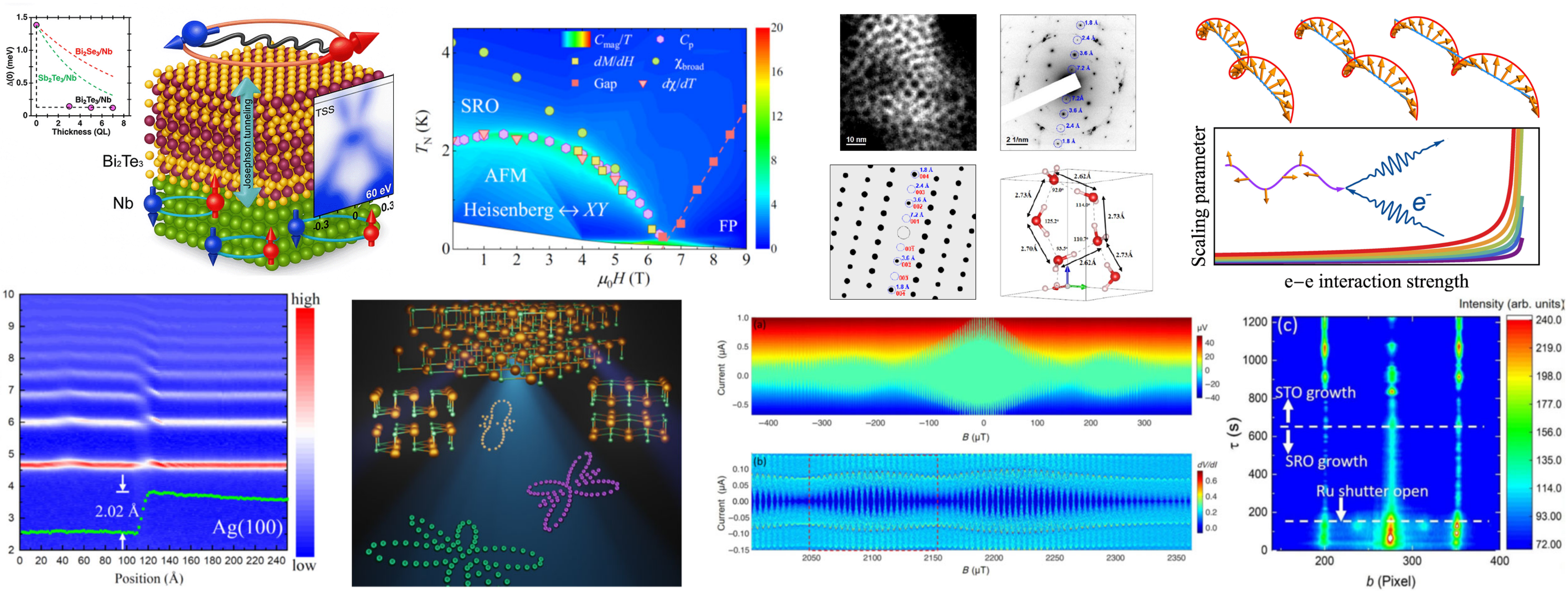
QMP Group Report



Outline

Grand challenge topic proposed by MK

Grand challenge topic proposed by Yu-Chieh

QMP responses to AAC Report

Grand Challenge Projects in M.K. Wu's Lab

1. Artificial Intelligence (AI)-based Design for Material Discovery and *in-situ* Spectroscopic Analysis

   Together with a Germany research team (the Chair of Electrode Design for Electrochemical Energy Storage at the University of Bayreuth, headed by Prof. Francesco Ciucci), we have recently submitted a joint proposal entitled "***Physics-grounded hybrid AI for PFAS-free battery polymers (PHASE)***" in response to the Funding Line A of the BMFTR-NSTC call for proposal. PHASE aims at developing physics-grounded hybrid AI methods for sustainable electrochemistry. The project treats AI methodology as the central research object and uses PFAS-free binders and bio-based polymer electrolytes as a demanding and societally relevant testbed. This is a three-year project.

2. Superconducting Wires for AI-Data Center Application

   In collaboration with the Pacific Electric Wire & Cable Co. LTD (太平洋電線電纜), we'll develop ***High Temperature Superconducting Wires and Tapes***. The goal is to establish the superconducting wire fabrication technology in Taiwan and use the developed wires and cables for data center power transmission application. This program can possibly lead to a long-term collaboration with the company to develop an efficient micro-grid system with superconducting technology.

