, we can see that the output power and the corresponding slope efficiency of the ceramic decreased with the increasing of the transmission. This should be attributed to the increase of up-conversion losses that came with the higher inversion ratio at higher transmission. When the output coupler of 10% transmission was used, the threshold was increased to around 1.5 W and the slope efficiency dropped to 6.2%. The maximum laser output power was limited to only 150 mW.

The emission spectrum of the Tm, Ho: YAG ceramic (3at.% Tm, 0.5at.% Ho) laser at different absorbed pump powers are presented in Fig. 6(a). Dual-wavelength laser operation was obtained with the two emission peaks centered around 2090 and 2096 nm. The full width at half maximum (FWHM) of the spectrum were 0.25 nm and 0.3 nm, corresponding to the laser wavelength of 2090 nm and 2095.6 nm at the highest output power. When the absorbed pump power was increased,

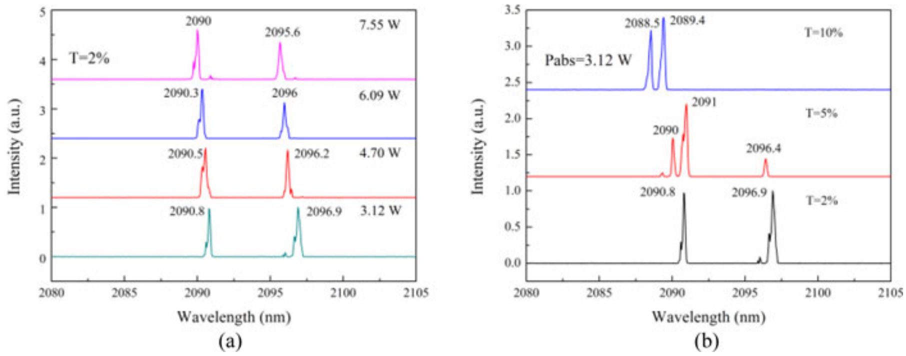

Fig. 6. (a) Laser emission spectrum of Tm, Ho: YAG ceramics laser at different absorbed pump power. (b) Laser emission spectrum of Tm, Ho: YAG ceramics laser with different output coupler transmission.

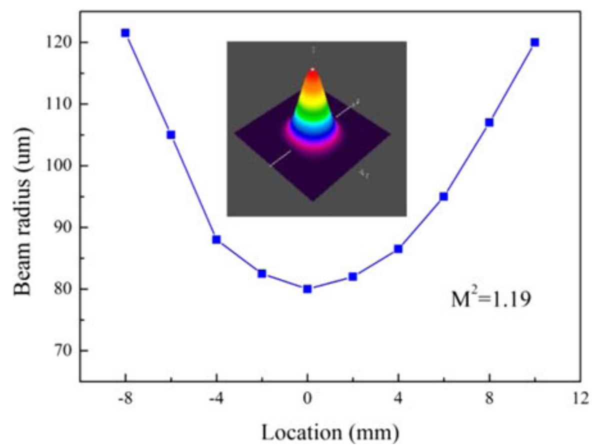

Fig. 7. Beam profile evolution of the Tm, Ho: YAG ceramics laser as a function of the distance from the focusing lens.

obvious blue-shift of the emission wavelength was observed. This may be attributed to the accumulating thermal effects improved the ceramic temperature and the particle population was changed due to the temperature increase which could change the inversion ratio in quasi-three level laser system [8].

The increase in transmission of the output coupler also led to a laser wavelength shift to shorter wavelength, as shown in Fig. 6(b). For T $=$ 2%, the Tm, Ho: YAG ceramic laser operated at a rather long wavelength region of the emission spectrum, with the two emission peaks locating at 2090.8 and 2096.9 nm. Three-wavelength emission was observed when the transmission was changed to 5%. The oscillation at the longer wavelength weakened and two shorter wavelengths of 2090 and 2091 nm occurred. When the transmission of the output coupler was further increased to 10%, the emission peak at around 2096 nm disappeared while the shorter ones shifted to 2088.5 and 2089.4 nm. We attributed the wavelength variation to the change of inversion ratio that came with the change in the transmission of the output coupler. The resultant change in the up-conversion rate further changed the emission wavelength. This multi-wavelength emission in Tm, Ho: YAG ceramic laser may have potential applications in Doppler lidar and THz radiation generation.

Using an additional focusing lens behind the output coupler, the evolution of the laser beam profile was monitored by a beam profiler (Nanoscan, Photon Inc.), and the results are shown in Fig. 7. The beam quality factor was determined by fitting the Gaussian beam propagation equation to the measured results. The beam quality factor at the maximum output power was measured to be $M^2 = 1.19$ with this method.

5. Conclusion

In conclusion, the continuous operation of a diode-pumped dual-wavelength Tm, Ho: YAG ceramic laser was experimentally demonstrated. The spectroscopic characteristic of the 3at.% Tm, 0.5at.% Ho: YAG ceramic was reported. The influences of the Tm, Ho doping ratio and the output coupler transmittance on the laser performance were investigated in our experiment. The evolution of the laser spectrum under different configurations was also discussed in detail. A maximum output power of $\sim$1.2 W with a beam quality factor $M^2 = 1.19$ was obtained, corresponding to a slope efficiency of 16.7% with respect to the absorbed pump power. As far as we know, this is the highest output power achieved in Tm, Ho: YAG ceramic laser system and the first demonstration of the Tm, Ho: YAG ceramic laser operating at CW mode.

