Real-space nanoimaging of THz polaritons in the topological insulator Bi_2Se_3

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Andrei Bylinkin, Shu Chen, Zhengtianye Wang, Martin Schnell, Greeshma Chandan, Peining Li, Alexey Y. Nikitin, Stephanie Law, Rainer Hillenbrand

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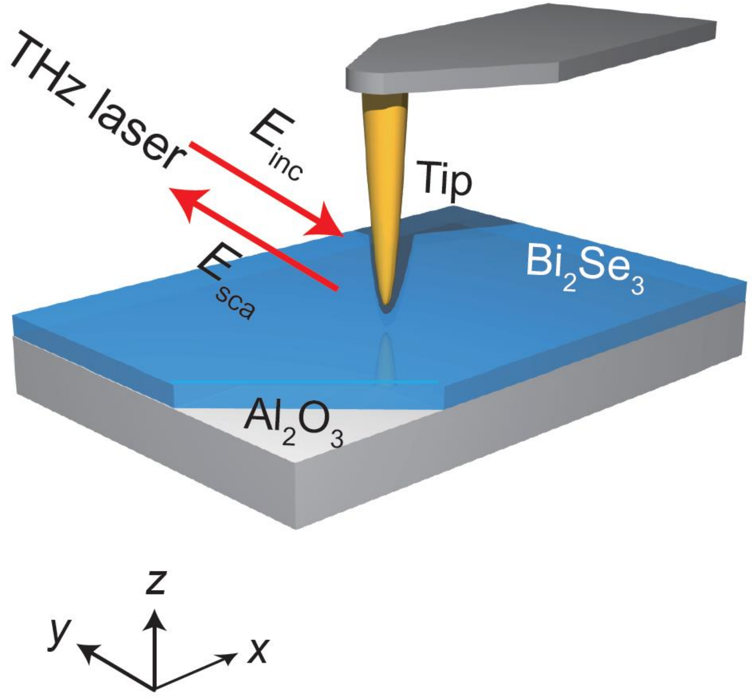
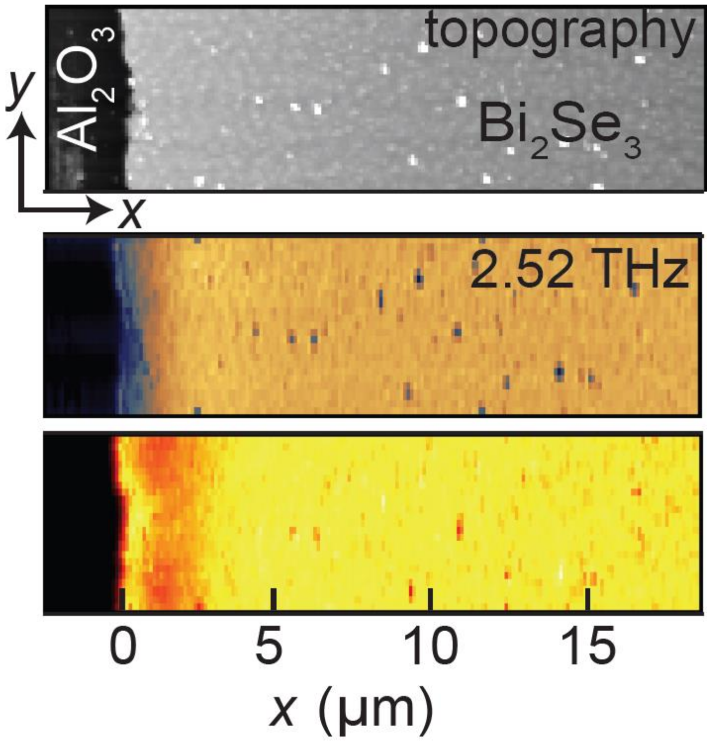
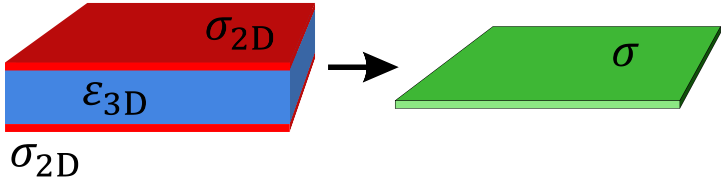




Analytical polariton dispersion

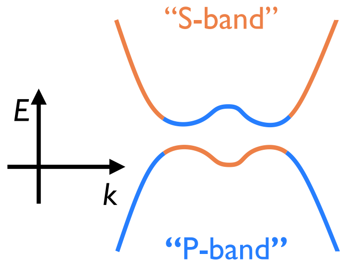
$$q_p(\omega) = i \frac{c}{4\pi} \frac{\varepsilon_{sub} + 1}{\sigma(\omega)}$$



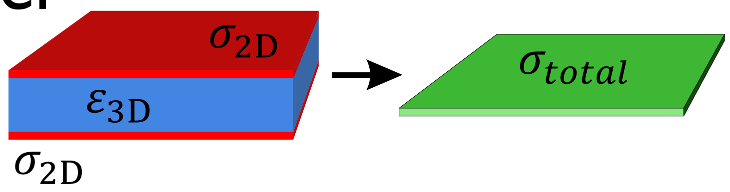
Shu Chen, Andrei Bylinkin, *et al*, in press

Plan

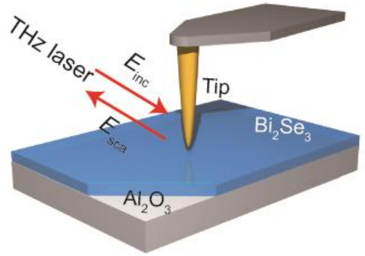
- ❑ Introduction and motivation



- ❑ Analytical polariton dispersion in complex multi-layer systems using the effective conductivity model

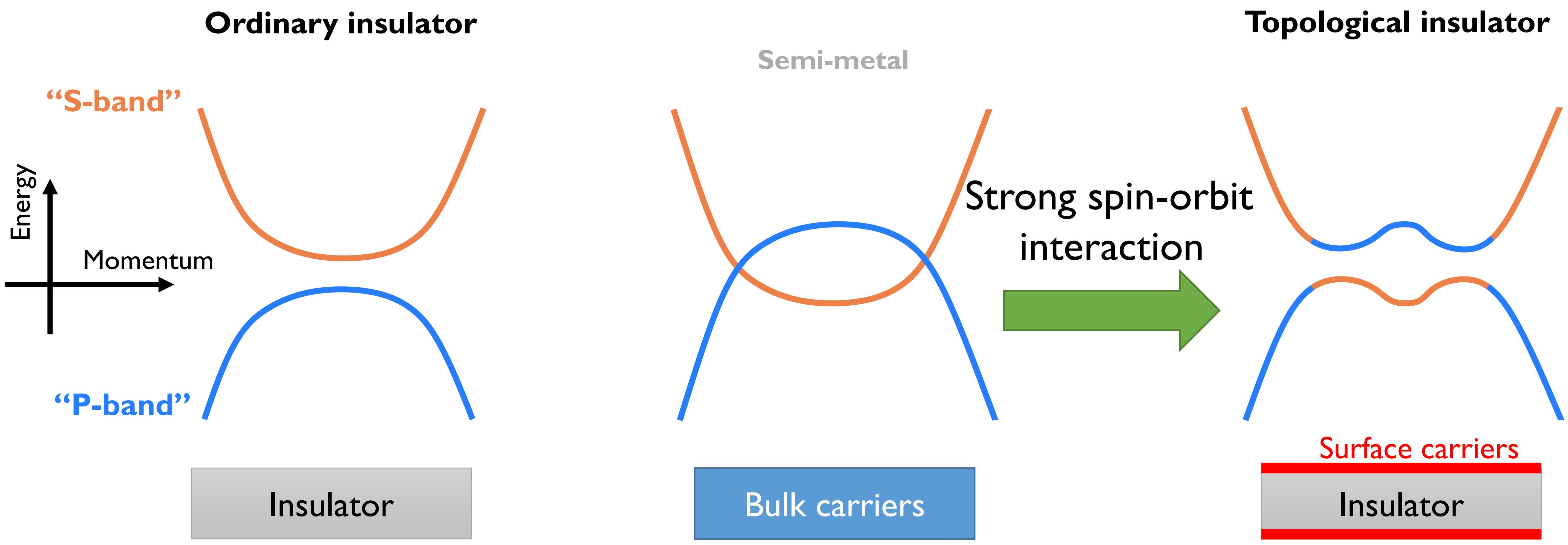


- ❑ THz real-space nanoimaging and complex analysis of polaritons in Bi_2Se_3



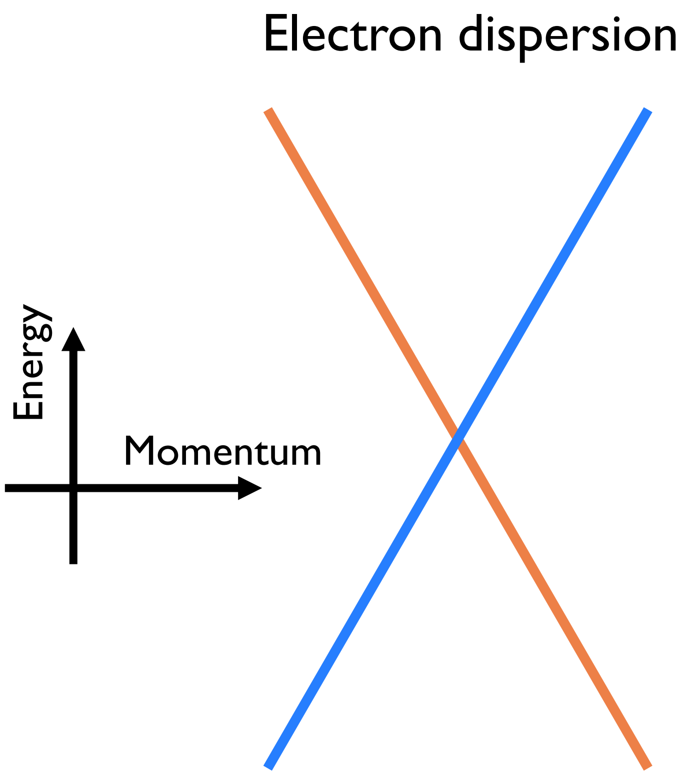
- ❑ Summary and outlook

What is a topological insulator?



