Graphene-Based Metasurfaces for Tunable Directional Thermal Emission

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Thermal emission is a fundamental process with significant implications for energy conversion, sensing, and imaging technologies. However, thermal radiation is typically incoherent and omnidirectional, leading to inefficiencies in many applications. As such, controlling and directing thermal emission remains a critical challenge. Graphene, with its tunability and unique electronic properties, offers an ideal solution for precisely controlling thermal emission. Previous work demonstrated a graphene-integrated metasurface structure that uses Fabry-Pérot (F-P) resonance for electrically tunable directional control of thermal emission [1]. By varying the graphene's Fermi level, the accumulated phase of the F-P mode shifts, altering absorption and emission directions. However, the broadness of the F-P resonance reduces angular selectivity and efficiency, requiring improvements such as enhancing the quality factor, exploring alternative resonance mechanisms, or optimizing metasurface geometry for sharper emission and better directionality.

In this work, we present a novel method for achieving graphene-based directional thermal emission steering that does not rely on F-P resonance. By using MEENT [2], a back-propagation-enabled RCWA method, we optimize thermal emission tuning and design a structure that tunes the thermal emission angle based on the variation of graphene's Fermi energy, without relying on a specific underlying principle. This structure consists of a gold (Au) substrate, with a layer of silicon (Si) on top, followed by 70 nm of Al_2O_3, graphene, and a gold pattern, with a period of 10 μm and thermal emission occurring at a wavelength of 8 μm. The periodic arrangement includes eight symmetric Au bars. The thickness of the Si layer and the size of each Au bar are optimization parameters for the structure. As shown in **Figure 1**, as the Fermi energy of the graphene varies between 0.15 eV and 0.6 eV, the thermal emission is effectively steered over an angle greater than 10°, with near-perfect thermal emission characteristics maintained throughout the tuning process. This new approach provides an efficient and controllable mechanism for directing thermal emission without the constraints imposed by traditional F-P resonance.

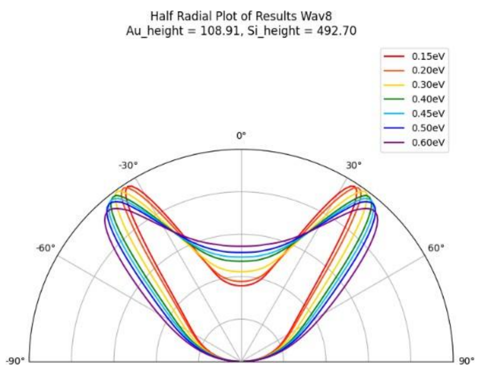

Figure 1. Thermal emission steering as the Fermi energy of graphene is varied between 0.15 eV and 0.6 eV, showing the directional shift of the emission angle.

References

1. Siegel, Joel, et al. "Electrostatic steering of thermal emission with active metasurface control of delocalized modes." *Nature Communications* 15.1 (2024): 3376.
2. Kim, Yongha, et al. "Meent: Differentiable electromagnetic simulator for machine learning." *arXiv preprint arXiv:2406.12904* (2024).