Spintronic THz Emission from AFM/FM without External Magnetic Fields

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Beihang University

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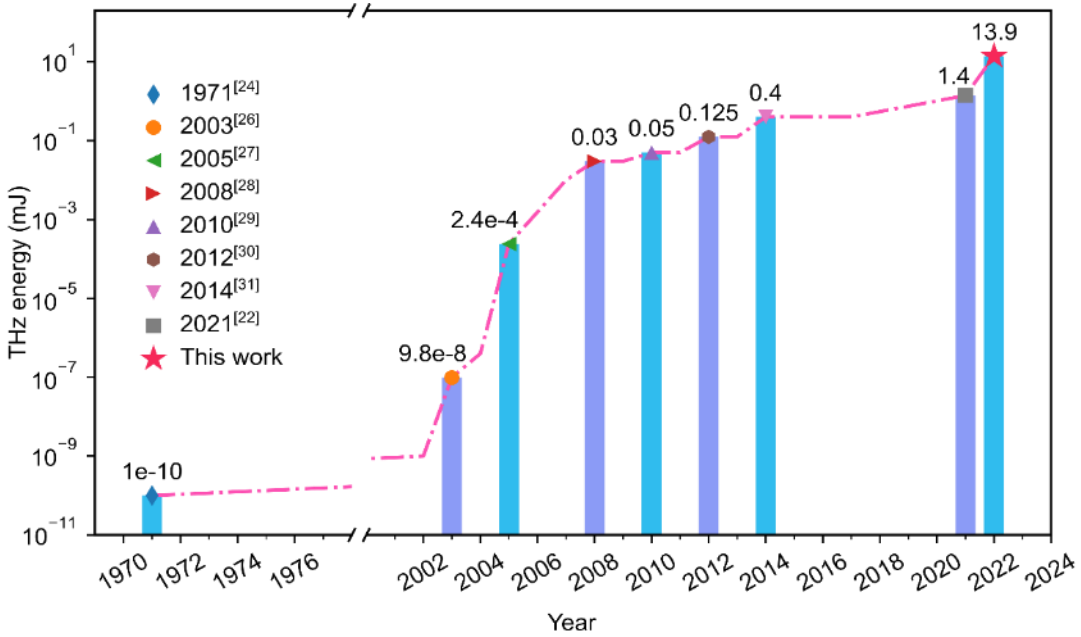
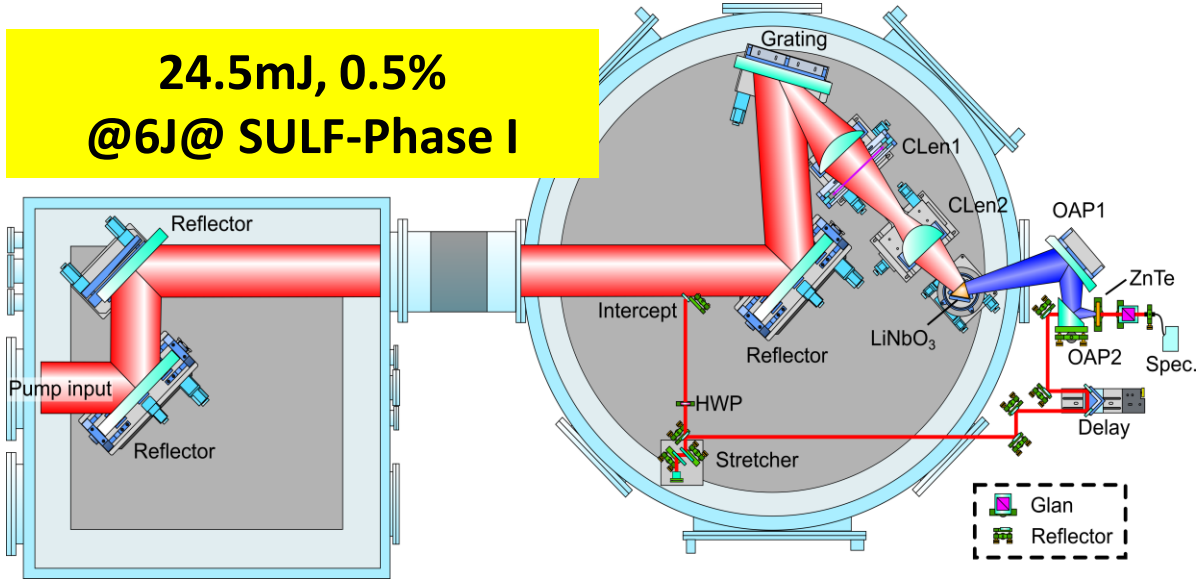
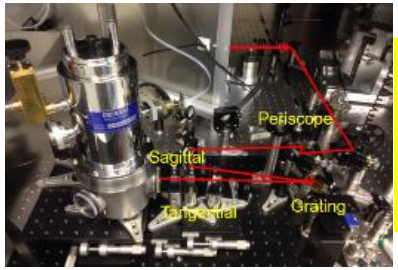
Lithium Niobate-THz Source

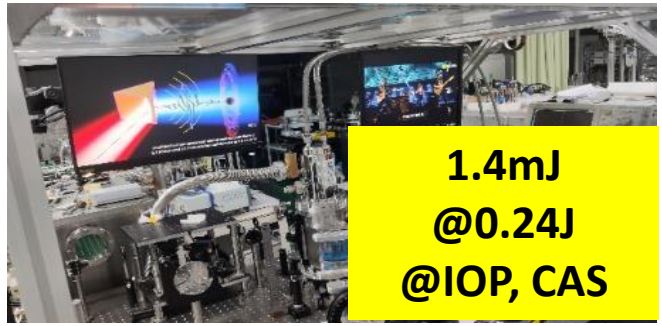


24.5mJ, 0.5%
@6J@ SULF-Phase I



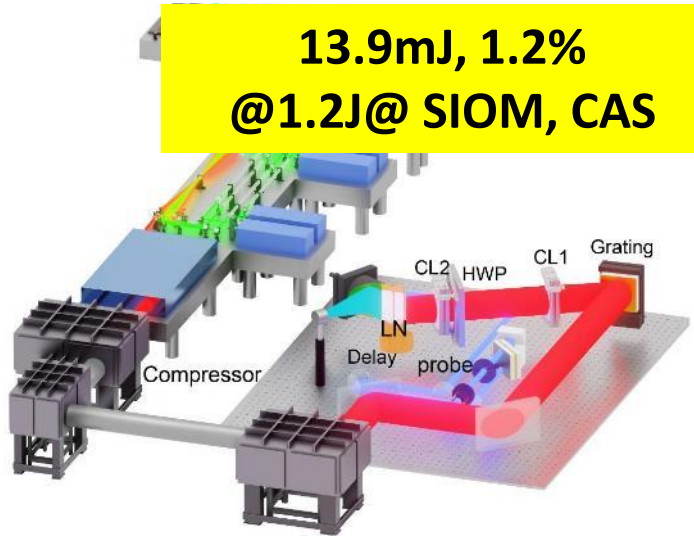


0.13mJ
@ 0.05J
@DESY



1.4mJ
@0.24J
@IOP, CAS

13.9mJ, 1.2%
@1.2J@ SIOM, CAS

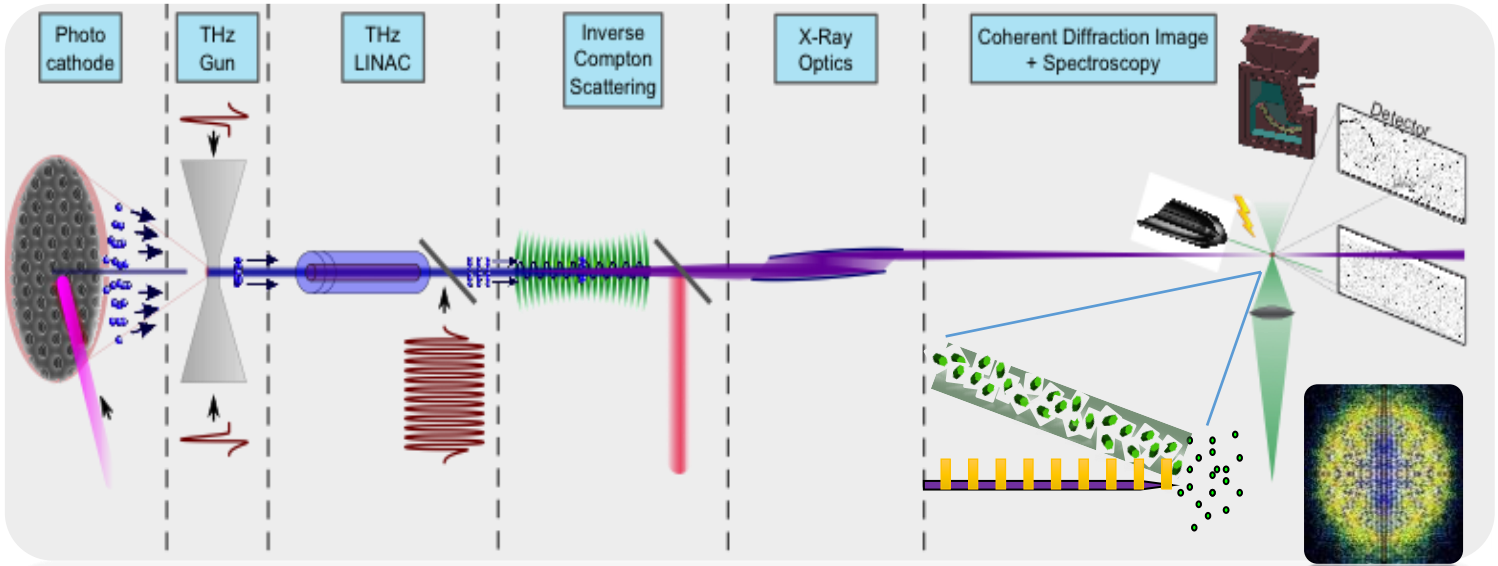


X. Wu*, et al., Opt. Lett. 39, 5403 (2014)
X. Wu*, et al., Opt. Express 23, 29729 (2015)
X. Wu*, et al., Opt. Express 24, 21059 (2016)
https://ufox.cfel.de/

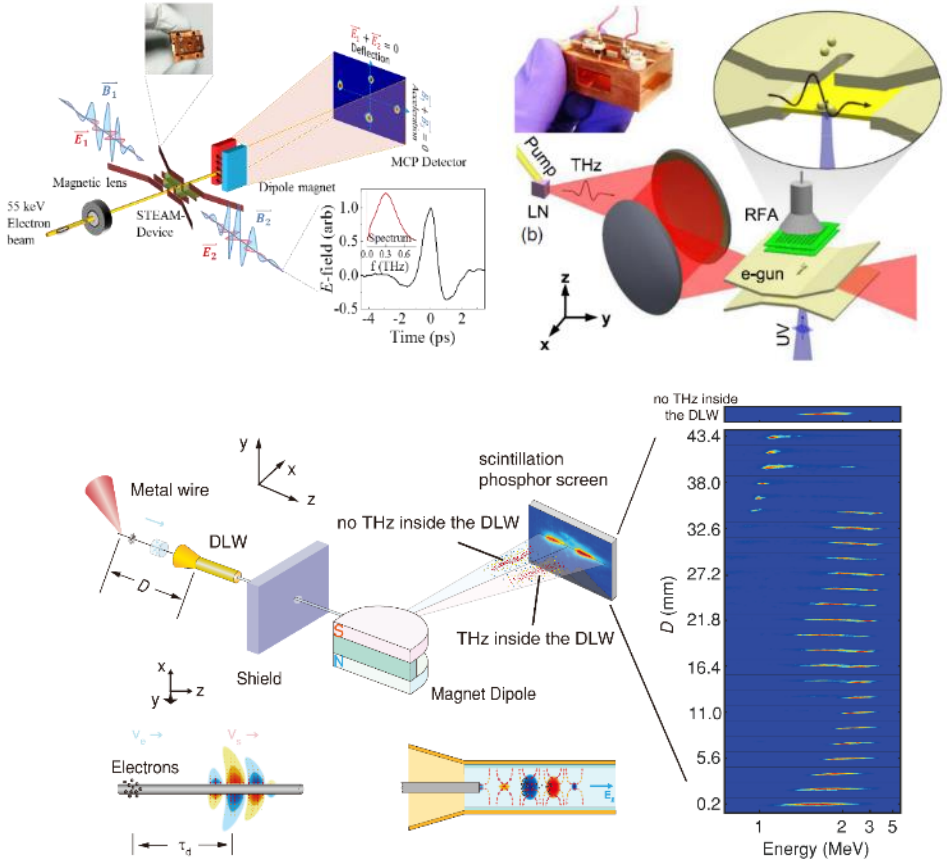
X. Wu*, et al., Opt. Express 26, 7107 (2018) ; B. Zhang, **X. Wu***, et al., Photonics Res. 6, 959 (2018) ; B.L. Zhang, **X. Wu***, Y.T. Li*, ***Laser Photonics Rev***. 15, 2000295 (2021, ESI)

X. Wu*, D. Kong, S. Hao, Y. Zeng, et al., L. Song*, Y. Tian*, R. Li, Advanced Materials (2023)

THz Electron Acceleration



km → m



ERC-AXSIS project

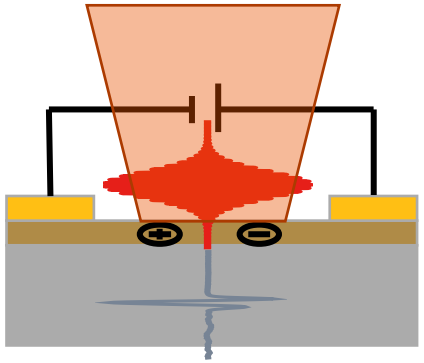
Attosecond X-ray： imaging and spectroscopy

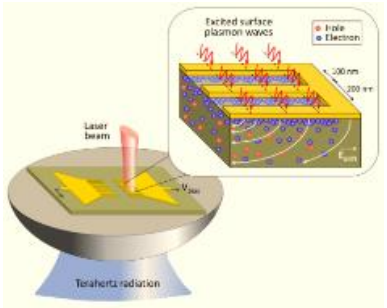
The world's first THz electron accelerator to generate attosecond X-ray source for ultrafast time-resolved spectroscopy and imaging

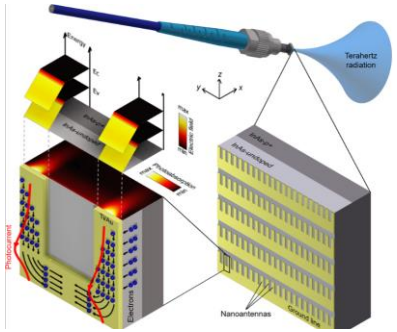
- L. Song*, X. Wu* et al., ***Nat. Photonics*** (2023)
- H. Xu, et al., ***Nature Photonics*** 15, 426 (2021)
- H. Tang, et al., ***Phys. Rev. Lett.***, 127, 074801 (2021)
- M. T. Hibberd, et al., ***Nat. Photonics*** 14, 755 (2020)
- D. Zhang, et al., ***Nat. Photonics*** 12, 336 (2018)
- W. R. Huang, et al., ***Optica*** 3, 1209 (2016)
- E. Nanni, et al., ***Nat. Commun.*** 6, 8486 (2015)

Photoconductive Antenna

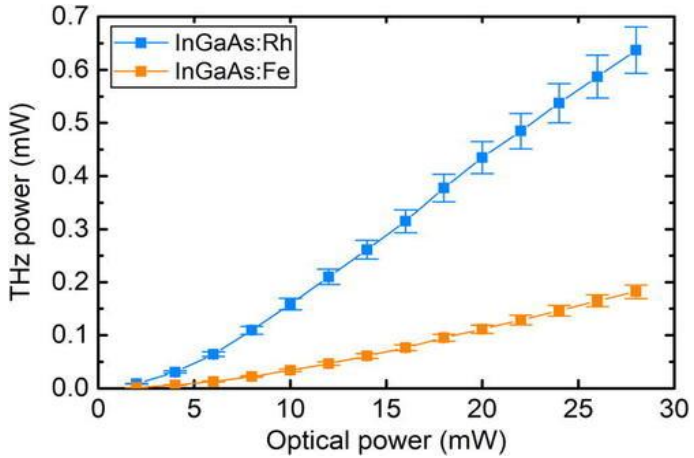
the most mature solution for commercialization

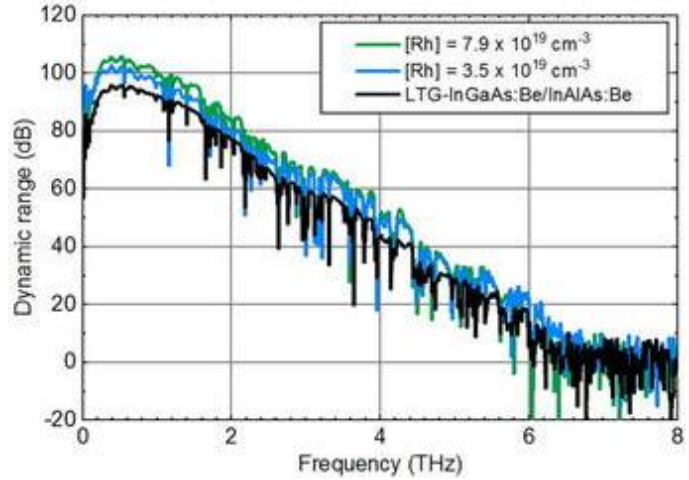






Appl. Phys. Lett. 55 (4), 337 (1989)
Appl. Phys. Lett. 117, 131105 (2020).
Nat Commun **12**, 4641 (2021).





DAS NANO

Limitations

- **Bandwidth**
- **Expensive deposition (MBE)**
- **Large area**

THz Radiation: Fs Laser + Electron Charge

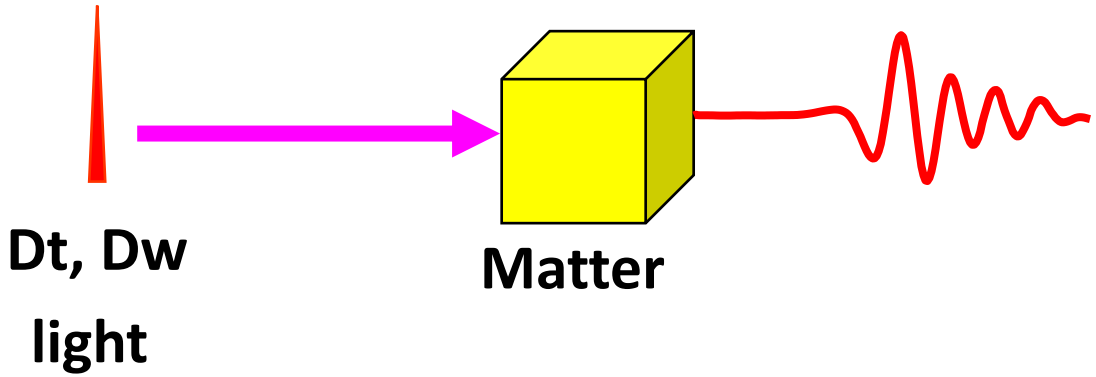
$$E_{THz}(t) \propto \chi^{(2)} \frac{\partial^2 P(t)}{\partial t^2} + \frac{\partial I_f(t)}{\partial t} + \mu_0 \frac{\partial \vec{M}(t)}{\partial t}$$

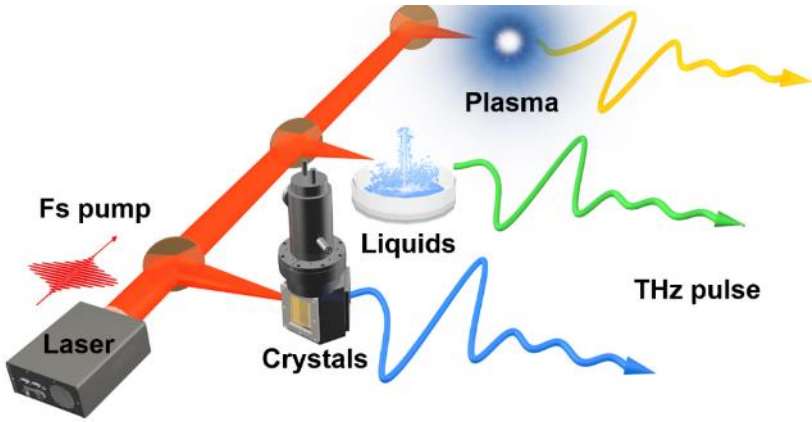
Charge

Spin?

Fs pulses: I(t, w, Dw)

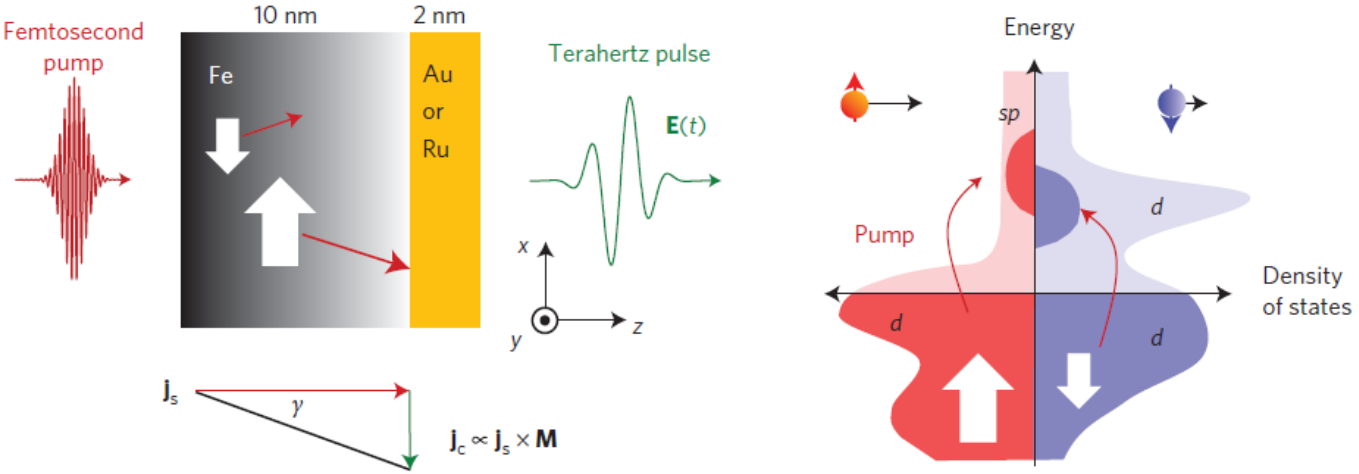
THz pulse: E_{THz}(t, W)





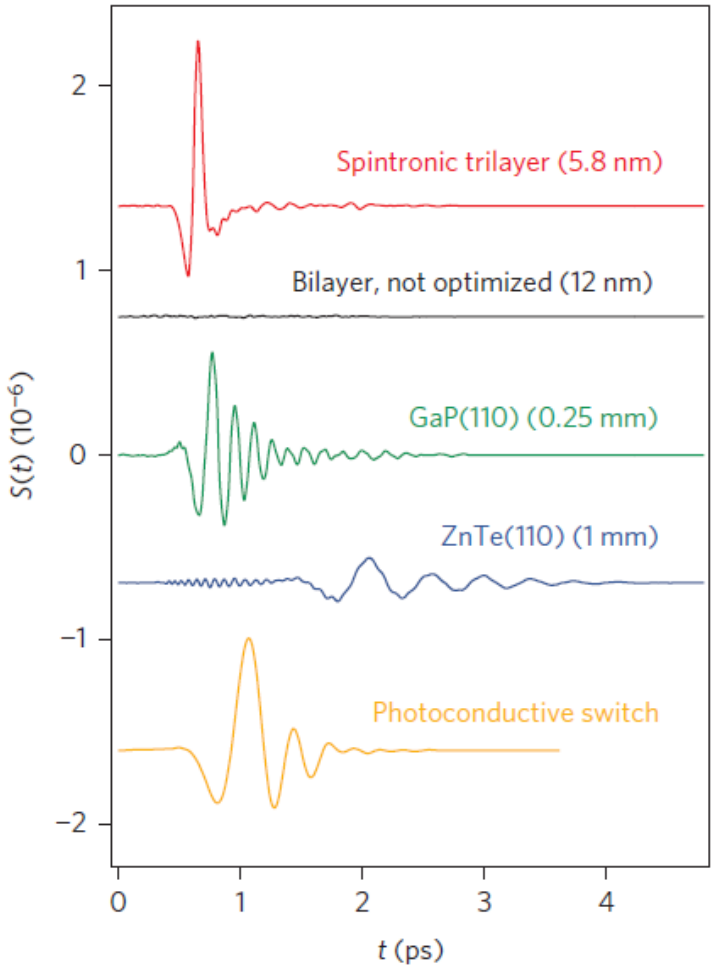
Spintronic THz Emitters

Using 10fs ultrashort laser oscillator to pump W|CoFeB|Pt trilayer heterostructure to realize high-efficiency ultrabroadband THz emission (30THz) and can also produce strong-field THz radiation (1.5MV/cm)



