

# Intracavity testing of $\text{KTiOPO}_4$ crystals for second-harmonic generation at 532 nm

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We have developed a diode-pumped  $\text{Nd:YVO}_4$  cw laser for testing  $\text{KTiOPO}_4$  crystals designed for intracavity second-harmonic generation at 532 nm. We demonstrate that this source is extremely sensitive to defects inside the crystal, inducing losses at 1064 nm and an index mismatch between fundamental and harmonic waves. © 1999 Optical Society of America

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## 1. Introduction

$\text{KTiOPO}_4$  (KTP) nonlinear crystals are frequently used in numerous Nd-doped lasers emitting at 532 nm by second-harmonic generation.<sup>1-4</sup> Its excellent nonlinear properties make KTP particularly suitable for generating green light at 532 nm in cw operation up to the watt level. In this regime the KTP crystal is generally placed inside the laser cavity to increase the conversion efficiency. It is well known that the laser emission is highly sensitive to intracavity elements, in particular to induced losses.<sup>5</sup> For a manufacturer of KTP crystals it is therefore extremely important to be able to evaluate crystal performances and homogeneity in an intracavity doubling configuration.

In this paper we describe a diode-pumped laser source designed for intracavity testing of KTP crystals cut for second-harmonic generation at 532 nm. We identify defects in KTP crystals by using this testing bench and discuss the advantages of using this source for testing KTP crystals compared with use of an extracavity testing bench.

## 2. Description of the Intracavity KTP Tester

We have designed a diode-pumped laser source inside which the KTP crystal can be easily installed for

rapid testing. All the KTP crystals tested were cut for second-harmonic generation at 532 nm, with plane and parallel faces normal to the phase-matching direction. The experimental setup is described in Fig. 1. We used a laser diode with an output facet area of  $500 \mu\text{m}$  by  $1 \mu\text{m}$ , emitting 4 W of power at 808 nm (SDL 2380-P1). The output beam was collimated and focused by two high-numerical-aperture (N.A. of 0.5) objectives ( $O_1$  and  $O_2$ ), with 8-mm focal length. An anamorphic prism pair with  $3\times$  magnification reshaped the pump beam in the direction parallel to the diode junction. With these optics, the pump beam spot was reduced to  $170 \mu\text{m}$  inside the gain medium ( $\text{Nd:YVO}_4$ ). The laser cavity consisted of four mirrors with high-reflection coating at 1064 nm. Mirror  $M_1$  was directly coated onto a 1-mm-long, 1.1% doped  $\text{Nd:YVO}_4$  crystal.  $M_2$  was a concave mirror with radius of curvature of 200 mm. With this value, the beam waist inside the  $\text{Nd:YVO}_4$  crystal was  $190 \mu\text{m}$  (diameter), wide enough to overlap the pump beam.  $M_3$  and  $M_4$  were also concave mirrors with radii of curvature of 150 and 100 mm, respectively. These values were chosen to have relatively high conversion efficiency at 532 nm and to be easily installable upon the KTP crystal. The KTP crystal was placed at the waist position between  $M_3$  and  $M_4$ , where the spot size, determined by  $M_3$  radius of curvature, was  $140 \mu\text{m}$  (diameter). The distance between the KTP and  $M_3$  was approximately 75 mm, and it was approximately 100 mm between the KTP and  $M_4$ . So there would be only one output in the green,  $M_4$  was high-reflection coated at 532 nm and  $M_3$  was antireflection coated at 532 nm. To test the crystal homogeneity we mounted the KTP crystal upon two translation stages moving perpendicularly to the optical cavity axis.

To obtain stable green output power we chose a

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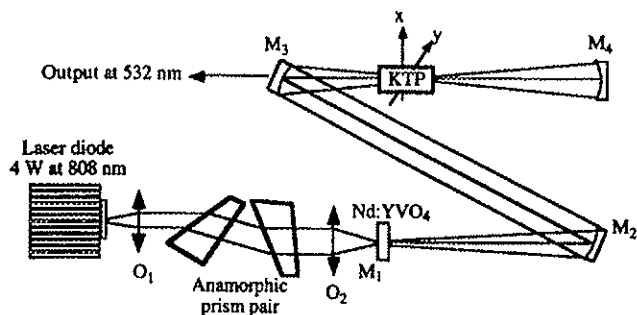


Fig. 1. Experimental setup for intracavity testing.

relatively long cavity (110 cm) such that the laser emitted many axial modes. In this regime, sum-frequency effects between adjacent longitudinal modes at 1064 nm (the so-called green problem<sup>6</sup>) are averaged.<sup>7</sup> We recorded the green output power for a 5-mm-long reference crystal, antireflection coated at 1064 and 532 nm with a thermal detector (bolometer) during 15 min. (Fig. 2). We obtained 300 mW of output power with a good stability (1.5% rms). Part a of Fig. 3 presents the same experiment but with an uncoated reference crystal. One can observe that there the output power was much less stable (9% rms). To understand this difference one has to consider the high Fresnel reflection coefficient (8% at 1064 nm) for the uncoated faces of the KTP. Instabilities induced by end faces of crystals perfectly