用於超寬頻頻率轉換的量子材料
— 邁向新世代太赫茲通訊與量子轉換

PI: 溫昱傑;　Co-PI: 柯忠廷、李尚凡、莊天明、林新、Raman Sankar

中央研究院物理研究所

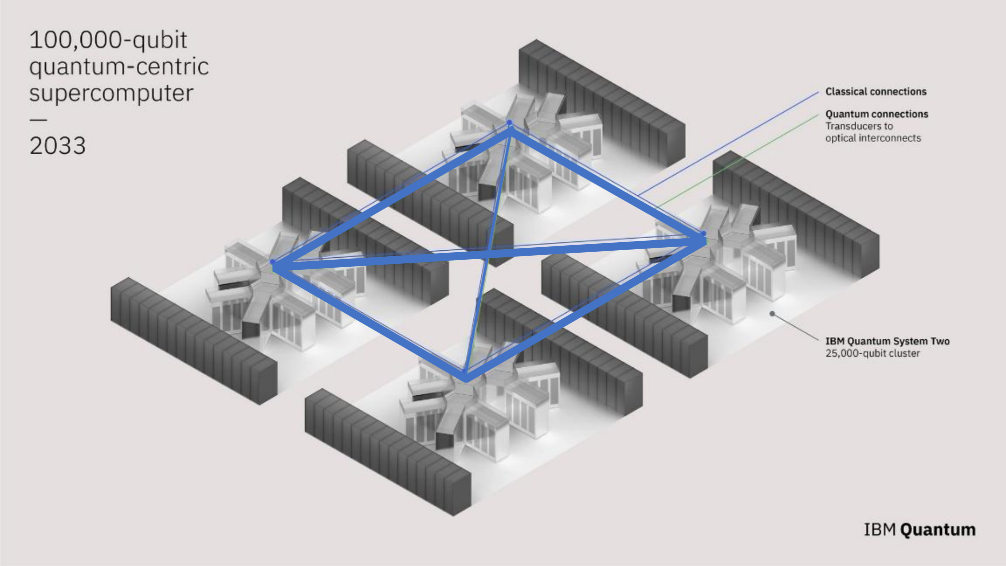
Growing demands for high-frequency signal conversion

Internet of Things, THz communication, millimeter-wave systems
call for

Efficient frequency mixer
between GHz and sub-THz domains

Scaling of quantum computation with interconnected processors
calling for

Efficient quantum transducer
from GHz to optical domains
for coherent, low-latency optical interconnects

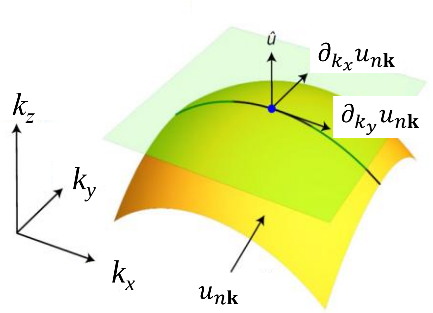


Transformative approaches via emerging quantum material physics

Quantum Geometry (QG):

Geometric interpretation of
the (gauge-invariant) **Structure of Bloch Wave Functions**

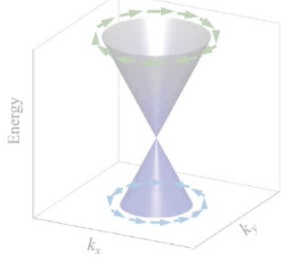
ex: Quantum metric,
Berry curvature,
Christoffel symbols, ….



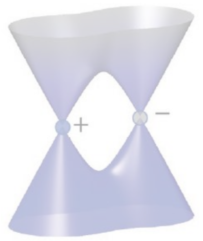
Topological materials

— with nontrivial nodes serving as “hot zones” of QG properties

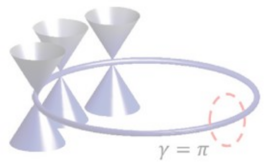
Topological insulator



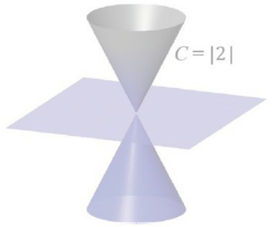
Weyl semimetal



Nodal fermion

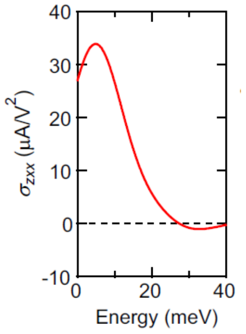


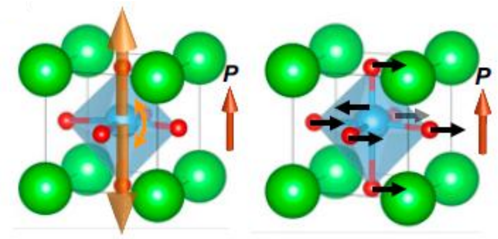
Multifold fermion



THz collective bosonic excitations:

ex: phonon-induced shift current [PNAS 2022]

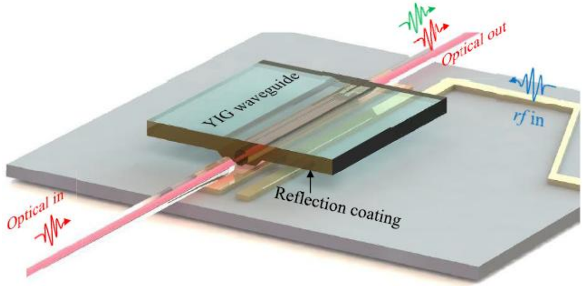




Relaxational mode ($E||c$)

Slater mode ($E||a$)

ex: magnon-assisted electromagnetic coupling [Optica 2020]



Transformative approaches via emerging quantum material physics

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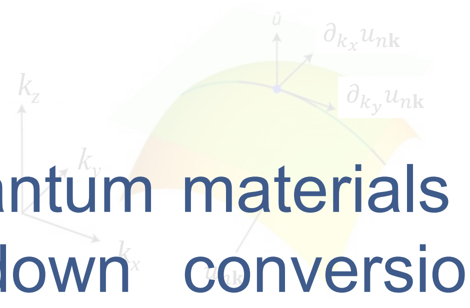

Topological materials

— with nontrivial nodes serving as "hot zones" of QG properties

Topological insulator | **Weyl semimetal** | **Nodal fermion** | **Multifold fermion**

Quantum materials for GHz-to-(sub)THz electronic up/down conversion or GHz-to-optical quantum transduction **remains unexplored or rare**.

