Continuous-wave laser performance of 10 at% Yb:YSAG transparent ceramics

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Abstract

We report on the continuous-wave and tunable laser operation of transparent 10 at% Yb:Y\(_3\)Sc\(_1.5\)Al\(_3.5\)O\(_{12}\) (Yb:YSAG) ceramics, which have a dense and homogenous microstructure after being sintered at 1820 °C for 10 h. The Yb:YSAG ceramics have excellent optical in-line transmittance characteristics. The broad absorption and emission spectra of Yb:YSAG demonstrated that these ceramics are suitable for laser-diode pumping solid-state lasers. For the 2-mm thick ceramic, a continuous-wave output power of 1.79 W at 1031 nm was measured with a slope efficiency of 18.3%, and a smooth tunable spectra ranging from 1021 nm to 1040 nm has been obtained, with a tunable wavelength exceeding approximately 19 nm.

1. Introduction

Since the invention of the first Nd:Y\(_3\)Al\(_5\)O\(_{12}\) (Nd:YAG) ceramic laser in 1995, \(^[1]\) there has been enormous progress on the study of rare-earth-doped polycrystalline ceramics. Recently, Nd:YAG ceramics have been fabricated to achieve high average power in excess of 67 kW and >100 kW \(^[2, 3]\). To refine laser performance, the study for finding better solid-state laser gain media to replace existing ones has never stopped. Subsequently, some research findings on Yb:YAG ceramic lasers show that ytterbium ions with three energy levels, possessing theoretical quantum efficiency of 90% \(^[4]\), are more efficient than neodymium ions with four energy levels when employed as the laser gain media. Moreover, compared to Nd:YAG ceramics, Yb:YAG ceramics have some other advantages, such as no concentration-dependent quenching, longer fluorescent lifetimes, and much smaller thermal loadings\(^[5]\). Therefore, there have been numerous efforts to use ytterbium ions instead of Nd ions, and Yb:YAG ceramics have been widely studied as gain media for high power lasers.

To further improve the properties of ceramics, abundant studies have explored numerous ways to refine the ceramic substrate. In order to solve the high-temperature problems and improve the efficiency, the Yb:YAG ceramics lasers are generally cooled to low temperature. The cryogenic cooling results in the improvements of the thermos-optic \(^[6, 7]\) and spectroscopic properties \(^[8, 9]\). However, the emission bandwidths of Yb:YAG ceramics decrease tremendously \(^[10, 11]\), restraining the generation of short pulses. Some mixed garnets are used to broaden the narrow bandwidth, which will have similar material properties comparing with YAG and possess better thermomechanical properties. These mixed garnets can be obtained by replacing some of the aluminum metal ions with other metal ions, such as gallium and scandium, which results in an inhomogeneous broadening in the host matrix. Some special materials could be used to fabricate novel laser materials, such as sesquioxides. With substitution of Al\(^{3+}\) with Sc\(^{3+}\) in YSAG ceramics, the thermal and mechanical properties are maintained. Moreover, benefiting from the introduction large Sc\(^{3+}\) ions in ceramics, the distance between lattice sites is enlarged, broadening absorption and emission spectra compared to Yb:YAG ceramics.
In the past ten years, there have been some reports on Yb:YSAG ceramic lasers. In 2004, Saikawa et al. firstly fabricated 15 at% Yb:Y\textsubscript{3}Sc\textsubscript{1.5}Al\textsubscript{3.5}O\textsubscript{12} ceramics\cite{12}. The SESAM was used for passive mode-locking laser, and a 580 fs short pulse at an output power of 62 mW was obtained. In addition, the highest output power of the laser was 810 mW with a slope efficiency of 72% through the CW laser operation. In addition, a 280 fs pulse with an output power of 62 mW was obtained through passive mode-locking laser operation shown on the 5 at% Yb:Y\textsubscript{3}(Sc\textsubscript{0.5}Al\textsubscript{0.5})\textsubscript{5}O\textsubscript{12} ceramics\cite{13}. In 2017, Ma et al. used a 10 at% Yb:Y\textsubscript{3}Sc\textsubscript{1.5}Al\textsubscript{3.5}O\textsubscript{12} ceramic to achieve 96-fs pulses at a central wavelength of 1052 nm with a maximum average output power of 51 mW through a SESAM of mode-locked laser operation\cite{14}. Recently, a slope efficiency of 67.8% at the highest power of 6.3 W were obtained using a quasi-CW pumping scheme at 936 nm, and a broad tuning range from 991.5 nm to 1073 nm was achieved in the first report on Yb:YSAG ceramics by Angela Pirri\cite{15}.

