Efficient GaAlAs diode-laser-pumped operation of Nd:YLF at 1.047 μm with intracavity doubling to 523.6 nm

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Diode-laser-pumped Nd:YLF lasers are demonstrated at 1.047 μm with less than 1-mW thresholds and internal quantum efficiencies approaching 70%. Operation at 1.053 μm has also been achieved. Intracavity second-harmonic generation using MgO:LiNbO₃ has generated up to 145-μW output at 523.6 nm for 30.1 mW of diode-laser pump power.

The use of semiconductor diode lasers as pump sources for solid-state lasers was demonstrated as early as 1964. In the past few years the dramatic increase in output power of diode lasers has made pumping of solid-state lasers practical. Recently it was shown that diode-laser-pumped Nd:YAG lasers offer advantages over lamp-pumped lasers, including high efficiency and good frequency stability. Gain-switched versions of these sources have been used for injection seeding of high-power pulsed lasers. In addition, intracavity second-harmonic generation (SHG) by placing a nonlinear material in the cavity of a diode-pumped Nd laser was previously proposed and recently demonstrated using the combination KTiOPO₄ (KTP) and Nd:YAG. Diode pumping of other solid-state laser materials besides Nd:YAG is also possible and has been demonstrated using stoichiometric Nd materials such as LiNdP₂O₇ and NdAl₃(BO₃)₄.

In this Letter we present results of diode-pumped Nd:LiYF₄ (YLF) at 1.047 and 1.053 μm and intracavity second harmonic with MgO:LiNbO₃ as the doubling material in an end-pumped geometry. High efficiencies are shown using low-cost, low-power single-stripe GaAlAs diode lasers as opposed to using diode arrays as in Refs. 3 and 7.

There are a number of potential advantages to using Nd:YLF as opposed to Nd:YAG or stoichiometric Nd compounds. In Nd:YLF the σᵣ product (σ is the stimulated-emission cross section and 𝜌ᵣ is the fluorescent lifetime) is 1.5 greater than for Nd:YAG and greater than the stoichiometric materials. Cw thresholds are inversely proportional to this product, so Nd:YLF has a lower threshold if other factors are equal. This is not such an important factor in end-pumped systems in which demonstrated thresholds are at the milliwatt level, but it may be an important factor in other geometries, such as side-pumped slabs, in which thresholds may be higher. Nd:YLF also has a factor-of-2 longer fluorescent lifetime than Nd:YAG. This means that in pulsed systems to obtain equivalent pulse energy to Nd:YAG, one half of the number of diode lasers must be used, so a pulsed Nd:YLF system is potentially less expensive than a Nd:YAG system. The output wavelengths of Nd:YLF, 1.047 μm for the π polarization and 1.053 μm for the σ polarization, match the the peak of the gain for Nd-doped silicate and phosphate glasses, respectively, so this material could be used as an injection seeder or a master oscillator for glass systems. Nd:YLF also naturally oscillates polarized since YLF is uniaxial with the 1.047-μm line the high gain transition. This property is attractive for intracavity SHG with 90° phase matching of MgO:LiNbO₃ because it yields polarized operation without intracavity polarizing elements. An additional advantage for SHG of YLF with MgO:LiNbO₃ is the relatively short emission wavelength of 1.047 μm, which noncritically phase matches at 65°C as opposed to 115°C for SHG of 1.064-μm Nd:YAG. MgO:LiNbO₃ was chosen as the nonlinear material for intracavity SHG because of the recent interest in the reduced photorefractive damage exhibited in this material with the MgO doping and the successful use of this material in previous intracavity SHG experiments.

Two samples of Nd:YLF were fabricated for these experiments. One was 4 mm long and 3 mm in diameter with the end faces having a 1.8-cm radii of curvature. One end face was a coated high reflector (HR) at 1.05 μm, and the other was 0.3% transmitting at 1.05 μm and high reflecting at 810 nm, which is near the pump wavelength. The other sample was 5 mm long and 3 mm in diameter with one face flat and the other with a 1.8-cm radius of curvature. The flat face had a multilayer antireflection (AR) coating, and the curved face had a HR coating at 1.05 μm. The two samples are referred to as samples 1 and 2, respectively. Based on a fluorescent lifetime of 440 μsec for the ⁴F₉/₂ upper laser level, the Nd concentration is 2 at.%. The MgO:LiNbO₃ was 8 mm × 3 mm × 3 mm with the crystal c axis perpendicular to the 8-mm direction. The 3 mm × 3 mm faces were AR coated at 1.06 μm.

