











window corresponding to the time delay between echos. High-resolution Fourier transform of the entire waveform shows no sign of narrow spectral features other than the interference fringes of the periodic pulse train.

Combining Eqs. (1) and 2 with  $t_{ij}$ , and  $r_{ij}$ , the relative field transmission of the  $m$ -th pulse is predicted to be

$$t_{rel}^{(m)}(\sigma_s) = \frac{E_{G-Si}^{(m)}}{E_{Si}^{(m)}} = \frac{t(\sigma_s)}{t_{13}} \left( \frac{r(\sigma_s)}{r_{13}} \right)^{m-1}, \quad (4)$$

where  $E_{G-Si}^{(m)}$  is the electric field of the  $m$ -th pulse after transmission through graphene/Si and  $E_{Si}^{(m)}$  is the electric field of the  $m$ -th pulse after transmission through Si. Assuming  $\sigma_s = 2.04 \times 10^{-3} \Omega^{-1}$  (the spatially-averaged sheet conductivity of graphene obtained from the power transmission measurement), Eq. (4) predicts  $t_{rel}^{(1)} = 0.852$ ,  $t_{rel}^{(2)} = 0.495$ , and  $t_{rel}^{(3)} = 0.288$ , in good agreement with the pulse-energy ratios ( $t_{rel}^{(m=1,2,3)} = 0.855, 0.454, \text{ and } 0.299$ ) seen in Fig. 4.

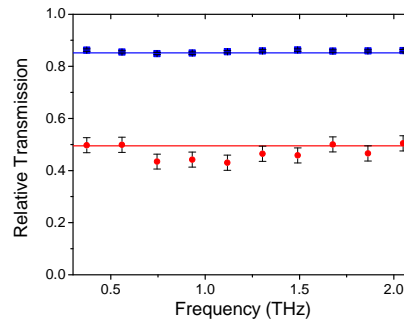


Fig. 5. Relative amplitude transmission spectra of  $m = 1$  (blue square) and  $m = 2$  (red circle) pulses (graphene-on-Si transmission spectra divided by the Si transmission spectra). Solid lines at  $t_{rel} = 0.852$  and  $0.495$  show the expected relative amplitude based on the spatial-average of our local sheet conductivity measurements  $\sigma_s = 2.04 \times 10^{-3} \Omega^{-1}$ . The experimental spectra were obtained by averaging the transmission through five different spots on the graphene.

Figure 5 shows the relative transmission spectra through the graphene/Si sample for pulses  $m = 1$  and  $m = 2$  (i.e., transmission through graphene/Si relative to transmission through bare Si). The spectra are flat and in close agreement with the expected values  $t_{rel}^{(1)} = 0.852$  and  $t_{rel}^{(2)} = 0.495$ . The flat spectral response seen in Fig. 5 indicates that the period of the applied electric field (0.5-3 ps) is much longer than the room-temperature carrier scattering time in our graphene sample [16,24].

## 5. Conclusion

We conclude that THz imaging and spectroscopy is of great use for rapidly characterizing the local free carrier dynamics in graphene. We have demonstrated that the strong THz absorption of graphene leads to high contrast imaging and the ability to accurately map sheet conductivity with sub-mm resolution over large areas.

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