In this work, we employ the continuous-wave and tunable laser to research the properties the transparent 10 at% Yb:YSAG ceramics. In the laser experiment, for the ceramic with a 1.2-mm thickness, the highest output power (\(P_{\text{out}} = 1.47\) W) and the corresponding slope efficiency (\(\eta_s = 17.3\%\)) are obtained with \(T_{\text{oc}} = 11\%\); for the ceramic with 2-mm thickness, the highest output power (\(P_{\text{out}} = 1.79\) W) and the corresponding slope efficiency (\(\eta_s = 18.3\%\)) are obtained with \(T_{\text{oc}} = 11\%\). In the spectroscopy experiment, for the 2-mm thickness ceramic, we obtain a smooth tunable spectra from 1021 nm to 1040 nm and wavelength range tuning over 20 nm; for the 1.2-mm thickness ceramic, a tunable curve from 1025 nm to 1040 nm and tunable wavelength range over 15 nm are obtained. CW and tunable laser operation demonstrate that Yb:YSAG ceramics can be used to generate laser emissions with broad tunable bandwidth, providing the evidence that of Yb:YSAG ceramics is a suitable gain medium for ultrafast laser sources.

2. Fabrication and optical properties of Yb:YSAG ceramics

The 10 at% Yb:Y\textsubscript{3}Sc\textsubscript{1.5}Al\textsubscript{3.5}O\textsubscript{12} transparent ceramics were fabricated through the solid-state reaction method combined with vacuum sintering. For the ceramic with a thickness of 2 mm, the results can be seen in \cite{16}.

Figure 1 reports that the in-line transmittances of the ceramic with a thickness of 1.2 mm are 82.3% at 1100 nm and 78.1% at 400 nm. The photograph of the ceramic is shown inset of figure 1.

Figure 2 shows the spectral properties of 1.2-mm thick 10 at% Yb:YSAG ceramics at room temperature. The intensities of absorption and emission spectra are normalized, respectively. From the absorption spectrum, we are well aware of that there are four main peaks, which are located at 913, 941, 968, and 1030 nm. And these peaks are resulted from the radiation transition of the Yb\textsuperscript{3+} ions from the low \(2F_{7/2}\) to the high \(2F_{5/2}\) energy level. From the emission spectrum, we also get four main peaks, which are located at 944, 969, 1031, and 1050 nm. Hence, the ceramic is a good gain medium for laser generation and amplification near 1 \(\mu\)m.

3. Experimental procedures

We use both a plano–plano laser cavity (figure 3(a)) and a three-mirror laser cavity (figure 3(b)) to study the laser properties of the 10 at% Yb:YSAG transparent ceramics\cite{17–19}. The pump laser used a 30 W fiber coupled
The pump light is struck at the center of the ceramic by two 40 mm convex lenses focusing on 100 μm. The Yb:YSAG ceramic was wrapped with Indium foil and mounted in a water-cooled copper heat sink. The temperature of the flowing water is 20 °C. For the CW laser operation, the ceramics were placed between a dielectric mirror (M1, AR: 940–980 nm, HR: 1020–1130 nm) and a 5% or 11% output coupler (OC). In the tunable laser operation, a concave mirror with a radius of curvature of 500 mm was used as M2 (HR: 1020–1130 nm), and a dispersion prism with a Brewster angle incidence was inserted into the cavity as part of the wavelength tuning. As shown in the inserted photograph in figure 1, the 10 at% Yb:YSAG transparent ceramics were cut into thin cylinders with thicknesses of 2 mm or 1.2 mm, possessing optically polished circular apertures with 8-mm radius on the faces. The lengths of the plano-plano cavity and three-mirror cavity were approximately 35 mm and 600 mm, respectively.

