Single-mode operation of a standing wave miniature Nd laser pumped by laser diodes

Richard Scheps and Donald F. Heller

Single-longitudinal-mode operation is reported for miniature Nd:YAG and Nd:BEL standing wave resonators. The best performance obtained was 18 mW with laser diode pumping and 31 mW with dye laser pumping. The miniature lasers were also operated multimode at power levels as high as 470 mW. A completely integrated, miniature Nd:BEL laser was constructed and is described. Results for several different resonator configurations are compared and it is concluded that the threshold pump power for multimode oscillation in each is consistent with an earlier observation that energy diffusion increases with absorbed pump power density. This allows single frequency oscillation to be obtained at high excitation rates with axially extended cavities.

While single-longitudinal-mode operation of a standing wave laser resonator is common for index-guided semiconductor laser diodes, for solid state lasers a ring configuration is generally preferred, particularly when high output power is desired. A report[1] of single-longitudinal-mode performance in a miniature $LiNdP_4O_{12}$(LNP) laser pumped by an argon ion laser suggests that, for low power, laser pumped standing wave lasers can provide a simple and effective means of achieving single frequency output. The standing wave configuration has several important advantages compared with the ring, including ease of fabricating a monolithic device, low component costs, and alignment simplicity. Since longitudinal-mode competition in such lasers is affected by the mode spacing relative to the gain linewidth, short cavity lengths are desirable to increase the threshold power for oscillation of secondary axial modes.[2] To operate efficiently the laser must be end-pumped, and recent progress in laser diode pumping of Nd:host lasers provides the basis for developing an integrated approach to the laser design leading to a compact packaged device. To demonstrate that miniature diode pumped single mode standing wave lasers are a practical and simple alternative to the ring configuration for low power operation, several laser resonators were constructed. In addition, these devices were operated at pump powers high enough to produce multimode output to demonstrate their efficiency and power capability.

Several techniques requiring intracavity optics have been developed[3] over the years which produce single frequency output in a standing wave resonator, but these methods generally are unsuitable for compact or monolithic resonators. Monolithic diode-pumped standing wave resonators have previously been reported for Nd:YAG[4–6] and Nd:YALO,[7] where all except YALO operated single mode. Zhou *et al.*[4] reported 8 mW of single-mode output in a 3-mm-long rod, while Owyoung *et al.*[5] reported 0.025 mW in a 5-mm-long rod. Zayhowski and Mooradian[6] used a $Ti:Al_2O_3$ laser to obtain 22 mW of single frequency output in a 0.73-mm-thick plano–plano Nd:YAG resonator. While this laser operated in a single transverse mode, the authors could not completely explain why the output spatial mode was confined to the mode defined by the spatial profile of the pump excitation rather than one determined by the resonator configuration.

In addition to the standing wave resonators, a low power monolithic diode pumped Nd:YAG ring laser has been developed[8] and is available commercially. For uses where optical feedback is of concern, the ring is the best choice. However, the nonplanar ring geometry used in the design is difficult to fabricate, and the monolithic ring concept is applicable only to neodymium hosts having sufficiently high Verdet constants. Good single frequency performance has been reported[6] for the plano-plano standing wave resonator. Relative to this configuration, however, improved transverse-mode control can be obtained in the more stable plano–concave resonator. Moreover, the latter configu-

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Richard Scheps is with Naval Ocean Systems Center, Code 843, San Diego, California 92152. When this work was done Donald Heller was with Allied-Signal Corporation, Corporate Technology Center, Morristown, New Jersey 07960; he is now with Light Age, Inc., 6 Powder Horn Drive, Warren, New Jersey 07060.

