Mid-/far infrared anomalous Hall effect

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Mid-/far infrared spectrum

<table>
<thead>
<tr>
<th>Microwave</th>
<th>THz</th>
<th>Infrared</th>
<th>Visible</th>
</tr>
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<tbody>
<tr>
<td>10mm</td>
<td>300µm</td>
<td>10µm</td>
<td>500nm</td>
</tr>
<tr>
<td>Microwave</td>
<td>mm-Wave 100 GHz</td>
<td></td>
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<tr>
<td>5 GHz</td>
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- **Terahertz**:
  - 1 THz
  - 3 THz

- **Mid infrared**: 100 THz

- **Near infrared**: 200 THz

- **CO₂ laser**
- **CO laser**
- **Semiconductor lasers**

- **QCL**
- **THz-TDS**
- **FIR laser**
Applied physics research

Microwave
- 10mm
- 5 GHz
- mm-Wave 100 GHz

THz
- 1 THz
- 300μm

Infrared
- Mid infrared 100 THz
- Far infrared 3 THz
- Near infrared 200 THz

Visible
- 500nm

Terahertz
- 1 THz

Far infrared
- CO₂ laser
- CO laser
- Semiconductor lasers

Mid infrared
- 100 THz

Graphene hot electron bolometer (Nat. Nano. 2012)

Terahertz-TDS


Metalens (Opt. Ex. 2016)

Semiconductor lasers

Surface polaritonic metasurfaces (current project)
Under-explored infrared Hall spectrum

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  - mm-Wave 100 GHz

- **Terahertz**
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- **THz-TDS**
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- **Ferromagnetic semiconductor** (PRL 2009)
- **Itinerant ferromagnetic oxide** (PRB 2010, 2013)
- **Graphene** (Sci. Rep. 2013)
- **High-Tc superconductivity** (PRB 2007)
- **Semiconductors and insulators** (JOSAB 2011)

- **Topological insulator** (PRB 2012)
- **Quantum well system** (unpublished 2013)

- **Under-explored infrared Hall spectrum** (current project)
# Magneto-polarimetry tool development

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## Fourier transform spectrometer + Photoelastic modulator (2013 – now)

Ordinary Hall effect

\[ j_x = -n e v_x \]

\[ \rho_H = R_0 B = \left( \frac{1}{nq} \right) B \]

Independent of scattering rate, \( \frac{1}{\tau} \)
Anomalous Hall effect (AHE)

Classical scattering

Electron (quasi-particle) → Non-magnetic ion

Transverse (Hall) component

Quantum scattering

Electron (quasi-particle) → Magnetic ion

Spin-orbit coupling

Additional transverse (Hall) component

We measure angle difference optically

\[ \rho_{H}^{AHE} (M, \rho_{xx}) = \rho_{H}^{AHE} \left( M, \frac{1}{\tau} \right) \]

Goal: deep understanding of abnormal quasi-particle scattering in time-reversal symmetry broken system using low optical excitation energy.
Angle measurement

\[ \theta_F(x, \omega, T) \]
\[ \theta_K(x, \omega, T) \]
Complex Faraday and Kerr angle

\[ \sigma_{xx}(x, \omega, T) \]
\[ \sigma_{xy}(x, \omega, T) \]
Complex longitudinal and Hall conductivities

M.-H. Kim et. al. PRB 2007
Limitation

No deep mid and far infrared polarimetry (Hall angle measurement)

Itinerant ferromagnet

Superconductivity

M.-H. Kim et. al. PRB 2013

D. C. Schmadel et. al. PRB(R) 2007
AHE mechanisms

Ref) N. Nagaosa et. al. Rev. Mod. Phys. 82, 1539 (2010)
AHE in transition metal films

At DC

At optical frequency

Ref) N. Nagaosa et. al. Rev. Mod. Phys. 82, 1539 (2010)
Summary

• **The infrared Hall angle measurement** is one of the most powerful ways to disclose Fermi surface information from simple ferromagnetic metal systems to highly correlated electron systems including normal state superconductivity.

• **The Hall results are comparable with** the results acquired from angular-resolved photoemission spectroscopy (ARPES) and de Hass-van Alphen oscillations at dc.

• The objective of this project is to address the fundamental question of how dc anomalous Hall effect evolves at underexplored finite frequencies to provide insight into new developing ideas about how to resolve quasiparticle scatterings in the time-reversal symmetry broken system.
Acknowledgement

DC Hall measurements
Dr. Martirosyan, Physics, UTRGV

Polarimetric Spectroscopy
THz-FIR-NIR
Dr. Kim, Physics, UTRGV

Transition metal film growth
Dr. Huq, EE, UTRGV
Univ. of Houston, Nanofab.

Magnet with optical access
Dr. Kono, ECE & Physics, Rice U.

Theory
Dr. Qian Niu, UT Austin