4. Thermal conductivity considerations.

In order to improve the optical-optical conversion efficiency of CW end-pumped solid state lasers, the thermal effects must be considered [20–23]. One important effect is thermal lensing. The temperature result in the changes from the refractive index of the gain medium. In order to model the thermally induced index changes and obtain an appropriate temperature distribution, one must be solved is the heat equation for the laser media. In this paper, the circular Yb:YSAG ceramic was pumped on the end face of the laser diode and cooled by the surrounding air at constant temperature. In addition, the temperature field is modeled by equation (1):
The temperature solution we can get to the Poisson equation is equations (2) and (3):

\[
\begin{align*}
\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2} &= -\frac{\rho V}{\lambda} \\
u(r, z)|_{z=R} &= 0 \\
\frac{\partial u(r, z)}{\partial z} \bigg|_{z=0} &= \frac{\partial u(r, z)}{\partial z} \bigg|_{z=L} = 0
\end{align*}
\]

The only temperature solution we can get to the Poisson equation is equations (2) and (3):

\[u = \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} A_{mn} \cos \left( \frac{m\pi}{L} z \right) J_0 \left( \frac{\mu_n^{(0)}}{R} r \right)\]

\[A_{mn} = \frac{4\beta^2 \rho L_3 (1 - e^{-\beta L}) \cos (m\pi)}{\lambda (\beta^2 L^2 + m^2 \pi^2) [m^2 \pi^2 R^2 + L^2 (\mu_n^{(0)})^2] J_0^2 (\mu_n^{(0)})} \times \int_0^R e^{-2\beta s / \omega^2} J_0 \left( \frac{\mu_n^{(0)}}{R} r \right) r dr\]

where \(L\) is the ceramic length, \(\omega\) is the pump radius, \(J_0\) is the zero order Bessel function, \(\mu_n^{(0)}\) is the \(n_{th}\) zero of the zero order Bessel function, and \(J_1\) is the first order Bessel function. The internal temperature field of the crystal can be calculated by using MATLAB.

Based on the above temperature field model, we calculate the temperature field with specific parameters as below. The pump power is 20 W, and the Gaussian radius of the pump light is set as 100 \(\mu\)m. And the size of the ceramic is 8 mm (diameter) \(\times\) 2 m (or 1.2 mm). For a Yb:YSAG ceramic doped with 10 at\% Yb\(^{3+}\) ions, the absorption coefficient of the 974-nm pumped ceramic (974 nm) is 9.1 cm\(^{-1}\), and the coefficient of thermal conductivity is 0.013 W \(\cdot\) mm\(^{-1}\) K\(^{-1}\).

As reported in figures 4(c) and (d), the central temperature of 2-mm thick ceramic with a thickness of 2 mm is lower than the 1.2-mm ceramic, and the temperature gradient is more obvious. The simulation results show that the internal temperature gradient could be reduced, and the thermal lens effect would be mitigated if the ceramic is of an appropriate thickness. Moreover, the simulation also shows that the pump light power and the pump spot radius can significantly affect the temperature distribution inside the ceramic.

