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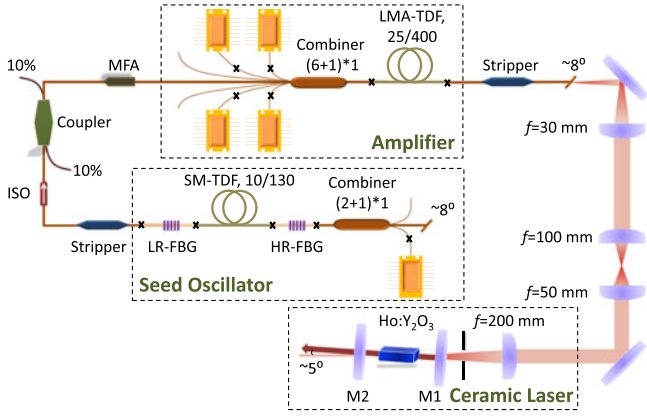

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High-Power Ho-Doped Sesquioxide Ceramic Laser In-Band Pumped by a Tm-Doped All-Fiber MOPA

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Abstract: We report on a high-power Ho:Y_2O_3 ceramic laser in-band pumped by a home-made Tm-doped all-fiber MOPA at 1941 nm. The Ho:Y_2O_3 ceramics fabricated by vacuum sintering and hot isostatic pressing present uniform ceramic grain and high optical homogeneity. The 24.6 W output power at ~2117 nm is successfully achieved by exploiting the advantages of in-band pumping technique, which to our knowledge is one order of magnitude higher than the previous results obtained from the Ho-doped sesquioxides ceramic lasers, indicating the power scalability of sesquioxides ceramic compared to other bulk materials in high-power laser.

Index Terms: Laser ceramics, solid-state lasers, infrared and far infrared lasers.

1. Introduction

Although the first ceramic laser (Dy:CaF_2 in cryogenic conditions) was demonstrated as early as in 1964 [1], less attention had been paid to such material since its considerably low lasing efficiency until 1995, a high performance polycrystalline Nd:YAG ceramic laser with comparable slope efficiency to Nd:YAG single crystal laser was reported [2]. Since then, fabrication of laser-grade transparent ceramics with ultralow-scattering-loss has undergone considerable development. Up to now, transparent ceramic is undoubtedly an alternative candidate for compact solid-state lasers because of its numerous advantages over single crystal, such as a possibility to fabricate large volumes samples, heavy and homogeneous doping for active ions, and the ability for composition in complicated structures. Moreover, some novel, high-melting laser materials that are challenging for common crystal growth techniques, can be fabricated in polycrystalline ceramics, such as sesquioxide ceramics [3]. The cubic sesquioxides (RE_2O_3, where RE = Lu, Y, Sc, or their mixture) characterized

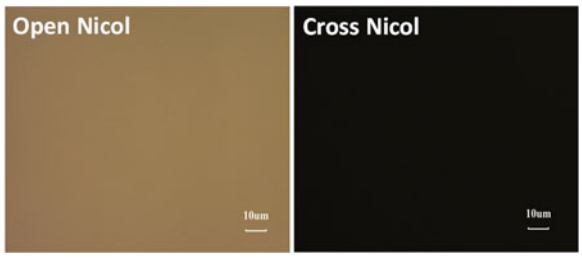

Fig. 1. Open Nicol (left) and Cross Nicol (right) images of 0.7 at.% Ho:Y_2O_3 transparent ceramics on the microscopic scale.

by outstanding thermal properties and low maximum phonon energy (~600–700 cm^{-1} [4]) are attractive for high power laser operation in 2 μm spectral range when doped with Thulium (Tm^{3+}) [5] and/or Holmium (Ho^{3+}) ions [6]. In comparison, Ho^{3+} ions offer approximately 5 times larger cross section and slightly longer emission wavelength [7], is more expected, especially for the Ho-doped sesquioxides, in which the emission wavelength exceed 2.11 μm due to the modulation of their strong crystal field [6].

