Measurement of thermal lensing in a CW BaWO$_4$ intracavity Raman laser

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Abstract: The thermal lens induced in an a-cut BaWO$_4$ crystal by stimulated Raman scattering is measured using lateral shearing interferometry. The strength of the lens is proportional to the Stokes output power. For light polarized parallel to the a-axis, and a Stokes mode radius of 120 µm, the lens is negative and highly astigmatic: $-0.8 \text{ D W}^{-1}$ in the plane parallel to the a-axis and $-7.7 \text{ D W}^{-1}$ in the plane parallel to the c-axis. The implications of this thermal lens for Raman laser design are discussed.

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References and links
1. Introduction

Solid state Raman lasers are practical and efficient sources of laser radiation offering access to parts of the spectrum that are difficult to reach using conventional technology. A range of wavelengths in the near infrared (1.1 – 1.5 µm) can be accessed by combining mature Nd³⁺ laser technology with Raman active crystals such as tungstates, vanadates and molybdates, while frequency doubling of the 1st Stokes field gives rise to yellow/orange radiation [1]. Continuous wave (CW) output powers of up to 5.1 W in infrared [2] and 5.3 W in the visible [3] have been demonstrated, with a diode-visible conversion efficiency of 21% in the latter case.

The performance of CW Raman lasers is frequently limited by thermal problems [4–7]. In the case of an intracavity pumped Raman laser, heat is deposited in the laser medium, by way of absorption of the diode laser pump light, and in the Raman medium because of the inelastic nature of the stimulated Raman scattering (SRS) process. These two heat loads give rise to two thermal lenses, or one strong lens in the case of a self-Raman material such as Nd:GdVO₄. Such thermal lensing impacts on the stability of the cavity and associated aberrations can degrade the output beam quality. The two lenses scale differently – the heat load in the laser gain medium depends on the absorbed diode laser pump power, while that in the Raman medium depends on the number of Stokes photon/phonon pairs generated – in
the exceptional thermal conductivity of diamond (~2000 W m\(^{-1}\) K\(^{-1}\)). The heatspreader improves thermal management, and thereby permits the use of Nd:YVO\(_4\) disks up to 0.5 mm thick, which absorb sufficient diode laser pump light on a single pass so that the complex multi-pass optics of conventional thin disk lasers are not required [11,13].

Much less work has been done on the thermal lens in the Raman crystal. In most laser designs, the nonlinear SRS process requires a reasonably large interaction length and this makes it difficult to design a geometry with favorable heat flow. Therefore, the thermal properties of the Raman crystal are particularly important. Raman crystals, e.g. vanadates, tungstates and molybdates, typically have thermal conductivities of order 1 – 10 W m\(^{-1}\) K\(^{-1}\). The notable exception is diamond, which has recently emerged as a competitive Raman material [2,14–19]. The extremely high thermal conductivity of diamond should greatly reduce the thermal lens induced via SRS. However, it remains desirable to use a variety of crystals with different Stokes shifts in order to generate a variety of wavelengths. Thermal conductivity is not the only important material property – the thermal expansion coefficients and the variation of refractive index with temperature and stress are also key parameters, and the last two are particularly challenging to determine. It is therefore important to directly measure the thermal lenses that develop in such crystals when they are used as intracavity Raman gain media.

Estimates of the thermal lenses in self-Raman and Raman crystals have been made based on measurements of the cavity stability range [4,20] and cavity mode sizes [21]. The thermal lens in a Q-switched self-Raman laser (based on Nd:GdVO\(_4\)) has been measured by locating the focal point of a collimated HeNe probe beam that passed through the crystal [22]. Some of the authors recently used lateral shearing interferometry to measure the thermal lens in a Nd:GdVO\(_4\) self-Raman laser and found focal lengths as short as 28 mm [23]. However, to our knowledge, no direct measurements have been made of the thermal lenses in CW intracavity Raman lasers using separate laser and Raman crystals.

In the present work, BaWO\(_4\) was used as the Raman crystal. BaWO\(_4\) has recently emerged as a promising Raman medium. It has a high Raman gain (8 cm GW\(^{-1}\) at 1064 nm [24]) and the principal Stokes shift is 925 cm\(^{-1}\), with a linewidth of 1.6 cm\(^{-1}\) [1]. The thermal conductivity of BaWO\(_4\) is 2.6 W m\(^{-1}\) K\(^{-1}\) along the a-axis and 2.7 W m\(^{-1}\) K\(^{-1}\) along the c-axis [25]. Multi-watt CW output powers with good efficiency have been reported in the infrared (3.36 W at 1180 nm, 13.2% conversion efficiency with respect to diode pump power [26]) and in the visible (2.9 W at 590 nm, 11% diode-yellow conversion efficiency [5]). Therefore it is highly desirable to characterize thermal lens in this crystal.