5. Experimental results and discussion

Figures 5 and 6 show the output power with increasing absorbed pump power obtained by employing two OCs with different transmissions (\(T_{oc} = 5\%\) and \(T_{oc} = 11\%\)). Figure 5(a) shows the results in a plano–plano cavity, and figure 5(b) shows the results in a three-mirror laser cavity. Continuous-wave laser operation is realized at
1.93-W absorbed pump power. As the pump power increasing until the absorbed power reaches 12 W, the output power increases linearly. In the plano–plano laser cavity, the highest output power ($P_{\text{out}} = 1.47$ W) and slope efficiency ($\eta_s = 17.3\%$) are obtained with $T_{\text{oc}} = 11\%$. The laser emission spectral bandwidth is 0.2 nm at the maximum power (inset in figure 5(a)). In the three-mirror laser cavity, the highest output power ($P_{\text{out}} = 1.79$ W) and slope efficiency ($\eta_s = 18.3\%$) are obtained with $T_{\text{oc}} = 11\%$. The laser emission spectral bandwidth is approximately 0.2 nm at the maximum power (inset in figure 5(b)).

Figure 6(a) shows the output power varying with the different absorbed pump power obtained by employing two OCs with different transmissions ($T_{\text{oc}} = 5\%$ and $T_{\text{oc}} = 11\%$) in the plano–plano laser cavity, and figure 7(b) shows the results in the three-mirror laser cavity. CW laser operation is realized at 1.71 W absorbed pump power. In a plano–plano laser cavity, the highest output power ($P_{\text{out}} = 0.41$ W) and slope efficiency ($\eta_s = 8.1\%$) are obtained with $T_{\text{oc}} = 11\%$. The laser emission spectral bandwidth is 0.2 nm at the maximum power (inset in figure 6(a)). In a three-mirror laser cavity, the highest output power ($P_{\text{out}} = 0.79$ W) and slope efficiency ($\eta_s = 11.7\%$) are obtained with $T_{\text{oc}} = 11\%$. The laser emission spectral bandwidth is approximately 0.2 nm at the highest power (inset in figure 6(b)).

Table 1 reports the slope and power conversion efficiencies obtained for two thicknesses of ceramics, different cavity structures and two values of the transmission of the output coupler. It can be seen that in both laser configurations, as larger transmission ratio output couplers are used, the maximum output powers and slope efficiencies increase successively. The three-mirror laser cavity is more efficient than the plano–plano one in the case of the same transmission output coupler. The ceramic efficiency curve shows that both kinds of ceramics with different thicknesses show obvious saturation as the pump power improves. The difference is that the ceramic with 1.2-mm thickness has a lower saturation power than that with 2-mm thickness. This result is
mainly dependent on the difference gain length with the same doping concentration. When the temperature distribution inside the ceramic is taken into account, due to the center temperature of the short-gain ceramic being higher and its gradient being more intensive, the ceramic with 1.2-mm thickness is more prone to power fluctuations in the unsaturated state.

As reported in figure 3(b), with an output coupler (OC) of $T = 5\%$, we use a spectrum analyzer (YOKOGAWA, AQ6370) to measure the laser output wavelength by adjusting the output mirror and use an optical power meter (Thorlab PM100D) to receive the output power at different wavelengths. For the Yb:YSAG ceramic with 2-mm thickness, figure 7(b) shows that the output spectra wavelength could be adjusted from 1021 nm to 1040 nm, and the tunable wavelength covers more than 19 nm. As the three-mirror laser cavity owns more stable configuration in the aspect of better thermal dissipation, the $M^2$ at an output power of 0.9 W is 1.139 along the cavity-folding plane and 1.145 in the perpendicular direction. The far field beam profile in CW is shown in the inset of figure 8(a). Similarly, for the Yb:YSAG ceramic with 1.2-mm thickness, the output spectra wavelength could be adjusted from 1025 nm to 1040 nm, as shown in figure 7(a), and the tunable wavelength range exceeded 15 nm. The $M^2$ at an output power of 0.9 W is 1.039 along the cavity-folding plane and 1.039 in the perpendicular direction. The far field beam profile in CW laser is reported in the inset of figure 8(b).

Other than the above, we estimated the loss on the Yb:YSAG ceramic. It is found that the ceramic maximum transmitted pump power is 14.56 W under a pump power of 30 W. This result indicates the saturated absorption efficiency of ceramics for the pump is approximately 51.5% due to the absorption loss and reflection loss of ceramics. Some of these losses may be caused by the uncoated ceramic surface. Apart from these, further improvement of the laser performance can be expected through optimizing the design of the laser resonant cavity.