- Topological insulators exhibit conductive surface states with the linear dispersion

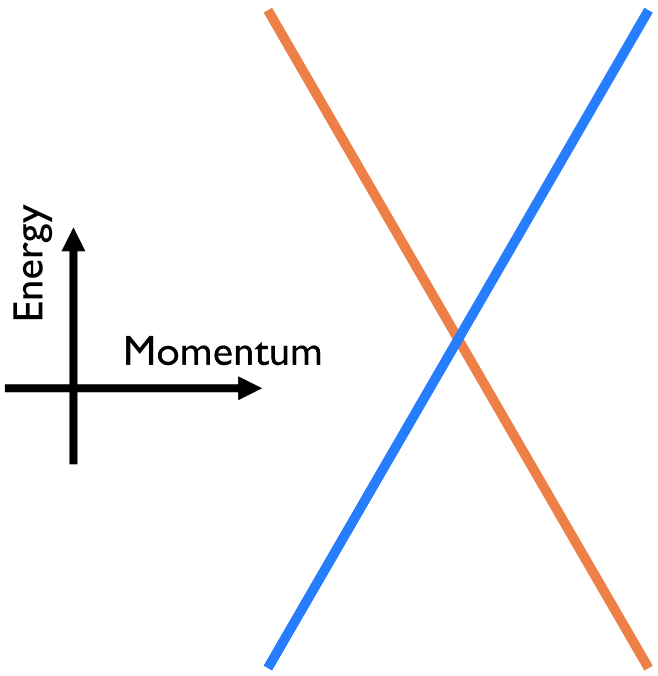
What is interesting about topological insulators?



- Dirac carriers
- Spin-momentum locking

What is interesting about topological insulators?

Electron dispersion

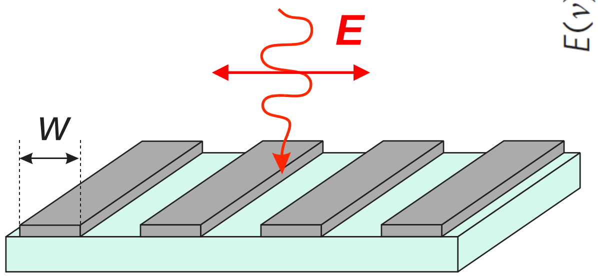


Plasmon polaritons

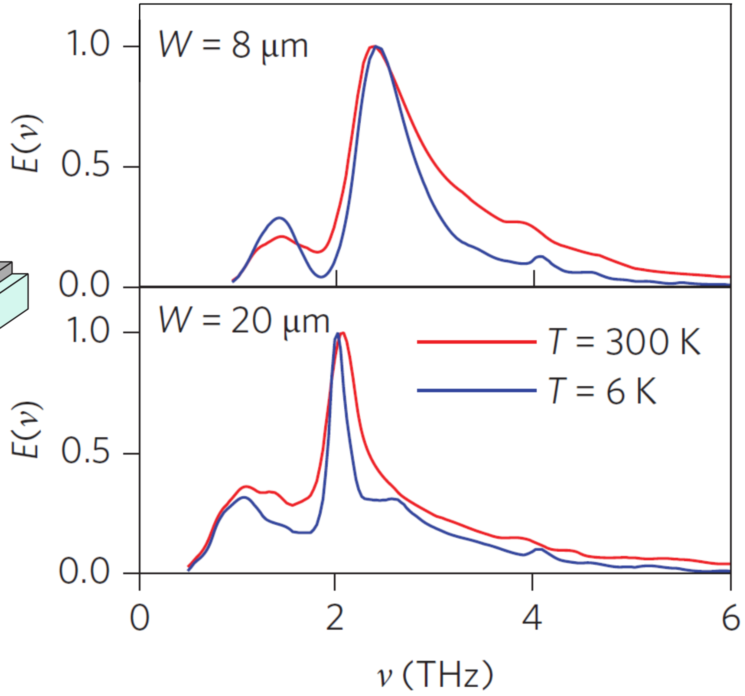
- Dirac carriers ➡ $\omega_p \propto n^{1/4}$
- Spin-momentum locking ➡ Spin-polarized plasmon waves

THz far-field spectroscopy reveals polaritons in topological insulators (e.g. Bi_2Se_3)

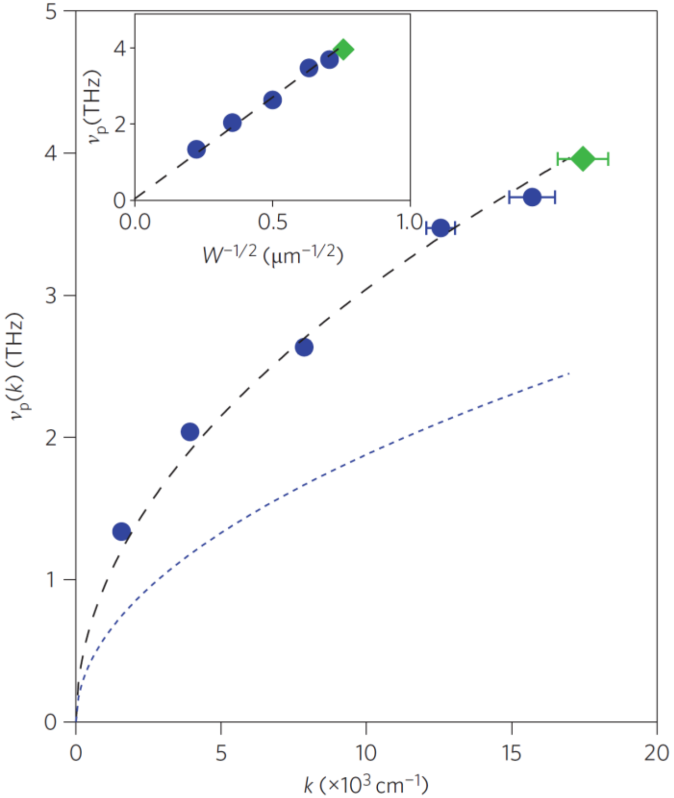
Bi_2Se_3 ribbons



Extinction coefficient



Plasmon dispersion



Dirac carriers

Bulk carriers

- Authors considered only bulk and Dirac carriers

Nature Nanotech. **8**, 556-560 (2013)

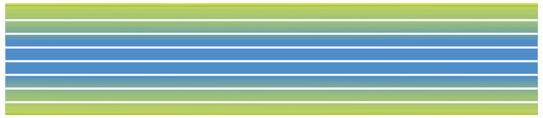
Bi_2Se_3 is a complex material with surface (2D) and bulk (3D) states

Surface – 2D

Dirac carriers

$$\sigma_{\text{Dirac}} = \frac{e^2 v_{\text{F}} \sqrt{\pi n_{\text{Dirac}}}}{2\hbar\pi} \frac{i}{\omega + i\gamma_{\text{Dirac}}}$$

2D electron gas



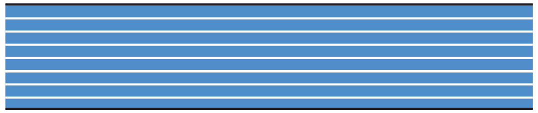
$$\sigma_{\text{2DEG}} = \frac{e^2 n_{\text{2DEG}}}{m^*} \frac{i}{\omega + i\gamma_{\text{2DEG}}}$$

Bulk – 3D

Bulk carriers

$$\varepsilon_{\text{Drude}} = -\frac{4\pi n_{\text{bulk}} e^2}{m^*} \frac{1}{\omega^2 + \text{i}\omega\gamma_{\text{D}}}$$

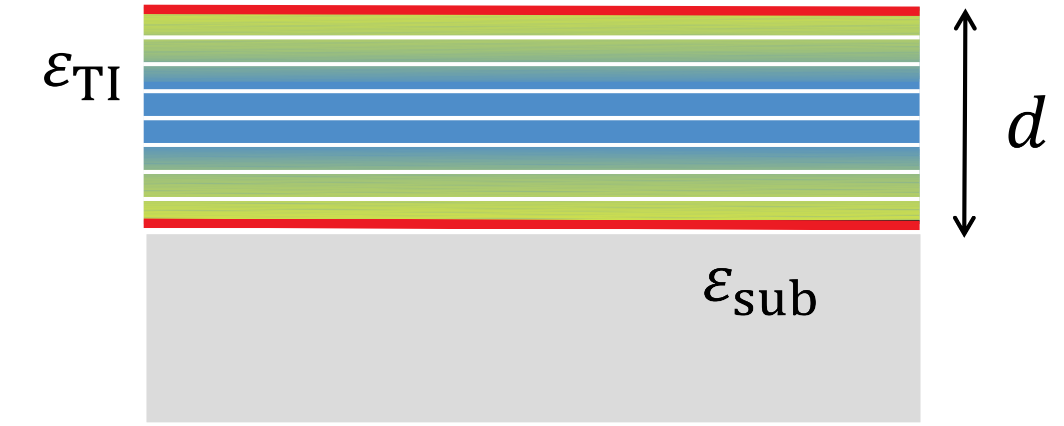
Optical phonons



$$\varepsilon_{\text{ph}} = \varepsilon_\infty + \sum_{i=1}^{3} \frac{\omega_{\text{p},i}^2}{\omega_{0,i}^2 - \omega^2 - \text{i}\omega\gamma_i}$$

Advanced Optical Materials 6.13 (2018): 1800113.
Opt. Express 24, 7398-7410 (2016)
Phys. Rev. B 92, 205430 (2015)

