

Self-compensating amplifier design for cw and Q-switched high-power Nd:YAG lasers

Michelle S. Roth, Valerio Romano and T. Feurer

Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

michelle.roth@iap.unibe.ch

<http://www.iap.unibe.ch>

Thomas Graf

Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart, Germany

Abstract: We experimentally demonstrate a self-adaptive compensation of the pump power dependent thermal lens in an Nd:YAG laser through a thin layer of a medium with a negative temperature dependence of the refractive index. The layer is thermally coupled to the laser rod and leads to a strikingly improved beam quality over a large stability range. The scheme allows for a scaling to high powers as well as pulsed-mode operation.

© 2006 Optical Society of America

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched; (140.3580) Lasers, solid-state; (140.6810) Thermal effects.

References and links

1. J.D. Foster and L.M. Osternink, "Thermal Effects in a Nd:YAG Laser," *J. Appl. Phys.* **41**, 3656–3663 (1970).
2. W. Koechner, *Solid-State Laser Engineering*, (Springer, Berlin, 1999).
3. N. Hodgson and H. Weber, *Optical Resonators*, (Springer, Berlin, 1997).
4. H. Glur, R. Lavi and T. Graf, "Reduction of thermally induced lenses in Nd:YAG with low temperatures," *IEEE J. Quantum Electron.* **40**, 499–504 (2004).
5. U.J. Greiner and H.H. Klingenberg, "Thermal lens correction of a diode-pumped Nd:YAG laser of high TEM₀₀ power by an adjustable-curvature mirror," *Opt. Lett.* **19**, 1207–1209 (1994).
6. A.V. Kudryashov, "Intracavity laser beam control," in *Laser Resonators II. 1999 San Jose*, A.V. Kudryashov, ed., Proc. SPIE **3611**, 32–41 (1999).
7. S. Jackel, I. Moshe and R. Lavi, "High performance oscillators employing adaptive optics comprised of discrete elements," in *Laser Resonators II. 1999 San Jose*, A.V. Kudryashov, ed., Proc. SPIE **3611**, 42–49 (1999).
8. D.C. Hanna, C.G. Sawyers and M.A. Yuratich, "Telescopic resonators for large-volume TEM₀₀ mode operation," *Opt. Quantum Electron.* **13**, 493–507 (1981).
9. R. Koch, "Self-adaptive optical elements for compensation of thermal lensing effects in diode end-pumped solid state lasers - proposal and preliminary experiments," *Opt. Commun.* **140**, 158–164 (1997).
10. R. Weber, T. Graf and H.P. Weber, "Self-Adjusting Compensating Thermal Lens to Balance the Thermally Induced Lens in Solid-State Lasers," *IEEE J. Quantum Electron.* **36**, 757–764 (2000).
11. E. Wyss, M.S. Roth, T. Graf and H.P. Weber, "Thermo-optical compensation methods for high-power lasers", *IEEE J. Quantum Electron.* **38**, 1620–1628 (2002).
12. T. Graf, E. Wyss and H.P. Weber, "Self-adaptive compensation for the thermal lens in high-power lasers," in *Advanced Solid-State Lasers*, Ch. Marshall, ed., Vol. 50 of OSA Trends in Optics and Photonics Series (Optical Society of America, 2001), pp. 688–692.
13. M. S. Roth, E. Wyss, H. Glur, and H.P. Weber, "Generation of radially polarized beams in a Nd:YAG laser with self-adaptive overcompensation of the thermal lens," *Opt. Lett.* **30**, 1665–1667 (2005).