THz collective bosonic excitations:

ex: phonon-induced shift current [PNAS 2022]

ex: magnon-assisted electromagnetic coupling [Optica 2020]

To leverage quantum geometry and magnetic excitations for development of

ultrabroadband frequency conversion, the “*quantum mixer* ”,

as high-efficiency mediators for bridging GHz-to-THz and GHz-to-optical domains

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林新

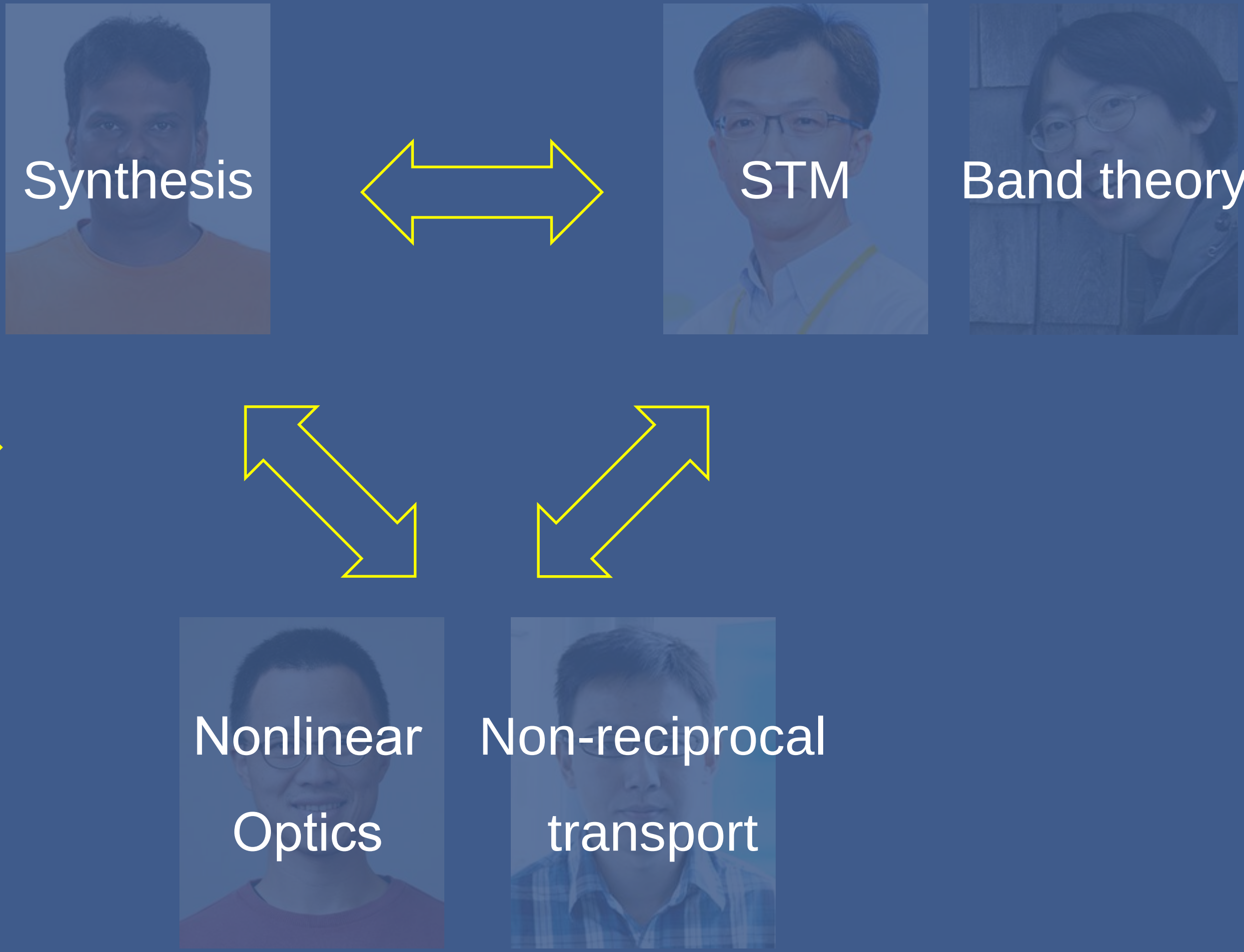
李尚凡

Raman Sankar

莊天明

Device Team

Material Exploration

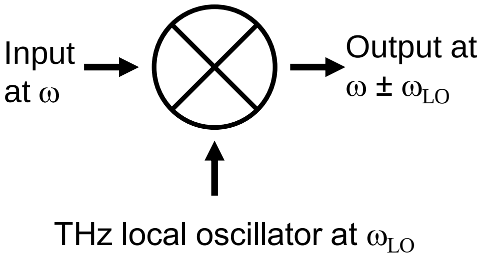


Sub-Project I: Developing QG-based quantum mixer

We aim to extend the 6G bands, e.g., 40–100 GHz, into **sub-THz domain**

