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Rapid Communication

High-Efficiency Flashlamp-Pumped Nd:KGW Laser

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Abstract. The laser performance of a Nd:KGW rod has been studied in a single flashlamp cavity in the free running as well as in the Q-switched mode of operation at input energies ranging from 1–25 J. The results of Nd:KGW have been compared with Nd:YAG operated under identical experimental conditions. The laser extraction efficiency of the Nd:KGW rod was observed to be 2.5 times higher at a much lower threshold than that of the Nd:YAG rod. The intrinsic slope efficiency was determined to be 2.25% and 8.840% for Nd:YAG and Nd:KGW rods, respectively.

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There has been a considerable interest in the development of high-efficiency solid-state lasers for potential applications in materials processing, remote-sensing, medical and optical communication, etc. The neodymium (Nd) doped garnets such as yttrium aluminum $Y_3Al_5O_{12}$ (YAG) [1–5], gadolinium gallium $Gd_3Ga_5O_{12}$ (GGG) [6, 7], and gadolinium scandium garnet $Gd_3Sc_2Al_3O_{12}$ (GSGG) [5, 8–10] have been studied extensively in the past and high efficiency and high average power have been reported. The most commonly used host for Nd doping is the YAG, which suffers from the core formation in large boules using the Czochralski crystal growth method and Nd-concentration quenching of the excited state Nd^{3+} ions. The Nd:GGG and Nd:Cr:GSGG materials suffer from solarization or the thermal lensing effect and laser action is observed at a relatively higher threshold during flashlamp pumping of these rods as compared to the Nd:YAG rod under identical experimental conditions. The neodymium doped potassium gadolinium tungstate, $KGd(WO_4)_2$ (KGW), is a relatively new but promising laser crystal and may be an alternative to the Nd:YAG crystal for generating laser radiation around the one-micron range. Unfortunately, the laser performance characteristics of this crystal, i.e., Nd:KGW, is not known in detail as compared to other crystals mentioned above. Flashlamp laser action was first reported by Kaminskii et al. [11] at 1.067 µm due to the transition Nd^{3+} ($^4F_3/_2$–$^4I_{11}/_2$) at room temperature. The radiative and thermochemical properties of the Nd:YAG and Nd:KGW crystals are compared in Table 1. The KGW crystal is a tetragonal crystalline compound and becomes monoclinic with the point space group $C_2/c(C^6_{2h})$ and unit cell dimensions: $a = 8.10$ Å, $b = 10.43$ Å, $c = 7.6$ Å. In Nd-doped KGW, the Nd^{3+} ions replace Gd^{3+} ions going into the point space group symmetry C_2 [11]. Based on the radiative properties of the Nd:KGW and Nd:YAG (Table 1), it is clear that when the Nd:KGW rod is exposed to flashlamp light, it may produce a higher pulsed energy than the Nd:YAG under identical experimental conditions. It is known that the concentration quenching of the fluorescence due to the transition Nd^{3+} ($^4F_3/_2$–$^4I_{11}/_2$) in Nd:YAG is a major problem and Nd concentration is limited to 1.0 or 1.1 atomic percentage in most ot the commercially available Nd:YAG lasers at 1.064 µm. In case of the Nd:KGW, however, Nd concentrations as high as 3–7 atomic percentage [12] has been observed to have no significant quenching effect on the fluorescent emissions such as Nd^{3+} ($^4F_3/_2$–$^4I_9/_2$) (≅ 0.91 µm), Nd^{3+} ($^4F_3/_2$–$^4I_{11}/_2$) (1.067 µm), and Nd^{3+} ($^4F_3/_2$–$^4I_{13}/_2$) (≅ 1.35 µm). Because of this reason, together with the higher stimulated emission cross section in Nd:KGW as compared to the Nd:YAG, a

Table 1. Selected laser parameters of Nd:YAG and Nd:KGW crystals

Parameters	Nd:YAG	Nd:KGW
Peak emission cross-section [10^{-19} cm^2]	2.8 [a]	3.3 [b]
Storage time [10^{-6} s]	230 [a]	120 [b]
Transition wavelength ($^4F_{3/2} - {}^4F_{11/2}$)	1.064 µm	1.067 µm [b]
Thermal conductivity [W/m · K]	9.76 [c], 12.9 [d]	3.8 [e]
Moh hardness	8.5 [a]	4 [e]
Density	4.54 [a]	7.27 [e]
dn/dT [10^{-6} K^{-1}]	7.3 [a]	0.4 [e]

[a] [1], [b] [11], [c] [6], [d] Cited in [6], [e] [14]

much higher pulsed energy at lower threshold may be produced from a flashlamp pumped Nd:KGW rod or slab with dimension identical to those of the Nd:YAG rod to be compared with.