A schematic of the experimental apparatus used in the intracavity doubling experiment is shown in Fig. 1. A single-stripe Sharp LT-024 diode laser was used as the pump source at the absorption line around 791 nm
in the \( \pi \) polarization of Nd:YLF. A microscope objective was used to focus the pump light into the samples through the HR coated faces at 1.05 \( \mu \)m. Since sample 1 has the cavity mirror directly coated onto its faces, no other elements are needed. With sample 2, an external cavity mirror was used, which permitted variation of the output coupling, insertion of the doubling crystal for intracavity SHG, and insertion of a Brewster window to allow polarization control. The oven was used to heat the MgO:LiNbO\(_3\) to the phase-matching temperature.

Our laser results for the \( \pi \)-polarized output at 1.047 \( \mu \)m are shown in Fig. 2 for the two samples. The maximum slope efficiency is 35\%, with 3.1\% output coupling with overall efficiency of 29\%. A Brewster window was placed into the cavity to permit oscillation of the \( \sigma \) polarization at 1.053 \( \mu \)m. The threshold was 5.3 mW, and the slope efficiency was 13\% for 0.58\% output coupling. The low value of the output coupling was limited by mirror availability. These efficiencies are based on output power to power incident upon the cavity as opposed to absorbed power. Of the power incident upon the cavity, 17\% is reflected at the input mirror and 80–90\% of that remaining is absorbed, so the quantum slope efficiency in the best care for absorbed photons approaches 70\% at 1.047 \( \mu \)m. Cavity losses can be calculated from the slope efficiency and output coupling.\(^{14}\) For 0.22\% output coupling the slope efficiency was 28\% based on incident power; the calculated loss is \( \approx 0.3\% \). For operation at 1.053 \( \mu \)m the loss is \( \approx 1.8\% \), which appears to be due to the Brewster window. Higher slope efficiencies can be expected for higher output coupling in this case.

It appears that either excited-state absorption (ESA) of the pump or energy-transfer upconversion (ETU) is occurring in this material because yellow emission is observed from the pumped region. ESA is due to an ion in the excited state absorbing an incident photon. ETU involves two nearby excited ions, which transfer energy causing one ion to relax to a lower state while the other is simultaneously excited to a higher state. This is analogous to concentration quenching in Nd\(^{3+}\)-doped solids, except that case involves one excited and one unexcited ion. ETU has been found to occur in Nd\(3P_3/2\) (Refs. 15 and 16) and is likely to occur in all Nd-doped solids to varying degrees, just as with concentration quenching. Estimates of a pump density requirement of \( 10^6 \) W/cm\(^2\) for ETU to become significant have been made for Nd:YAG.\(^{17}\) The yellow emission decreases sharply when the cavity is aligned and laser oscillation begins, which implies that the \( 4F_{3/2} \) upper laser level takes part in the process. These processes have different pump wavelengths, concentrations, and temporal dependences. ESA of the pump could be decreased by simply changing pump wavelength, and ETU could be decreased by lowering Nd\(^{3+}\) concentration. It has been shown that ETU can affect laser operation by increasing threshold and changing laser dynamics.\(^{18}\)

We have demonstrated intracavity SHG with the combination Nd:YLF and MgO:LiNbO\(_3\). The results for single-ended output at 523.6 nm are shown in Fig. 3 and indicate a maximum output power of 145 \( \mu \)W for 30.1 \( \mu \)W of incident pump power. The output beam is an easily visible TEM\(_{00}\) spot. It is clear that better performance can be achieved. Insertion losses of the
LiNbO$_3$ are $\sim$3% round trip, which is high. It is not clear whether the losses are surface or bulk, but striations are visible to the naked eye. Low insertion loss is critical since conversion efficiency decreases rapidly with increasing loss.$^{10}$ The mirror coatings could be improved, with the output coating being more transmissive at 523.6 nm and the other coating being more transmissive at 791 nm. At present, the reflectance of the output mirror is 16% at 523.6 nm. In principle, it is also possible to increase single-ended output by having a HR coating at 523.6 nm for the cavity mirror opposite the output mirror.$^{10}$ In this case, this technique would provide little enhancement because the $\sigma$ polarization of Nd:YLF absorbs at this wavelength.$^{13}$

In conclusion, a high-efficiency, diode-pumped Nd:YLF oscillator has been demonstrated. Optimization could yield even higher efficiencies. Intracavity SHG using MgO:LiNbO$_3$ has also been shown with good conversion efficiency, and it appears that SHG can be greatly increased with simple improvements.

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