Searching for Two Higgs Modes in Superconducting MgB_2 Using Terahertz Pump – Terahertz Probe Spectroscopy

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MgB_2, a metallic superconductor, is known to exhibit a two-superconducting-gap structure associated with two bands, termed π and σ bands, at the Fermi level. This two-band structure serves as the perfect platform to study some interesting physical phenomena. Here, we utilize this two-band structure to detect and study the two distinct Higgs modes in MgB_2 and their interactions. Using terahertz pump – terahertz probe spectroscopy, we examined the ultrafast reactions of the order parameter of our 60-nm-thick MgB_2-film sample to nonadiabatic excitation in the π-band caused by a monocycle THz pulse. In our initial test for the Higgs mode, we generated and detected forced oscillations of the order parameter in the π-band and high-frequency forced oscillations in the larger σ-band. Whereas the π-band Higgs mode is considered to be excited through the nonadiabatic excitation by the incident THz pulse, the σ-band Higgs mode excitation suggests coupling between the two Higgs modes since the incident pulse was not in the nonadiabatic excitation regime of the σ-band. With this, we believe that there is a distinct connection between the two Higgs modes, and through further tests of MgB_2, we hope to detect the relaxed oscillations and interactions of the two Higgs modes. This ongoing study can lead to a fundamental understanding of how multiple Higgs modes interact and, at the same time, provided us with a powerful tool to study more complex multiband superconductors such as iron-based superconductors.

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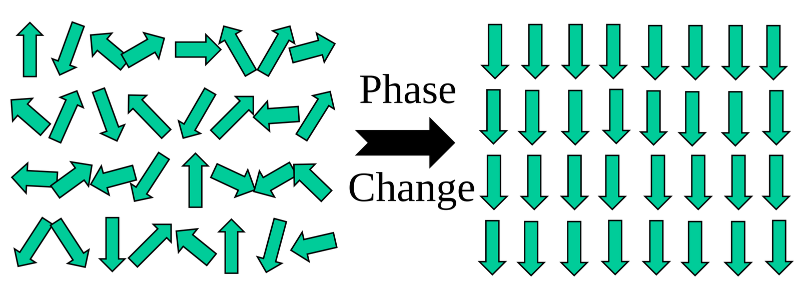
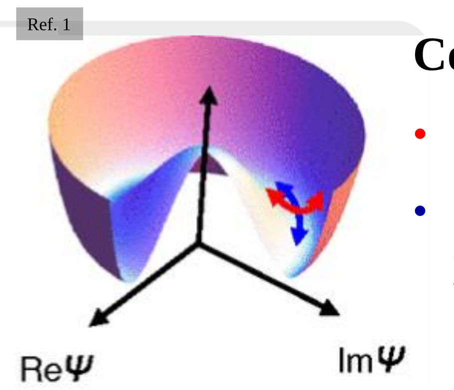
Introduction

The Higgs Field pervades the universe, giving mass to particles. Excitations in this field are known as Higgs bosons. Higgs bosons are known as Higgs amplitude modes in condensed matter physics. Here, we study these amplitude modes.





Nambu-Goldstone Potential

Collective Modes:

- Higgs amplitude mode
- Nambu-Goldstone phase mode

Spontaneous symmetry breaking ➔ collective modes emerge.

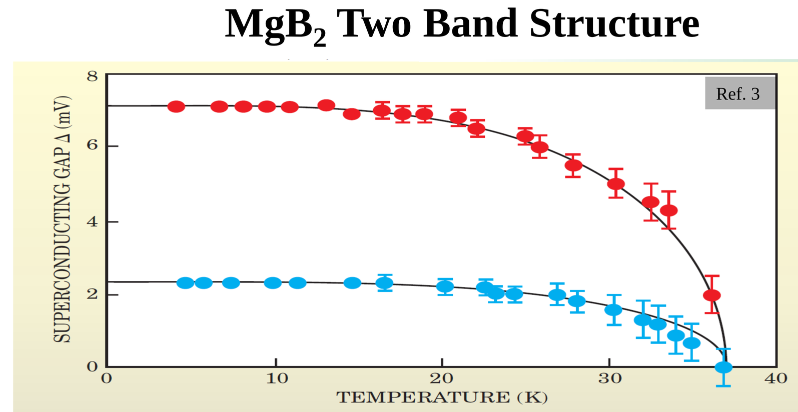
NbN Single Band Tptp:

NbN has only a single band gap
➔ **1 Higgs Mode**

MgB_2 Two Band Structure

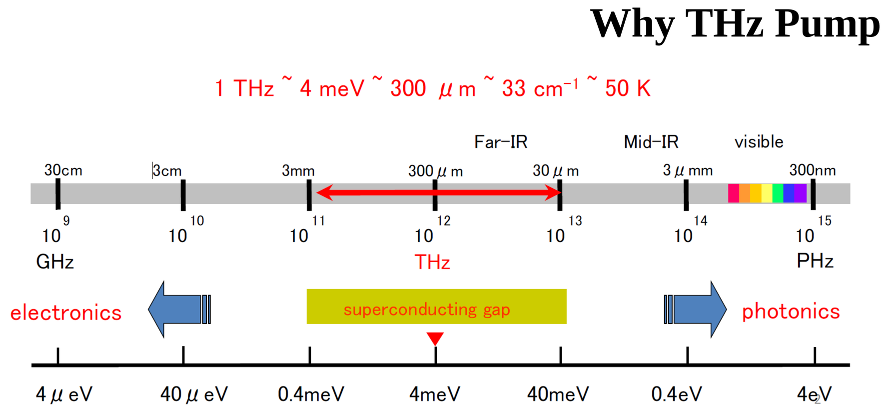
σ-band gap: $2\Delta \sim 3.4$THz

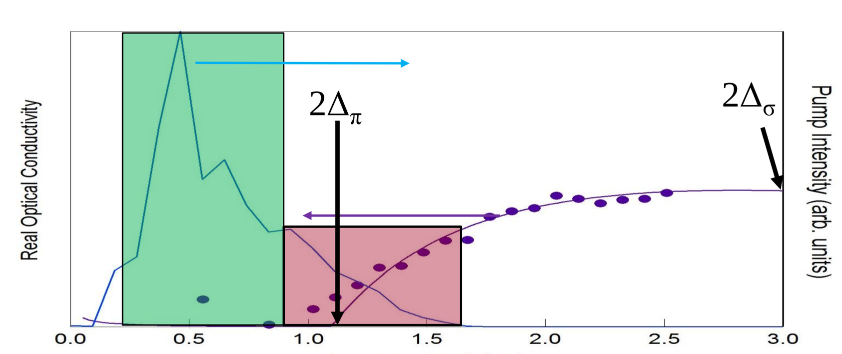
π-band gap: $2\Delta \sim 1.1$THz



2 band gaps ➔ 2 Higgs modes

Why THz Pump and THz Probe?





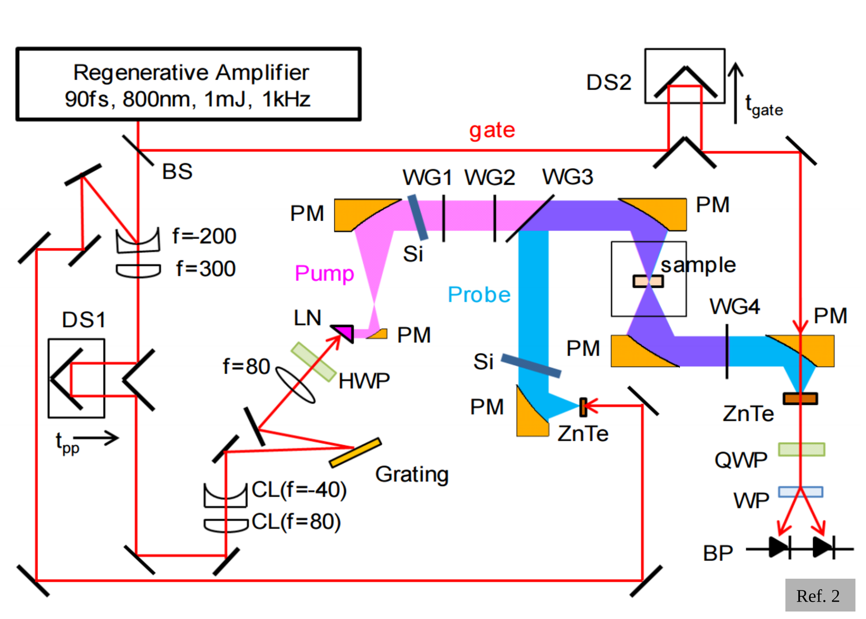
Probe pulse:
Superconducting gap exists in the THz range ➔ probe pulse must be in the THz range to probe the gap.