In this communication, we report the laser extraction efficiency at 1.067 µm from a Nd:KGW (Nd: 3 at.%) rod pumped by a single Xe flashlamp at different pump energies in the free running and Q-switched modes of operation. The Nd:KGW results have been compared with those of the Nd:YAG rods (Nd: 1.0 and 1.1 at.%) under identical experimental conditions.

1 Experimental Details

A schematic diagram of the experimental setup is shown in Fig. 1. It consists of a water-cooled laser cavity, a Xe gas filled flashlamp, input and output mirrors, Q-switch and driver, and a pulse forming network (PFN, 24.5 µF capacitor and 60 µH inductor) to initiate a flash. The laser rod and flashlamp are closely coupled by using a diffusely reflecting Spectralon material. The reflectance of the Spectralon is over 97% at wavelengths ranging from 400–1600 nm which insures blockage of unwanted UV radiation. The filtering of the UV radiation reduces the divergence of the laser beam without affecting the lasing efficiency. The introduction of the Spectralon material into the laser cavity insures uniform pumping of the gain media resulting in a uniform laser beam, free from the thermal distortion or hot spots which are often associated with specular laser cavities [13].

The Nd:YAG (Nd = 1.0 and 1.1 at.%) and Nd:KGW (Nd = 3 at.%) laser rods (5 mm in diameter and 80 mm long) were flat ended, parallel, polished, and antireflection coated at 1.064 µm. These rods were properly aligned in the laser cavity between a pair of mirrors separated by about 50 cm. The end mirror of 5 m radius of curvature was highly reflective (99.9%) whereas the output mirror was flat with different reflectivities (60%, 80%, or 95%) at 1.064 µm. The laser was operated by using a single simmered Xe flashlamp at a pulse repetition rate of 1 Hz. The laser pulse energy was measured by using a calibrated energy meter. The Q-switched operation was performed by inserting a KDP crystal antireflection coated at 1.064 µm and a polarizer combination between the total reflector and the laser rod. The optimum operating voltage and delay time used in the Q-switch experiments reported here were 3 kV and 145 µs, respectively.

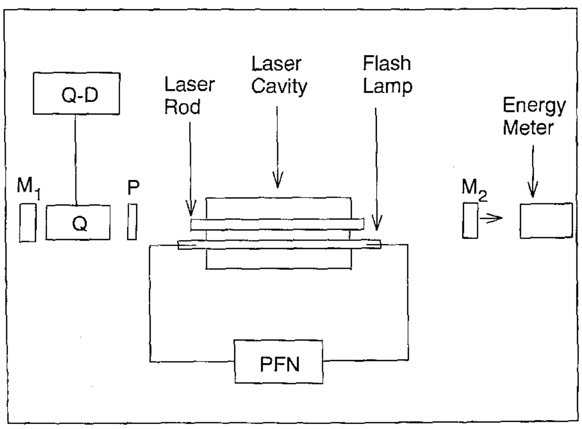

Fig. 1. The experimental setup used in the present study. M_1 and M_2 are the total (99.9%) and partial reflectors, Q, Q–D, and P are the KDP Q-switch, Q-switch driver and polarizer, respectively. PFN is the pulse forming network

2 Results and Discussion

Our goal in this investigation was to compare the laser performance of the Nd:YAG and Nd:KGW crystal rods under identical experimental conditions except for the Nd:concentration in these rods. The single-shot laser experiments were performed with input energies ranging from 1–25 J with output coupler reflectivities of 60, 80, and 95% at 1.064 µm. For Nd:KGW, these results are shown in Fig. 2. In Fig. 3, we display the results from the Nd:YAG and Nd:KGW at 80% reflectivity of the outcoupling mirror. It is clear from this figure that the energy extracted from the Nd:KGW rod

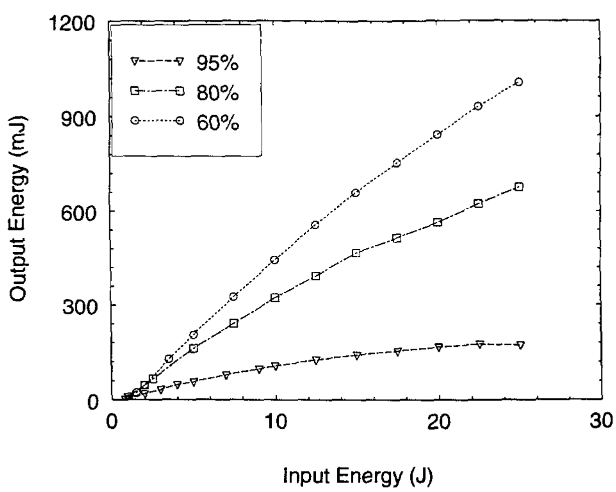

Fig. 2. Observed output laser energies (mJ) from the Nd:KGW rod at different pump energies (J) of the flashlamp for output mirror reflectivity of 60%, 80%, and 95%