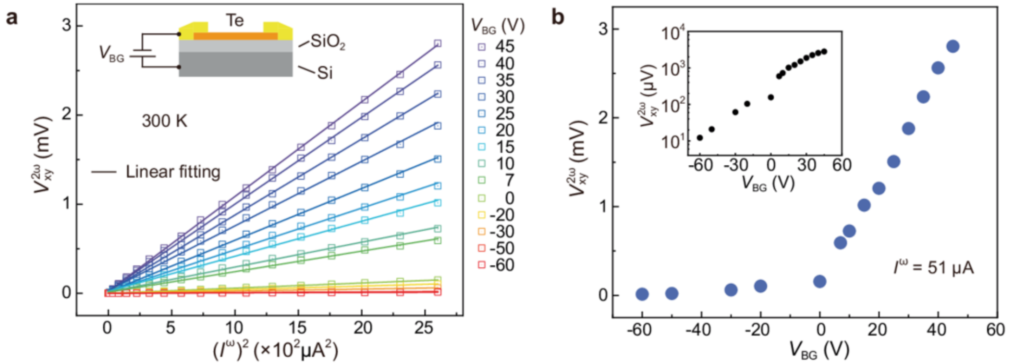
1. by exploiting **QG-induced nonlinearity** with dimensional tuning or strain/defect engineering.
2. by engineering the **Josephson junction mixer** or leveraging on the Diode effect.

Quantum Mixer



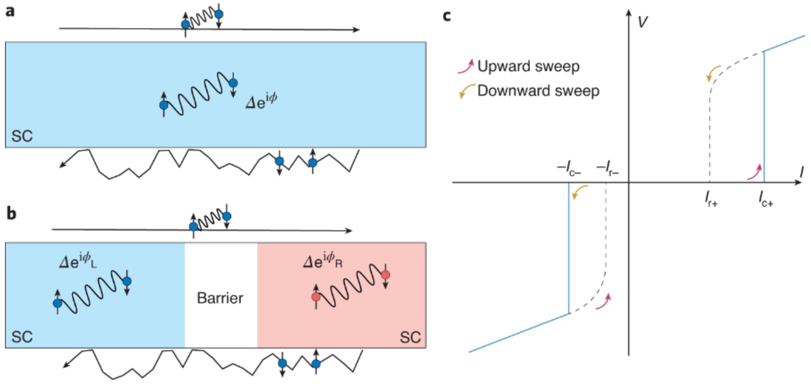
Nonlinear Hall effect

B. Cheng, et al, Nat. Commun. 2024



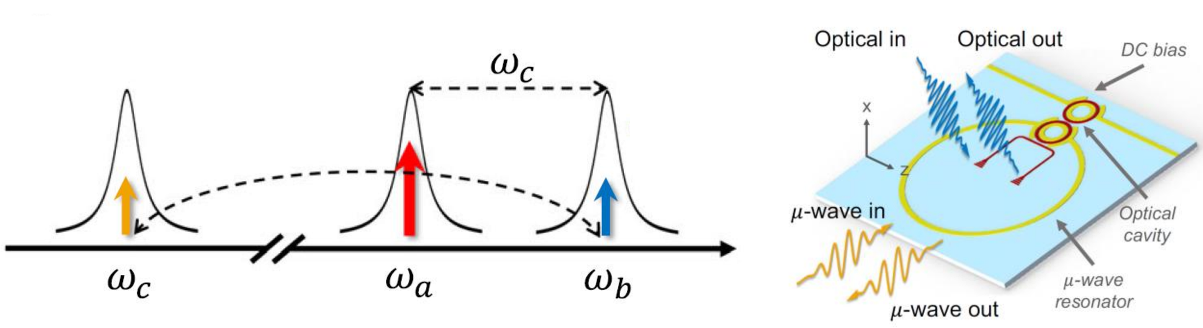
Superconducting diode effect

Kun Jiang & Jiangping Hu Nat. Phys. 2022

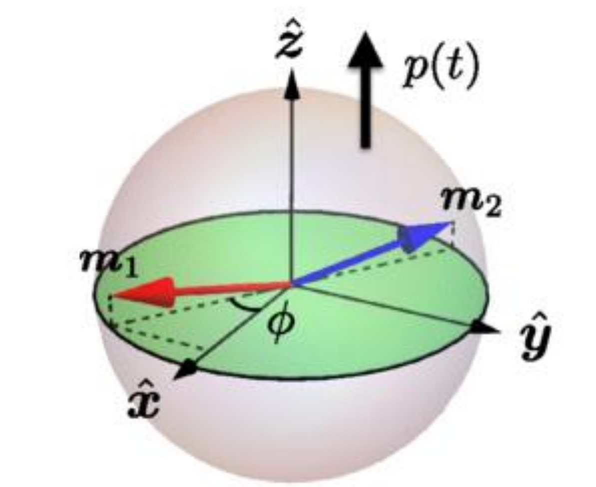


GHz-to-optical quantum transduction

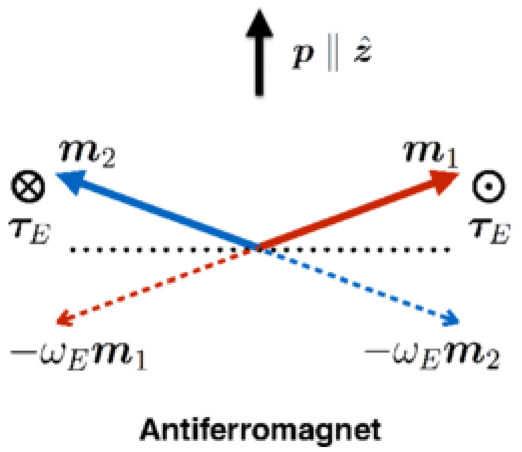
~1 % efficiency using AlN and $LiNbO_3$ (Y. Xu et al. Nat. Commun. 2021)