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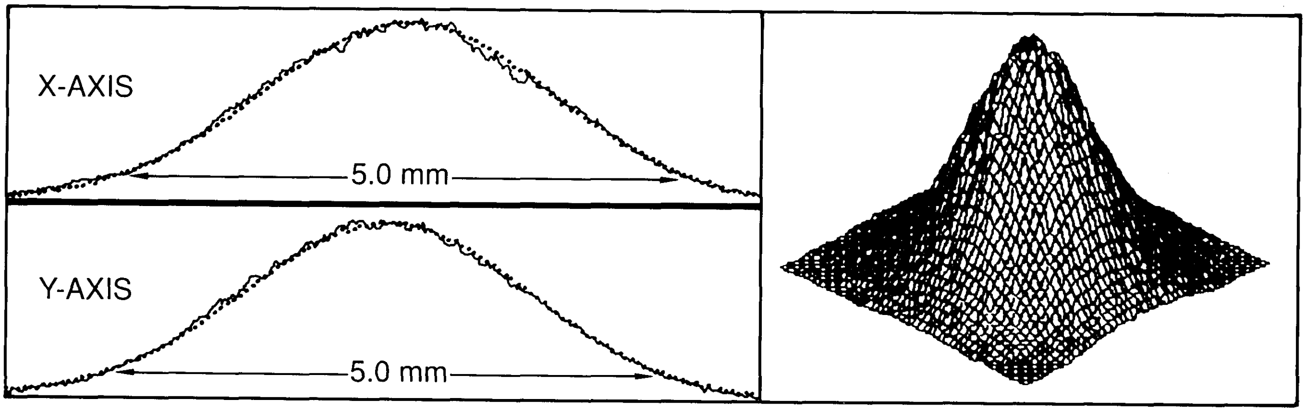

Fig. 1. Intensity profiles of the single-mode output from a 1-mm thick Nd:BEL resonator. The intensity is shown along the x and y axes through the centroid of the far field pattern, and the fit to a Gaussian is shown by the dots. The correlation coefficients are 0.96 and 0.97 for the x and y axis, respectively. A 3-D contour of the laser intensity is shown on the right-hand side of the figure.

ration has been found[9] to relax restraints on the cavity length, and higher single mode power should be achieved. From the point of view of longitudinal diode pumping, the plano–concave resonator has given the lowest threshold and highest efficiency, and we have therefore chosen to demonstrate single frequency operation of Nd:YAG and Nd:BEL in resonators of this type.

Three different resonators were constructed. The first was a monolithic Nd:BEL rod, 1 mm thick with a 25-cm radius of curvature (ROC) output coupler, coated for 98% reflectivity. The second was a monolithic Nd:YAG rod, 1 mm thick with a 25-mm ROC output coupler coated for 98% reflectivity. The third resonator was not monolithic, consisting of a 1 mm long plate of Nd:BEL and a 25-mm ROC, 98% reflective output coupler placed in a near hemispherical configuration. In all cases the exterior flat face of the laser rod was coated for high reflectivity at the laser wavelength and high transmission at the pump wavelength. The interior face of the 1-mm flat plate of Nd:BEL was coated for low reflectivity (AR) at the laser wavelength. The pump lasers consisted of two 1-W single stripe cw laser diodes polarization combined in an arrangement previously described.[10] Such high pump power was not necessary to obtain single mode operation, since threshold was found to occur at pump levels of $\sim$18 mW. However, these miniature lasers performed quite well multimode at high output power and the two 1-W pump diodes were required to provide this demonstration.

The pump image at the rod face for each laser diode was rectangular, measuring 100 μm in length and was brightest at the stripe edges. The short dimension was measured to be 10 μm, which is the resolution limit of our measurement system; we anticipate that its actual value is substantially smaller. To learn if the Nd:host single frequency performance was affected by the extended size of the pump beam, the resonators were pumped with the output of an argon ion-pumped styryl 9 dye laser. The beam diameter of the focused image of the dye laser tuned to 808 nm and operating at 250 mW was less than the resolution limit of the measurement system; the calculated diffraction limited spot size is 1.9 μm. In addition, beam diagnostics were performed on the dye laser, which was found to have a nearly Gaussian beam profile (average correlation coefficient of 0.94) and a beam divergence of 2.8 mrad. Using the dye laser, then, was considered an acceptable substitute for a single-mode laser diode, and was particularly useful since it was capable of much higher output power.