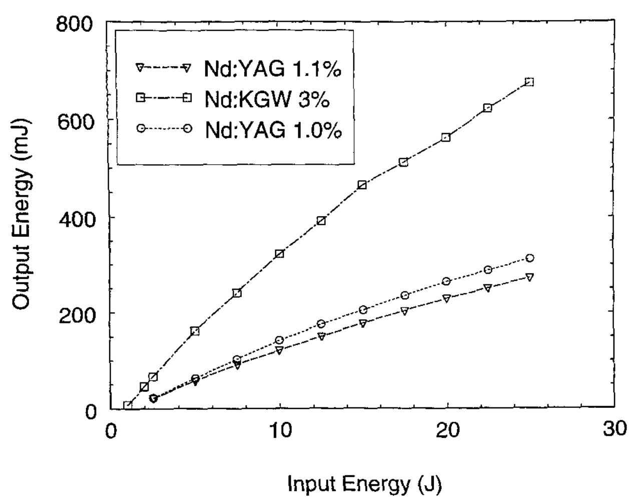

Fig. 3. Observed output energies from Nd:KGW and Nd:YAG rods at different Nd concentrations and flashlamp input energies. The output mirror reflectivity was 80%

is about a factor of 2.5 times more than that extracted from the Nd: YAG rod under identical experimental conditions. The effect of concentration quenching is clearly noticeable in the Nd: YAG rods with Nd: concentrations of 1.0 and 1.1 at.%, leading to a slightly less extracted energy from 1.1% Nd: doped YAG rod compared to that from the 1.0% Nd: doped YAG rod. The extrapolated energy thresholds for Nd: KGW and Nd: YAG with 80% output coupler were determined to be 0.55 J and 1.3 J, respectively.

In the free running mode of operation the laser slope efficiency was determined by using the following expression [5]:

$$\eta_s = \eta_0 \ln R_{out} / (\ln R_{out} - L)\,, \qquad (1)$$

where η_s is the measured slope efficiency, η_0 is the intrinsic efficiency (the efficiency without loss in the laser resonator), R_{out} is the reflectivity of the output coupler, and L is the round trip loss parameter mainly due to scattering and reflection, etc. The loss parameter L was determined by using the method described by Findlay and Clay [15] and modified by Koechner [1]. In this method the resonator losses are determined by varying the reflectivity of the output coupler and determining the energy threshold for lasing according to the following equation [1]:

$$-\ln R_{out} = 2KP_{th} - L\,, \qquad (2)$$

where K is the pumping coefficient and P_{th} is the threshold power or energy for lasing. In Fig. 4, we plot $-\ln R_{out}$ and the extrapolated threshold energies for Nd: YAG and Nd: KGW at 60%, 80%, and 95% mirror reflectivity of the output coupler. A straight line fit to the data points yielded a round trip loss L ($L = 2\delta l$, δ is the loss per unit length l of the rod) of 0.11 and 0.34 and a pumping coefficient K ($K = g_{th} l / P_{th}$, g_{th} is the small-signal gain at threshold) equal to 0.193 and 0.385 for Nd: YAG and Nd: KGW, respectively. The measured slope efficiencies η_s were determined by using the extrapolated values of the output energies at a particular flashlamp input energy and were found to be equal to 1.5% and 3.6% with 80% output mirror for the Nd: YAG (Nd = 1.0 at.%) and Nd: KGW rods, respectively. The intrinsic efficiencies η_0 were determined by substituting the values of L and η_s in (1) and were found to be equal to ≅ 2.5% and ≅ 8.8% for Nd: YAG and Nd: KGW rods, respectively. From the expressions $L = 2\delta l$ and $K = g_{th} l / P_{th}$, the round trip loss (2δ) and the small-signal gain at threshold g_{th} per unit length were determined to be approximately equal to 0.014 cm^{-1}, 0.043 cm^{-1}, and 0.031 cm^{-1}, 0.027 cm^{-1}, for Nd: YAG and Nd: KGW rods, respectively. By using the value of g_{th}, the small-signal gain coefficient, determined above and the stimulated emission cross sections from Table 1 for Nd: YAG and Nd: KGW, the population inversion density at threshold may be estimated by using the expression: $g_{th} = \sigma \Delta N$, $\Delta N = (N_2 - N_1)_{th}$, where N_1 and N_2 are the ground and excited state densities, respectively. The ΔN values for Nd: YAG and Nd: KGW were found to be equal to $11.0 \times 10^{16}\,cm^{-3}$ and $8.2 \times 10^{16}\,cm^{-3}$, respectively.