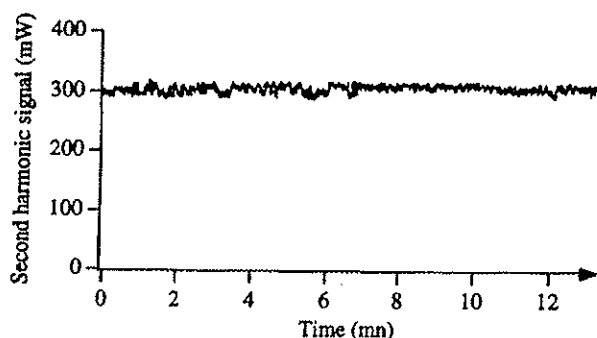


Fig. 2. Output power at 532 nm as a function of time for an antireflection-coated KTP crystal in the intracavity tester.

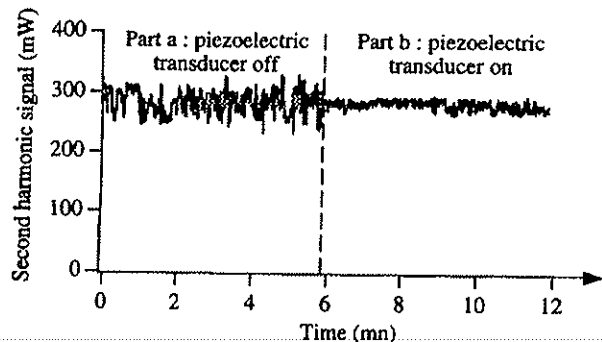


Fig. 3. Stability for an uncoated KTP crystal when the piezoelectric transducer was off and on.

perpendicular to the cavity axis have already been observed in intracavity frequency-doubled lasers.<sup>7,8</sup> Two explanations for this phenomenon can be given: First, as the faces were plane and parallel, the KTP acted as an intracavity Fabry-Perot etalon, reducing the number of longitudinal modes and so increasing the instabilities induced by the mode coupling by sum-frequency generation.<sup>7</sup> The second explanation comes from the phase-locking process of the longitudinal modes that plays a role in stabilizing the green output power.<sup>8</sup> This process was perturbed by the mode frequency shift caused by the uncoated faces of the KTP crystal at normal incidence.

For manufacturers involved in the nonlinear crystals market, testing the conversion efficiency of uncoated pieces just after cutting and polishing is highly appropriate. To achieve this testing it is necessary to use a laser source with stable output during the entire test. To improve the stability of the output signal with uncoated KTP crystals we mounted mirror  $M_4$  onto a piezoelectric transducer, which was driven with a square electrical signal of 20-V amplitude (peak to peak) and 1-kHz frequency. We estimated the displacement of mirror  $M_4$  to be  $\sim 0.5 \mu\text{m}$ . As the cavity length moved at a frequency of 1 kHz, the interference effects induced by coupled cavities were also at the same or a higher frequency. Thus the instabilities in output power were moved from a scale of seconds to one of milliseconds. As the time response of our detector (bolometer) was  $\sim 0.1 \text{ s}$ , the output fluctuations recorded by our detector were smaller when the piezoelectric transducer was on. Part b of Fig. 3 shows that we obtained fluctuations of 2% rms, as opposed to 9% rms when the piezoelectric transducer was off.

Another problem in intracavity doubling comes from possibly ambiguous results between low-loss operation of the laser when the KTP uncoated faces are exactly perpendicular to the cavity axis and the higher conversion efficiency off axis if the KTP phase-matching direction is not perfectly perpendicular to the crystal faces. In fact, we found that the green output power depended strongly on the KTP orientation. To test the different KTP crystals under exactly the same conditions in the cavity we carefully oriented the crystal faces perpendicular to the optical cavity axis. After that, the crystal orientation was never modified. We regulated the crystal in temperature to adjust the phase-matching direction perfectly parallel to the cavity axis. To prove that temperature adjustment allowed the phase-matching direction to be realigned with the cavity axis, we used two reference KTP crystals that had different phase-matching directions relative to their faces:  $0.08^\circ$  for the first crystal and  $0.98^\circ$  for the second. After temperature adjustments (to  $24.4^\circ \text{C}$  for the first crystal and to  $46.5^\circ \text{C}$  for the second), we obtained approximately the same output power from the two crystals (290 and 280 mW, respectively).

By the method described above, we could obtain reliable information about the quality of KTP crystals.

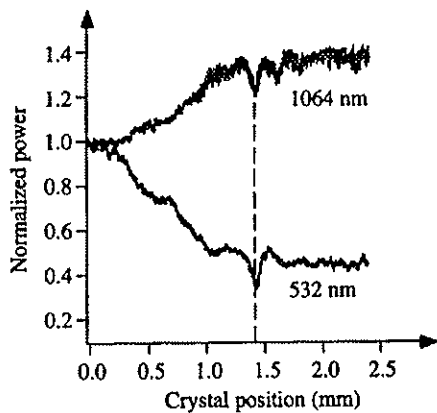


Fig. 4. Comparison of normalized power at 1064 and 532 nm in the intracavity configuration for a specific test crystal.

