Suppression of Higher-Order Transverse Modes in a $Nd:YVO_4$ Laser Using Hard and Soft Aperturing

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Abstract. Laser resonators possess higher-order transverse modes (HOTMs) corresponding to solutions of Maxwell's equations within cavity boundary conditions. Thermal lensing at high pump powers in the gain medium can facilitate HOTMs, creating nonuniform intensity profiles that are detrimental if the laser drives nonlinear processes. This study investigates two methods of inhibiting HOTM onset: an intracavity iris ("hard" aperture) and a reduced pump laser radius ("soft" aperture). Data show that for 808-nm input power between 0 and 7.145 W, a hard aperture eliminates HOTMs, decreasing slope efficiency by 65.3%, whereas a soft aperture delays HOTM appearance, increasing slope efficiency by 11.0%.

INTRODUCTION

The $Nd:YVO_4$ 1064-nm laser discussed in this paper will be used to pump a tunable, long-wave infrared optical parametric oscillator (OPO) for scanning breast cancer tissue for microcalcifications.[1] Calculations performed using the SNLO software package (AS Photonics, Albuquerque, NM) indicate that the OPO in this system will require ~6.5 W of average power to have sufficient intensity to drive the frequency conversion process when Q-switched (producing short, high-energy pulses). This conversion requires the $Nd:YVO_4$'s output beam, which is powered by an 808-nm laser, to have a smooth, Gaussian phase front—a transverse electromagnetic (TEM) mode signified by TEM_{00}. TEM modes (propagating beam shapes) are represented by solutions to Maxwell's equations in a lasing cavity based on the cavity's boundary conditions, which are dictated by its physical geometry.[2] At low pump powers corresponding to weak thermal lenses, higher-order transverse modes (HOTMs) diverge too rapidly to be supported by a cavity designed for only TEM_{00}. However, as the 808-nm pump power approaches the level required to achieve 1064-nm output power greater than 6 W, the thermal lens focal length shortens. HOTMs which previously had high diffractive losses may now be supported by the cavity and impact the output beam.

A thermal lens forms when pump light absorption deposits heat into the gain crystal, leading to temperature gradients. One gradient is in the radial direction, and since the index of refraction is a function of temperature, the radial temperature gradient gives rise to an index of refraction gradient, creating a lensing effect. However, an abrupt axial gradient on the input and output faces of the crystal and the corresponding "bulging" of those ends due to thermal expansion dominates the overall thermal lens established by the pump beam.[3] Thermal lensing increases with laser pump power, therefore HOTMs become more supported by the cavity as pump power increases. These HOTMs have radii larger than TEM_{00}, as shown in Fig. 1.

One way to reduce this thermal lensing effect is to use a $Nd:YVO_4$ crystal that has undoped regions on one or both axial faces. This substantially reduces the temperature gradient at the physical end faces and reduces the thermal lens effect arising from bulging.[5] The laser crystal used in this experiment has an undoped front face, free of Nd ions.

Common practices for eliminating HOTMs include (1) placing a physical ("hard") aperture within the cavity to create losses for the larger-in-diameter HOTMs[2] and (2) using a "soft" aperture—a reduction in diameter of the incident 808-nm pump beam, creating an aperture that provides gain preferentially within a radius that is too small to support HOTMs but large enough to generate the TEM_{00} beam.[6]

While hard apertures impose diffractive losses on HOTMs because of the latter's larger diameter, they also cause diffractive losses for the TEM_{00}, reducing output power.[2] Soft apertures introduce no such losses, using a gain bias that favors the TEM_{00} mode while providing a gain distribution insufficient to support HOTMs.

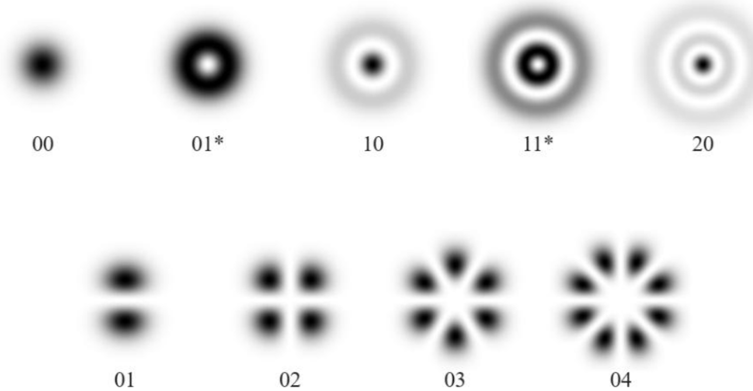

FIGURE 1. Theoretical spatial intensity profiles of various higher-order transverse modes (HOTMs).