In this paper, lateral shearing interferometry was used to measure the phase distortions experienced by a probe beam passing through the BaWO\(_4\) crystal. From these distortions, the strength of the thermal lens was calculated. Lateral shearing interferometry has been used...
previously to measure thermal lensing in various laser systems [27–29]. It is straightforward to implement as it is insensitive to vibration and there is no requirement for perfect spatial overlap between the probe beam and the pumped volume within the crystal (a collimated probe beam is used to give a plane wavefront over the entire surface area of the crystal).

In the next section the principles of lateral shearing interferometry will be outlined and the experimental setup and laser cavity used will be described. Then the results for a BaWO$_4$ Raman laser will be presented, showing that BaWO$_4$ develops a negative and highly astigmatic thermal lens, and the implications for Raman laser design will be discussed.

2. Experimental method

Lateral shearing interferometry was performed by passing a collimated probe beam through the BaWO$_4$. The probe beam then passed through a holographic shearing plate just prior to being imaged onto a CCD camera. Two offset diffraction gratings, holographically written into the shearing plate, split the probe beam into two beams propagating at slightly different angles. These beams then interfere on the CCD and the resulting interferogram contains information about the phase distribution of the probe beam. By taking the Fourier transform of the fringe pattern, filtering out the carrier frequency and then taking the inverse Fourier transform, the differential phase of the probe beam can be retrieved [30] and the strength of the lens inferred. The strength of a bulk lens of known focal length was also measured in order to calibrate for the magnification of the probe beam optics.

The Raman laser cavity and probe beam optics are shown in Fig. 1. A 0.5 mm thick disk of 1at%, a-cut Nd:YVO$_4$ was capillary bonded to a 0.5 mm thick CVD-grown single crystal diamond heatspreader and mounted in a water cooled brass mount. The c-axis was oriented vertically. A 25 mm long a-cut BaWO$_4$ crystal, grown at the at State Key Laboratory of Crystal Materials, Shandong University, China, was mounted in a water-cooled copper block, with the a-axis oriented vertically.

![Fig. 1. Experimental setup for the measurement of the thermal lens in the BaWO$_4$ crystal. Cavity optic separations are shown in mm.](image-url)

Up to 14 W of polarized pump light from an 808 nm fibre-coupled laser diode was incident on the Nd:YVO$_4$/diamond unit. The polarization was oriented along the c-axis of the Nd:YVO$_4$ for strongest absorption and the pump spot radius was 180 µm.

A Z-fold resonator was chosen to facilitate easy access for the probe beam. The resonator was folded with flat mirror M3 so that the probe beam could access either the BaWO$_4$ or the Nd:YVO$_4$ without passing through any curved mirrors. (Attempts to measure the thermal lens in the Nd:YVO$_4$ were ultimately unsuccessful, as discussed below.) The probe beam was from a 532 nm laser and was polarized parallel to the Raman laser polarization (ie parallel to the a-
axis of the BaWO$_4$ crystal). To avoid passing the probe beam through the curved mirror M4, it was double passed through the BaWO$_4$ using probe mirror, PM, which transmitted the infrared cavity fields but reflected the visible probe beam. The distorted probe beam was then imaged onto the CCD (Cohu 4800) using lenses of 200 and 400 mm focal length to give a magnification factor of 2. Between the lenses and the CCD, the beam passed through the shear plate (spatial frequency of fringes 4 line/mm, diffraction efficiency ~5%). Neutral density filters were used to avoid saturation of the CCD. The probe beam encountered a large number of surfaces and multiple reflections were observed. An iris was placed between the imaging lenses and used to select the beam that had made the double pass through the BaWO$_4$ crystal. To measure the lens in the vertical plane, the shearing plate and the CCD were rotated by 90°. (The CCD was rotated to avoid having to modify the analysis to account for camera’s rectangular pixels.)

All mirrors were plane except M4 which was concave with a radius of curvature of 100 mm. The coating on the back of the Nd:YVO$_4$ disk was highly reflecting (HR) at 1064 and 1180 nm, as were mirrors M3 and M4. The front surface of the diamond heatspreader and both surfaces of the BaWO$_4$ crystal were anti-reflection (AR) coated at 1064 and 1180 nm. The output coupler, M5, was HR at 1064 nm and transmitted 0.4% of incident light at 1180 nm. M2 was a dichroic mirror that transmitted 1064 nm but reflected 1180 nm (the Stokes wavelength) and thereby prevented the Stokes field from experiencing any losses in the disk unit. This was important as the anti-reflection coating on the diamond heatspreader was not optimal at 1180 nm. The reflectivities of components are given in Table 1. ABCD matrix modeling predicts length-averaged 1064 nm TEM$_{00}$ mode radii of 220 $\mu$m and 80 $\mu$m in the Nd:YVO$_4$ and BaWO$_4$ crystals respectively for cold cavity conditions.