### 3. Identification of Defects in KTP

Two kinds of defect may decrease the green output power in a laser source that uses a KTP crystal. The first are localized defects in the bulk material or at the surface (dusts or streaks), which induce losses inside the laser cavity. Such additional intracavity losses cause the IR intracavity power and thus the green output power to decrease. The second kind of defect is index inhomogeneities at fundamental or harmonic wavelengths. These inhomogeneities lead to changes in the phase-matching conditions for efficient second-harmonic generation. So the IR intracavity power is not directly affected by these defects but the green output power can be strongly affected even by a small index inhomogeneity.

A simple method to identify these two kinds of defect is to record the IR power leakage at mirror  $M_2$  and the green output at the same time. We did this for a crystal that had these two kinds of defect. Figure 4 shows a scan along the X axis (defined in Fig. 1). The IR and green powers were normalized at the abscissa  $x = 0$ . At position  $x = 1.4$  mm we observed a decrease in both IR and green power. This fact could be attributed to losses induced by a localized defect. From  $x = 0$  to  $x = 2.5$  mm we observed a smooth decrease in the green output power, whereas the IR power increased. This behavior could be attributed not to localized defects but to index variations. At  $x = 0$  the green output power was high (280 mW). This corresponded to high nonlinear output coupling for the laser cavity<sup>5</sup> and thus to moderate intracavity power ( $\sim 5$  W) at 1064 nm. At  $x = 2.5$  mm, the green output was low. A phase mismatch between fundamental and harmonic waves induced a decrease in the green output, a decrease in the nonlinear output coupling for the laser cavity, and thus an increase in IR intracavity power ( $\sim 8$  W).

### 4. Advantages of Intracavity Testing

Traditionally, the efficiency of nonlinear second-harmonic crystals has been tested with energetic nanosecond pulses at the fundamental wavelength. In this case, the peak power was high enough that a

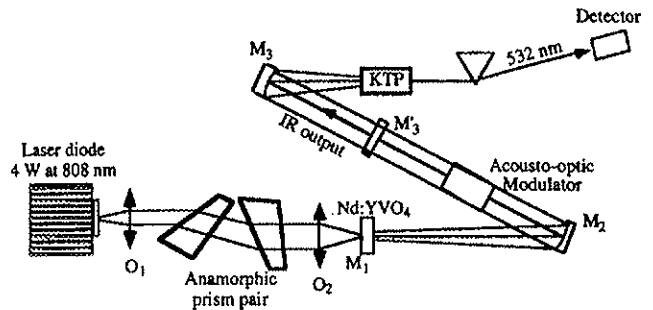


Fig. 5. Experimental setup for extracavity testing.

simpler extracavity experimental scheme could be used. Therefore it is important to compare the sensitivity of our intracavity source with that of an extracavity testing bench.

To do so, we modified our laser source and developed a diode-pumped Q-switched Nd:YVO<sub>4</sub> laser based on the same pumping scheme (Fig. 5). The laser cavity consisted of three mirrors,  $M_1$ ,  $M_2$ , and  $M_3$ .  $M_1$  and  $M_2$  were the same as before.  $M_3$  was a plane output mirror with 30% transmission at 1064 nm. An acousto-optic modulator was inserted into the collimated arm of the cavity, between  $M_2$  and  $M_3$ . The laser operated at a 30-kHz repetition rate and emitted 150-ns pulses with 500-mW average power (corresponding to a peak power of 110 W at 1064 nm). The output beam was focused in the KTP by mirror  $M_3$  described above. A prism separated the green and the fundamental beams. The average output power reached 3 mW at 532 nm for 5-mm-long KTP crystals. With the experimental schemes described in Figs. 1 and 5 we were able to scan the same crystal in the extracavity and the intracavity configurations at the same place and with the same spot size for the fundamental beam. To compare the two testing benches we used the same specific crystal as previously. Figure 6 shows the normalized green output power versus the crystal position for the two configurations. In the extracavity scheme one can see a very small decrease, corresponding to the index mismatch observed previously. Moreover, the localized defect at  $x = 1.4$  mm is absolutely invisible.

These experiments demonstrate the much greater sensitivity to losses and to index mismatch of the

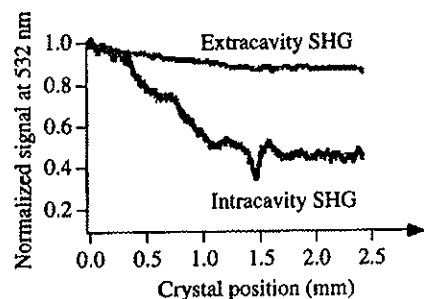


Fig. 6. Comparison of second-harmonic generation (SHG) in intracavity and extracavity testing for the same crystal as in Fig. 4.