Quasi-DC Probing of Electrical Conductivity in Warm Dense Matter

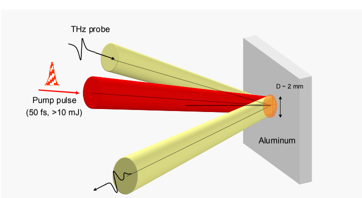
G. Rodriguez, K. Y. Kim, B. Yellampalle, A. J. Taylor, and J. H. Glownia
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

We report transient terahertz (1 THz = 10^{12} Hz) measurements of the electrical conductivity of intense ultrashort laser-heated solids, transforming from the cold solid to the dense plasma state.[1] Using optical-pump, THz-probe spectroscopy, we measured the phase shifts and absorption of THz probe pulses reflected from the warm dense plasma. In contrast to the previous measurements of conductivities at optical frequencies, our THz non-contact probe method can directly measures quasi-DC electrical conductivities, revealing potential discrepancies with the Drude model and thus providing further insight into the transport nature of warm dense matter. In the case of warm dense aluminum, we observe a noticeable deviation from the Drude model even in the ~10^{13} W/cm² laser intensity regime. In addition, we observed strong coherent THz emission produced by a current surge in the laser-produced plasma.

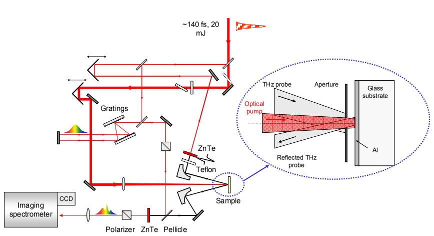
1. Optical-pump THz-probe spectroscopy

THz conductivity measurements of laser-heated aluminum



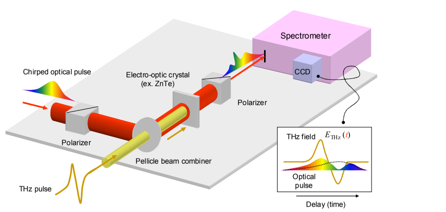
Complex electrical conductivity of laser-heated aluminum at THz (quasi-DC) frequencies can be directly determined from THz probe phase shift & absorption measurements.

2. Experimental Layout

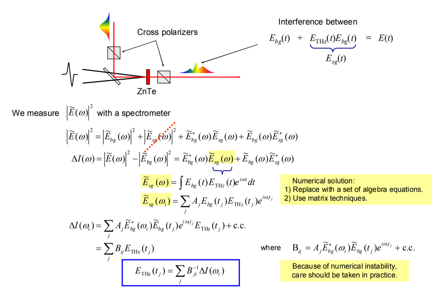


3. Single-shot THz diagnostic

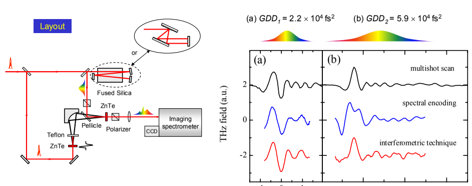
Chirped pulse spectral encoding [2]:



Interferometric technique [3,4]:

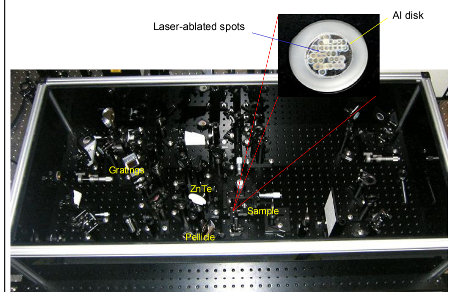


Experimental result:

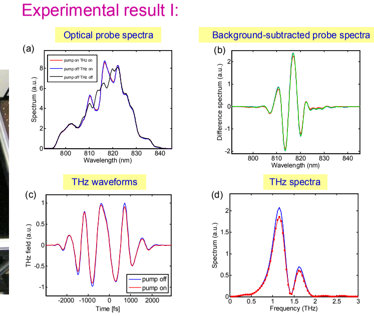


- **Pros:** 1D spatio-temporal THz imaging possible.
- **Cons:** THz field retrieval process required (relatively easy).
- **Potential temporal resolution:** limited by the spectral bandwidth.

