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## Characterization of Propagation Effects on Terahertz Beam Through Diamond-Anvil Cell for High Pressure Experiments on Quantum Materials

Quantum materials exhibit strong interactions of electrons in d and f electron shells [1], which result in unique macroscopic properties, such as colossal magnetoresistance [2], superconductivity at high temperature (~120 K) [3], and they have great potential for ultrafast electronics [4]. Quantum materials are known to exhibit unique phase transitions under external stimuli, such as pressure. To study these transitions under pressure, we use a diamond-anvil cell (DAC). To monitor changes in the material under pressure, terahertz (THz) spectroscopy is a valuable technique, as it provides information on collective excitations (phonons and magnons) and physical parameters of free carriers. The THz spectroscopy of materials in the DAC could be used to study the evolution of these parameters across quantum phase transitions. However, the combination of two techniques yields challenges due to the diffraction-limited spot of the THz beam ( $\approx 400 \mu\text{m}$ ) being comparable to or even larger in size than the aperture of the DAC (i.e., the gasket opening with the diameter in range 200-400  $\mu\text{m}$ ). This creates two problems: first, only a fraction of the beam interacts with the sample in the DAC, which makes conventional spectroscopy data analysis no longer valid; second, the diffraction effects are enhanced by the subwavelength size of the gasket, which needs to be accounted for in quantitative data analysis.

We address these problems using a combination of simulations and experiments. We first study the THz beam propagation through the metallic gasket only (omitting diamonds, the pressure medium, and the sample in this stage). We achieved this by calculating the THz electromagnetic fields transmitted through the gasket close to the focal plane employing two methods. The first method, the finite-difference time-domain (FDTD) calculation, was used to define the broadband THz pulse with an infinite planar wavefront and propagate it through the metallic aperture. The second method, applying steady-state Helmholtz's equations, allowed us to account for the size of the diffraction-limited spot varying with the frequency of the THz beam (full-width-at-half-maximum changes from 500 to 100  $\mu\text{m}$  in the frequency range 1-5 THz, respectively). The preliminary results suggest that the divergence angle of the beam, transmitted through the metallic aperture, increased from  $\theta$  (free-space propagation) to  $\theta'$  (with the gasket placed in the focal plane), as shown in Fig. 1 (a) and (b), and this change of divergence angle is frequency-dependent. This knowledge will be used to develop further methodology to accurately estimate the frequency-dependent transmission of the gasket.

In this work, we employ the electro-optic sampling (EOS) technique to detect broadband THz pulses in the time domain. In EOS, the THz field induces a transient birefringence in an electro-optic crystal, which is read out by a time-delayed infrared (IR) gate pulse. In standard EOS, it is assumed that the beam center is representative of the full transverse THz profile; accordingly, the probe samples only the THz field near the beam center, as shown in Fig. 1 (c). To resolve spatial beam profile distortions caused by the gasket aperture and the diamond edges, the THz beam propagation through the DAC will be experimentally characterized using two different methods to measure the THz beam profile at the detection plane. Firstly, we will perform a line scan of the small-diameter optical probe beam across the THz beam in the detection plane by changing the position of the IR gate beam on the EOS crystal, as illustrated in Fig. 1 (d). Secondly, we plan to expand the optical probe beam to fully overlap with the THz beam and use a CMOS (Complementary Metal-Oxide-Semiconductor) camera to simultaneously record the intensity information in the detection plane [5], as shown in Fig. 1 (e). Based on the spatially resolved THz beam profile after transmission through the metallic gasket, we will quantify the actual beam divergence angle and map how the field evolves away from the focal plane. Incorporating these propagation effects together with the spectral response of the pressure medium, diamonds, and gasket [6] will establish a reliable background correction, allowing an accurate extraction of the artifact-free THz spectrum of the sample under pressure.

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