A Time-Dependent Analytical Thermal Model To Investigate Thermally Induced Stresses In Quasi-CW-Pumped Laser Rods

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One of the main problems that limit the power scaling of diode-end-pumped solid-state lasers is the generation of heat inside the laser gain medium which can ultimately cause fracture. When the continuous wave (CW) pump power exceeds the critical power at which crystal fracture occurs, a quasi-continuous wave (QCW) pump is often used to reduce the average pump power to below the fracture pump power.

In previous work, we investigated the time-dependence of the temperature and the thermally induced stresses in QCW-pumped Tm:YLF laser rods by means of finite element numerical simulations [1]. This enabled the prediction of the incident fracture power as a function of QCW-pump duty cycle.

In this paper a time-dependent analytical thermal model that determines the temperature and the thermally induced stresses in isotropic rods is presented. Even though the model is developed for isotropic rods, it is shown that it can also be used to accurately estimate the thermal effects in anisotropic rods. By ignoring axial heat-flow in the radially symmetric rod, the temperature profile on the pumped face of the rod is given by

$$T(r,t) = \sum_{m=1}^{\infty} \int_0^R \int_0^t \frac{2sJ_0(\frac{\mu_m r}{R})J_0(\frac{\mu_m s}{R})Q(s,\tau)e^{\frac{-D\mu_m^2(t-\tau)}{R^2}}}{R^2 J_1^2(\mu_m)}d\tau ds \tag{1}$$

where R is the radius of the rod, J_i is a Bessel-function of the first kind with order i, μ_m are the roots of J_0 and $D=k/(\rho c_p)$ with k the thermal conductivity, ρ the density and c_p the specific heat capacity of the laser rod. $Q(r,t)=I(r,t)\alpha/(\rho c_p)$ is the heat load where $I(r,t)$ is the transverse pump intensity profile and α is the absorption coefficient at the pump wavelength. In the case of a top-hat transverse pump profile, equation (1) reduces to

$$T(r,t) = \sum_{m=1}^{\infty} \frac{2wJ_0(\frac{\mu_m r}{R})J_1(\frac{\mu_m w}{R})}{J_1^2(\mu_m)\mu_m R} \int_0^t Q(r,\tau)e^{\frac{-D\mu_m^2(t-\tau)}{R^2}}d\tau \tag{2}$$

where w is the pump beam radius. The integral in equation (2) can easily be solved numerically for a QCW-pumped laser.

Figure 1 shows the temperature in the centre of the pumped-face of the Tm:YLF rod as a function of time while the rod is subjected to two different QCW-pump power and pulse repetition frequencies. The analytical model reduces the computation time of the thermal effects from ~5.5 hours in the case of the finite element numerical model to less than a minute. By using the analytical model, it is possible to efficiently calculate the thermal influence of various pump scenarios within a short time.
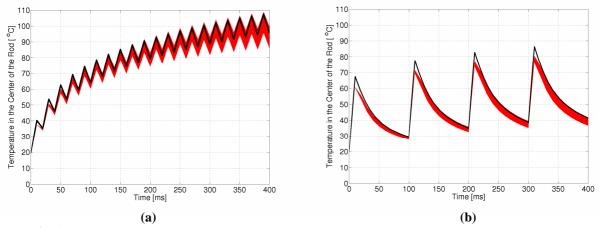

(a)   (b)

Fig. 1 The temperature in the centre of the Tm:YLF rod as a function of time while the rod is subjected to a QCW-pump of **(a)** 90 W @ 50 Hz **(b)** 200 W @ 10 Hz. The two respective boundaries of the shaded regions indicate the analytical solution as determined with the thermal conductivity of the a- and c-axis of YLF respectively. The black curve shows the solution of the three-dimensional time-dependent coupled-thermal-stress finite element numerical simulation.

References

[1] E.H. Bernhardi, C. Bollig, L. Harris, M.J.D. Esser, A. Forbes, "Investigating Thermal Stresses in Quasi-CW Pumped Tm:YLF Laser Crystals", Advanced Solid-State Photonics International Conference, ISBN 1-55752-850-0, 27-30 January, 2008, Nara, Japan