### Table 1. Details of Coatings on Cavity Optics

<table>
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<tr>
<th>Component</th>
<th>Reflectivity (%)</th>
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<tr>
<td>Nd:YVO$_4$</td>
<td>99.96 n/a</td>
</tr>
<tr>
<td>Diamond heatspreader</td>
<td>&lt; 0.03 n/a</td>
</tr>
<tr>
<td>M2</td>
<td>Side 1 0.24 &gt; 99.95</td>
</tr>
<tr>
<td></td>
<td>Side 2 0.07 n/a</td>
</tr>
<tr>
<td>M3, M4</td>
<td>&gt; 99.96 &gt; 99.98</td>
</tr>
<tr>
<td>BaWO$_4$ (per surface)</td>
<td>0.19 -0.01</td>
</tr>
<tr>
<td>M5</td>
<td>99.91 99.57</td>
</tr>
<tr>
<td>PM (per surface)</td>
<td>(R = 97.7% @ 532 nm) 0.05 0.03</td>
</tr>
</tbody>
</table>

**3. Results**

Without the intracavity probe mirror (PM) in place, a maximum output power of 1.05 W at 1180 nm was obtained for an absorbed diode laser pump power of 11.4 W, corresponding to a diode-Stokes conversion efficiency of 9.2%. The Raman threshold was around 1.7 W of absorbed pump power. The insertion of PM increased the cavity losses and reduced the maximum output power to 0.67 W, corresponding to a diode-Stokes conversion efficiency of 5.9%. The threshold increased to 2.1 W. With PM in place the beam quality M$^2$ factor of the output Stokes radiation was 1.5 in both planes, and therefore we estimate a length-averaged Stokes mode radius of 120 $\mu$m in the BaWO$_4$ crystal. Figure 2 shows a sample power transfer with the PM in place in the cavity.
Typical fringe distortions are shown in Fig. 3 for the case of maximum pump power (11.4 W absorbed), along with reference fringes collected with the pump laser off, for both the horizontal and vertical planes. The shape of the distortion of the fringes indicated that the thermal lens was negative (i.e., a diverging lens) and that the lens in the horizontal plane was much stronger than that in the vertical plane (as can be seen in Fig. 3(c) the distortion in the vertical plane is very weak).

The fringes were analyzed as described above, using a fitting region of 300 µm diameter, and the lens strengths are shown in Fig. 4. For the thermal lens strengths measured in the horizontal plane we estimate an uncertainty of ±5% in the strength of the lens, primarily due to uncertainties in the fringe analysis process. Note that the imaging system was calibrated by measuring the strength of a bulk lens of known focal length. The very weak fringe distortions observed in the vertical plane led to considerably larger uncertainties, perhaps as large as ±50% at low powers.

The thermal lens strength in the BaWO₄ is found to be proportional to the Stokes power, suggesting that the Stokes mode size in the BaWO₄ does not vary strongly with pump power in this cavity design (this is consistent with ABCD modeling of the cavity). There is a significant anisotropy in the lens – in the horizontal direction (the c-axis of the BaWO₄) the gradient of the lens strength with respect to the Stokes output power is $-7.7 \text{D W}^{-1}$, while in the vertical direction it is only $-0.8 \text{D W}^{-1}$.
Fig. 3. Lateral shearing interferograms for (a) horizontal plane, maximum power (11.45 W absorbed pump power, 0.67 W Stokes output power); (b) horizontal plane, references fringes (pump off); (c) vertical plane, maximum power (11.45 W absorbed pump power, 0.56 W Stokes output power – lower than for the horizontal case due to drift in laser performance between experiments); (d) vertical plane, reference fringes (pump off).

Fig. 4. Strength of thermal lens in BaWO₄ in the horizontal and vertical planes (containing the c- and a-axes respectively), plotted as functions of Stokes output power.
4. Discussion

The large anisotropy in the thermal lens strength implies an anisotropy in the thermal properties of BaWO$_4$. The thermal conductivities and thermal expansion coefficients of BaWO$_4$ measured by Ran et al [25] are shown in Table 2. While the thermal conductivities are similar along the a- and c-axes, the thermal expansion is highly anisotropic. To the best of our knowledge, there has been no measurement of dn/dT. To obtain some indication of the value of dn/dT, we placed the BaWO$_4$ crystal in one arm of a Rayleigh interferometer and examined the movement of fringes at 633 nm while the temperature of the crystal was changed using a resistive heater placed beneath the BaWO$_4$. For each polarization, the direction of movement of the fringes indicated that there was a net decrease of optical path length with increasing temperature, which means that dn/dT must be sufficiently large and negative as to cancel out the positive contribution from thermal expansion. On this basis, we calculate that dn/dT must be negative and have a magnitude of at least $9 \times 10^{-6}$ K$^{-1}$. The experiment was not precise enough to give an absolute value.

