Concept of equivalent temperature of the nonlinear-optical crystal interacting with nonuniform laser radiation

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Crystal temperature control with high precision is necessary condition for the efficient conversion of laser radiation in critically phase matched nonlinear-optical processes. However till now methods for precise temperature control of crystals heated by laser radiation are not devised. Conventional techniques imply temperature measurement of air surrounding nonuniformly heated crystal. These methods cannot ensure sufficient accuracy due to high air temperature gradient in the vicinity of the crystal surface. Moreover in process of laser frequency conversion changes occur of crystal-air heat transfer coefficient as well as optical absorption coefficients at pump and converted radiation wavelengths. Thus nonlinear-optical crystal temperature measurement and control is topical problem in laser physics.

Present work is dedicated to both the theoretical model elaboration and experimental performance of the precise temperature measurement of crystal nonuniformly heated by laser radiation. Acousto-resonance spectroscopy technique is employed for these purposes. The idea of simultaneous combination of optical and acoustical measurements proved to be fruitful [1-3]. The reason is that all nonlinear-optical crystals possess piezoelectric properties. As follows both direct noncontact excitation and detection of acoustical vibrations in crystals can be performed by using external radiofrequency (RF) electric field. Piezoelectric resonance is observed when the electric field frequency f coincides with the crystal intrinsic vibration mode frequency Rf_{n} (n – mode index). Recently novel concept of "crystal equivalent heating temperature $\Delta\Theta_{\mathrm{eq}}(P)$" has been introduced in laser physics [1]. This concept is based on experimental determination of the piezoelectric resonance frequencies $Rf_n(\mathrm{T})$ dependence on crystal uniform temperature T and theoretical model of the crystal nonuniform heating by laser radiation of power P. Crystal nonuniform temperature change $\Delta\mathrm{T}_{\mathrm{cr}}(x,y,z,P)$, which is calculated, is then substituted by $\Delta\Theta_{\mathrm{eq}}(P)$ value that is independent on coordinates. The $\Delta\Theta_{\mathrm{eq}}(P)$ is directly measured from the piezoelectric resonance frequency shift $\Delta Rf_n(P)$ for the given laser power distribution $P(x,y,z)$. Crystal true thermodynamic temperature distribution is expressed: $\mathrm{T}_{\mathrm{cr}}\left(x,y,z,P\right)=\mathrm{T}_0+\Delta\Theta_{\mathrm{eq}}\left(P\right)+\delta\mathrm{T}\left(x,y,z,P\right)$. Here T_0 is crystal temperature at P=0. Using the proposed mathematical model of the crystal heating by laser radiation it was shown that temperature nonuniformity inside the crystal satisfies the following condition $\delta\mathrm{T}\left(x,y,z,P\right)<<\Delta\Theta_{\mathrm{eq}}\left(P\right)$ [2]. Here mathematical problem definition and solution are based on variation principle. Mechanical and electrical boundary conditions should be specified for calculating motion state of the medium. Electrical boundary conditions of the first type suggest specification of the surface charge density $\bar{\sigma}$ and those of the second type suggest specification of the electrical potential φ. The following expression for the action functional can be written.

$$L_0\left(u_i,\varphi\right)=\int_{t_0}^{t}\left[\iiint_{\Omega}\left(\frac{1}{2}\rho\dot{u}_i^2-\frac{1}{2}c_{ijkl}S_{ij}S_{kl}+\frac{1}{2}\varepsilon_{ij}E_iE_j\right)d\Omega\right]dt+\int_{t_0}^{t}\left[\iint_{\Gamma_f}\bar{F}_iu_idA-\iint_{\Gamma_D}\bar{D}_in_i\varphi dA+\iint_{\Gamma_u}T_{ij}n_j\left(u_i-\bar{u}_i\right)dA-\iint_{\Gamma_\varphi}D_in_i\left(\varphi-\bar{\varphi}\right)dA\right]dt\cdot$$

Here D_i – electric displacement vector; $E_i=-\partial\varphi/\partial x_i$ – electric vector; c_{ijkl} – tensor of elastic constants of the sample; e_{ijk} – tensor of piezoelectric modules; ε_{ij} – dielectric tensor; S_{ij} – strain tensor; T_{ij} – stress tensor; ρ – density of the sample; u_i – components of mechanical displacement of the sample points; F_i – force; n – normal vector; $d\Omega$ – volume element; dA – surface (boundary) element; t – time; Γ denotes boundary; horizontal bar above function denotes its value at the boundary. For the case of natural boundary conditions the derivation of equations for crystal intrinsic modes was made. It was shown that for all unknown functions (mechanical displacement and electric potential) the dependence on time is harmonic and is characterized by the certain frequency. The last one is the intrinsic vibration mode frequency. After calculating the eigenfrequencies and spatial distributions of the functions u_i, φ the piezoelectric resonance thermal shifts are calculated using known dependence of the elastic constants $c_{ijkl}(\mathrm{T})$ on crystal uniform temperature. Nonuniform temperature distribution inside the crystal results in additional piezoelectric resonance frequency shifts. The reason for that is spatial dependence of the elastic constant values, which is typical for the case of crystal nonuniform heating.

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[3]. O.A. Ryabushkin, A.V. Konyashkin, D.V. Myasnikov, V.A. Tyrtyshnyy, and A.I. Baranov, "Equivalent Temperature of Nonlinear-Optical Crystals in Process of Laser Frequency Conversion", Conference on Lasers and Electro-Optics – International Quantum Electronics Conference CLEO/EUROPE-IQEC 2013, Munich Germany, 12-16 May 2013, Conference digest CE-8.5 WED.