Experimental Characterization of a Hybrid Graphene/Metal Plasmonic Antenna Array

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ABSTRACT

We fabricated terahertz-frequency plasmonic antenna arrays using patterned metallic structures atop a layer of graphene. The antenna design was developed through numerical simulations that were informed by experimentally obtained graphene parameters. Experimental characterization reveals a clear reflection enhancement at $3\lambda/2$, the intensity of which was modified by underlying graphene.

CCS CONCEPTS

• **Hardware → Plasmonics**; *Emerging tools and methodologies*; Wireless devices;

KEYWORDS

Terahertz-band communications, graphene, two-dimensional materials, plasmonic antennas, antenna arrays

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1 INTRODUCTION

The more bandwidth becomes available, the more data we want to transfer and the more devices we wish to connect; and we want to do all of this wirelessly. This insatiable hunger has been driving technology, resulting in a doubling of wireless data rates approximately every 18 months. [3] This trend—known as Edholm's law of bandwidth—predicts Terabit-per-second (Tbps) data rates within a few years. [7] However, just as Moore's law has pushed the limits of silicon technology, Edholm's law is pushing the limits of the wireless spectrum. In order to realize Tbps links, we are developing new technologies by incorporating plasmonic materials to access the currently unutilized terahertz band.

The major challenge to operating in the THz band (0.1 THz to 10 THz) is significant path loss, which is primarily due to absorption by water vapor. Improving THz sources and detectors is one way to overcome this problem, and there have been considerable advances in recent years. [1, 8] In addition to increased detector sensitivity and emitter power, directional antenna arrays are necessary to concentrate and steer the transmitted signals. Consequently, there is a critical need for compact antenna arrays capable of transmitting and receiving information in the THz band. In order to achieve this goal, control of the array response is essential.

Here we report measurements of a hybrid graphene/metal antenna array consisting of metallic elements fabricated atop graphene, which is a two-dimensional carbon allotrope with many impressive properties [4] and supports THz-frequency plasmons at room temperature. [2] The Fermi energy of graphene can be easily tuned by electrostatic gating, so graphene/metal hybrid structures are an important step toward controllable THz reflectarrays.

2 FABRICATION

We grew graphene on copper foil by chemical vapor deposition (CVD) at 1000 °C using methane as a carbon source. Graphene growth on copper is self-terminating, [6] resulting in continuous, primarily monolayer coverage over an area limited, in principle, by the size of the furnace and area of the foil. We used a piece of copper foil approximately 15 mm × 15 mm, and transferred the resulting graphene using a combination of poly(methyl methacrylate) (PMMA) and a compatible copolymer [5] onto a silicon substrate with 300 nm oxide layer. After transfer, we patterned gold antennas atop the graphene using electron-beam lithography. Antenna dimensions and spacing were determined by COMSOL Multiphysics simulations. Graphene parameters used in the simulations were determined from the complex conductivity, which we extracted using time-domain terahertz spectroscopy. [9] Simulation results are shown in the upper left frame of Figure 1, and the upper right part of the same figure shows an optical image of the fabricated antenna array. Raman spectra taken before and after transfer show no D peak near 1350 cm^{-1}, indicating the graphene is of high quality. Intensity of the 2D peak (near 2700 cm^{-1}) roughly double that of the G peak (near 1590 cm^{-1}) indicates monolayer graphene.