MODEL

To model the TEM_{00} mode, the open-source software tool reZonator was used.[7] reZonator is designed for modeling, analyzing, and optimizing laser resonators and TEM_{00} beam propagation using the ABCD matrix method. Initial use of this tool for a flat input coupler (IC) and flat output coupler (OC) laser cavity design reported an unstable resonator. Only after including the thermal lens effect in the gain crystal was the laser resonator stable and reZonator able to calculate the TEM_{00} mode size at any location in the laser cavity.

This laser's geometry and crystal possessed the same physical dimensions and dopant concentration as studied by Zhuo et al.[5] That study calculated and measured the focal length of the thermal lens within the crystal at different pump powers for a pump spot size of 320 μm ($1/e^2$ diameter in intensity). In this study, the model reported by Zhuo et al. was used to estimate the thermal lens for slightly smaller pump spot sizes over a range of pump powers.

In the reZonator model, the doped region of the crystal was split in half and a thin lens, whose focal length represented the thermal lens for a given pump power, was inserted. Doing so enabled calculation of the TEM_{00} mode size within the cavity for any pump power and guided the choice of diameter and location of a hard aperture.

According to this model, the TEM_{00} beam had a radius of 193.7 μm at 3.15-W pump power at a location downstream from the Nd crystal. The ideal location for mode discrimination would be close to the IC, but a 4-mm gap between the IC and the crystal made aperture placement logistically impossible at that location.

An equation for HOTM sizes in cavities with cylindrical symmetry is[4]

$$w_{pl} = (2p + l + 1)^{1/2} w_0, \tag{1}$$

where l is the number of angular nodes, p is the number of radial nodes in the intensity transverse to the propagation axis, and w_0 is the TEM_{00} beam's radius ($1/e$ in the electric field amplitude, or $1/e^2$ in intensity). Based on the TEM_{00} calculation from reZonator, the two lowest HOTMs (TEM_{01} and TEM_{10}) have $1/e$ amplitude radii of 268.7 and 329.1 μm, respectively.

EXPERIMENT

This experiment began with characterizing a baseline laser configuration which involved a flat IC; $Nd{:}YVO_4$ crystal; 200-mm focal length, UV-fused, silica AR-coated intracavity lens; and an 85% reflectivity output coupler. The crystal had 0.5% neodymium doping concentration. Its cross section was 4 mm × 4 mm and its total length was

11 mm. The front 4 mm in the axial dimension were undoped to reduce thermal lensing. An 808-nm, fiber-coupled diode laser was used to pump the $Nd:YVO_4$ crystal. For optical power input and output data collection, a Thorlabs S425C thermal power sensor was used. Its optical power range was from 2 mW to 10 W, with a 100-μW resolution. A diagram of the system is shown in Fig. 2. The physical cavity length was 147 mm, long enough for a Q-switch to be added at a later stage. Input 808-nm pump powers ranged from 0 to 7.15 W. The output beam's TEM modes were observed with the aid of a Kentek 1.37-in VIEW-IT infrared laser detector disc, which was placed in the far field near the power sensor. HOTM presence was judged visually via the lack of radial symmetry or the presence of radial nulls. Typically, both types of deviations from TEM_{00} were observed simultaneously, displaying a mix of HOTMs.

Following the characterization, a physical or "hard" aperture with a 320-μm radius was introduced into the cavity. While nonoptimal, the aperture was placed 42 mm downstream from the IC. This is where the TEM_{00}, TEM_{01}, and TEM_{10} modes' radii were calculated to be 193.7, 268.7, and 329.1 μm, respectively. Power data were again taken.

The final set of laser data was taken after the hard aperture was removed and the relative distance of the lens pair upstream from the IC was adjusted to shorten their effective focal length. This reduced the 808-nm pump radius from 274 to 265 μm. The pair was translated as a group to ensure the pump waist location was centered longitudinally (along the laser propagation axis) in the crystal.

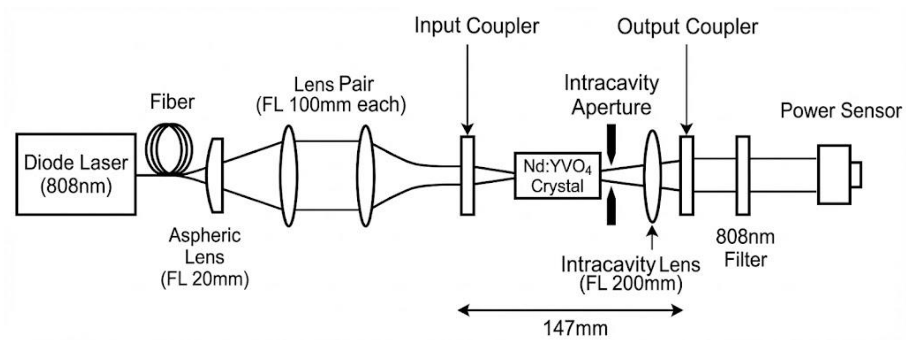

FIGURE 2. Experimental laser setup.

