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# Simultaneous measurement of thermal lens and temperature map in ytterbium-doped fluoride crystals

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**Abstract :** We report on the simultaneous characterization of temperature map and thermal lensing in  $\text{Yb}^{3+}:\text{CaF}_2$  and  $\text{Yb}^{3+}:\text{SrF}_2$  crystals under high-power pumping with/without laser operation. This *in situ* measurement would allow proper designs of high-power cavities.

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OCIS codes: 140.5680 Rare earth, solid state laser, 140.3480 Laser, diode-pumped

## 1- Introduction

Interest in  $\text{Yb}^{3+}$ -doped materials is still growing, owing to the increasing availability of high power InGaAs laser diodes emitting around 980nm. Ytterbium has very attractive properties including a weak quantum defect, and no problem of concentration quenching. Fluoride crystals, having the cubic Calcium fluoride structure, are well-known to be transparent in a large wavelength region (from IR to VUV) and mix the advantages of the oxide crystals and glass. In particular, they feature broad absorption and emission bands. Fluoride ytterbium-doped crystals are therefore very promising for the development of solid-state lasers and amplifiers[1,2]. Here, we present the experimental assessment of both the temperature map and the thermal lens (TL) properties of  $\text{Yb}^{3+}:\text{CaF}_2$  and  $\text{Yb}^{3+}:\text{SrF}_2$  under high power pumping, with or without laser operation.

## 2- Experimental set up

The experimental setup is shown in Fig.1. The 5 mm 3-at %  $\text{Yb}^{3+}:\text{CaF}_2$  or 3-at %  $\text{Yb}^{3+}:\text{SrF}_2$  is directly pumped with a 120 W 400  $\mu\text{m}$  core fiber-coupled laser diode (LIMO) emitting at 980 nm. The probe beam, generated by a fiber-coupled LED emitting at 660 nm, is collimated and superposed with the pump beam. The crystal is imaged through a magnifying system composed of two lenses to a Shack-Hartmann wave-front sensor (HASO64, Imagine Optics). A bandpass filter at 660 nm is placed in front of the analyzer to remove the parasitic beams. With pump off, a reference wavefront is recorded to cancel all static aberrations from the optical elements and the cold crystal. The reference is subtracted from the measured wavefront when the pump is on. Simultaneously, an 8 $\mu\text{m}$ -12 $\mu\text{m}$  high resolution thermal camera with a germanium objective is used to measure the temperature map of one facet of the crystal.

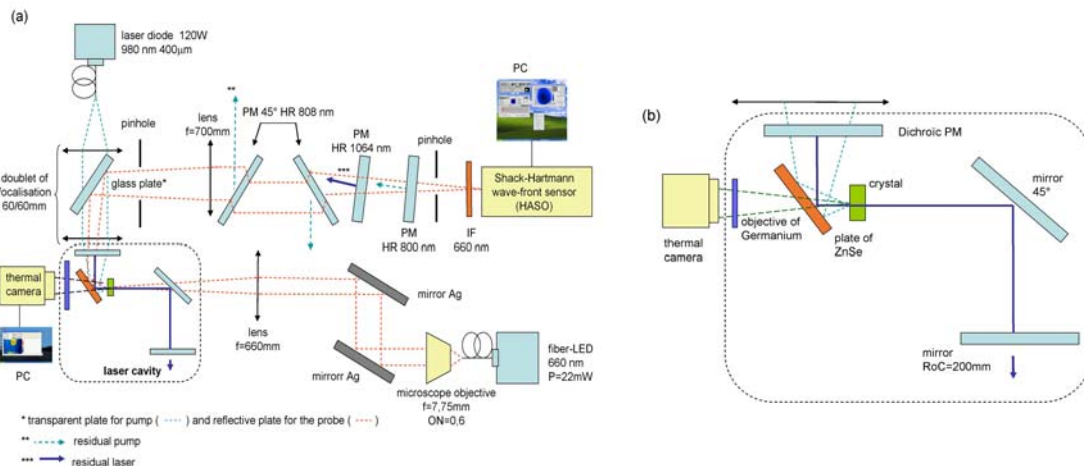


Fig. 1. (a) Experimental setup and (b) zoom of the laser cavity design. PM = plane mirror and IR = interferential filter.

