Transient GaAs Plasmonic Metasurfaces at Terahertz Frequencies

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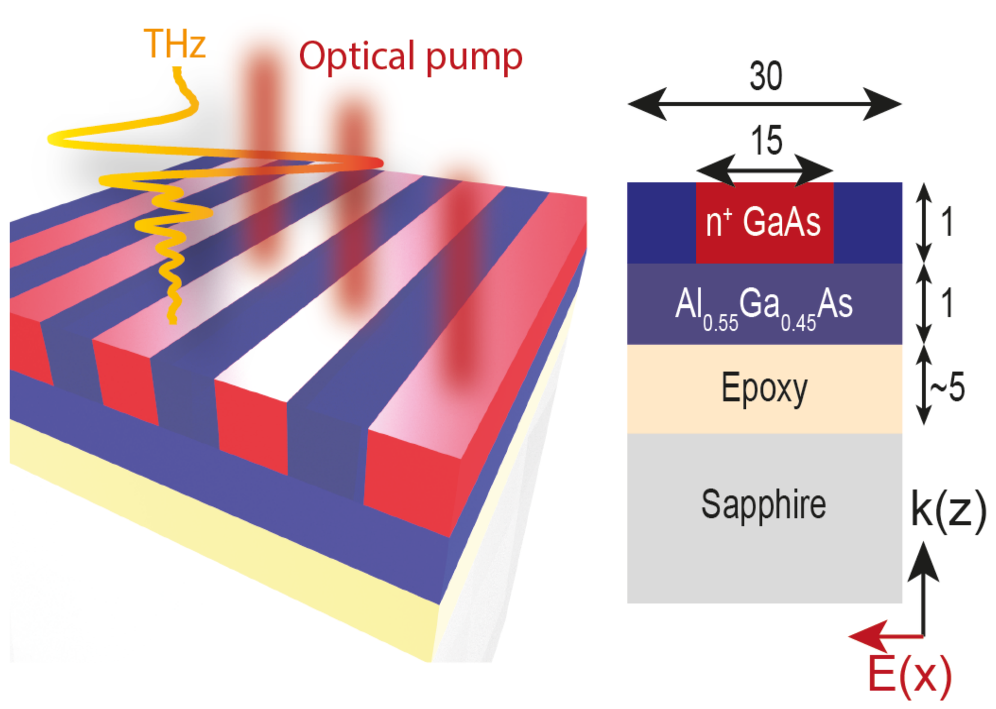
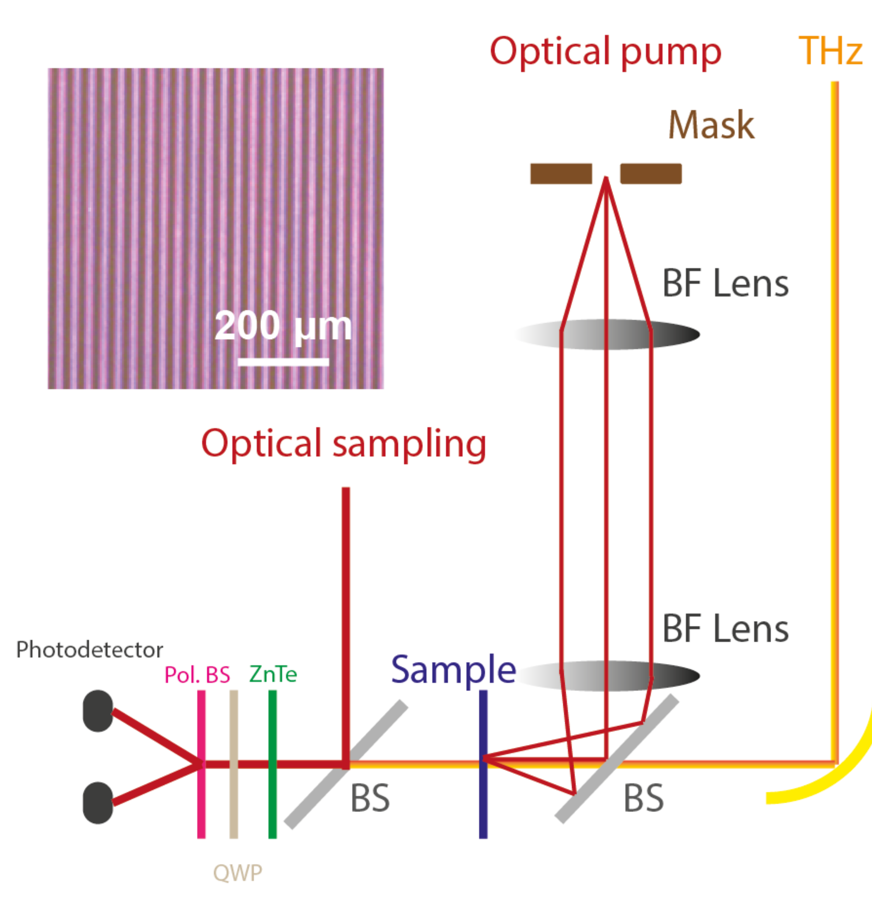
Introduction