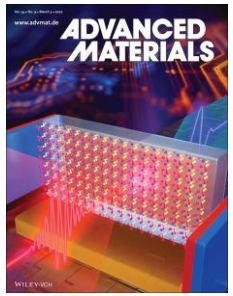
Inverse Spin-Hall Effect

$$\overrightarrow{E_{THz}} \propto \vec{j}_c = \gamma \vec{j}_s \times \frac{\vec{M}}{|\vec{M}|}$$

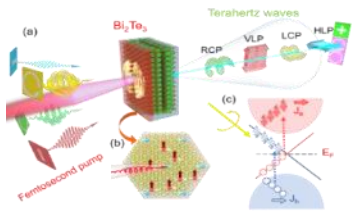


T. Kampfrath, et al., Nat. Nanotech. 8, 256 (2013)
T. Seifert, et al. Nat. Photon. 10, 483 (2016)

What we have done in BHU

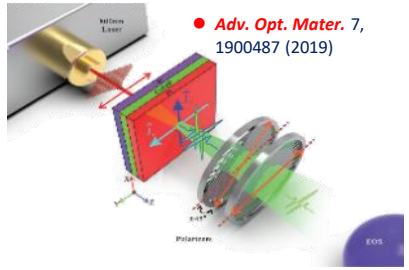


● *Adv. Photon*. 2, 066003 (2020)



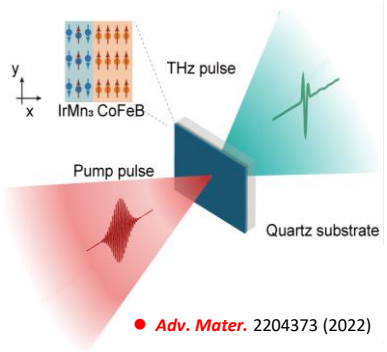
① Spin Hall Angle

● *Adv. Mater*. 34, 2106172 (2022)



● *Adv. Opt. Mater.* 7, 1900487 (2019)

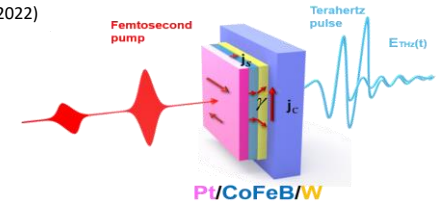
② External Magnetic Fields



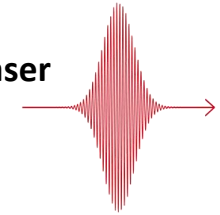
● *Adv. Mater.* 2204373 (2022)

③ Spin-to-Charge Conversion

Appl. Phys. Lett. 115, 121104 (2019)

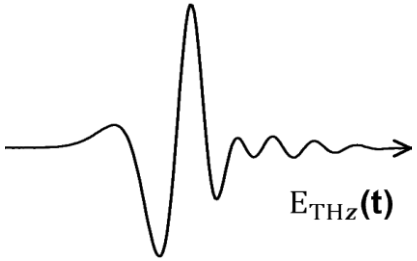


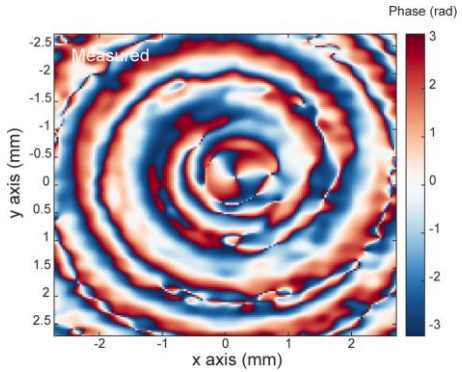
Fs laser



$$\overrightarrow{E_{THz}} \propto \overrightarrow{j_c} = \gamma \overrightarrow{j_s} \times \frac{\overrightarrow{M}}{|\overrightarrow{M}|}$$

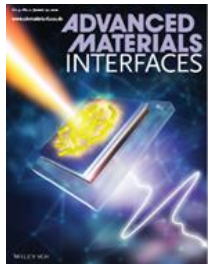
① ② ③

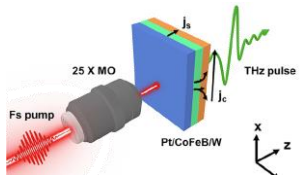




S. Chen, X. Wu* et al. *Adv. Opt. Mater.*, 2300899 (2023)

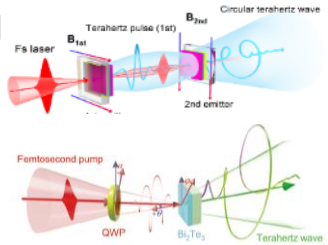
✓ Efficiency





● *Adv. Mater. Interfaces* 2101296 (2021)
● *Appl. Phys. Lett.* 120, 201102 (2022)

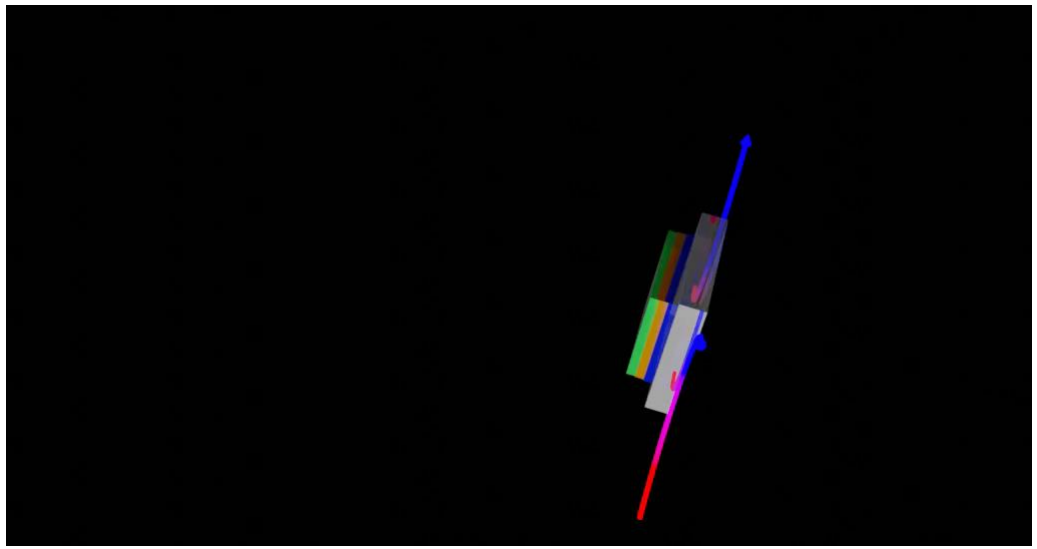
✓ Functional

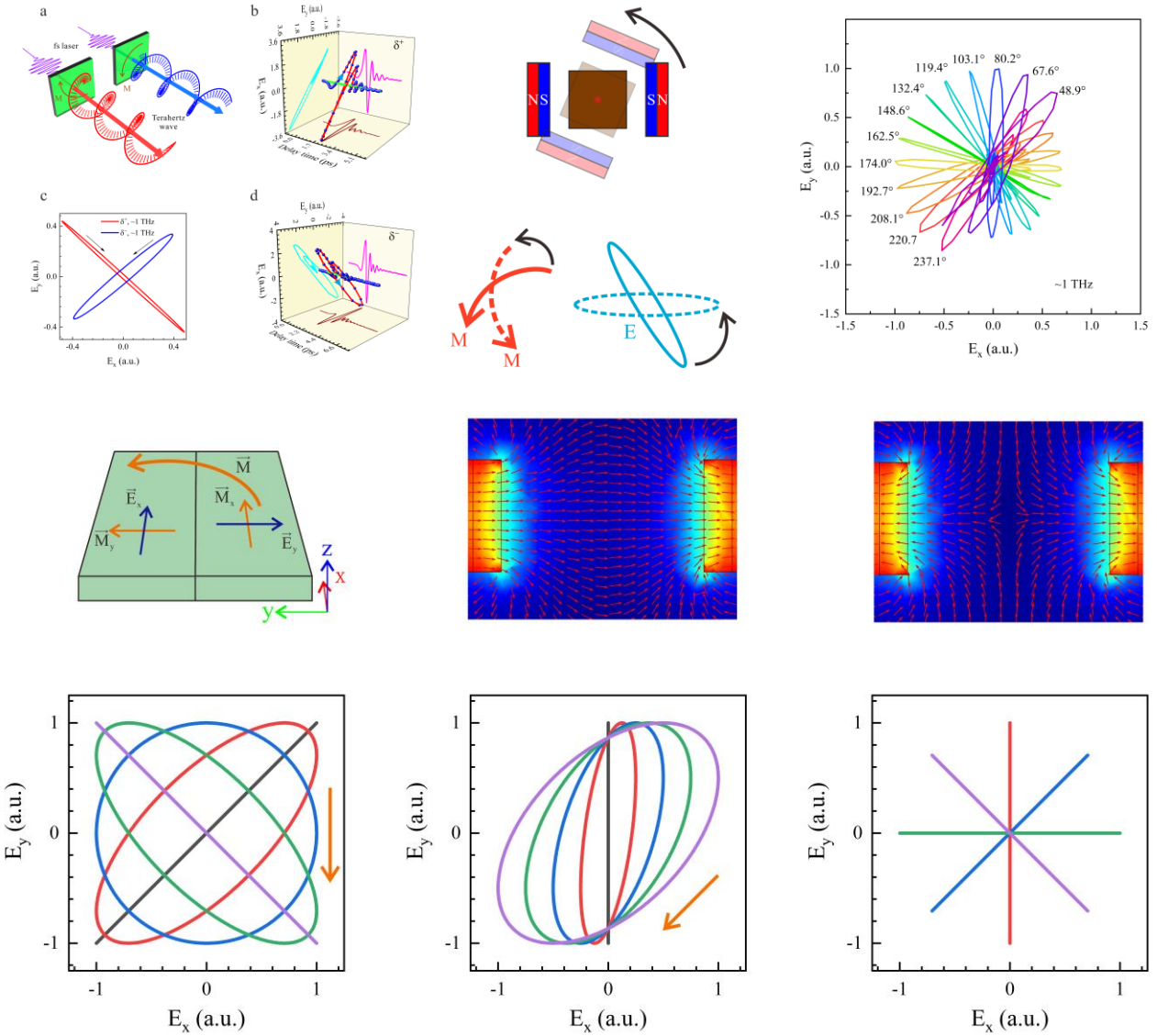


● *Appl. Phys. Lett.* 115, 221104 (2019)
● *Adv. Photonics Res*. 2000099 (2021)

Twisting THz at the Source: Elliptically Polarized

- **Defect induced spin-lattice scattering**
  - For generation of a transmission phase
  - Nonuniform magnetic field controlled
- **Chirality and principle-axis manipulation**
  - Twisting the magnetic field distribution
  - The maximum ellipticity is ~9.6%



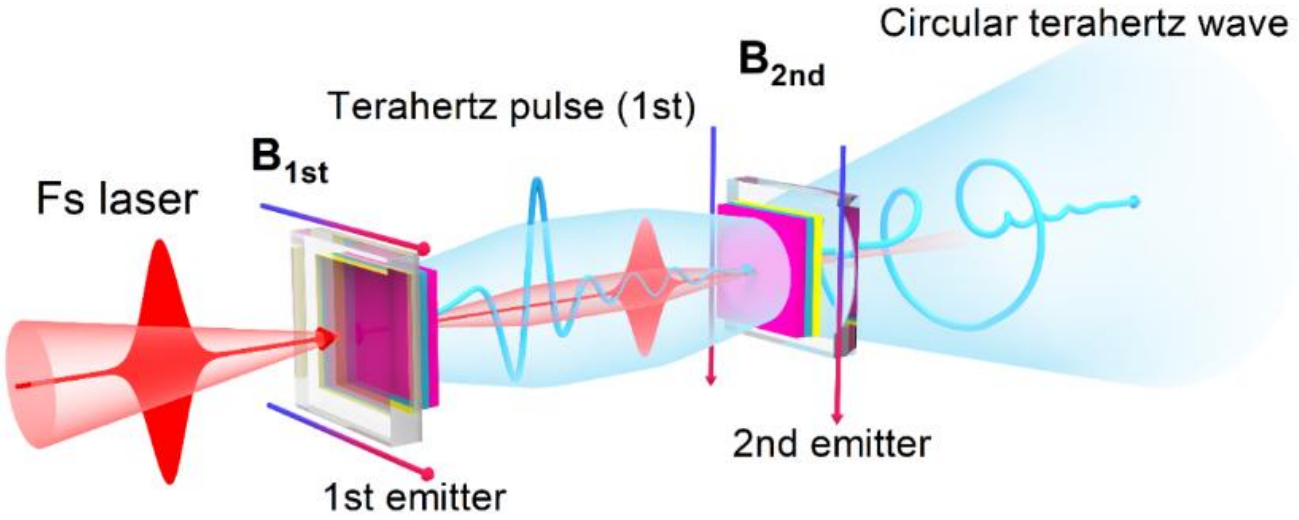


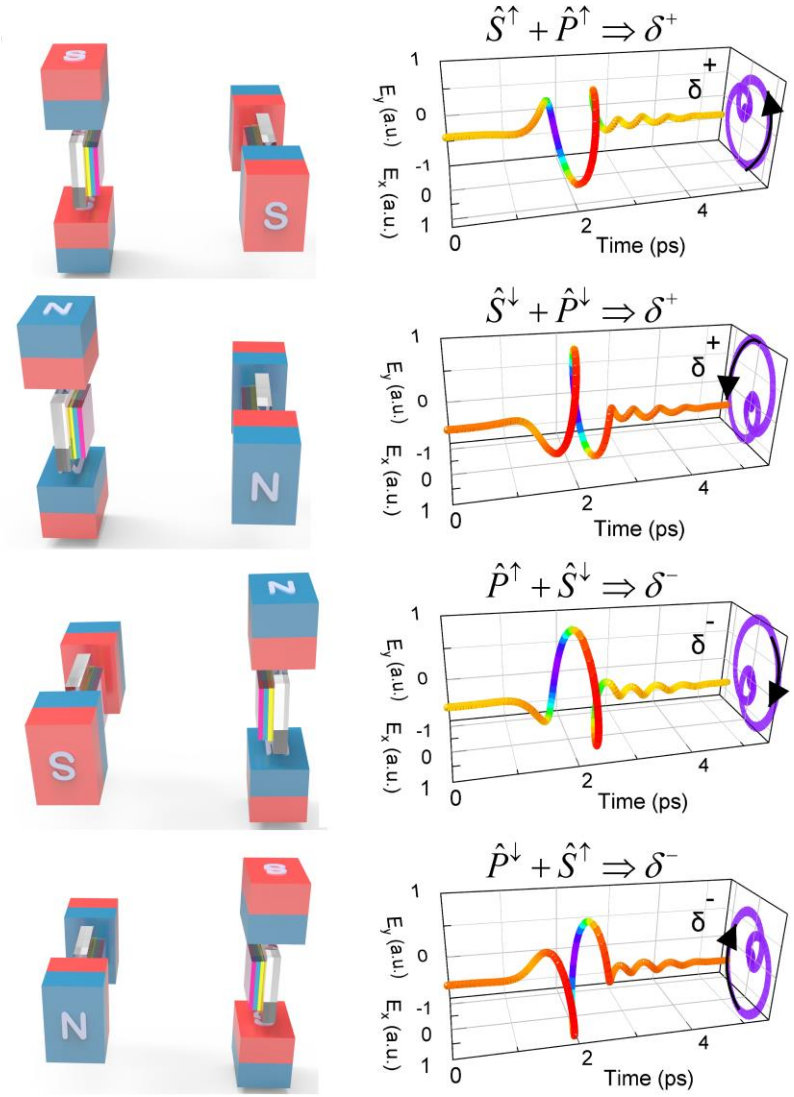
D. Kong, X. Wu*, et al., Adv. Opt. Mater. 7, 1900487 (2019)

Twisting THz at the Source: Circularly Polarized

Cascade emission method

- Perpendicular electric fields
- Equal amplitudes
- 90 degree phase difference



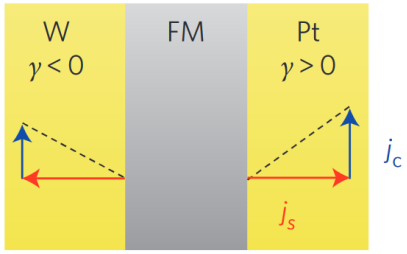


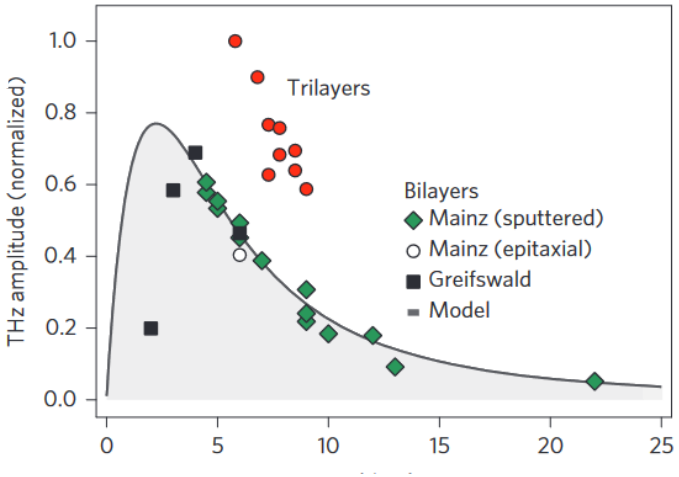
X. Chen, X. Wu*, et al., Appl. Phys. Lett. 115, 221104 (2019)

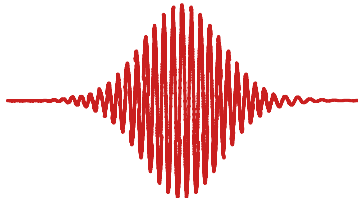
Twisting THz at the Sources: Metasurfaces

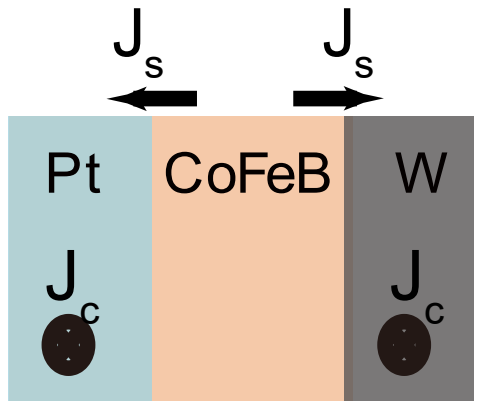
Deposition Sequence→ spin flow

Tri-layer sample has best performance

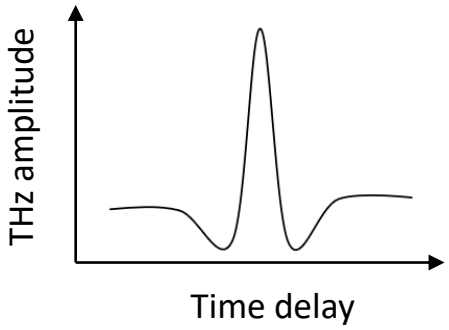


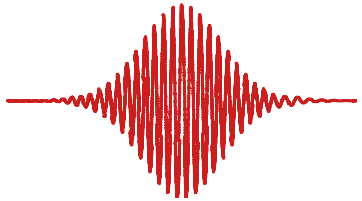


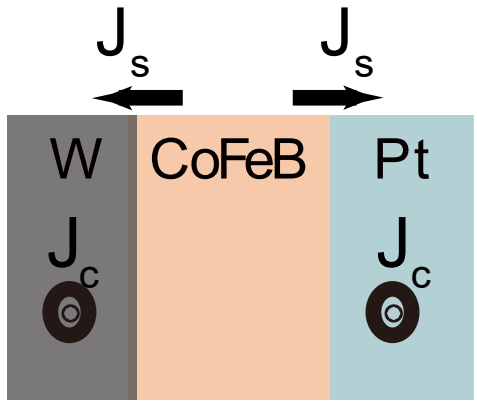




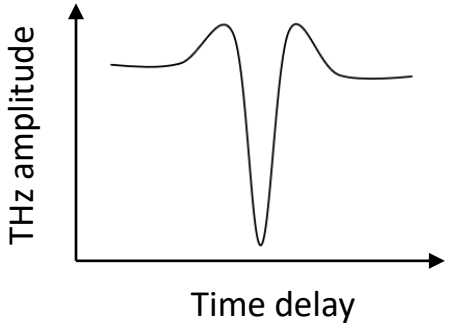
phase: "0°"







phase: "180°"



Based on the W-$Co_{20}Fe_{60}B_{20}$-Pt samples

Seifert, T et al, Nat. Photon. 10, 483 (2016)

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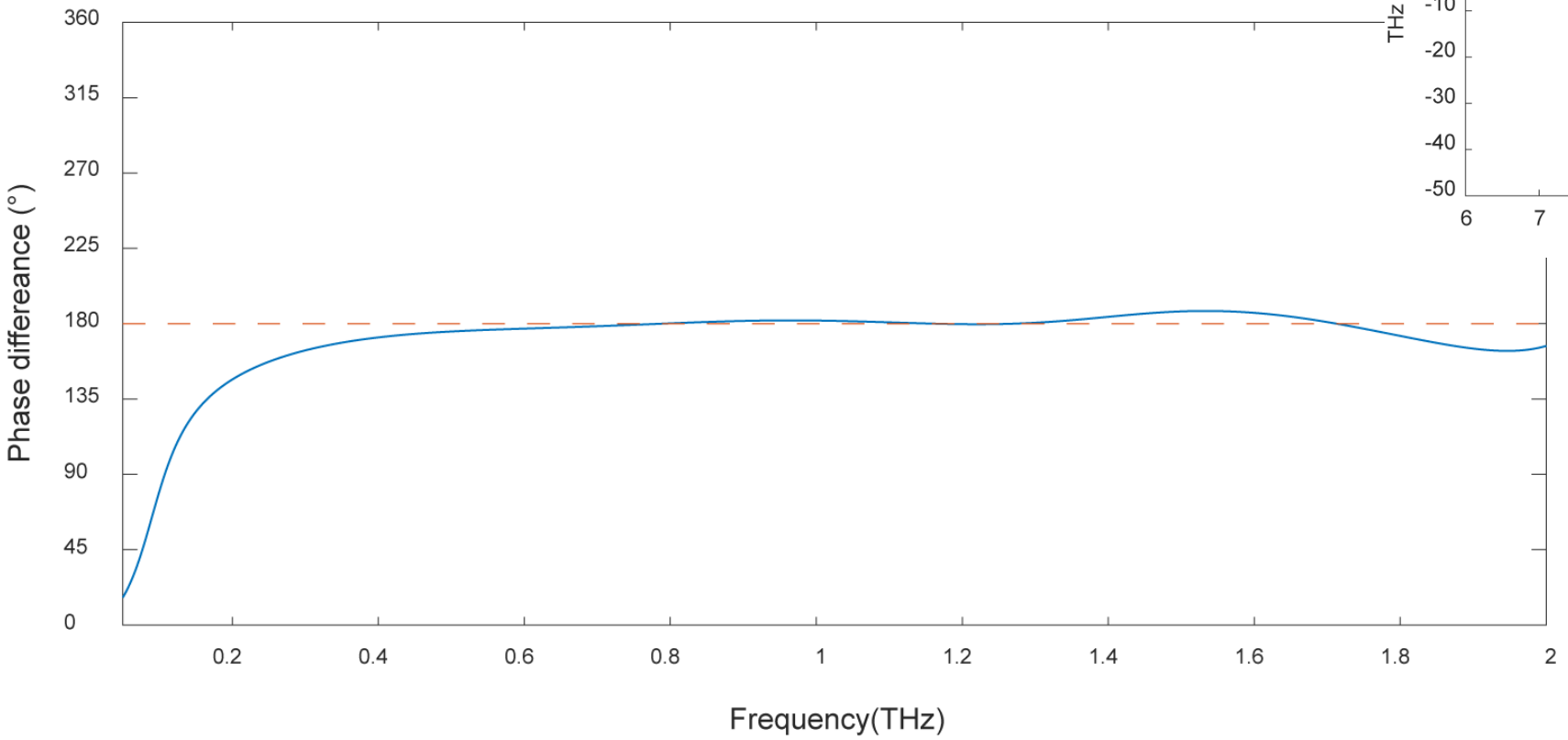
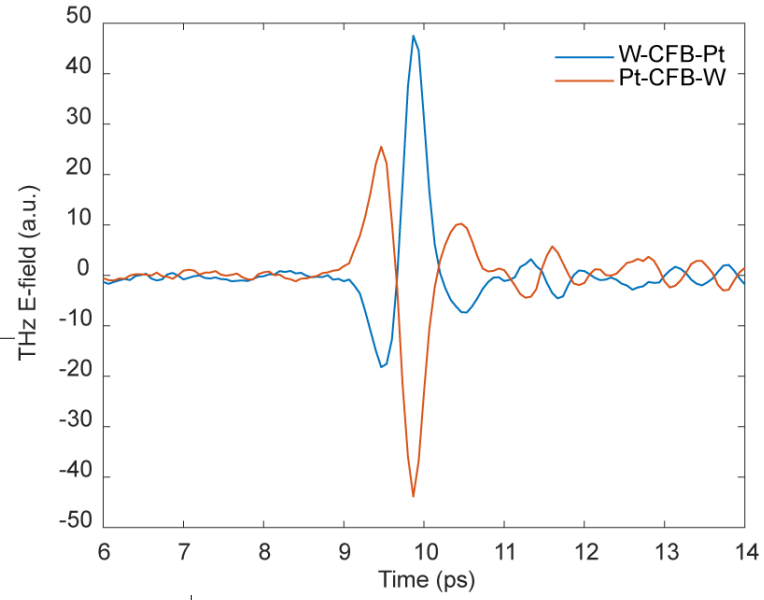
Phase Spectrum of the Coded THz Emitter

