OUTPUT POWER CHARACTERISTICS OF SOLID STATE LASERS WITH THERMAL LENSING AND HIGH TEM$_{00}$ MODE VOLUME

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The effects of thermally induced lens in a Nd:YAG resonator, optimized for high output power and thermal stability, are analyzed. The highly non-linear output power behavior of these lasers makes difficult the task of calculating relevant parameters like slope efficiency, pumping coefficient and optimum output coupling. Using an approximation for the beam waist inside the rod as a function of pump power we obtain a simple expression for the output power which is in good agreement with the experimental values.

INTRODUCTION

High power and high brightness cw Nd:YAG lasers are of fundamental importance whenever high intensity and coherence is necessary. In particular, there is an increasing interest in the industry in using this laser for precision cutting, drilling and welding applications whereas in science the Nd:YAG has long become the common pump source for OPO's, crystal and fiber lasers.

High output power in the TEM$_{00}$ mode is obtained when a larger mode cross section inside the rod is used. This is done by considering in the resonator analysis the rod as a thin, positive lens which is induced by the thermally generated birefringence of the crystal. The mode characteristics are therefore determined mainly by the dioptric power of this lens which is proportional to the pump power. Because of the large cross section of the mode inside the rod, any changes in the dioptric power have a strong influence upon the diffraction losses of the mode. The fact that these losses are not constant makes hard the task to characterize the laser by analyzing its output power behavior. Therefore it is very difficult to calculate pumping coefficient, slope efficiency and related parameters like the optimum output coupling.

Here we present an analysis, which is capable of calculating these parameters and compare the results to an optimized Nd:YAG laser. The analysis is especially easy to do, once all important effects can be related to the lamp input power.

THEORY

The central idea of stabilizing the TEM$_{00}$ mode by a thermally induced lens is to design the resonator in such a way that the beamwaist of the mode within the rod is a defined minimum, w_0, at the chosen input power P_0. This minimum is still big enough to avoid oscillation of higher order modes. For any input power other than P_0 the beamwaist inside the rod is larger and diffraction losses as well as birefringence losses become more important. When the beam radius approaches the size of the rod diameter the lower ($P<Po$) and upper ($P>Po$) threshold of laser operation are reached. In order to calculate the losses, we need to know the beam diameter within the rod as a function of pump power. Applying the rules of Gaussian beam propagation one may calculate the beam waist inside the rod as a function of the thermally induced focal length, the mirror radii and the resonator dimensions [1]. For practical reasons it is more convenient to express the beam waist as a function of lamp input power, P_p, instead of focal length. Theory [2] predicts that the focal length, f, should vary inversely with heat input, but experimental results from the measurement of the thermally induced focal length of the rod show that 1/f scales non-linearly with pump power [3], depending probably on lamp age and pump geometry. From above considerations it becomes clear that the beam waist within the rod is a very complicated function of the lamp pump power. The whole procedure of calculating the beam diameter inside the rod can be considerably simplified when using the following approximation:

$$\mathrm{w}^4 = w_o^4\left(\frac{(P_1-P_0)^2}{(\mathrm{P}_2-\mathrm{P}_1)(\mathrm{P}_\mathrm{p}-\mathrm{P}_1)}+\frac{(P_2-P_0)^2}{(\mathrm{P}_2-\mathrm{P}_1)(\mathrm{P}_2-\mathrm{P}_\mathrm{p})}\right), \quad \text{with } \mathrm{P}_1 < \mathrm{P}_\mathrm{p} < \mathrm{P}_2 \tag{1}$$

where w^4 is the fourth power of the normalized beam waist inside the rod. w_0 is the minimum normalized beam waist which occurs at the input power P_0 power for which the resonator was designed for. The lower threshold, P_1, and upper threshold, P_2, are determined experimentally. Using this approximation we may now calculate the losses.

