ENHANCED EFFICIENCY OF A C.W. MODE LOCKED ND:YAG LASER BY COMPENSATION OF THE THERMALLY INDUCED, POLARIZATION DEPENDENT BIFOCAL LENS.

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***ABSTRACT** : New measurements of the bifocal, thermally induced lenses of a c.w. Nd:YAG laser were obtained. We observed the existence of four different focal lengths, polarization and direction dependent, that are thermally induced in the gain medium. The focal distance values were used to calculate very stable resonators with large fundamental mode filling in the laser gain medium, good beam profile and very well defined polarization. We developed a general approach for the optimization of single lamp, cw pumped Nd:YAG lasers. Up to 22 Watts of cw output power in the vertically polarized TEM_{00} mode and 15 W in the horizontal polarization are obtained, for moderate lamp currents. In particular we demonstrate mode-locking with 56 ps pulse duration at 33 A of lamp current and up to 15 W of average output power.*

INTRODUCTION

Continuous wave mode-locked Nd:YAG lasers are widely used in pulse compression experiments in optical fibers as well as pumping sources for color center lasers [1-3]. All these applications need high stability and output power in the TEM_{00} mode. In spite of being a very well known and important laser system, only recently it was possible to increase the output power and stability of the fundamental mode TEM_{00}, at no expense of pump power. Due to the thermal load in the laser rod, produced by the lamp pumping, there is a thermally induced lens (f) in the gain medium. High stability and output power were achieved by increasing the fundamental mode volume within the laser rod, considering the thermally induced lens in the resonator design. Nevertheless, commercial configurations mostly use small diameter beams in the active region to diminish the effects of thermally induced birefringence [4] and spatial variation of the beam mode. Resonators with large mode volume, can be specially designed to compensate for some of these effects [5-7]. Magni et al. [8-11] demonstrated that for any resonator with an internal dynamical lens, there are two distinct stability zones ($0 < g_1 g_2 < 1$) corresponding to two different sets of values of f. The minimum of the beam radius in the laser rod, in each of these stability zones, corresponds to a large range of focal distances. In the case of thermally induced focal length it means a large range of pump powers. In these zones, the resonator remains stable and shows very little output power fluctuations. In their work, optimization was achieved for one single polarization.

However, Koechner [4] has shown that there are two thermally induced, polarization dependent, focal lengths in the rod. Assuming a cylindrical symmetry, there is a focal length for the radial polarization of light (f_R) and a different focal length for tangential polarization (f_Φ). Defining the parameter α as:

$$\alpha = f_\Phi / f_R \qquad \text{(exp 1)}$$

α can be calculated by considering the appropriate photoelastic coefficients of Nd:YAG; its theoretical value is $\alpha = 1.2$. The experimental values are in the range between 1.35 and 1.5 [4].

EXPERIMENTAL

The laser under investigation is a commercial model, polarized by an intracavity Brewster plate [12]. In order to measure the polarization and direction dependent focal length, an aperture was introduced, with two small rectangular slits, just before the laser rod. The use of two slits is twofold: avoids the central part of the rod where all the focus coincides and; provides the crossover of the two beams for precise determination of the focus. An expanded, collimated and polarized He-Ne beam illuminates uniformly the whole slit area. If the polarization of the HeNe beam is along the direction of the slits, the thermal lens for radial polarization is measured (figure 1); if the polarization is perpendicular to the direction of the slits, the thermal lens for tangential polarization is measured. The results of the focal length measurements for different lamp currents are shown in figure 2. Also, it is shown the best fit considering that f depends on the inverse of the lamp pump power. It is clearly seen that there are four different curves instead of the two expected ones, showing a spatial asymmetry of the geometrical index profile.

For the case of horizontal polarization of the light we measured a constant ratio of f_Φ^H to f_R^H of 1.35 (Fig. 2). In the case of vertical polarization, f_Φ^V and f_R^V show approximately the same value, which was not accounted for before, due to the assumption of an angular independence on these parameters.