Polariton dispersion in topological insulator from literature



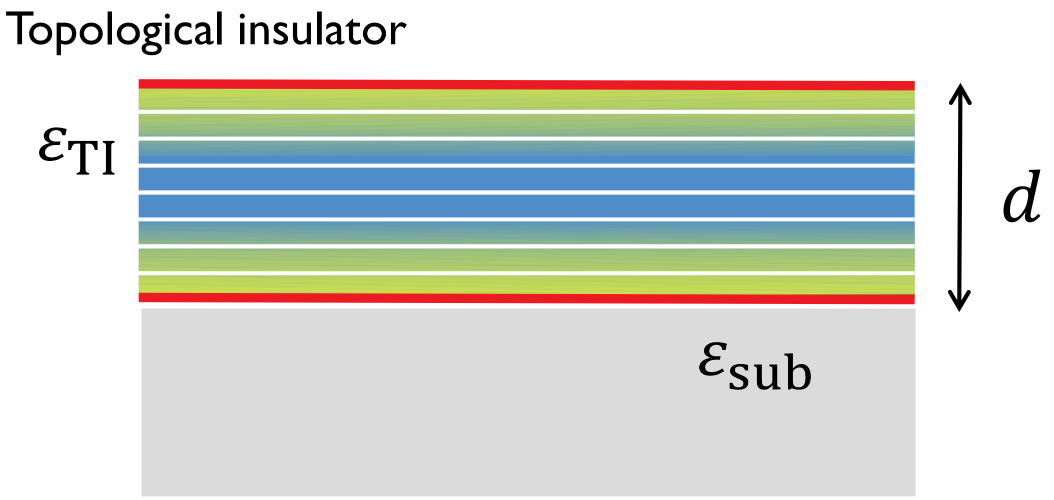
k_{p} – polariton wavevector

$$\omega_{\mathrm{p}}^2 = \frac{2\alpha_{\mathrm{d}} v_{\mathrm{F}} E_{\mathrm{F}}}{\hbar(\varepsilon_{\mathrm{sub}}+1)} k_{\mathrm{p}} \left[1 + \frac{k_{\mathrm{p}} d \varepsilon_{\mathrm{TI}}}{\varepsilon_{\mathrm{sub}}+1}\right]^{-1}$$

- It is difficult to separate surface (2D) and bulk (3D) contributions
- Equation is not valid when Fermi level of surface states are zero, $E_{\mathrm{F}} = 0$

Phys. Rev. B 88, 205427 (2013)

Polariton dispersion in topological insulator from literature



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Surface contribution (2D)

$$E_{\mathrm{F}} = E_{\mathrm{F,Dirac}} + 4E_{\mathrm{F,2DEG}}$$

Bulk contribution (3D)

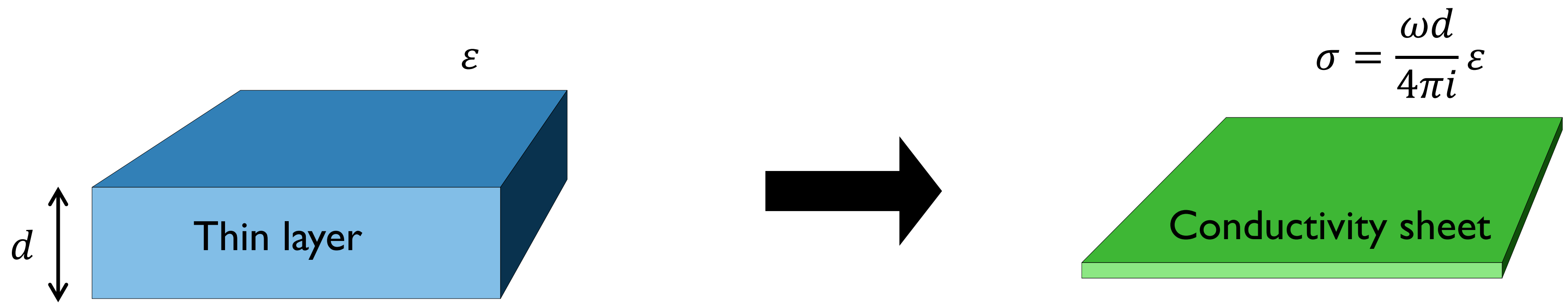
$$\varepsilon_{\mathrm{TI}} = \varepsilon_{\mathrm{Drude}} + \varepsilon_{\mathrm{ph}}$$

- It is difficult to separate surface (2D) and bulk (3D) contributions
- Equation is not valid when Fermi level of surface states are zero, $E_{\mathrm{F}} = 0$

Phys. Rev. B 88, 205427 (2013)

We used conductivity layer approximation to derive more intuitive equation

Step 1



- Thin layer material can be replaced by conductivity sheet assuming $k_{\mathrm{p}} d \ll 1$

Nature communications 10.1 (2019): 1-7

We generalized conductivity layer approximation for multi layer system

Step 2

Analytical polariton dispersion:

$$q(\omega) = \frac{k_p}{k_0} = i\frac{c}{4\pi}\frac{\varepsilon_{\text{sub}} + 1}{\sigma(\omega)}$$

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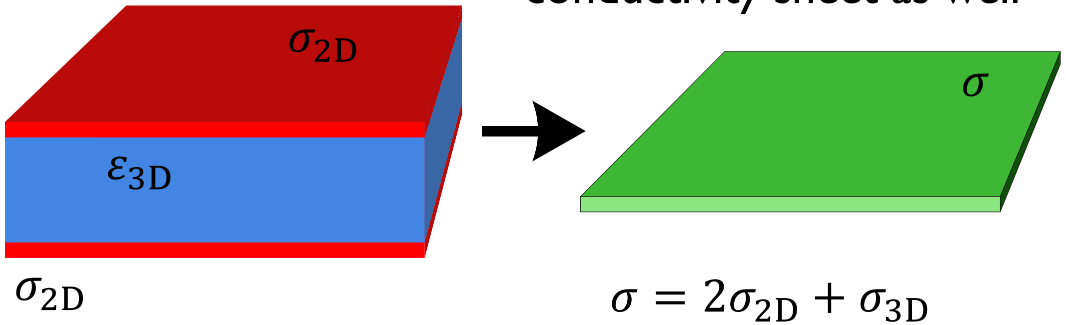
Multi layer systems can be approximated by conductivity sheet as well



$$\sigma = 2\sigma_{2D} + \sigma_{3D}$$

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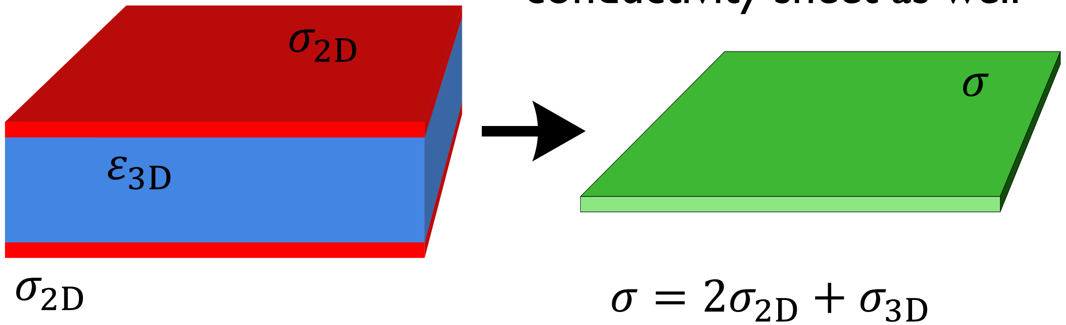
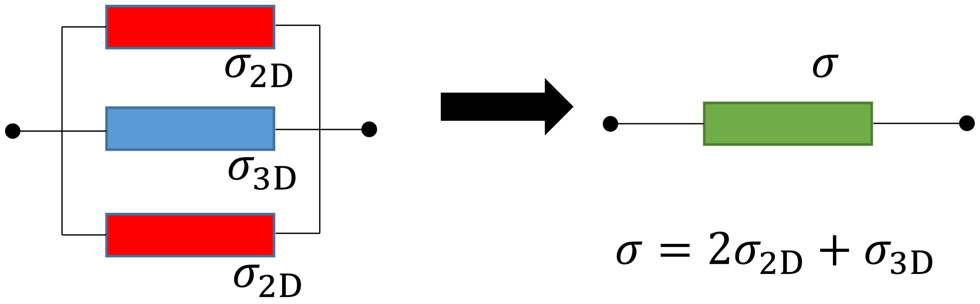


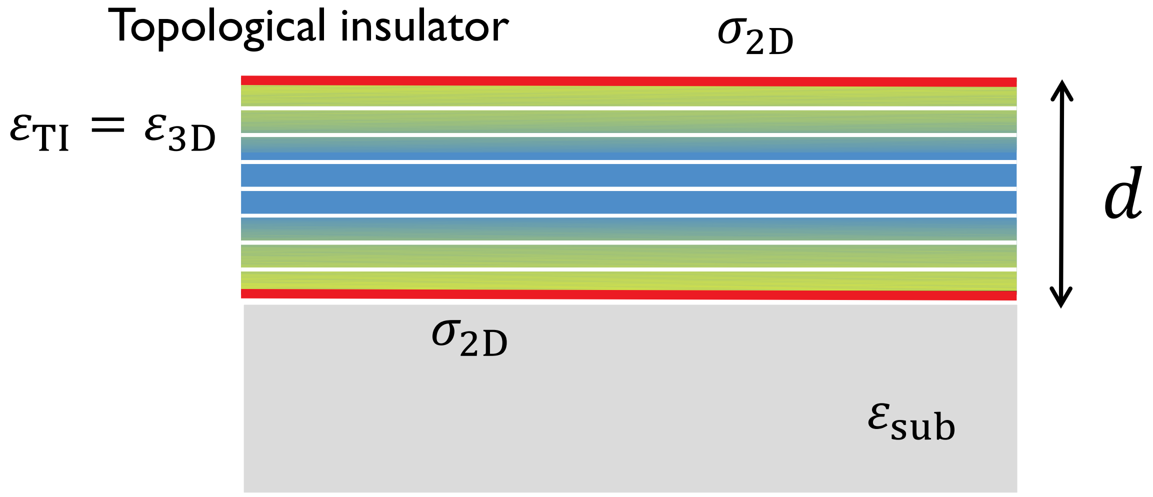
$$\sigma = 2\sigma_{2D} + \sigma_{3D}$$

Analogy from circuit design:
parallel connection of resistors



$$\sigma = 2\sigma_{2D} + \sigma_{3D}$$

Polariton wavector is proportional to inversed total sheet conductivity



k_p – polariton momentum

$$\omega_p^2 = \frac{2\alpha_d v_F E_F}{\hbar(\varepsilon_{sub}+1)} k_p \left[1 + \frac{k_p d \varepsilon_{TI}}{\varepsilon_{sub}+1}\right]^{-1}$$

Phys. Rev. B 88, 205427 (2013)

$$q(\omega) = \frac{k_p}{k_0} = i\,\frac{c}{4\pi}\,\frac{\varepsilon_{sub}+1}{\sigma(\omega)}$$

$$\sigma(\omega) = 2\sigma_{2D} + \sigma_{3D} = 2(\sigma_{Dirac} + \sigma_{2DEG}) + \sigma_{Drude} + \sigma_{ph}$$

