DYNAMIC COMPENSATION OF THERMAL LENSING AND BIREFRINGENCE IN A HIGH BRIGHTNESS Nd:Cr:GSGG OSCILLATOR

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ABSTRACT

In this work, five fundamental concepts were combined to allow development of high efficiency, low divergence, narrow bandwidth, flashlamp pumped oscillators capable of operation over a broad operating range. These concepts were: flashlamp pumped Nd:Cr:GSGG to achieve high efficiency, a "Reentrant Cavity" to eliminate birefringence losses, a Variable Radius back Mirror (VRM) in a hemispherical cavity to achieve maximum Gaussian beam fill factor, a very high damage threshold, spectrum narrowing output coupler fabricated using a stack of uncoated etalons to form a resonant reflector, a cylindrical zoom lens to completely eliminate astigmatism. The results were successful, and yielded an oscillator that produced 150 mJ, TEM00 300 MHz bandwidth, 75 ns pulses, over a repetition rate of 1-20 Hz, and at a slope efficiency of 2%. These techniques were also successfully applied to a YLF oscillator. They may, in part, be adapted for use to unstable resonators.

Key words: Adaptive optics, variable radius mirror, thermal lensing, birefringence, hemispherical resonators, oscillators, Nd:Cr:GSGG, solid-state lasers

1. Introduction

Stable laser resonators usually have poor efficiency, due to the aperture that prevents higher order transverse modes. Enhancing efficiency of such resonators can be done by increasing the beam size in the rod. For a given pump source, the efficiency can also be increased by selection of an efficient laser material. In this work, Nd:Cr:GSGG was chosen for the laser material. This material was found to be twice as efficient as Nd:YAG due to the broad band absorption of the Cr and the relatively efficient nonradiative energy transfer to the Nd.1 Flashlamp pumping was selected because of its cost effectiveness compared to diode pumping. A hemispherical configuration was employed in order to increase the beam size in the laser rod.2 In a hemispherical configuration, the rear mirror focuses the beam onto the front mirror. The beam size is a minimum on the front mirror and a maximum on the rear mirror, the diameters being limited by diffraction effects from a limiting aperture. By placing the laser rod near the rear mirror, the rod can be made to act as the limiting aperture. The hemispherical configuration achieve good beam quality (TEM00) and maximum Gaussian beam fill factor.

The challenge encountered with use of a hemispherical resonator is its sensitivity to rod thermal lensing. Thermal lensing occurs because the laser rod is volume pumped but surface cooled, so that a
radial (and near parabolic) temperature distribution is produced. The material's index of refraction and the rod length will then have a radial dependence.

2. **A solution to the problem of thermal aberrations**

Consider the rod and back mirror as a compound element (Figure 1a) and assume the cavity length has been adjusted for optimum operation at one average pump power level. If the pump power level is increased and if there now is too much lensing, then the focus will fall interior to the front mirror and lasing will stop. If, conversely, the pump power level is decreased and if there is too little lensing, then the focus will fall exterior to the front mirror and multiple transverse modes may be excited. By its nature, a low divergence, high fill factor hemispherical resonator operates at a stability limit. A solution is to use a back mirror with a variable radius of curvature (Fig. 1b).

![Figure 1 - Affect of thermal lensing on hemispherical cavities with static and variable radius mirrors](image)

Control of thermal lensing is an important factor when using Nd:Cr:GSGG because its thermo-optical performance is five time worse than Nd:YAG (for equal pump power). Because of this, we replaced the static mirror with an adaptive optic, a Variable Radius Mirror (VRM).

Stresses induced birefringence is also an important factor. It arises whenever polarization sensitive elements are used near optical elements that cause nonuniform beam depolarization. In our case, the Q-Switch polarizer is the polarization sensitive element and the laser rod is the depolarizer (Fig. 2). A polarized beam that double passes the GSGG rod experiences a significant loss on the polarizer, and this results in a substantial decrease in oscillator efficiency. In this work, we prevented the losses due to birefringence phenomena, by using a reentrant cavity. This cavity added a reentrant mirror which returned polarizer reflected light back into the cavity and a 45° Faraday rotator (FR). The FR (located between the rod and the rear mirror) and the rear mirror, acted as a polarization conjugator (POC). A "P" polarized component incident on the POC returns to the rod with "S" polarization. An "S" polarization component also experiences polarization flipping with respect to the polarizer axes. In this
way, the phase delay difference due to rod birefringence averages out, and depolarization is prevented. The oscillator acted as a three mirror cavity, with photons reflected from the output coupler and the reentrant mirror on alternate round-trips. Different degrees of thermal lensing in the two arms can be compensated for by adjusting the individual arm lengths.