However, until now, there are only three reports on the polycrystalline Ho-doped sesquioxide ceramics lasers with a much lower power level compared to their single-crystalline lasers [6], e.g., 2.5 W output power from a liquid nitrogen cooled Ho:Y_2O_3 ceramic laser resonantly pumped by an indium phosphide laser diode at ~1.93 μm [8], 182 mW Ho:Lu_2O_3 ceramic laser with a slope efficiency of only 1% which was attributed to the scattering loss caused by trace amount of phase/morphological impurities [9], and 1.3 W output power from a Ho:Y_2O_3 ceramic laser pumped by a Tm-doped fiber oscillator at ~1.94 μm [10]. Considering the current state-of-the-art, laser performance is limited either by the poor ceramic quality (mainly the scattering losses caused by the grain boundary phase, secondary phases, and/or the residual pores [3]) or the insufficient power level of the pump sources.

Due to the perfect ionic radius matching between Y^{3+} (0.90 Å, in VI-fold oxygen coordination) and Ho^{3+} ions (0.90 Å, in VI-fold oxygen coordination) [11], little disturbance will be induced to the lattice periodicity of Y_2O_3 when doped with Ho^{3+} ions, this will allow for simple fabrication and preserve the high optical properties of the host [12]. On the other hand, Tm-doped all-fiber laser characterized by power scalability and excellent beam quality offers an outstanding pathway of pumping for high power Ho-doped bulk lasers.

In this work, we report on a Ho:Y_2O_3 ceramic laser resonantly pumped by a home-made high power, Tm-doped all-fiber master oscillator power amplifier (MOPA) at 1941 nm. 24.6 W output power at 2116.8 nm is achieved, which is higher than the 18.8 W that obtained with the Ho:Y_2O_3 single crystal [13], and comparable with the highest output power of 25.2 W generated from the Ho:Lu_2O_3 crystal laser [13]. This indicates the great potential of Ho-doped polycrystalline sesquioxide ceramic for high power lasers with emission wavelength above 2.11 μm.

2. Optical Properties of the Fabricated Ceramics

Most recently, we have reported the fabrication and preliminary optical characterization of the 0.7 at.% Ho:Y_2O_3 transparent ceramics [10]. The laser-grade ceramic was fabricated by 12 h vacuum sintering at 1500 °C and thereafter hot isostatic pressing (HIPing) at 1450 °C for 4 h. The ceramic grain is uniform with an average size of ~1 μm, much smaller than the previous reports of 5 μm for Ho:Y_2O_3 [8] and 40 ~ 50 μm for Ho:Lu_2O_3 ceramic [9]. Its thermal conductivity at room temperature is measured to be 11.1 W/m·K, which is lower than that of pure Y_2O_3 ceramic (13.6 W/m·K) due to the mass difference between holmium and yttrium ion [14], but similar to that of ~10 W/m·K [6] for 1 at.% Ho:Y_2O_3 single crystal (the slightly higher value for ceramic is due to the lower Ho^{3+} ions doping concentration [14]).

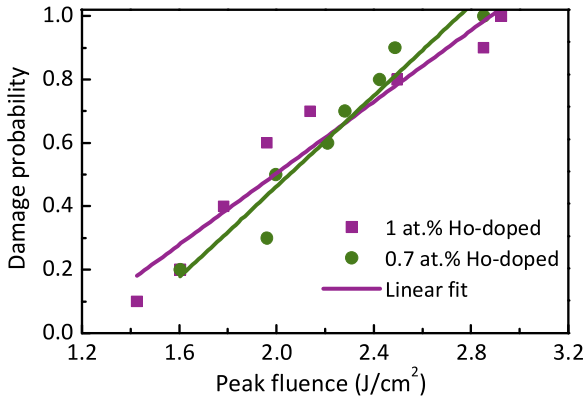

Fig. 2. Damage probability curves of the 0.7 at% and 1 at% Ho:Y_2O_3 ceramics versus the peak fluence at 1064.2 nm. The uncoated ceramics are irradiated for 1 min (i.e., 6000 shots) at each step.

Fig. 1 shows the open Nicol (left) and cross Nicol (right) images of the 0.7 at.% Ho:Y_2O_3 sample (3-mm in thickness) that were recorded by a polarizing transmission microscope in a micron scale. No residual pores or secondary phases were observed in the depth direction of the sample by the open Nicol and high optical homogeneity can be confirmed by the dark-filed cross Nicol image, both indicating the high optical quality of the fabricated ceramics.

