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# Investigation on the thermal characteristic of MgO:PPSLT crystal by transmission spectrum of a swept cavity

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**Abstract:** A method of evaluating the thermal focal length of nonlinear crystal via transmission spectrum of a swept cavity (TSSC) is presented. By recording the resonant point offset of the TSSC, the thermal focal length can be successfully measured. Furtherly, by distinguishing the absorption of ultraviolet (UV) laser and UV laser induced infrared absorption (ULIIRA), it is clear that the ULIIRA is the important factor which induces the thermal lens effect compared to the absorption of UV laser for MgO-doped periodically poled stoichiometric lithium tantalate (MgO:PPSLT) crystal and it becomes serious with the increase of the generated UV laser. The ULIIRA coefficient measurement and thermal focal length evalution of MgO:PPSLT crystal can supply an useful reference for researchers to generate high quality UV laser and squeezed or entangled state of optical field by using MgO:PPSLT crystal. The presented method can also be used to precisely evaluate the thermal focal length of other nonlinear crystals.

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**OCIS codes:** (140.3610) Lasers, ultraviolet; (140.3515) Lasers, frequency doubled; (140.6810) Thermal effects; (190.1450) Bistability; (140.3560) Lasers, ring.

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## 1. Introduction

Single-frequency UV laser is a type of important laser source owing to its extensive applications in fields of bio-medicine, metrology, laser printing, high resolution spectroscopy and so on [1]. Especially, single-frequency UV laser can be used to pump an optical parametric oscillator (OPO) to generate squeezed or entangled state of optical field, whose wavelength can be resonant on the absorption line of alkali metal atoms [2]. So far, the main method of generating single-frequency UV laser is frequency doubling technology and there are various nonlinear crystals to act as the frequency doublers, such as lithium triborate (LBO), bismuth triborate (BIBO), periodically poled potassium titanyl phosphate (PPKTP) and so on. Though critical-phase-matching BIBO and LBO crystals have wide transparent range and are suitable to generate UV laser with high output power, intrinsic characteristics of walk-off effect make the beam of generated UV laser imperfect [3,4]. Compared to BIBO and LBO, quasi-phase-matched (QPM) PPKTP crystal receives the favor of majority of scientists owing to its advantage of being free of walk-off as well as high effective nonlinearity (deff=10pm/V) [5]. However, the second harmonic (SH) wavelength of 400 nm is close to the transmission window edge of KTP, the severe absorption of the generated UV laser and the intrinsic gray tracking limit the output power of the generated UV laser and shorten the lifetime of the crystal. Recently, a new nonlinear crystal MgO:PPSLT is attached to importance owing to its intrinsic advantages including high thermal conductivity, high photo-refractive damage as well as broad transmission wavelength range and has been successfully used to generate green and yellow lasers [6–9]. Some groups also used MgO:PPSLT crystals to generate UV laser, but the powers were all at low level [10, 11]. Recently, our group generated 407 mW continuous-wave (CW) single-frequency 397.5 nm UV laser with long lifetime and perfect beam quality by using a MgO:PPSLT crystal in an external enhancement cavity. The experimental results have revealed the superiority of the MgO:PPSLT crystal compared to other nonlinear crystals [12]. Furtherly, in this paper, we investigate the thermal characteristic of MgO:PPSLT crystal via the TSSC when it is used to generate 397.5 nm UV laser in an external enhancement cavity. The relationship between the thermal focal length and cavity detuning is firstly deduced. By recording the cavity detuning according to the observed TSSC, the source of thermal effect in the frequency doubling process is investigated. Compared the total cavity detuning to that caused by second harmonic wave (SHW) absorption, the ULIIRA is turned out to be existent in MgO:PPSLT crystal and the absorption coefficient is determined. Then the thermal focal length of MgO:PPSLT crystal at different intracavity power level is obtained experimentally.

