Terahertz plasmonic nonlinearity in graphene

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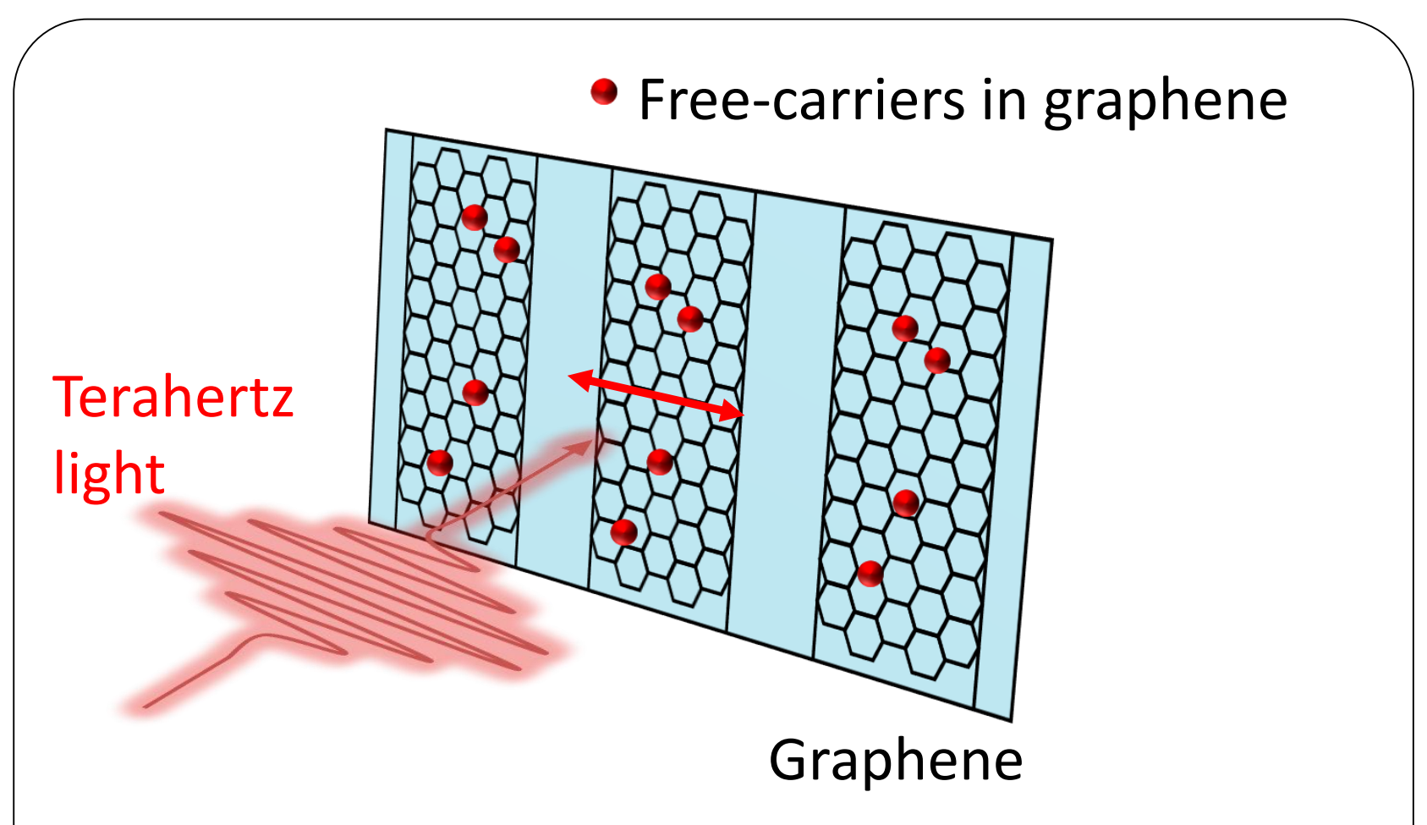
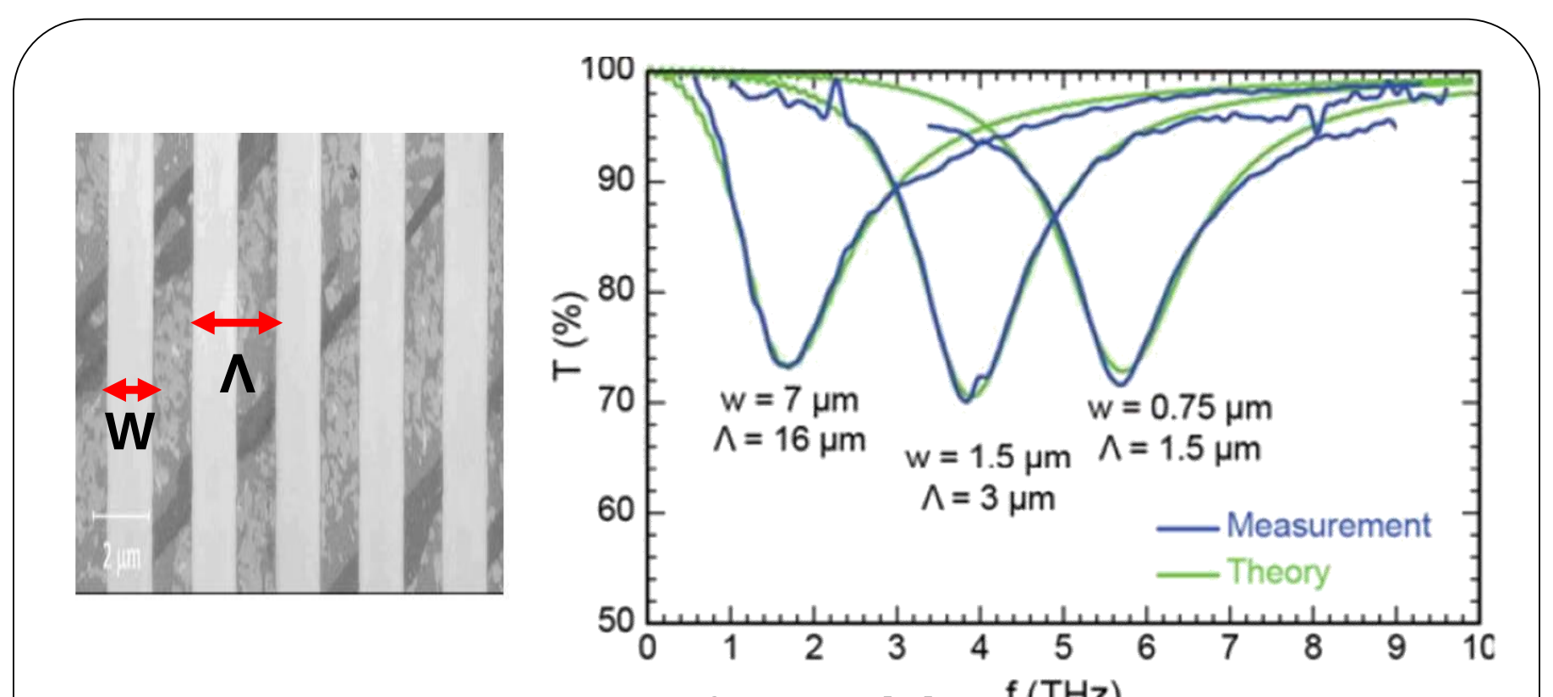
Motivation