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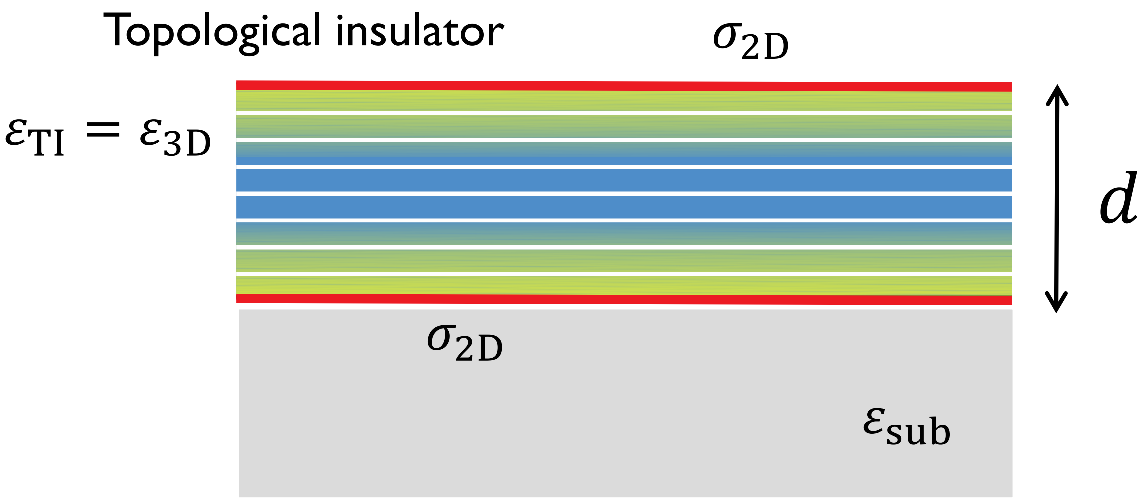

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Phys. Rev. B 88, 205427 (2013)

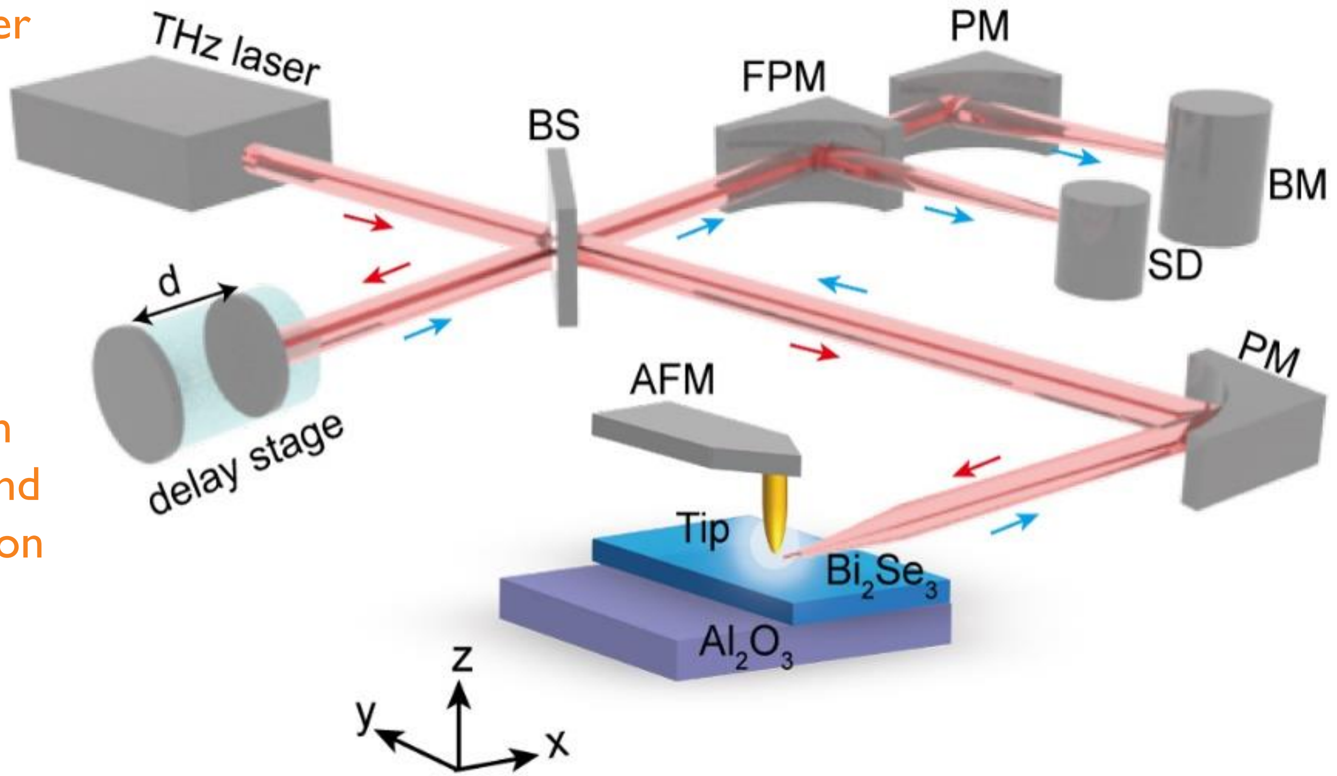
$$q(\omega) \propto \frac{1}{\sigma(\omega)}$$

$$\sigma(\omega) = 2\sigma_{2D} + \sigma_{3D} = 2(\sigma_{Dirac} + \sigma_{2DEG}) + \sigma_{Drude} + \sigma_{ph}$$

THz s-SNOM setup for spectroscopic nanoimaging

Tunable gas laser

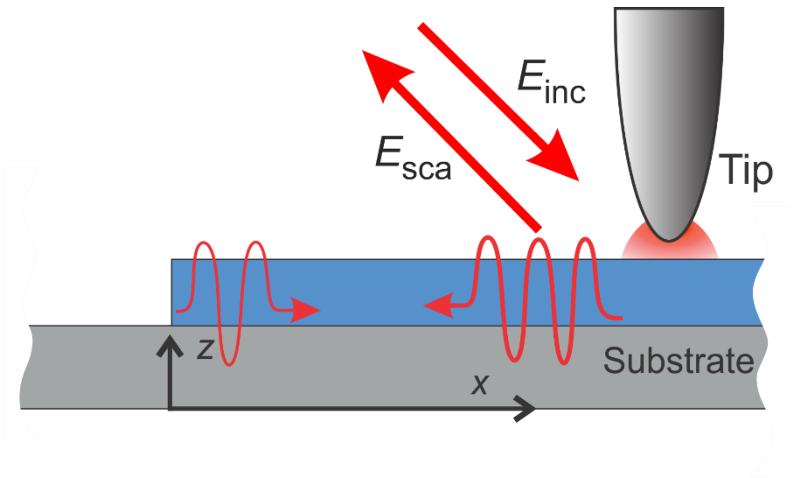
Reference arm
for amplitude and
phase information

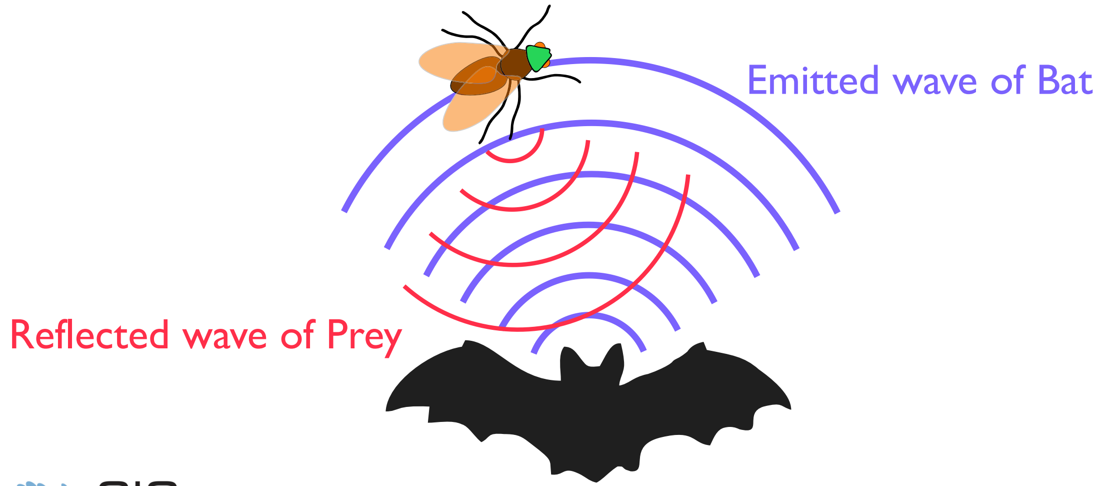


Detectors

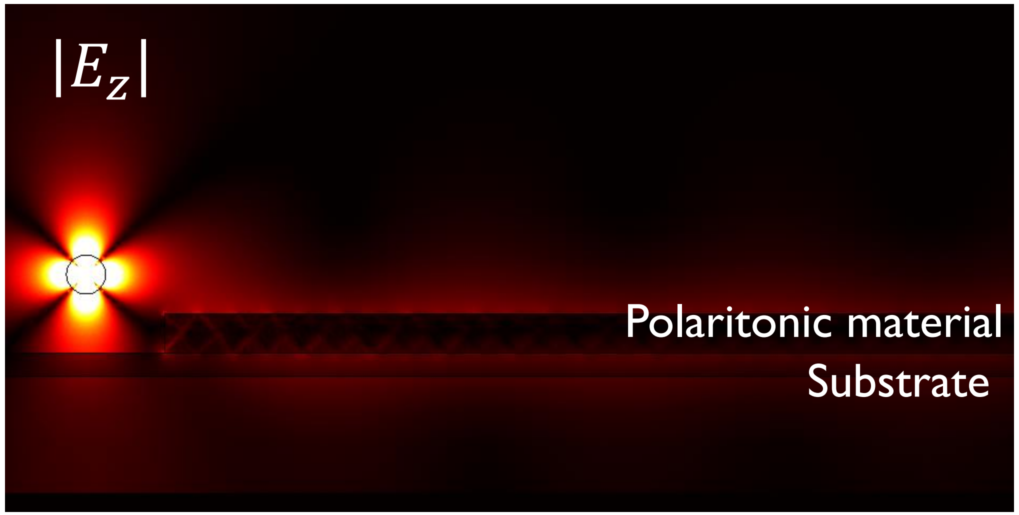
See also ACS Photonics 2020, 7, 12, 3499–3506