We demonstrate the ultrafast formation of macroscopic terahertz (THz) metasurfaces through all-optical creation of spatially modulated carrier density profiles in a deep-subwavelength GaAs film. The switch-on of the transient plasmon mode, governed by the GaAs effective electron mass and electron-phonon interactions, is revealed by structured-optical pump THz probe spectroscopy, on a time scale of 500 femtoseconds. By modulating the carrier density using different pump fluences, we observe a wide tuning of the electric dipole resonance of the transient GaAs metasurface from 0.5 THz to 1.7 THz. Furthermore, we numerically demonstrate that the metasurface presented here can be generalized to more complex architecture for realizing functionalities such as perfect absorption, leading to a 30 dB modulation depth. The platform also provides a pathway to achieve ultrafast manipulation of infrared beams in the linear and potentially, nonlinear regime.



Schematic of a transient GaAs metasurface induced by a structured femtosecond optical pump beam and the dimensions of the structure (in μm).

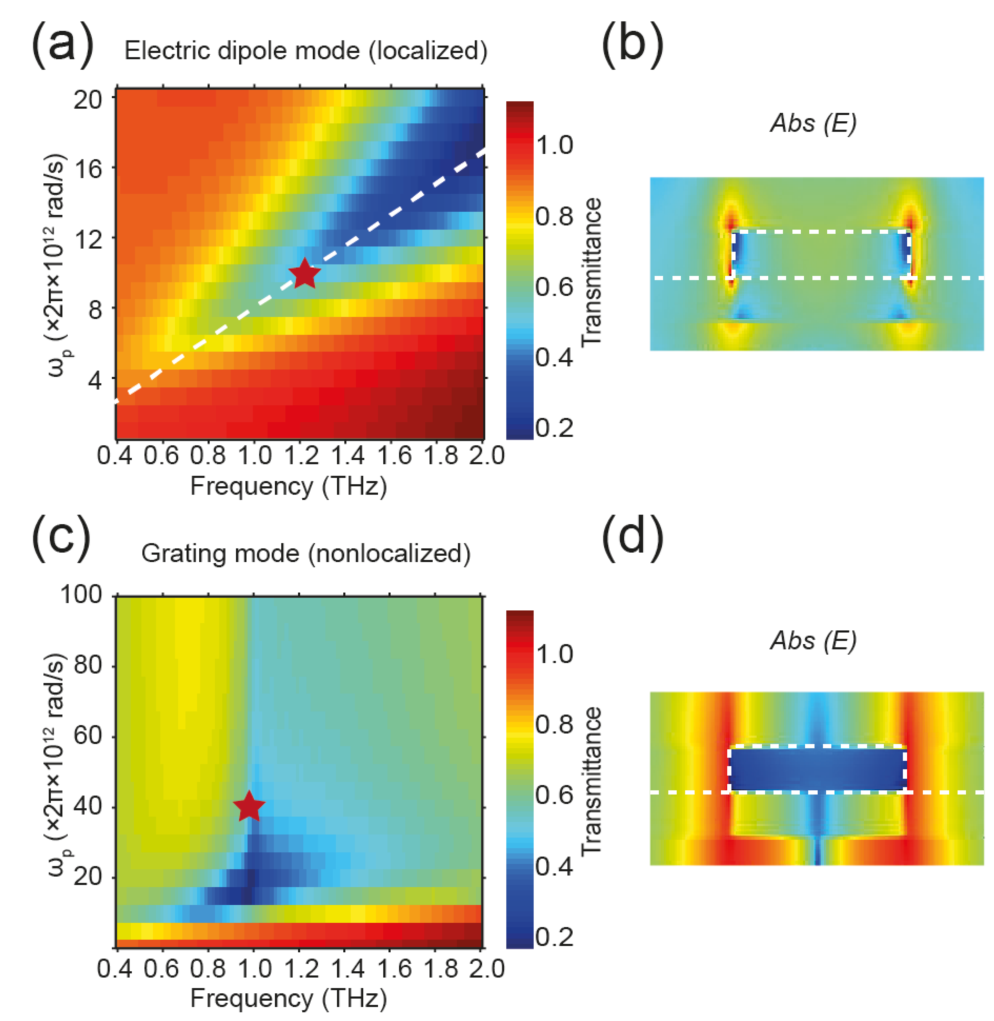
Experimental Setup



Schematic of the s-OPTP configuration by integrating a 4-f imaging system into the optical pump path of a conventional OPTP setup. The inset shows the pump beam profile on the GaAs metasurface, measured by replacing the sample with a silicon CCD.