Realizing 180° phase difference





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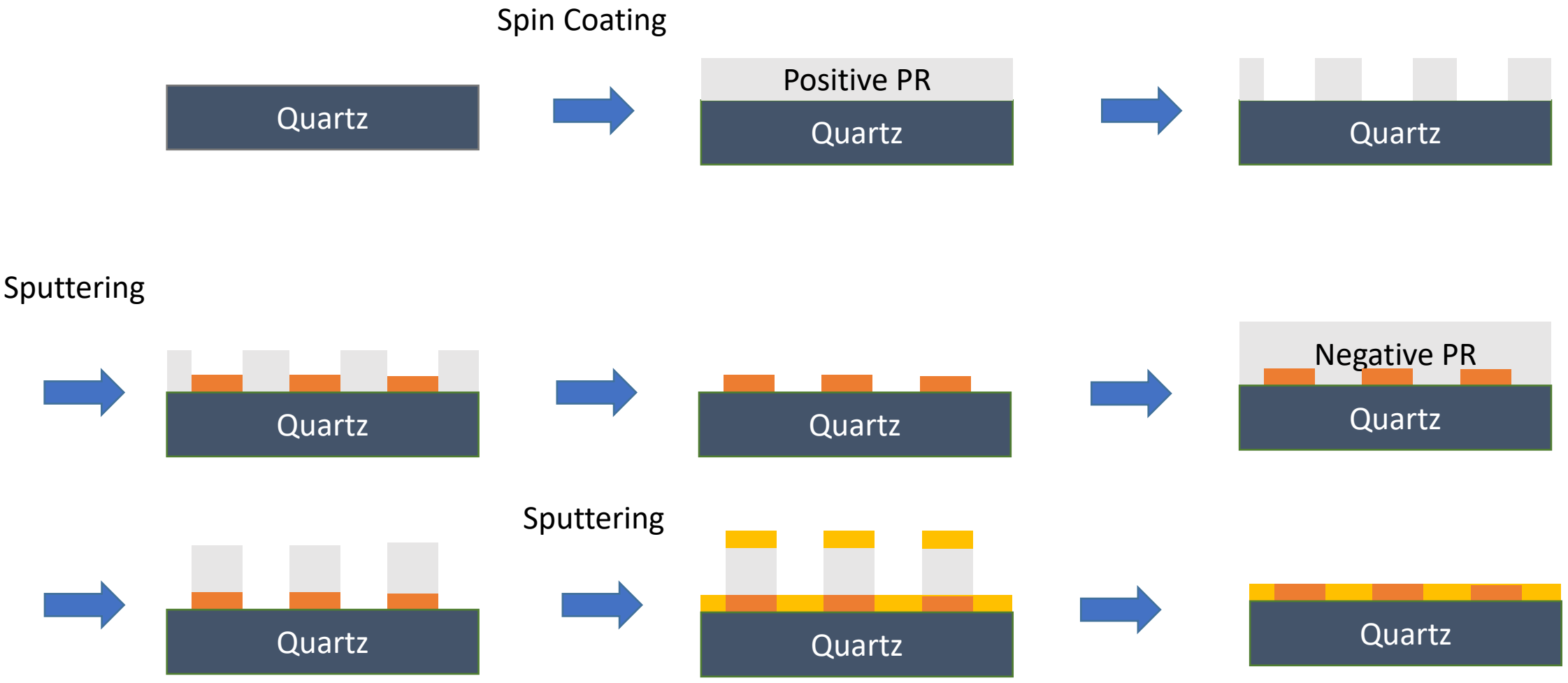
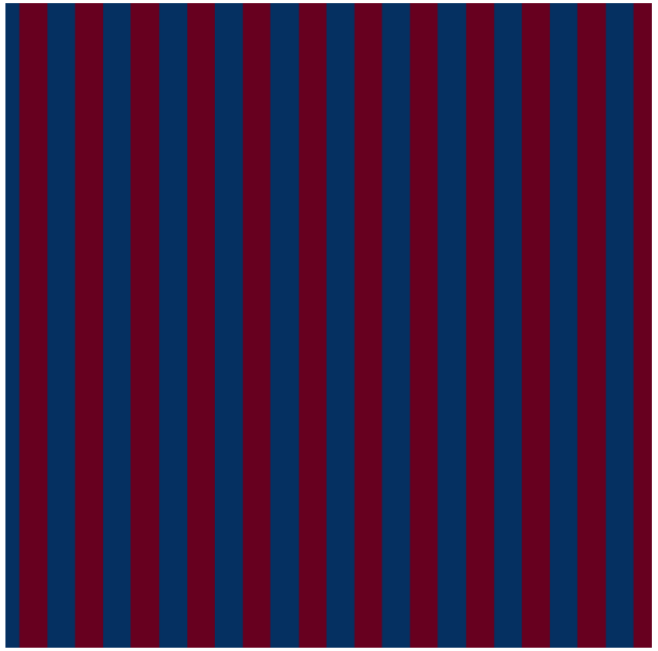
Fabrication Flow



Function 1： Beam Splitting

Beam splitting is performed at 10° and 20° diffraction angles of 1THz



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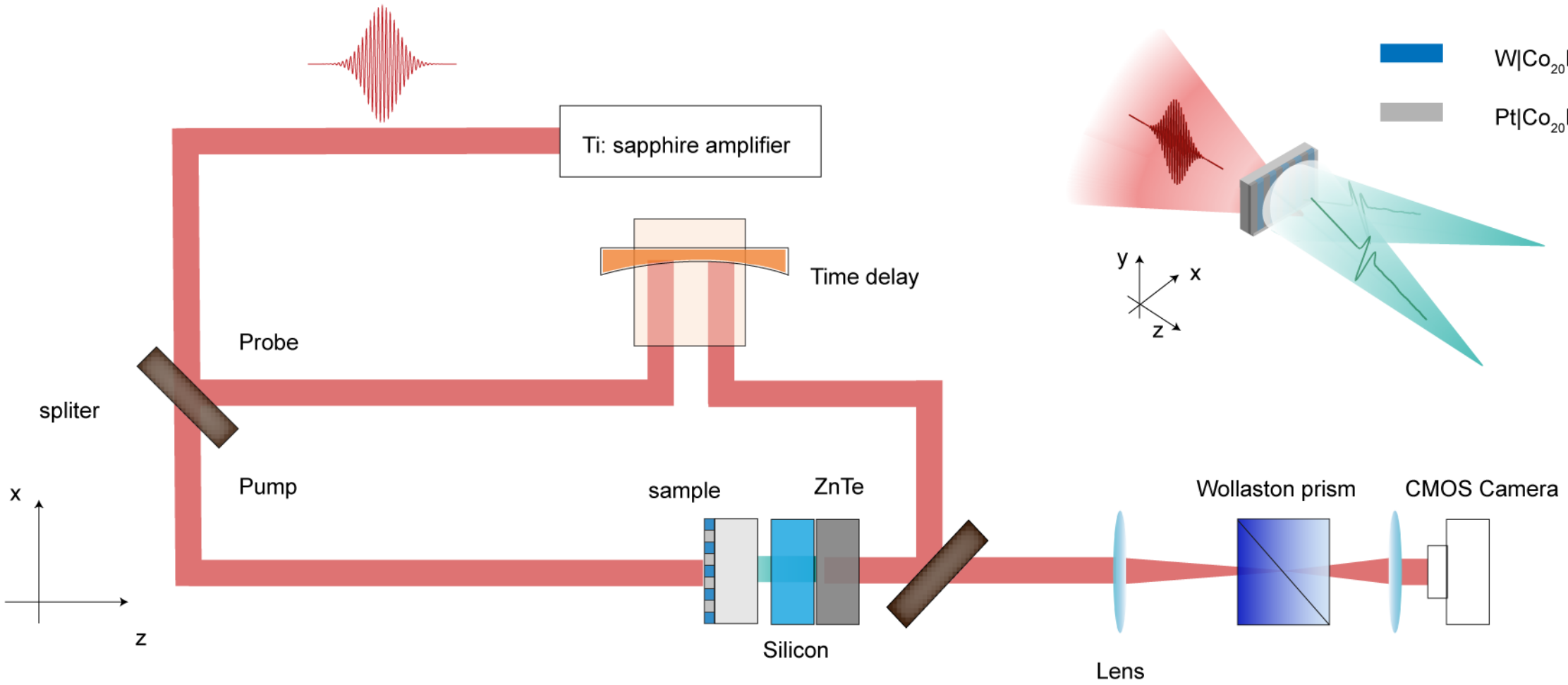
Experimental Characterization

In Prof. Yan Zhang's LAB (Capital Normal University)



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Function 1： Beam Splitting

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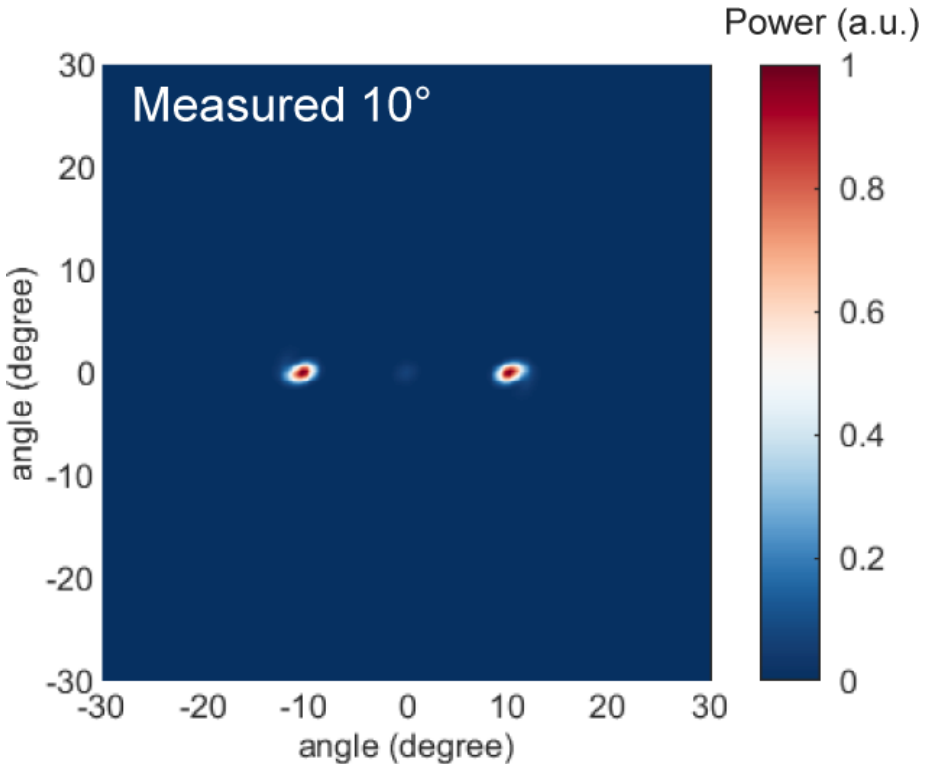

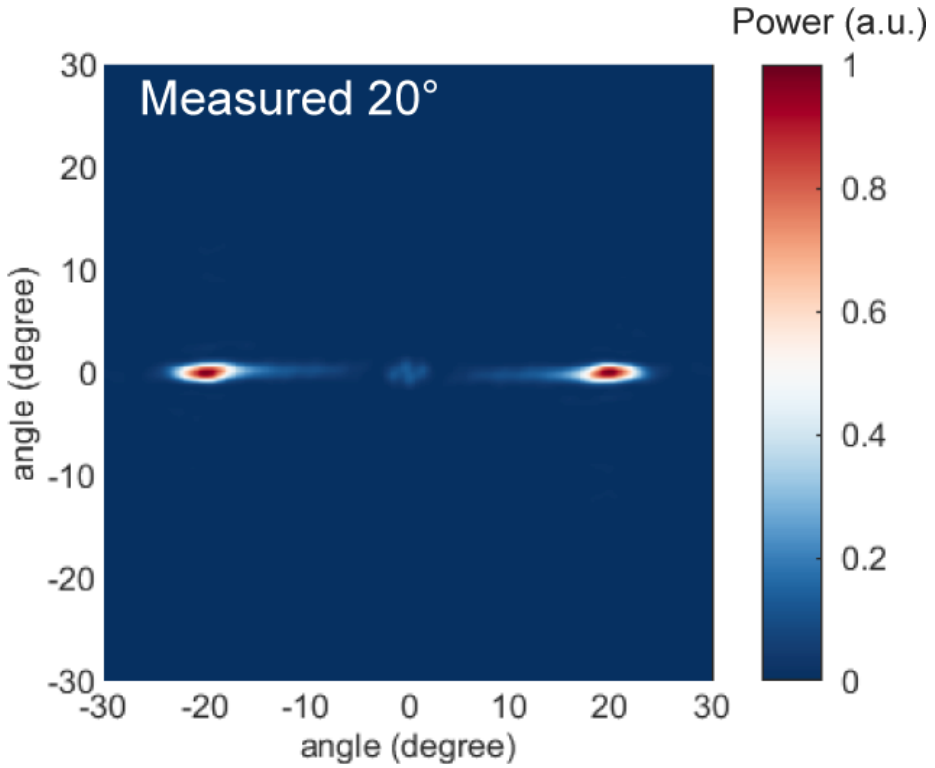

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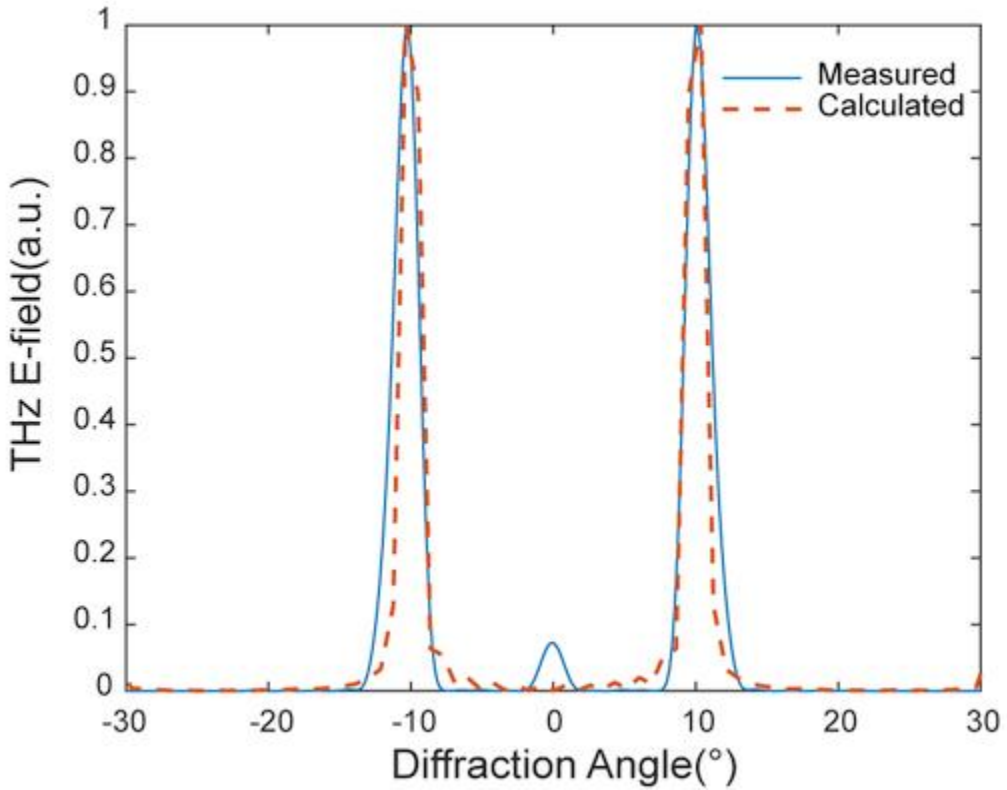
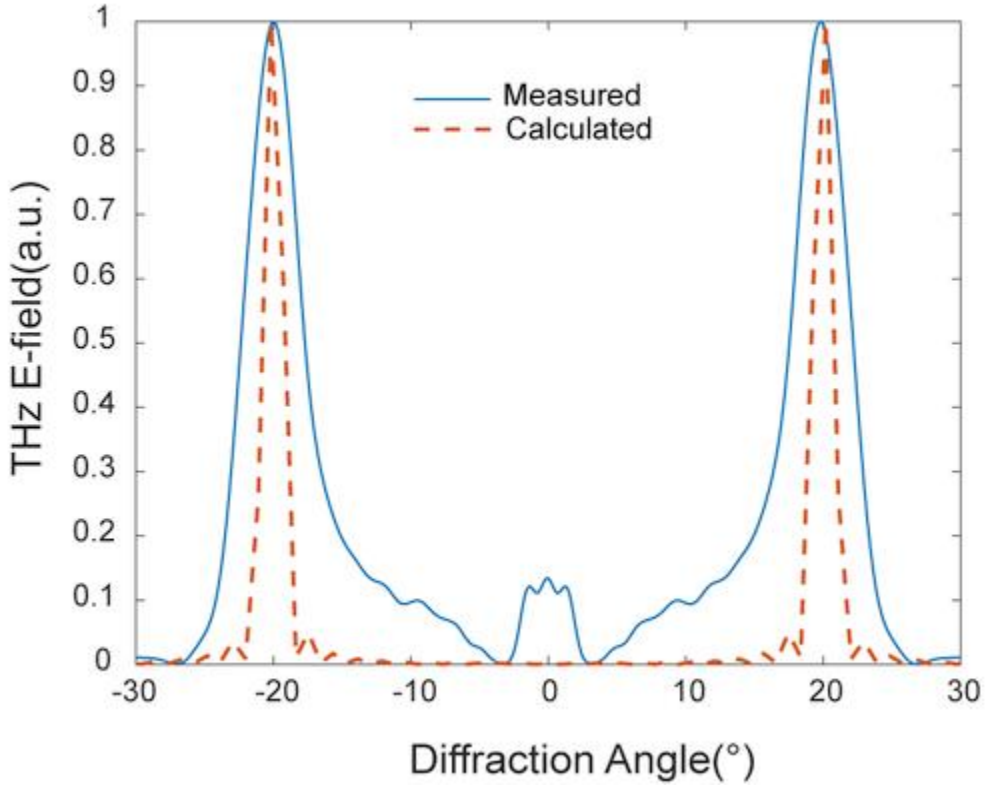
Function 1： Beam Splitting

The experimental results agree with the theoretical design





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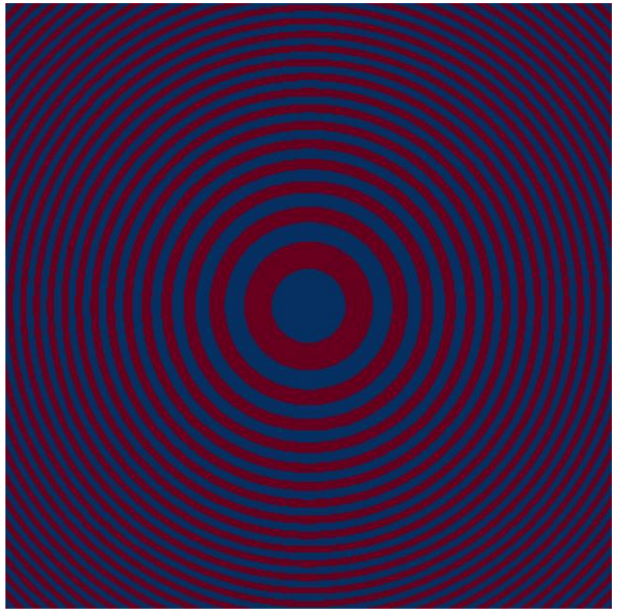
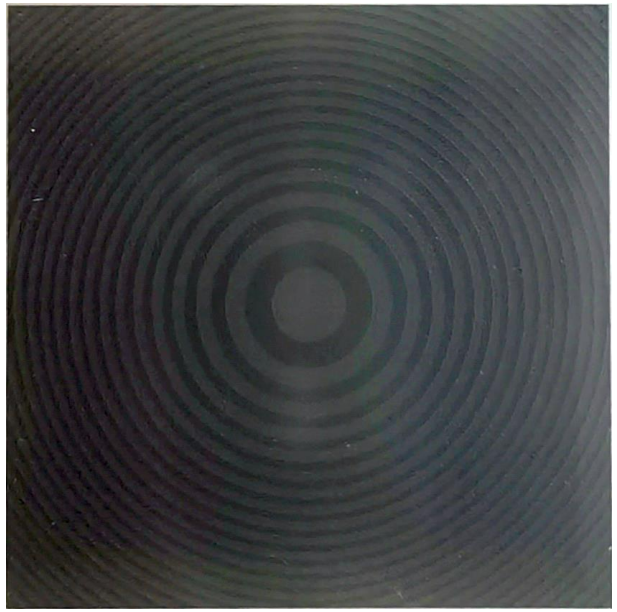
Function 2： Beam Focusing