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## 2. Theoretical analysis

In order to obtain high power single-frequency 397.5 nm UV laser, a MgO:PPSLT crystal was inserted into an external enhancement cavity which could increase the intensity by one or two orders of magnitude compared to the single-pass process. By optimizing the parameters of the external enhancement cavity, the maximal power of 407 mW was achieved. In that case, the TSSC was so wide that the laser could not stably be locked to the frequency of the injected fundamental wave (FW) laser, which was presented in our previous paper [12]. The observed TSSC could be attributed to the thermal effect of the MgO:PPSLT crystal. It was expected that the heating of the MgO:PPSLT crystal was due to the residual FW absorption and the SHW absorption as well as the ULIIRA. In order to furtherly quantify the role of thermal effect and research the thermal characteristic of the MgO:PPSLT crystal, it is necessary to know the relationship between thermal focal length and the TSSC. Taking SHW absorption as well as ULIIRA into account and ignoring the FW absorption owing to its tininess [13], the thermal focal length of the MgO:PPSLT crystal can be described as following [14],

$$\frac{1}{f} = \frac{1}{f_s} + \frac{1}{f_u} \tag{1}$$

where $f$ is the total thermal focal length, $f_s$ and $f_u$ are the thermal focal length generated by SHW absorption and ULIIRA, respectively. According to the radial heat diffusion model [15], the thermal focal length of $f_s$ and $f_u$ can be expressed as,

$$f_s = \frac{\pi\omega^2}{2\eta P_s} \cdot \frac{K_C}{dn/dT} \tag{2}$$

and

$$f_u = \frac{\pi\omega^2}{\eta P_u} \cdot \frac{K_C}{dn/dT} \tag{3}$$

where $\omega$ is the waist radius of the FW laser in the center of nonlinear crystal, $\eta$ is the thermal conversion coefficient, which equals to unit because the absorbed laser radiations are overall converted to heat, $K_C$ and $dn/dT$ are the thermal conductivity and thermo-optic coefficient of the nonlinear crystal, respectively. $P_s$, $P_u$ are the absorbed power of SHW and ULIIRA, respectively, and can be expressed as [16],

$$P_s = [exp(\frac{\alpha_s l}{2}) - 1]\Gamma_{eff} P^2 \tag{4}$$

and

$$P_u = [1 - exp(-\alpha_u l)]P \tag{5}$$

where $P$ is the total intracavity power of the FW, $\alpha_s$, $\alpha_u$ are the absorption coefficient of SHW and ULIIRA, respectively. $l$ and $\Gamma_{eff}$ are the length and nonlinear conversion efficiency of the MgO:PPSLT crystal, respectively. Owing to the distribution of the SHW laser in the nonlinear crystal is nonuniform, the waist radius of the SHW laser is defined as $\omega/\sqrt{2}$, which leads to the occurrence of the factor of 2 in the Eq. (2). At the same time, the thermal effect of MgO:PPSLT crystal can result in the cavity detuning and the transmission scanning fringe of the cavity is broadened, which is given as [16]

$$\Theta = \frac{P_s F}{2\pi\lambda_\omega} \cdot \frac{dn/dT}{K_C} \tag{6}$$

and

$$\Delta = \frac{P_u F}{2\pi\lambda_\omega} \cdot \frac{dn/dT}{K_C} \tag{7}$$

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where Θ and Δ are the cavity detuning caused by SHW absorption and ULIIRA, respectively. $F$ and $\lambda_\omega$ are the finesse of the external enhancement cavity and wavelength of FW laser, respectively. Combining Eq. (1) to Eq. (7), the total thermal focal length $f$ can be derived as following,

$$f = \frac{\omega^2 F}{2\lambda_\omega \cdot \Delta + 4\lambda_\omega \cdot \Theta} \tag{8}$$