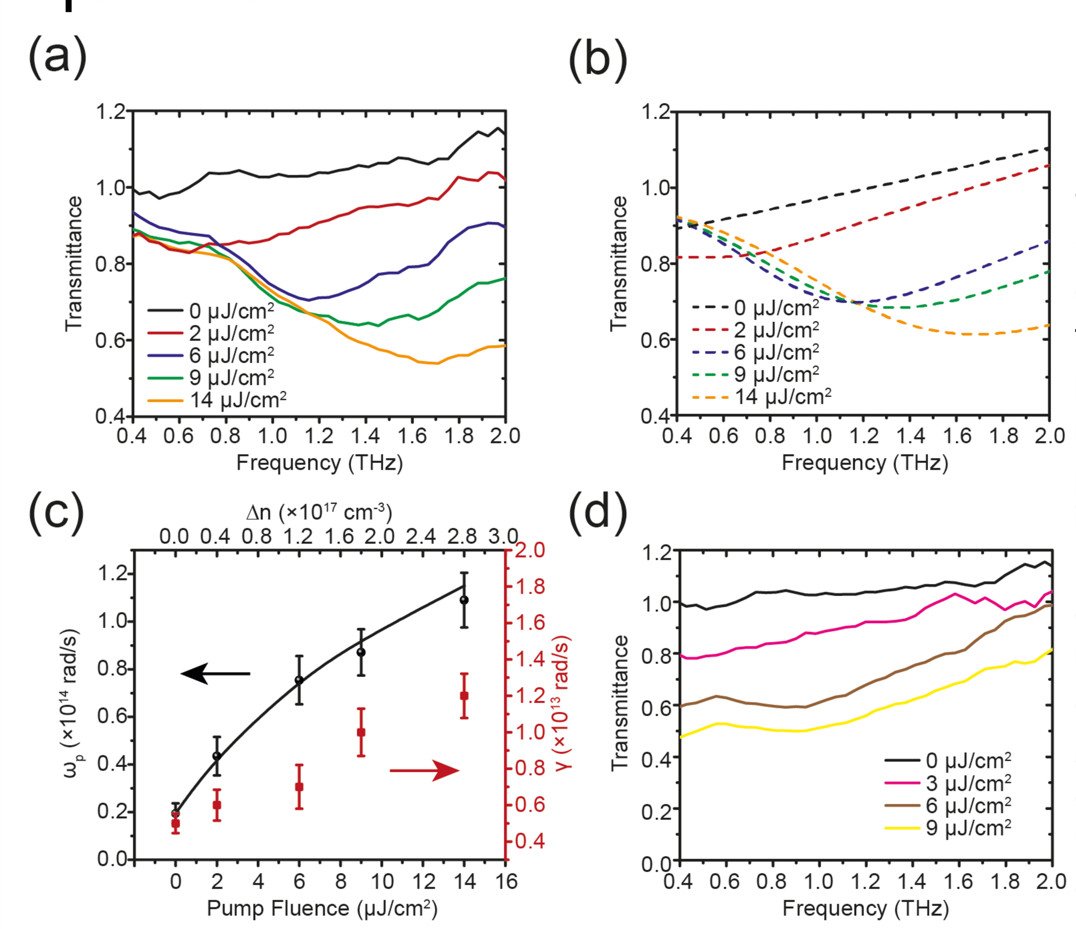
Wide Spectral Tuning

Localized electric dipole resonance



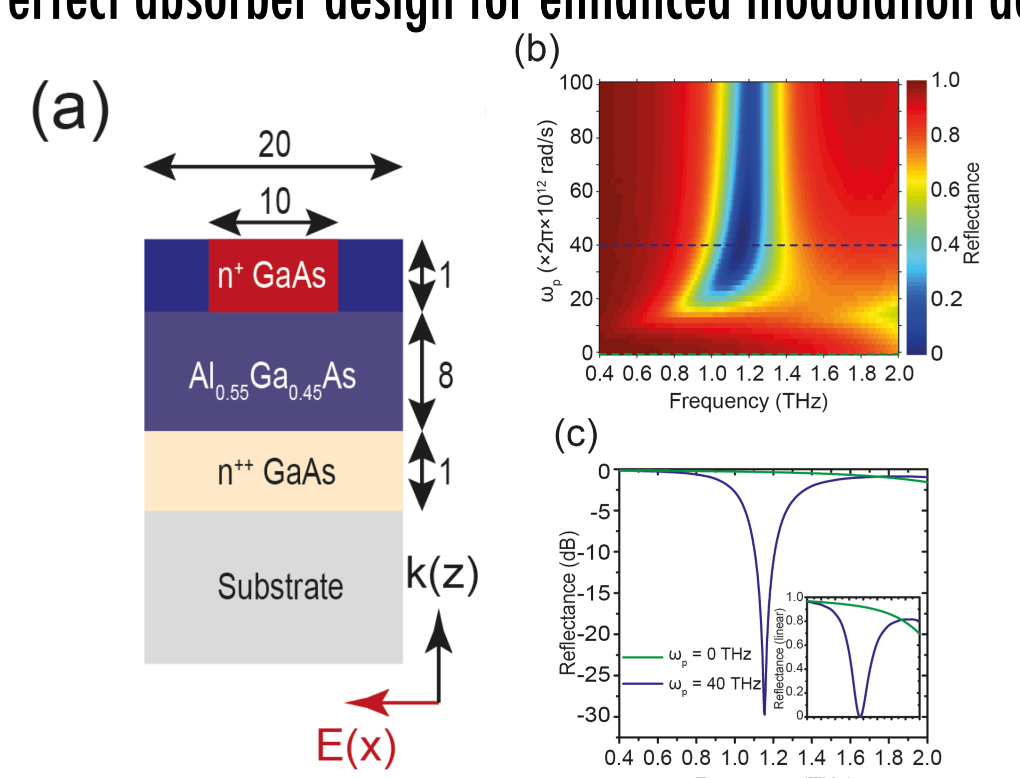
(a) 2D colormap of the numerically simulated transmittance of the GaAs metasurface with 30 μm grating period as a function of the GaAs plasma frequency. The white dashed line is a guide to the eye of the location of the electric dipole resonance. (b) The electric field magnitude Abs(E) in log scale at the electric dipole resonance (noted as the star in panel a). (c) 2D colormap of the numerically simulated transmittance of the GaAs metasurface with 100 μm grating period as a function of the GaAs plasma frequency. (d) The electric field magnitude Abs(E) in log scale at the non-localized resonance (noted as the star in panel c).