Significant enhanced light-matter interaction in graphene using plasmons.



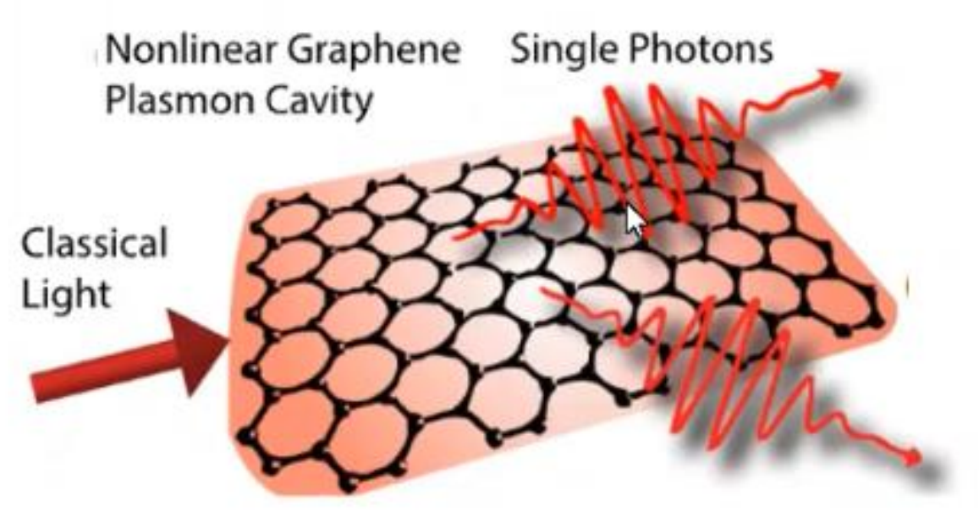
Schematic diagram of graphene plasmon. Free-carriers in graphene are collectively oscillated following with incident terahertz (THz) light, which can enhance light-matter interaction.



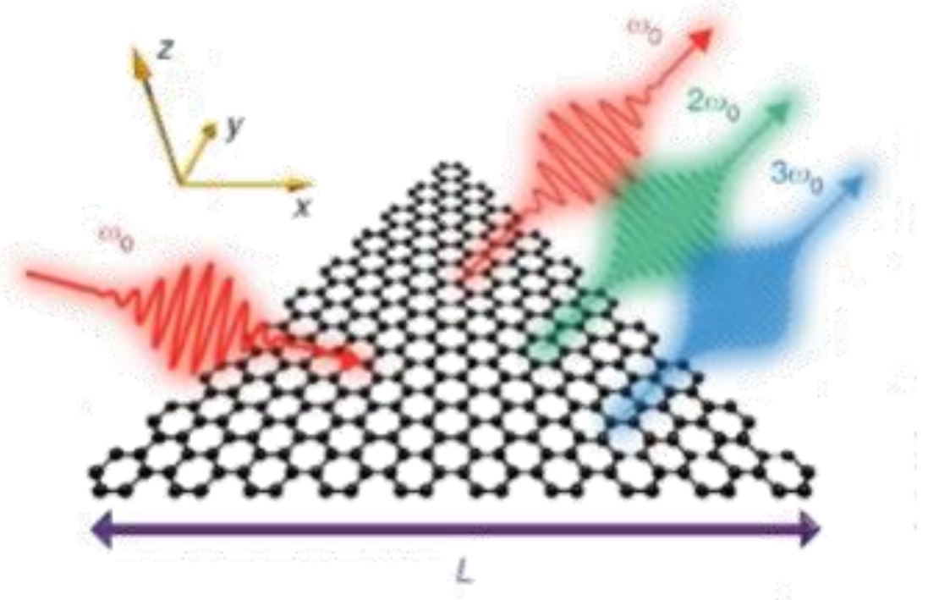
Reference [1]

1. Significant enhanced absorption was reported, which can be achieved by means of the plasmonic devices.
2. Plasmon frequency can be tailored by changing the width of the graphene ribbons.