Design for 10mm focal length of 1THz

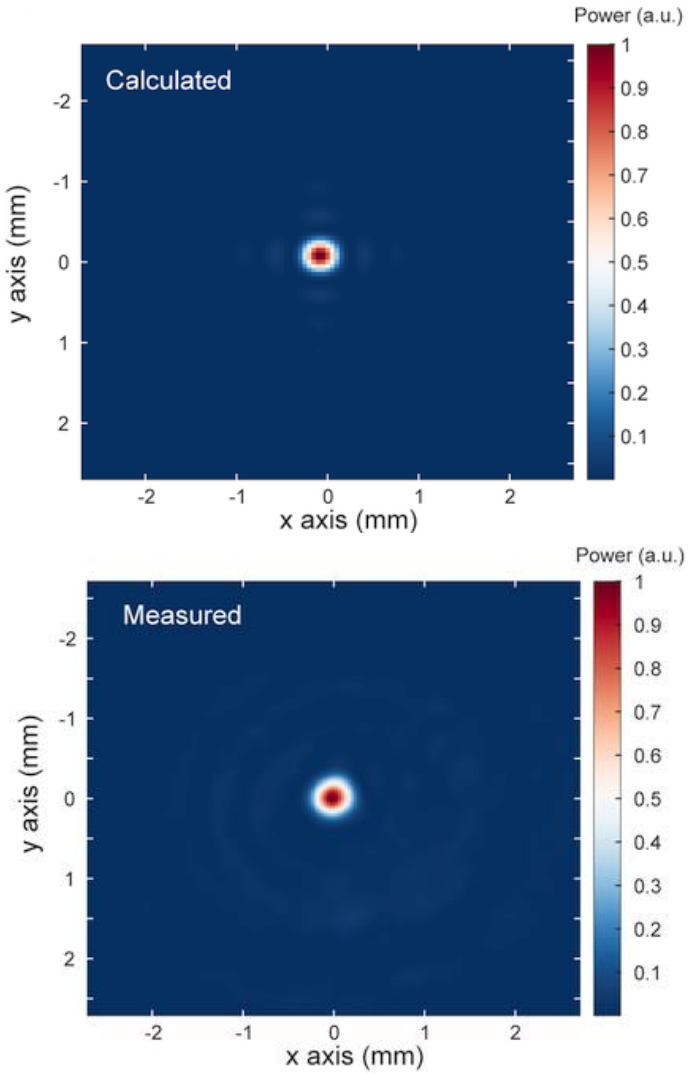


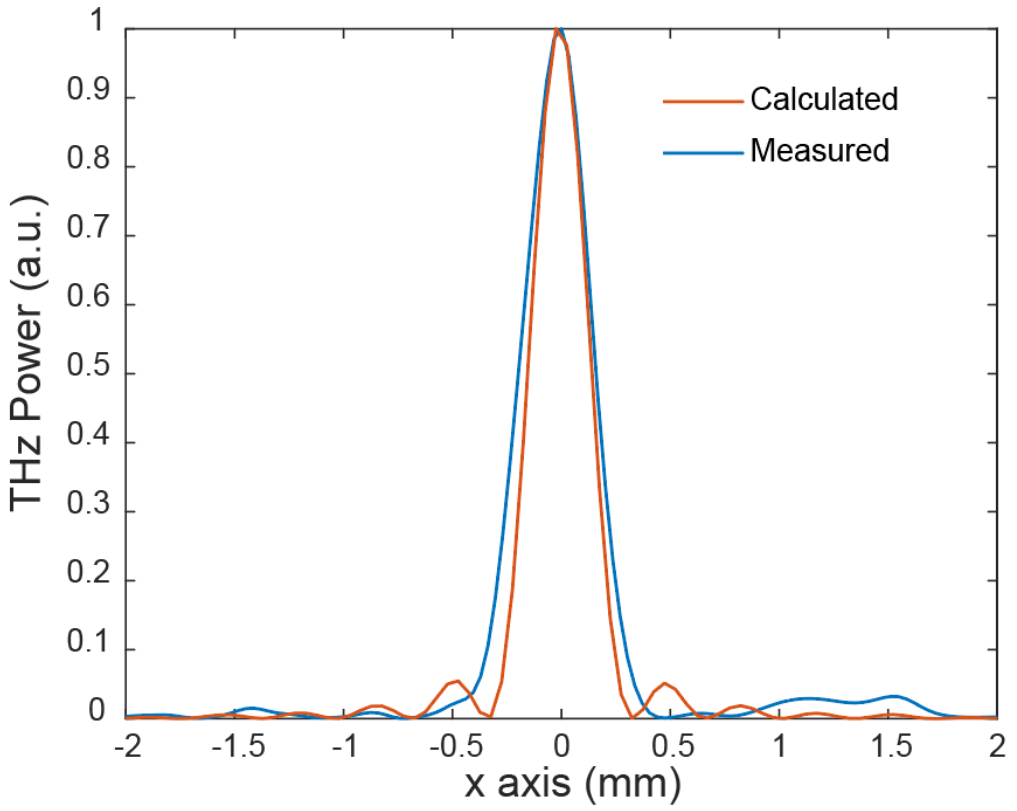


S. Chen, et al. X. Wu*, Adv. Opt. Mater., 2300899 (2023)

Function 2： Beam Focusing

Design for 10mm focal length of 1THz

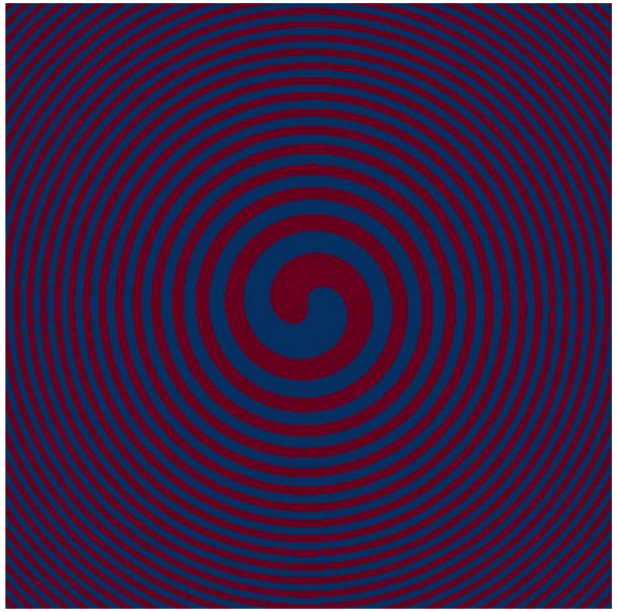


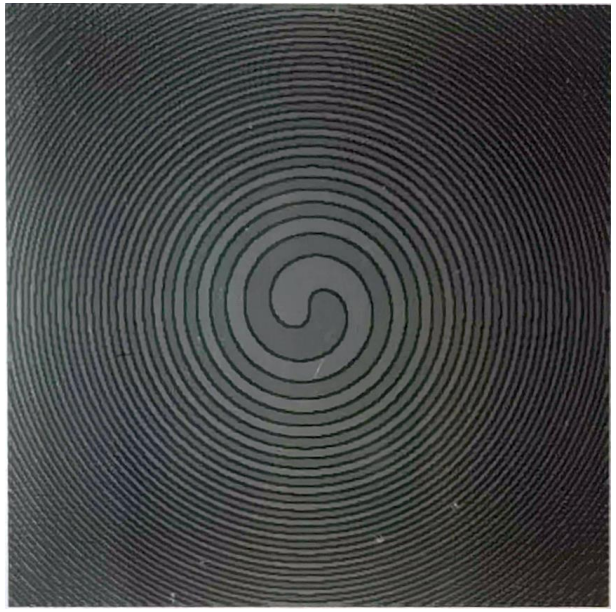


S. Chen, et al. X. Wu*, Adv. Opt. Mater., 2300899 (2023)

Function 3： Vortex Beam

Focused Vortex Beam Design for 10mm focal length of 1THz

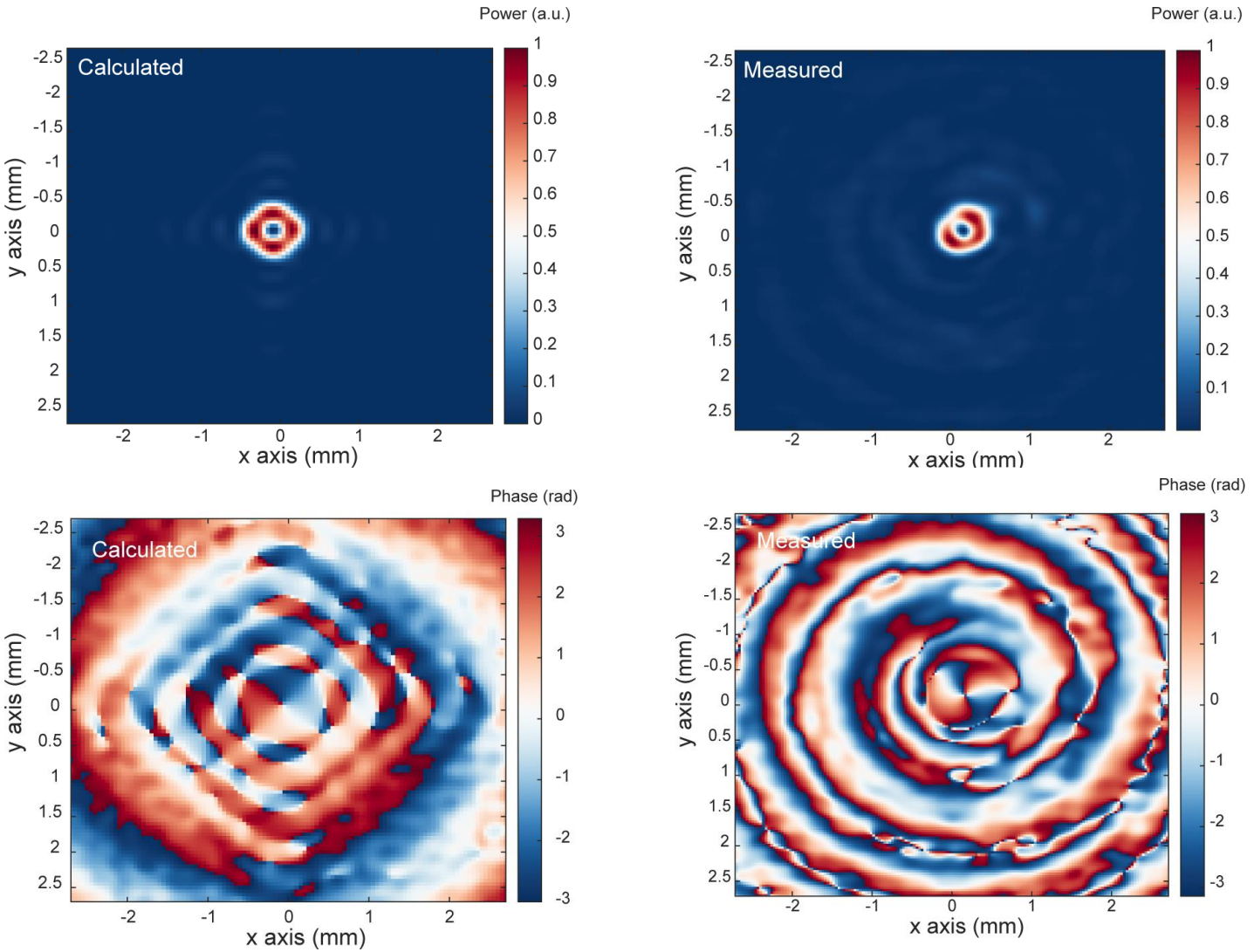




S. Chen, et al. X. Wu*, Adv. Opt. Mater., 2300899 (2023)

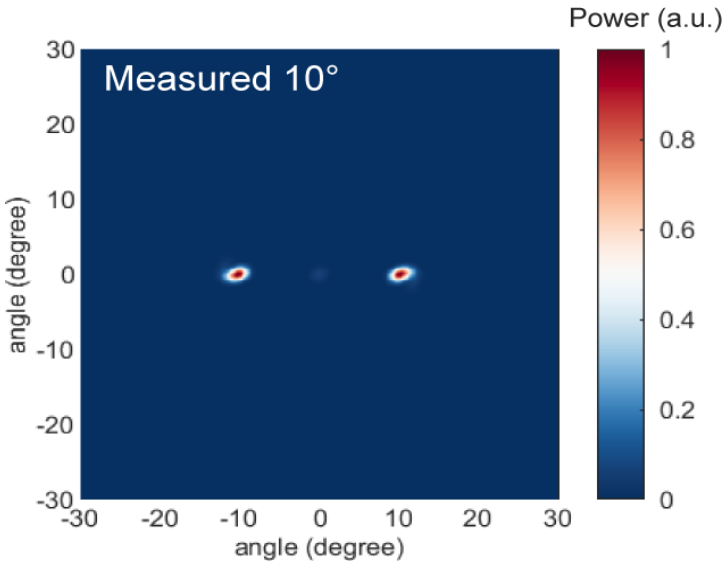
Function 3： Vortex Beam

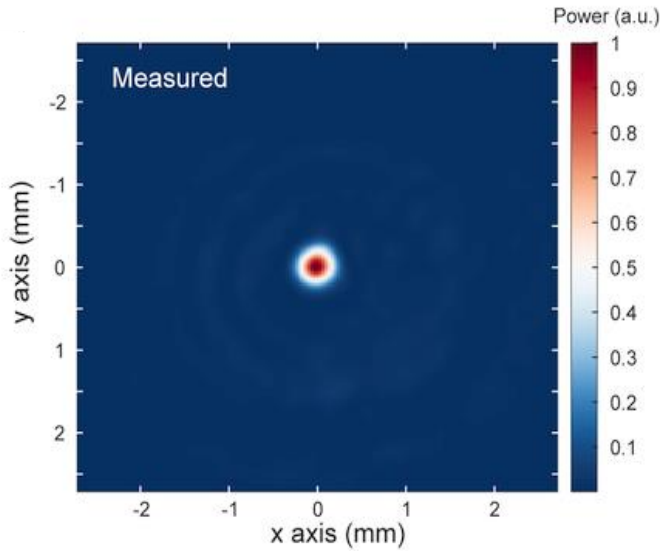
Focused Vortex Beam Design for 10mm focal length of 1THz

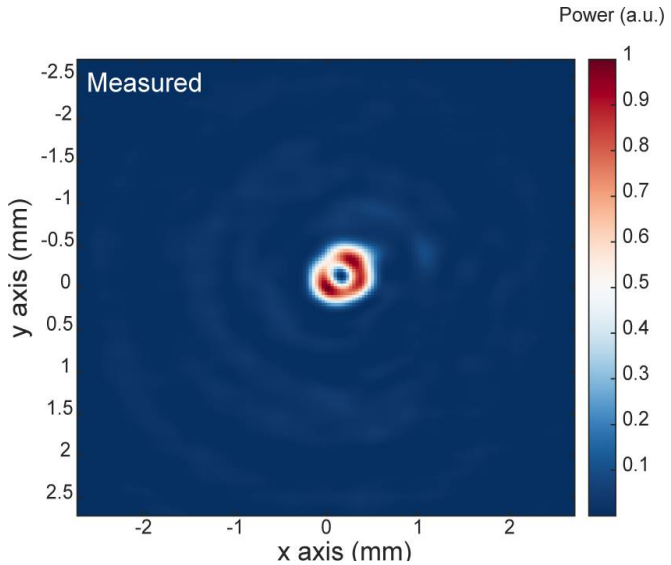


S. Chen, et al. X. Wu*, Adv. Opt. Mater., 2300899 (2023)

Summary: Spintronic Coding Metasurface



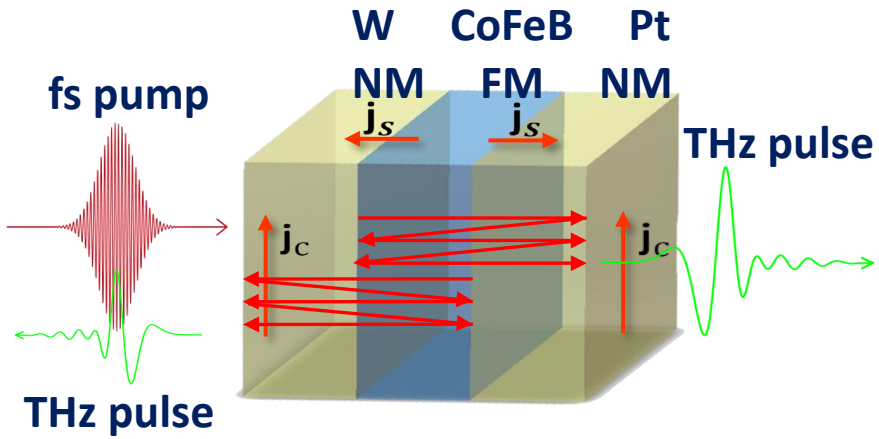


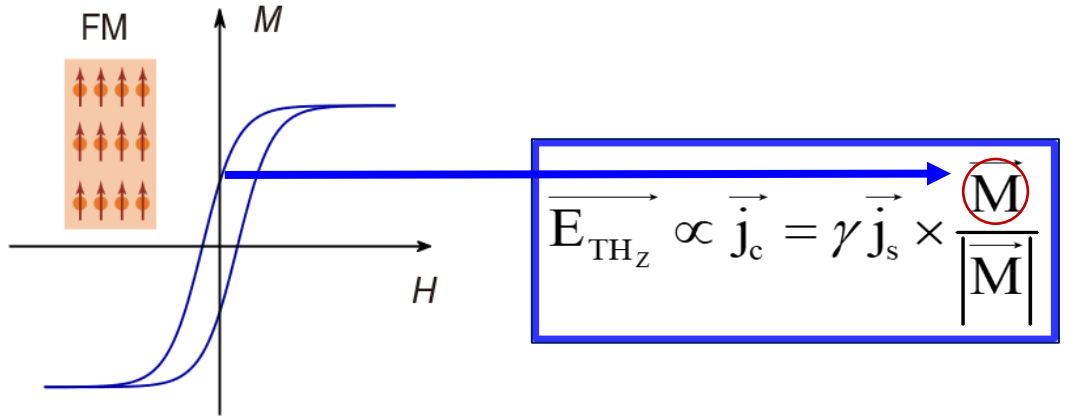


- ✓ **Binary Phase modulation**
- ✓ **Easy fabrication & Low Cost**
- ✓ **Normal incidence**
- ✓ **High damage threshold**
- ✓ **Work with kHz/MHz fs laser system**

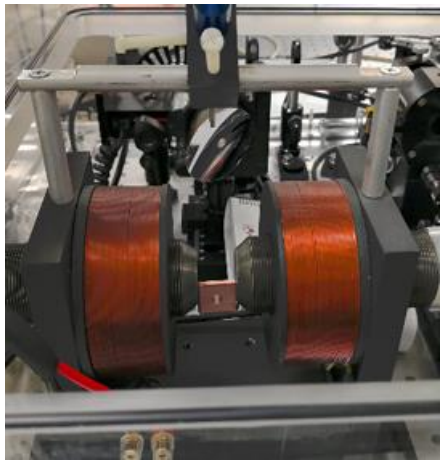
S. Chen, et al. X. Wu*, Adv. Opt. Mater., 2300899 (2023)

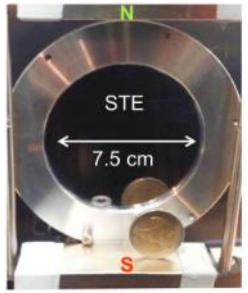
Do we have to use External Magnetic Fields ?

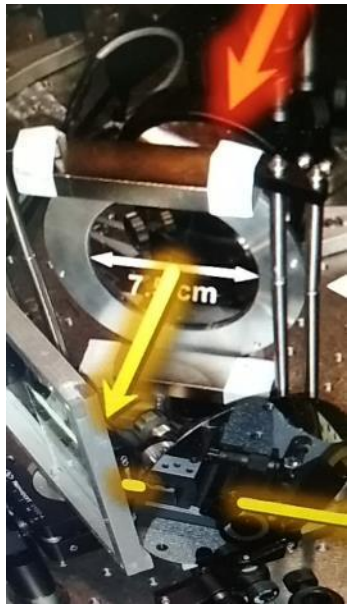




- ✓ Ultrabroadband
- ✓ Low cost
- ✓ Easy for integration→functionalization
- ✓ Polarization tunable by ***H***







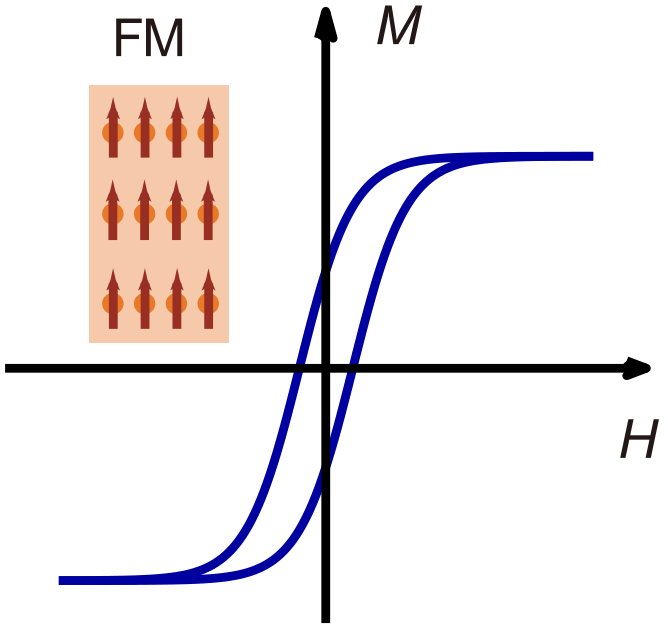
External Magnetic field is required!

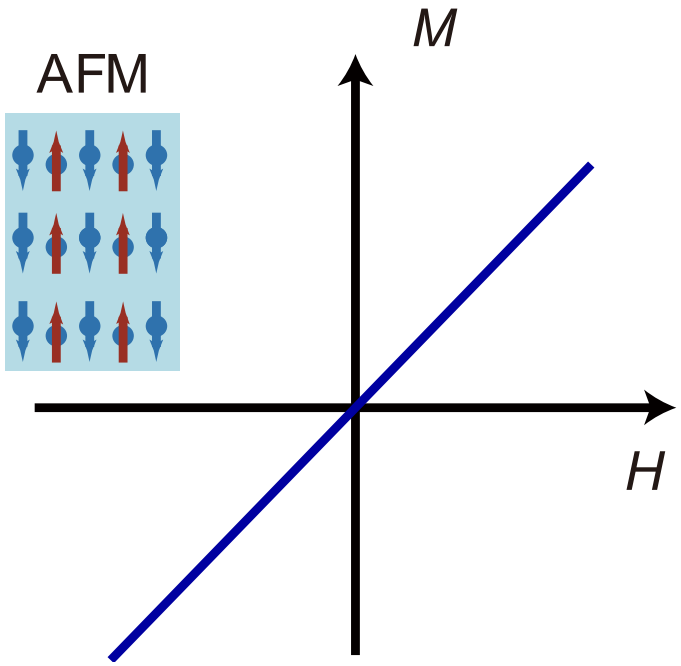
T. Seifert, et al., Nat. Photon. 10, 483 (2016)
Appl. Phys. Lett. 110, 252402 (2017)

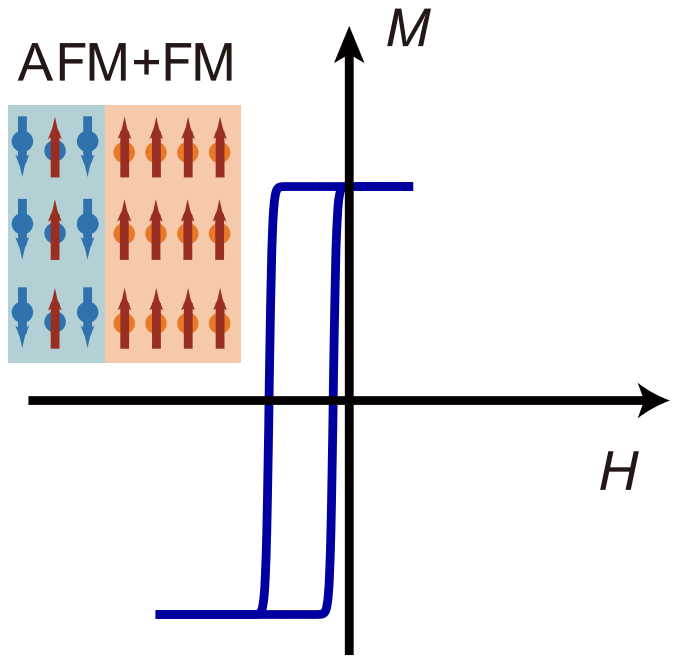
Part 1

FM/AFM without *H*

Exchange Bias Effect (Spin Pinning)



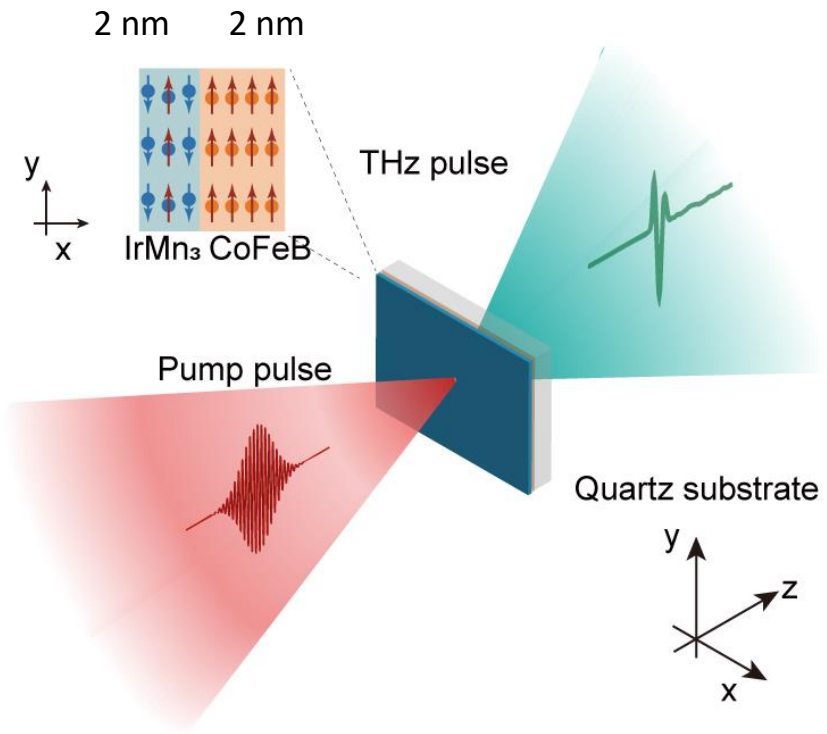


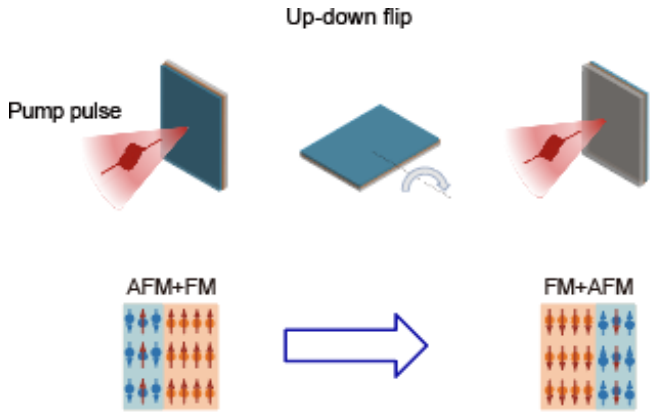


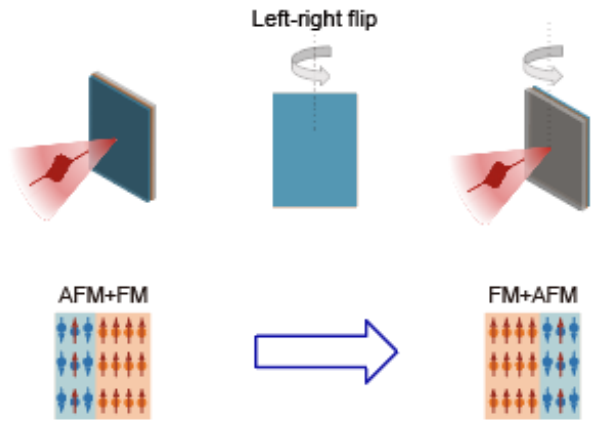
$$\overrightarrow{E_{THz}} \propto \vec{j}_c = \gamma \vec{j}_s \times \frac{\vec{M}}{|\vec{M}|}$$