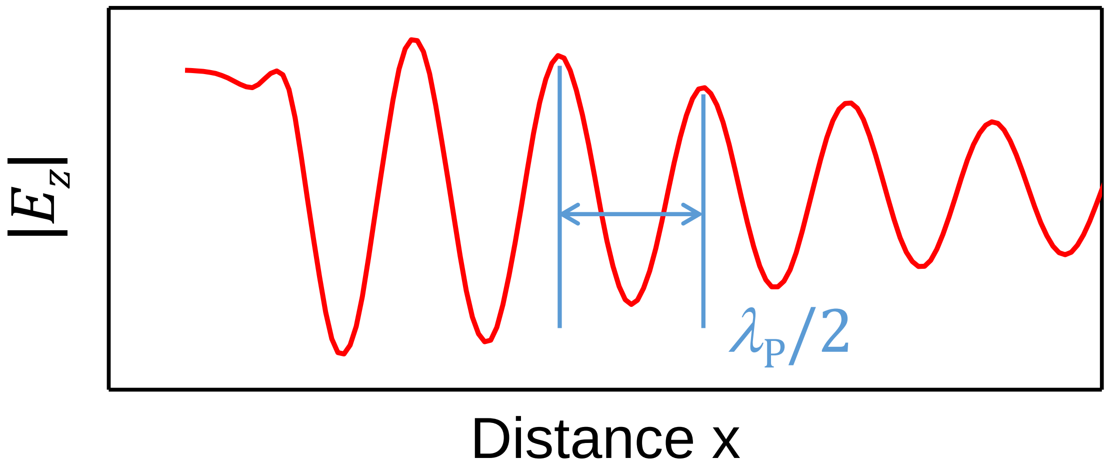
Polariton interferometry reveal the complex-valued polariton wavevector



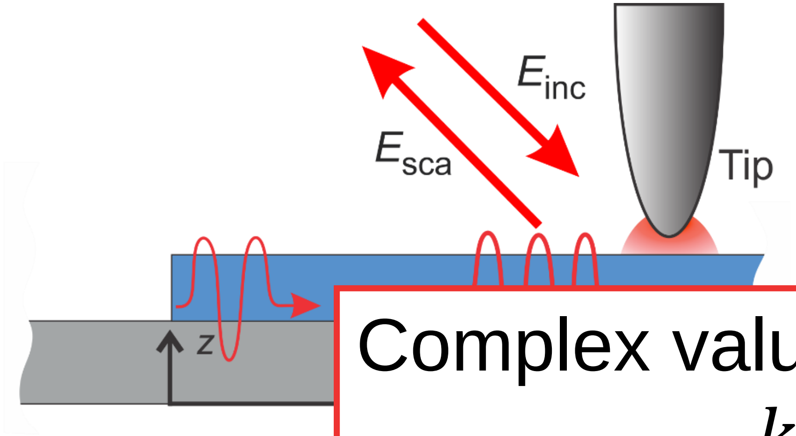


Point dipole is mimicking the SNOM tip





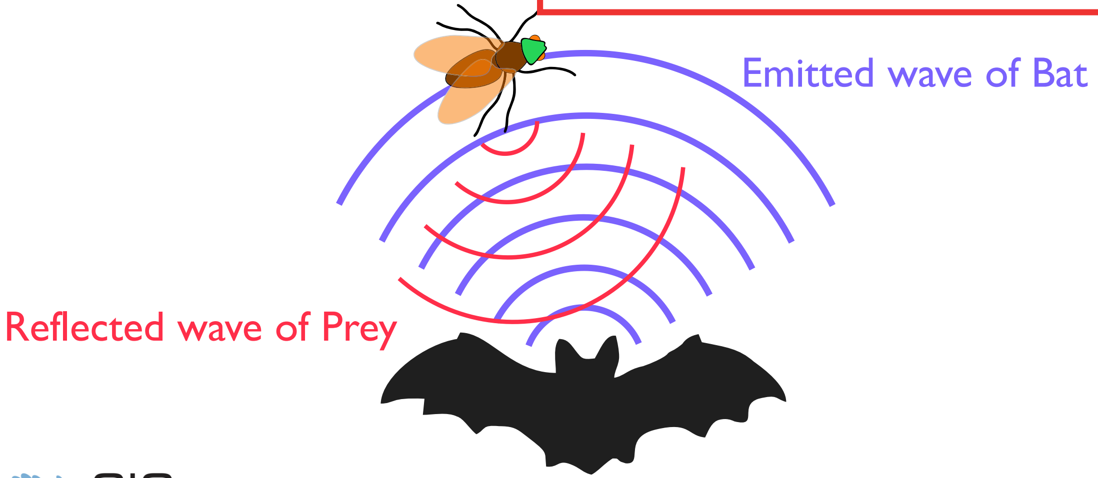
Polariton interferometry reveal the complex-valued polariton wavevector