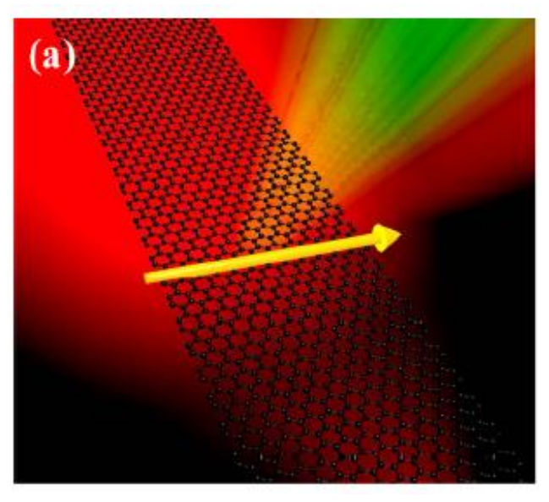
Theoretical predictions for the enhancement of nonlinear properties



Reference [2]



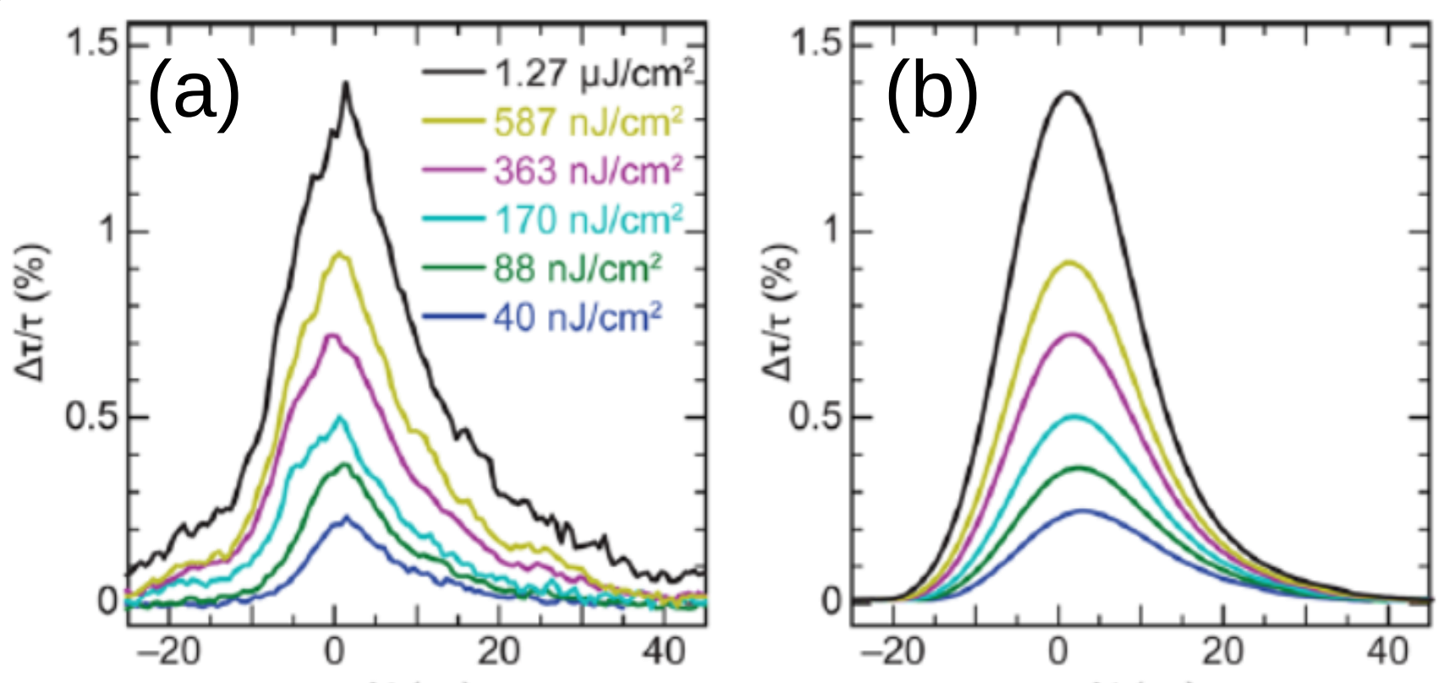
Reference [3]



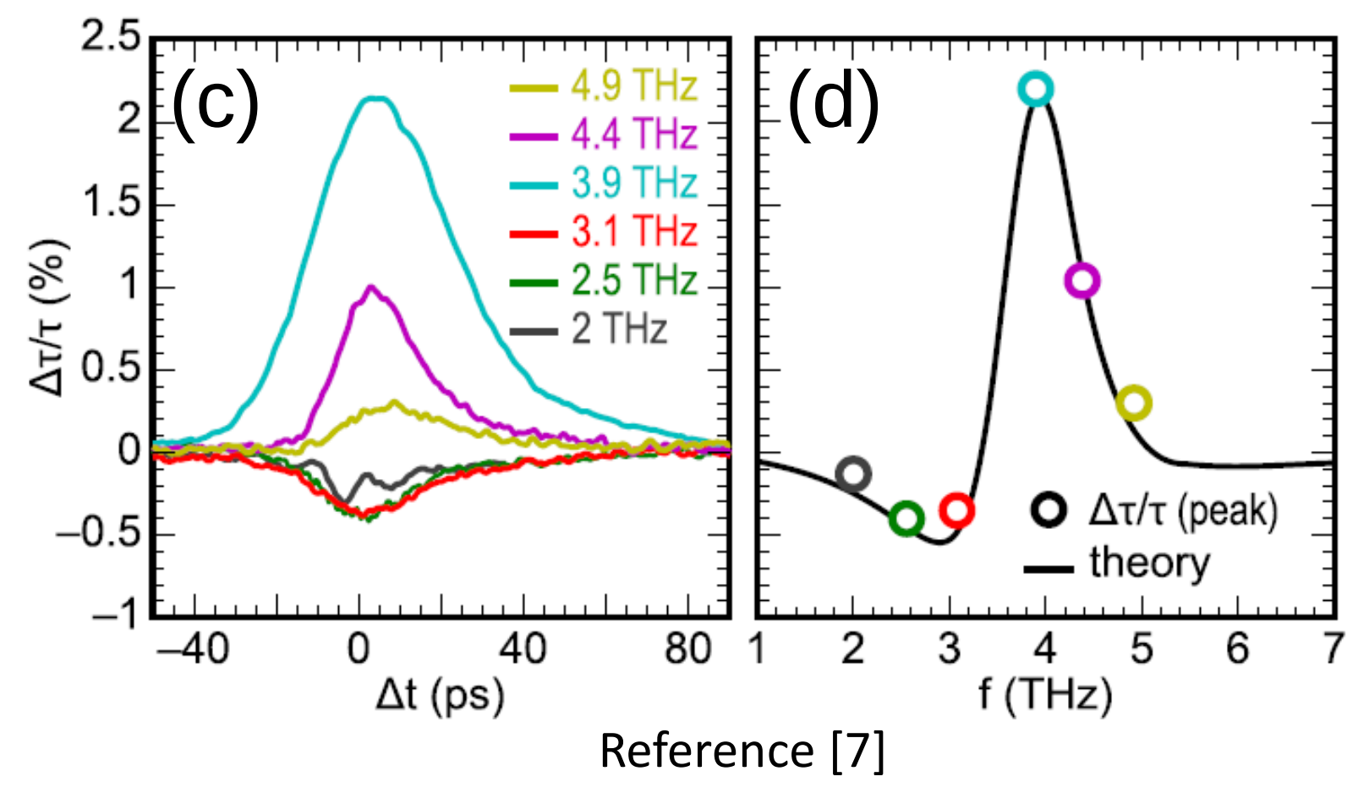
Reference [4]