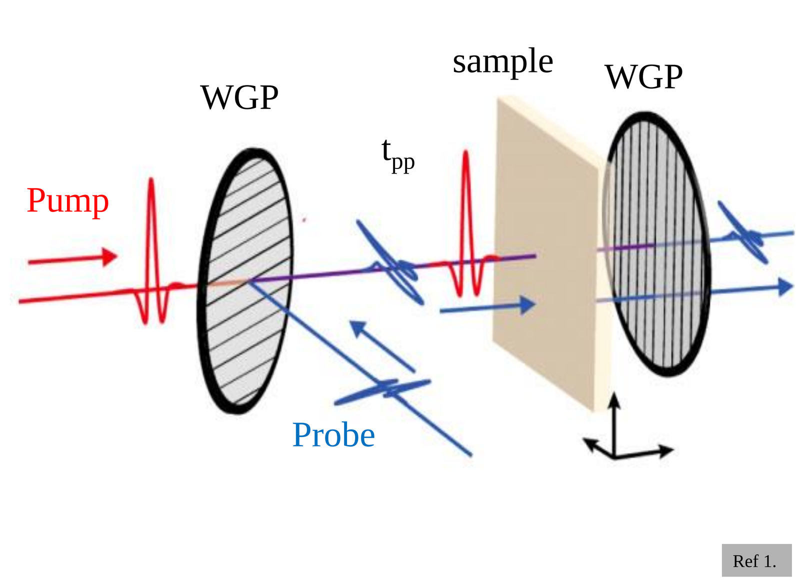
Pump pulse:
Low frequency component($\omega<2\Delta_\pi$) ➔ forced oscillation of the order parameter.
High frequency component($\omega>2\Delta_\pi$) injects quasiparticles into the system non-adiabatically ➔ relaxed oscillation.

Purpose of this work:

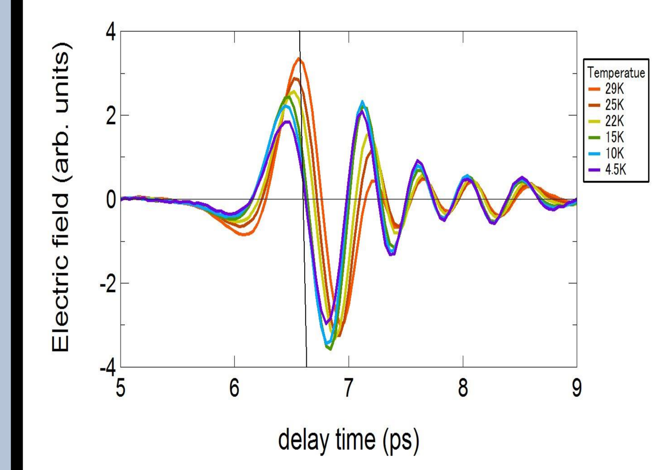
- To study and understand the fundamental interaction between two Higgs Modes in MgB_2, which mimics two symmetry broken universes interacting with each other
- To develop a method to study more complex, multi-gap superconductors like iron pnictides
- To develop a method to optically control superconducting states

