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Carbon-Based Optics and Photonics

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Carbon nanomaterials, i.e., single-wall carbon nanotubes (SWCNTs) and graphene, attract much attention due to novel electronic, photonic, and mechanical properties that can find application in a variety of devices [1–4]. In particular, they have promising properties for developing optoelectronic devices at long wavelengths, i.e., in the mid-infrared (MIR) and terahertz (THz) ranges, including polarizers, modulators, detectors, and sources. It has been predicted that they have superior performance over existing devices in these ranges [5].

During the past decade, a large number of fundamental optical spectroscopy studies have been performed on these materials, establishing the basic properties of one-dimensional carriers, excitons, and phonons. However, most of these studies were carried out in the weak-excitation, quasi-equilibrium regime. In order to probe and assess their performance characteristics as optoelectronic materials under device-operating conditions, it is desirable to strongly drive them and examine their optical properties under highly non-equilibrium conditions.

In this presentation, we will summarize recent results of our experimental studies of the THz and ultrafast dynamics of carriers and phonons performed on graphene [7–9] and SWCNTs [10–16]. We use time-domain THz spectroscopy to probe frequency-dependent optical conductivities and determine the density and scattering time of low-dimensional charge carriers. Gate-tunable Fermi energies in graphene can be used to effectively modulate the transmission of THz waves [7]. In addition, when graphene is placed on a grating, normal incidence THz radiation can excite a propagating surface plasmon polariton [8], which can be used as a notch filter. We further demonstrate that the modulation contrast ratio can be significantly enhanced by placing a metallic aperture on graphene via the effect of the extraordinary optical transmission [9].

Free carrier absorption in metallic and doped semiconducting SWCNTs occurs in the form of plasmon resonance, which can be excited when the incident THz wave is linearly polarized along the nanotube axis. We have demonstrated the plasmonic nature of THz/MIR absorption in type-separated SWCNT samples [11], and the effect can be collectively enhanced when a macroscopic number of SWCNTs are aligned [10].

Finally, ultrafast optical spectroscopy allows us to make time-domain observations of coherent lattice vibrations [12,14,15,16]. Using femtosecond pump-probe differential transmission spectroscopy, we have observed coherent phonons (CPs) corresponding to the low-frequency radial breathing mode (RBM) and the high-frequency G-mode. CP signals can be resonantly enhanced when the pump pulse resonantly excites excitons (interband excitation), allowing us to obtain precise information on the nanotube chiralities present in a given SWCNT ensemble. Furthermore, because the bandgap and diameter in SWCNTs are inversely proportional to each other, the bandgap coherently oscillates as the lattice undergoes coherent RBM oscillations [14], resulting in modulation of interband optical absorption at THz frequencies

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