A higher thermal gradient in the horizontal direction is expected due to the closer proximity of the rod to the pump lamp. Due to the non uniformity of the thermal gradient, the focal lengths of the polarization components are related by a function of the lamp current, $\beta(I)$. Therefore we have

$$f_R^V = \beta(I) \cdot f_R^H \qquad \text{(exp. 2)}$$

and accordingly :

$$f_\Phi^H = \beta(I) \cdot f_\Phi^V \qquad \text{(exp. 3)}$$

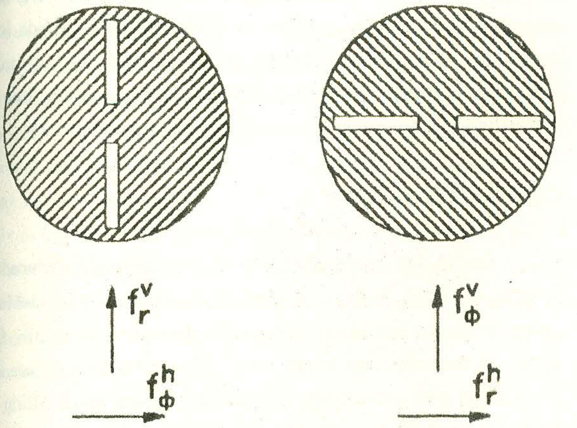

Fig.1 Rectangular aperture used for measuring the different focal distances f_Φ and f_R for horizontal (h) and vertical (v) polarization directions of the He-Ne beam.

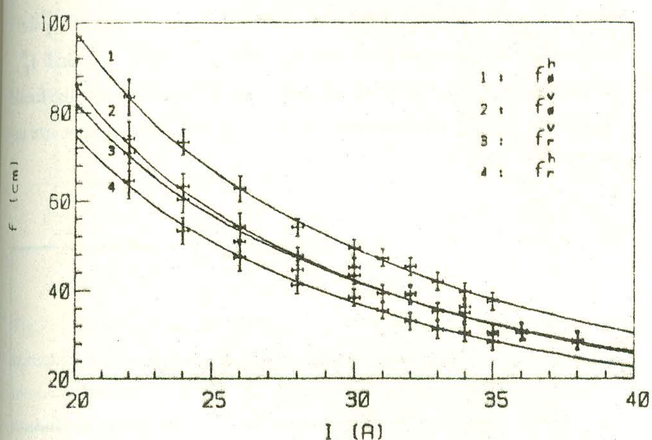

Fig.2 Measured values of the focal distances for the different polarizations as a function of the lamp current. The lamp voltage is 127V.

Combining the effects of axially symmetrical birefringence, α, and the non uniformity of the thermal gradient, β(I), we now can explain the observed difference between the factors correlating f_Φ and f_R in the horizontal and vertical polarization. By combining expressions 1, 2 and 3 we have:

$$f_\Phi^H = \alpha.\beta(I) \cdot f_R^H \qquad \text{(exp.4)}$$

$$f_\Phi^V = \frac{\alpha}{\beta(I)} . f_R^V \qquad \text{(exp 5)}$$

By analyzing fig. 2 we note that f_Φ^V and f_R^V show approximately the same value for lamp currents from 28 A up to 38 A. Therefore, α = β and α.β = 1.35 for lamp currents within this range. Thus, α is 1.18 which is in good agreement with the theoretical prediction of α = 1.2.

OPTIMIZATION OF THE RESONATOR DESIGN

The idea of increasing the mode volume and maintaining high stability, developed by Magni et al [8-11], will be followed here, but considering different, polarization dependent, focal distances.

In order to obtain a clean and round beam shape it was experimentally found that one should use ratios of rod diameter (r) to TEM_{00} spot size (w) of the order of 2.0 < r/w < 2.2. This ratio still prevents higher order modes from oscillation and minimizes the effects of depolarization due to birefringence stress that leads to distortion of the beam shape. Particularly, this effect becomes stronger in the outer part of the rod. Due to the presence of the polarizing element (the Brewster window) inside the laser, the larger the beam mode in the rod, the higher the internal losses, in the presence of Brewster windows. Therefore, there is a trade off between the maximum mode size and the polarization dependent losses. That is the reason for choosing the mode filling ratio of 2.2 in our case.