THz Pump-Probe Experimental Setup



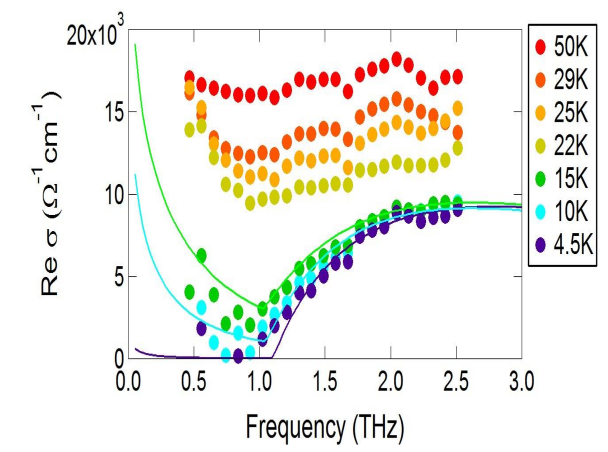


Characterization of 60nm MgB_2 Sample



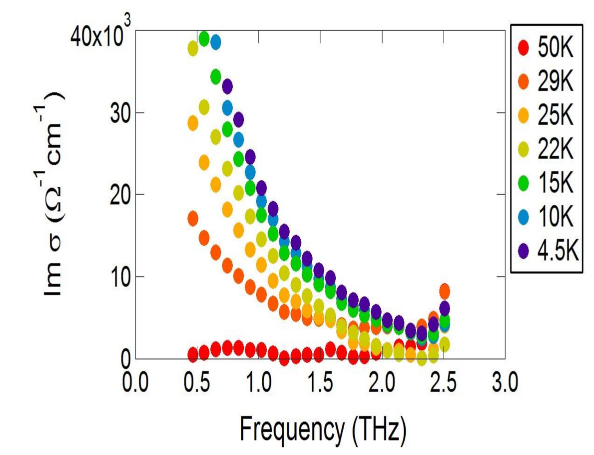
Probe pulse waveform

Characterizes the gate time delay (t_g) at which the sample is most temperature dependent.



Real Optical Conductivity
(with Mattis-Bardeen fits)

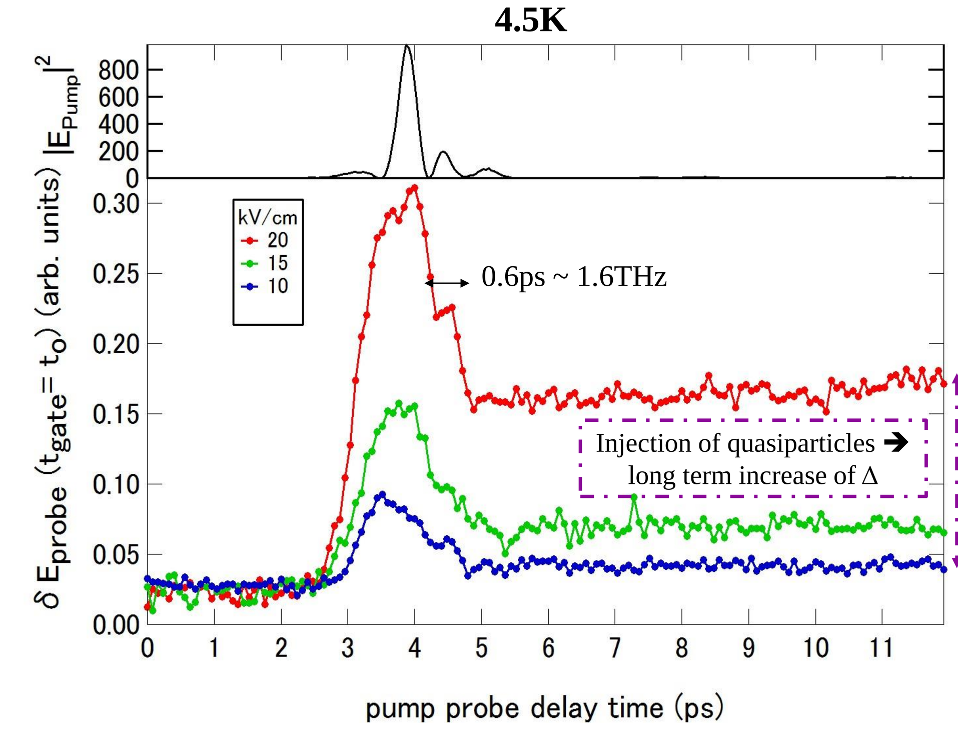
Characterizes the superconducting π-band gap size as 1.1 THz at 4.5K