Using plasmon in graphene, several theoretical predictions have suggested that nonlinear properties can be enhanced as well.

Experimental verifications for the enhancement of nonlinear properties



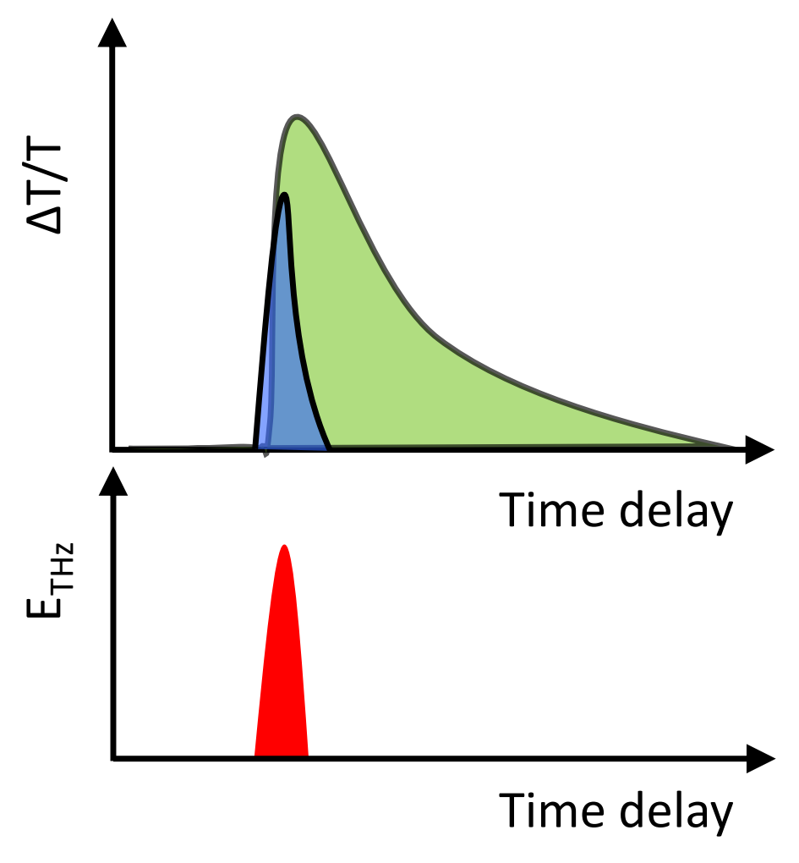
Reference [5]



Reference [7]

1. Strong-pump induced transmission was observed (Fig. (a)), which matches well with a two-temperature model (Fig. (b)).
2. Red shift of the plasmon frequency was predicted [5].
3. To confirm the red shift of plasmon frequency, pump-induced transmission was obtained at various frequencies, change of sign of pump-induced transmission was observed (Fig. (c) and (d)) [6, 7].
4. These experimental studies suggest that **thermal nonlinearity** plays a pivotal role for nonlinear plasmonics in graphene.

