Efficient Second-Harmonic Generation from Nanostructured Hyperbolic Metamaterials on the Quantum Scale

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We propose and theoretically study the second-harmonic generation (SHG) from the nanostructured hyperbolic metamaterials (HMMs), constituted by arrays of dissimilar metal-insulator–metal (MIM) junctions. On the quantum scale (i.e. with a sub-nanometre scale insulting layers), the photon-assisted electron tunneling across the MIM junction could introduce relevant quantum conductivities that have both linear and nonlinear components, which contribute to power dissipations and harmonic losses (e.g. second-harmonic generation and third-harmonic generation). We show that the tunneling-induced nonlinearities, such as the second-order conductivity responsible for the SHG effect, may be significantly enhanced by the strongly localized optical fields inside the plasmonic MIM nanojunctions. We have characterized the relationship between the SHG conversion efficiency and the intensity of pulsed pump laser, with the rigorous calculations based on nonlinear Maxwell's equations. By designing particular HMM-based, effectively tailoring the eigenmode profiles and resonances of nanostructured HMM, we observed the dual resonance phenomenon at the fundamental frequency and its second harmonic, allowing for efficiently couple the pump laser into the massively parallel nonlinear nanojunctions and outcouple the second-harmonic waves to free space. Our results show a high SHG conversion efficiency in the mid-infrared region, orders of magnitude larger than a traditional nonlinear optical material slab of the same thickness. We envisage that the interplay between the photon-assisted tunneling and the plasmon coupling within specific MIM metamaterial-structures, such as the nanopatterend HMM substrate in this work, may substantially enhance the tunneling-induced conductivities and hence make useful wavelength conversion and wave mixing devices for nanophotonic and nano-optical applications.