VERTICAL POLARIZATION

The vertical polarization presents the same focal distances, (f_Φ^V and f_R^V), as shown in figure 2. A general scheme of the laser configuration is shown in figure 3. To optimize the resonator for mode locking we set the effective length of the cavity to L = 150 cm (mode locker frequency 49.95 MHz [13]) and optimized it for a thermal focal length of 40 cm, which corresponds to 31 A of lamp current (refer to Fig. 2). The back mirror radius, R_1, is -40 cm, and the output coupler, R_2, is flat, with a transmission of 12%. The distance L_1 is 54.5 cm. It is pumped by single-lamp and the rod is a Nd:YAG crystal with dimensions 4x78mm. Optimization in higher lamp currents is possible using a different set of mirrors.

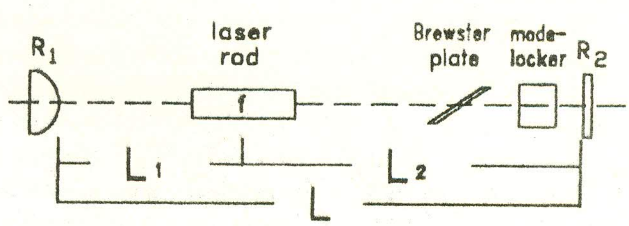

Fig.3 Laser resonator scheme showing the relative distances of the mirrors and the laser rod. These are the parameters used for high power optimization.

The mode locked pulses were monitored with a high speed photodiode [14] (rise time 35 ps) attached to a sampling scope [15] and measured with a background-free autocorrelator. Power measurements were done with a calibrated detector [16]. The output power results for pure c.w. operation are shown in figure 4. A maximum power of 15 W were obtained at 33 A of lamp current. The shift between the expected (31 A) and obtained (33 A) optimum current may be justified by a possible non-optimum choice of the filling ratio (r/w =2.2) for this polarization. In mode-locked operation an average output power of 13 W was measured. The autocorrelation trace of the pulses corresponding to 9 W of average power is shown in figure 5. Assuming a gaussian profile, the pulse duration is 56 ps. Increasing the output power the pulse width broadens to 100 ps at 12 W. The shortest pulse width observed was 50 ps, however, the required rf power (> 5 W) exeeded the capability of the mode-locking system. Typical daily performance is 9W, 60 ps and peak to peak amplitude fluctuations smaller than 3 %, at 33 A of lamp current.

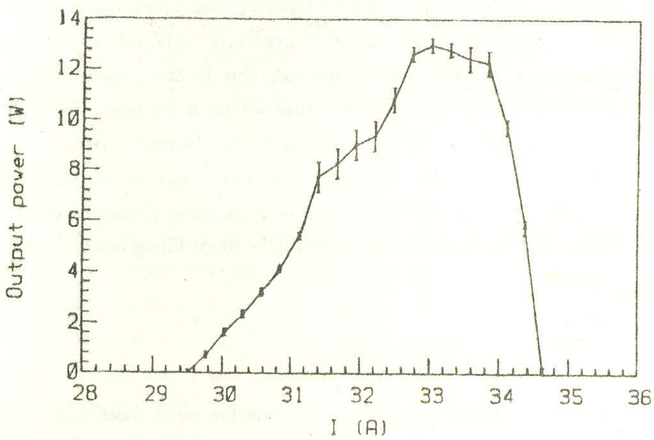

Fig.4 Average Laser output power as a function of the lamp current for the optimized laser configuration in the vertical polarization for a effective resonator length of 150 cm. The error bars indicate the observed fluctuation.