### 3- Experimental results

The TL dioptric power versus absorbed pump power is plotted in Fig. 2 for CaF<sub>2</sub> and SrF<sub>2</sub> crystals with or without laser operation. We notice that all TL dioptric powers ( $D_{th}$ ) are negative. Since the thermal lens focal length ( $f_{th}$ ) is inversely proportional to  $D_{th}$ , the measured thermal lenses are divergent for both crystals. This result can be understood as follows. The TL dioptric power can be expressed as [3]:

$$D_{th} = \frac{1}{f_{th}} = \frac{\eta_h P_{abs}}{2\pi w_p^2 \kappa_c} \left[ \left( \frac{dn}{dT} \right) + (n-1)(1+\nu)\alpha_T + 2n^3 \alpha_T C_r \right] = \frac{\eta_h P_{abs} \chi}{2\pi w_p^2 \kappa_c} \quad (1)$$

where  $\eta_h$  is the fractional thermal load,  $P_{abs}$  the absorbed pump power,  $w_p$  the pump beam waist radius,  $\kappa_c$  the thermal conductivity,  $n$  the refractive index,  $\nu$  the Poisson's ratio,  $\alpha_T$  the coefficient of thermal expansion,  $C_r$  the photo-elastic constant,  $\chi$  the thermo-optic coefficient. The absolute values of the  $(n-1)(1+\nu)\alpha_T$  and  $2n^3 \alpha_T C_r$  terms are similar and compensate each other. So, the last term of  $\chi$  determines the sign of  $D_{th}$ , all the other terms being positive. Since the values of  $(dn/dT)$  for the CaF<sub>2</sub> and SrF<sub>2</sub> are equal to  $-10.6 \cdot 10^{-6} \text{ K}^{-1}$  and  $-12 \cdot 10^{-6} \text{ K}^{-1}$  respectively, divergent thermal lenses are expected.

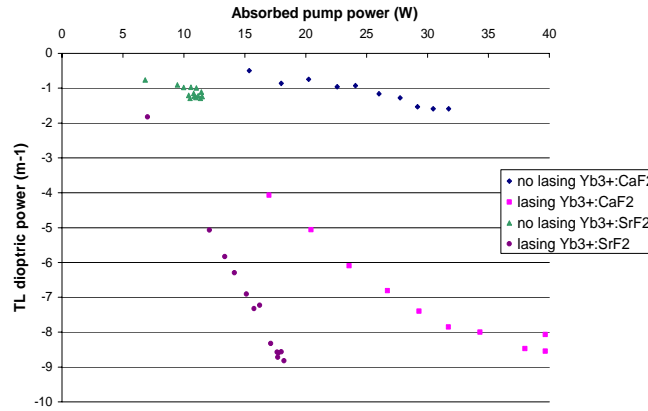


Fig 2. TL dioptric power versus absorbed pump power for CaF<sub>2</sub>:Yb<sup>3+</sup> and SrF<sub>2</sub>:Yb<sup>3+</sup> crystals with and without laser operation.

The values of TL focal lengths for CaF<sub>2</sub>:Yb<sup>3+</sup> and SrF<sub>2</sub>:Yb<sup>3+</sup> crystals are equal to -119 cm for an absorbed power of 40 W and -113 cm for an absorbed power of 18 W respectively (fig. 2). Note that the CaF<sub>2</sub>:Yb<sup>3+</sup> crystal needs a higher absorbed pump power to measure the same TL focal length. This difference could be explained by the lower values of the thermal conductivity  $\kappa_c$  and the coefficient of thermal expansion  $\alpha_T$  for the SrF<sub>2</sub>:Yb<sup>3+</sup> crystal: the SrF<sub>2</sub> crystal is not as efficient as CaF<sub>2</sub> to dissipate the heat. Therefore, the temperature gradient is higher in SrF<sub>2</sub> and TL focal length increases more quickly with absorbed power.

Using the expression of the TL dioptric power (1), and taking into account the divergence of the pump beam in the expression of  $w_p$ , we are able to fit the measured TL dioptric power with laser effect versus incident power (fig. 3). The values of the parameters for the fits are summarized in Table 1.

Crystals	CaF <sub>2</sub> :Yb <sup>3+</sup> (3%)	SrF <sub>2</sub> :Yb <sup>3+</sup> (3%)
$\kappa_c$ (W.m <sup>-1</sup> K <sup>-1</sup> )	6.0	3.3
$\eta_h$	0.07	0.07

Table 1. Parameters used for the fit of the TL dioptric power.

When operating in laser condition, the fractional thermal load  $\eta_h$  was set to a value slightly higher than the quantum defect  $1-(\lambda_p/\lambda_l)$  where  $\lambda_p$  is the pump wavelength and  $\lambda_l$  the laser wavelength (quantum defects for CaF<sub>2</sub> and SrF<sub>2</sub> are equal to 0.067 and 0.069 respectively). Indeed, the intracavity power is high enough to consider that the laser

extraction efficiency is equal to one over the whole lasing crystal volume. Given this assumption, the good agreement with the experimental data indicates that the heat generated in these crystals is mostly due to the quantum defect, and that the contribution of nonradiative effects is negligible.

