Conference Paper

Equivalent Surface Temperature of Optical Elements Interacting with Laser Irradiation

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Abstract

We propose a novel technique for measuring the surface temperature distribution of optical elements interacting with high power laser radiation. This technique is based on measuring temperature sensitive piezoelectric resonance frequencies of nonlinear-optical crystals that are transparent at involved laser radiation wavelengthes. Using small thermoresonators made of the lithium niobate ($LiNbO_3$) crystal the kinetics of the surface temperature distribution of the silica lens heated by 11W CW laser radiation at 1064 nm was measured. According to measured data, the optical absorption coefficient of the lens was evaluated to be $\alpha = 6 \times 10^{-5}$cm^{-1}.

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1. Introduction

Interaction of high power laser radiation with optical elements results in its nonuniform heating, which can lead to the changes of the material optical properties, as well as its degradation or even destruction. Thus, it is important to measure and control the temperature distribution of the optical element surface during laser exposure.

Most common ways for this purpose are to use thermal imaging cameras or contact sensors (thermistors, thermocouples, etc.). As a rule, thermal radiation spectra correspond to the middle infrared range. This complicates measurements in the case optical elements interact with radiation from the same wavelength range. In turn external detectors require a good thermal contact and can be considerably heated due to the absorption of the scattered radiation.

An alternative approach for the temperature measurement was proposed in [1]. All nonlinear-optical crystals possess piezoelectric properties. Concept of “equivalent temperature” Θ_{eq} of crystal nonuniformly heated by laser radiation was introduced.

Piezoelectric resonance laser calorimetry (PRLC) is based on measuring the temperature dependence of piezoelectric eigenmode frequencies of the crystal. At first resonance frequencies Rf_i should be calibrated during uniform heating of the crystal. Then for all measured eigenmodes the piezoelectric resonance thermal coefficients are obtained, describing the resonance frequency change with temperature:

$$K_i^{prt} = \frac{dRf_i}{dT} \tag{1}$$

During nonuniform heating of the crystal, the resonance frequency shift can be associated with the equivalent temperature change:

$$\Delta\Theta_{eq}(P) = \frac{\Delta Rf_i(P)}{K_i^{prt}} \tag{2}$$

For surface temperature measurements it was proposed to use tiny nonlinear-optical crystals – thermoresonators [2]. Thermoresonators should have a high heat transfer coefficient, low optical absorption at the involved laser irradiation wavelengths, small sizes and high Q-factors of the piezoelectric resonances. In the case a thermoresonator is placed onto the investigated surface, its temperature can be associated with the surface temperature of the corresponding region. Thus it is possible to introduce a notion of the "surface equivalent temperature" Θ_{eq}^{Sur} of the crystal heated by laser radiation.

2. Materials and Methods

We measured the surface temperature distribution of the lens (diameter - 32 mm, height - 5 mm) made of the fused quartz, exposed to 11W CW laser radiation at 1064 nm. Thermoresonators made of the lithium niobate were used.

Numerical experiments were conducted in order to investigate a correlation between the temperature measurement errors and thermoresonator dimensions. 2D model contained a rectangular thermoresonator placed on a infinite plate. Bottom of the plate was heated with constant power. The nonstationary heat transfer equation was solved:

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \tag{3}$$

where ρ, c, λ - density, heat capacity and thermal conductivity of the materials respectively. Initial temperature T_0 was the same for all elements of the system.

The thermal contact between the thermoresonator and the plate was described using the thermal impedance [3].

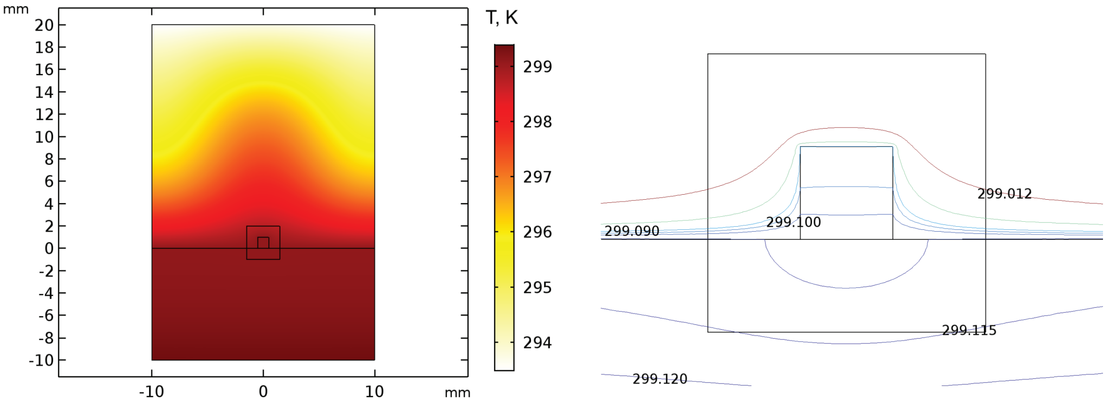

Figure 1: Typical temperature distribution calculated for the thermoresonator placed onto the infinite plate surface. Temperatures at points 1 and 2 - correspond to minimum and maximum thermoresonator temperatures, points 3 and 4 – thermoresonator and plate temperatures near the contact, 5 – plate temperature far away from the thermoresonator.