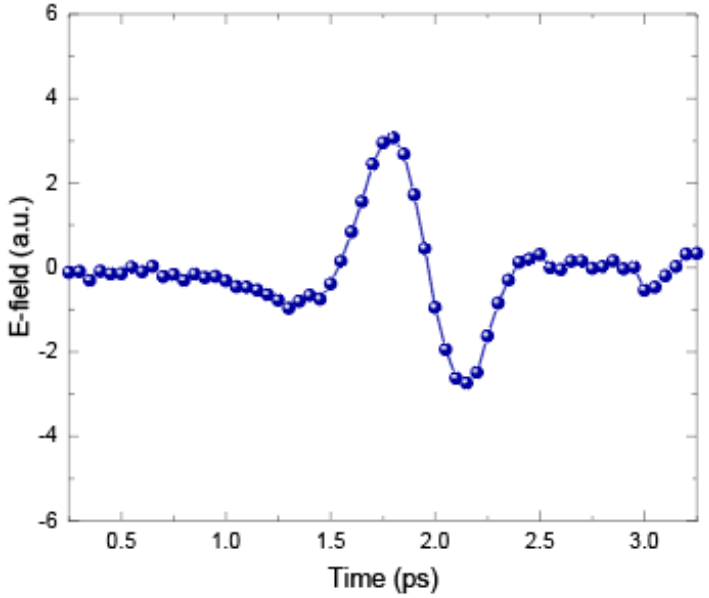
X. Wu*, et al., *Advanced Materials* 34, 2204373 (2022)

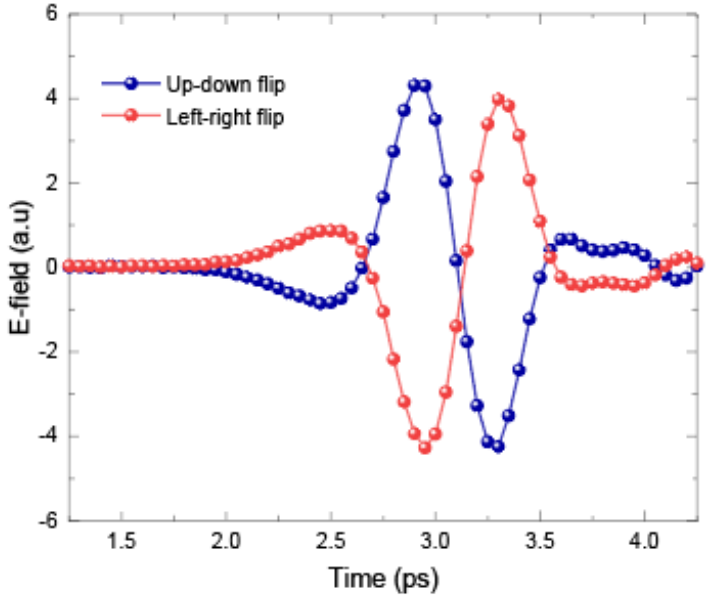
AFM-FM without Magnetic Fields





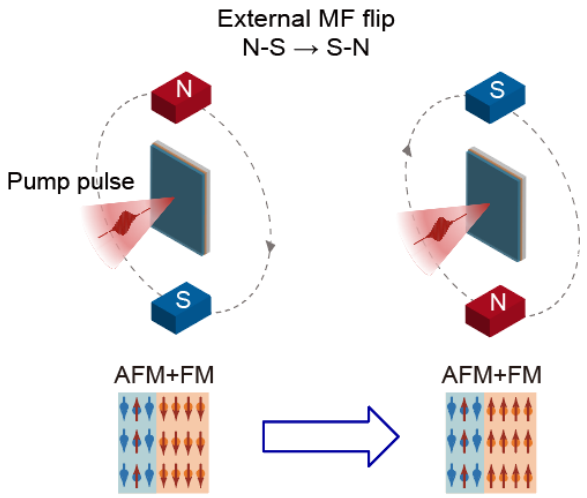


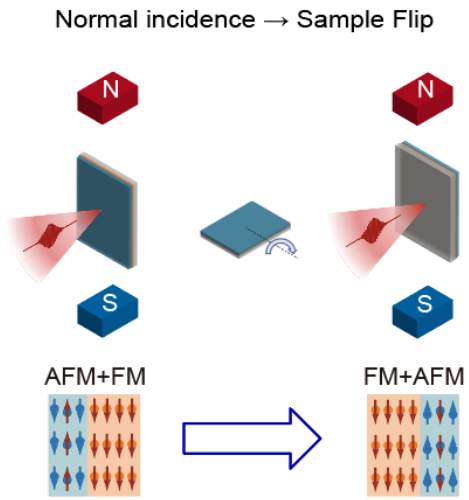


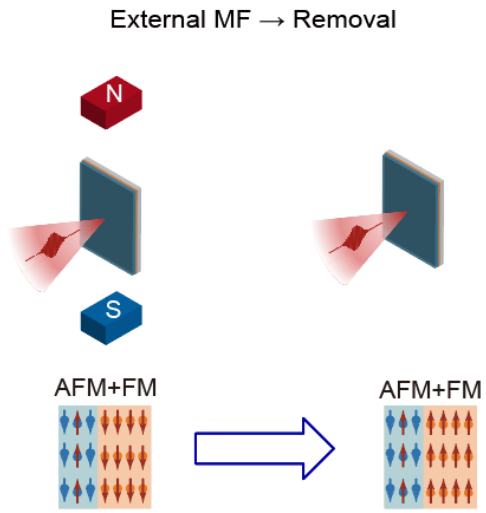


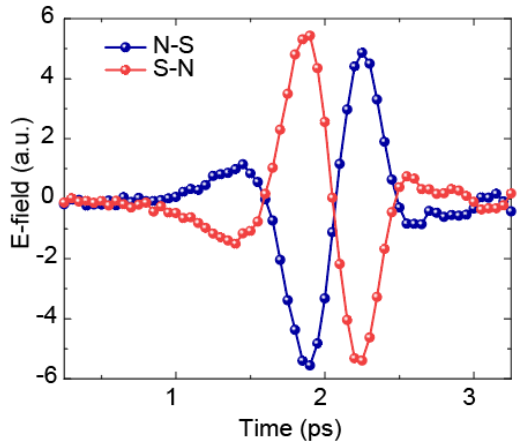
X. Wu*, et al., *Advanced Materials* 34, 2204373 (2022)

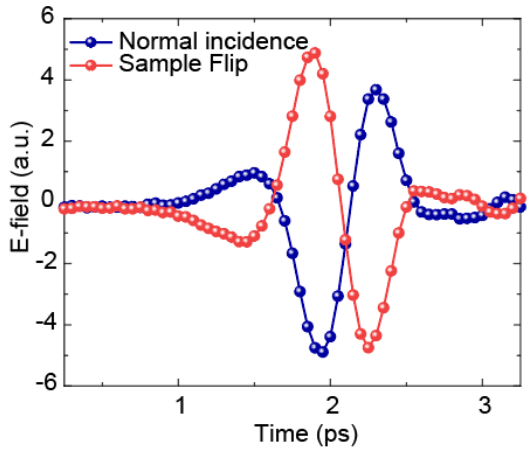
Spin-to-Charge Conversion

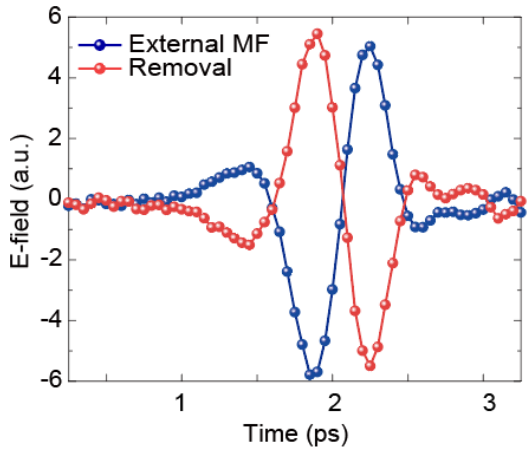






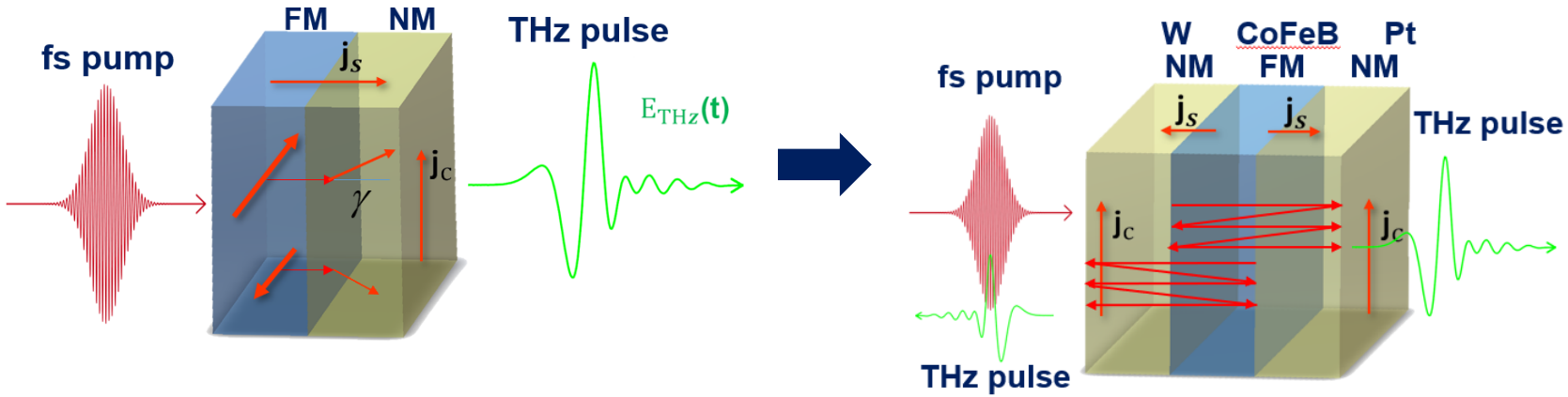


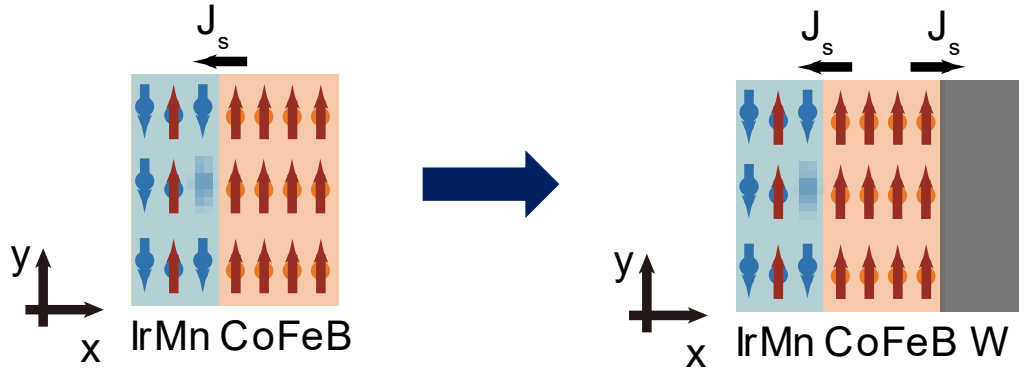


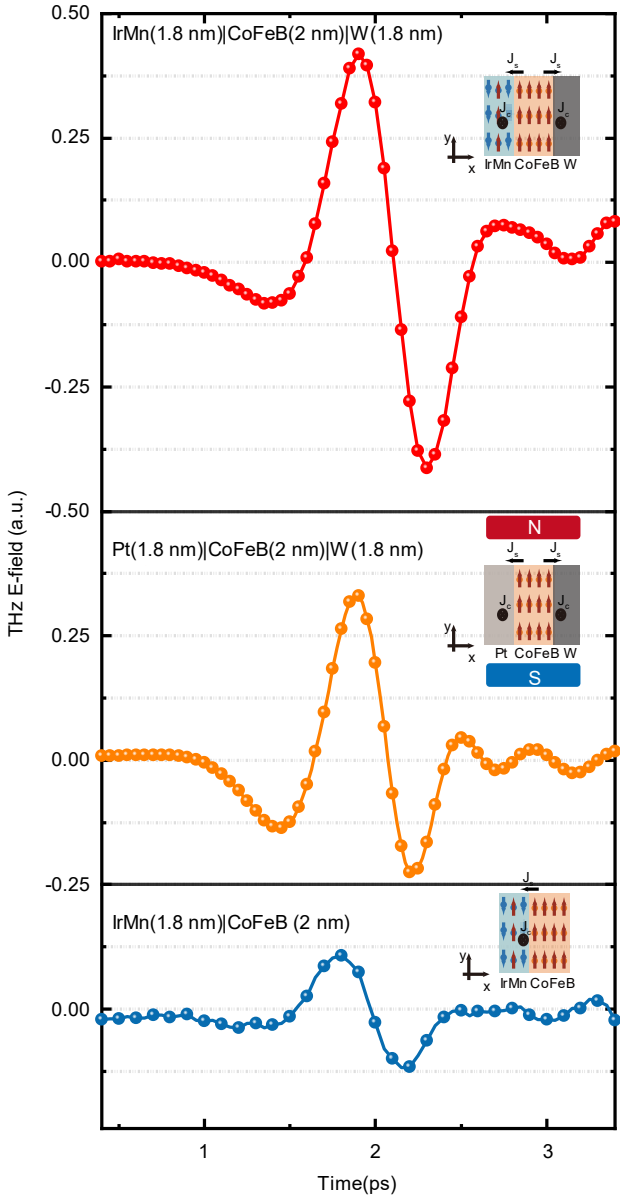


X. Wu*, et al., *Advanced Materials* 34, 2204373 (2022)

Boosted THz in IrMn/CoFeB/W

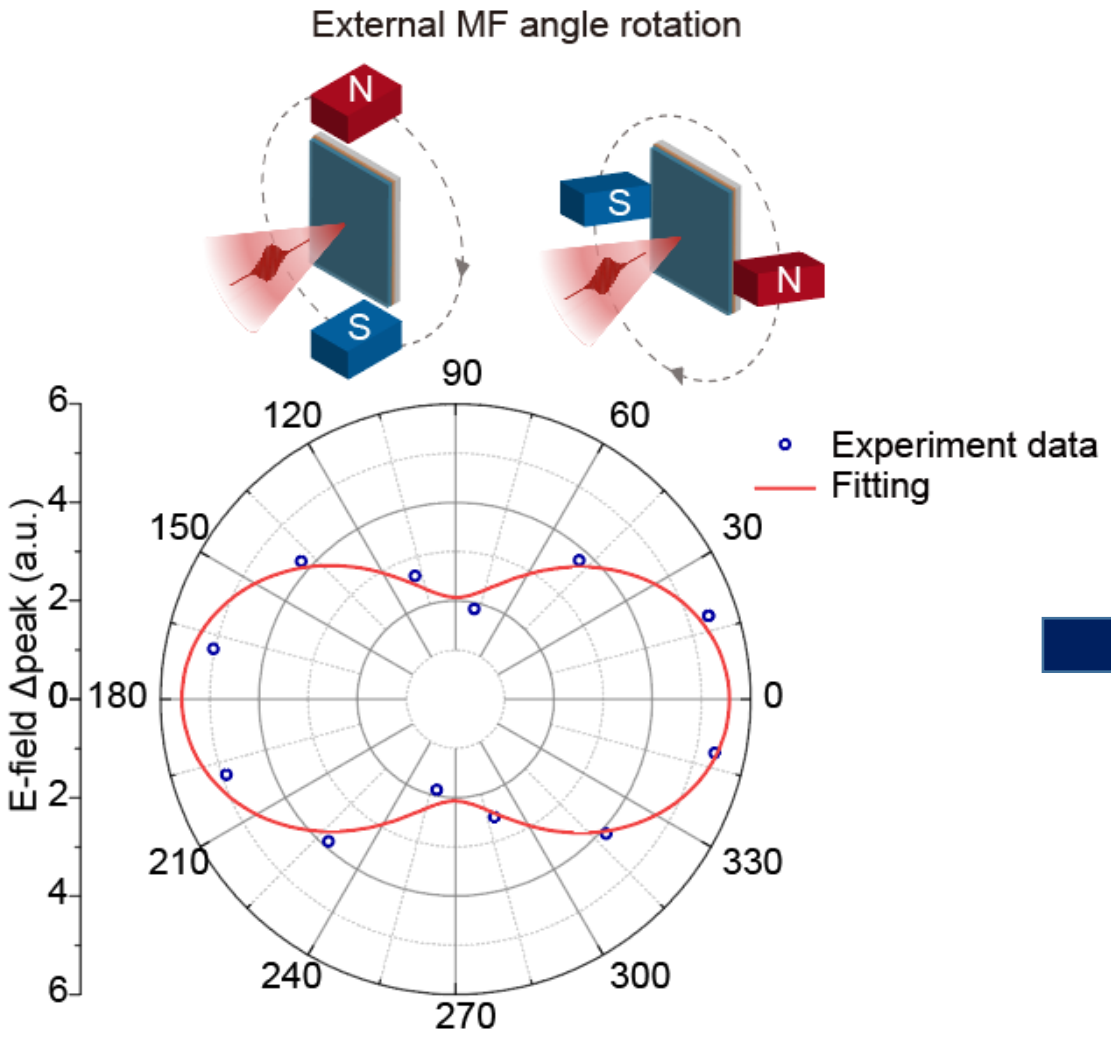


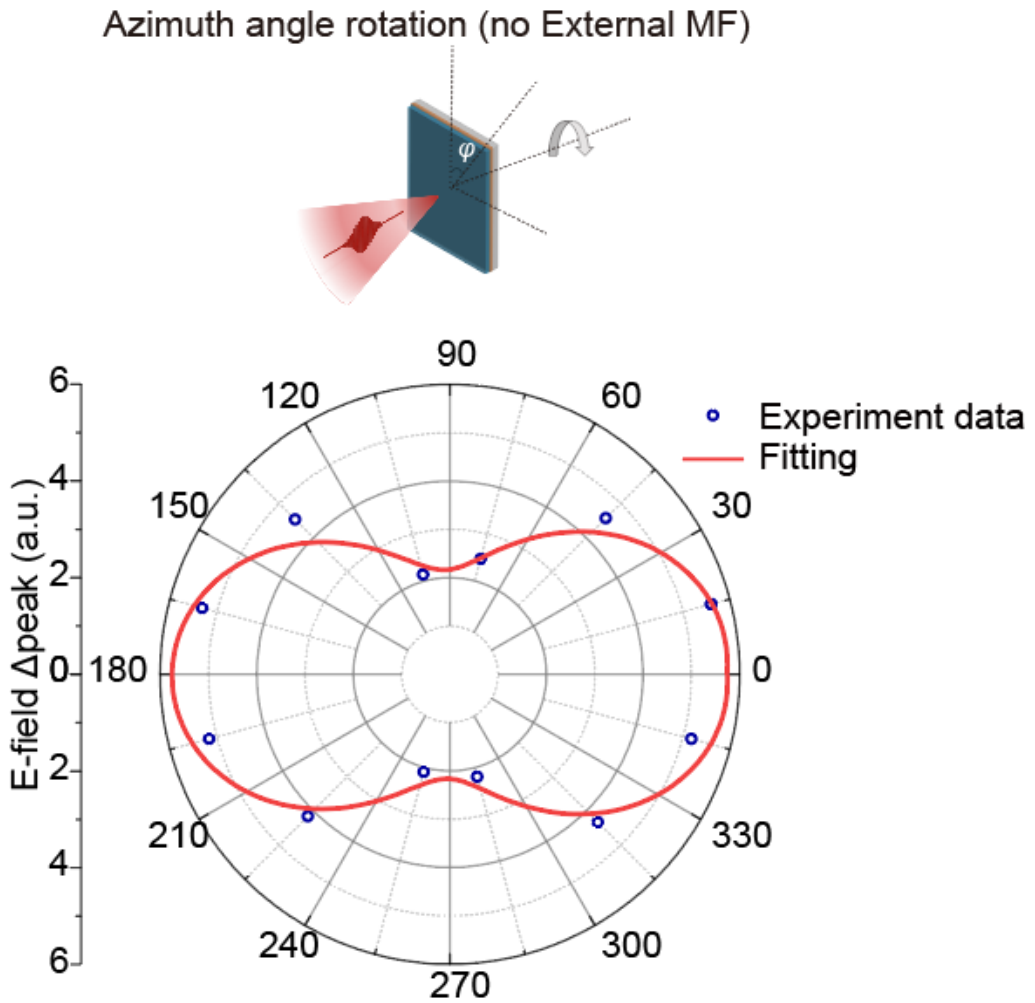




X. Wu*, et al., *Advanced Materials* 34, 2204373 (2022)

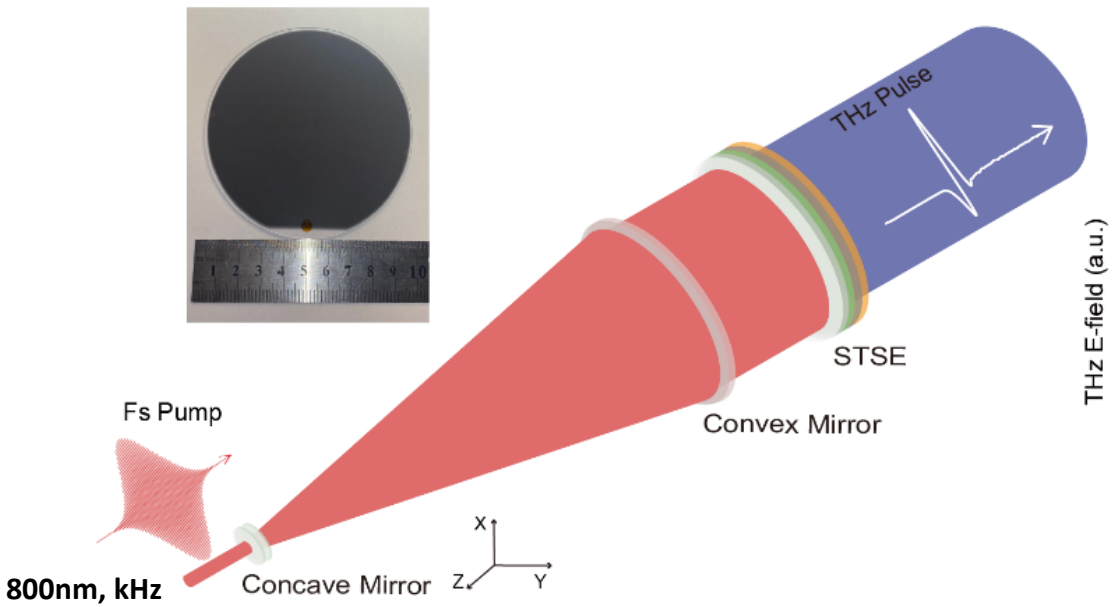
Polarization Control via Sample Azimuth

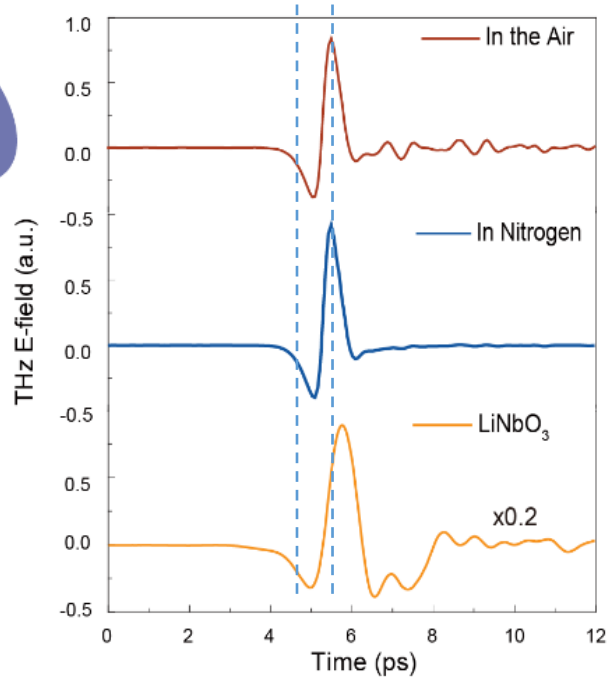


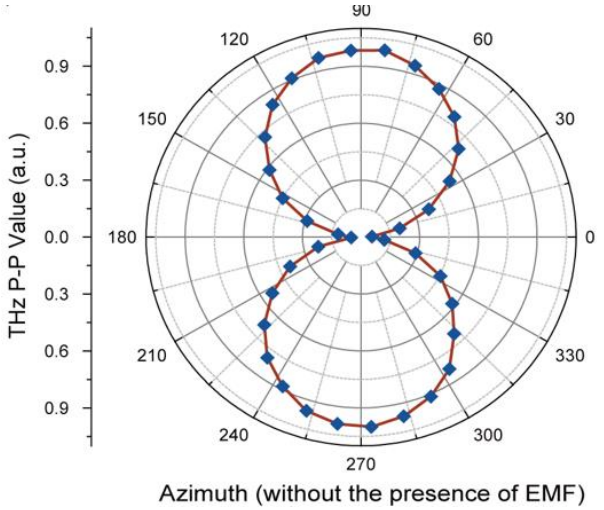


X. Wu*, et al., *Advanced Materials* 34, 2204373 (2022)

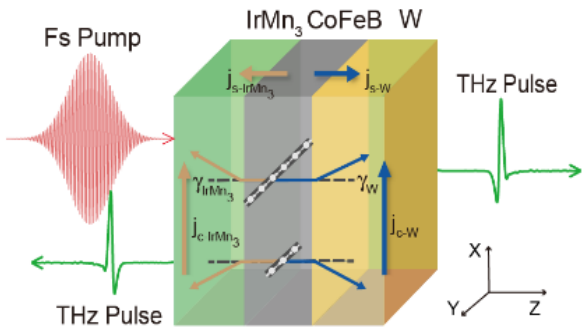
Strong-Field THz Radiation from IrMn/CoFeB/W without *H*