The diode-pumped monolithic Nd:BEL resonator operated single longitudinal mode up to an output power of 8.5 mW. The resonator mode diameter was calculated to be 108 μm at the rod exterior face, which is comparable to the long dimension of the pump beam. The output beam was measured to be highly Gaussian with a correlation coefficient of 0.97 and a divergence of 7.5 mrad or 1.3 times diffraction limited (DL). The intensity profile was fit to a Gaussian, and is shown in Fig. 1. Single frequency operation was verified with a scanning Fabry-Perot, which was found to be substantially more sensitive in detecting the threshold for the second longitudinal mode than a spectrometer, although the latter was used as well. At higher pump power the laser operated multitransverse as well as multilongitudinal mode, with its divergence increasing to 2.1 DL. This is primarily due to a combination of thermal effects and the spatial mismatch between the pump and resonator modes. Over 460 mW was obtained from this miniature laser with a pump input of 1.17 W, and at this power level seven longitudinal modes were identified. The maximum pump power was limited by thermal dissipation in the rod. The calculated optical conversion efficiency of $>$40% is comparable to that obtained with a longer resonator.[10]

The performance of the monolithic Nd:YAG resonator was similar to that of the monolithic Nd:BEL. Single-mode operation was obtained up to 7.6 mW, and a spectrum analyzer trace of the output is shown in Fig. 2. A linewidth measurement was performed using a 300-MHz free spectral range scanning Fabry-Perot optical spectrum analyzer with a stated finesse of 200.

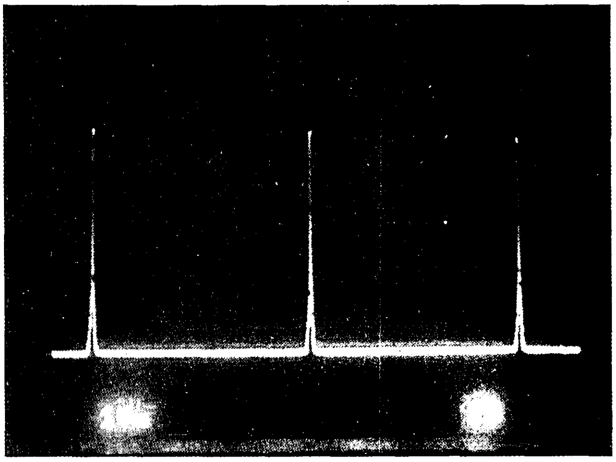

Fig. 2. Fabry-Perot optical spectrum analyzer trace showing the single frequency output of a 1-mm thick Nd:YAG resonator producing 7.6 mW. The free spectral range of the Fabry-Perot is 300 MHz.

The linewidth measured in this manner was 2.1 MHz but is likely resolution limited. Indeed, previous measurements[6] on a single-mode standing wave laser show a linewidth of <5 KHz, and the linewidth of the resonator reported in this work should be comparable. The beam divergence of the single-mode monolithic Nd:YAG resonator was measured to be 17.6 mrad or 1.5 DL, with a Gaussian correlation coefficient of 0.90. The calculated resonator mode diameter is 60 μm, substantially smaller than the pump dimension, making the resonator more susceptiable to multitransverse mode operation. This was most apparent in the higher output power measurements, where 458 mW was obtained when pumping with 1.41 W. The transverse modes in this rod were much higher order than in the monolithic Nd:BEL resonator, resulting in a higher divergence (41 mrad) and a lower pump to laser photon conversion efficiency.

The discrete (nonmonolithic) resonator was found to have the best overall performance for single-mode operation. It had the lowest threshold, and produced 18.6-mW single mode. We believe this is the highest single-mode power reported for a diode-pumped standing wave resonator. The divergence of the single-mode output was 7.5 mrad, similar to the monolithic Nd:BEL resonator, and the output was highly Gaussian with a correlation coefficient of 0.97. As one might expect, at higher pump power the output beam remained single transverse mode. Pumping with 1.03 W, 470 mW was obtained at a divergence of 6.5 mrad.

Two additional measurements were performed with the monolithic Nd:BEL resonator. The miniature resonator was placed inside a temperature controlled enclosure which could be regulated to 0.010°C to test the stability of the laser output frequency. Using the 300-MHz Fabry-Perot as a diagnostic, noticeable frequency jitter was observed with the oven off. However, with the oven on and the temperature stabilized, no jitter could be observed over a period of 30 min. Because of the small size of the gain medium and the low diode pump power levels required for single frequency operation, thermal stabilization of the rod proved to be quite simple.