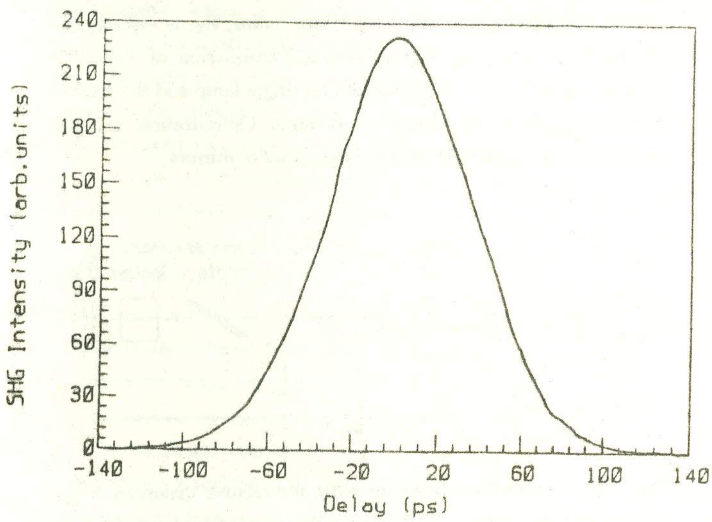

Fig.5 Background-free SHG autocorrelation trace of the mode-locked pulse. Assuming a Gaussian pulse shape, the full width at half maximum is 77 ps.

In order to optimize the output power for higher lamp currents and, using our set of mirrors, the resonator length was setted to 116.8 cm, preserving the distance L_1 = 54.5 cm. It was observed pure TEM_{00} mode operation with maximum output power of 22 W at 35 A of lamp current (f = 33 cm). The output characteristics are similar to the observed in the mode-locked configuration. Amplitude fluctuations were less than 4%. It is important to point out that, in principle, it should be possible to obtain 22 W for mode locking operation, with the appropriate set of mirrors for 1,5 m long resonator. It should be mentioned that output powers in this range were already achieved for higher lamp pump powers [17-18].

HORIZONTAL POLARIZATION

In this configuration, there are two thermally induced focal lengths, as shown in fig. 2. It is of great importance for stable laser output to design resonators where both thermal focal length, f_R and f_Φ are at the minimum of the two different stability zones. For a given set of laser parameters, L ,f, and the chosen mode filling ratio, the figure 6 shows the values of R_1 and R_2 as a function of L_1 (the rod to the back mirror distance). The curvature of mirror R_1 is independent of the focal length (dashed line in the figure). The calculations are performed for the two focal lengths, f_Φ^H and f_R^H, as indicated in the figure. Of course, the values of R_2 that stabilize the laser are quite different; however, there are some values of R_2 that will optimize the resonator, for both focal lengths, f_Φ^H and f_R^H, simultaneously (shown by the arrows in fig. 6). In this case, the focal lengths f_Φ^H and f_R^H correspond to the same, stable TEM_{00} spot size in the rod.

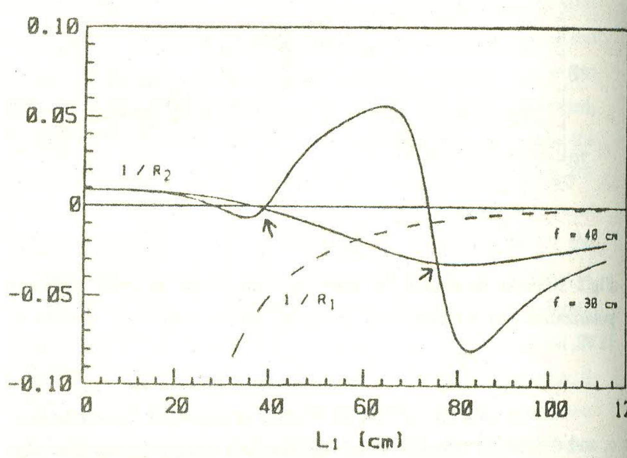

Fig. 6 Values of R_1 and R_2 as a function of the distance L_1 for f_Φ^H = 40 cm, f_R^H = 30 cm and mode filling (r/w) of 2.2.