It is clear that the thermal focal length of the MgO:PPSLT crystal can be evaluated when the Θ and Δ are measured. In the experiment, Θ can be obtained by measuring the absorption rate of SHW, and the total cavity detuning Ψ = Θ + Δ can be obtained by measuring the resonant point offset of the transmission spectrum, which is expressed as [15]

$$\Psi = \frac{\nu - \nu_0}{c/[L + l(n-1)]/2F} \tag{9}$$

where $\nu$ is the resonating frequency of doubling cavity at different pump power, $\nu_0$ is the resonating frequency of cold cavity where the power of injected pump laser and generated UV laser are both so small that the heating of the MgO:PPSLT crystal can be ignored, $c$ is the speed of light in vacuum, $n$ is the refractive index of the nonlinear crystal, $L$ is the geometrical length of the cavity, $\nu - \nu_0$ is the resonant point offset of the transmission spectrum, and $c/[L + l(n-1)]/2F$ is the half-width at half-maximum (HWHM) of the cold cavity, which can be directly measured in experiment. Once the total cavity detuning Ψ and cavity detuning Θ caused by SHW absorption are measured, the ULIIRA coefficient $\alpha_u$ of the MgO:PPSLT crystal and the total thermal focal length $f$ can be further calculated.

## 3. Experimental setup

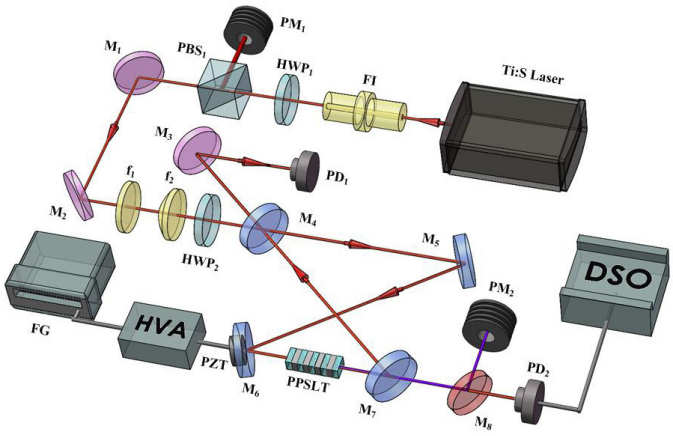



Fig. 1. Schematic of the experimental setup. $HWP_1$-$HWP_2$: half-wave plate; $PBS_1$: polarization beam splitter; $PM_1$-$PM_2$: power meter; $PD_1$-$PD_2$: photo detector; FG: function generator; HVA: high-voltage amplifier; DSO: digital storage oscilloscope.

In order to experimentally investigate the thermal characteristic of the MgO:PPSLT crystal by TSSC, the experimental setup is sketched in Fig. 1. The FW laser is supplied by a homemade Ti:S laser which is pumped by a homemade single-frequency Nd:$YVO_4$ 532 nm laser with a maximal output power of 14 W [17, 18]. A Faraday isolator (FI) is adopted between the Ti:S laser and frequency doubling enhancement cavity to prevent the optical feedback into Ti:S laser. The power adjuster composed of a half-wave-plate ($HWP_1$) and a polarization beam splitter