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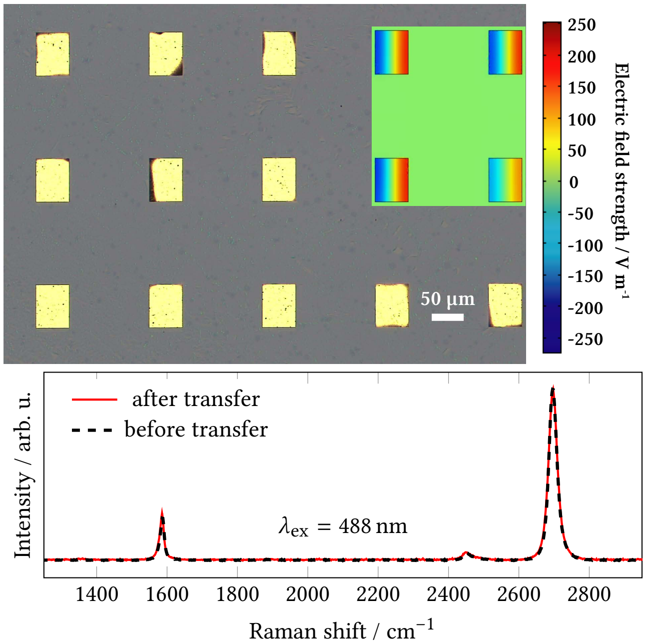

Figure 1: (Top) Optical micrograph showing an array of gold antennas fabricated atop graphene. Inset shows a numerical simulation of electric field response in a 2×2 antenna array. Scale bar applies to inset as well. (Bottom) Normalized Raman spectra obtained before and after graphene transfer.

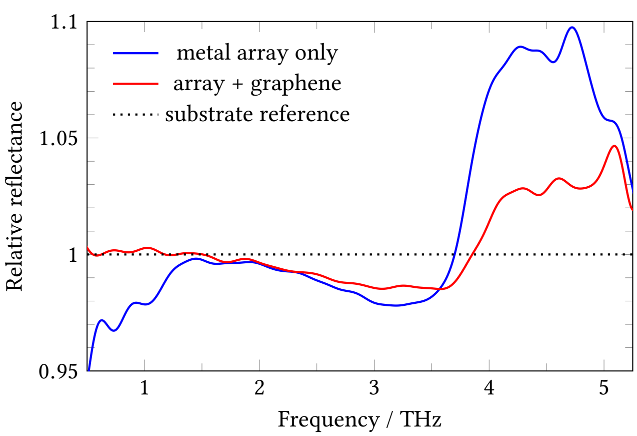

Figure 2: THz reflectance spectra relative to the underlying substrate. Increased reflectance by the array is apparent at 4.5 THz and is weakened by the presence of graphene.

3 RESULTS AND DISCUSSION

In Figure 2 we plot the response of the graphene/metal hybrid antenna array shown in Figure 1, as well as a metal array with identical dimensions but no underlying graphene. Reflectance is calculated relative to the underlying substrate reference, thus a value larger than unity corresponds to enhanced reflection by the array. The array elements were designed to resonate near 1.5 THz. While we observe no change at 1.5 THz, the reflectance is clearly enhanced at 4.5 THz, corresponding to resonance at $3\lambda/2$. The lack of a response at $\lambda/2$ is under investigation, but imperfect periodicity caused by errors in the fabrication process may have caused the primary reflection to be oriented away from our detector.

The decrease in reflectance when graphene is present can be understood by considering that, while it is a good conductor, graphene typically has a small density of states at the Fermi level. Having graphene on the surface under the array softens the electronic boundary condition at each element, making them slightly "leaky." The result is suppressed reflection at the boundary and reduced overall reflected power. This is advantageous because it facilitates modulation of the array response because the Fermi energy of graphene—and by extension the charge carrier concentration and electrical conductivity—can be tuned by electrostatic gating. The effect of such modulation would soften or sharpen the boundary, thereby changing the plasmon reflection from the edges and, consequently, the reflected power. Modulation of this hybrid array is currently being studied.

4 CONCLUSION

We designed and fabricated a hybrid reflect array comprised of metal elements atop graphene. Experimental measurements show a clear reflectance at 4.5 THz that is modified by the presence of graphene. This result opens the door to control of the reflectarray response by electrostatic gating of the graphene. Moreover, the use of CVD for graphene synthesis combined with array fabrication by standard lithography suggests excellent potential to scale the array dimensions and number of elements for the purpose of manufacturing large scale reflectarrays.

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