With a diode-pumped, Q-switched Nd:YAG laser/amplifier (1064.2 nm emission wavelength, 100 Hz repeatition frequency, 250 mJ maximum single pulse energy, and ~8 ns pulse duration), the laser-induced damage threshold (LIDT) of the ceramic samples (0.7 at.% and 1 at.% Ho:Y_2O_3 ceramics with both dimensions of $2 \times 3 \times 12\,mm^3$) were tested using the R-on-1 procedure [15]. The laser was focused by a lens ($f = 200$ mm) and then irradiated the samples with a beam diameter of 760 μm in horizontal and 940 μm in vertical direction (The beam mode was measured slightly behind the focus using the knife-edge technique). Ten independent sites on the $3 \times 12\,mm^2$ face (polished but uncoated) were respectively irradiated until damage occurs with gradually increased fluence. The irradiation time was 1 min (i.e., 6000 shots since 100 Hz repeat frequency) at each step. Fig. 2 shows the tested damage probability of the two samples. Through the linear fitting we can roughly estimate the 0%-damage probability LIDT of the 0.7 at.% Ho:Y_2O_3 ceramic is 1.4 J/cm^2, and about 1.2 J/cm^2 in the case of 1 at.% Ho-doped. The lower LIDT compared to the YAG ceramic in somehow indicates their poor mechanical properties. The Vickers hardness and fracture toughness of the 0.7 at.% Ho:Y_2O_3 ceramic were measured to be 8.5 GPa and $1.2\,MPa \cdot m^{1/2}$, respectively, smaller than the 14.6 GPa and $1.59\,MPa \cdot m^{1/2}$ in the case of YAG ceramic [16].

According to the absorption spectrum that was measured by a UV-VIS-NIR spectrophotometer (Lambda 950, Perkin Elmer, Waltham, MA, America), the absorption cross section (σ_a) of the 0.7 at.% Ho:Y_2O_3 ceramic in $^5I_8 \rightarrow {}^5I_7$ transition was determined (see Fig. 3) by the formula $\sigma_a = \alpha / N_c$, where α is the measured absorption coefficient and N_c is the concentration of Ho^{3+} ions in Ho:Y_2O_3 ceramic. The maximum absorption peak is located at 1932 nm with a cross section of 9.7×10^{-21} cm^2. Considering the adjacent absorption peak at 1943 nm, the total absorption spectral width (full width at half-maximum, FWHM) is about 16 nm, suitable for pumping by both the diode laser that typically has a broad emission spectrum, and the Tm-doped bulk or fiber lasers that without specially wavelength narrowing. Even so, in this work, we chose a spectrum narrowed Tm-doped fiber laser as pump source to carry out the high power laser operation, since its high pumping efficiency, power scalability and high beam quality.

3. Tm-Doped All-Fiber MOPA

As discussed above, apart from the high quality of the ceramics, high power pump sources with excellent beam quality are desired for high power laser generation. With a Tm-doped all-fiber oscillator as pump source, the first room temperature Ho:Y_2O_3 ceramic laser with 1.3 W output

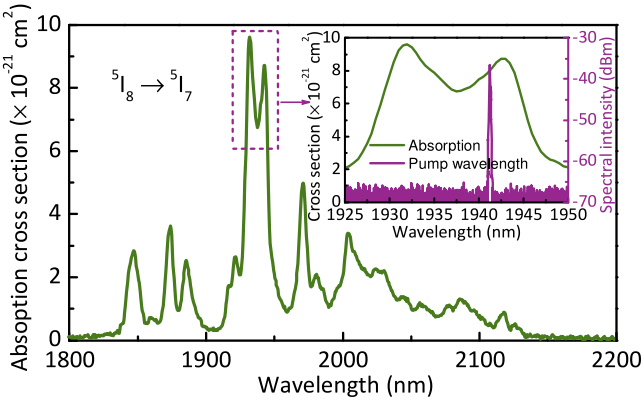

Fig. 3. Absorption cross section of the Ho:Y_2O_3 ceramic in the transition of $^5I_8 \rightarrow {}^5I_7$. Inset, scale enlarged absorption spectrum in 1.9 μm spectral range, and the output spectrum of the used Tm-doped all-fiber MOPA at 1941 nm.