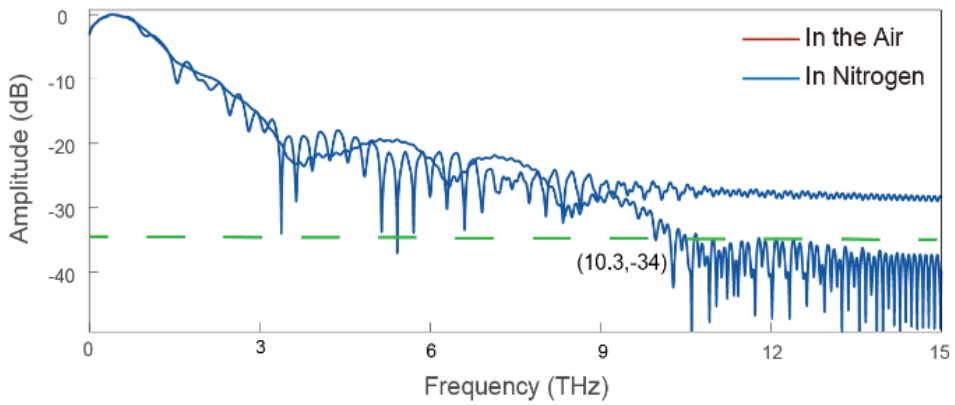


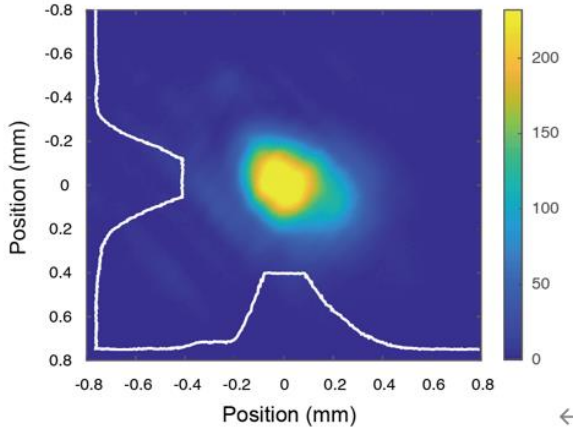




Better polarization



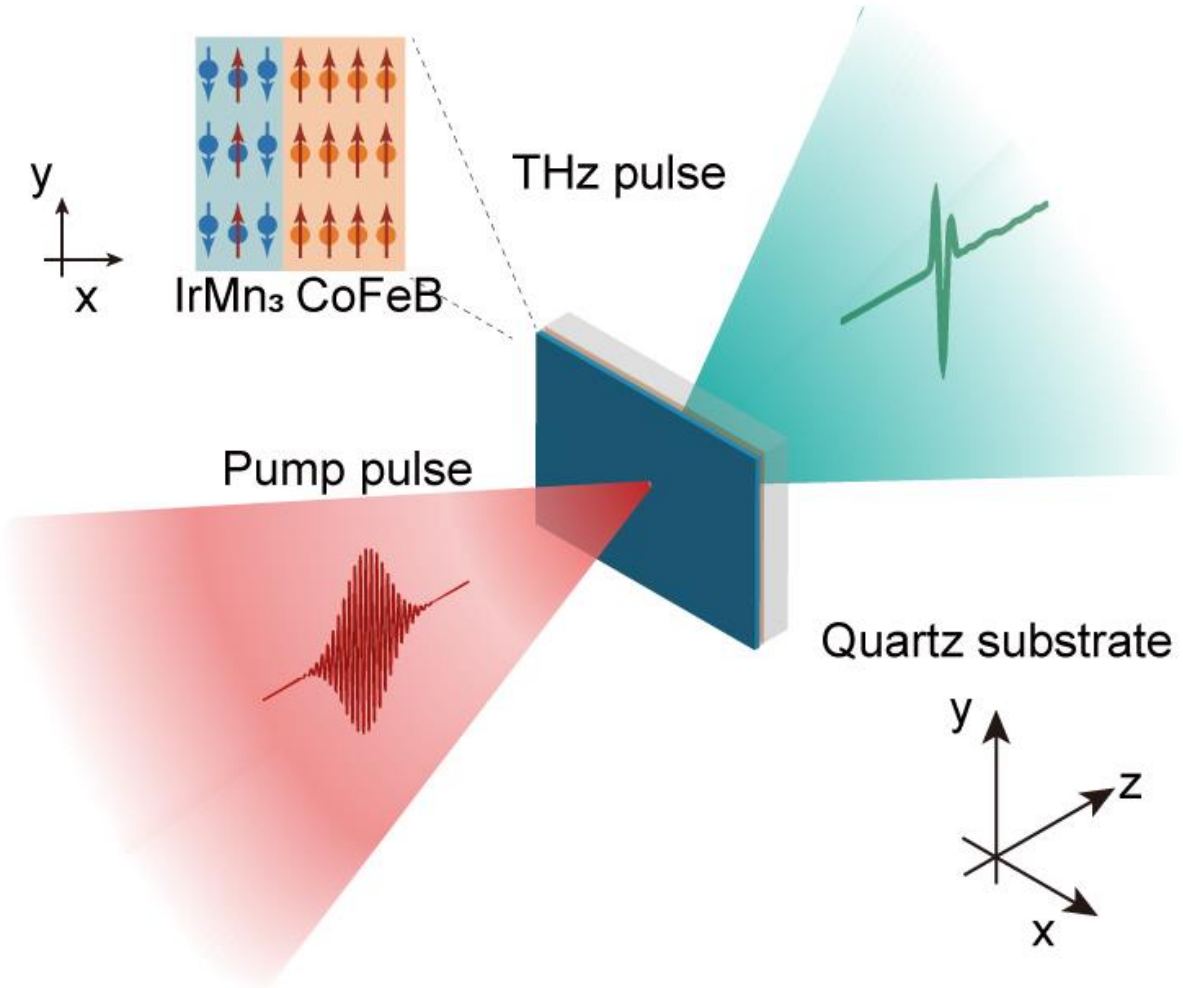




Field strength ~100kV/cm

Unpublished

Spintronic THz Emitters based on AFM-FM without *H*



- ✓ Ultrabroadband
- ✓ Shorter in the time domain
- ✓ Low cost
- ✓ Easy for integration→functionation
- ✓ Without *H*
- ✓ Polarization tunable
- ✓ Efficiency scaling up

Part 2

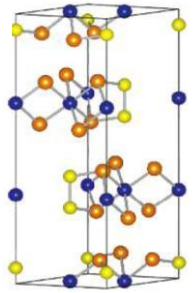
2D FM-AFM without *H*

2D Magnetic Material Spintronics

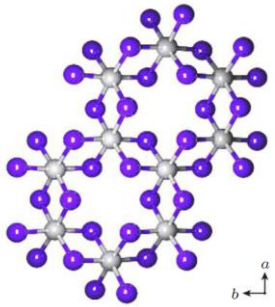
Two-dimensional(2D) magnetic materials

B. Huang, et.al., X. Xu*, ***Nature*** 546, 270 (2017)

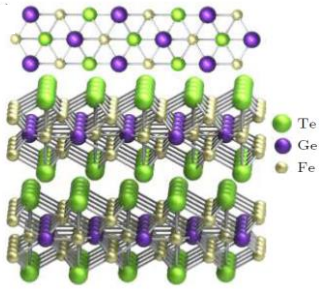
S. Liu, et.al., F. Xiu*, ***npj 2D Mater. Appl***. 1, 30 (2017)



$Cr_2Ge_2Te_6$



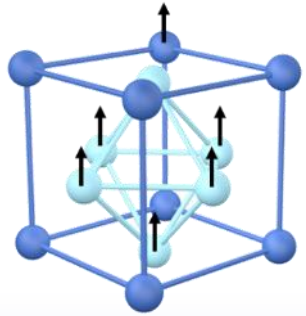
CrI_3

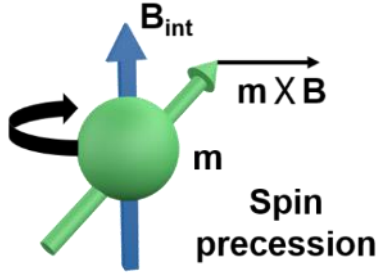


Fe_3GeTe_2

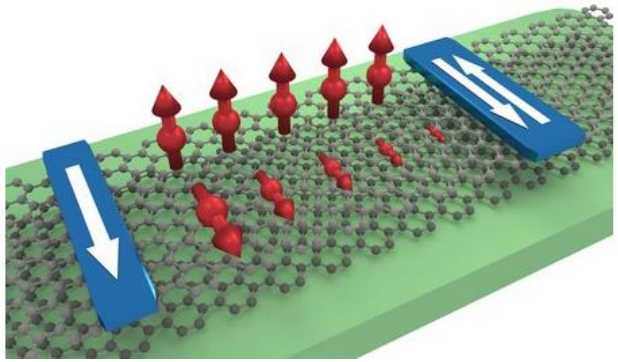
+

Spintronics

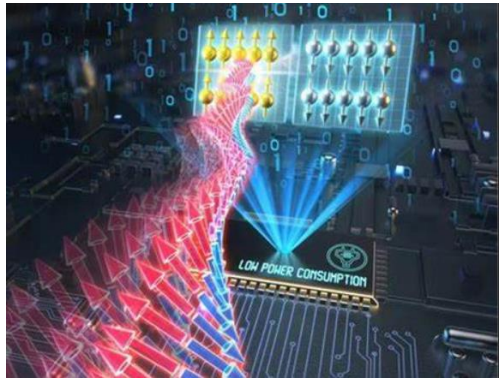




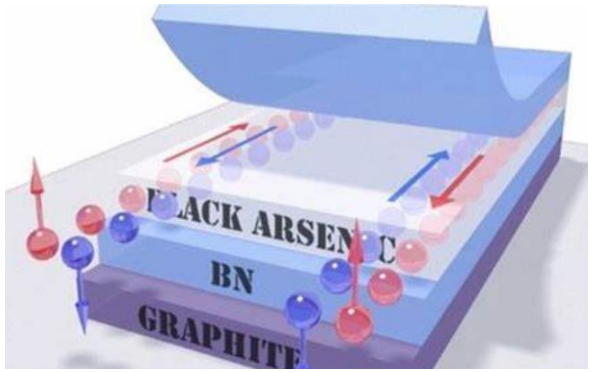
Z. Ma, et.al., X. Wu*, ***Nanophotonics*** (2022)



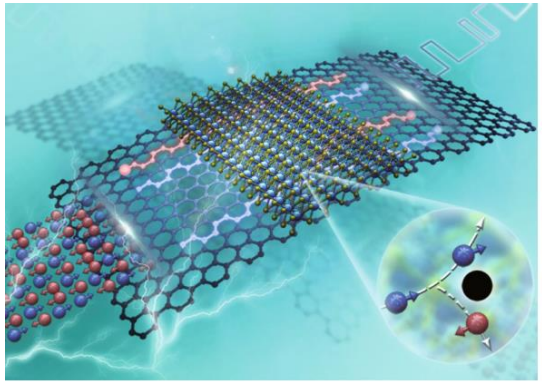
J. C. Leutenantsmeyer*,et.al., ***Phys. Rev. Lett***. 121, 127702 (2018)



Y. Wang, et.al., Hyunsoo Yang*, ***Science***, 366, 1125 (2019)



F. Sheng, et.al., Y. Zheng*, ***Nature***, 593, 56 (2021)



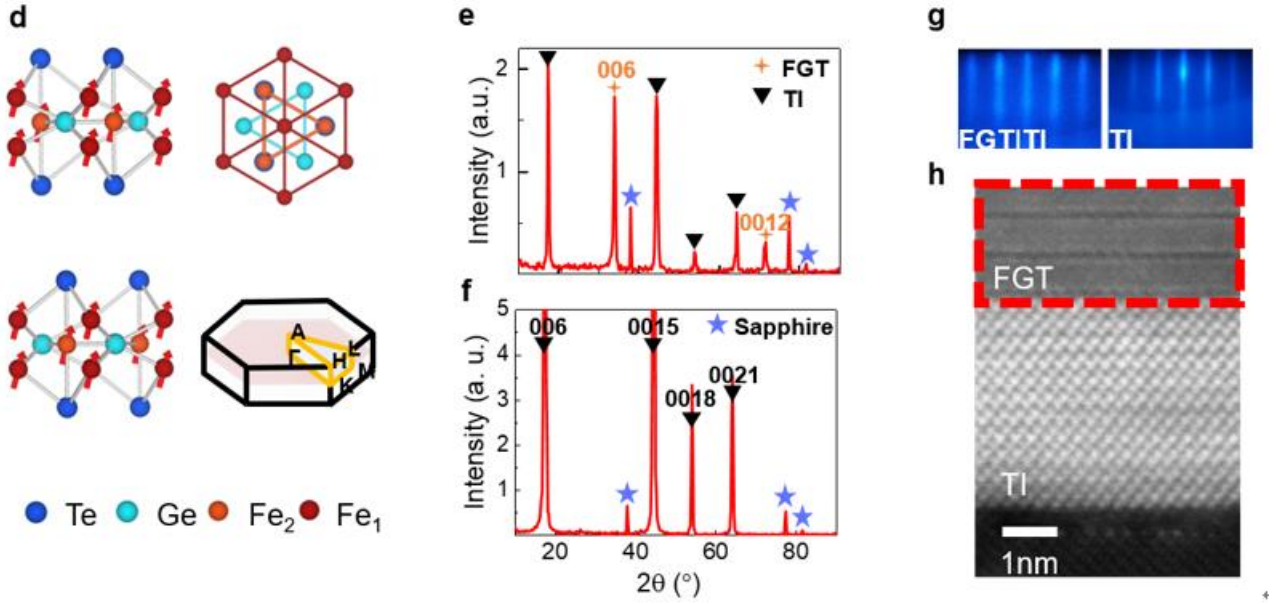
Y. Liu*, et.al., ***Nano-Micro Lett***., 12, 93 (2020)

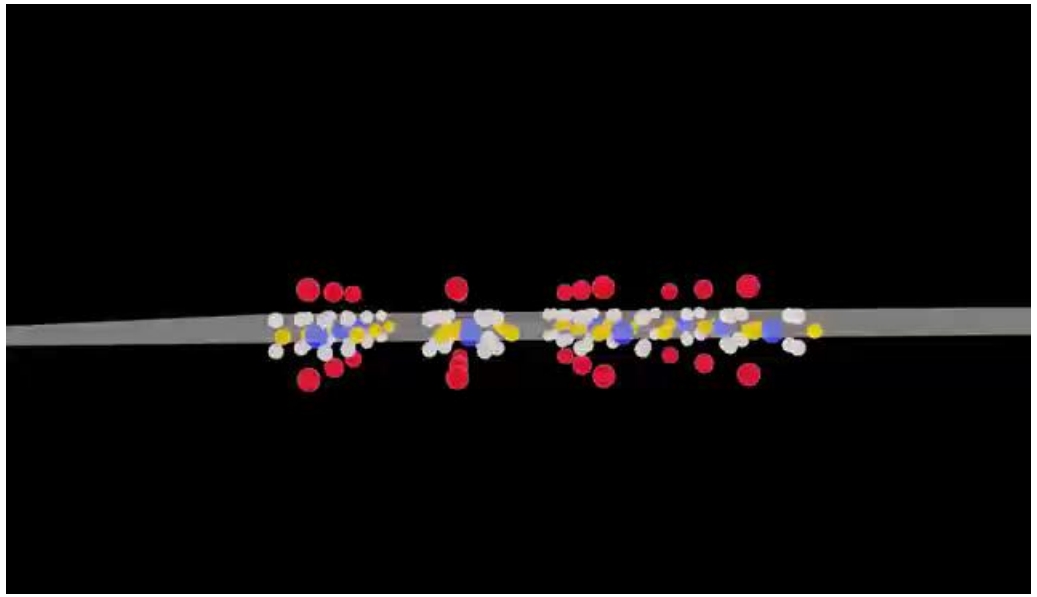
How to realize the room temperature magnetism of Fe_3GeTe_2 ?

Fe_3GeTe_2 and topological insulator Bi_2Te_3 heterostructure

Two functions of TI: Induced room temperature magnetism

and large spin Hall angle

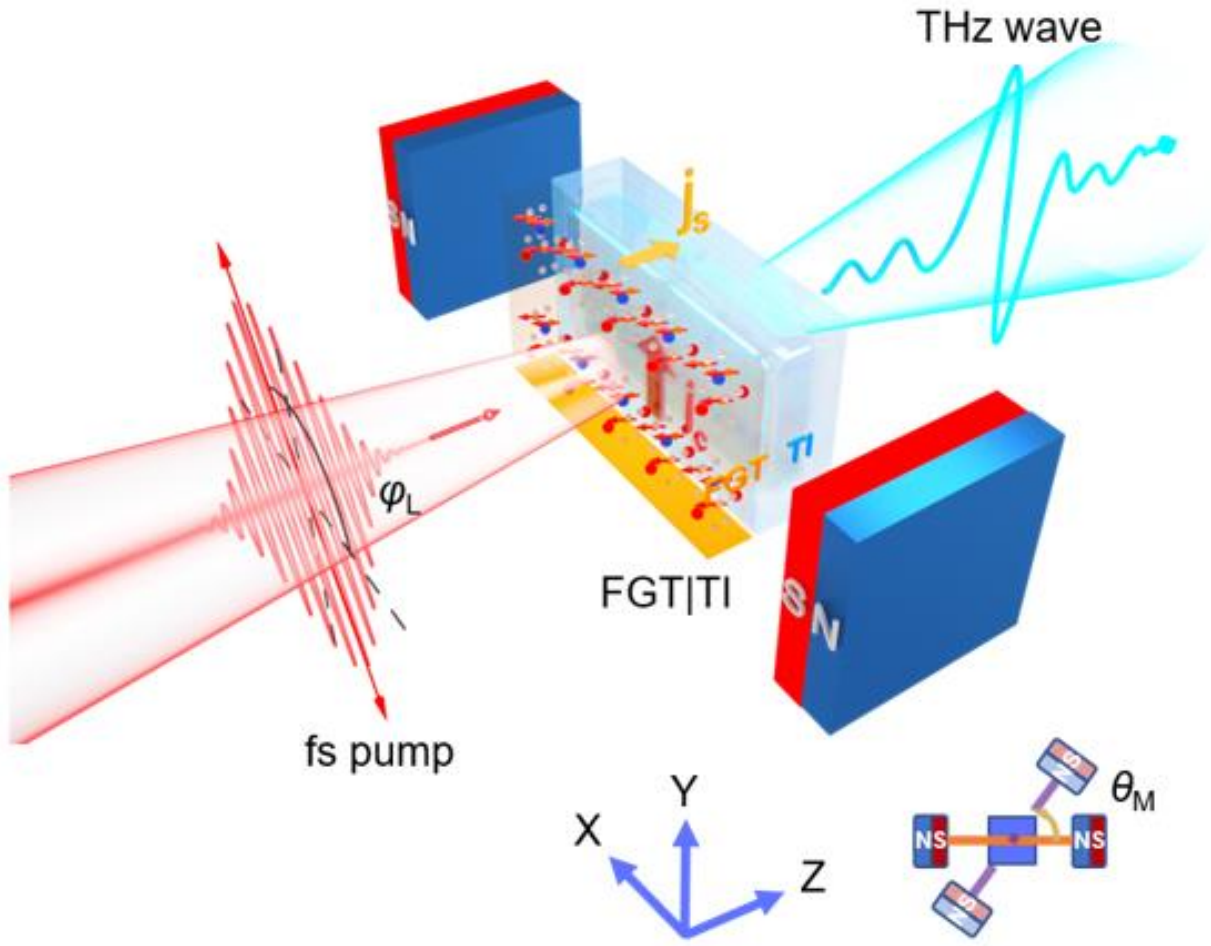




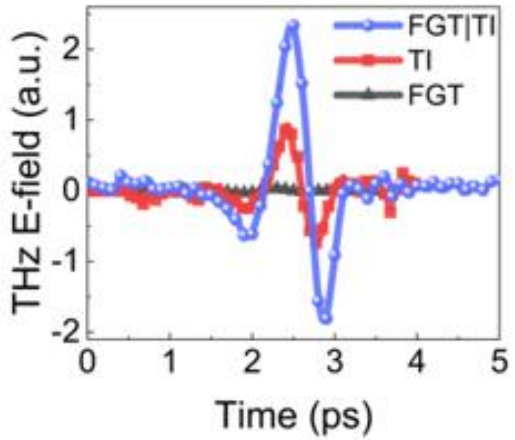
X.H. Chen, et al., X. Wu*, *Adv. Mater*. 34, 2106172 (2022)

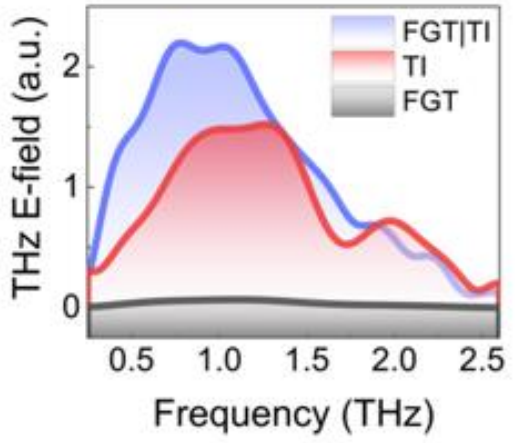
How to generate and detect femtosecond spin current in FGTs ?