Ultrafast response time of plasmonic nonlinearity



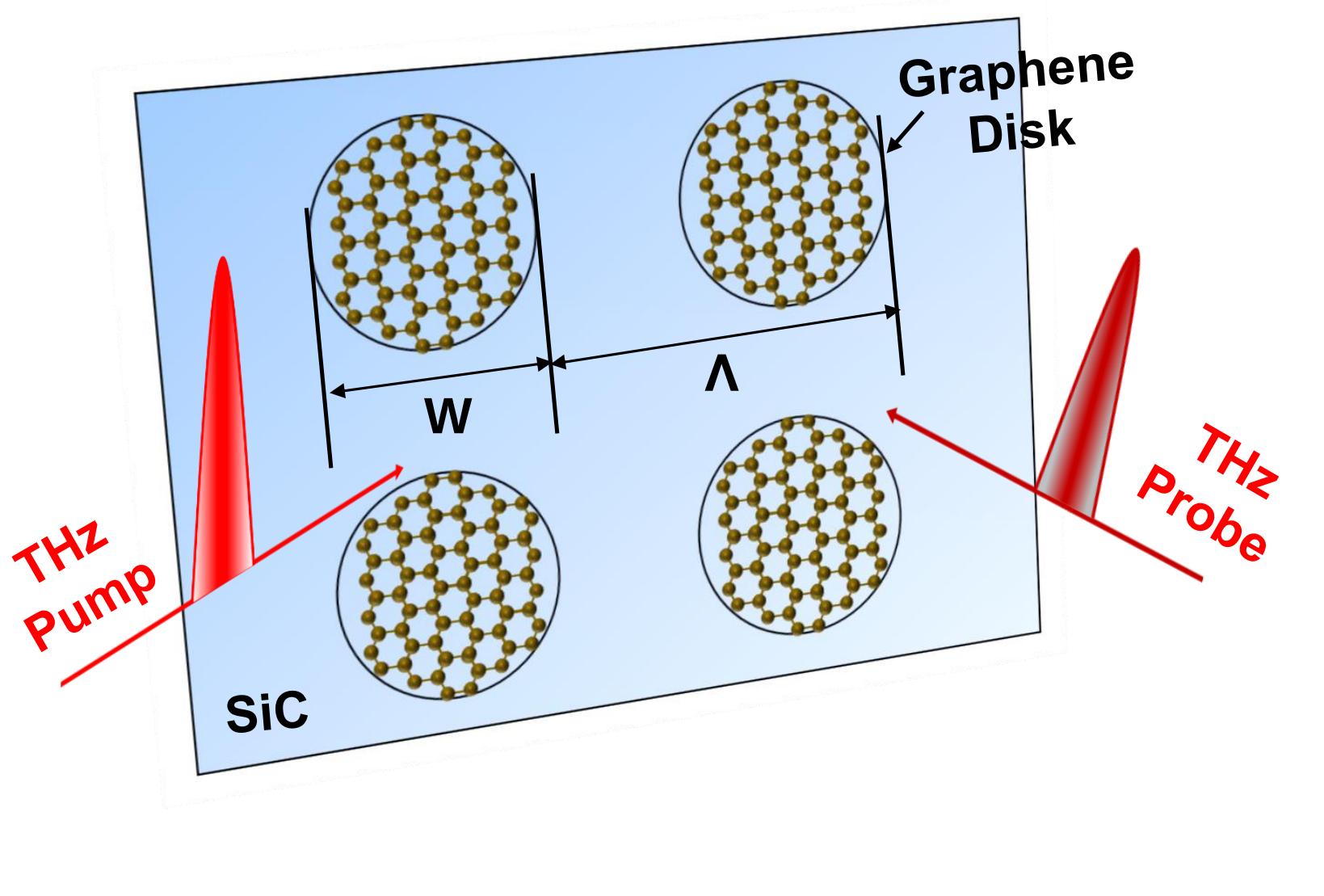
1. Thermal nonlinear effect depends on the electron temperature, leading to slow response (green curve in left figure).
2. Ultrafast response is expected for plasmonic nonlinearity (blue curve in left figure) [8, 9].

→ lack of experimental studies that characterized plasmonic nonlinearity!