3. **Experimental results**

3.1. **Resonator configuration**

The resonator used in this work is shown in Fig 2.

![Figure 2 - Reentrant cavity for stable operation of TEM00 beam](image)

The resonator length (between the rear mirror and the output mirror) was selected as 150cm in order to achieve a relatively long laser pulse (75ns). The resonator arm lengths were both 94cm and the laser rod was placed 15cm from the rear mirror. The Q-Switch consist of a Pockels cell and a dielectric coated Brewster polarizer. The Pockels cell was placed in the arm with the 100% mirror, so as to
provide maximum hold-off under conditions of extreme depolarization. We used a 0.635 x 7.62 cm Nd:Cr:GSGG rod from Litton-Airtron close coupled to a cerium doped flashlamp in a diffuse reflecting FE-253 Kiger laser had. The rod faces were 0° parallel and AR coated.

The Faraday Rotator contained a TGG AR coated crystal in a permanent magnet housing.

3.2. **Birefringence correction with reentrant configuration**

Birefringence loss and output energy reduction in a standard two mirror configuration were measured using the setup of figure 3. The results are shown in figure 4 as a function of pump power. Also shown is the oscillator performance with the reentrant configuration.

![Figure 3 - The set up to measure birefringence losses and degradation in output power.](image)

![Figure 4 - Birefringence loss and laser energy in standard and reentrant configurations.](image)
These results show that GSGG birefringence was a serious problem even at low pump powers. This problem was totally eliminated by using a reentrant cavity (over the tested pump range).

4.3 Lasing efficiency of Nd:Cr:GSGG in a hemispherical reentrant resonator

Lasing efficiency was measured with various output couplers (figure 5). Slope efficiency was found to be around 2% (Electrical to light) for a TEM$_{00}$ beam. The system tested was a reentrant cavity.

![Graph of lasing efficiency](image)

**Figure 5 - Efficiency of the hemispherical reentrant oscillator for various output couplers**

Efficiencies of hemispherical and nonhemispherical plano-concave configurations were compared (figure 6). Results show that the hemispherical configuration was the most efficient. The beam was recorded at an image plane just behind the rod (figure 7). The beam size was largest for the hemispherical configuration and decreased with increasing rear mirror radius.

![Graph of lasing efficiency](image)

**Figure 6 - Lasing efficiency of plano-concave resonators for fixed cavity length of 1.5m.**
3.3 Dynamic compensation of the thermal lensing

We chose to compensate thermal focusing variations by using a Variable Radius Mirror (VRM) as the rear mirror. Changes in thermal lensing are compensated by conjugate changes to the rear mirror's radius of curvature. This compensation keeps the hemispheric condition over a wide range of pump powers. Figure 8 describes the influence of the thermal focusing on the laser energy for a resonator length of 1.5 m and rear static mirrors radii of 1.5 m and 2 m. In case of 1.5 m, the cavity is hemispherical at low pump power. Increasing the power causes a drastic energy decrease. In the case of 2 m, too little thermal focusing cause the resonator to oscillate with multiple transverse modes (MTM) while too much thermal focusing causes the energy to decrease. Only a limited pump power range (55 - 85 W) enables the oscillator to generate a TEM$_{00}$ beam with good efficiency.

Figure 7 - Beam images behind the rear mirror for plano-concave resonators of 1.5m length (The fringes are an artifact of the diagnostic system).

Figure 8 - Influence of thermal focusing on output energy.
The VRM consists of a high reflectance mirror and a negative lens (Figure. 9), where the separation Δ determines the compound element's radius of curvature (Figure 10). The VRM's mirror can be translated with a micropositioner in order to reach the desire effective radius. We chose a rear mirror with radius of 20cm and a negative lens with focal length of (-)10cm.

The required separation Δ needed to correct thermal lensing $F_t$ can be easily shown to be given by the equation:

$$\Delta = R - \frac{f (L \cdot F_t + l(F_t - L))}{F_t \cdot (f + L + l) - L(f + 1)}$$

where $R$ is the radius of curvature of the VRM back mirror, $f$ is the focal length of the VRM lens, $F_t$ is the rod focal length, $L$ is the separation between the front mirror and the rod, and $l$ is the separation between the rod and the VRM’s negative lens.