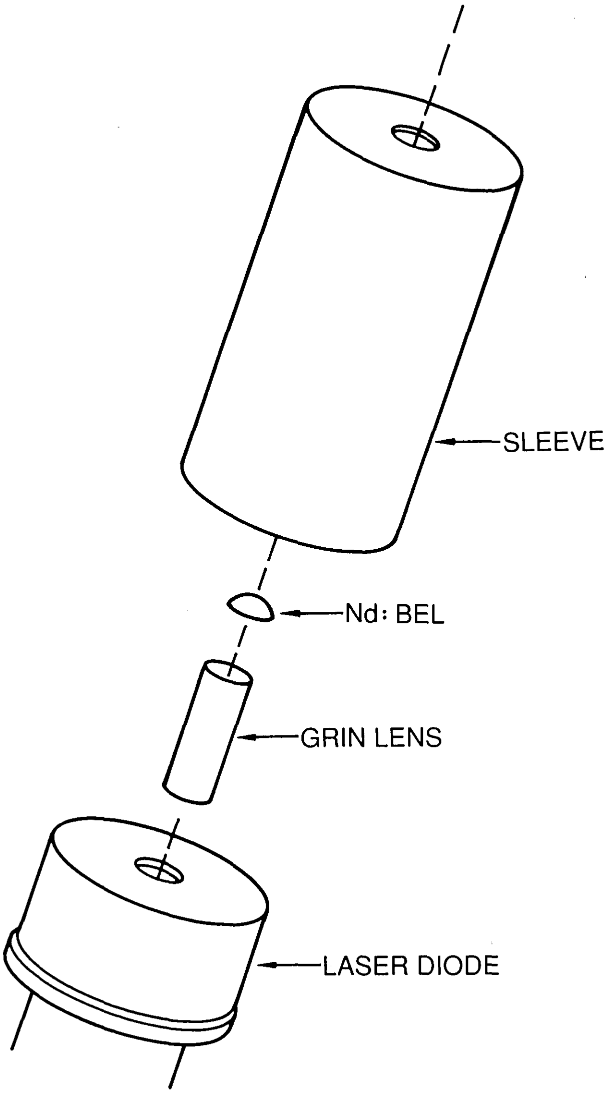

Fig. 3. Exploded view of the miniature, integrated diode-pumped Nd:BEL laser.

The second measurement involved the performance of a completely integrated, miniature Nd:BEL laser. To this end, a package was assembled consisting of a single 1-W laser diode (in a 9-mm can), a grin lens, and the laser rod. The device length was 1.5 cm and is shown schematically in Fig. 3. The performance of this device was somewhat poorer than that of the resonator with the standard pump optics. The imaging grin lens used (0.29 pitch) was found to be an inefficient means of relaying the pump light onto a small spot on the exterior face of the rod. The smallest pump spot size that could be obtained was measured to be 157 μm, and, due to the spatial mismatch between the pump and resonator spots, the threshold was high and only ~10% of the pump light incident on the rod was converted to laser output. Operating the laser diode at 1 W, the rod received 721 mW of pump power, producing 68 mW at 1.07 μm. The threshold power was 250 mW and the slope efficiency was ~15%. This laser did not operate single frequency, even at low power. Near threshold, three longitudinal modes operated simultaneously, while at higher pump power 8 modes were observed. The output power was quite stable, however, and the alignment of the optics was straightforward, so that we believe such a device would be appropriate for applications requiring small, low power 1.07-μm lasers. In addition, we note that for the sake of compactness the laser diode was not actively cooled and therefore did not operate at the correct wavelength at all drive currents. Our experience shows that such an effect might reduce the output power in Nd:BEL by 20–40%. It is also worth noting that, with some modification to the diode package, the grin lens and Nd:BEL resonator can be made to fit completely inside the diode housing, leading to further miniaturization.

To determine if the extended size of the pump beam affects the threshold for the second longitudinal mode in the minature lasers, the laser diodes were replaced with the styryl 9 dye laser described above. The dye laser output was focused with two different lenses. For the monolithic Nd:YAG laser a short focal length highly corrected plastic aspheric lens was used, while for the discrete Nd:BEL resonator both this lens and a 2.5-cm focal length lens were used. Substantially improved performance was obtained with the short focal length lens. The monolithic resonator produced 20.8 mW of single-mode output while the discrete resonator produced 31 mW. On the other hand, with the longer focal length lens the single frequency output of the discrete resonator was not as strong. Although the larger pump spot size on the laser rod affects the multimode performance,[11] it appears that it also affects the maximum single frequency power obtainable.

