Supplementary Information for

Broadband Graphene Terahertz Modulators Enabled by Intraband Transitions

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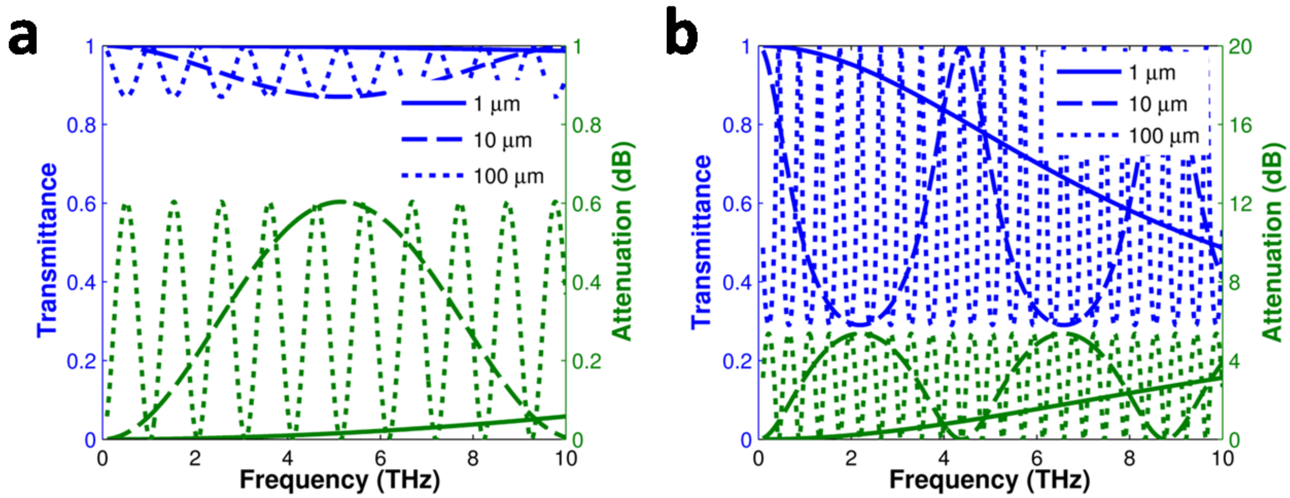
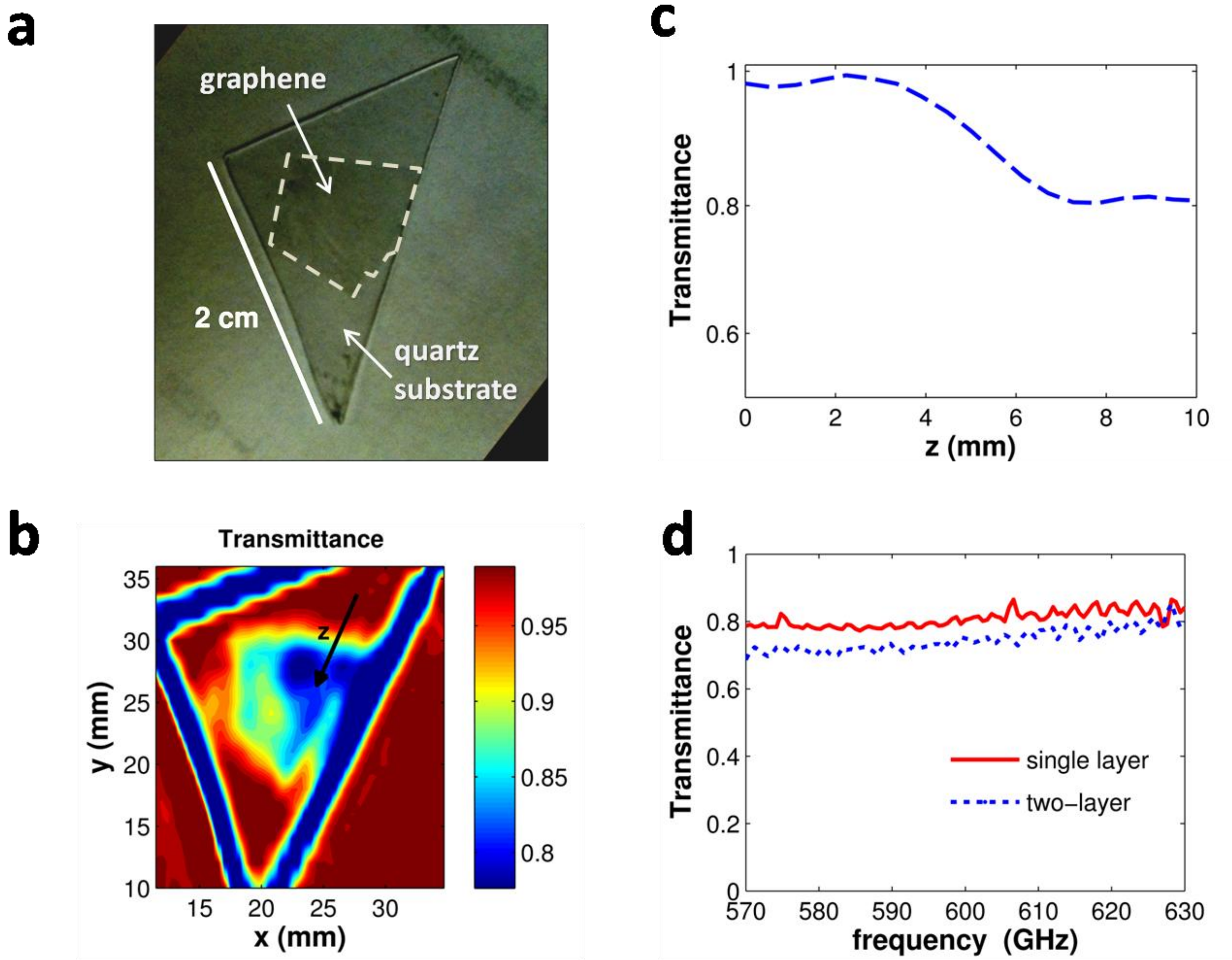
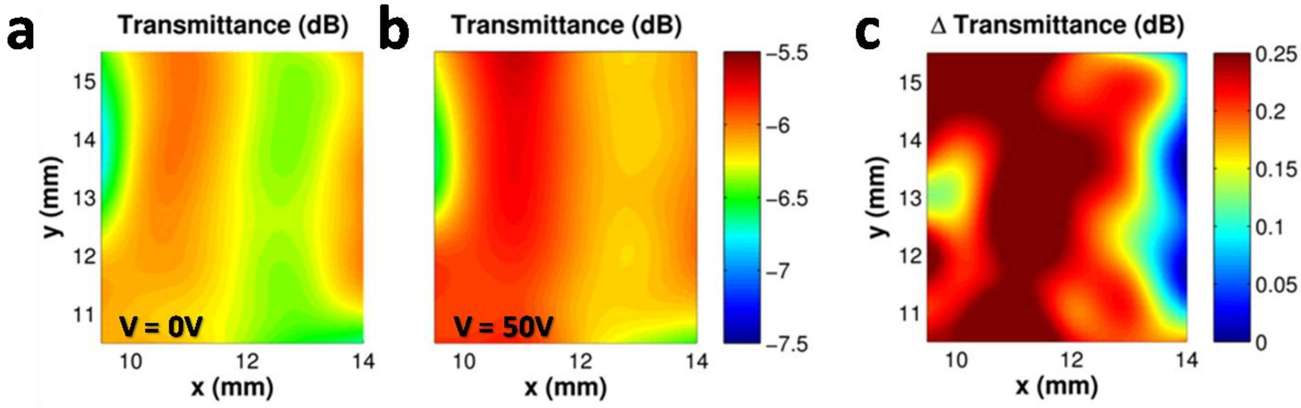


