

# Measurements of Heat Flow from Surface Defects in Lithium Triborate

D. Broege and J. Bromage

Laboratory for Laser Energetics, University of Rochester

With laser sources being pushed to larger bandwidths and higher average powers every day, the importance of thermal effects in nonlinear optics has become an increasingly important area of study. It has been shown that absorption in the bulk of crystals, as well as their coatings, can lead to significant changes in temperature that can have a negative impact on nonlinear processes. One common but often overlooked source of heat in optics exposed to high average powers is the more-localized type, which can be the result of crystal defects, contamination, or damage spots. We have performed what is to our knowledge the first interferometric measurements of temperature distributions in a nonlinear optic resulting from absorption in a localized defect. A supporting analytical model is shown to elucidate features of the resulting temperature distribution and assist in estimating the total absorbed power at the site, with a sensitivity of one part in  $10^5$ . This technique also provides a method of measuring absorption from a defect without the need for collection and measurement of a transmitted beam.

The setup used to perform these measurements consisted of a Mach–Zehnder interferometer with the sample in one arm. A 1064-nm kilowatt beam with a diameter of 2 mm was passed through the sample at a slight angle to induce heating. Changes in optical path length were measured across the face of the crystal, and a differential measurement was made between path lengths under ambient conditions and when the heated crystal reached equilibrium. These values were then used to calculate the corresponding longitudinally integrated temperature change with published material parameters.

The materials used in this study were all uncoated low-bulk-absorption lithium triborate (LBO) crystals, principally cut into 1-cm cubes and polished on four sides. This allowed for pump and probe beams to sample single crystallographic axes. This was used to qualify the measurements, in that a particular heat distribution could be probed with two separate polarizations, yielding two similar signals, but with different amplitudes. The ratio of these amplitudes could be calculated from material parameters and were shown to agree with measured values to within  $\sim 10\%$ . The localized absorbers—the focus of our study—were single unintentionally produced damage spots on the crystal surfaces.

The 2-D changes in optical path length that were measured from these crystals showed a distinctive shape. It consisted of a sharp central peak, no larger than  $100\ \mu\text{m}$ , with rapidly decaying amplitude moving outward from the source. This stands in stark contrast to the more Gaussian-like distributions seen when heating is the result of absorption in the bulk or in a coating. Thermal imaging measurements showed that the heating occurred on only one face of the crystal, indicating that it was solely the result of localized absorption. Also observable was an asymmetry in the vertical direction, but not the horizontal, indicating that the crystal was warmer at the top surface than at the bottom, which was the result of heat loss into the mount.

With access to finite element analysis tools, calculations of heat flow can be made, but the higher resolutions required to accurately model such a small source require significant memory. We instead employed an analytical model that can be easily derived by relating the total absorbed power to heat flow through a spherical surface at distance  $r$  from the absorber through Fourier's law. This results in a temperature distribution of the following form for all points outside the absorber:

$$T(r) = \frac{P}{4\pi\kappa r} \tag{1}$$

and can be shown to be

$$T(r) = \frac{-Pr^2}{8\pi\kappa R^3} + \frac{3P}{8\pi\kappa R} \tag{2}$$

for all points inside the absorber, where  $r$  is the observation radius,  $\kappa$  is the thermal conductivity,  $R$  is the radius of the absorber, and  $P$  is the total absorbed power. For this model to be valid, the source must be small compared to the length of the crystal, and the heat flow through the crystal must be large compared to convective cooling at the surface.

What is immediately evident from the functional form of this distribution is that outside the absorber, its amplitude is proportional to the absorbed power, but completely insensitive to the size of the absorber. Calculations show that a 20-fold decrease in the size of the heat source results in only a factor-of-2 increase in the resulting peak temperature. *This implies that without detailed knowledge of the morphology of the absorber, a decent estimate can be made of the total power absorbed.* Figure 1 shows an overlay of measured changes in optical path length and a simulated data set using the simple model, with an absorbed power of 15.5 mW. The matching between the two is sensitive to the mW level, allowing for a very sensitive estimation of absorbed power at a localized defect. With this knowledge, one can use microscopy to determine the maximum spatial extent of the defect and determine a range of possible absorbances and sizes. In the case of our test spot, with a maximum possible size of 100  $\mu\text{m}$ , assuming absorption is uniform across its face results in an average absorbance of 5%. If, on the other hand, absorbance is 100%, the size of the spot can be no smaller than 22  $\mu\text{m}$ .

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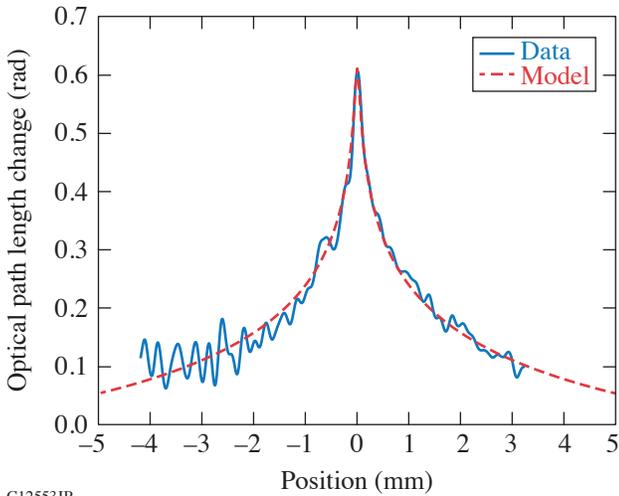


Figure 1  
Comparison of measured optical path length change in LBO with an analytical model for 15.5 mW. This model was used along with interferometric measurements of temperature to estimate power absorbed at a localized spot with a sensitivity of one part in  $10^5$ .

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