It is instructive to discuss the single-mode results obtained in this work in terms of the effects of energy diffusion on spatial hole burning. In the absence of energy diffusion, the maximum single-mode output power will be limited by the high unsaturated gain for secondary axial modes present even near threshold. One means of overcoming this problem is to make the device short enough so that the secondary-mode frequencies lie outside the gain bandwidth, but such short gain lengths generally put low limits on the overall power available. Energy diffusion serves to reduce spatial inhomogeneity in the axial population inversion and has been addressed in detail for Nd:YAG by Danielmeyer.[2] It was shown that even the small energy diffusion rates associated with resonance transfer in Nd:host materials lead to significant effects on the single-mode operation of these lasers. For example, diffusion in Nd:YAG is sufficient to increase the single frequency output power from 65 to 92% of the traveling wave power at low excitation levels, and reduce the unsaturated net gain for secondary longitudinal modes by an order of magnitude. In addition, diffusion reduces the effective relative bandwidth for oscillation by a factor of 5. It was concluded that in cases where the diffusion parameter is considerably larger than the single frequency excitation parameter, spatial hole burning will be insignificant. For Nd:YAG, the diffusion parameter is equal to the excitation parameter when the single-mode output power is 20 mW (with a cavity waist of 50 μ), and assuming a comparable diffusion parameter for Nd:BEL one might expect maximum single-mode output power levels on the order of several milliwatts for the resonators considered in this work. The highest single frequency output power obtained was 31 mW in a device where the axial mode spacing was small compared to the gain bandwidth (approximately 6 and 156 GHz, respectively), and, in fact, all three resonators showed higher single-mode power than expected based solely on diffusion due to resonance transfer. We must therefore look beyond Danielmeyer's calculations to obtain a sufficient explanation of these results.

A more complete understanding of the single-mode operation of these lasers in relation to diffusion comes from a different group. In measuring the single-mode operation of end-pumped LNP lasers, Otsuka and Kubodera[9] were led to the conclusion that diffusion increases with absorbed pump power density. At low power, diffusion is determined solely by recombination (resonance transfer), but at higher pump power density Auger recombination, which depends quadratically on the excited state density (and hence pump power density), will contribute to diffusion as well. This was confirmed by experiment, and calculations showed that the Auger recombination process is responsible for increasing the effective diffusion parameter as the density of excited states increases. Our results are entirely consistent with this concept. In the discrete element cavity the resonator is near-hemispherical and the beam waist is small. This, in turn, gives the highest excitation density and also the highest single-mode power. The monolithic resonators have substantially larger waists (30 and 54 μm for Nd:YAG and Nd:BEL, respectively) and therefore the pump power density in these rods will be lower. However, the pump power density in the monolithic resonators must still be high enough to increase the effective diffusion parameter over the low pump power (recombination-only) limit to explain the higher than expected 8-mW single-mode output power obtained for these devices. It was predicted[12] that Auger recombination will have a significant effect on the overall diffusion rate at a pump power density of 10^5 W/cm^3 for Nd:YAG. For the 1-mm rods used in this work (and assuming a comparable Auger recombination rate for Nd:BEL), this requires a pump flux of 10^4 W/cm^2 or 100 mW for a 100 by 10-μm pump spot. As previously noted the actual pump size is likely to be <1000 μm^2, and the nonuniform intensity across the pump image makes the local power density higher still. From these considerations we anticipate that Auger recombination will be significant even at low pump powers, as had been observed with LNP lasers, and note further that with dye laser pumping the area pumped is greatly reduced, leading to substantial Auger recombination rates at all power levels. It should be emphasized that the resonator waists by themselves do not bear on the pump power density. However, due to the nonuniform laser diode pump image, the waist (if smaller than the pump waist) will, through the alignment optimization procedure, circumscribe the most intense part of the pump image. In this sense the resonator waist is a determining factor of pump power density in the resonator. Finally, it is worth noting that Auger recombination can occur at pump powers near threshold and, in fact, is responsible[9] for raising the pump threshold in the LNP laser by associated quenching.