in focus of this study: observation of plasmonic nonlinearity

Sample and experimental setup

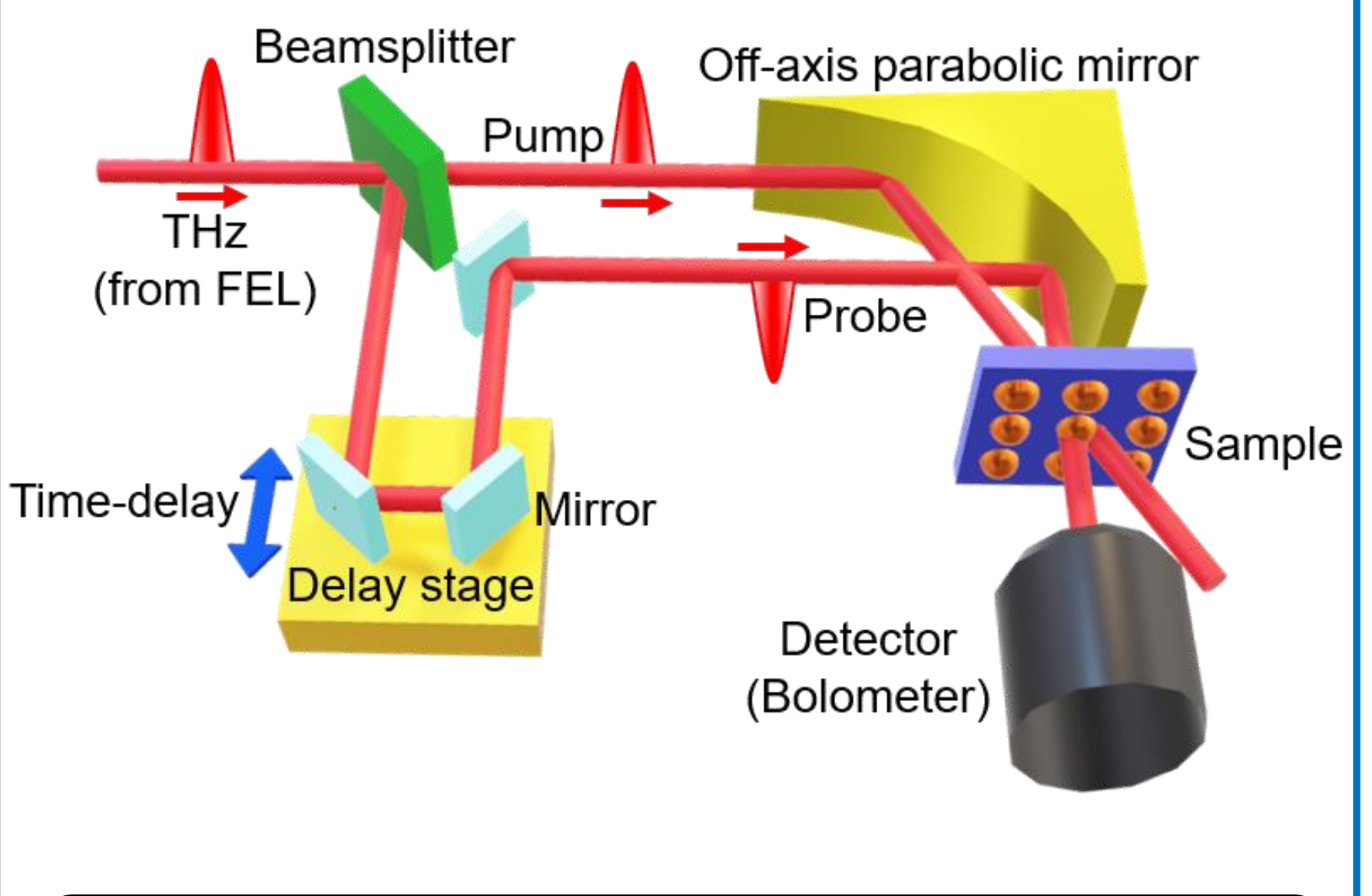
Sample (Graphene disks) geometry



Graphene disks were fabricated from hydrogen intercalation of epitaxial graphene on SiC.

W: Width of graphene disks (1280 nm)
Λ: Period of graphene disks (1.85 µm)

Experimental setup



THz source: Helmholtz-Zentrum Dresden-Rossendorf
Center wavelength: 3.5 THz
Repetition rate: 13 MHz

References

[1]: K. M. Daniels *et al.*, 2D mater. **4,** 025034 (2017).
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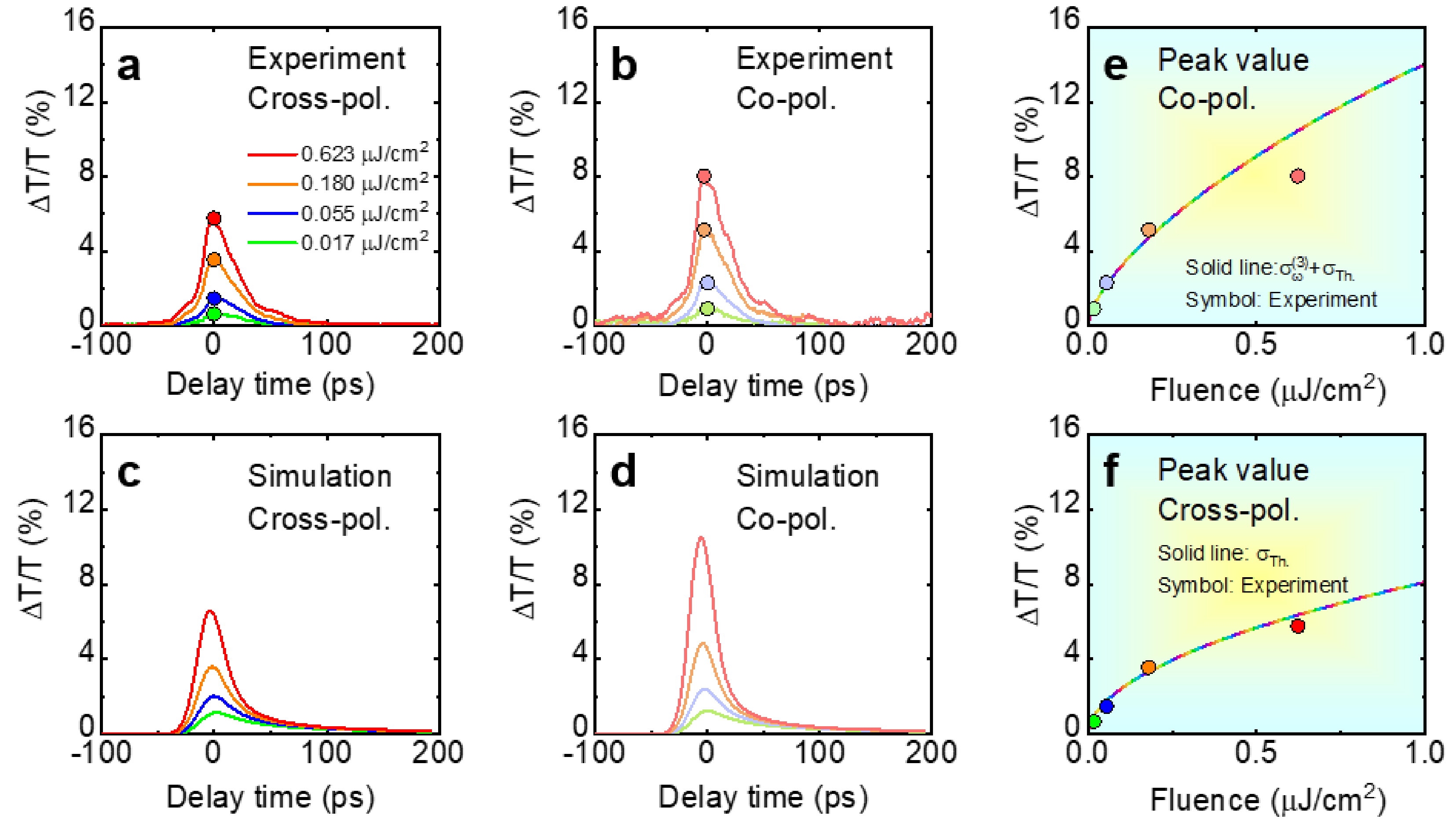
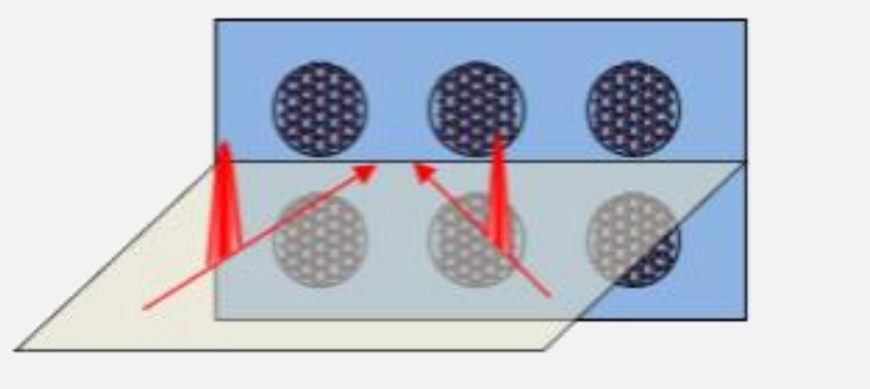
[7]: M. M. Jadidi *et al.*, ACS Photonics **6,** 302 (2019).
[8]: J. D. Cox *et al.*, ACS Nano **10**, 1955 (2016).
[9]: M. Kauranen *et al.*, Nat. Photonics **6**, 737 (2012).