Thermally induced birefringence inside the crystal rod causes partial depolarization of the TEM_{00} mode [4]. This may severely affect the output power, especially in the presence of an intracavity polarizer which will reject part of the depolarized beam. To calculate the roundtrip cavity loss, L, in the presence of a Brewster polarizer (fused silica) as a function of the normalized beam waist, w, one has to solve the following integral [5]:

$$L = 0.584*\left(1-4\int_0^{\pi/2}\int_0^b e^{-\frac{2r^2}{w^2b^2}}\left[1-sin^2 2\varphi sin^2\left(B\frac{r^2}{b^2}\right)\right] rdrd\varphi\right) \tag{2}$$

where b is the rod radius and B is a factor which includes the dissipated power in the Nd:YAG rod (normally between 0.5% and 5% [2,6]). The solution of the above integral has the following approximation:

$$L = 0.584*\frac{B^2}{4/w^4+4B^2} \tag{3}$$

As the TEM_{00} beam waist inside the rod becomes larger for pump powers other than P_0, the Gaussian beam becomes more diffracted by the circular aperture of the rod. The fractional power transmitted per round-trip as a function of the normalized beam radius inside the rod, w, is

$$\mathrm{T}^2 = \left(1-\mathrm{e}^{-\frac{2}{\mathrm{w}^2}}\right)^2 \tag{4}$$

In order to calculate the output power one generally uses [2]

$${}_{\mathrm{out}} = \eta(\mathrm{P}_\mathrm{p}-\mathrm{P}_\mathrm{th}) \quad \text{or} \quad {}_{\mathrm{out}} = -\ln(\mathrm{R}_\mathrm{out})\mathrm{I}_\mathrm{s}\,{}^{A}\!/_{2}\left(\frac{\mathrm{P}_\mathrm{p}}{\mathrm{P}_\mathrm{th}}-1\right) \qquad (5a),\ (5b)$$

where η is the slope efficiency and P_{th} is the threshold pump power given by

$$P_{th} = \frac{1}{2K}\left(L + 2e^{-\frac{2}{w^2}}\right) \tag{6}$$

L being the constant losses including the birefringence losses, w is given by equation (1), K is the pumping coefficient [2] and where we expanded the logarithmic diffraction losses retaining only the first order. L may be determined by measuring the fractional transmitted power when the crystal is placed between parallel polarizer and analyzer [5]. A is the average cross sectional area of the TEM_{00} inside the rod, I_s is the saturation intensity for Nd:YAG (920 W/cm^2, [2]) and R_{out} is the reflectivity of the output mirror.

EXPERIMENTAL ANALYSIS

The measurement of the thermal focal length and the calculation of the compensating resonator are described elsewhere and will not be treated here [3]. The resonator used in this experiment was designed for an optical length of 136.5 cm (mode-locking at 50 MHz) and a thermally induced focal length of 45 cm, corresponding to approximately 31,5 Amp of lamp input current (input power P_o of 3620 Watt). The corresponding minimum beam waist, chosen when designing the resonator to impede higher order modes, is 1.7 mm calculated at $1/e^2$ points. Inside our 4 mm diameter rod this gives a normalized minimum beam waist w_0 of 0.42. The measured output versus input curve (triangles in figure 1a) shows the typical behavior of high TEM_{00} output power lasers compensated for thermal lensing. Care must be taken when measuring this curve. We found that the insertion of a mode- locker is capable of strongly distorting the characteristic output power curve (see also references [7]).