Terahertz Oscillator based on spin torque induced AFM resonance



Effective model of the staggered field switching. (a) Perpendicular spin torque cant $m_{1,2}$ slightly out of the basal plane.

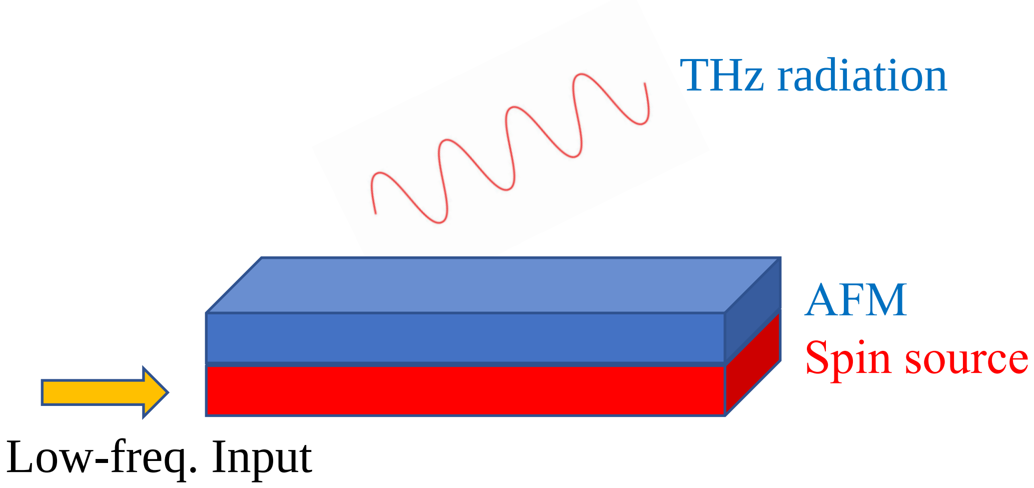


For $\boldsymbol{p} \parallel \hat{\boldsymbol{z}}$, an AF precession is implemented by the exchange torque.

Ultrafast switching of antiferromagnets via spin-transfer torque, by R. Cheng et. al., PRB 91, 064423 (2015)

Proposal:

- Sample: Spin source / AFM bilayer structure
- Low-frequency current as charge to spin source, coupled with the AFM resonance in materials with large out-of-plane spin component
- Spin-torque induced AFM resonance enhances **non-linear Hall response**.
- The inverse effect serves as THz detectors

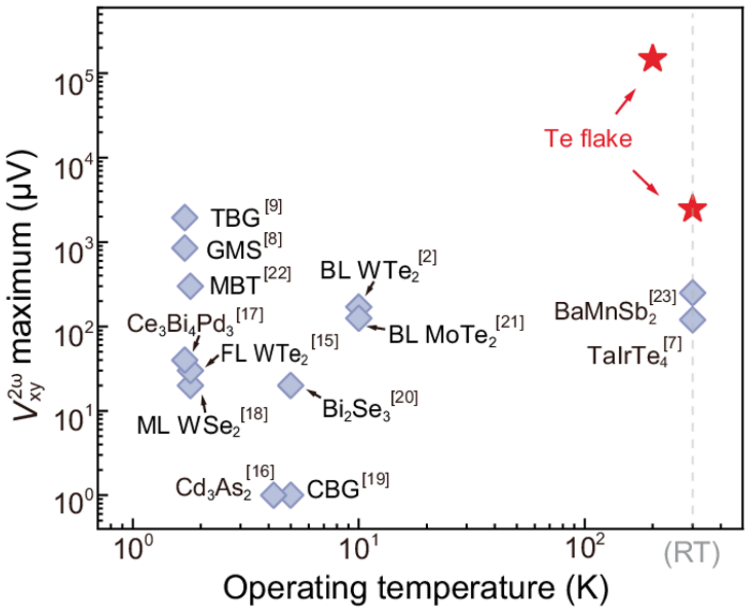


Attractive material candidates in reports

We shall start from materials with strong **nonlinear Hall effect** (MHz-to-DC) and **bulk photovoltaic effect** (optical-to-DC) at room temperature.