In summary, single frequency output has been demonstrated in several Nd:host miniature resonators at power levels as high as 31 mW. While these devices work well when the gain length is short, it is not necessary to have the gain medium perform the function of an etalon by making the resonator length so small that the longitudinal mode spacing is larger than the gain bandwidth. Spatial hole burning will eventually lead to oscillation of additional longitudinal modes, but the threshold pump power for secondary axial modes is dependent on the effective energy diffusion parameter. For Nd:YAG, energy diffusion of excited states has a transfer time of 300 ns and suppresses spatial population inhomogeneity[13] but the reduction of spatial hole burning is not sufficient to prevent multimode operation at all output powers. The results obtained in this work are consistent with the concept that energy diffusion increases with absorbed pump density. The higher single frequency power obtained with dye laser pumping and the lower power obtained with the 2.5-cm focal length lens relative to the short focal length lens can both be explained in a straightforward manner based on pump density considerations. Seen in this light, Nd:BEL has two significant advantages compared with Nd:YAG for this type of application. Since its absorption at 810 nm is stronger and broader[10] than that of YAG at 808 nm, energy diffusion may be more rapid in BEL at the same pump power level and higher single-mode power should therefore be achievable. In addition, because of the short absorption path for the thin rods, BEL will absorb more of the pump light than YAG and will be more efficient.

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References

1. K. Kubodera, K. Otsuka, and S. Miyazawa, "Stable $LiNdP_4O_{12}$ Miniature Laser," Appl. Opt. **18**, 884–890 (1979).
2. H. G. Danielmeyer, "Effects of Drift and Diffusion of Excited States on Spatial Hole Burning and Laser Oscillation," J. Appl. Phys. **42**, 3125–3132 (1971).
3. A review of many of these methods is given by P. W. Smith, "Single Frequency Lasers," in *Lasers, Vol. 4*, A. K. Levine and A. J. DeMaria, Eds. (Dekker, New York, 1976) pp. 73–118.
4. B. Zhou, T. J. Kane, G. J. Dixon, and R. L. Byer, "Efficient, Frequency-Stable Laser-Diode-Pumped Nd:YAG Laser," Opt. Lett. **10**, 62–64 (1985).
5. A. Owyoung, G. R. Hadley, P. Esherick, R. L. Schmitt, and L. A. Rahn, "Gain Switching of a Monolithic Single-Frequency Laser-Diode-Excited Nd:YAG Laser," Opt. Lett. **10**, 484–486 (1985).
6. J. J. Zayhowski and A. Mooradian, "Single-Frequency Microchip Nd Lasers," Opt. Lett. **14**, 24–26 (1989).
7. D. Scarl, R. Burnham, S. R. Bowman, and B. J. Feldman, "Diode-Pumped 1.34-μm Nd^{3+}:$YALO_3$ Laser," Appl. Opt. **27**, 5005–5008 (1988).
8. T. J. Kane and R. L. Byer, "Monolithic, Unidirectional Single-Mode Nd:YAG Ring Laser," Opt. Lett. **10**, 65–67 (1985).
9. K. Otsuka and K. Kubodera, "Effects of High Density Pumping on Relaxation Oscillations and Mode Spectra in Lasers," IEEE J. Quantum Electron. **QE-16**, 419–424 (1980).
10. R. Scheps, "Efficient Laser Diode Pumped Nd Lasers," Appl. Opt. **28**, 89–91 (1989).
11. W. P. Risk, "Modeling of Longitudinally Pumped Solid-State Lasers Exhibiting Reabsorption Losses," J. Opt. Soc. Am. B **5**, 1412–1423 (1988).
12. H. G. Danielmeyer, M. Blatte and P. Balmer, "Fluorescence Quenching in Nd:YAG," Appl. Phys. **1**, 269–274 (1973).
13. H. G. Danielmeyer, "Progress in Nd:YAG Lasers," in *Lasers. Vol. 4*, A. K. Levine and A. J. DeMaria, Eds. (Dekker, New York, 1976) pp. 1–71.