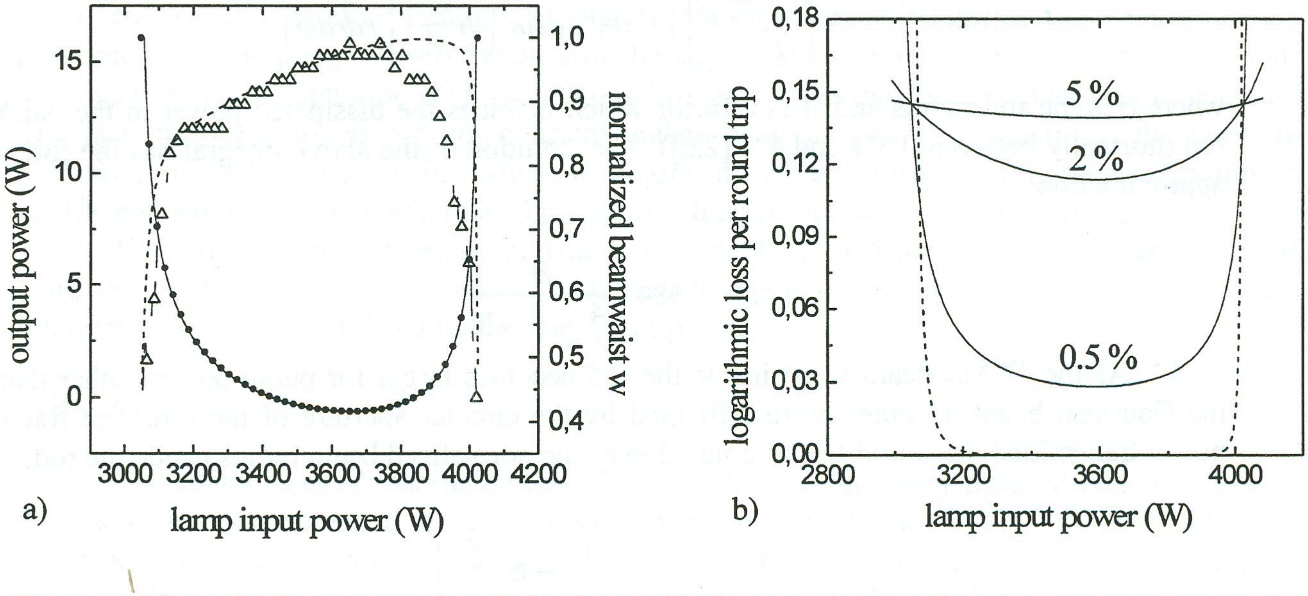

Figure 1: **a)** The *solid dots* represent the calculated, normalized beam waist versus lamp input power using equation (1) with w_o =0.42, lower threshold P_1 =3050 W and upper threshold P_2 =4020 W. The *straight line* is an exact calculation of the beam waist using reference [1] and the data from the measured focal length of the thermal lens of our laser. The measured output power curve (*triangles*) is then fitted (*dotted line*) using equations (1) to (6) using 2 % of heat conversion in the rod. **b)** diffraction losses (dotted line) and birefringence losses as a function of pump power percentage converted into heat.

As a result of the fit in figure 1a (dotted line), using equation (5a) we obtain a slope efficiency of 0.8(2) %, assuming 2 % of heat conversion inside the rod. As we used the same optical components inclusively the same output coupling as the original resonator (Quantronix 116) we may compare the results: When compared to the original resonator, which had a average slope efficiency of 0.25(5) %, the mode filling inside the rod improved the efficiency by a factor of three. This is in good agreement with the more than three times higher output power obtained with the thermally compensated laser. In figure 1b it becomes clear that the only significant change in loss between the lower and upper threshold is due to diffraction in the rod, whereas in comparison the birefringence losses show very little variation. We may therefore lump the birefringence losses into the constant losses and obtain, by fitting the output power curve with (5b), a pumping coefficient of 12(5)x10^{-5} W^{-1} and total losses, without output coupling, of 0.17(5). This gives an optimum output coupling [2] of R_{out} =80(9)%.

CONCLUSIONS

Solid-state lasers with high TEM_{00} mode-volume show a highly non-linear output power behavior which makes hard the task of determining experimentally measured parameters. By using a approximate fit for the TEM_{00} beam waist inside the rod, we obtain important laser parameters which are necessary for further laser optimization and characterization. The in this way obtained data are in good agreement with our experimental results and data from the literature. We also show that the birefringence losses may be considered independent of the beam waist inside the rod when compared to the diffraction losses, which considerably simplifies the analysis.

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