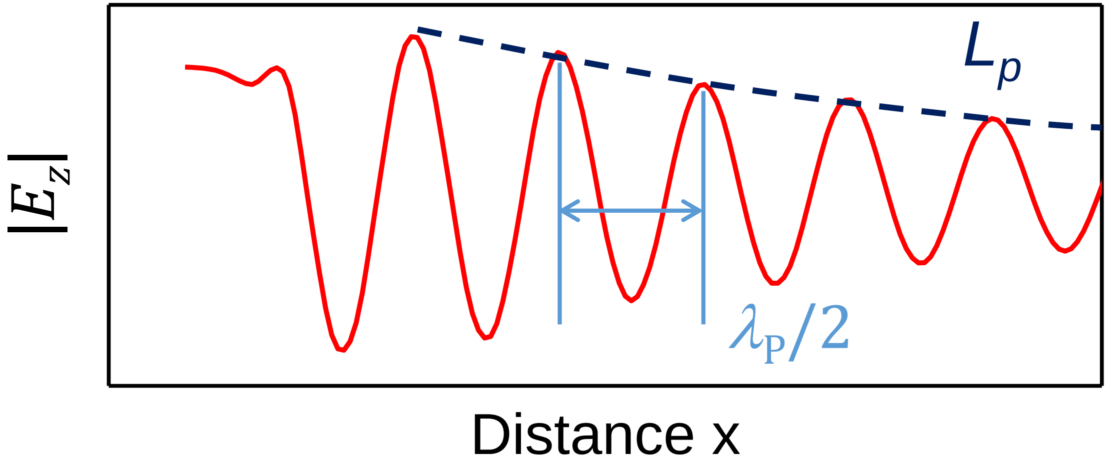


Point dipole is mimicking the SNOM tip

Complex valued polariton wavevector

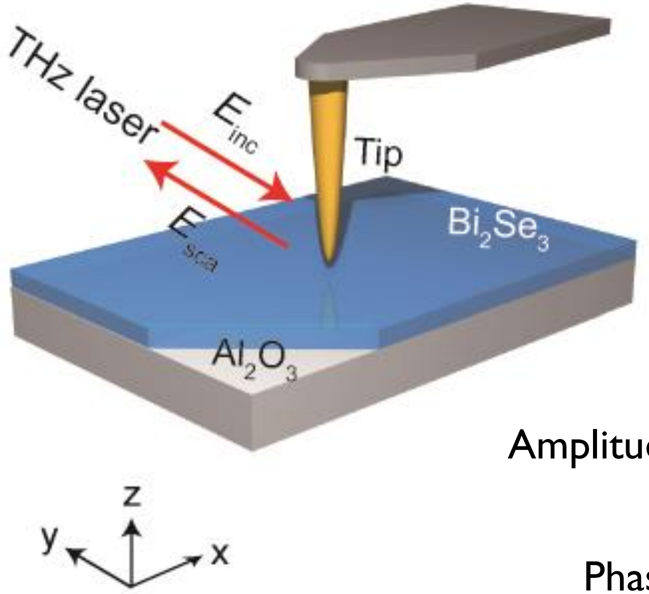
$$k_p = k'_p + ik''_p$$

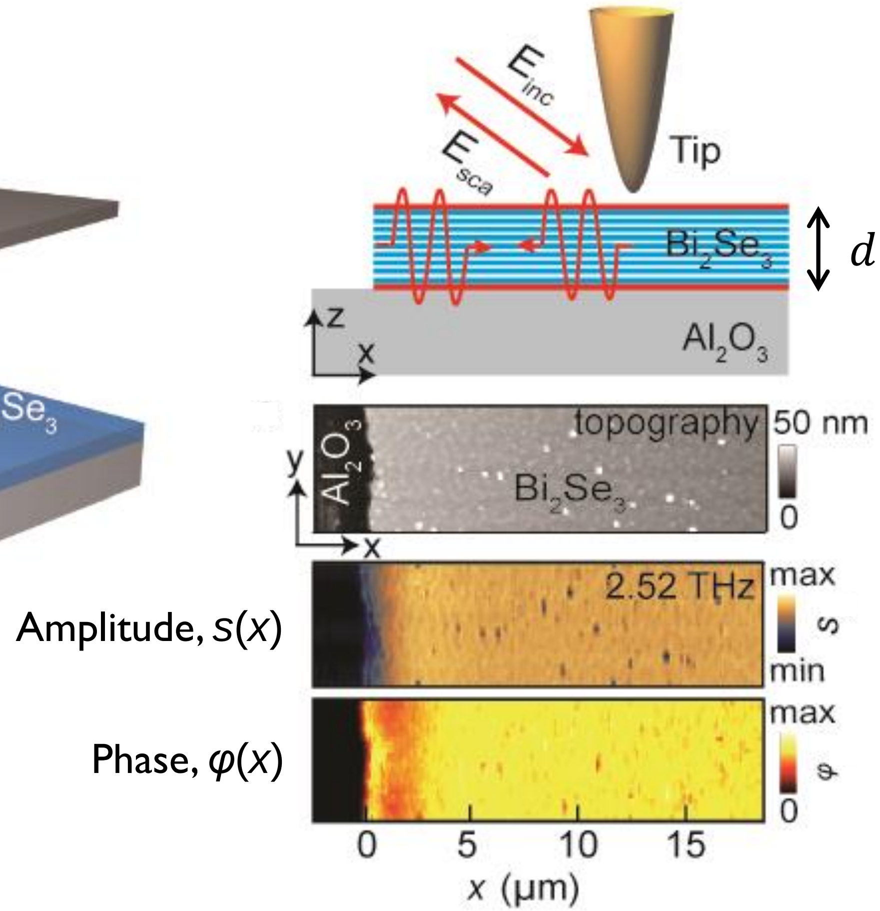


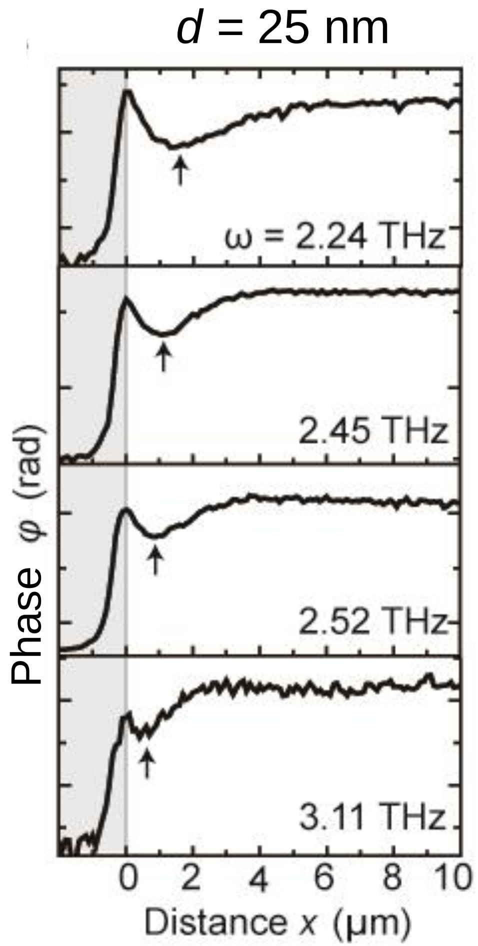


We performed polariton interferometry in Bi_2Se_3

Interferometric detection yields amplitude, $s(x)$, and phase, $\varphi(x)$

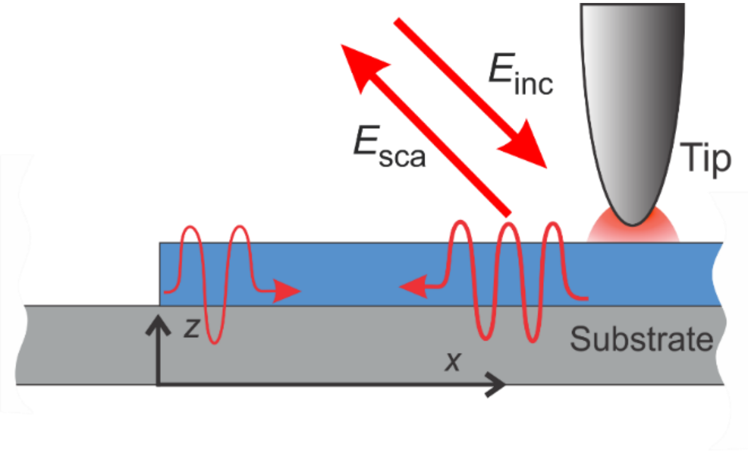




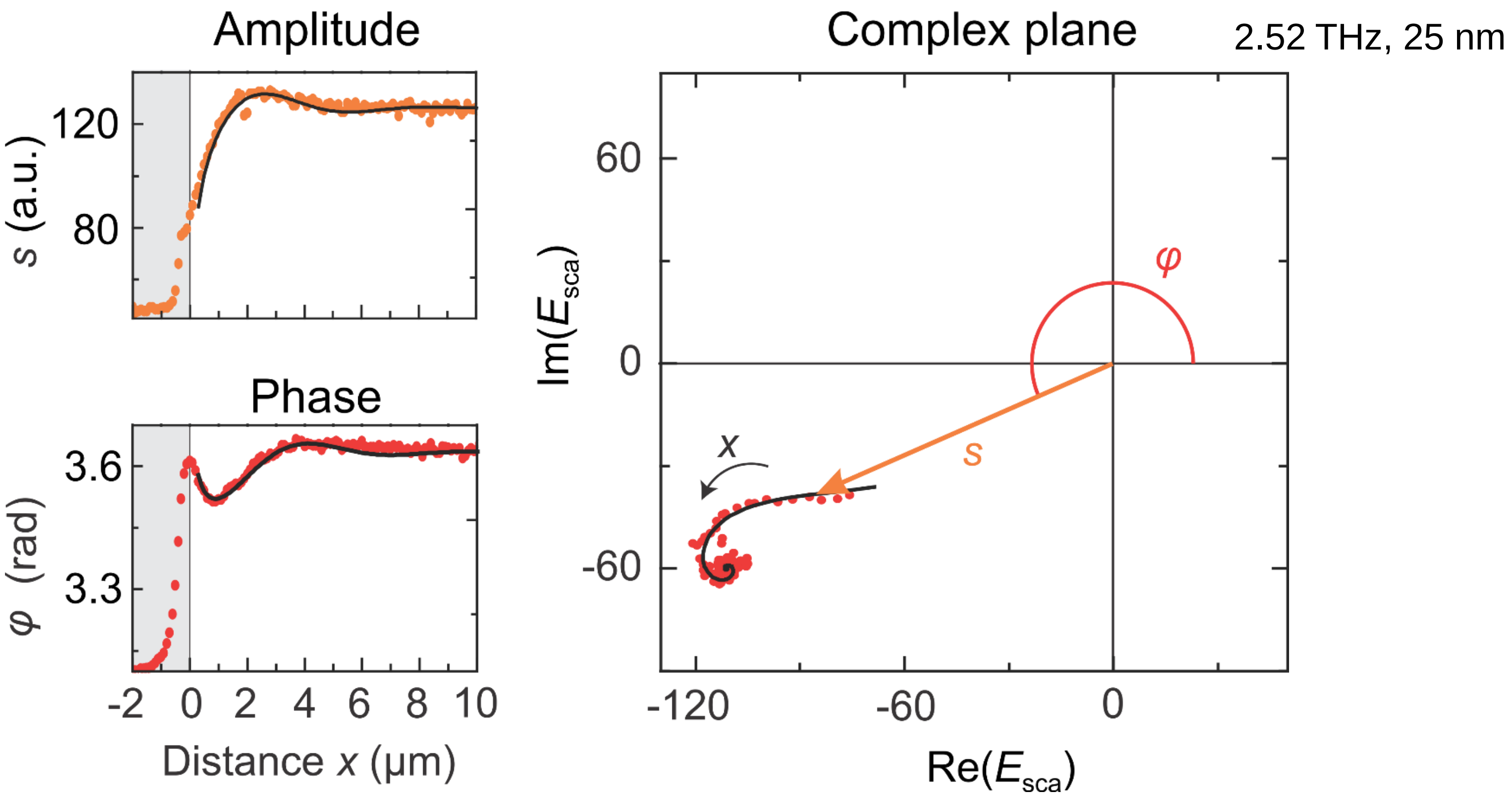


We used complex-valued analysis of THz line profiles to extract polariton wavevector