- **Weyl semimetal** $TaIrTe_4$, TaAs
- **Chiral multifold fermion** (Co,Rh)(Si,Ge)
- **Dirac semimetal** with defect/strain/interface engineering Cd_3As_2, $(Pt,Pd,Ni)Te_2$
- **Topological insulator** with magnetic proximity effect, Bi_2Te_3/Cr_2Te_3

Examples of nonlinear Hall voltage



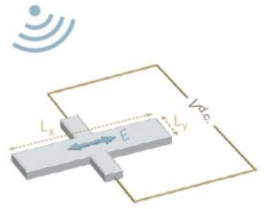
B. Cheng, et al, Nat. Commun. 2024

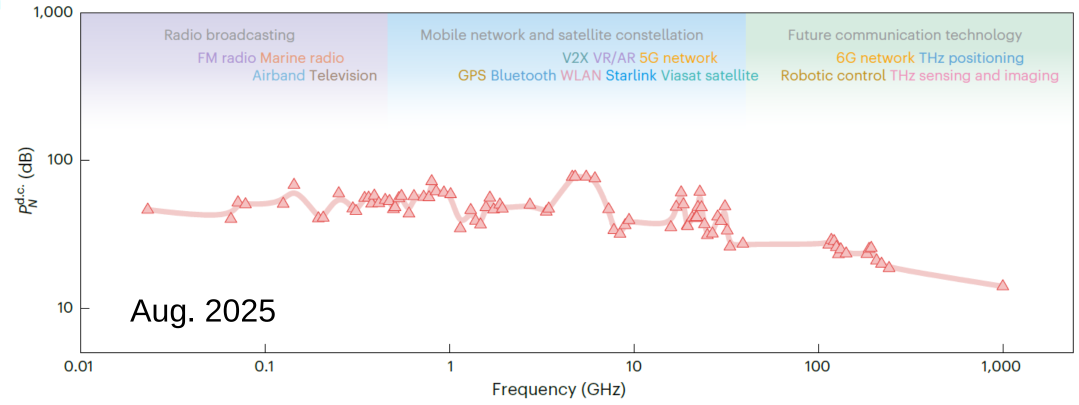

nature nanotechnology

Article

https://doi.org/10.1038/s41565-025-01993-2

Ultrabroadband nonlinear Hall rectifier using SnTe



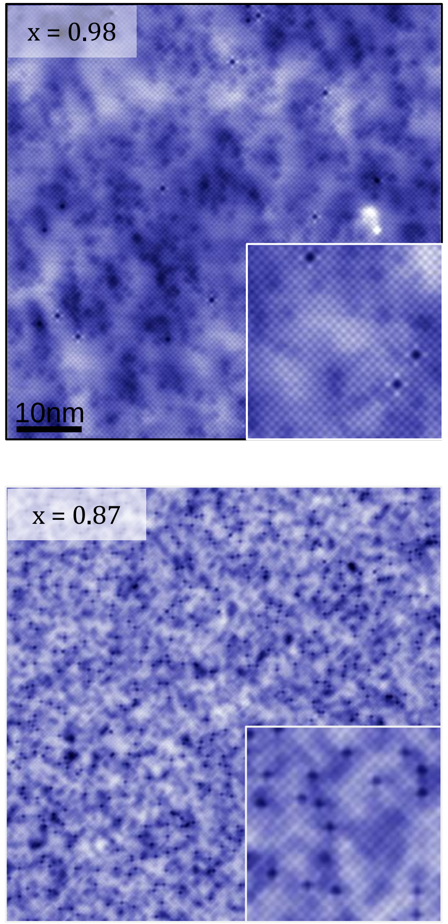


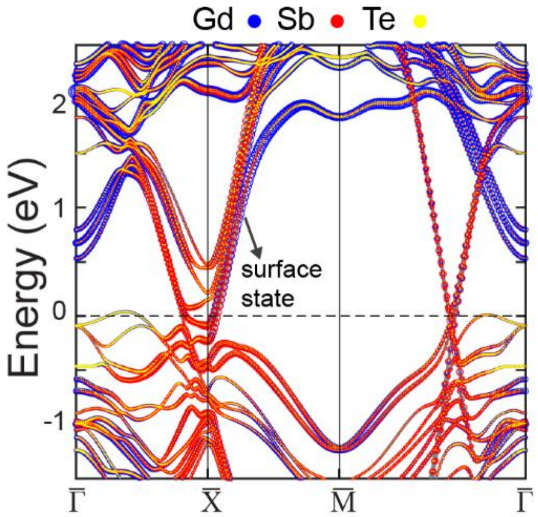
Large unexplored material parameter space for (Ge,Sn)(Te,Se) family from topological crystalline insulator to ferroelectric semiconductor

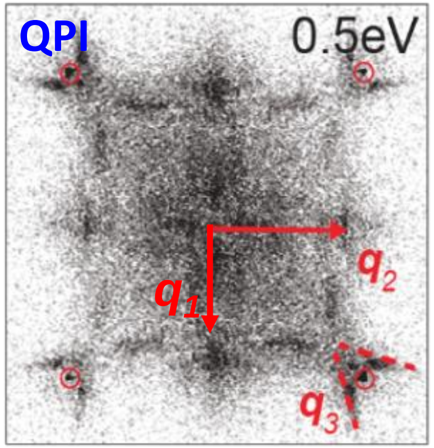
Sub-Project III: Material exploration and optimization (Ge,Sn)(Te,Se)