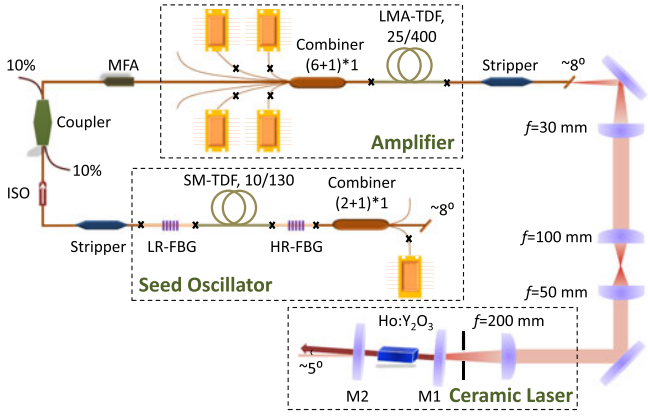

Fig. 4. Setup of the Tm-doped all-fiber MOPA and the in-band pumped Ho:Y_2O_3 ceramic laser, where the MOPA consists of a seed oscillator and an amplifier. LR/HR-FBG: low/high reflectivity fiber Bragg grating, ISO: isolator, MFA: mode-field adaptor.

power was demonstrated most recently [10]. In which the maximum output power was limited by available pump power of the used fiber laser, and the laser conversion efficiency was low due to the large cavity loss. In order to further scale the output power, in this work, we at first constructed a high power Tm-doped all-fiber laser source at 1941 nm based on MOPA configuration (see Fig. 4).

The MOPA consisted of a seed oscillator and a one-stage fiber amplifier. The oscillator was formed by a pair of fiber Bragg gratings (FBGs, i.e., high-reflectivity (>99.6%) FBG with 2 nm reflective bandwidth and low-reflectivity (10%) FBG with 1 nm reflective bandwidth at 1941 nm) and a 3 m double cladding single mode Tm-doped fiber (SM-TDF, 10 μm core (0.15 NA) and 130 μm cladding diameter (0.22 NA), 3 dB/m cladding absorption at 793 nm). A 12 W laser diode (LD) with emission wavelength at 793 nm was used as the pump source. A home-made stripper was used to strip the residual pump light. The seed was injected into the amplifier after passing through an isolator (ISO), a 10:90 coupler and a homemade mode-filed adaptor (MFA). The active fiber used in the amplifier was a large mode area (LMA) double cladding fiber (~4 m) with the core and cladding diameters of 25 μm (0.09 NA) and 400 μm (0.49 NA), respectively. A $(6+1) \times 1$ combiner was used to guide the pump light into the active fiber with cladding absorption at 793 nm of 4 dB/m. The end of the fiber was ~8° cleaved to minimize the Fresnel reflection.

Fig. 5 shows the laser performance of the MOPA. Output power of the seed oscillator linearly increased to 5 W versus the pump power, corresponding to a slop efficiency of 55.4%. However,

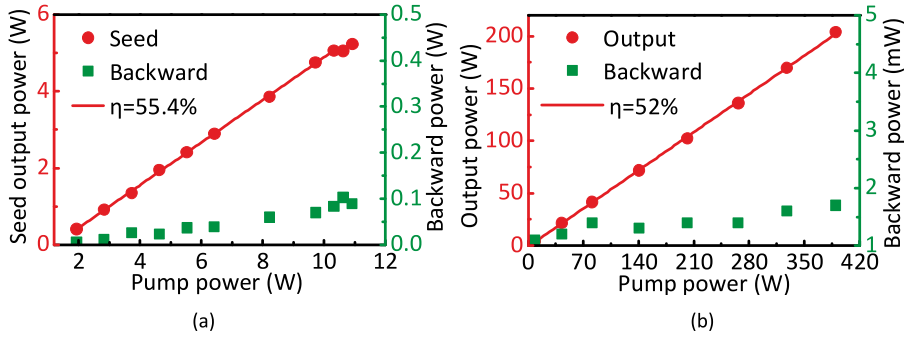

Fig. 5. Output and backward power of the SM-TDF oscillator (a), and the LMA-TDF amplifier (b).

power fluctuation was observed by further increasing the pump power, indicating the emergency of high-order transverse mode [17]. This was further confirmed by the measured output spectra, in which double peaks located at 1940.7 and 1941.2 nm were observed. Considering the laser stability during the amplifying process, 2.6 W seed power was chosen to be injected into the amplifier. In this case, the output spectrum located at 1941.2 nm with 3dB linewidth less than 70 pm (limited by the resolution of the optical spectrum analyzer (OSA), AQ6375, YOKOGAWA).

