High-efficiency, argon-laser-pumped Nd:YLF laser system

E. P. Maldonado, I. M. Ranieri, N. D. Vieira, Jr., and S. P. Morato

An Ar-ion laser was used to pump a Nd:YLF laser, in both σ and π polarizations, in a longitudinal scheme. In spite of the small absorption coefficient at the pump ($\sim$0.25 cm $^{-1}$), a careful laser design can circumvent this problem, and efficiencies as high as those attained with semiconductor pumping schemes are reported. The laser fundamental parameters were experimentally determined. A double-pass net gain as high as 10^3 was measured, and an output power of 1 W was obtained with a pumping power of 6 W.

Key words: Solid-state lasers, end pumped, laser characterization.

1. Introduction

Recently, Nd-ion lasers have gained new interest as a result of semiconductor laser pumping, mostly now that there are strong pumping sources in the near-infrared region. These compact systems are currently achieving high emission efficiencies. Among the several hosts for Nd ions, $LiYF_4$ (YLF) is a very attractive one because of a broad homogeneous spectral emission band. Besides, Nd:YLF crystals show two emission lines, at 1047 and 1053 nm, corresponding to the π and σ polarizations, respectively. The latter coincides with the laser emission line of Nd:glass lasers, and it is commonly used as the master oscillator for high-power systems.[1]

The Nd ions in many crystalline hosts show several absorption lines all over the visible and the near-infrared spectrum; the strongest ones are located around 800 nm, with typical absorption coefficients of few inverse centimeters, usually one order of magnitude larger than the visible absorption lines. We show, for the first time to our knowledge, that the strongest Ar-ion laser line (514.5 nm) can be efficiently used to pump a Nd:YLF crystal longitudinally, with a laser performance comparable to semiconductor pumping. The Ar laser has been already used to pump Nd ions in glasses, but in these cases the absorption bands are broad and intense. However, in spite of the strong absorption of pump radiation, reported optical efficiencies for these Nd:glass lasers are of the order of only 1%.[2,3]

A characterization of the Ar-laser-pumped Nd:YLF laser developed here was carried out, and the laser parameters were determined. As an Ar-ion laser is a standard tool in many laboratories, its use as a pumping source for a Nd:YLF system extends the available laser lines to the near infrared.

2. Laser Design

The active-medium length l was determined to fulfill the condition of maximum output power, following the model presented in Ref. 2 but considering two constraints in the system design. First, the crystal length must correspond to the pump-beam confocal parameter. This leads to a nearly constant pump-beam area inside the active medium. Second, the emission TEM_{00} mode must also have the same confocal parameter, corresponding to a mode-matched configuration. When numerical calculations were performed, the optimum value of the length was found to be $l \cong 60$ mm, which corresponds to a beam waist of 70 µm for the pump beam and a beam waist of 100 µm for the Nd:YLF resonator TEM_{00} mode, inside the active medium. We used these values for the pump and the emission beams, but the available high-optical-quality sample length was $l = 33$ mm. As we show, even with this smaller length we could obtain good results.

A well-known expression for the round-trip unsaturated logarithmic gain is[4,5]

$$\Gamma^0 = P_P[1 - \exp(-\alpha_A l)] \frac{4(\lambda_P/\lambda)\beta}{\pi(w_0{}^2 + w_P{}^2)I_S}, \tag{1}$$

The authors are with the Supervisão de Materiais Optoelectrônicos MMO Instituto de Pesquisas Energéticas e Nucleares, Comissão Nacional de Energia Nuclear São Paulo, Caixa Postal 11049, CEP 05422-970, São Paolo/SP, Brazil.

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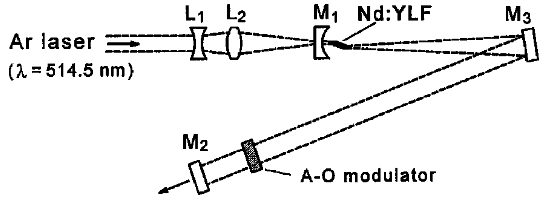

Fig. 1. General scheme of the Nd:YLF resonator. The lenses, L_1 and L_2, are used to mode match the pumping beam. A-O, acousto-optic.

where P_P is the pump power; w_P and w_0 are the pumping and the emission beam waists at the active-medium region; β is the thermal population distribution factor, at room temperature in this case, for the σ and the π metastable states; $I_S = (h.\nu)/(\sigma.\tau)$, is the saturation intensity, where $h.\nu$ is the emitted photon energy, τ is the upper-laser-level lifetime, and σ is the stimulated-emission cross section; $\sigma \cong 3 \times 10^{-19}\ \mathrm{cm}^2$ and $\beta = 0.43$ for the π polarization; and $\sigma \cong 2 \times 10^{-19}\ \mathrm{cm}^2$ and $\beta = 0.57$ for the σ polarization. Other parameters are $h.\nu = 1.9 \times 10^{-19}$ J and $\tau \cong 530\ \mu\mathrm{s}$.[6]

Considering that $P_P \cong 6$ W, we note that the calculated unsaturated gain for each polarization is approximately $\exp(\Gamma^0) = \exp(6.7) \cong 800$ for the π polarization and $\exp(\Gamma^0) = \exp(5.2) \cong 150$ for the σ polarization.