RESULTS AND DISCUSSION

Figure 3 presents the data sets gathered for the three laser configurations. Linear fits of the experimental data reveal a significant difference in performance between the original cavity and the hard-aperture configuration. Without the aperture, the system had a slope efficiency of 43.8% and HOTMs appeared at 3.12 W of input power. When the 320-μm intracavity aperture was placed in the system, the slope efficiency dropped to 15.3% but no HOTMs appeared over the entire pump power range. In theory, such a large loss in slope efficiency is not expected for this aperture size; less than 1% round trip loss for the TEM_{00} mode is expected.[2] This loss may be due to the hard aperture not being precisely centered radially about the TEM_{00} beam. Mounting the aperture to a finely adjustable *x-y* stage is the next step in testing this hypothesis.

In the soft-aperture configuration, the slope efficiency increased from 43.8% to 48.6% and the laser threshold pump power was reduced from ~1.1 to ~1.0 W. Such efficiency improvements are expected in a four-level laser, wherein small signal gain is proportional to pump intensity and the smaller pump radius leads to a higher intensity for the same pump power.[4] However, and more relevant to this study, the smaller gain aperture delayed the onset of HOTMs until 5.82 W of input pump power—a marked improvement.

Decreasing pump spot size to deter HOTM onset may initially seem counterintuitive, as a smaller pump spot increases the strength of the crystal's thermal lens, promoting HOTM appearance. These data, however, suggest that for slight reductions in spot size, soft-aperture HOTM discouragement outweighs the stronger thermal lens support. Future work on this system may include performing thermal lens focal length and mode size calculations to predict at what pump spot size this trend changes. A set of parametric measurements of HOTM onset and pump spot size could then be made to assess the validity of those predictions and find the optimal pump spot size.

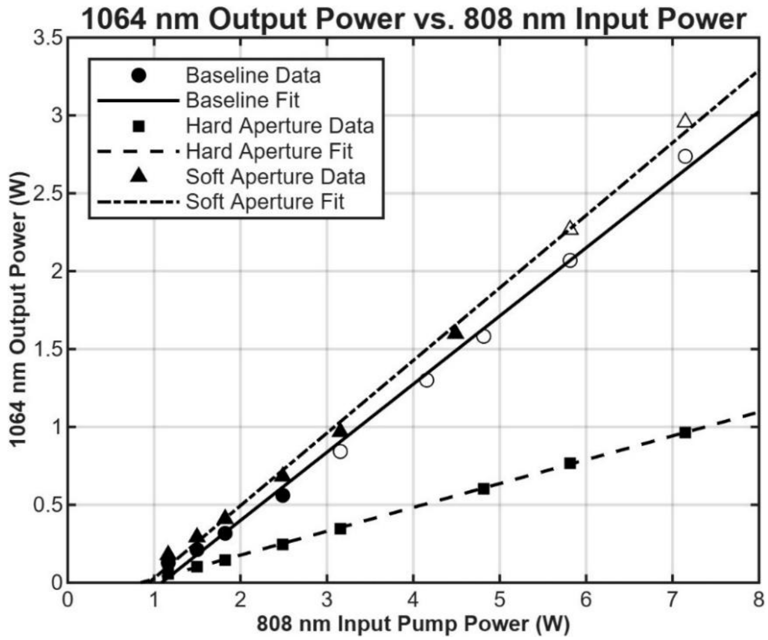

FIGURE 3. Output power of 1064-nm light vs. 808-nm pump power. The lines represent linear least-squares fits. Solid data points represent TEM_{00} power and hollow data points indicate HOTMs. The standard deviation of each data point was ~0.01 W, which is smaller than the data markers in this plot.

CONCLUSION

The inclusion of a 320-μm-radius intracavity hard aperture in the $Nd:YVO_4$ laser system proved effective in enforcing TEM_{00}-mode-only operation in the 1064-nm laser output. However, this mode purity came at a substantial cost to the laser's optical efficiency. While much of that efficiency loss is likely due to hard-aperture misalignment, the increased efficiency of the soft-aperture approach makes it more desirable for our 6.5-W TEM_{00} goal. With a pump beam area reduction of only 6.5% yielding successful HOTM suppression, exploring smaller pump spot configurations will comprise future studies of this system.

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