The seed power was thereafter linearly amplified to 204 W [see Fig. 5(b)] in the LMA-TDF amplifier, corresponding to a slope efficiency of 52%. Further power scaling was just limited by the available pump power. The backward power recorded behind the 10% port of the fiber coupler was lower than 2 mW, which indicates the small splice loss of the whole MOPA system. The output spectrum is shown in the inset of Fig. 3, the central wavelength is 1941.2 nm and the 3 dB spectral width is ~70 pm. No amplified spontaneous emission (ASE) and nonlinear effects were observed at the highest power level. The beam propagation factor (M^2) was measured to be ~1.3 at 100 W output power. This high power Tm-doped all-fiber MOPA with narrow spectral width and high beam quality should be a desired pump source for Ho:Y_2O_3 ceramic laser.

4. Laser Performance of the Ho:Y2O3 Ceramic Laser

Utilizing two 45° reflective mirrors and four-lens system (f = 30, 100, 50, and 200 mm, see Fig. 4), the MOPA laser was focused on the ceramics with a measured diameter of ~426 μm. The Ho:Y_2O_3 ceramics with Ho^{3+} doping concentration of 0.7 at.% and 1 at.% were respectively used as the gain media and water cooled to 15°. To compare their laser performance, both of them are in the same size, i.e., 2 × 3 × 12 mm^3, with the 2 × 3 mm^2 faces polished but uncoated. Due to the devastating impacts of feedback to the MOPA, the ceramic was tilted by about 5° to prevent the feedback caused by the Fresnel reflection. The laser cavity with a total length of 18 mm was composed of an input mirror (M1, plane mirror, anti-reflection coated at 1650-1950 nm and high-reflection coated at 2050–2250 nm) and an output coupler (OC, plano-concave mirrors with R = 200 mm), where the transmission T of the used OCs was 5%, 10%, and 20%.

Considering the Fresnel reflection of the pump beam (~8% on each end face at 5° incident angle), the single-pass absorption efficiency was firstly measured under no-lasing conditions. As the incident pump power increased from 3.5 to 62 W, the single-pass absorption decreased from 60.3% to 43.6% for 1 at.% Ho:Y_2O_3 ceramic and from 51.4% to 37.8% for 0.7 at.% Ho:Y_2O_3 ceramic, leading to an average absorption of 48.6% and 40.3%, respectively. The decrease in absorption can be attributed to the absorption bleaching under high power intensity pumping. Thereafter, considering the high-reflective coating of the OCs in this work, the average double-pass absorption efficiency was calculated to be 65% and 59%, respectively. Fig. 6 shows their laser power versus the absorbed pump power. Laser thresholds for the OCs of 5%, 10% and 20% were roughly measured (since the output power of the used Tm-doped all-fiber MOPA can not be tuned continuously) to be 0.6 W, 1 W and 1.5 W for 1 at.% Ho:Y_2O_3 ceramic laser, and 1 W, 1.5 W and 2.5 W for 0.7 at.%

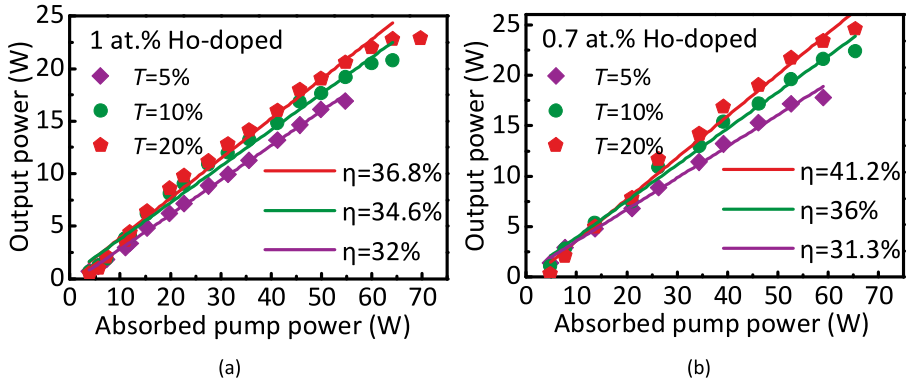

Fig. 6. Output power of the 1 at.% Ho:Y_2O_3 (a) and 0.7 at.% Ho:Y_2O_3 (b) ceramic lasers versus the absorbed pump power.