In our case, the resonator overall length is 117.6 cm; the output coupler radius is R_2 = -120 cm and its transmission is 12 %. The focal lengths, at 34 A (lamp current) are f_R^H = 30 cm and f_Φ^H = 40 cm. In order to optimize both thermal focal lengths, the ideal mirror radius would be R_1 = -34 cm, for the distance L_1 =40,9 cm. The avaliable mirror radius was R_1 = -40 cm, with 100% reflection at 1.064 nm. At the optimized current the resonator is unstable for the vertical polarization.

The behavior of the laser output power as a function of the lamp current is shown in figure 7. We obtained 15 W of output power at 35 A of lamp current, that corresponds to the calculated optimum configuration lamp current. Stability was better than 3 % for cw operation at this current, which shows that the optimization was successful. Opposed to the elliptical beam shape that one would expect due to the different thermal lenses, we obtained a completely circular beam shape for the polarized TEM_{00} mode, as verified at various distances from the output coupler. This result can be explained by examining the beam profile inside the resonator. The change in focal length of the rod affects the resonator beam profile mostly in the region comprised between the rod and the back mirror and only slightly in the front mirror. The calculated output beam radius for f = 30 cm is 395 μm and for f = 40cm is 397 μm at 34 A. As a matter of fact, no observed beam assymmetry is seen in all the current range.

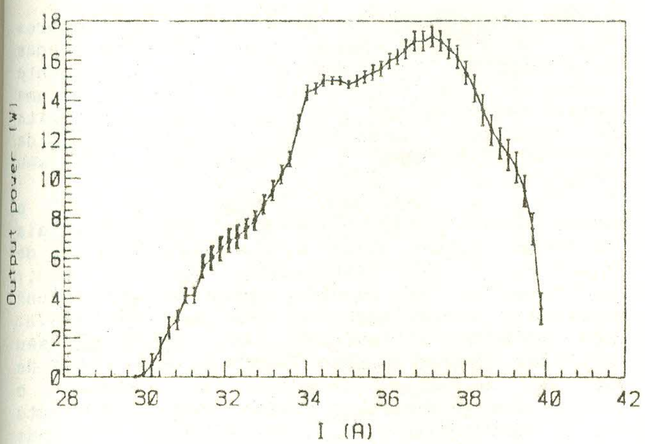

Fig.7 Output power as a function of the lamp current for the optimized configuration in the horizontal polarization. The effective resonator length is 117.6 cm. The error bars indicate the observed fluctuation.

Also shown in figure 7, there is a second peak in the output power curve, corresponding to a strongly diffracted TEM_{00} mode with 17 W of output power. We believe that this second peak is due to the use of the back mirror with a value different from the ideal (-40 cm rather than -34 cm). Nevertheless, the good stability of our configuration shows that this method of optimization permits slight changes from the optimized resonator.

At the optimized lamp current, all of the tested laser configurations oscillate in the desired polarization without the Brewster window. This is due to the fact that the thermal lenses of the other polarization directions will not fulfill the stability condition. Without the Brewster window, we observed that, increasing the lamp current, the polarization of the output beam changes between horizontal and vertical. Simultaneously, the output power drops to zero at the polarization switching points. Nevertheless, the insertion of the Brewster windows assures that only the desired polarization is dominant, in the whole range of lamp currents. The output power is a smooth function of the lamp current, as shown in figure 4 and 7, for the desired range of operation.

CONCLUSIONS

An extensive measurement of the thermally induced focal lengths of a Nd:YAG rod was made. It was determined that there are four different, polarization and direction dependent, focal lengths. By relating these focal components, it was possible to determine that the the coefficient α agrees well with the theoretically predicted value. We configured several resonators considering the measured values of the focal distances to test the predictions of our results. We could obtain high output power and good stability in all configurations; in particular, it was demonstrated optimized laser performance for the vertical polarization either for pure c.w. mode or for mode-locked operation. Very high c.w. output power (15 W) at a moderate lamp current (33 A), with a stability of 3% and with a typical pulse width of 60 ps were obtained. It is important to note that good stability and beam shape, with a well defined polarization, are fundamental for a variety of short pulse applications like pulse compression, synchronous pumping and APM.

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