Experiments



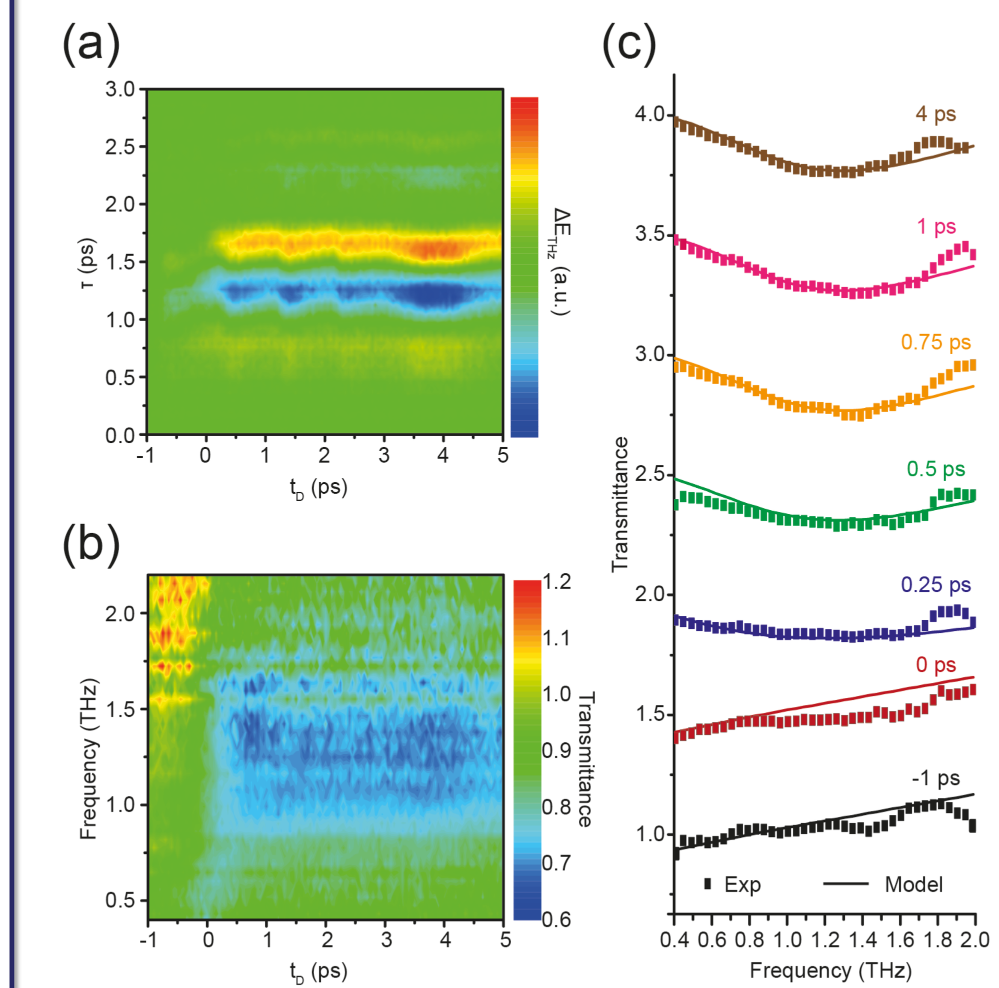
(a) Measured transmittance spectra of the photo-imprinted GaAs metasurface as a function of pump fluence. (b) Simulated transmittance spectra of the photo-imprinted GaAs metasurface as a function of pump fluence, accounting for inhomogeneous carrier profiles. (c) Drude model parameters extracted by fitting the numerical simulation to the experimental data. (d) Measured transmittance spectra of the homogeneously pumped GaAs metasurface as a function of pump fluence.

