ABSTRACT

The interaction of electromagnetic radiation with matter is central to modern physics and underpins a wide range of technologies, from spectroscopy and sensing to communication and quantum information processing. While the optical and microwave frequency regimes have been extensively explored, the terahertz (THz) spectral range offers unique access to low-energy excitations such as phonons, collective charge dynamics, superconducting gaps, and other many-body phenomena that remain difficult to probe using conventional techniques. Despite major advances in ultrafast THz spectroscopy, achieving strong, coherent, and tunable THz light-matter interaction remains challenging due to weak intrinsic dipole coupling, poor field confinement, dissipative losses, short coherence times, and limited tunability in natural materials.

In this thesis, these challenges are addressed using artificially engineered THz metamaterials that enable tailored resonances, strong field confinement, and interference-based control of light-matter interactions. Electromagnetically induced transparency (EIT)-*like* responses are investigated in metamaterial systems where destructive interference between a radiative bright mode and a weakly radiative dark mode produces a narrow transparency window. The work extends beyond conventional EIT metamaterials by introducing strong coupling between the EIT resonances and phonon modes, leading to the formation of hybrid phonon-polariton states.

A hybrid system consisting of a THz-EIT metamaterial integrated with a phonon-active $MAPbI_3$ perovskite layer is developed and characterized. Strong coupling between the metamaterial resonances and the perovskite phonon mode is demonstrated through clear avoided crossings and Rabi splitting in the transmission spectra, with an interaction potential of $V = 0.538\,\text{meV}$ exceeding the dissipative strong coupling threshold of $V_{\text{st}} = 0.294\,\text{meV}$. Rabi splittings of 0.26 THz are observed for the SRR-phonon subsystem, and the original transparency window at 1.3 THz splits into two distinct transparency peaks near 0.9 THz and 1.2 THz. This hybridization fundamentally reshapes the interference pathways responsible for transparency, replacing a single window with a dual EIT-*like* response originating from interference between hybridized upper and lower polaritonic modes rather than from purely geometric resonances. Rotational and translational tunability of the structure

further enables reversible switching between the dual-EIT and conventional Rabi splitting regimes without any modification to the device geometry.

To uncover the dynamical origin of the original transparency window, two-dimensional coherent THz spectroscopy is applied to the EIT metamaterial. This phase-resolved technique provides direct access to the coupled resonator dynamics through pump-probe and photon-echo signals. From the temporal decay of the pump-probe signal, a bright-mode population relaxation time of $T_1 = 1.96\,\text{ps}$ is extracted. From the oscillatory decay of the photon-echo signal, a phase coherence lifetime of $T_2 = 1.0\,\text{ps}$ is determined. The inequality $T_2 < 2T_1$ indicates the presence of pure dephasing with $T_\varphi = 1.34\,\text{ps}$, primarily attributed to structural inhomogeneity arising from lithographic dimensional variations across the fabricated array. These results establish that inter-mode coherence between the bright and dark resonator modes persists on the picosecond timescale but decays faster than energy relaxation. The multi-peak structure of the photon-echo signal in the 2D frequency domain directly visualizes the dressed-state doublet underlying the EIT window and enables a quantitative separation of homogeneous and inhomogeneous broadening contributions, identifying structural disorder as the dominant limit on EIT linewidth in lithographically fabricated metamaterials.

The thesis establishes a unified framework linking spectral interference, strong coupling, and ultrafast coherence dynamics in THz metamaterials, and demonstrates that the coherence quality of EIT metamaterials is directly measurable and addressable through controlled fabrication improvements.