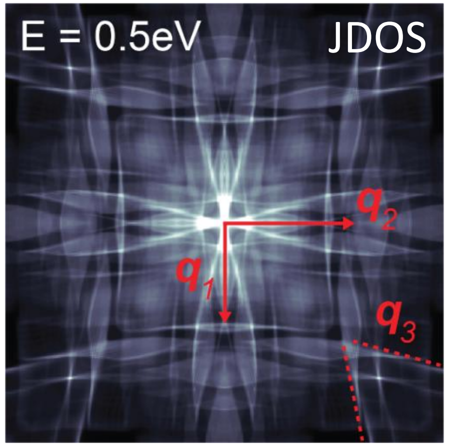
ex: Tuning band structure via doping in $GdSb_xTe_{2-x}$

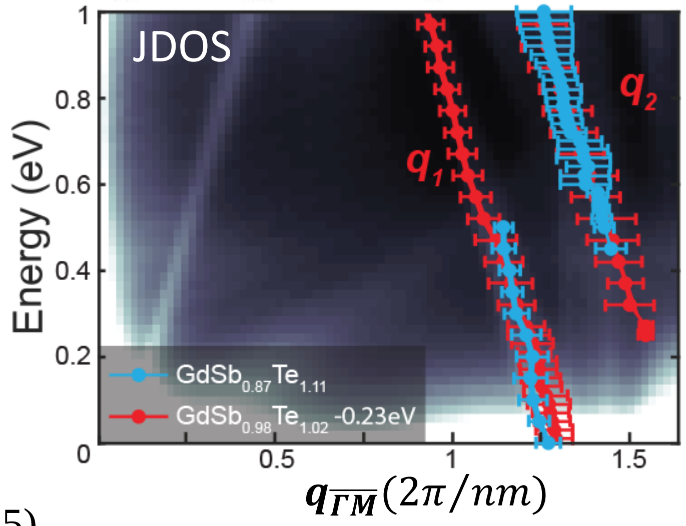
STM topograph @ T = 4.2K

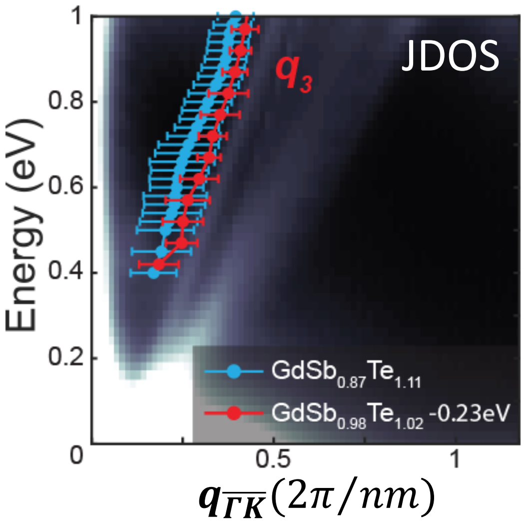










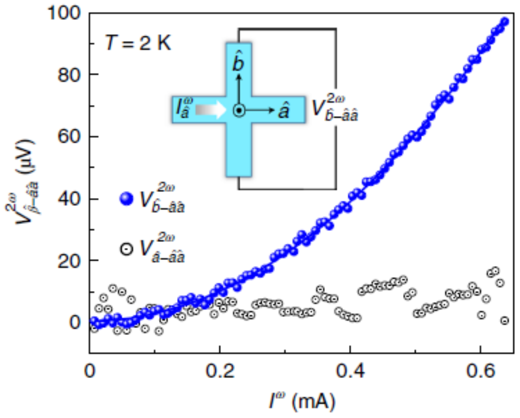


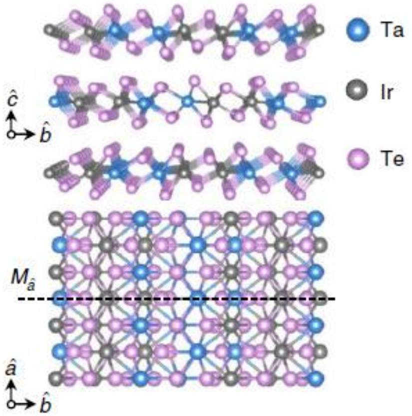
Venkatesan *et al.*, *npj Quantum Mater*. 10, 56 (2025)

Sub-Project III: Characterization of nonlinear Hall response

Non-reciprocal electrical transport (< MHz)
— exploring materials with **large nonlinearity**