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($PBS_1$) and $HWP_2$ before the enhancement cavity are used to adjust the incident pump power and ensure the polarization requirement for phase-matching condition of the MgO:PPSLT crystal, respectively. The pump beam is coupled to the enhancement cavity by a telescopic system composed of two lenses $f_1$ ($f_1$=110 mm) and $f_2$ ($f_2$=40 mm). The enhancement cavity is formed by four mirrors, two flat mirrors ($M_4$ and $M_5$ ) and two plano-concave mirrors ($M_6$ and $M_7$) with 100 mm radius of curvature. $M_4$ is used as the input coupler and coated with the transmittance of 11% at 795 nm film. $M_5$ and $M_6$ are coated with high reflection (HR) film at 795 nm ($R_{795}$>99.8%). $M_7$ is the output coupler and coated with HR film at 795 nm ($R_{795}$>99.8%) and high transmittance (HT) film at 397.5 nm ($T_{397.5}$>95%). The MgO:PPSLT crystal with the dimension of $2\times0.8\times10\ mm^3$ is made by Oxide corporation and positioned at the center of $M_6$ and $M_7$. Two end faces of the crystal are coated with antireflection films for wavelength of both 795 nm and 397.5 nm. In order to precisely control the phase-matching temperature of the MgO:PPSLT crystal, it is mounted in a small copper holder which is attached to a thermoelectric cooler (TEC). The reflected beam from $M_4$ is injected to a photo detector ($PD_1$) to lock the enhancement cavity to the frequency of the injected FW laser. The distance between $M_6$ and $M_7$ and total cavity length are 114.2 mm and 534 mm, respectively. In this case, the calculated radium of beam waist at the MgO:PPSLT crystal is 42.18 $\mu$m which has been optimized, and the output power of the generated UV laser reaches up to 407 mW under the incident pump power of 1.9 W. The generated SHW laser are reflected by $M_8$ to a power meter ($PM_2$) to monitor the output power. The FW leaked from $M_8$ is detected by another photo detector ($PD_2$) and recorded by a digital storage oscilloscope (DSO) to record the TSSC.

## 4. Experimental results

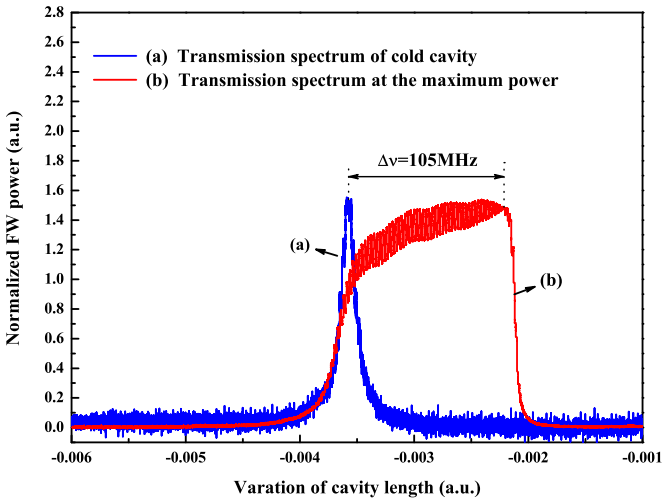



Fig. 2. The transmission spectra of frequency doubling cavity.

In the experiment, in order to obtain stable 397.5 nm UV laser, we had to lock the external enhancement cavity to the frequency of injected FW laser. To this end, a (30Hz 150V) triangle signal which was generated by a function generator (FG, DG1022U, RIGOL) and amplified by a homemade high-voltage amplifier (HVA, YG2009A, YG CO., Ltd), was used to scan the cavity to search for the resonant point. However, in this process, it was found that when the incident pump power gradually increased, the severe difference between the transmission spectrum of rising and falling edges was observed, which was attributed to the thermal effect of the

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MgO:PPSLT crystal. The observed phenomenon, which was named bi-stability, was similar to that of the nonlinear crystals reported in other references [19–22]. In order to quantitatively evaluate the thermal focal length of the MgO:PPSLT crystal, we firstly recorded the resonant point offset of the transmission spectrum at the maximal incident pump power of 1.9 W, corresponding to the intracavity power of 35.33 W, relative to the cold cavity, which was shown in Fig. 2. It was clear that the measured scanning fringe was broadened $\nu - \nu_0$=105 MHz. With decrease of the incident pump power, the resonant point offsets were recorded in turn and the results were listed in Table.1. According to Eq. (9), the corresponding total cavity detuning of different intracavity power was obtained as shown in Fig. 3(a). The total cavity detuning increased with the increase of the intracavity power and reached up to $\Psi = 19$ when the intracavity power and the generated SHW power were 35.33 W and 414.5 mW, respectively.