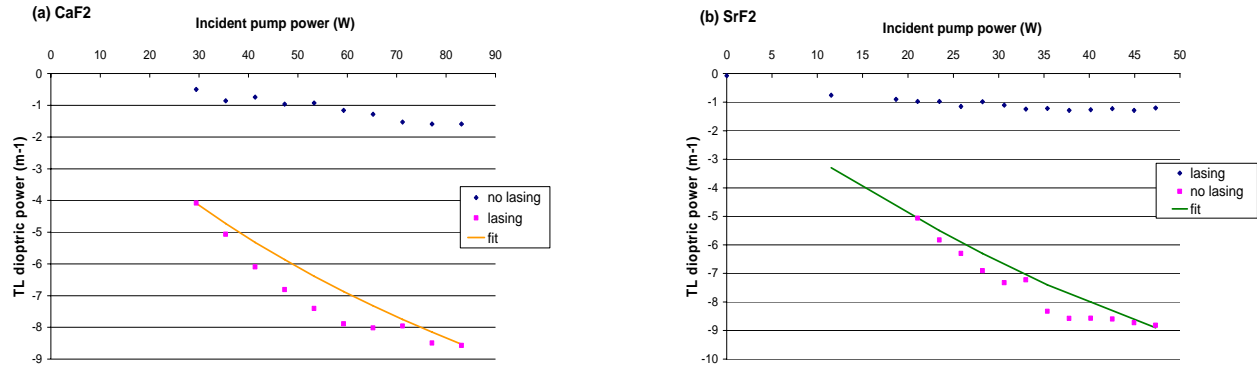


Fig. 3. The TL dioptric power versus incident power fitted for (a)  $\text{CaF}_2:\text{Yb}^{3+}$  and (b)  $\text{SrF}_2:\text{Yb}^{3+}$  crystals with laser effect or not.

The evolution of the temperature gradient in the crystal ( $\Delta T$ ) versus incident pump power is shown in Fig. 4 with or without laser operation. A weak temperature gradient is observed for both crystals when the laser is off. This result corroborates the weak measured TL dioptric power without laser operation.

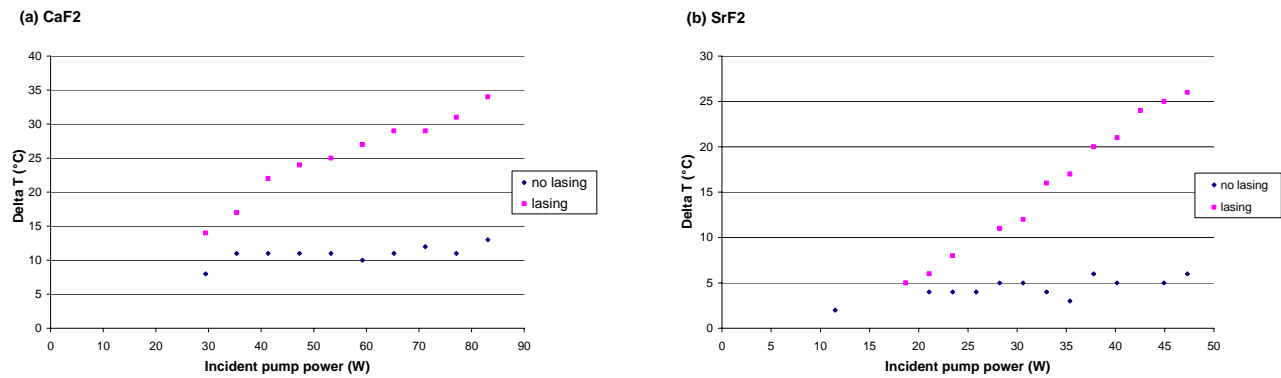


Fig. 4. Temperature gradient versus incident pump power for (a)  $\text{CaF}_2:\text{Yb}^{3+}$  and (b)  $\text{SrF}_2:\text{Yb}^{3+}$  crystals with or without laser operation

#### 4- Conclusion

To our best knowledge, this is the first combined measurement of both thermal lens properties and temperature map in ytterbium-doped  $\text{CaF}_2$  and  $\text{SrF}_2$  crystals. These *in situ* measurements indicate different interesting quantitative results: first the presence of a small negative thermal lenses resulting from various competing (thermo-optics and thermo-mechanical) effects; second, strong differences of behaviour between lasing and not lasing conditions which is important since it may imply high thermal shocks; third, that the thermal loads are mainly due to the quantum defect implying very few other parasitic non-radiative processes.

#### 5- References

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