1. Introduction

Many applications require high-power lasers with good beam quality over a wide range of output powers. However, the thermal lens in solid-state lasers has a strong impact on the beam properties and deteriorates its quality [1, 2]. As the thermal lens increases with pump power, a good beam quality can only be achieved within a limited power range [3]. The maximum pump power range ΔP for stable laser oscillation can be denoted as [4]

$$\Delta P = (2M^2 - 1) \frac{4\lambda}{D^*} \quad (1)$$

where M^2 is the beam propagation factor and λ the laser wavelength. The quantity D^* , henceforth denoted as specific dioptric power, depends on the thermo-optical material properties and the geometry. Equation (1) shows that for large values of D^* it is not possible to simultaneously achieve a wide stability range ΔP and a good beam quality, i.e. a low M^2 . Hence, D^* has to be as small as possible, which can be achieved by compensating the thermal lens.

In principle, the thermal lens in a laser rod can be compensated for by static methods, such as an intracavity negative lens, but this only corrects the thermal lens exactly at one specific power. As thermal effects are power-dependent it is advantageous to use adaptive compensation methods to counter them. A variety of possible methods has been reported, such as deformable mirrors [5, 6], moveable lenses [7], or telescopic resonators [8]. All of them require more or less sophisticated mechanical arrangements and active external control. A much simpler method is to take advantage of the thermal lens effect itself and to generate self-adjusting negative lenses in heated optical elements which can compensate for the thermal lenses in the laser material. In end-pumped lasers the compensating thermal lens can be generated through absorption of a small fraction of the pump beam in a resonator mirror or an additional intracavity element [9]. For high-power lasers, transverse pumping is usually preferred due to its simpler scalability. In this case the compensating element was heated by partial absorption of the intracavity laser radiation [10]. To generate a negative lens, the compensating element must possess a negative thermal dispersion. Weber et al. [10] have proposed to use Schott LG-760 but numerical simulations revealed that glass-based compensation elements would only be suitable for gain media with comparatively weak thermal lenses, such as Nd:YLF [11]. For laser materials that feature a stronger thermal lens, such as Nd:YAG, liquids are much better suited [11]. Liquids possess a strong negative thermal dispersion and already small amounts of heating power are sufficient to generate a negative thermal lens of the desired strength.

Here, we show that a thin gel layer, sandwiched in between two laser crystals can serve as a sufficiently strong self-adaptive element. Thermal heat diffusion between the crystals and the compensating element ensures that the temperature profile attains the correct spatial dependence. That is, the method works even in the absence of absorption, in contrast to previously published results [12]. We start by explaining the basic principles of self-adaptive compensation and then proceed with the experimental demonstration of the novel concept. We show that, first, this method is scalable to very high power levels and, second, it is suitable not only in continuous wave but also in pulsed mode operation.

2. Self-adaptive compensation

In order to generate a thermal lens in the compensating element a radial temperature distribution is required that corresponds roughly to the radial temperature profile in the pumped and edge-cooled laser rod. This was recently achieved with the assembly depicted in Fig. 1.

The compensating element consisted of two BK-7 glass rods assembled in a water-cooled copper mount. The small gap (< 1 mm) between the two rods was filled with a liquid. The liquid was heated by absorption of a small fraction of the intracavity laser power. Due to the cooling

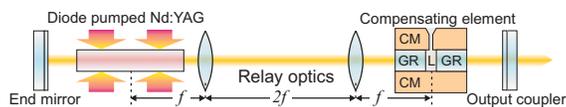


Fig. 1. Laser resonator with a self-adaptive compensating element. A thin layer of a liquid (L) is sandwiched in between two glass rods (GR) placed in a cooling mount (CM).

the heat was dissipated in radial direction yielding the desired temperature profile. The power-dependant negative thermal lens that was generated in the liquid was imaged to the positive thermal lens in the laser rod by means of an $f - 2f - f$ relay optics. This compensation scheme was successfully applied in several experiments [12, 13]. An alternative scheme, the so-called thermo-optically self-compensating amplifier (TOSCA), was theoretically analyzed [11], but has not been experimentally verified until now. A tremendous advantage of the TOSCA scheme is its extremely compact design. The thermal lens is compensated directly at its origin, in the laser rod. Hence, the additional intracavity element plus the relay optics are superfluous.

