Photothermal absorption measurements in optical materials

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Materials studied to date:

- Lithium tantalate
- Lithium niobate
- RTP
- PPLN
- PPLT
- Spinel
- KTP
- LBO
- Fused silica
- BBO
- Sapphire
- YAG
- Paratellurite
Absorption (and photorefractivity) in some optical materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha_{1064\text{nm}}$ (cm$^{-1}$)</th>
<th>$\alpha_{514\text{nm}}$ (cm$^{-1}$)</th>
<th>Green induced IR absorption</th>
<th>Track formation</th>
<th>Photo- refractivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN</td>
<td>$8\times10^{-4}$</td>
<td>$8\times10^{-3}$</td>
<td>strong</td>
<td>-</td>
<td>Strong</td>
</tr>
<tr>
<td>SLN</td>
<td>$7\times10^{-4}$</td>
<td>0.03</td>
<td>strong</td>
<td>-</td>
<td>Strong</td>
</tr>
<tr>
<td>LN:Mg</td>
<td>$6\times10^{-4}$</td>
<td>0.03</td>
<td>very weak</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>LT</td>
<td>$7\times10^{-4}$</td>
<td>$5\times10^{-3}$</td>
<td>very weak to moderate</td>
<td>-</td>
<td>weak to strong</td>
</tr>
<tr>
<td>SLT</td>
<td>$3-6\times10^{-4}$</td>
<td>0.1-0.006</td>
<td>very weak</td>
<td>-</td>
<td>Weak</td>
</tr>
<tr>
<td>LT:Mg</td>
<td>$4\times10^{-4}$</td>
<td>-</td>
<td>no</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>PPLN</td>
<td>$5-20\times10^{-4}$</td>
<td>$\sim 0.01$</td>
<td>strong</td>
<td>weak, at $&gt;200^\circ\text{C}$</td>
<td>Weak</td>
</tr>
<tr>
<td>PPLT</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 0.01$</td>
<td>weak</td>
<td>-</td>
<td>Weak</td>
</tr>
<tr>
<td>KTP</td>
<td>$2-50\times10^{-6}$</td>
<td>$5-50\times10^{-5}$</td>
<td>weak to moderate</td>
<td>weak to strong</td>
<td>no to weak</td>
</tr>
<tr>
<td>PPKTP</td>
<td>$4\times10^{-5}$</td>
<td>$3\times10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>RTP</td>
<td>$2\times10^{-5}$</td>
<td>$2\times10^{-4}$</td>
<td>moderate</td>
<td>moderate</td>
<td>Weak</td>
</tr>
<tr>
<td>BBO</td>
<td>$&lt;1-2\times10^{-6}$</td>
<td>$&lt;2-10\times10^{-6}$</td>
<td>no</td>
<td>strong with UV pump</td>
<td>No</td>
</tr>
<tr>
<td>LBO</td>
<td>$&lt;1-10\times10^{-6}$</td>
<td>$&lt;2-8\times10^{-6}$</td>
<td>no</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>$10^{-3}-10^{-4}$</td>
<td>$&gt;0.01$</td>
<td>very weak to strong</td>
<td>weak to strong</td>
<td>no</td>
</tr>
<tr>
<td>YAG</td>
<td>$\sim 10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>Sapphire</td>
<td>$4-10\times10^{-5}$</td>
<td>$6-13\times10^{-4}$</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Spinel</td>
<td>$\sim 10^{-4}$</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>Fused silica</td>
<td>$1-20\times10^{-6}$</td>
<td>-</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
Motivation

• Absorption effects in UV-VIS and IR:
  ✷ $10^{-6}$ cm$^{-1}$ may be of importance for high-average-power applications;
  ✷ bulk and surface effects are to be detected separately;
  ✷ photochromic effects (such as ‘Green Induced IR Absorption’) are essential for nonlinear materials.

• Spectrophotometry and calorimetry are not precise, limited in capabilities.

• Photothermal technique proved to be a unique match!