Ex: $TaIrTe_4$



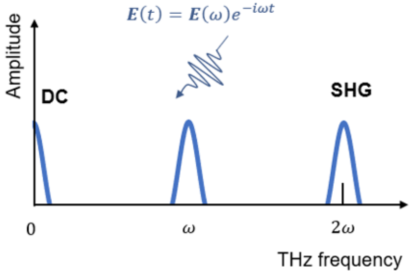


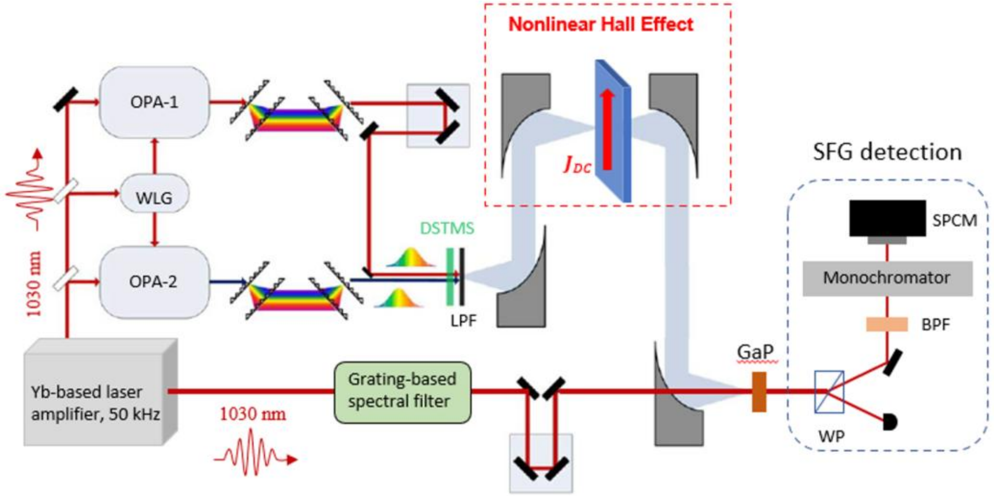
Nat. Nanotech. 16, 421 (2021)

Frequency-scanning nonlinear THz spectroscopy ($\omega\tau$ ~ 1)
— **Spectroscopic characterization** of nonlinear Hall effect and dynamic Hall effect

Proposal:

- DFG of two linearly chirped NIR pulses via organic nonlinear crystal for generating **μJ-level** tunable THz pulses (**4 ~ 18 THz**) with bandwidth less than 1 THz [Optics Letters 42, 129 (2017)]
- **THz parametric up-conversion detection scheme** for achieving THz detection sensitivity down to the **zeptojoule energy level** [Optica 12, 239 (2025)]





Material Exploration

溫昱傑、莊天明、林新、

Raman Sankar、柯忠廷

Synthesis

STM &
Band theory

Nonlinear optics and transport

Synergistic efforts

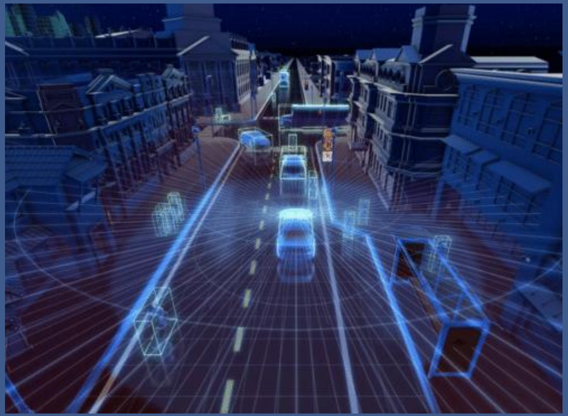
Device Demonstration

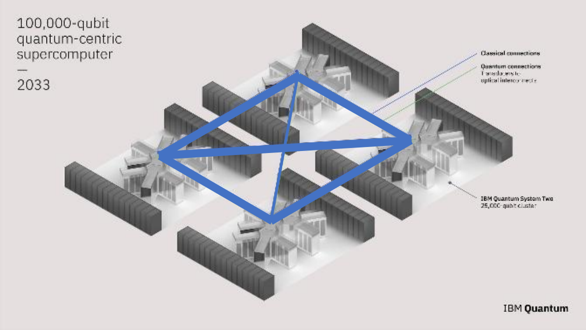
柯忠廷、李尚凡

Quantum mixers

ultrabroadband frequency conversion for bridging GHz-to-THz and GHz-to-optical domains

THz communication & quantum transduction





Responses to AAC Report

1. MAGACH facility management: actively seek additional external funding to support researches program based on MAGACH facility

Responses:

Currently, there are two funded program based on MAGACH facility led by Dr. Wei-Li Lee: one is the NSTC nano innovative program and the other one is the AS grand challenging seek projects. There will be more internal discussions within QMP group to initiate proposals for the coming year based on MAGACH facility to compete for bigger projects, such as the NSTC Summit, NSTC Vanguard, and AS grand challenging programs.

Responses to AAC Report

2. Single crystal growth facility : Internal collaborations within QMP could be strengthened and should be made a high priority of this facility

Responses:

This facility is managed by Dr. Raman Sankar. As Sankar serves as a Co-PI of Yu-Chieh's Project, his internal collaborations with QMP will be further strengthened, and this facility will provide priority support for this project. Additionally, QMP PIs encourage Sankar to leverage this unique materials synthesis facility to pursue research directions with the highest potential impact.

Responses to AAC Report

3. Long tem strategic plan for QMP: to maximize the long-term research impact of the QMP group, it would be strategically beneficial to identify those grand challenges in modern science and technology that may be addressed by the research expertise in QMP

Responses:

In response to this issue, QMP PIs have begun to propose ambitious and challenge-driven research directions. For example, Yu-Chieh, together with five QMP colleagues, has proposed a project to study Quantum Materials for Ultrabroadband Frequency Conversion—Toward Next-Generation THz Communication and Quantum Transduction." In addition, MK's project aims to develop PFAS-free battery polymers using AI–assisted approaches. Both projects are aligned with grand challenge themes in modern science and technology.

Responses to AAC Report

4. Maintenance of QMP shared facilities:

Responses:

Cleanroom is not QMP shared facility. It has its own committee that includes members from both the QMP and PALM groups.

At present, the cleanroom facility is able to operate on a self-sustaining basis; however, the equipment is aging, and therefore significant updates are anticipated in the future.