Scattering loss and efficiency of the multi-pass mini-slab Nd:YAG ceramic lasers

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Multi-pass mini-slab (MPMS) Nd:YAG ceramic lasers with a single-mode output of 38 W is examined corresponding to an optical conversion efficiency of 47%. Although several characteristics of various ceramic samples are almost similar, such as transmission, emission and absorption spectra, cross section, and thermal conductivity, their optical conversion efficiencies can vary from 5% to 40%. We present a simple technique to on-line measure the influence of scattering loss of ceramic on laser performance. This particular technique provides convenience and accuracy in pre-monitoring ceramic sample quality. Experimental results of the MPMS Nd:YAG ceramic laser agree with evaluations.

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Transparent laser ceramics have attracted wide research focus for solid-state lasers in the past years. The unique characteristics of laser ceramics offer huge potential in high-power and ultra-short lasers. Ceramic laser has been an attractive choice for high-power outputs, as it improves the average output power of various diode-pumped solid-state lasers (DPSSL). A near 100-kW average power has been generated by Nd:YAG ceramic slab lasers[1]. As short as 70-fs ultra-short pulse has also been obtained from Yb:YAG ceramic lasers[2].

Although laser ceramics have been extensively investigated in laboratories[3,4], only few ceramic lasers have been made available commercially. Typically, local inhomogeneous mode[5] and different doping concentrations around the grain boundary[6,7] of ceramics have been observed. The stabilities and identifications of different batches are critical for commercial production. Most state-of-the-art ceramics have shown the same physical and optical properties (e.g., transmission, emission and absorption spectra, cross section, and thermal conductivity) as that of single crystals. However, the laser efficiencies are quite different for these ceramic samples, even for the samples obtained from the same ceramic roughcast.

Multi-pass mini-slab (MPMS) DPSSL has emerged as a compact, highly efficient, and stable candidate for commercial lasers[8,9]. A single MPMS module can provide 40-W continuous wave (CW) power from a 4×15×1.5 (mm) Nd:YVO_4 crystal mini-slab[10]. The manufacturing technique of ceramic has been well preferred for the slab geometry of laser media. MPMS incorporated with ceramic can offer a competitive approach to a low-cost, compact, efficient, and superior beam quality laser output.

We collected five ceramic samples from different companies and laboratories (Konoshima Chemical Company Ltd., World Lab Inc., Shanghai Institute of Ceramics, Shandong University, and Shanghai Institute of Optics and Fine Mechanics). All samples were of 1.0% Nd-doped YAG ceramics and were cut to 8×22×1 (mm) mini-slabs. Two laser diode (LD) bars operated at 808 nm were used to pump the slab from both sides. A total pump power of 80 W was collimated to form a 0.6×10 (mm) gain sheet in the middle of slab. The laser beam passed the slab five times by means of folded-mirrors (Fig. 1). The slab was cooled by two micro-channel heat sinks from the bottom and upper surfaces. A plane high-reflectivity mirror was used as rear mirror whereas a cylindrical convex mirror was used as output coupler. In the lateral direction, the mirrors were constructed to a plane-convex unstable resonator. In the transversal direction, the plane-plane stable resonator was fabricated by taking into account thermal lens effects. Optimized output coupling was 28%. The radius of curve of the cylindrical convex mirror was 700 mm.

The performance of the MPMS laser depended strongly on the type of ceramic sample used (Fig. 2). For the best case, we obtained 38-W output power with a beam quality factor of M^2=1.2, corresponding to an optical-optical conversion efficiency of 47%. The result is more exceptional than that of the Nd:YAG single crystal slab laser. To the best of our knowledge, the demonstration of an MPMS laser based on the ceramic material is

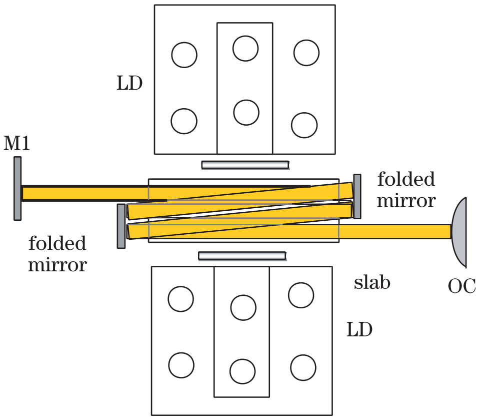

Fig. 1. Configuration of MPMS lasers. M1: rear mirror; OC: output coupler.

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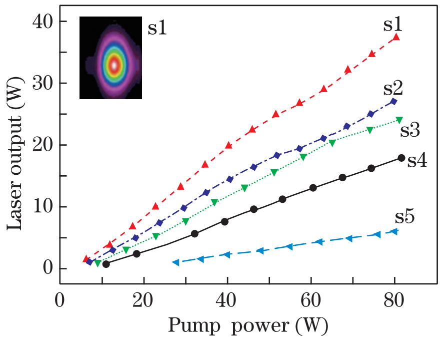

Fig. 2. Laser performance for various Nd:YAG ceramic samples. Inset: output beam pattern of laser with s1 slab.

a novel approach. Meanwhile, in the worst case, output power was only set to 4.1 W, corresponding to an optical-optical conversion efficiency of 5%. The threshold pump power in the worst case was two times higher than the result in the best case. Except for the scattering coefficients, these ceramic samples exhibit almost the same transmission and emission parameters. Scattering loss is the dominant reason for the effects in the performance of ceramic lasers.