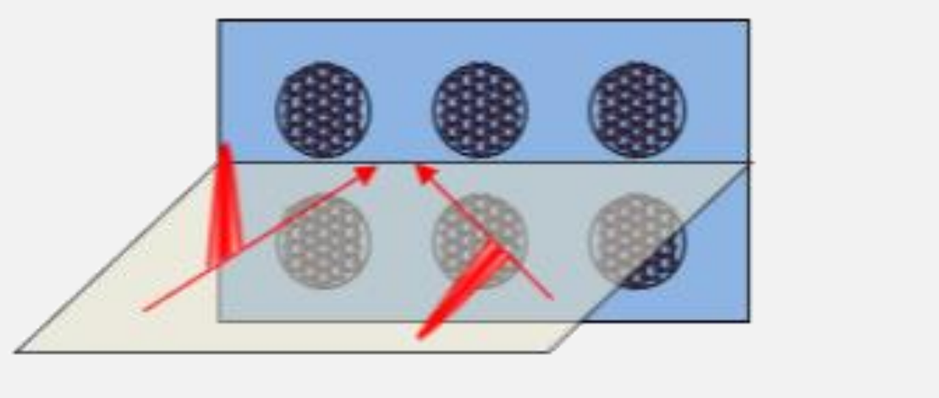
Experimental/simulation results

Experimental/simulation results with linearly polarized-light





Co-pol. configuration

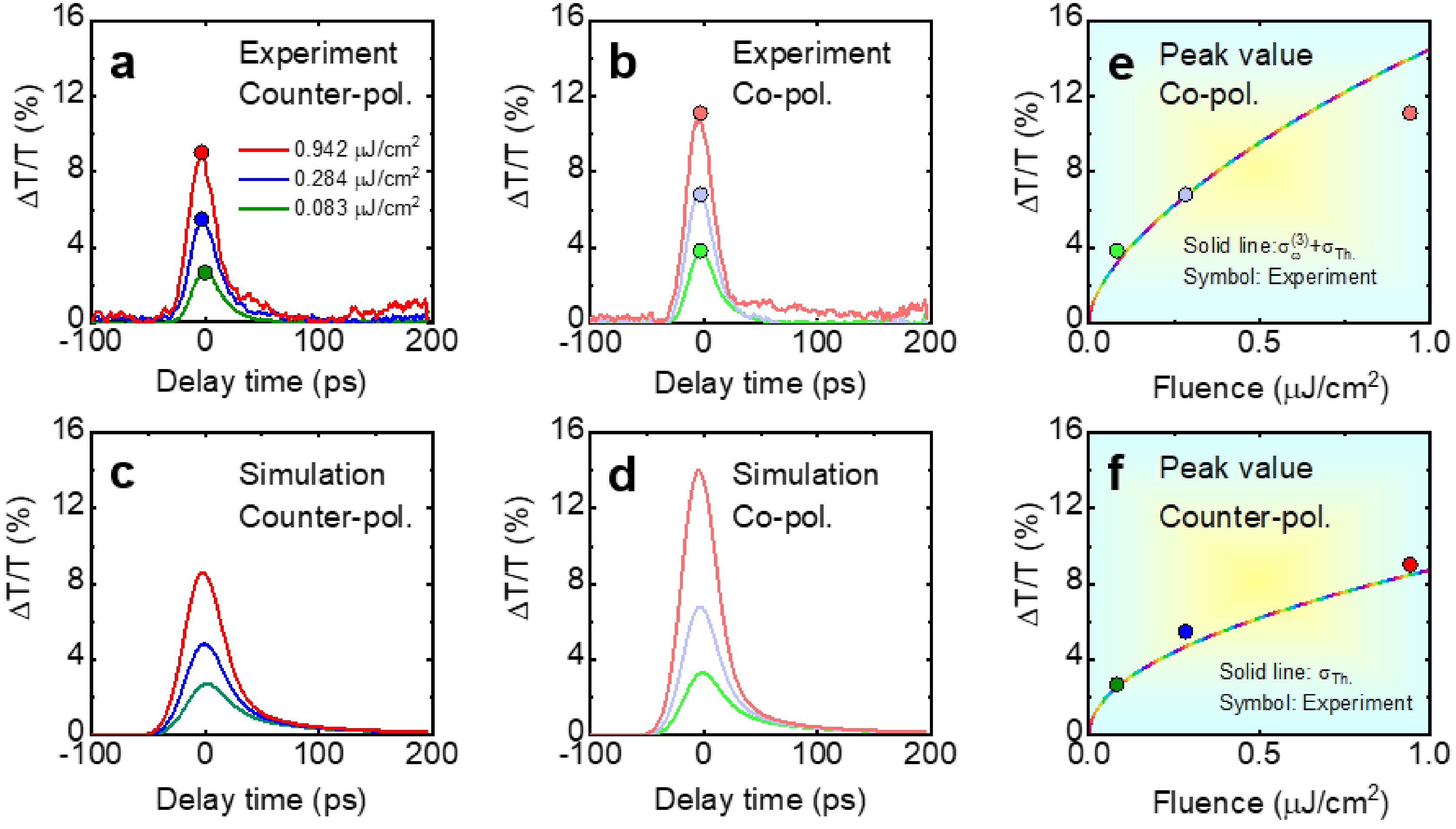


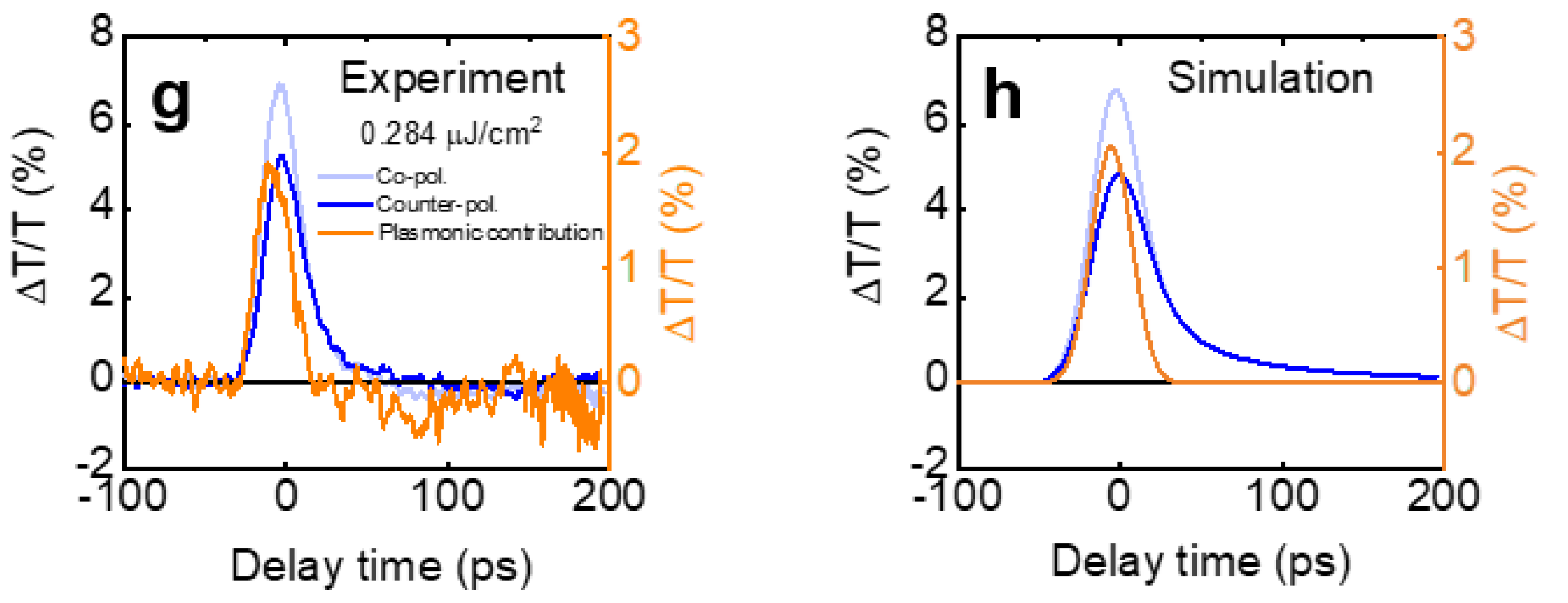
Cross-pol. configuration

Co-pol. configuration
Thermal nonlinearity
+
Plasmonic nonlinearity

Cross-pol. configuration
Thermal nonlinearity

Experimental/simulation results with circularly polarized-light





1. **pump-induced increase of transmission in both polarization configurations**
2. **more enhanced increase of transmission is observed in co-polarization configuration**
3. **→ clear experimental evidence showing plasmonic nonlinearity beyond thermal effects**
4. **fast response time of plasmonic nonlinearity**

Simulation model

Thermal nonlinearity

$$\sigma_\omega^{(1)} = \frac{w}{\Lambda}\frac{iD(T_e)}{\pi}\frac{1}{(\omega_{eff}(T_e)+i\Gamma(T_e))}$$

$D(T_e)$: Temperature-dependent Drude weight.
$\Gamma(T_e)$: Temperature-dependent scattering rate.