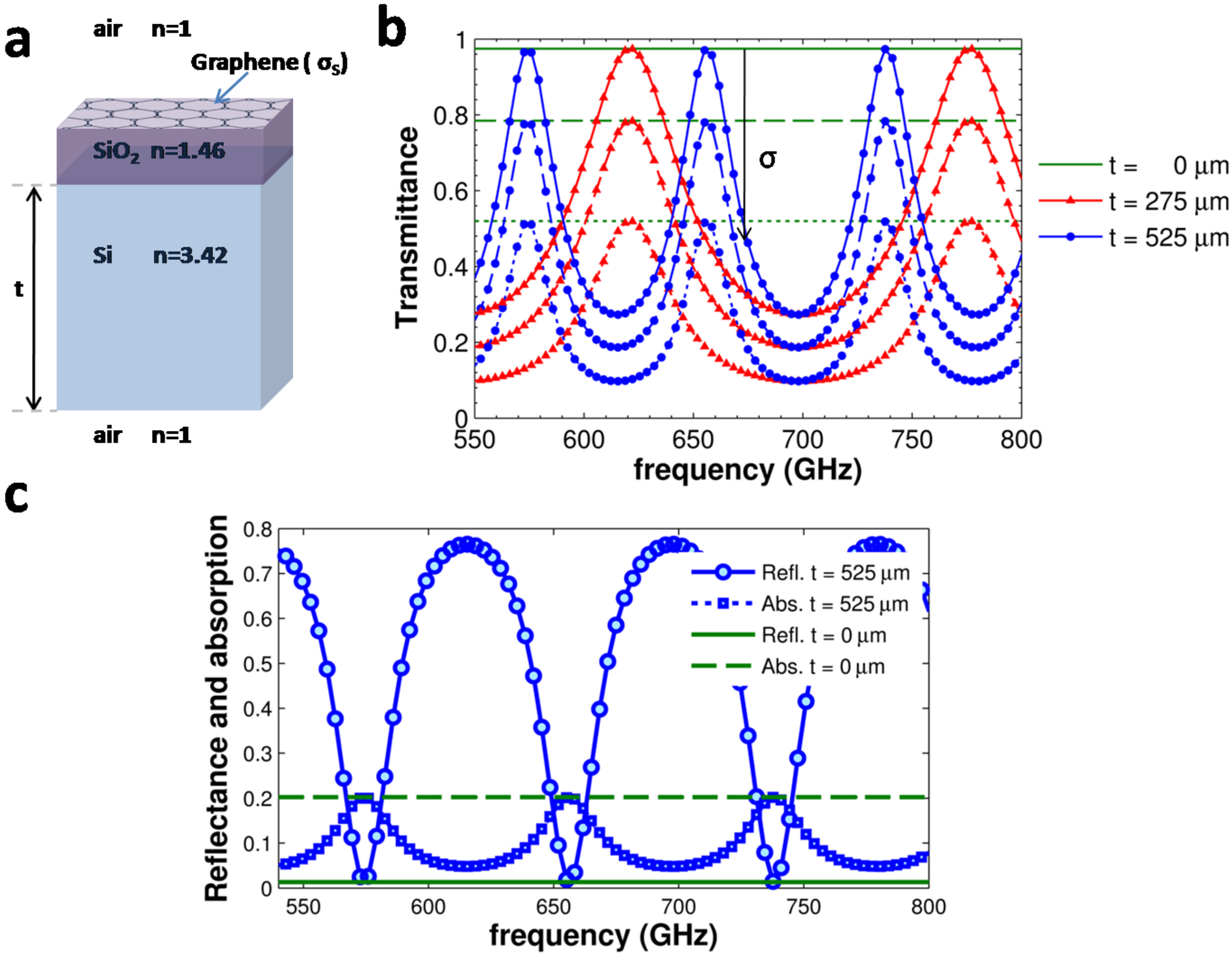
Supplementary Figure S1. Calculated terahertz transmittance and attenuation through various substrates. Transmittance and attenuation as a function of frequency for various substrate thicknesses of (**a**) quartz (n=1.46) and (**b**) silicon (n=3.42). Normal incidence is assumed. Employing a substrate with small thickness and/or low refractive index, the substrate effects can be minimized. For example, signal attenuation of < 0.1 dB (i.e. ~ 2%) can be achieved in the range of 0 – 1.33 THz using 10 um quartz; however, a 10 um Si substrate introduces a signal attenuation of up to 4.2 dB (i.e. ~ 60%) in the same frequency range. These dielectric property dependent effects are also observed in our experiments using quartz and Si. Supplementary Fig. S2(c) shows that the attenuation through a quartz substrate (~ 200 um) is less than 5% (i.e. 0.2 dB) in the 570-630 GHz frequency range. Fig. 2b in the main text shows a stronger oscillation due to the thicker Si substrate used (~ 480 um). Broadband transmittance with low insertion loss can be realized in optically thin substrates with low dielectric constant.