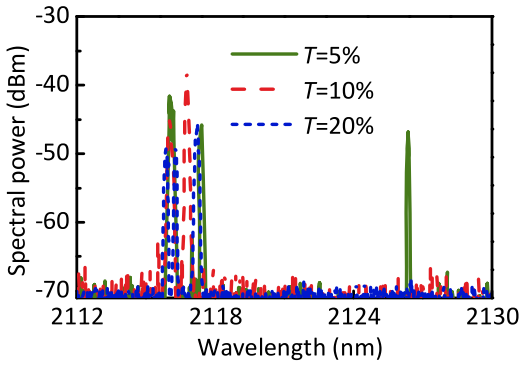

Fig. 7. Laser spectra of the 0.7 at.% Ho:Y_2O_3 ceramic laser for different OCs at 21.7 W output power.

Ho:Y_2O_3 ceramic laser. The best laser performance in both cases were obtained with $T = 20\%$, i.e., 22.9 W output power with 36.8% slope efficiency [see Fig. 6(a)], and 24.6 W with 41.2% slope efficiency [see Fig. 6(b)]. The low conversion efficiency was mainly caused by the low mode volume overlap between the pump and laser beam since a 5° misalignment. In addition, absorption bleaching and intracavity loss (~6.5%, mainly caused by the ceramic [18]) will also decrease the laser conversion efficiency.

Further power scaling was limited by the power instability of the MOPA, which was caused by the strongly increased feedback from several milliwatts to nearly one watt. Three possible reasons for this suddenly increased power feedback were as follows: (i), deterioration of the MOPA beam quality due to the increment of high-order transverse modes under high power level, which further resulted in spatial overlap between the incident and back-reflected pump beam on the surface of the lens ($f = 200$ mm); (ii), thermal induced birefringence in the ceramic changed the propagation direction of the reflected pump light thereby also resulting in the beam spatial overlap with the incident light; (iii), absorption bleaching of the ceramic under high intensity pumping (~0.13 MW/cm^2) led to an enhanced back-reflection, further enhancing the unwanted feedback. Even so, the obtained 24.6 W output power is one order of magnitude higher than 2.5 W (liquid nitrogen cooled Ho:Y_2O_3 ceramic laser [8]) that of the maximum power ever reported from the Ho-doped sesquioxide ceramics lasers, and even higher than 18.8 W that obtained with the Ho:Y_2O_3 single crystal [13]. This indicates the strong competitiveness of Ho-doped sesquioxide ceramics in both fabrication and high power laser performance compared to the single crystals.

Fig. 7 shows the output spectra of the 0.7 at.% Ho:Y_2O_3 ceramic laser for different OCs. Peak wavelengths for both $T = 10\%$ and 20% OCs were located around 2116.8 nm, the longer emission

wavelength compared to the other hosts was attributed to the strong crystal field of the sesquioxides [6]. For the OC of $T = 5\%$, the unwanted double-wavelength emission was observed and the laser operation was very unstable. The longer wavelength located at 2126.4 nm was caused by the strong reabsorption effect due to the lower required population inversion ratio for laser oscillation at lower T. The beam quality factor M^2 at 21.7 W output power was analyzed using a beam profiler (NanoScan, Photon Inc.), which were 1.72 and 1.67, respectively in x- and y-directions.

5. Conclusion

In summary, we have experimentally demonstrated the power scalability of the Ho-doped sesquioxides ceramic laser above 2.11 μm, by employing a high optical quality Ho:Y_2O_3 ceramic as gain medium and a Tm-doped all-fiber MOPA delivering 204 W power at 1.941 μm as pump source. The maximum output power of 24.6 W was achieved with a corresponding slope efficiency of 41.2%, which is one order of magnitude higher than the previously reported results. For further power scaling, high transmittance coating at pump light is required for the ceramics in order to remove the unwanted feedback. In addition, lower Ho^{3+} doping concentration is desired to mitigate thermal effects during the lasing process, as well as the large size ceramics with sufficient length to ensure higher absorption of the pump light.

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