$\omega_{eff}(T_e)$: $(\omega^2-\omega_{PO}^2(T_e))/\omega$ (ω_{PO}: Resonance frequency of plasmon).

Plasmonic nonlinearity (Kerr effect)

$$\sigma_\omega^{(3)} = \frac{w}{\Lambda}\frac{i9e^6v_F^2}{4\pi\hbar^4 D(T_e)}\frac{1}{(\omega_{eff}(T_e)+i\Gamma(T_e))(-\omega_{eff}(T_e)+i\Gamma(T_e))(2\omega_{eff}(T_e)+i\Gamma(T_e))}$$

v_F: Fermi-velocity of graphene. (10^8 cm/s)

Electronic temperature T_e (balanced equation)

$$\alpha_s T_e\frac{dT_e}{dt}+\beta_s(T_e^3-T_L^3)=\beth(\omega_0,T_e)I(t)$$

α_s: Specific heat of electron in graphene.
β_s: Super-collision cooling coefficient.
T_L: Lattice temperature.
$\beth(\omega_0,T_e)I(t)$: Increase of temperature via absorption.

Total conductivity and transmission (equivalent circuit model)

$$\sigma_{tot} = Q_1\sigma_\omega^{(1)}+Q_2\sigma_\omega^{(3)}[E\cdot E] \Rightarrow T=\frac{4\sqrt{\varepsilon_1\varepsilon_2}}{Z_0^2\left|\frac{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}}{Z_0}+\sigma_{tot}\right|^2}$$

Z_0: Impedance of free space (377 Ω).
ε_1: Dielectric constant for vacuum (1).
ε_2: Dielectric constant for SiC (10).