The convective cooling was described using Navier-Stokes equations [4].

Fig. 1 shows the temperature field after 3 minutes heating together with isothermal contours near the thermoresonator. Big square indicates the region with a finer spatial grid.

The following error types were assessed in order to determine measurement error:

1. $\epsilon_{eq} = \frac{T_2 - T_1}{T_2 - T_0}$ - the equivalent temperature, measured in the experiment, deviation from the average temperature of the crystal (the equivalent temperature is between minimum and maximum temperatures of the crystal [1]).

2. $\epsilon_{cont} = \frac{T_3 - T_4}{T_3 - T_0}$ - the nonideal heat contact between the sample and the thermoresonator.

3. $\epsilon_{sur} = \frac{T_5 - T_4}{T_5 - T_0}$ - the temperature field distortion due to the thermoresonator.

Taking into account all these errors it is possible not only to estimate the overall inaccuracy of this method but also to find the most appropriate thermoresonator dimensions.

For measuring the lens surface temperature distribution five cubic thermoresonators with 1 mm side were used. Full error dependence on time is shown in Fig. 2.

Numerical calculations reveal the error decreases to a constant level, depending on the thermoresonator size and its thermal impedance. For the thermoresonators we used in the experiment was evaluated to be 2,5%.

Block-scheme of the experimental setup is shown in Fig. 3.

Thermoresonators were placed on a flat surface of the lens at the distance of 3, 5, 8, 13 and 15 mm from the center of the lens, which was heated by collimated

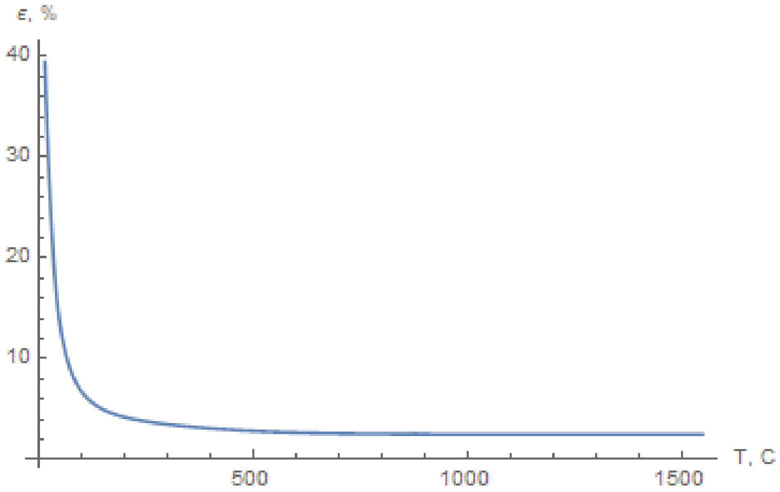

Figure 2: Numerically evaluated temperature error dependence on time.

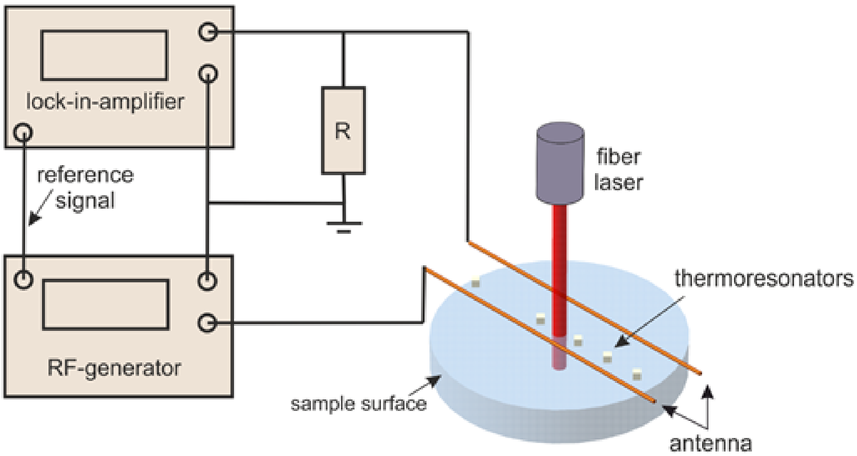

Figure 3: Block-scheme of the experimental setup.

(beam diameter is 1.8 mm) laser radiation. This excludes direct laser heating of the thermoresonators. Eigenmodes of the thermoresonators were excited noncontactly by the probe radiofrequency voltage applied to the electrodes connected in series with the radiofrequency generator and load resistor R. A thermoresonator response was measured by the lock-in amplifier. Near the resonance frequency the response has some specific features shown in Fig.4.

Resonance frequency correspond to the phase minimum. In order to evaluate K_i^{prt} coefficients the lens together with all thermoresonators was placed in a thermostat. By changing its temperature, the resonance frequency dependence on temperature was measured.