Table 1. Frequency offset corresponding to different intracavity power

| Cold cavity | FSR=550MHz | HWHM=5.51MHz | |
|---|---|---|---|
| Intracavity power/W | Offset/MHz | Intracavity power/W | Offset/MHz |
| 35.33 | 105.05 | 24.27 | 46.13 |
| 34.36 | 97.08 | 23.58 | 33.64 |
| 33.16 | 88.88 | 21.60 | 18.39 |
| 30.62 | 85.05 | 19.93 | 12.26 |
| 28.76 | 74.63 | 18.45 | 6.13 |
| 27.37 | 70.72 | 16.71 | 3.83 |
| 25.49 | 60.07 | 14.01 | 2.29 |

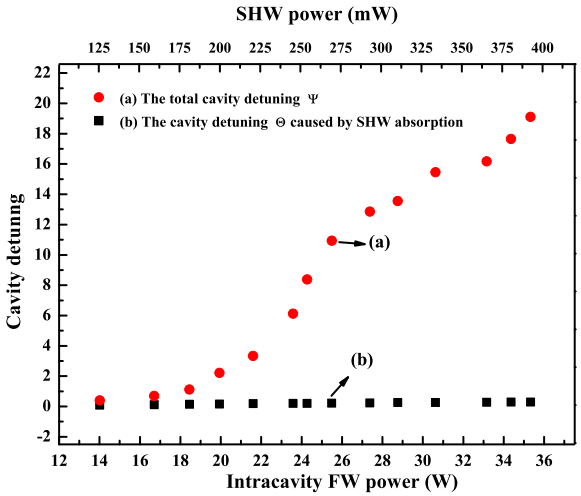



Fig. 3. The cavity detuning at different intracavity power level.

In order to further distinguish the contribution of the SHW absorption and ULIIRA to the total cavity detuning, the absorption of the 397.5 nm UV laser was solely measured by single-pass configuration with another 397.5 nm laser. The measured absorption efficiency at 397.5 nm was 4.5%, which was showed in Fig.4, and the corresponding absorption coefficient was 4.6% $cm^{-1}$. On this basis, the cavity detuning $\Theta$ as a function of SHW power was plotted in Fig. 3(b). Comparing Figs. 3(a) to 3(b) demonstrated that the cavity detuning caused by SHW ab-

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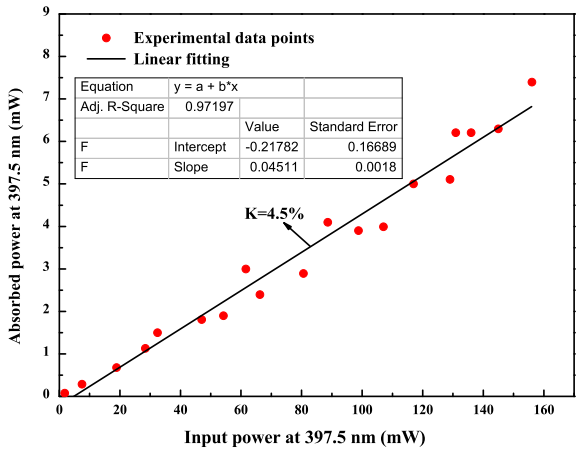



Fig. 4. Absorption at 397.5 nm of MgO:PPSLT.

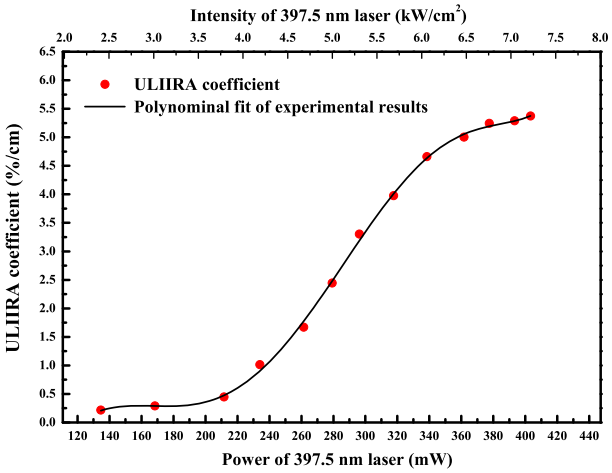



Fig. 5. ULIIRA coefficient as a function of internal UV laser.