Femtosecond laser pulse pumped FGT generates femtosecond spin current, which is detected by coherent THz emission spectroscopy



800nm Oscillator





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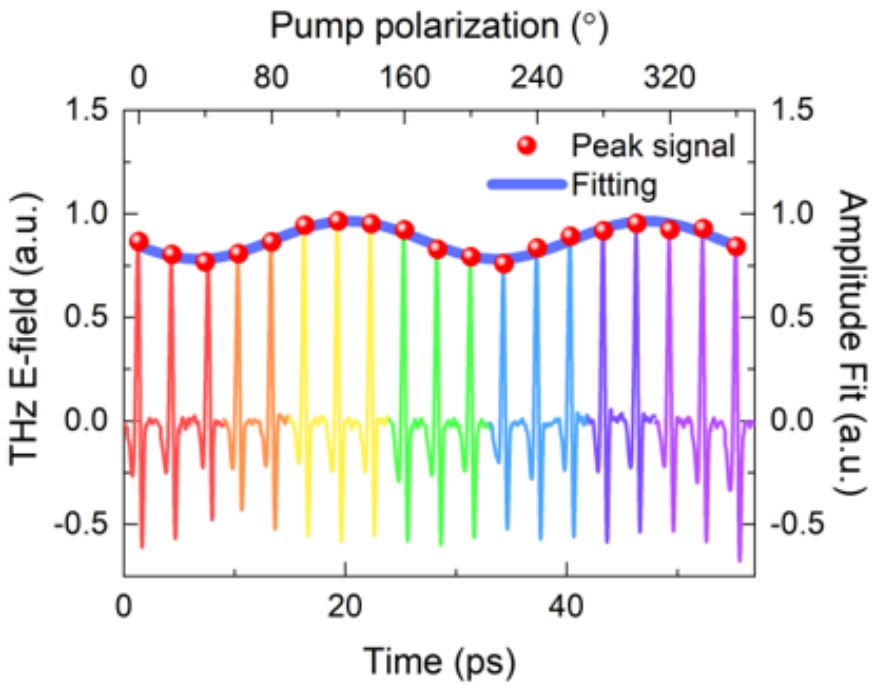
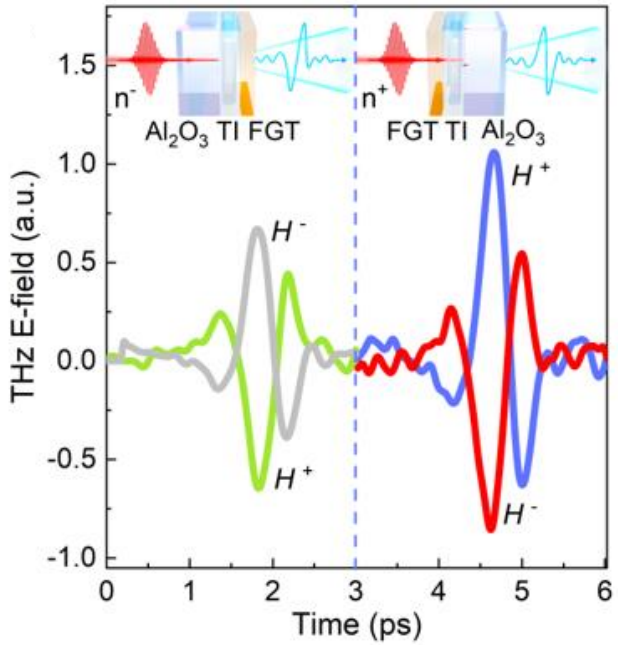
What is the mechanism of THz radiation ?

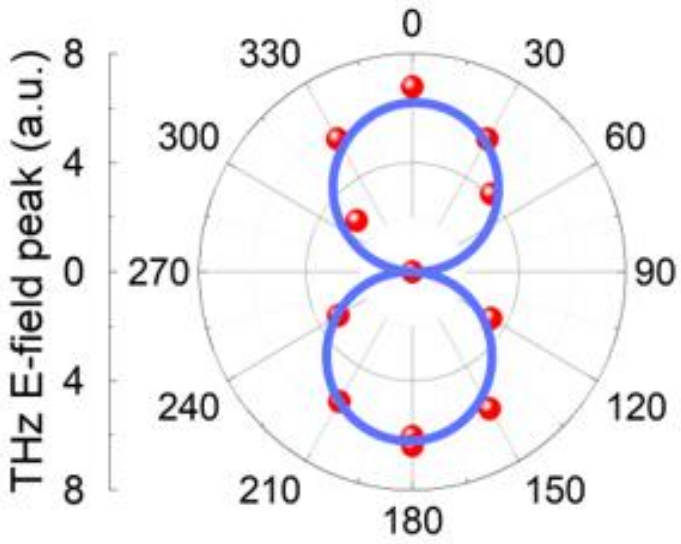
Polarization dependence of pump laser



Influence of incident surface



Influence of applied magnetic field direction



Spin-to-charge conversion effect:

$$\overrightarrow{E_{THz}} \propto \vec{j}_c = \gamma \vec{j}_s \times \frac{\vec{M}}{|\vec{M}|}$$

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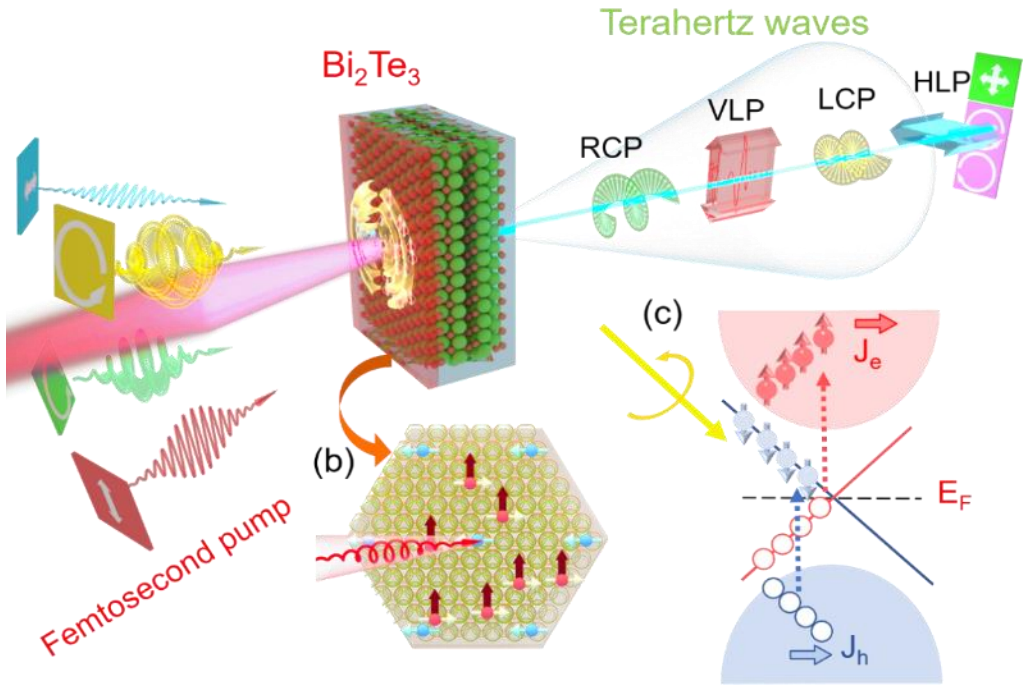
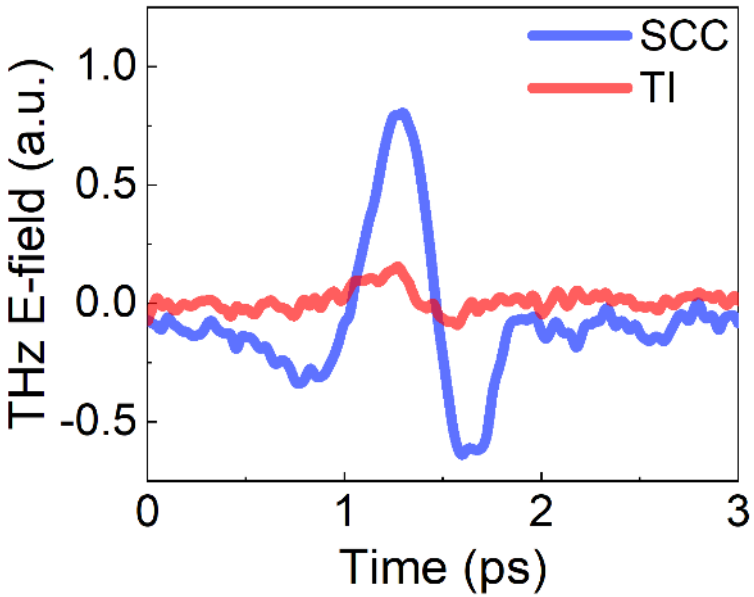
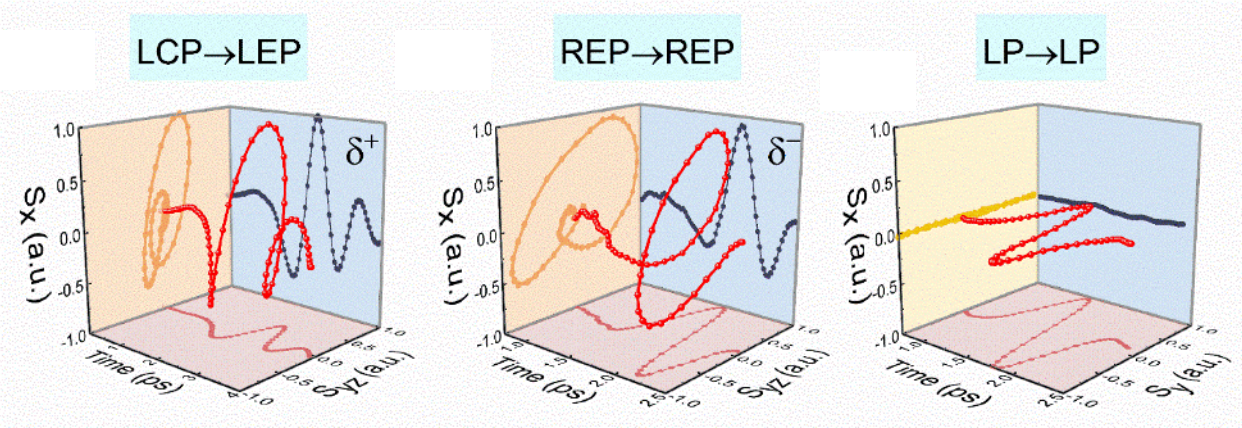
How to deduct THz emission interference from TIs ?







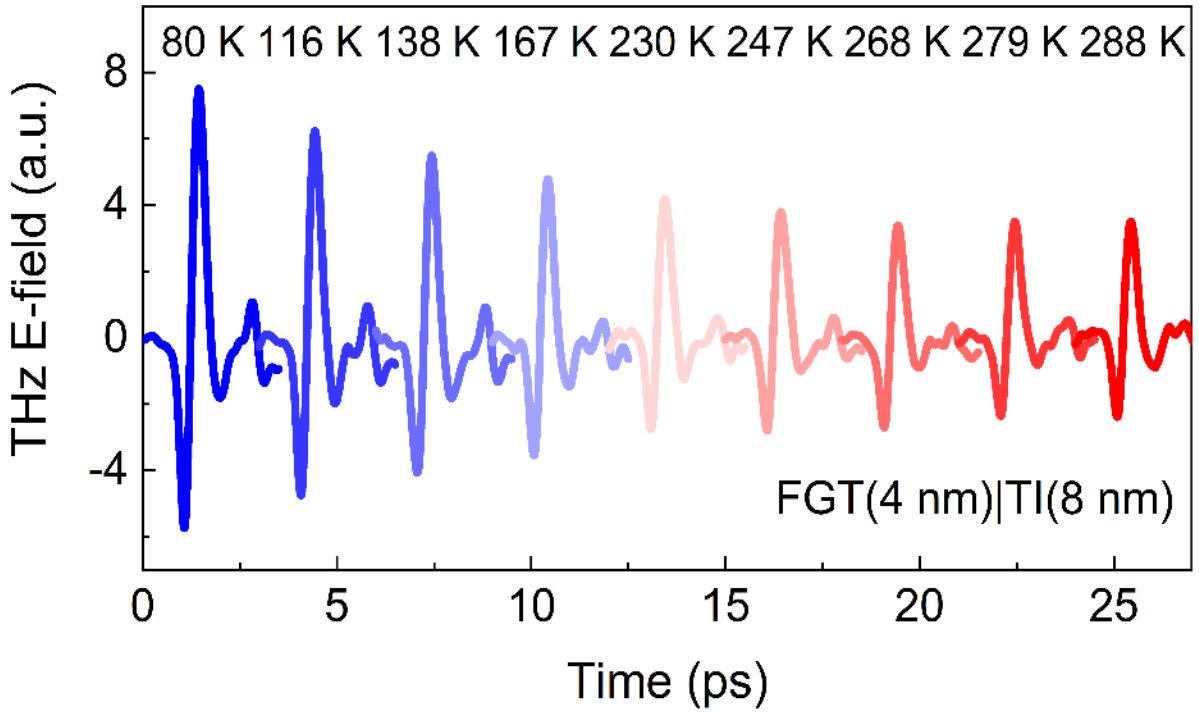
The linear photovoltaic effect of TI depends on the linear polarization direction of pump light, and the spin-to-charge conversion effect is independent of polarization

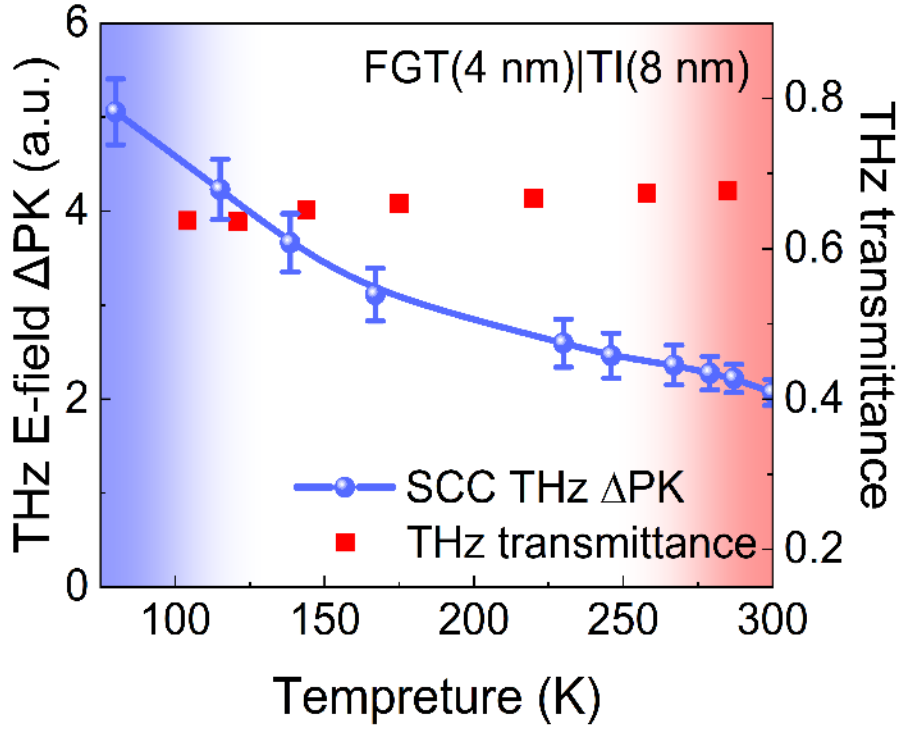
H. Zhao, et al., X. Wu*, *Adv. Photon.* 2 (6), 066003 (2020)

Does the sample temperature have an effect on THz emission ?

Cryogenically cooling the sample by the liquid nitrogen,

and the magnetism of FGT is enhanced so as the THz emission





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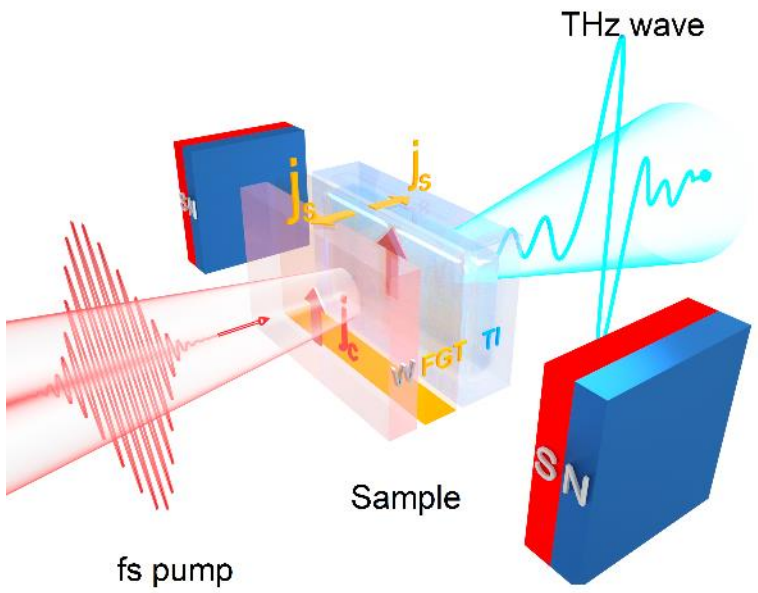
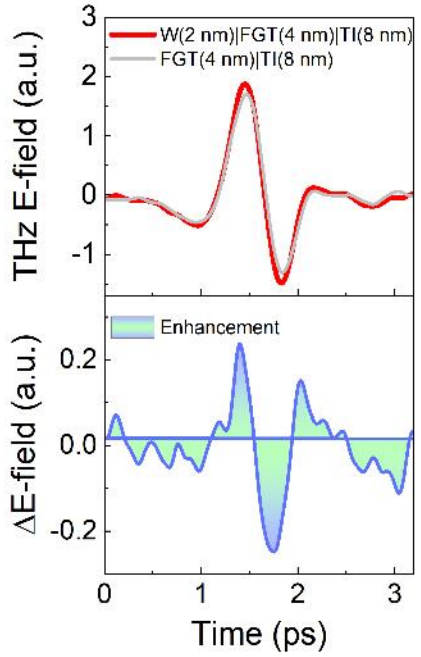
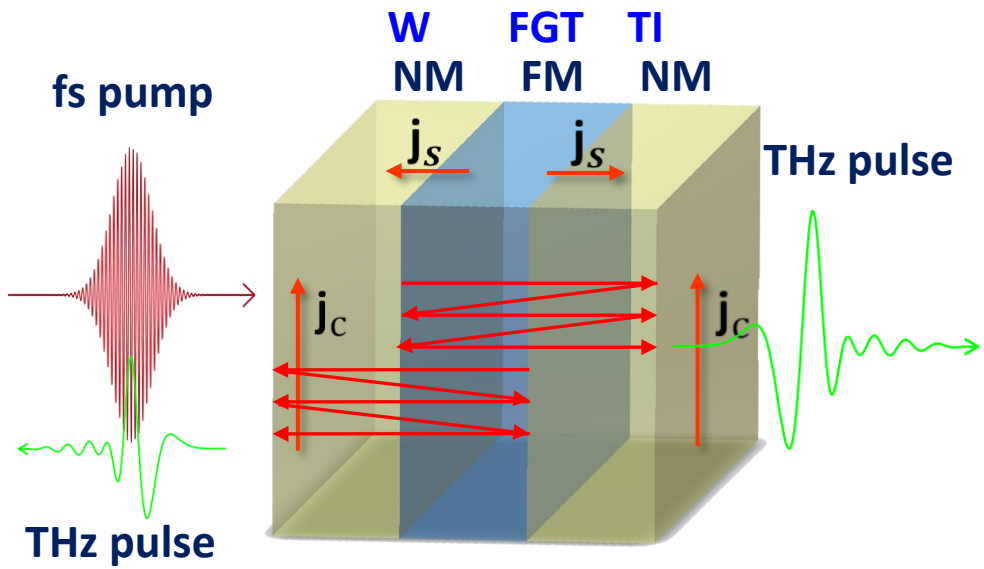
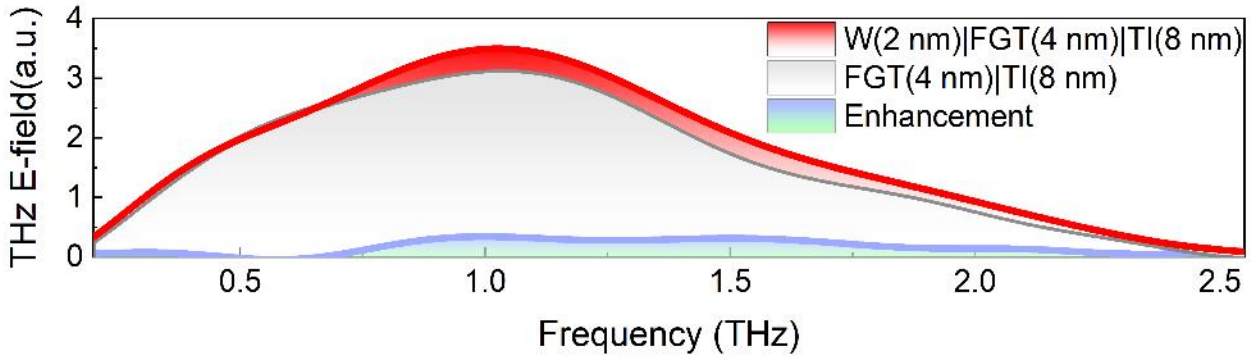
Further enhancement from trilayer heterostructure ?





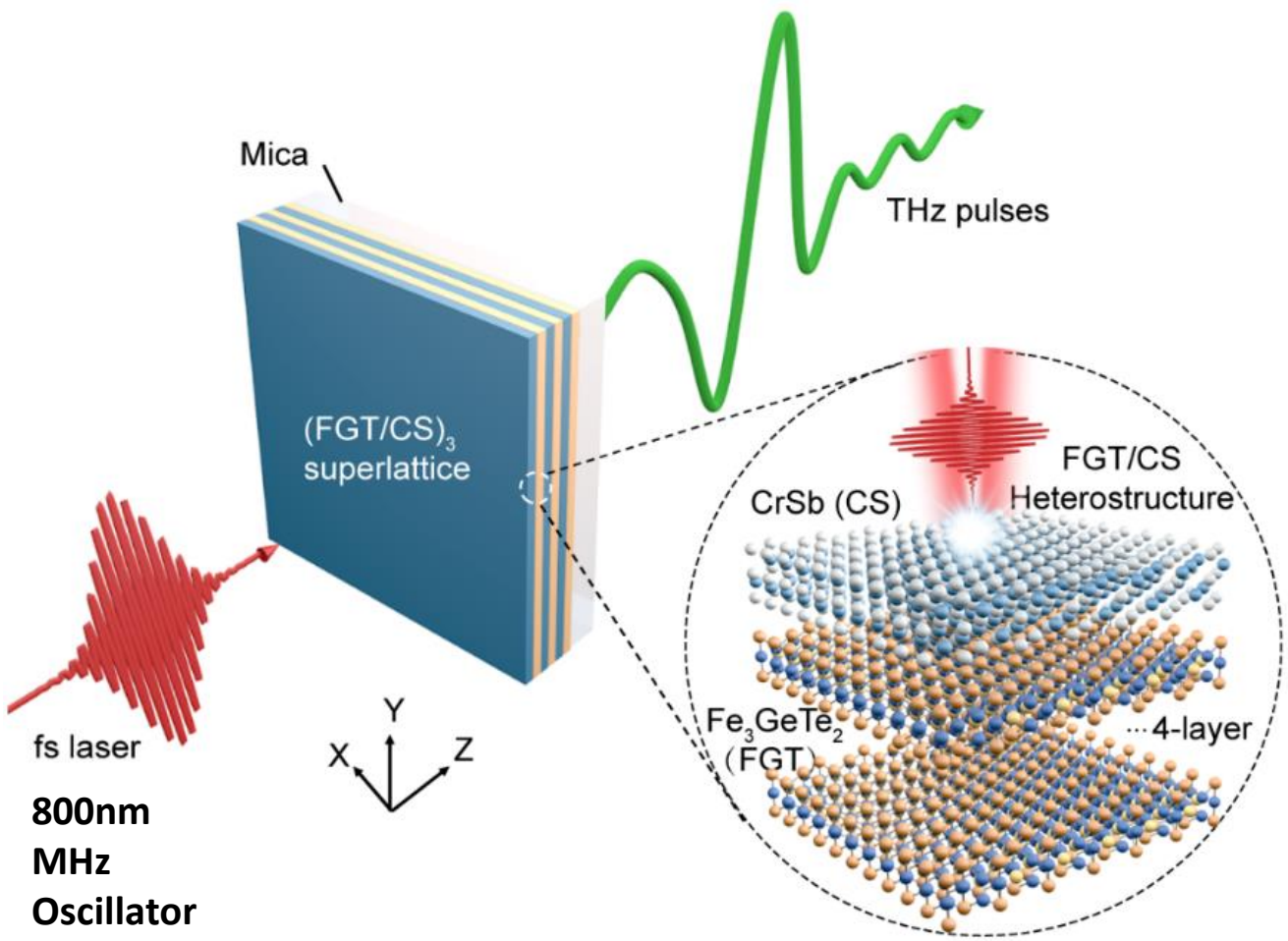




- **Recycling reverse spin current**
- **Improve THz emission efficiency by 12%**

X.H. Chen, et al., X. Wu*, *Adv. Mater*. 34, 2106172 (2022)

Can spin pinning effect be applied on 2D magnetic materials ?