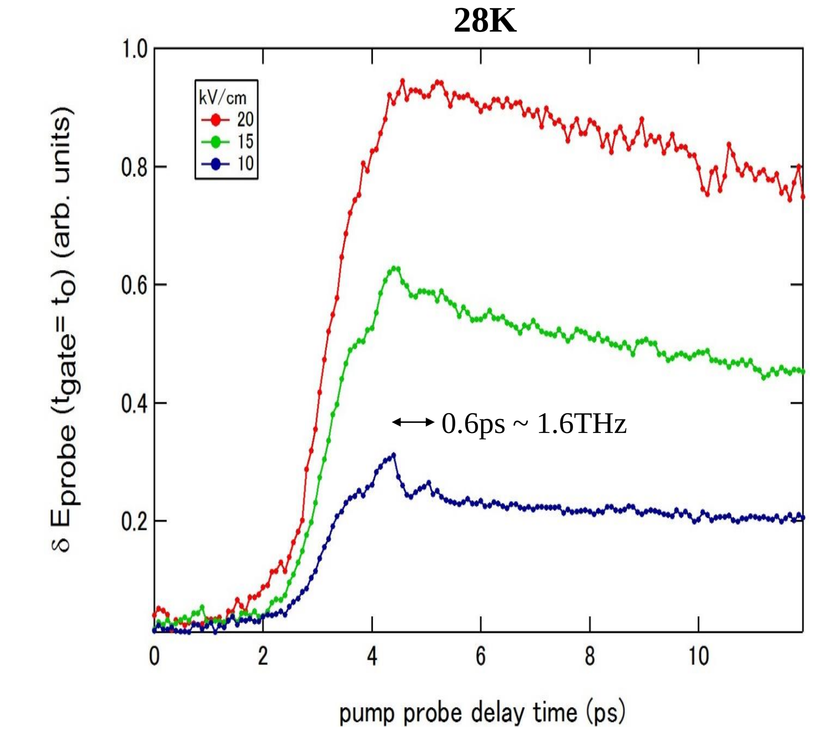


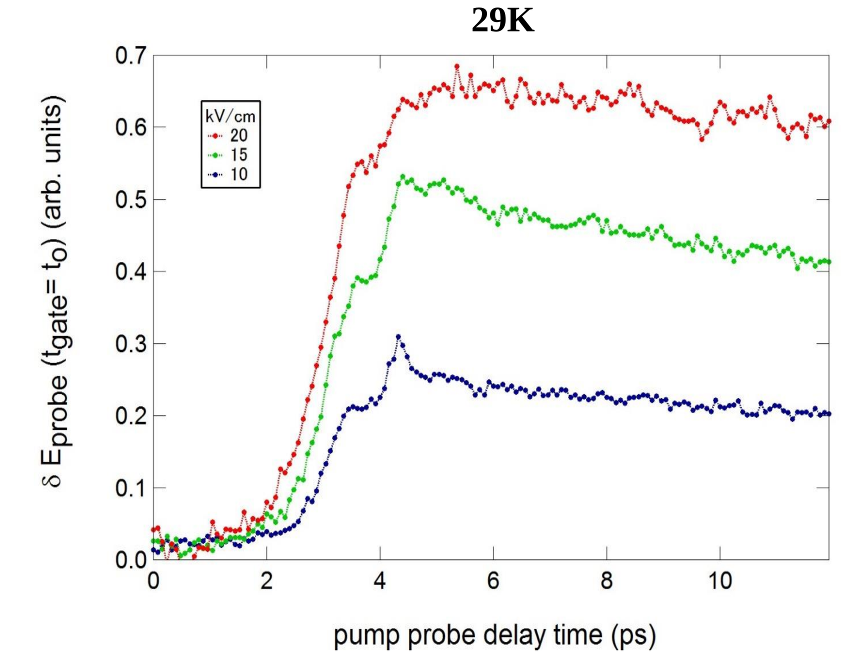
Imaginary Optical Conductivity

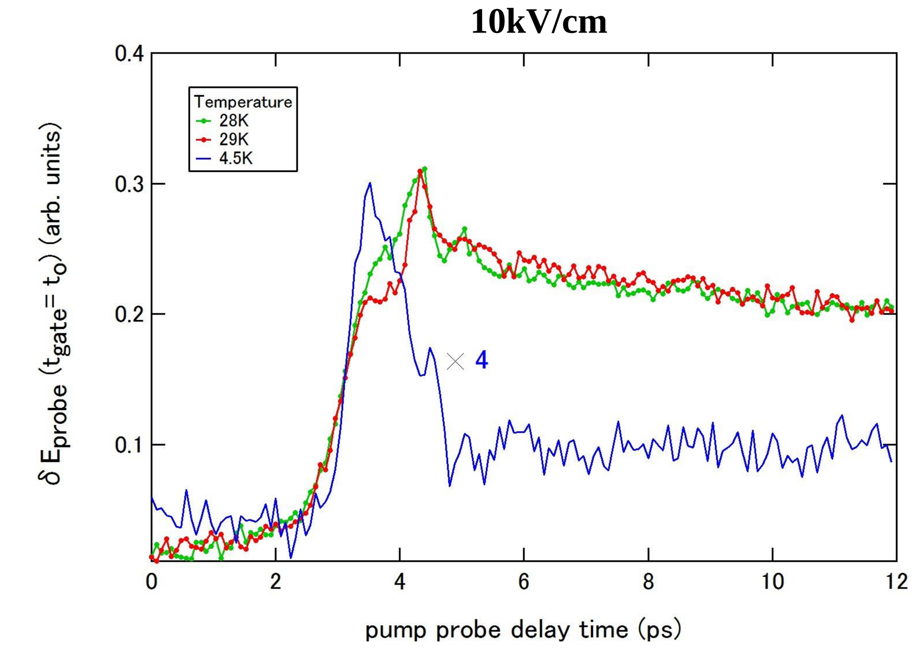
Characterizes the growth of superfluid density with lowering the temperature below Tc~29K.

