Tunable mid-infrared plasmonic metasurfaces

Ewald Janssens

Quantum Solid State Physics, Department of Physics and Astronomy, KU Leuven, Belgium

Metasurfaces are artificial two-dimensional materials with a periodic pattern of subwavelength-scaled structures, the meta-atoms. They can control the properties (amplitude, phase, polarization) of the light with which they interact. However, most conventional metasurfaces are "passive'', i.e. fixed by the geometric design, and cannot be "actively'' controlled by an external stimulus of thermal, electrical, mechanical, or optical origin. For advanced applications, it is highly desirable to develop real-time actively controllable metasurfaces.

The first part of the talk deals with our recent work on hybrid graphene-metal metasurfaces. Although graphene has exceptional tunable electrical properties, its zero-bandgap nature, low optical absorption (~2.3%), and difficult integration with metallic nanostructures have limited its use in photonic devices. By optimizing the graphene-metal metasurface design and the addition of an alumina barrier layer, we could enhance the real-time plasmonic resonance tuning [1]. Other steps forward were the inclusion of a Fabry-Perot cavity to enhance the light-graphene interaction and the addition of an encapsulating dielectric layer for stable operation in ambient conditions [2]. Bias-controlled reflectance tuning could be further enhanced, reaching modulation depths of 60%, by the reduction of the gaps between neighboring plasmonic antennas (figure). Gaps below 10 nm could be fabricated by combining lift-off, physical vapor deposition, and ion milling techniques [3].

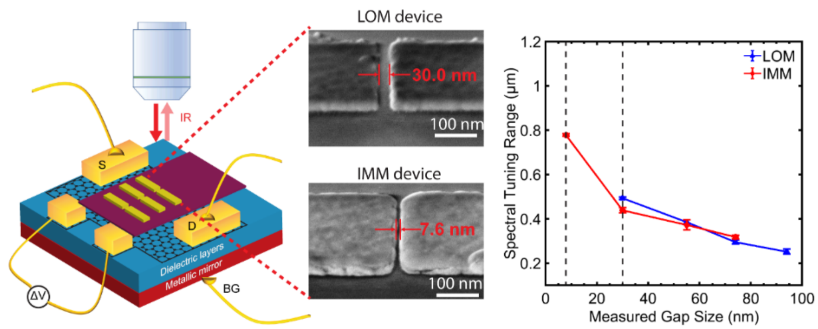

Figure: An enhanced spectral tuning of mid-infrared metasurfaces that integrate graphene and metal antenna arrays could be obtained by reducing the gap sizes between neighbouring antennas.

The second part of the talk concentrates on all-optical modulation of plasmonic metasurfaces. The most common method to modulate the optical characteristics of materials is via optical pumping through a semiconductor bandgap, which requires high photon energies. We demonstrated that career multiplication by impact ionization in a silicon substrate following the interaction of the metasurface with sub-bandgap mid infrared radiation strongly modulates the optically transmitted signal on ps time scales [4]. An analytical model and numerical simulations clarify the roles of plasmonic field enhancement and impact ionization in shaping carrier dynamics [5]. These findings may trigger applications in low-photon energy ultrafast all-optical modulators.

[1] F. Han, T.L. Pham, …, E. Janssens, Advanced Optical Materials 12 (2024) 2303085.

[2] F. Han, …, X. Zheng, N. Verellen, E. Janssens, Lasers and Photonics Reviews (2025) 2402258.

[3] F. Han, …, X. Zheng, N. Verellen, E. Janssens, Advanced Science e06898 (2025).

[4] M. Bejide, …, N.T. Tung, E. Janssens, Optics Express 29 (2021) 170-181.

[5] M. Bejide, T.L. Pham, A. Amirjani, …, E. Janssens, Materials Advances 6 (2025) 5035.