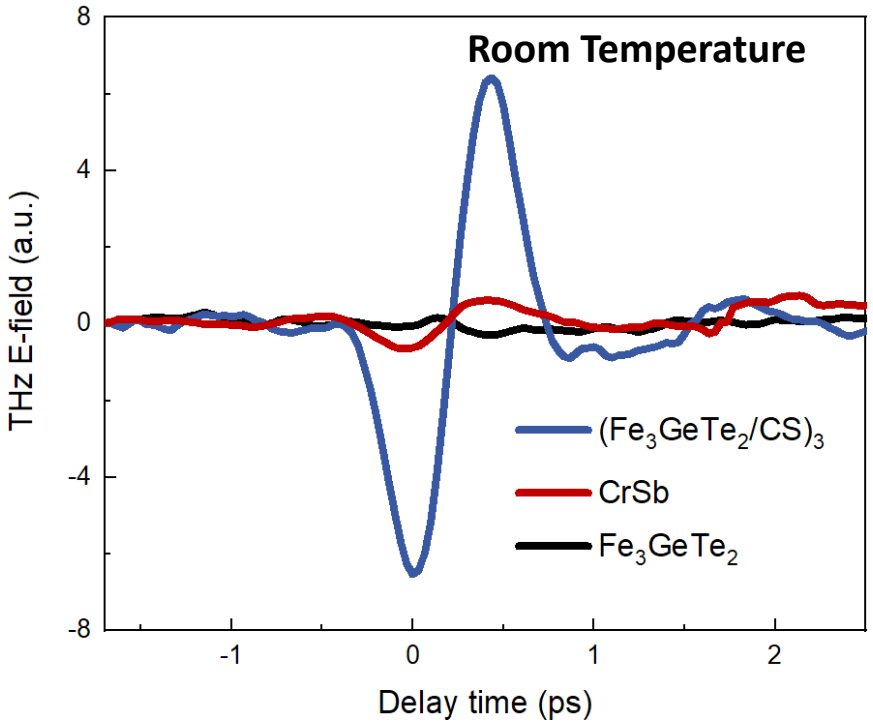
800nm
MHz
Oscillator

Curie Temperature：~200K

S. Liu, et al. and F. Xiu*, Nat. Sci. Rev. 7, 745–754 (2020)

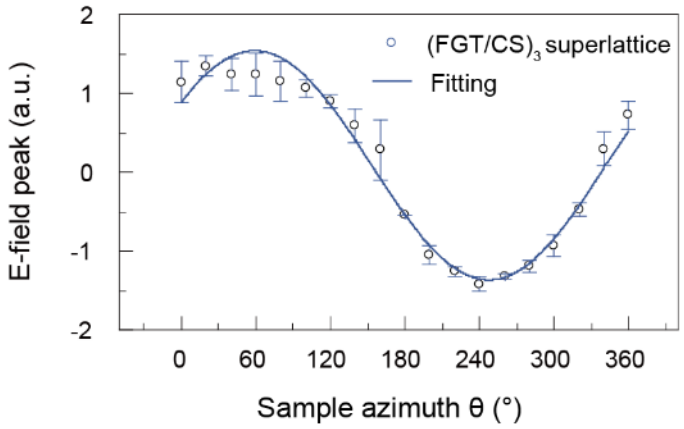
◆ **Lower temperature、**
（After saturation magnetization） B=0

◆ **Room temperature、**
（After saturation magnetization） B=0

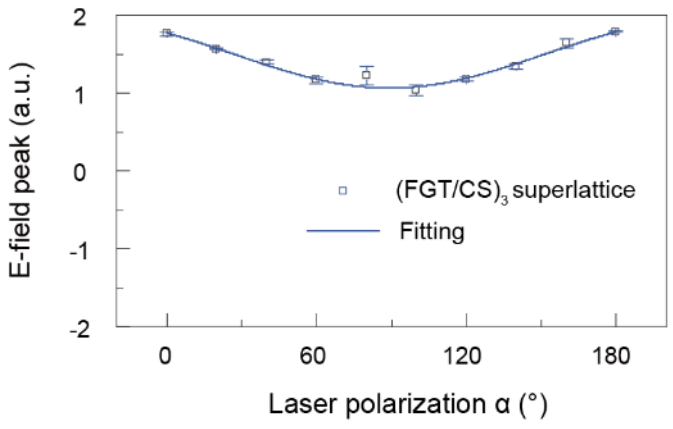


Unpublished

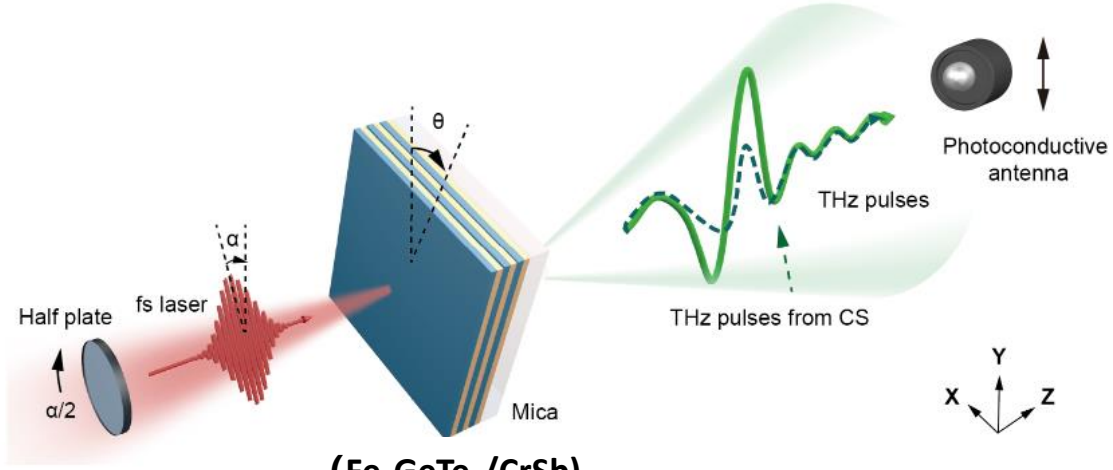
Dependence on sample azimuth and pump laser polarization



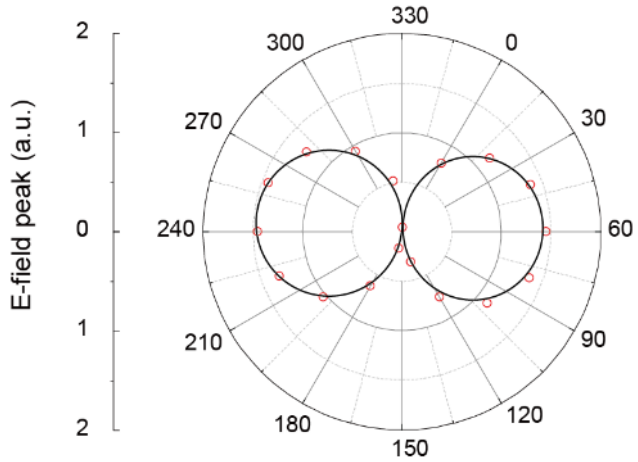
Azimuthal angle



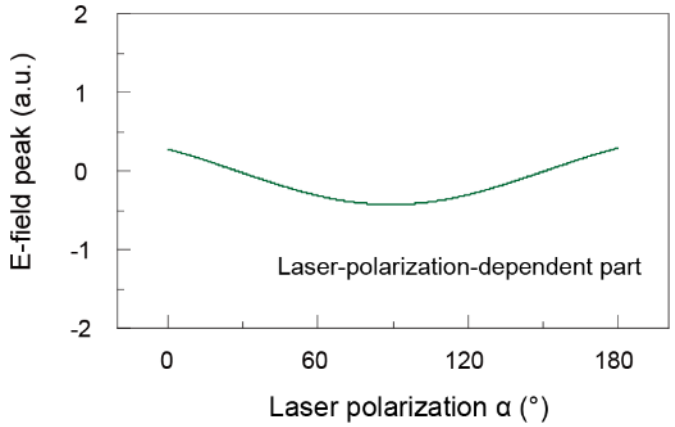
Pump laser polarization



$(Fe_3GeTe_2/CrSb)_3$



SCC component



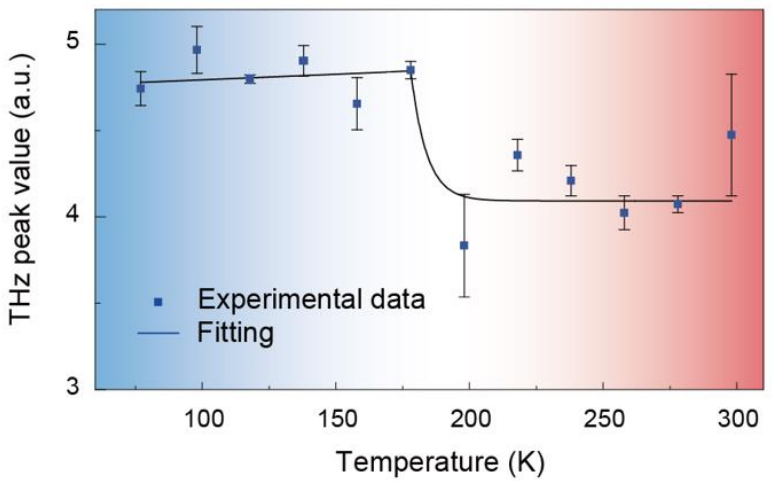
Pump laser dependent component

Spin-to-charge conversion

$$\overrightarrow{E_{THz}} \propto \vec{j}_c = \gamma \vec{j}_s \times \frac{\vec{M}}{|\vec{M}|}$$

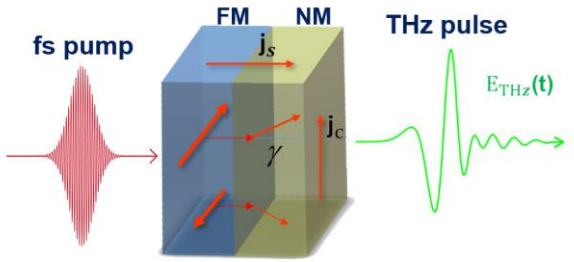
Unpublished

Where do spin currents originate ?



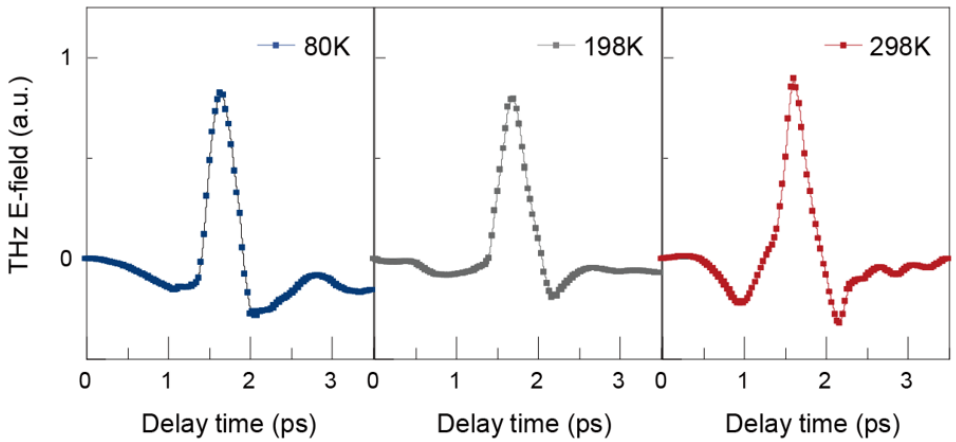
< 198K

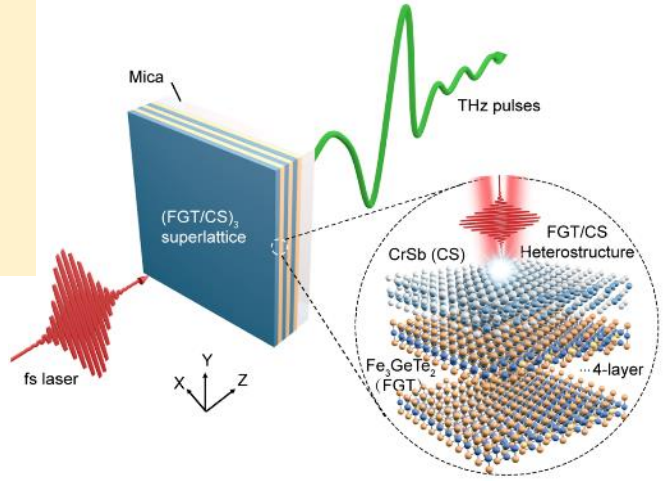
ultrafast demagnetization



> 200K

ultrafast magnetization



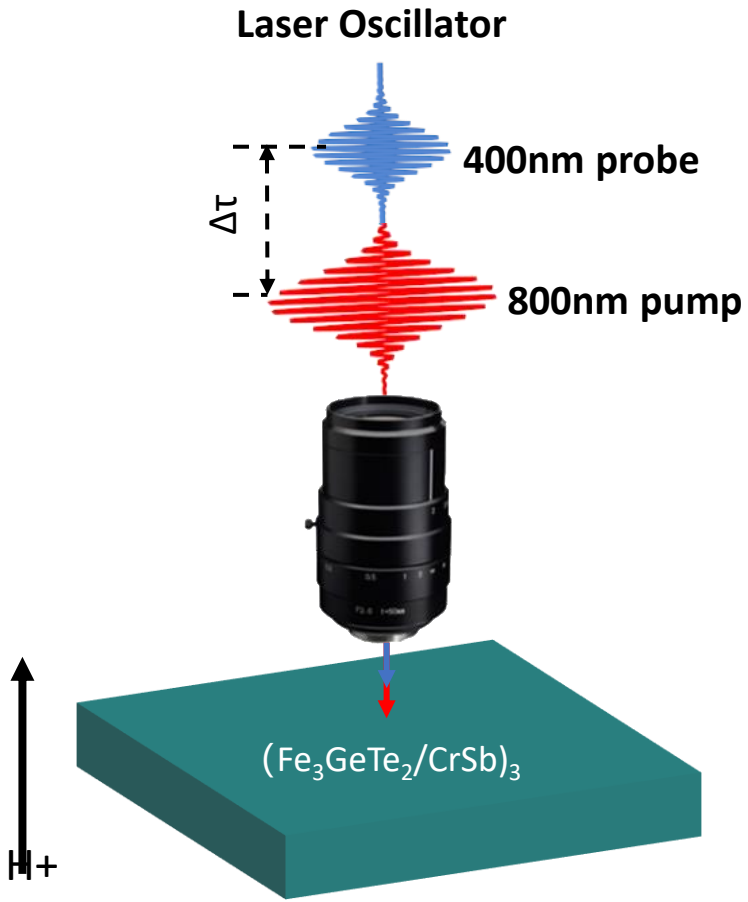


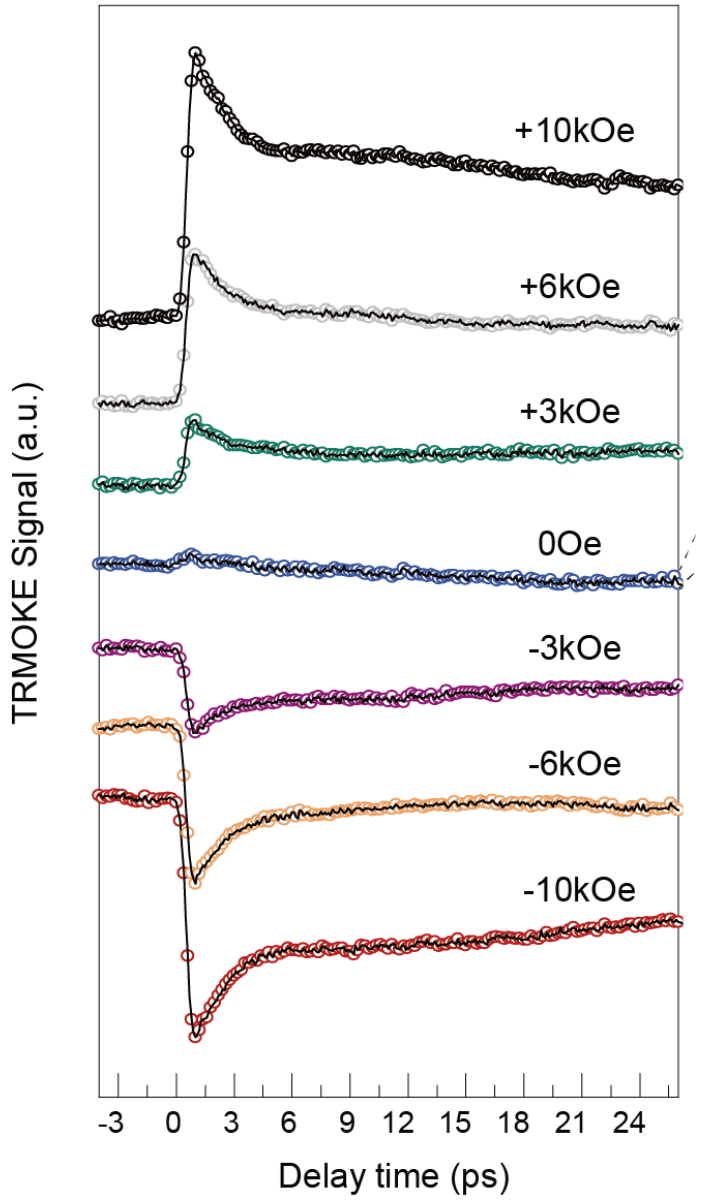
4- layers Fe_3GeTe_2 140.3K → proximity effect → **Superlattice 206.3K** → 800nm pump laser → **Room temperature**

S. Liu, et al. and F. Xiu*, Nat. Sci. Rev. 7, 745–754 (2020)

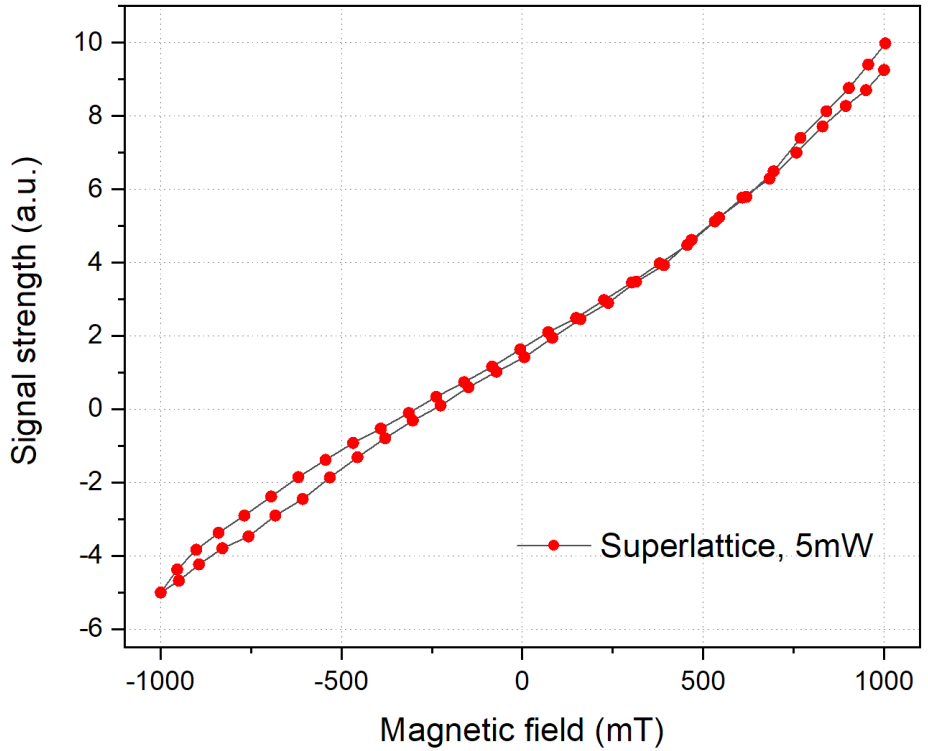
Unpublished

Time-resolved magneto-optical Kerr effect measurement





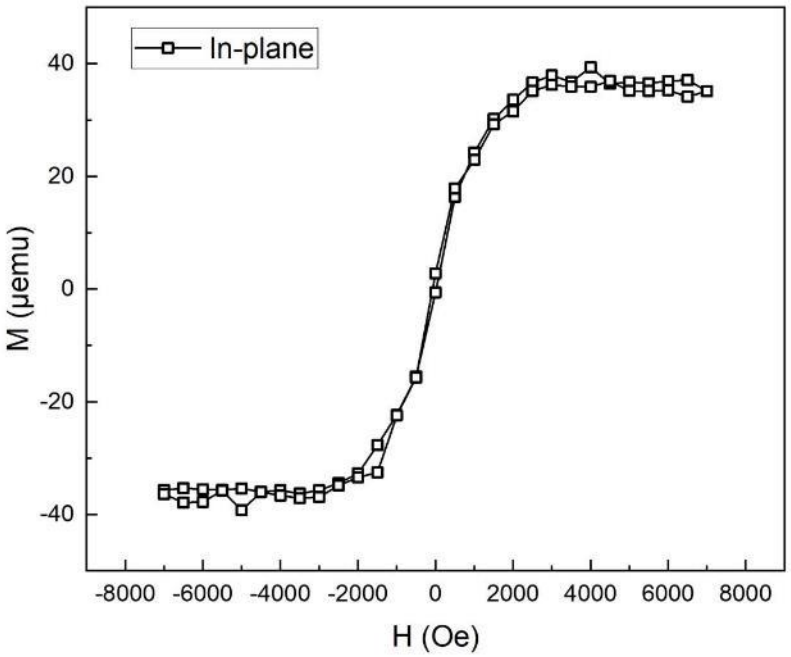
- **Maximum remagnetization**

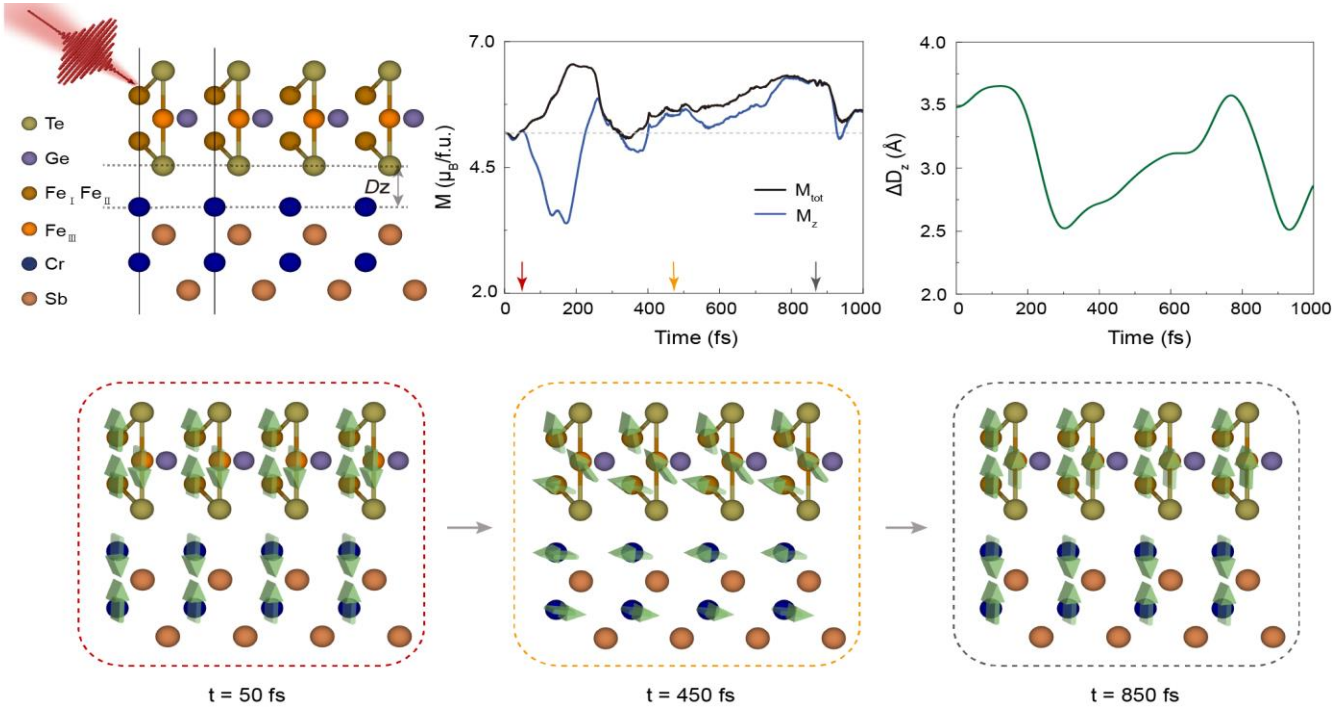


Unpublished

VSM and Theoretical simulations

✓ **No femtosecond laser pump, no in-plane magnetism**





✓ **Interlayer displacement**

✓ **Enhanced magnetic exchange interaction**

Unpublished

Questions

1. Ultrafast magnetization vs ultrafast demagnetization ?
2. Influences from the CrSb antiferromagnetism ?
3. Both magnetism and topological properties in one ?
4. Ultrafast magnetization in other 2D FM or AFM ?

Acknowledgements

Special Thanks to

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- Peiyan Li



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2022


2020


2019