Continuous-wave operation of a room-temperature, diode-laser-pumped, 946-nm Nd:YAG laser

T. Y. Fan and Robert L. Byer

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Received June 4, 1987; accepted July 21, 1987

Single-stripe diode-laser-pumped operation of a continuous-wave 946-nm Nd:YAG laser with less than 10-mW threshold has been demonstrated. A slope efficiency of 16% near threshold was shown with a projected slope efficiency well above a threshold of 94% based on results under Rhodamine 6G dye-laser pumping. Nonlinear crystals for second-harmonic generation of this source were evaluated. KNbO3 and periodically poled LiNbO3 appear to be the most promising.

There has been a revival of interest in using diode lasers as pump sources for solid-state lasers. While much of the recent work has focused on the lasers as pump sources for solid-state lasers, there have been other transitions of interest in Nd3+, such as the 4F2/2 → 4I 11/2 1.06-μm Nd3+ transition, which has a similar cross section to the 946-nm transition in the 900-950-nm range. The difficulties with this transition are typically lower stimulated emission cross section than the lower laser level at room temperature since the lower laser level is less than 1000 cm⁻¹ above the ground state. A way to overcome these difficulties is to confine the pump beam and the laser mode in a Nd-doped single-mode glass fiber to achieve high pump densities and gain. Alternatively, we recently demonstrated through modeling and experiment that diode-laser pumping of the 946-nm transition in Nd:YAG in a bulk device at room temperature is possible. We also proposed second-harmonic generation (SHG) of this source to generate coherent blue radiation in an all-solid-state device similar to solid-state green sources by frequency doubling of the Nd3+ transition. Blue generation was subsequently demonstrated by intracavity SHG of a 946-nm Nd:YAG laser pumped by a Rhodamine 6G (R6G) dye laser. In this Letter we report on experimental results of the first diode-laser-pumped 946-nm Nd:YAG laser at 300 K and discuss some aspects of SHG of this source.

The primary difficulties with this transition in Nd:YAG are an approximately order-of-magnitude-lower stimulated emission cross section than that of the 1.06-μm line and a lower laser level at 857 cm⁻¹ above the ground state. The first laser operation on this transition was demonstrated at 77 K to reduce the lower laser level population. In 1969, Wallace and Harris demonstrated laser action on this transition with flash-lamp pumping at room temperature. The question is whether diode-pumped laser operation at room temperature is possible. The low stimulated emission cross section of 4×10⁻²⁰ cm² itself is not a problem; low threshold and high slope efficiency have been demonstrated in Nd:glass at 1.053 μm, which has a similar cross section. However, one difficulty with the low cross section is parasitic oscillation on the 1.064-μm transition, which previously prevented operation at 946 nm in a room-temperature, end-pumped Nd:YAG laser. We have shown that when proper design is used, parasitic oscillation in cw operation is not a problem.

The lower laser level population, 0.0074 of the dopant concentration at 300 K, leads to an increase in threshold. The increase in threshold can be viewed in either of two equivalent ways. Either the laser must have enough gain to overcome reabsorption at the laser wavelength in addition to the other cavity losses or additional pump power is needed just to reach population inversion. Modeling of quasi-three-level laser transitions showed that thresholds of less than 10 mW at 300 K are possible under diode pumping.

Figure 1 shows our experimental apparatus. The output of a single-stripe diode laser operating at 808.5 nm is combined with the output of a R6G dye laser at 588 nm with part of the diode-laser beam sent to a monochromator to allow its wavelength to be monitored. The beams pass through a polarizer and a Fresnel rhomb to provide isolation against feedback for the diode laser. The beams are focused to spots with slightly less than ~20-μm radii in the Nd:YAG rod by a 4-cm focal-length lens. The YAG rod is doped with nominally 1% Nd and is ~0.13 cm long with 1-cm radius-of-curvature faces polished on the ends. One face is coated with a higher reflector (HR) at 946 nm and the other with an antireflection coating at 946 nm. For this rod length, 87% of the incident power at 588 nm and 67% at 808.5 nm is absorbed. The output coupler located approximately 5 cm from the rod has a 5-cm radius of curvature and is either a HR or a 99% reflector at 946 nm with greater than 60% reflectivity. The output coupler located approximately 5 cm from the rod has a 5-cm radius of curvature and is either a HR or a 99% reflector at 946 nm with greater than 60% reflectivity.
due to this population appears as a real loss near threshold. The slope efficiency near threshold is dependent on the amount of reabsorption loss due to the lower laser level population and on the tightness of focus of the pump beam with higher slope efficiencies for tighter focus and less reabsorption loss. The output under diode-laser pumping rises at least 1.1 times faster than that under R6G dye-laser pumping near threshold. The threshold numbers indicate that the dye-laser pump is focused tighter than the diode-laser pump, so it appears that the only difference between R6G dye and diode-laser pumping is the quantum defect. If this is the case, the slope efficiency well above threshold should approach 34% under diode-laser pumping based on the 24% slope efficiency under R6G dye-laser pumping.