Experimental Results and Analysis







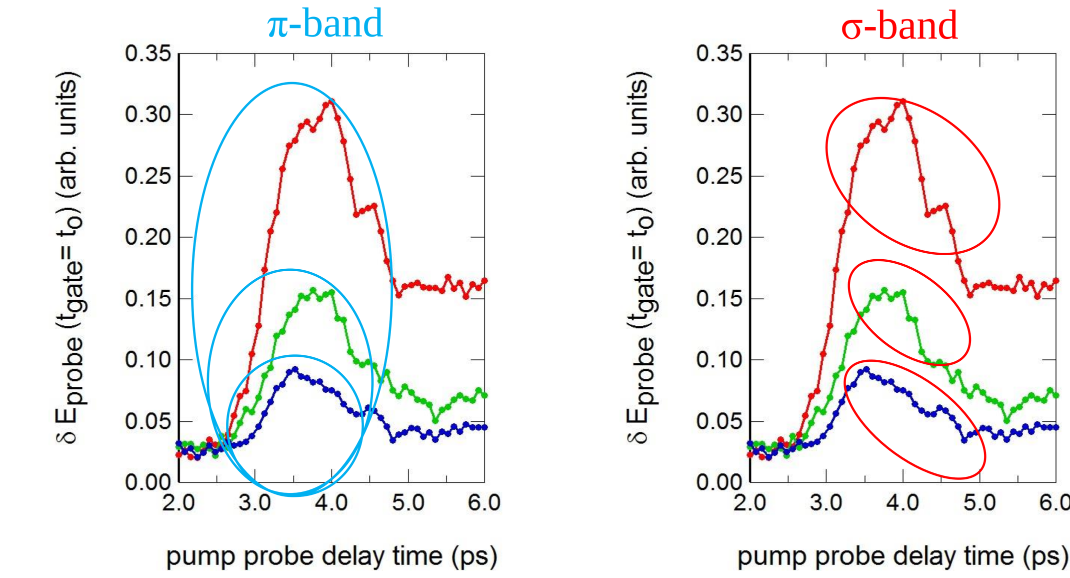


Analysis of TPTP experiments

- At 4.5K, there is a large overshoot beginning around 2.5ps ➔ forced oscillation of the π-band Higgs mode
  - Shrinking of the π-band superconducting gap due to increasing temperatures **($\omega > 2\Delta$)**. ➔ No large overshoot at 28K or 29K
- Higher frequency oscillations (1.6THz) of the order parameter present in the latter half of pump irradiation
  - $2\Delta_\pi < 1.6\text{THz} < 2\Delta_\sigma$
  - Chirped pump pulse has high-frequency component with $2\omega \sim 1.6$THz in the latter half of pump pulse
  ➔ Forced oscillations of the σ-band Higgs mode with frequency $2\omega < 2\Delta$

Conclusions

- Detected forced oscillations of two Higgs modes through THz Pump-THz Probe spectroscopy
  - π-band Higgs mode oscillation caused by center frequency of chirped THz pump pulse
  - σ-band Higgs mode oscillation caused by high-frequency component of chirped THz pump pulse



Next Steps

- Improve experimental setup to reduce noise and improve overlap of pump and probe pulse
- Conduct more comprehensive testing to detect relaxed oscillation of the Higgs modes and the interaction between the two Higgs modes
- Develop a model to describe the theoretical interaction between the two Higgs modes

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Acknowledgements

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