sorption was much smaller than the total cavity detuning, which indicated that ULIIRA existed in MgO:PPSLT crystal and was really severe in high power region. Then the value of cavity detuning which was caused by ULIIRA was calculated. Therefore, the ULIIRA coefficient at different SHW power level were obtained and showed in Fig. 5. It indicated that the ULIIRA coefficient increased with the increasing of intensity of 397.5 nm laser internal to crystal. When the intensity was below 3.5 kW/$cm^2$, the ULIIRA coefficient was as low as 0.5% $cm^{-1}$. However, it increased rapidly when the intensity was larger than 4 kW/$cm^2$. When the intensity was up to 7 kW/$cm^2$, the ULIIRA coefficient was as large as 5.5% $cm^{-1}$. As a result, the ULIIRA could lead to a severe thermal effect in high power region. After determining every part of cavity detuning, the total thermal focal length could be determined in turn by Eq. (8). The thermal focal length of MgO:PPSLT crystal as a function of intracavity power was plotted in Fig. 6. It showed that the thermal focal length was longer than 120 mm when the intracavity power was lower than 14 W. When the power increased from 14 W to 24 W, the thermal focal length was getting short rapidly. When the power increased continuously, the thermal focal length was up

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to 3 mm, in this condition, the cavity was seriously influenced by the thermal effect, and could not operate steadily.

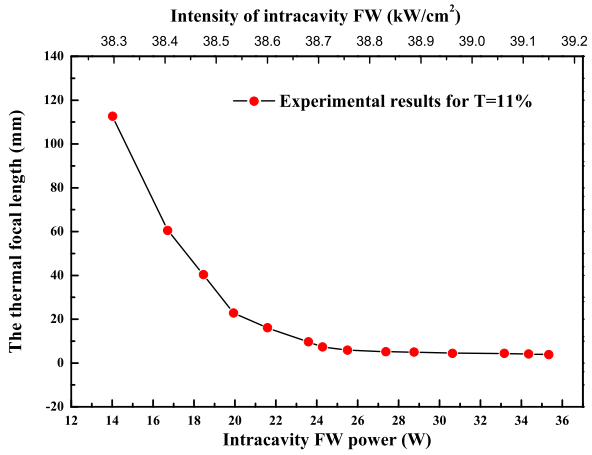



Fig. 6. The total thermal focal length at different circulating power level.

## 5. Summary

In summary, we have investigated the thermal characteristic of MgO:PPSLT crystal by the TSSC when it was used to generate the 397.5 nm UV laser. When the enhancement cavity was scanned with a triangle signal, the TSSC at different incident pump power were observed and recorded. Consequently, the total cavity detuning was measured and that caused by SHW absorption was also obtained with the measured absorption coefficient of 4.6% $cm^{-1}$ of SHW. Comparing these two parts of cavity detuning, the ULIIRA was turned out to be existent in MgO:PPSLT crystal and the ULIIRA coefficient was investigated quantitatively. When the intensity of UV laser was below 3.5 kW/$cm^2$, the ULIIRA coefficient was lower than 0.5% $cm^{-1}$. With the increase of the UV laser intensity, it increased rapidly and reached up to 5.5% $cm^{-1}$ when the UV laser intensity was up to 7 kW/$cm^2$. At last, with the obtained two parts of cavity detuning, the total thermal focal length was obtained. When the intracavity FW power was higher than 24 W, the thermal focal length was lower than 3 mm. In addition, it showed that this severe thermal effect was mainly caused by ULIIRA. The ULIIRA coefficient measurement and thermal focal length evalution of MgO:PPSLT crystal can supply an useful reference for researchers to generate high quality UV laser and squeezed or entangled state of optical field by using MgO:PPSLT crystal. The presented method can also be used to precisely evaluate the thermal focal length of other nonlinear crystals.

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