References

[1] T. S. Kubo and T. J. Kane, "Diode-pumped lasers at five eye-safe wavelengths," *IEEE J. Quantum Electron.*, vol. 28, no. 4, pp. 1033–1040, Apr. 1992.

[2] R. Targ *et al.*, "Coherent lidar airborne wind sensor II: Flight-test results at 2 and 10 μm," *Appl. Opt.*, vol. 35, no. 36, pp. 7117–7127, 1996.

[3] 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 $ZnGeP_2$ optical parametric oscillators," *J. Opt. Soc. Amer. B*, vol. 17, no. 5, pp. 723–728, 2000.

[4] V. Jambunathan *et al.*, "Crystal growth, optical spectroscopy, and continuous-wave laser operation of co-doped (Ho, Tm): KLu $(WO_4)_2$ monoclinic crystals," *J. Opt. Soc. Amer. B*, vol. 31, no. 7, pp. 1415–1421, 2014.

[5] G. L. Bourdet and R. A. Muller, "Tm, Ho: YLF microchip laser under Ti:sapphire and diode pumping," *Appl. Phys. B*, vol. 70, no. 3, pp. 345–349, 2000.

[6] H. Bromberger *et al.*, "Comparative investigations on continuous wave operation of a-cut and b-cut Tm, Ho: $YAlO_3$ lasers at room temperature," *Opt. Exp.*, vol. 19, no. 7, pp. 6505–6513, 2011.

[7] A. A. Lagatsky *et al.*, "Optical spectroscopy and efficient continuous-wave operation near 2 μm for a Tm, Ho: KYW laser crystal," *Appl. Phys. B*, vol. 97, no. 2, pp. 321–326, 2009.

[8] P. Loiko *et al.*, "Microchip laser operation of Tm, Ho: KLu $(WO_4)_2$ crystal," *Opt. Exp.*, vol. 22, no. 23, pp. 27976–27984, 2014.

[9] L. J. Li *et al.*, "CW and AO Q-switched operation of a dual-crystal Tm, Ho: $GdVO_4$ laser pumped by two diodes," *Laser Phys.*, vol. 23, no. 2, pp. 54–58, 2013.

[10] B. Q. Yao, G. Li, P. B. Meng, G. L. Zhu, Y. L. Ju, and Y. Z. Wang, "High power diode-pumped continuous wave and Q-switch operation of Tm, Ho: YVO_4 laser," *Laser Phys. Lett.*, vol. 7, no. 12, pp. 857–861, 2010.

[11] T. Y. Fan, G. Huber, R. L. Byer, and P. Mitzscherlich, "Spectroscopy and diode laser-pumped operation of Tm, Ho: YAG," *IEEE J. Quantum Electron.*, vol. 24, no. 6, pp. 924–933, Jun. 1988.

[12] T. Yokozawa, H. Nakajima, T. Yamamoto, and H. Hara, "Oscillation characteristics of diode-pumped Tm: YAG and Tm, Ho: YAG microchip lasers," *Rev. Sci. Instrum.*, vol. 66, no. 9, pp. 4453–4457, 1995.

[13] Y. L. Ju *et al.*, "Diode-pumped tunable single-longitudinal-mode Tm, Ho: YAG twisted-mode laser," *Chin. Opt. Lett.*, vol. 13, no. 11, pp. 111403–111406, 2015.

[14] C. Zhang *et al.*, "A compact High Power Laser-Diode Side-Pump Tm, Ho: YAG Laser Nearly at Room Temperature with Intracavity Tm: YAG Laser," *Chin. Phys. Lett.*, vol. 31, no. 4, pp. 54–56, 2014.

[15] H. Hazama, M. Yumoto, T. Ogawa, S. Wada, and K. Awazu, "Mid-infrared tunable optical parametric oscillator pumped by a Q-switched Tm, Ho: YAG ceramic laser," *Proc. SPIE*, vol. 7197, pp. 71970J-1–71970J-7, 2009.

[16] Y. Urata, T. Kozeki, A. Kudo, A. Sato, K. Asai, and S. Wada, "Characterization of thulium and holmium-doped YAG ceramic laser materials," *Proc. SPIE*, vol. 6409, pp. 64091J-1–64091J-8, 2006.

[17] Y. Urata, M. Yumoto, O. Louchev, and S. Wada, "Q-switch operation of thulium and holmium-doped YAG ceramic laser at room temperature," *Proc. SPIE*, vol. 7153, pp. 715315-1–715315-8, 2008.

[18] M. Doshida, K. Teraguchi, and M. Obara, "Gain measurement and upconversion analysis in Tm3+, Ho3+ co-doped alumino-zirco-fluoride glass," *IEEE J. Quantum Electron*, vol. 31, no. 5, pp. 910–915, May 1995.

[19] B. M. Walsh, N. P. Barnes, and B. Di. Bartolo, "The temperature dependence of energy transfer between the Tm 3F4 and Ho 5I7 manifolds of Tm-sensitized Ho luminescence in YAG and YLF," *J. Lumin.*, vol. 90, no. 1, pp. 39–48, 2000.