Title: Terahertz Time-Domain Spectroscopy in Pulsed Magnetic Fields up to 30 Tesla

Terahertz time-domain spectroscopy (THz-TDS) allows one to study low-energy dynamics in condensed matter systems such as traditional semiconductors, carbon nanotubes, heavy-fermion metals, Kondo insulators, high-temperature superconductors, and graphene by determining the complex conductivity. With applied magnetic field, various elementary and collective THz excitations occur associated with spin and orbital quantization.

This collaboration between IMR and Rice University has focused on ultrafast spectroscopy in pulsed high magnetic fields. We have developed a pulsed magnet system to measure the ultrafast and nonlinear response of materials in high magnetic fields up to 30 T and at low temperatures [1].

Recently at Rice University, we have developed a single-shot THz-TDS measurement system to measure the low-energy dynamics of materials with the pulsed magnet [2]. Our first measurements with this system were performed using intrinsic bulk silicon where we measured cyclotron resonance absorption to determine the effective mass of photoexcited carriers.

Currently, we have begun to study orthoferrite materials including $YFeO_3$ to determine how the ferromagnetic modes respond to applied high magnetic fields using the single-shot THz system. These materials hold promise for the manipulation of spins and understanding the fundamental interactions is crucial for development into viable technologies.

Figure 1 shows the THz time-domain waveform transmitted through $YFeO_3$ at 30 T and 0 T. By subtracting the two traces, one can isolate the frequency component that emerges at high magnetic field. The trace at 30 T is the average result after taking 25 measurements with a 7 minute wait time between magnet shot taking a total of ~3 hours. In order to also measure the magnetic field dependence in a reasonable amount of time, we must increase the efficiency of the data taking process. We have recently incorporated a high frame rate camera to take data during the entire ~10 ms duration of the magnet pulse instead of taking only one data point at the peak of the field.

Furthermore, we aim to increase the rate at which magnetic field pulses can be made. After each magnet shot, the coil must cool back to liquid nitrogen temperature after Joule heating. We have discussed changing the magnet pulse profile from an exponentially damped sine wave to simply a half sine wave where less total heat is created in the coil so that the cooling time decreases but still maintaining the same peak magnetic field strength. In the same amount of time, we could make more shots further increasing the the signal-to-noise ratios (SNRs) achievable with our system.

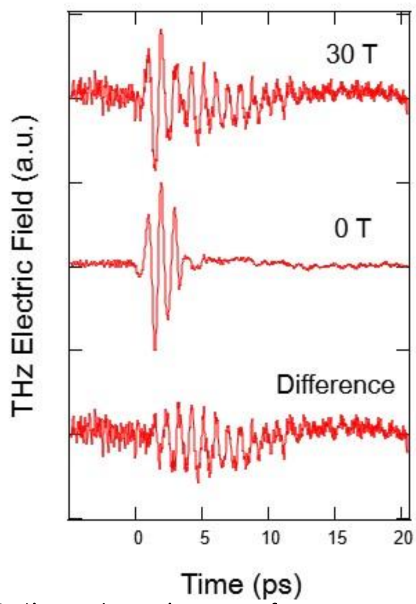

Fig.1 THz time-domain waveforms transmitted through orthoferrite $YFeO_3$ at 30 T and 0 T. The difference of the two traces reveals a new frequency component, ~1 THz, emerges at 30 T.

Furthermore, there is a future option to upgrade the control unit of our magnet system to automatically trigger the discharge of the capacitor bank for simple and easy operation so that we can automatically average over a large number of magnet shots.

At the IMR facility during our recent visit, Prof. Nojiri's group developed a smaller coil than our current 30 T coils located at Rice University. This new coil can achieve a magnetic field of 35 T, increasing the maximum field by over 16%. With a smaller coil, we lose the ability to insert a coldfinger extension into the bore of the magnet to cool the sample however $YFeO_3$ does not have to be cooled to cryogenic temperatures in order to see the ferromagnetic resonance in the THz range. Therefore, this smaller coil is well suited for THz-TDS measurements of orthoferrite materials up to 35 T.

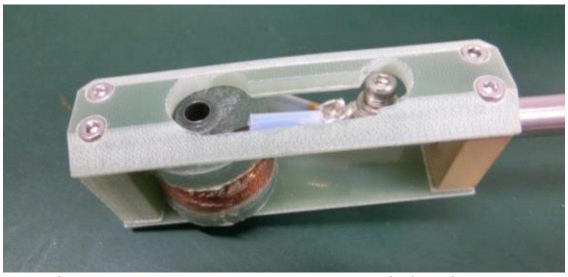

Fig.2 A new 35 T minicoil magnet developed at the IMR facility for THz-TDS measurements at Rice University.

In addition to orthoferrite materials, we are currently planning measurements of the THz response of graphene, aligned carbon nanotubes, high-temperature superconductors, and semiconductor quantum well samples.

References

[1] G. T. Noe et al., Rev. Sci. Instrum. **84**, 123906 (2013).
[2] G. T. Noe et al., Optics Express **24**, 30328 (2016).

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