$$E_{\mathrm{sca}}(x) = A\frac{e^{i2k_{\mathrm{p}}x}}{\sqrt{x}} + C$$

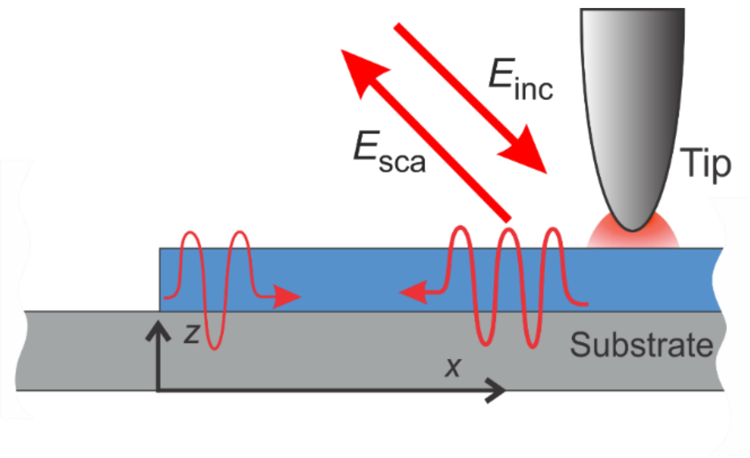


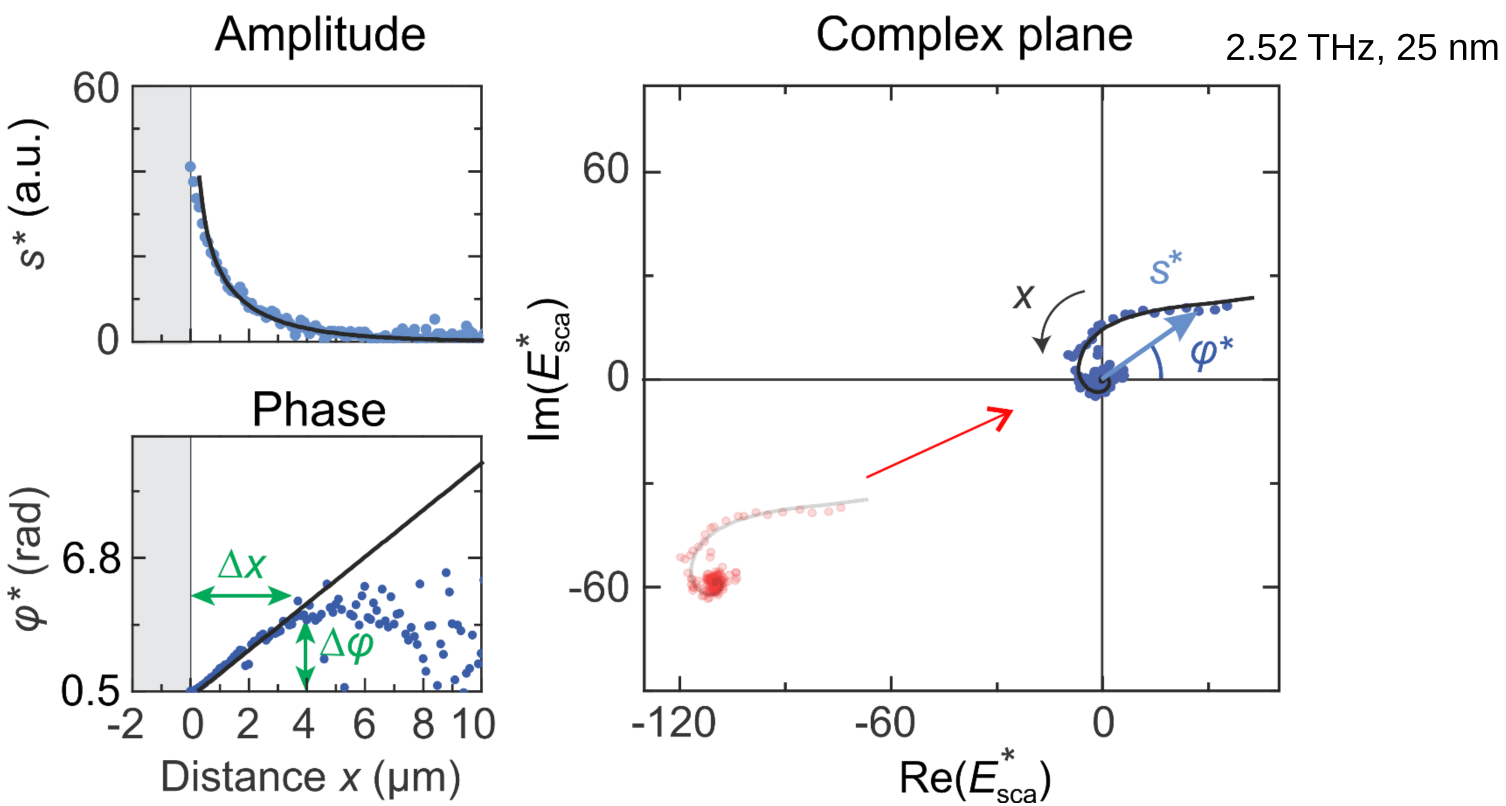
A – complex amplitude
C – complex offset
k_{p} – complex polariton wavevector



Complex offset subtraction allows to disentangle polariton amplitude and phase

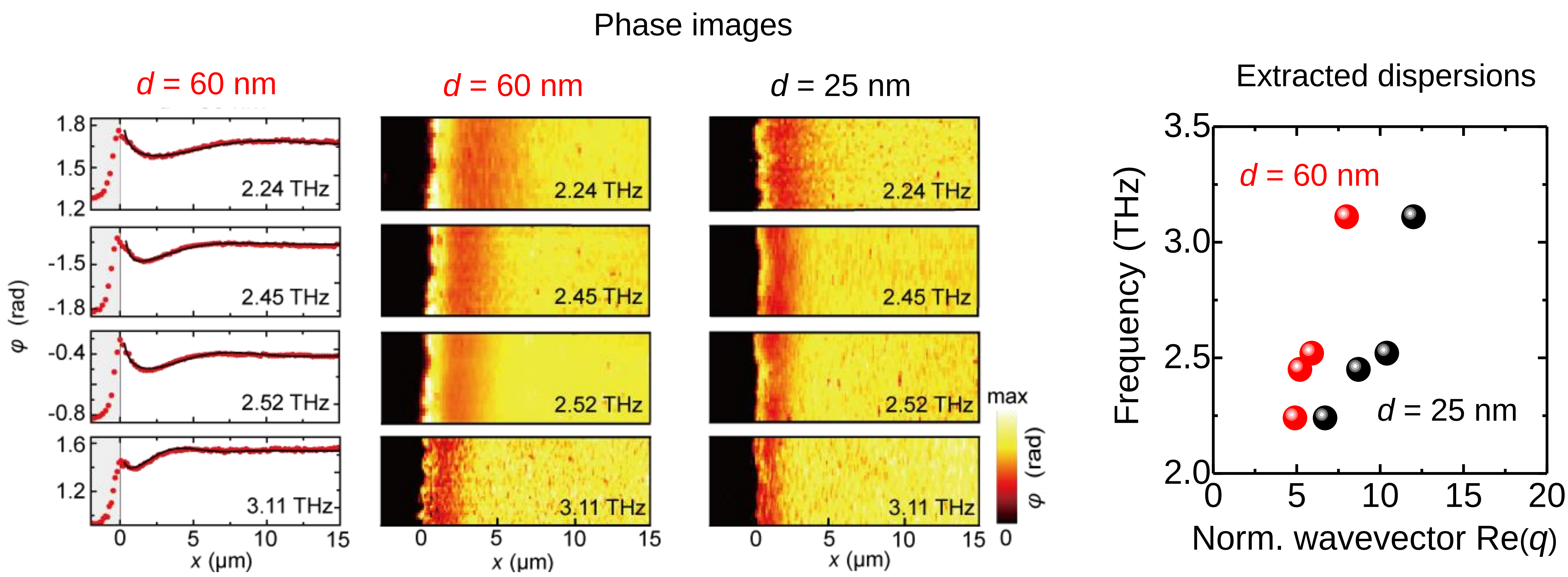
$$E_{\mathrm{sca}}(x) = A\frac{e^{i2k_{\mathrm{p}}x}}{\sqrt{x}} + C$$





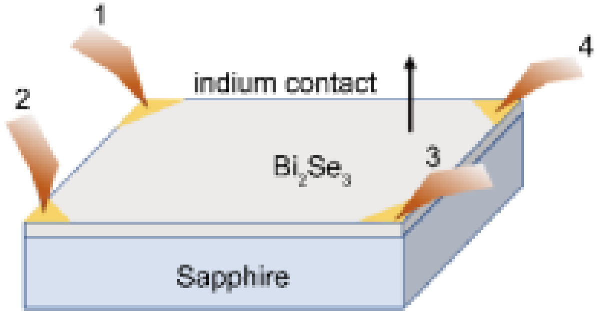
- Polariton wavelength from the linear phase ramp $\lambda_{\mathrm{p}} = 4\pi\Delta x/\Delta\varphi$

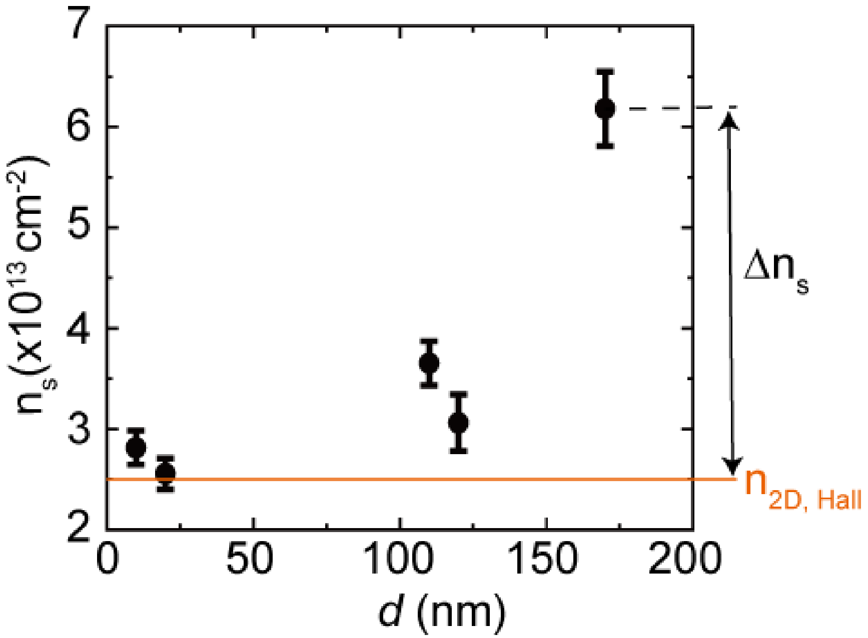
Nanoimaging of Bi_2Se_3 at different frequencies



- Complex-valued analysis allows to extract polariton dispersion for 25 and 60 nm flakes

Hall measurements provide an estimation of surface and bulk carrier concentrations





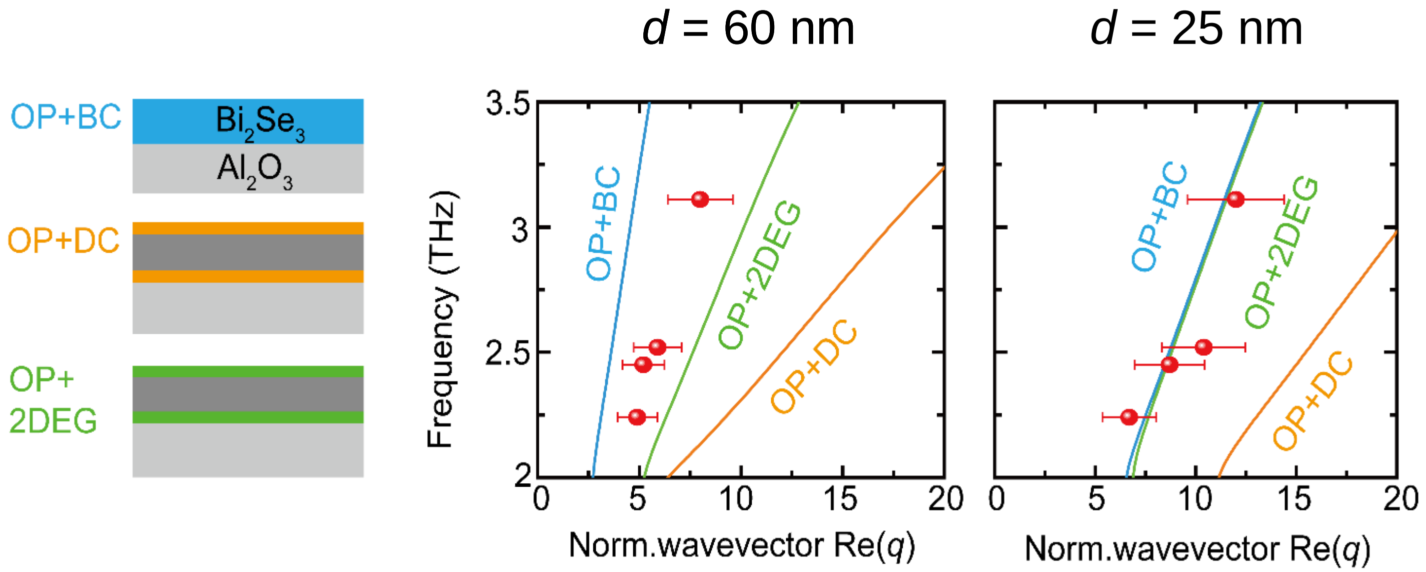
Thickness-dependent sheet carrier concentration from Hall measurements.