In Fig. 5, we display the results obtained in the Q-switched mode of operation with 80% reflectivity of the output coupler. It is clear from this figure that the threshold energy as well as the energy extraction efficiency is almost identical to the values obtained when the laser was operated in the free running mode of operation, i.e., lower threshold energy and about 2.5 times higher extraction efficiency for the Nd: KGW rod compared to the Nd: YAG rod at 1.064 μm. However, in the Q-switched mode of operation, the saturation in Nd: KGW to occur at ≅ 5 J, as compared to 12 J in Nd: YAG. At an input energy of ≅ 16 J, the output energy from the Nd: YAG and Nd: KGW rods are identical. At input energies higher than 16 J the output energy from the Nd: YAG rod is higher than that from the Nd: KGW rod. Unfortunately, we were not able to measure the Q-switched pulsed duration because of the lack of proper instrumentation.

In conclusion, we have studied the relative performance of Nd: YAG and Nd: KGW laser rods at different Nd concentrations pumped by a single Xe flashlamp in the energy range of 1–25 J. The laser was operated in the free running as well as in the Q-switched mode of operation and lasing threshold and extraction efficiency were measured at

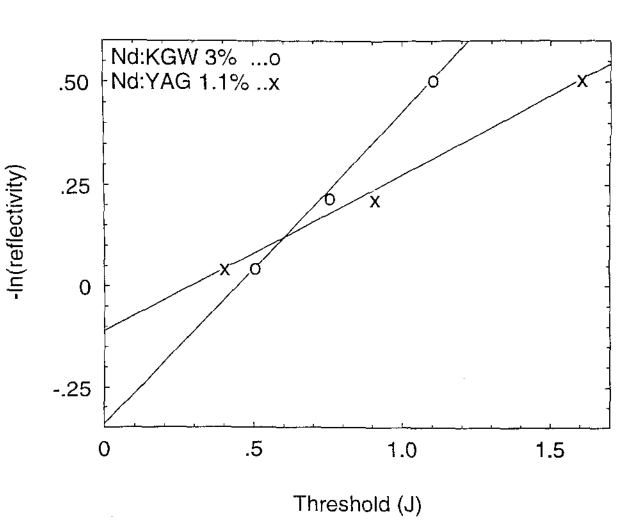

Fig. 4. Log plot of the output mirror reflectivity vs the extrapolated laser energy threshold for Nd: YAG and Nd: KGW rods

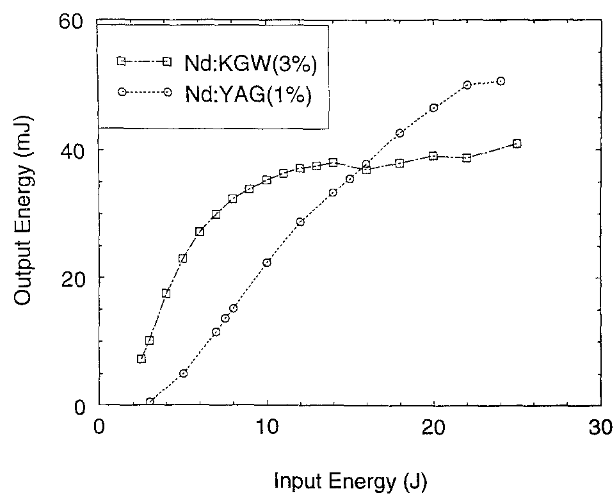

Fig. 5. Observed output energies from Nd: YAG an Nd: KGW rods at different input energies during Q-switched mode of operation. The reflectivity of the output coupler was 80%

1.064 μm. In both modes of operation, the laser threshold was found to be much lower in the case of the Nd:KGW rod than in the case of the Nd:YAG rod. The laser extraction efficiency of the Nd:KGW rod was found to be about 2.5 times better than that of the Nd:YAG rod. In the Q-switched mode, this difference in the efficiencies was limited to below 5 J of input power. In the free running mode, the intrinsic slope efficiency was determined to be about 2.3% and 8.8% for the Nd:YAG and Nd:KGW rods, respectively.

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