![Figure 9 - Hemispherical resonator with VRM as rear mirror.](image)

![Figure 10 - Range of VRM element spacings Δ needed to correct thermal focusing. This calculation takes thermal lensing of 5.3 Diopter/KW, R=20 cm, f = 10 cm, L=130 cm, and l = 20 cm.](image)
Examination of Figure 10 shows that $\frac{\partial \Delta}{\partial P_{in}}$ increases as $P_{in}$ becomes large. This places added constraints on VRM mechanical stability and feedback loop sensitivity, since the step interval for a fixed change in radius becomes increasingly small as $P_{in}$ increases. For most applications, though, this should not be a limiting factor.

Adjusting the VRM to the desired position needed to retain resonator hemispherity, results in constant output energy over a wide range of pump powers. Figure 11 compares the output energy for both static and dynamic VRM resonators.

![Graph](image)

**Figure 11 - Output energy as a function of pump power for static and dynamic VRM.**

The VRM's mirror translation needed to achieve efficient TEM00 beam, was found to be linear with the pump power over the range tested. The required positional accuracy was measured to be $\pm 25 \mu m$ (figure 12).

The hemispherical resonator with VRM was measured for one week on a daily basis and found to be stable and repeatable over the range of measured absolute micrometer positions.

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Figure 12 - VRM's mirror movement required to maintain a TEM00 output beam

3.4. Correction of the beam ellipticity

The output beam was initially found to be elliptical. This phenomena was very pronounced cavity for the hemispherical resonator. We define ellipticity as the width of the ellipse divided by the length, at 1/\(e^2\) of its intensity. The ellipticity was found to be 0.55±0.06 (figure 13). The orientation of the axes tracked the rod orientation i.e., rotating the rod around the optical axis by an angle \(\theta\) caused the ellipse to rotate by \(\theta\). The ellipticity was static and not dependent on pump power.

We corrected the ellipticity by using a cylindrical zoom lens consisting of two AR coated cylindrical lenses of focal length : 1m, (-)1m. The separation between them was adjusted to achieve a circular beam shape. The optimal shape was achieved for a 12 cm separation.

The beam was measured 6cm from the output coupler (a far-field position since it corresponded to the hemispherical resonator's back mirror focus) with a COHU CCD camera and a Spiricon LBA-100 beam analyzer. Corrected ellipticity was measured as 1±0.2, thus indicating complete correction.

Figure 13 - The elliptic beam (a) and the corrected beam (b).
3. 5. **Bandwidth narrowing**

The bandwidth was measured using a Burleigh PALSA-3500 single shot Fabry-Perot spectrum analyzer. This spectrum analyzer enables measurement of bandwidths between 0.2 and 200 GHz. Bandwidth narrowing by two methods was investigated:

1. Two tilted etalons were placed inside the cavity. One etalon (thin) transmitted wide bands with a large spacing between them. The second etalon (thick) transmitted narrow bands but with short spacing between them. The following set of etalons was used: 1.5 cm thick fused silica with 70% reflectivity coatings, and 0.02 cm thick fused silica with 20% reflectivity coatings. These etalons were tilted to achieve the best narrowing. The measured bandwidth was 270±30 MHz. The energy dropped by 50% due to the high losses of the thick, high reflectivity, tilted etalon.

2. A Resonant reflector was fabricated for use as the output coupler and to take the place of the thick tilted etalon. The Resonant Reflector reflected narrow bands with short spacing between them. A tilted etalon that transmitted wide bands with large spacing between them was used to suppress side-bands. The tilted etalon consisted of a 0.02 cm thick fused silica plate with 20% reflectivity coatings. The Resonant Reflector consisted of 1.5 cm and 1 cm thick fused silica uncoated etalons. The spacing between them was 5.6 cm. The measured bandwidth was 200±30 MHz. A Resonant Reflector comprised of two fused silica plates (n=1.45) has a peak reflectivity of 40% (close to the optimum required for our oscillator). There was no energy reduction caused by the Resonant Reflector.

4. **Conclusions**

Excellent beam quality (pure TEM00) beams were achieved by using a hemispherical cavity and by placing the laser rod close to the rear mirror. Energy was increased by a factor of four compared to an oscillator designed to operate at the point of maximum thermal stability. A Variable Radius Mirror compensated for dynamic thermal lensing over a broad range of pump powers. Birefringence losses were totally eliminated using a reentrant configuration. Astigmatism was completely corrected through use of a cylindrical zoom lens. Low loss, high damage threshold bandwidth narrowing was achieved with a two etalon uncoated resonant reflector and a thin moderate reflectivity tilted etalon.

5. **References**