- Hall measurements do not allow to measure concentration of different type of carriers

➡ $n_{2D} = 2.5 \times 10^{13}\ \mathrm{cm}^{-2}$ from very thin film;

➡ $n_{3D}^{bulk} = \frac{\Delta n_s}{170\ nm} = 2.15 \times 10^{18}\ \mathrm{cm}^{-3}$ from 170 nm

Exploring origins of THz polaritons in Bi_2Se_3

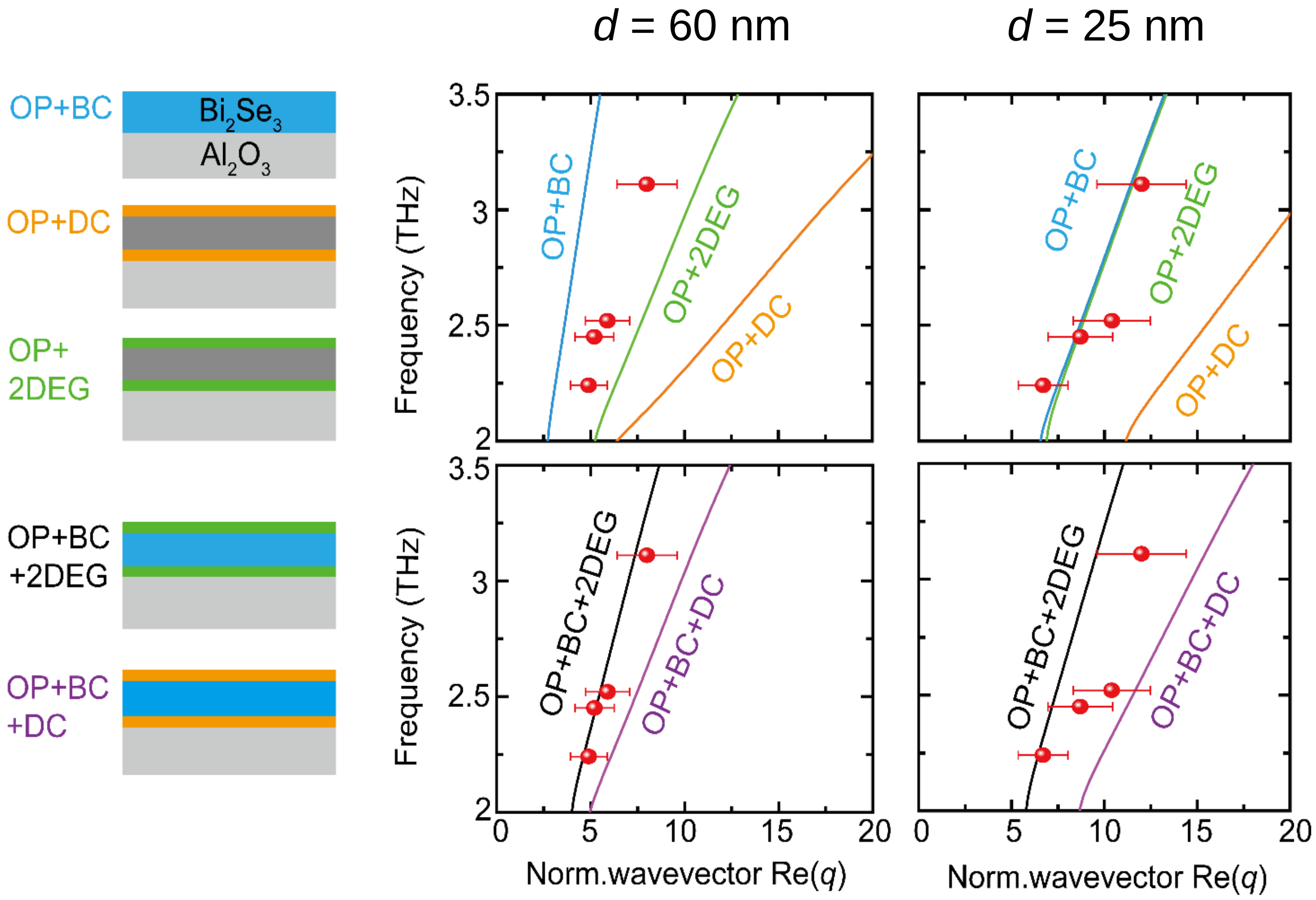


All carrier concentrations from the Hall measurements

$$\sigma(\omega) = \sigma_{\mathrm{ph}} + \begin{matrix} \sigma_{\mathrm{Drude}} \\ \sigma_{\mathrm{2DEG}} \\ \sigma_{\mathrm{Dirac}} \end{matrix}$$

Optical phonons + Bulk carriers / 2DEG / Dirac carriers

Exploring origins of THz polaritons in Bi_2Se_3



All carrier concentrations from the Hall measurements

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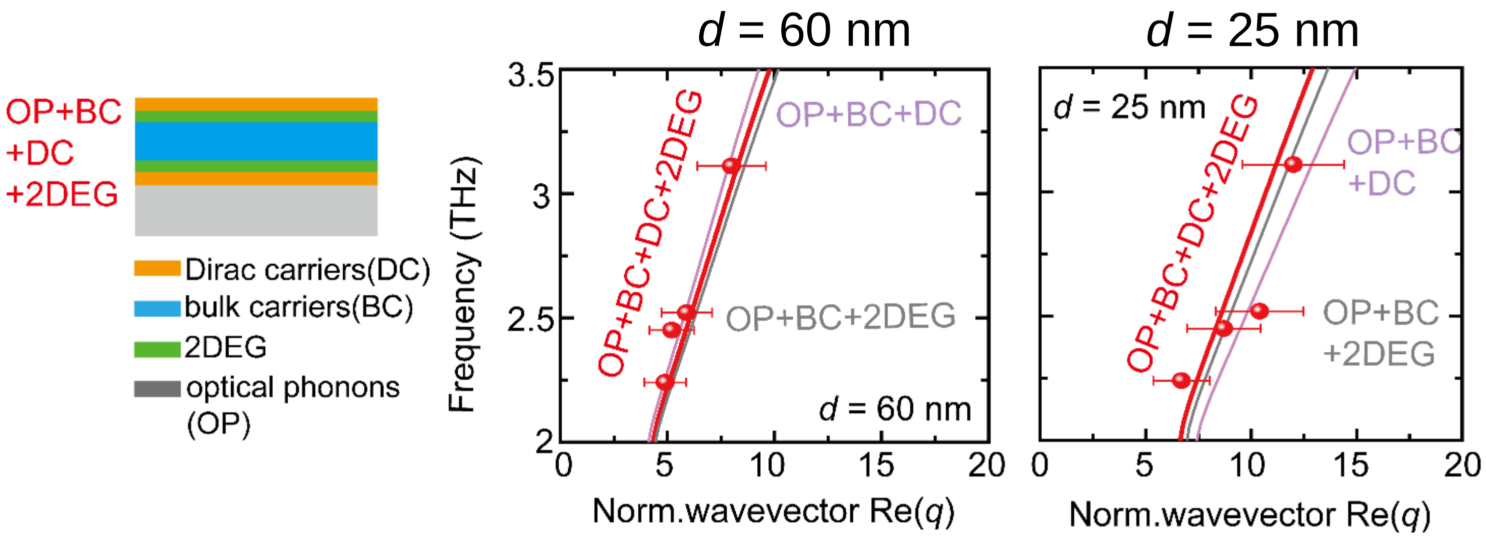
Optical phonons + Bulk carriers / 2DEG / Dirac carriers

$$\sigma(\omega) = \sigma_{ph} + \sigma_{Drude} + \begin{matrix} \sigma_{2DEG} \\ \sigma_{Dirac} \end{matrix}$$

Optical phonons + bulk electrons + 2DEG / Dirac carriers

We can fit polariton dispersion in multiple ways



Carrier concentration as a fit parameter

Optical phonons + bulk electrons + 2DEG

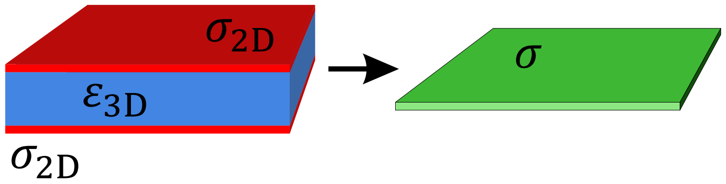
Optical phonons + bulk electrons + Dirac

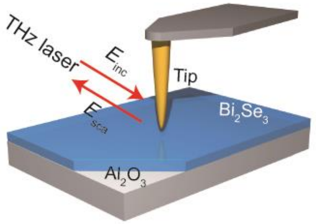
Optical phonons + bulk electrons + Dirac + 2DEG

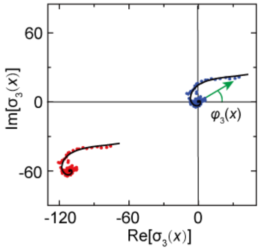
- Our fitting results indicate the hybrid origin of polaritons in Bi_2Se_3

Summary

➢ Effective conductivity model for the analytical analysis of polariton dispersion in the complex multi layer system

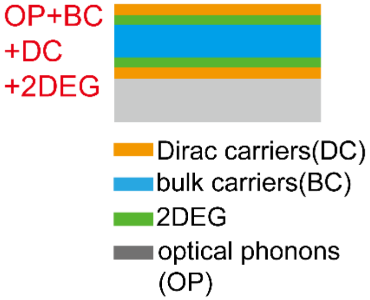






➢ Complex-valued analysis for the determination of polariton wavevector and propagation length of polaritons in TI

➢ Polariton dispersion can be explained by simultaneously coupling of THz radiation to different matter excitations



Acknowledgements

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MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

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Nanogune BRTA, Spain

Nanooptics group

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Martin Schnell
Peining Li
Rainer Hillenbrand

University of Delaware, USA

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