<table>
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<th>Table 2. Thermal Properties of BaWO$_4$ [25]</th>
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<td>Thermal conductivity/10$^{-4}$ W m$^{-1}$ K$^{-1}$</td>
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Thermal lenses can be described in terms of three contributions: the variation of refractive index with temperature (described by the thermo-optic coefficient dn/dT), the variation of refractive index with stress (the photo-elastic effect) and bulging of the end faces due to thermal expansion [31]. However, disentangling these effects experimentally is not trivial. Thermal expansion gives rise to positive thermal lensing due to bulging of the end faces; however it also contributes to the thermo-optic and photo-elastic components of the thermal lens [32,33]. The expansion contributes a negative component to dn/dT [32], while the sign of the stress contribution to the thermal lens is difficult to infer without complete knowledge of the compliance and elasto-optical tensors, which have been measured for very few laser crystals [31,33]. The astigmatism of the thermal lens likely comes from the stress component – the large anisotropy of the thermal expansion coefficient along the a- and c-axes of the crystal will lead to anisotropic stresses, and it is possible that the unknown elasto-optic coefficients are also anisotropic. For these reasons, it is difficult to infer much about dn/dT from our thermal lens measurements. Furthermore, concerns have been raised about calculating thermal lenses using dn/dT as it is conventionally measured [33]. All these considerations highlight the importance of measuring the total lens in situ, as we have done for BaWO$_4$. Such measurements of thermal lenses under operating conditions provide the best possible guide for cavity design.

We also attempted to measure the lens in the Nd:YVO$_4$ disk. While this is certainly possible in principle, it was very challenging in practice due to reflections of the probe from multiple surfaces in the Nd:YVO$_4$/diamond unit. Ultimately we were unable to obtain reliable data and as a consequence a numerical modeling approach was used to estimate the strength of the lens in the disk. Commercial finite element software (Comsol Multiphysics) and materials data from [31,34–36] were used. The absorbed pump power was assumed to be 11.5 W and the 1/e$^2$ radius of the Gaussian pump distribution was assumed to be 180 µm in line with the experiment. An axially symmetric approximation to the Nd:YVO$_4$/diamond unit and brass mount was used to enable simulation of the full device structure with the available computing resources. On this basis, the focal length of the thermal lens resulting from thermally induced changes in refractive index was estimated to be 150 mm. This estimate was made using a quadratic fit to the axially averaged refractive index profile over the pump radius [9]. The radius of curvature of the deformation of the mirrored face of the Nd:YVO$_4$ crystal resulting from thermal expansion was estimated to be 360 mm, also based on a
quadratic fit over the pump radius, that is to say the thermal effects create a concave end mirror for the cavity. The error resulting from the assumption of axial symmetry is estimated to be <5% for the thermal lens focal length and <15% for the end-face curvature based on comparison of axisymmetric and full 3-D models of a simplified structure.

Comparison of the measured lens in the BaWO₄ to the modeled lens in the disk indicates that the negative thermal lens in the Raman crystal is comparable in magnitude to the positive lens in the laser crystal. The design of future Raman lasers based on BaWO₄ will need to take account of its negative lens and ensure that the cavity can accommodate both this negative lens and the positive lens that develops in many commonly used laser gain crystals (e.g., Nd-doped YVO₄, GdVO₄, YAG). If it becomes necessary to compensate for the BaWO₄ lens at high power levels, this will be complicated by its marked astigmatism. One possible approach would be to use c-cut BaWO₄. This would increase the positive bulging component of the thermal lens (which is influenced mainly by the thermal expansion along the axis of propagation) but would lead to more symmetric transverse behavior and possibly a reduction in the maximum thermal lens strength, depending upon the balance of the dn/dT and end face bulging components against the stress component in the new orientation.

In conclusion we have measured the thermal lens induced in a BaWO₄ crystal in a CW intracavity Raman laser and found that the strength of this lens is proportional to the power generated at the Stokes wavelength, suggesting that the Stokes mode size in the BaWO₄ does not vary strongly with pump power in this cavity design. In the case of a-cut BaWO₄, with the fundamental and Stokes fields polarized parallel to the a-axis, the lens is negative and highly astigmatic. The slope of the thermal lens strength with Stokes output power was measured to be $-7.7 \text{ D W}^{-1}$ in the plane parallel to the c-axis, while it was only $-0.8 \text{ D W}^{-1}$ in the plane parallel to the a-axis, for a Stokes mode radius of 120 \(\mu\text{m}\). To the best of our knowledge, these results represent the first direct measurement of the Raman thermal lens in a CW intracavity Raman laser based on separate laser and Raman crystals. These measurements will be an important input for future design of Raman lasers based on BaWO₄.

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