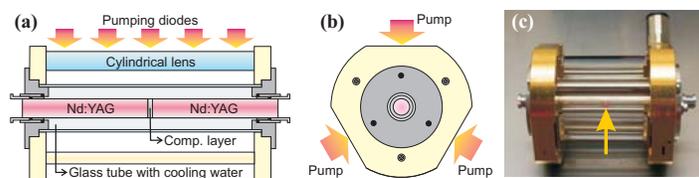


Fig. 2. TOSCA: (a) side view and (b) front view of the laser head. (c) Image of the laser head (the arrow marks the position of the compensating gel disk).

Figure 2 depicts the TOSCA assembly. A thin gel layer is sandwiched between two adjacent Nd:YAG rods, which are mounted in a water-cooled glass tube. The two laser rods have a diameter of 4 mm and a length of 38 mm each. They are tightly fixed at their outer ends and their inner ends with the compensating layer in between are hold in place by three supports. The rods are side-pumped by three stacks of laser diodes, hence a radial temperature distribution is generated, leading to a thermal lens. The temperature profile of the laser rods is transferred to the gel layer through heat contact. Owing to the negative dn/dT of the gel, a negative thermal lens is formed, which ideally compensates for the net positive lens of the laser rods.

3. Experimental results and discussion

Experiments were performed in three different configurations as shown in Fig. 3. First, a resonator with a single laser head was equipped with the compensating element in order to demonstrate the TOSCA principle. Second, a resonator with two laser heads was used to test whether the scheme allows for scalability to high powers by inserting multiple heads. Third, the single head configuration was equipped with an acousto-optic modulator to operate the laser in pulsed mode. In all three configurations the output power, the dioptric power of the thermal lens, and the beam quality (M^2) were measured versus the pump power, with and without compensation. In the latter case the two laser rods with the gel in between were replaced by a single rod with twice the length (70 mm). The effective dioptric power was measured by a Mach-Zehnder interferometer with a HeNe laser (633 nm). The M^2 was evaluated through measurements of the near and the far field beam profiles.

As compensating media different silicones and polymers have been tested. The results presented below were attained with EFIRON[®] UVF Primary Coating P-100 (Luvantix Co., Ltd.). The material has a refractive index of $n = 1.496$ and a thermal dispersion of $dn/dT =$

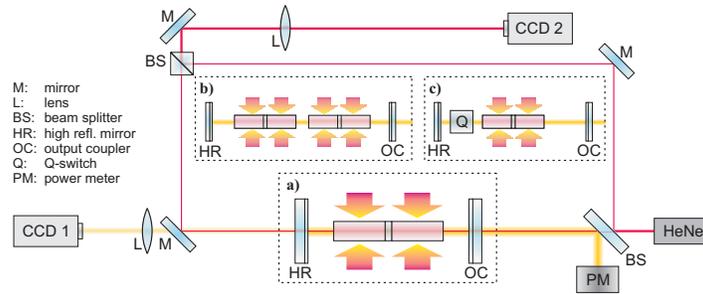


Fig. 3. Measuring output power (PM), beam quality (CCD 1), and thermal lens (CCD 2) for three configurations: (a) single-head, cw; (b) dual-head, cw; (c) single-head, Q-switched

$-3.4 \cdot 10^{-4} \text{ K}^{-1}$. The absorption at pump wavelength (809 nm) is 0.05 cm^{-1} . We would like to emphasize that the material is still not optimal as it exhibits a small residual absorption of 0.032 cm^{-1} at the laser wavelength (1064 nm). Because of lack of a better material, the optimal thickness was always a tradeoff between a perfect compensation and a low additional intracavity loss. With these constraints the optimum thickness of the polymer layer was experimentally found to be between 0.3 mm and 0.6 mm. Also, the inner end-faces of the laser rods were originally AR coated for a refractive index of 1.416. As the refractive index of P-100 is slightly higher, i.e. 1.496, additional though small intracavity losses were present at each inner end-face. With an appropriate end coating, however, they can be easily eliminated. The longest we have used a single compensating layer was about 100 h. Even when exposed to a maximum intracavity power of 500 kW/cm^2 in cw mode and 160 MW/cm^2 in pulsed mode P-100 showed no degradation.