We have analyzed a number of nonlinear materials for SHG of the 946-nm light. Efficient SHG of continuous-wave 946-nm radiation is more difficult than at 1.06 μm because a number of crystals with relatively high nonlinearity at 1.06 μm cannot be used for 946-nm SHG. KTiOPO₄ (KTP) has high effective nonlinearity at 1.06 μm but low nonlinearity at 946 nm because Type I instead of Type II phase matching must be used. Ba₂Na₂B₄O₉Cl₂ does not have enough birefringence to phase match at 946 nm. Regular LiNbO₃ does not phase match for 946 nm, but Li-diffused stoichiometric LiNbO₃ phase matches at −87°C for doubling 954 nm and may phase match 946 nm at lower temperatures. Thus it is important to evaluate materials appropriate for 946-nm SHG.

It has been shown that the SHG conversion efficiency for Gaussian beams is a function of the Poynting vector walk-off angle between the fundamental and the second harmonic, ρ, and |dₑff|²l₀/n³, where dₑff is the effective nonlinearity and n is the refractive index. For plane waves in the limit of undepleted fundamental power, the conversion efficiency is proportional to |dₑff|²l₀/n³, where l₀ is the length of the nonlinear crystal; but for finite diameter beams, both diffraction and double refraction limit the effective interaction length of the crystal. For nonzero Poynting vector walk-off, little increase in conversion efficiency is possible for a crystal longer than the aperture length lₐ, which is equal to √|w₀/ρ|, where w₀ is the Gaussian beam radius. Thus for nonzero Poynting vector walk-off the conversion efficiency goes as |dₑff|²l₀²/n³. For ρ = 0, the effective interaction length is limited by diffraction and is proportional to the focal distance for the beam. The general case of SHG with Poynting vector walk-off and focusing into the SHG crystal taken into account has been treated by Boyd and Klimov.

Table 1 lists a summary of calculations for the Poynting vector walk-off angle ρ, lₐ for w₀ = 30 μm, relative conversion efficiency given by |dₑff|²l₀²/n³ normalized to that of noncritically phase-matched KNB₅O₁₃ for which |dₑff|²l₀²/n³ = 28.7 pm²/N², and phase-matching angles where ϕₘ is the angle of propagation relative to the z axis and ϕₚ is the angle to the x–z plane. The references used to calculate these quantities are listed. All the calculations are for Type I SHG. Noncritically phase-matched KNB₅O₁₃ has a high relative conversion efficiency, but the phase-
matching temperature is 180°C. One intriguing possibility is periodically poled LiNbO₃. The calculated d_eff is that for the optimum case, periodically poled with flipped domains every coherence length. In practice, the lengths of these two crystals were limited by available crystal size and increasing loss for longer crystals. Thus the lengths of these two crystals were chosen to be 0.5 cm although their confocal distances for w = 30 μm are greater than 1 cm. Angle-tuned KNbO₃, which reduces the phase-matching temperature, also has a relatively large conversion efficiency. KTP, LIO₃, and β-BaB₂O₄ are poor choices for SHG of low-power sources because of their low d_eff and large ρ, which severely limits their low ρ and large length could be increased to absorb a larger fraction of the pump light. Eventually it may be possible to have higher slope efficiency for this device than for a 1.06-μm Nd:YAG laser. Other host materials, such as other garnets and perovskites such as YAlO₃, may be of interest. Both classes of material have a relatively large splitting for the ground-state manifold, which reduces the lower laser level population. However, spectroscopic data such as absorption in the diode-laser pump bands, stimulated emission cross section, and energy levels of the ground-state manifold need to be known before judgments can be formed on the desirability of a given host.

In summary, continuous-wave diode-laser-pumped operation of a 946-nm Nd:YAG laser at room temperature has been demonstrated with low thresholds and 16% slope efficiency near threshold. Slope efficiency as great as 54% in this device is projected for operation well above threshold. A number of SHG crystals have been evaluated for SHG of this laser; KNbO₃ and periodically poled LiNbO₃ are the most promising.

This research was supported by NASA. T. Y. Fan would like to thank the IBM Corporation for supporting him with an IBM Graduate Fellowship.

References