The active-medium samples were obtained from a boule of Nd:YLF crystal, with a diameter of 2.5 cm and a length of 7 cm, grown in our laboratories. The Nd concentration in the samples is 0.6(1) mol. %, as determined by the use of the x-ray fluorescence method. Two samples were cut in 3 mm × 3 mm × 33 mm rectangular prisms extracted along the growth direction [coincident with the (1, 1, 0) crystallographic direction]. The optical faces (polished to a flatness of $\lambda/4$) were at the Brewster angle, suitably oriented for the π polarization in one sample and for the σ polarization in the other. The transmission of the prepared samples at $\lambda = 1.06\ \mu\mathrm{m}$ was 0.995(5). At $\lambda_P = 514.5$ nm, the absorption coefficient is $\alpha_A = 0.18(2)\ \mathrm{cm}^{-1}$ for the σ polarization and $\alpha_A = 0.30(2)\ \mathrm{cm}^{-1}$ for the π polarization.

A general scheme of the optical resonator can be viewed in Fig. 1. We designed an optical resonator with the required Rayleigh parameter for the laser medium region that consisted of a three-mirror telescopic resonator with astigmatic compensation. The mirrors, M_1, M_2, and M_3, have radii $\rho_1 = 5$ cm, $\rho_2 = \infty$, and $\rho_3 = 100$ cm; M_1 and M_3 are highly reflective ($R_{1,3} \geq 0.995$). The incidence angle on M_3 must be 10° to compensate for the astigmatism.[7] The distance between M_1 and M_3 is 52.4 cm, and the distance between M_2 and M_3 is 97.6 cm.

3. Experimental Results

The laser output power as a function of the pump power, for both polarizations, is shown in Fig. 2; the output coupler reflectivity is $R_2 = 0.78$.

The Nd:YLF laser was characterized following the same technique used in Ref. 8, with an acousto-optic modulator, allowing us to determine the unsaturated gain and internal losses. The acousto-optic modulator permits the continuous variation of the output reflectivity while we monitor the laser output power. The output power behavior obtained is shown in Fig. 3 for a pumping power $P_P = 5.5$ W.

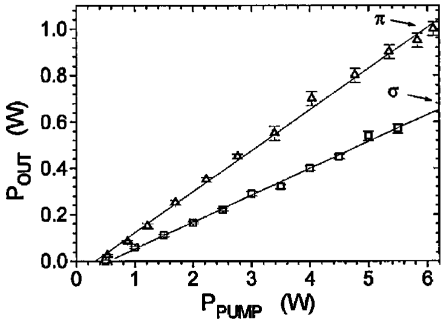

Fig. 2. Nd:YLF laser output power as a function of the pump power for both polarizations. The output coupler transmission is 22%.

We obtained the round-trip unsaturated gain $\exp(\Gamma^0)$ and the resonator transmission $\exp(-L)$ by fitting the theoretical expression to the data[8]:

$$P_{\mathrm{OUT}} = K[-\ln(R)]\left[\frac{\Gamma^0}{L - \ln(R)} - 1\right], \tag{2}$$

thus yielding $\Gamma^0 = 6.9(5)$, $L = 0.040(5)$, $K = 0.15(2)$ W for the π polarization and $\Gamma^0 = 3.6(5)$, $L = 0.050(5)$, $K = 0.19(2)$ W for the σ polarization. The L values do not consider the insertion loss of the modulator, 2% per pass. This loss is due to a residual reflectivity of the modulator surfaces.

4. Conclusion

In this Note we have demonstrated that it is possible, in a longitudinal pumping scheme, to obtain high laser efficiencies even if the gain-medium absorption coefficient at the pumping wavelength is small. In particular, Nd:YLF crystals can be conveniently pumped by Ar-ion lasers. It was shown that an output power level of 1 W and a double-pass net gain as high as $\exp(6.9) \cong 1000$ could be easily obtained with approximately 6 W of pump power. We calcu-

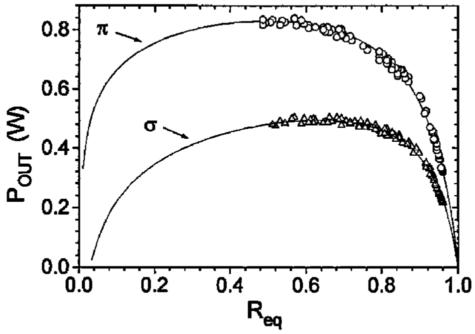

Fig. 3. Nd:YLF laser output power as a function of the output coupler reflectivity for both polarizations. The pump power is $P_P = 5.5$ W. The continuous lines are theoretical curves fitted to the data.

lated that if a Nd:YLF sample with length $l \cong 60$ mm was used, a 30% higher output power level could be attained for the same pump power.

The slope efficiency of the developed system is 18%. Considering that only ~50% of the pumping light is absorbed, we can estimate that slope efficiencies of approximately 40% can be expected when the Nd:YLF is pumped in the near-infrared absorbing lines (~800 nm).

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