### Table 1. Output power $P_{\text{out}}$, slope efficiency $\eta_s$, and threshold power $P_{\text{th}}$ for ceramics with two thicknesses, two cavity structures and two values of the transmission of the output coupler $T_{\text{OC}}$.

| Resonator structure | $T_{\text{OC}}$ | Thickness | $P_{\text{out}}$ (W) | $\eta_s$ (%) | $P_{\text{th}}$ (W) |
|---------------------|---------------|-----------|---------------------|--------------|-------------------|
| PP 5%               | 2 mm          | 1.21      | 13.0                | 1.93         |
| PP 5%               | 1.2 mm        | 0.32      | 5.8                 | 1.71         |
| TM 5%               | 2 mm          | 1.35      | 13.8                | 1.98         |
| TM 5%               | 1.2 mm        | 0.55      | 7.9                 | 1.82         |
| PP 11%              | 2 mm          | 1.47      | 17.3                | 1.93         |
| PP 11%              | 1.2 mm        | 0.41      | 8.1                 | 1.71         |
| TM 11%              | 2 mm          | 1.79      | 18.3                | 1.98         |
| TM 11%              | 1.2 mm        | 0.79      | 11.7                | 1.82         |

As reported in figure 3(b), with an output coupler (OC) of $T = 5\%$, we use a spectrum analyzer (YOKOGAWA, AQ6370) to measure the laser output wavelength by adjusting the output mirror and use an optical power meter (Thorlab PM100D) to receive the output power at different wavelengths. For the Yb:YSAG ceramic with 2-mm thickness, figure 7(b) shows that the output spectra wavelength could be adjusted from 1021 nm to 1040 nm, and the tunable wavelength covers more than 19 nm. As the three-mirror laser cavity owns more stable configuration in the aspect of better thermal dissipation, the $M^2$ at an output power of 0.9 W is 1.139 along the cavity-folding plane and 1.145 in the perpendicular direction. The far field beam profile in CW is shown in the inset of figure 8(a). Similarly, for the Yb:YSAG ceramic with 1.2-mm thickness, the output spectra wavelength could be adjusted from 1025 nm to 1040 nm, as shown in figure 7(a), and the tunable wavelength range exceeded 15 nm. The $M^2$ at an output power of 0.9 W is 1.039 along the cavity-folding plane and 1.039 in the perpendicular direction. The far field beam profile in CW laser is reported in the inset of figure 8(b).

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### 6. Conclusions

In conclusion, tunable continuous-wave laser performance is shown using a 10 at% Yb:YSAG transparent ceramic as the gain medium. In the laser experiment, for the ceramic with a thickness of 1.2 mm, a maximum...
output power \( (P_{\text{out}} = 1.47 \, \text{W}) \) and slope efficiency \( (\eta_s = 17.3\%) \) are obtained with \( T_{\text{oc}} = 11\% \). For the ceramic with a thickness of 2 mm, a maximum output power \( (P_{\text{out}} = 1.79 \, \text{W}) \) and slope efficiency \( (\eta_s = 18.3\%) \) are obtained with \( T_{\text{oc}} = 11\% \). In the spectroscopy experiment, for the 2-mm thickness ceramic, we obtain a tunable curve from 1021 nm to 1040 nm and tunable wavelength range over 19 nm. For the 1.2-mm thickness ceramic, a tunable curve from 1025 nm to 1040 nm and tunable wavelength range over 15 nm were obtained. The optical-to-optical conversion efficiency of ceramics can be improved by an appropriate coating treatment on ceramic samples. We believe this ceramic can possibly be used as an alternative material in the field of ultrafast lasers. Moreover, from the temperature field distribution inside the ceramic, the performance of ceramics can be improved by optimizing the ceramic composite structure.

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