3.1. Demonstration of the TOSCA principle

To proof the TOSCA principle the single head laser was characterized with and without compensation. Figure 4(a) shows the output power of an uncompensated and two compensated laser rods with different thicknesses of gel layer.

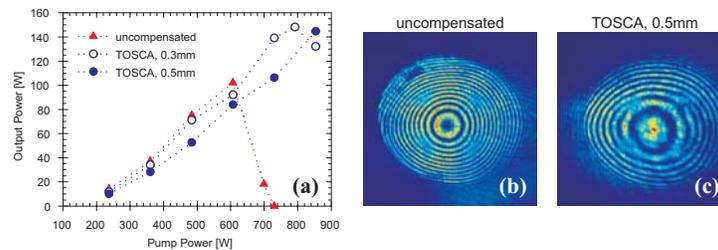


Fig. 4. (a) Output versus pump power of the single-head resonator with and without compensation. Interferograms (b) without and (c) with compensation.

All measurements were performed with a 40 cm long symmetric resonator with plane mirrors. While the uncompensated laser reached its stability limit at a pump power of about 600 W, the laser with a compensating disk of 0.3 mm thickness supported stable operation up to 790 W with an efficiency of about 30%. With a 0.5 mm thick layer the efficiency was slightly reduced due to the larger absorption, but the laser was stable up to the maximum pump power of 850 W. Measured interferograms are shown in Fig. 4(b) without and (c) with compensation (0.5 mm). While the spherical symmetry remains almost unaffected, the dioptric power was lowered from

13.5 ± 0.3 dpt/kW to 7.3 ± 0.2 dpt/kW, i.e. the thermal lens was reduced by almost a factor of two.

One of the main purposes of compensating a thermal lens is to improve the beam quality. In order to compare the uncompensated laser to the TOSCA in terms of beam quality, further experiments had to be carried out with a much shorter resonator where the uncompensated laser is stable over the whole pump power range. The results for a 17 cm long resonator are depicted in Fig. 5. The graph shows stable operation in both cases and the M^2 values versus output power. For the uncompensated laser the maximum output power was 194 W and the beam quality $M^2 = 54$. The TOSCA scheme reached a maximum output power of 160 W with $M^2 = 19$. Due to small additional losses (see above) the efficiency with compensation is somewhat lower than without. However, the beam quality shows a striking improvement by almost a factor of 3.

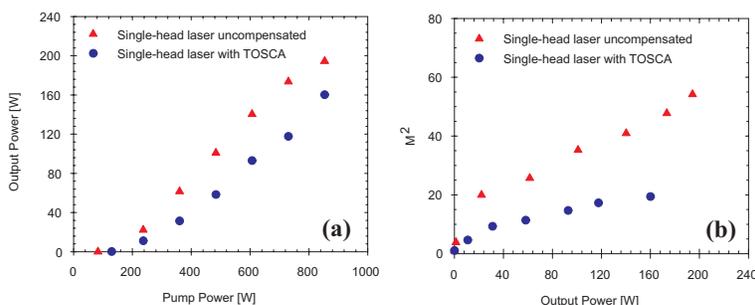


Fig. 5. (a) Output power versus pump power and (b) M^2 versus output power of the single-head resonator with and without compensation.

3.2. Scalability to high power levels

In order to scale the system to higher output powers a second TOSCA amplifier head was inserted into the resonator, increasing the total resonator length to 26 cm. Both laser heads were identical and were separated by 40 mm. The best performance was observed for a compensating layer of 0.3 mm in each laser head.