4. Experimental results

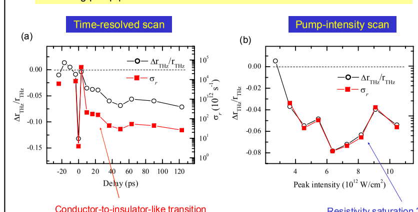


Experimental result I:



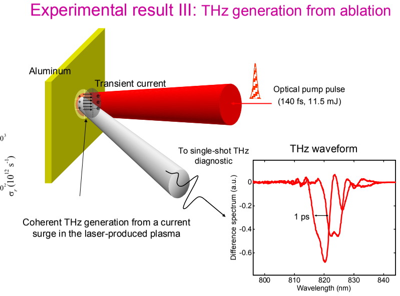
Experimental result II:

THz reflectivity change & the corresponding real part of electrical conductivity (σ_r) at 1.2 THz were measured as a function of (a) pump-probe delays and (b) increasing pump peak intensities.



Warm (~3 eV) dense (~3.7 g/cm³) matter produced with Laser pulsewidth ≈ 140 fs & Peak intensity ≈ 10^{13} W/cm²

Experimental result III: THz generation from ablation



Coherent THz generation from a current surge in the laser-produced plasma

5. Data analysis

From THz field (real & imaginary parts) temporal waveforms, we extract conductivity from reflection measurements using Fresnel relations and the reflected THz amplitude.

1.) Experimentally measure single-shot THz temporal waveforms: $E_{ref}(t), E_{in}(t)$

2.) Compute Fourier Transform reflection amplitude for (s- and p-polarizations): $\tilde{r}_{s,p}(\omega) = \tilde{E}_{ref}(\omega)/\tilde{E}_{in}(\omega)$

3.) Solve for dielectric function $\varepsilon(\omega)$ for a given angle of incidence, θ:

$$\tilde{r}_s = \left[\cos\theta - \sqrt{\varepsilon(\omega) - \sin^2\theta}\right] / \left[\cos\theta + \sqrt{\varepsilon(\omega) - \sin^2\theta}\right]$$

$$\tilde{r}_p = \left[-\varepsilon(\omega)\cos\theta + \sqrt{\varepsilon(\omega) - \sin^2\theta}\right] / \left[\varepsilon(\omega)\cos\theta + \sqrt{\varepsilon(\omega) - \sin^2\theta}\right]$$

4.) Compute conductivity from:

$$\mathrm{Re}(\sigma) = \omega\,\mathrm{Im}(\varepsilon)/4\pi$$
$$\mathrm{Im}(\sigma) = \omega\,[1 - \mathrm{Re}(\varepsilon)]/4\pi$$

6. Conclusions

We have measured the electrical conductivity of femtosecond intense laser-heated aluminum at THz frequencies using optical-pump, THz-probe reflection spectroscopy. For a warm (~2.6 eV) and near solid density (~2.7 g/cm³) aluminum, we measured the real part of electrical conductivity (~10^{14} s^{-1}) at 1.2 THz, which is at least order of magnitude lower compared to the AC conductivity measurements under similar conditions.[5] However, it is in a good agreement with other direct DC conductivity measurements using exploding wires.[6]

References

1. K. Y. Kim, B. Yellampalle, J. H. Glownia, A. J. Taylor, G. Rodriguez, "Terahertz-frequency electrical conductivity measurements of ultrashort laser-ablated plasmas," High Power Laser Ablation VI, ed. C.R. Phipps, Proc. of SPIE Vol. 6261, 62612Q (2006).

2. Z. Jiang and X. -C. Zhang, "Electro-optic measurement of THz field pulses with a chirped optical beam," Appl. Phys. Lett. **72**, 1945 (1998).

3. K. Y. Kim, B. Yellampalle, G. Rodriguez, R. D. Averitt, A. J. Taylor, and J. H. Glownia, "Single-shot, interferometric, high-temporal-resolution, terahertz diagnostic," Appl. Phys. Lett. **88**, 041123 (2006).

4. B. Yellampalle, K. Y. Kim, G. Rodriguez, J. H. Glownia, and A. J. Taylor, "Algorithm for high-resolution single-shot THz measurement using in-line spectral interferometry with chirped pulses," Appl. Phys. Lett. **87**, 211109 (2005).

5. H. M. Milchberg, R. R. Freeman, S. C. Davey, and R. M. More, "Resistivity of a simple metal from room temperature to 10^6 K," Phys. Rev. Lett. **61**, 2364 (1988).

6. M. P. Desjarlais, J. D. Kress, and L. A. Collins, "Electrical conductivity for warm, dense aluminum plasmas and liquids," Phys. Rev. E **66**, 025401(R) (2002).