Supplementary Figure S2. Terahertz transmittance through single and two-layer graphene. (**a**) Optical image of a CVD graphene sample on a 200 μm quartz substrate. (**b**) Intensity transmittance map at 600 GHz of the same sample shown in (a). The blue triangle delineates the edges of the quartz substrate owing to strong edge scattering effects, and low transmission in the center (blue) is due to absorption/reflection in graphene. The substrate attenuation is negligible because of the low dielectric constant of quartz, which reduces Fabry-Perot oscillations. (**c**) Transmittance as a function of position along the z direction line cut depicted in (b). (**d**) Measured transmittance as a function of frequency for single and two-layer graphene samples on quartz.



Supplementary Figure S3. Spatial maps of intensity transmittance in dB at 600 GHz through graphene/SiO_2/*p*-Si. (**a**) at V_{bg} = 0 V, (**b**) at V_{bg} = 50 V, and (**c**) the difference between (a) and (b). The non-uniformity in transmittance is currently ascribed to the quality of the transferred CVD graphene, where folds and breakage of graphene as well as debris of PMMA and Cu have been observed on the device as a result of our current transfer process. The analysis shown in the main text was carried out in the region with maximum transmittance modulation. With improved transfer process of graphene, much better uniformity is expected.



Supplementary Figure S4. Theoretical terahertz transmittance through graphene on Si. (**a**) Schematic of the graphene/SiO_2/Si structure used for modeling. (**b**) Calculated intensity transmittance of the structure shown in (a), normalized to that of air, as a function of terahertz beam frequency using three values of graphene optical conductivity and three Si-substrate thicknesses. The solid, dashed and dotted lines represent σ_S = 0.1, 1, and 3 mS, respectively. (**c**) Calculated reflectance (solid lines) and absorption (dashed lines) as a function of terahertz beam frequency for two Si-substrate thicknesses of 0 (green lines) and 525 μm (blue lines) and σ_S = 1 mS. The peak transmittance and absorption, and the minimum reflectance are independent of the substrate thickness. For a fixed substrate thickness and frequency, transmittance decreases with increasing graphene optical conductivity. The oscillatory behavior due to the substrate modes is absent for zero substrate thickness. With the presence of the cavity effect, the dependence of transmittance on graphene conductivity and thus tunability is the strongest at the peak transmittance frequencies while tunability is reduced for other frequencies.