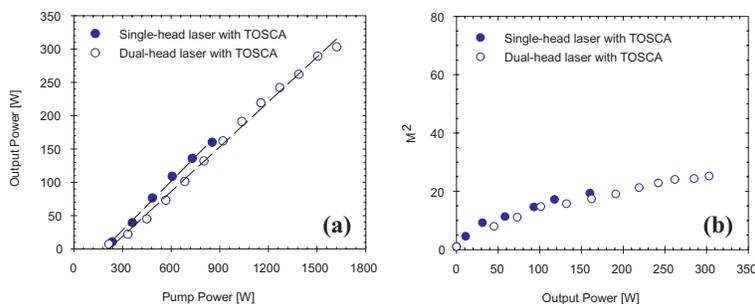


Fig. 6. Scaling of the output power through multiple but compensated laser heads. (a) Output power and (b) M^2 .

Figure 6(a) shows the output power versus pump power of the compensated single-head and the compensated dual-head resonator. The efficiency of the dual-head laser is slightly decreased compared to the single-head laser, mostly because of the difficulties in aligning the two heads, i.e. four laser rods. Nevertheless, the maximum output power of the single-head TOSCA of

158 W was almost doubled to 303 W. Figure 6(b) shows that the good beam quality was maintained to the highest pump power, indicating that the TOSCA principle can be scaled to high power levels. Even at the highest output power of 303 W M^2 is about 25 whereas the uncompensated laser reached this value already at 55 W. By heating P-100 in an oven it was found to be stable up to about 350 degC, that is, the compensation scheme is expected to work up to damage threshold of the laser rods.

3.3. Q-switch operation

To test the TOSCA for pulsed operation the resonator was equipped with an acousto-optical Q-switch. The repetition rate was 9.7 kHz. Again a symmetric plane-plane resonator was used but because of the extra element its length had to be extended to 49 cm. In accordance with the results presented above, the uncompensated laser became unstable at high pump powers. Using the TOSCA (thickness 0.5 mm) the laser could be operated in a stable regime over the whole power range that was available. Note, in pulsed mode operation the slightest impurity or surface contamination caused a power absorption high enough to destroy the compensating layer.

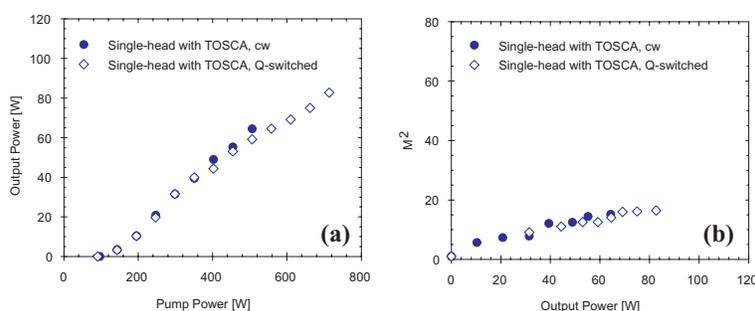


Fig. 7. (a) Output power versus pump power and (b) M^2 versus output power of the single-head resonator in cw and pulsed operation.

Figure 7(a) shows the output versus pump power. At a pump power of 710 W the average output power was 83 W. Pulse durations of approximately 80 ns (FWHM) were measured yielding a maximum pulse energy of 8.6 mJ and a maximum peak power of 107 kW. Figure 7(b) emphasizes that there is no significant degradation of the beam profile in pulsed mode. The measured values correspond very well to the ones obtained in cw mode. The maximum output power corresponds to fluence of about 10 J/cm² at the compensating layer and is close to damage threshold. Therefore, higher output powers can only be reached through an increase of the mode diameter.

4. Conclusions

We have experimentally demonstrated the principle of a thermo-optically self-compensating amplifier. The TOSCA setup is very compact and entirely self-adaptive. The compensation reduces the thermal lens leading to a larger stability range as well as to a significant improvement of the beam quality. Within the limits of the material properties, we were able to show scalability to high powers and pulsed mode operation.

Acknowledgments

The authors acknowledge Eva Krähenbühl for technical assistance. This work was supported in part by the Swiss Commission for Technology and Innovation (CTI).