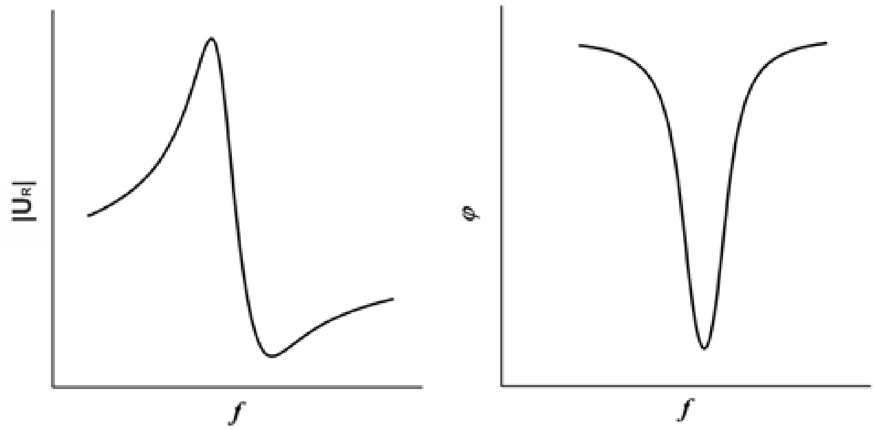

Figure 4: Typical dependence of the absolute value $|U_R|$ and phase ϕ of the voltage drop on a load resistor R near the piezoelectric resonance.

3. Results

Using this technique the lens surface temperature distribution kinetics were measured. Fig. 5. shows measured kinetics taking into account corresponding inaccuracy.

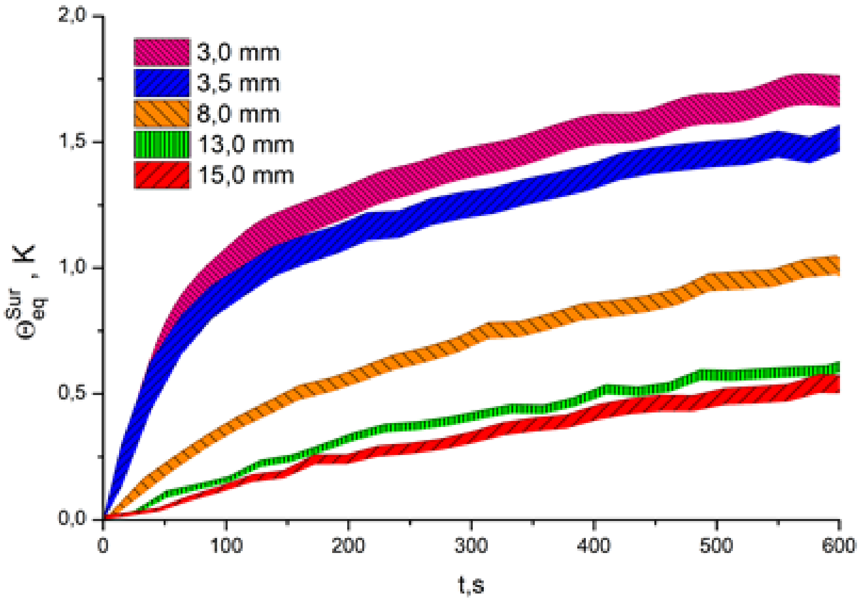

Figure 5: Equivalent surface temperature kinetics of the lens at different distance from the irradiation center.

As the lens and a heat source possess cylindrical symmetry, the measured dependence $\Theta_{eq}^{Sur}(t, r)$ can be used to evaluate the overall surface temperature of the lens.

4. Discussion

Measured surface equivalent temperature kinetics can be used to determine certain physical properties of the investigated samples, e.g. optical absorption coefficient. For this purpose, the nonstationary heat transfer equation was solved taking into account the convective cooling. Absorbed laser radiation was the heat source in the model. Subsequently the absorption coefficient was evaluated providing that the calculated surface temperature distribution matched the measured one. The absorption coefficient of the silica lens was evaluated to be $\alpha = 6 \times 10^{-5}\mathrm{cm}^{-1}$.

5. Conclusion

In present work we have demonstrated a novel approach for measuring the surface temperature distribution using thermoresonators made of piezoelectric crystals. A numerical model was implemented to evaluate the measurement inaccuracy of the surface temperature. By solving the inverse heat transfer problem, it is possible to determine certain physical properties of the sample, such as absorption coefficient, heat transfer coefficient and others.

References

[1] *Ryabushkin O.A. [et al.]* Equivalent temperature of nonlinear-optical crystals interacting with laser radiation // Journal of the European Optical Society. 2011. V. 6. P. 11032.

[2] *Aloyan G.A., Kovalenko N.V. and Ryabushkin O.A.* Determination of surface equivalent temperature of active elements for microelectronics and photonics // Proceedings of the 2016 International Conference on Mechanics and Materials Science (MMS2016). 2016. P. 1177-1182.

[3] *S.Yu. Mesnyankin, A.G. Vikulov, D.G. Vikulov* Solid-solid thermal contact problems: current understanding // Advances in Physical Sciences. 2009. V. 107, № 9, P. 945-970.

[4] *Chorin A. J.* Numerical solution of the Navier-Stokes equations // Mathematics of computation. – 1968. – T. 22. – №. 104. – C. 745-762.