• The power of the developed photothermal tool can help to understand mechanisms of optical loss in different materials.
Outline

- About Photothermal Common-path linterferometer (PCI)
- Spatial resolution of PCI
- Annealed sapphire: 3D map
- Coatings and surfaces
- Gray-tracking in KTP
- LBO: surfaces dominate!
Photothermal Common-path Interferometer (PCI)

- PCI is an improvement of the thermal lensing (TL) technique for the detection of a low absorption losses
- PCI was introduced in 1997-1998 in Stanford University
- PCI is designed to detect a weak phase distortion of a probe introduced by absorption of a focused pump
- PCI is the most sensitive photothermal device which utilizes an interferometric sensitivity for a phase distortion detection but uses a single probe beam
- PCI concept is applicable for solid, liquid and gaseous samples as well as for characterization of bulk samples, coatings, and multilayered devices
PCI basics

- **CW, chopped pump provides periodic heating**
- **CW probe beam experiences periodic phase distortion**
- Beams are crossed to allow some spatial resolution, i.e. crossed inside the sample to measure the **bulk** absorption
- Periodic distortion of the probe is detected after an aperture
- Lock-in is used to measure the detected AC-signal with a shot-noise-limited sensitivity
PCI: space resolution

\[ L_{\text{eff}} = \frac{\pi w_0}{\sqrt{2 \sin \beta}} \]
Space resolution: example (surface-to-surface scan)

Example: PCI signal for a 3 mm-thick neutral filter, 15%-absorbing
Leff = 0.25 mm
Sapphire: 20 mm-long, $\text{O}_2$-annealed sample

Absorption at 514 nm, scan from surface to surface
**Sapphire: the result of annealing in oxygen**

**O₂-annealed sample**

Wrap: no fluorescence, scattering, enhanced absorption

Core: red fluorescence, no scattering, normal absorption

Transition layer: low absorption
LBO: surfaces dominate!

Surface absorption in 3 x 3 x 5 mm, 8°-X-cut, coated LBO crystal

- The bulk absorption in LBO is very small
- The surface absorption effect is greatly enhanced because of strong thermal expansion
- Nearly the same happens for the green absorption, at 532nm.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Wavelength, polarization</th>
<th>Surface absorption*</th>
<th>Bulk**</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3x3x5 mm, AR coated</td>
<td>532 nm, Y</td>
<td>15 ppm</td>
<td>&lt; 5 ppm/cm</td>
<td>Surface signal bleaches</td>
</tr>
<tr>
<td></td>
<td>1064 nm, Y</td>
<td>2.5 ppm</td>
<td>&lt; 1.5 ppm/cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>532 nm, Z</td>
<td>13 ppm</td>
<td>&lt; 5 ppm/cm</td>
<td>Surface signal bleaches</td>
</tr>
<tr>
<td></td>
<td>1064 nm, Z</td>
<td>2.5 ppm</td>
<td>&lt; 1.5 ppm/cm</td>
<td></td>
</tr>
</tbody>
</table>
CW gray-track in KTP

Green scan (514 nm)

IR scan (1064 nm)

120 microns between peaks with a green spot of 70 microns
CW gray-track in KTP: model

**Laser induced electrochromic damage:** electrolysis in the green beam region initiated by a photogalvanic current

\[
\begin{align*}
  j_e &= \sigma_e E + kI \\
  j_i &= \sigma_i E \\
  j_e + j_i &= 0 \\
  E &= -\frac{kI}{\sigma_e + \sigma_i} \\
  E &\approx -\frac{kI}{\sigma_i} \rightarrow 0 \\
  j_i &= -kI
\end{align*}
\]

- KTP is known as an ionic conductor
- Rapid, within minutes, drift of the absorption maximum on the +Z side of green beam further in the +Z direction when the green pump is shifted in this direction
- Less gray-tracking corresponded with apparently high-resistivity KTP
- Photorefraction was directly observed in RTP and high-resistivity KTP
Conclusions

- PCI showed exceptional combination of sensitivity and versatility.

- The situation is much more complex than was believed to be: many materials show not only wide scatter in absorption values but display different types of photochromic, nonlinear behavior dependent on power, time, sample history, etc.

- The high sensitivity of PCI device to any index distortion ($\sim 10^{-6}$) allowed us to monitor photorefraction along with absorption measurements.

- In certain cases, especially with low-absorbing materials such as borates or fused silica, it was found that absorption at the degraded or coated surface dominates over the bulk one.