The sources for scattering in laser ceramics are the pores, second phase, and impurities. The scattering from these sources are usually dependent on position and angle. The scattering coefficient for a raw bulk ceramic measured with traditional techniques is not suitable for the evaluation of individual samples. A convenient and accurate on-line measurement of scattering loss in the laser cavity should be carried out, as this is valuable and important in pre-monitoring the quality of ceramic samples.

Measurement of scattering loss was conducted for the laser cavity (Fig. 3). A 5-mW microchip Nd:YAG crystal laser was used as probe source. Probe beam size was about 0.7 mm after collimation, which was equal to the beam size ($1/e^2$) inside the cavity. A half-reflected mirror was inserted to collect the reflected light from the Nd:YAG ceramic samples. To measure real scattering loss in the laser cavity, a pin-hole was fixed in front of the detector. The diameter of the pine-hole was 1.4 mm, such that more than 97% probe power could be captured by the detector just in case the probe beam would not scatter. Hence, the lost power lost in the cavity can be given by $I_{\rm lost} = 0.5I_{\rm prob} - 0.5I_{\rm ref} - (I_{\rm pin}/0.97)$, where $I_{\rm prob}$ is the power from the probe laser, $I_{\rm ref}$ is the reflected power, and $I_{\rm pin}$ is the power measured through the pin-hole.

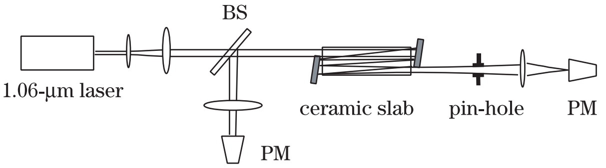

Fig. 3. On-line measurement of scattering losses. PM: power meter; BS: beam spliter.

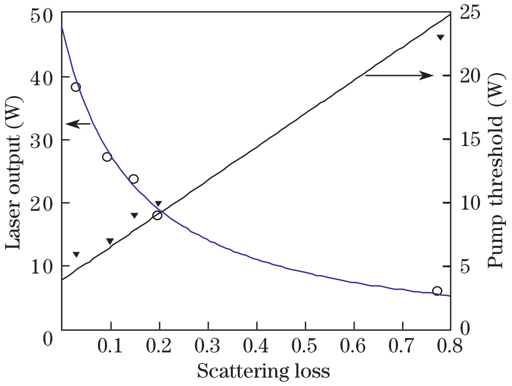

Fig. 4. Influence of scattering losses on laser performance.

Then, the scattering losses of several Nd:YAG ceramic samples were measured. The laser performance using these Nd:YAG ceramic samples were also determined. The dependence of the laser output on scattering losses can be given in the form[11]

$$I_{\rm out} = \left[\frac{2g_0 l_{\rm m}}{T_1+\delta_a} - 1\right]\frac{I_{\rm sat}T_1}{2}, \tag{1}$$

where g_0 is the laser gain, $l_{\rm m}$ is the effective length of active medium (equal to 5 times ceramic length in our case), $I_{\rm sat}$ is the saturated intensity, and T_1 is the transmission of the output coupler. Parameter δ_a represents intrinsic losses in the cavity and it includes diffractive losses, scattering losses, and losses from non-perfect coatings. In this case, scattering losses provide dominantly contribution to such parameters. The laser output was inversely proportional to the scattering losses of the ceramic samples, such that the larger the scattering losses, the lower the laser output.

From Eq. (1) and using the relationship between laser gain and pump power, we calculated threshold pump power using the following equation

$$P_{\rm th} = (T_1+\delta_a)\frac{Sh\nu_{\rm p}}{2\sigma_e}, \tag{2}$$

where S is the cross section area of the laser beam, σ_e is the emission cross section of the gain medium and $h\nu_{\rm p}$ is the photon energy of the pump light. Pump threshold is linearly proportional to scattering losses.

We plotted the measured laser output and the pump threshold for various Nd:YAG ceramic samples (Fig. 4). The plotted dotted curves are obtained using Eqs. (1) and (2). Clearly, the agreement between calculation and experimental data is apparent. Moreover, the measurement of losses in the cavity is accurate. When the losses measured for the Nd:YAG crystal is compared with that of the ceramic samples, we find that scattering losses mainly caused the degradation of laser performance.

In conclusion, for the first time, MPMS lasers based on a ceramic material are demonstrated. We obtain 38-W CW laser output from Nd:YAG ceramic MPMS laser with an optical conversion efficiency of 47%. The influence of scattering losses on laser performance is also investigated. We present a simple technique to on-line measure these scattering losses. The technique is valuable in monitoring the quality of ceramic samples before laser installation.

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