Perfect absorber design for enhanced modulation depth

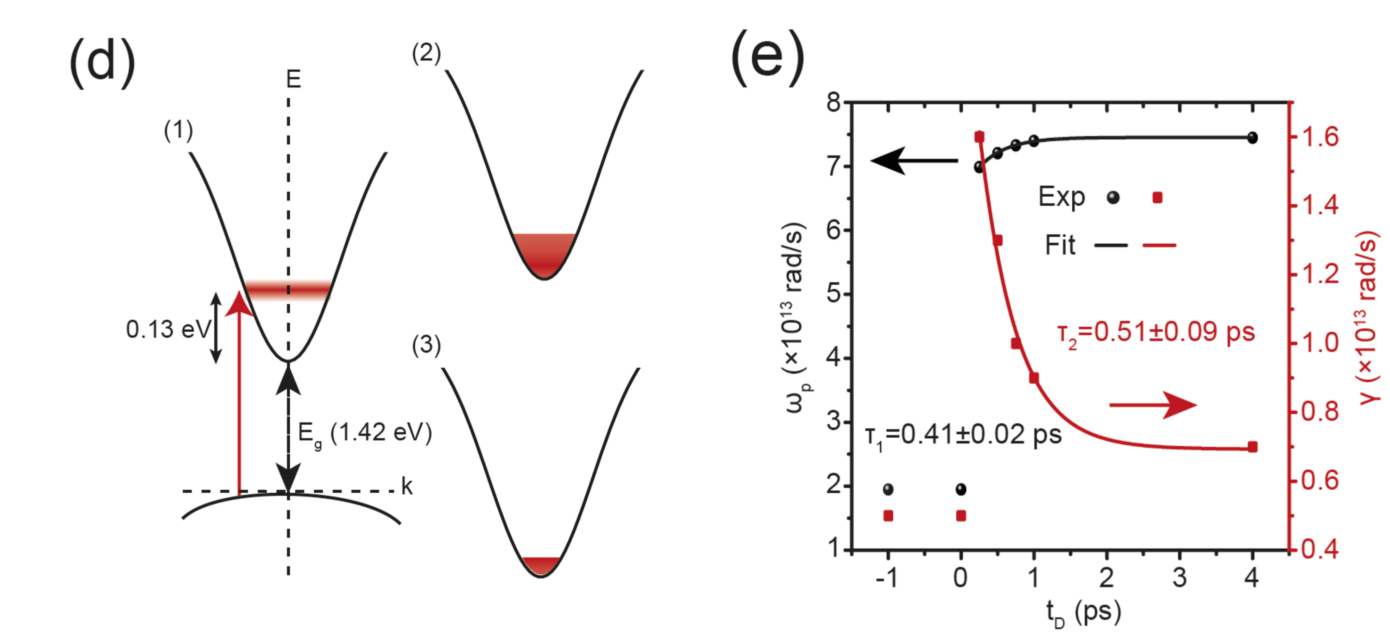


(a) Schematic and dimension (in μm) of a transient GaAs metasurface perfect absorber. (b) 2D colormap of the numerically simulated reflectance of the GaAs metasurface perfect absorber as a function of the GaAs plasma frequency. (c) Line-scans of the THz spectral reflectance after photo excitation in dB scale. The inset shows the same graph but with the reflectance in linear scale.

Ultrafast Dynamics of the Plasmon Mode



(a) Electric field change induced by optical photoexcitation versus the pump-probe delay time and the real THz trace τ. (b) Experimental THz spectral transmittance as a function of at 6 μJ/cm² pump fluence. (c) Line-scans of the THz transmittance spectra versus . Each set of traces is vertically offset by 0.5 for clarity. Symbols show the experimental data and lines show the numerical fit.



(d) Schematic illustration of ultrafast dynamics in the GaAs metasurface, consisting of photoexcitation, hot electron thermalization and electron-phonon coupling. (e), Extracted Drude model parameters (ω_p and γ) as a function of t_D, together with exponential fits.

Outlook

Future electrically tunable THz devices enabled by directly modulating the GaAs carrier density and plasmon modes can be envisioned for compact solid-state THz modulators. The structured illumination technique may also prove as a powerful tool for the investigation of light-matter interactions, including ultrafast dynamics, in a variety of delicate systems. Finally, the transient GaAs metasurface offers a great platform for the investigation of nonlinear plasmon dynamics of doped semiconductors under intense THz irradiation, which may lead to a new playground for nonlinear THz optics.

References:

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