Nonlinear Plasmonic Metasurfaces to Enhance Four-Wave Mixing

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Four-wave mixing (FWM) is a parametric nonlinear process that is widely used in optical signal processing, such as wavelength conversion, signal regeneration, and switching. It is a third-order optical nonlinear effect and usually requires very high input intensities to be excited in nanoscale dimensions, i.e. it has very poor efficiency. During this work, we present several new designs of nonlinear plasmonic metasurfaces [B. Jin and C. Argyropoulos, Sci. Rep. 6, 28746 (2016)] which can lead to giant FWM enhancement spanning different frequency ranges from visible to low terahertz. The presented nonlinear metasurfaces are designed by film-coupled silver nanostripes loaded with nonlinear materials. Standing waves are formed at the resonant frequencies of the proposed nanodevices, which are confined inside the spacer layer between the silver nanostripes and the bottom silver substrate. This leads to a dramatic increase in the optical intensity inside the spacer layer where the optical nonlinear material is placed. First, we utilize this field enhancement effect by choosing the frequencies of both incident waves to coincide close to the device's fundamental resonance. In this configuration, the power outflow of the generated visible FWM wave is enhanced by nineteen orders of magnitude compared to a bare silver film. Next, we design an alternative metasurface design, where we match the wavelengths of the two incident waves to the fundamental and high-order resonances, respectively, in order to excite efficient FWM radiation at low terahertz frequencies. In this case, it is demonstrated that a 13.5 THz FWM wave can be generated with radiation power fifteen orders of magnitude stronger than that coming out of a bare silver film. The proposed metasurfaces can significantly reduce the footprint and realize extremely compact frequency-mixing nonlinear nanodevices and efficient nonlinear sources.

It is demonstrated that the envisioned nonlinear sources have a directive far-field radiation pattern, which is stronger in the direction perpendicular to the metasurface. Besides, the FWM radiated power can be adjusted and controlled by the input intensities of the incident waves leading to tunable and reconfigurable compact nonlinear devices. The resulted FWM efficiency is extremely high and uniformly distributed within a wide range of the incident waves' excitation angles, in stark contrast to FWM based on surface plasmon resonances excited along a bare silver film. Finally, it is demonstrated that the nonlinearity of the material placed in the spacer layer dominates and is the main reason of the high nonlinear response. Thus, if the spacer is filled with materials with higher nonlinear coefficients, the radiation power of the generated FWM wave will be further increased. The proposed nonlinear plasmonic metasurfaces provide a new way to realize compact and directional sources from optical to terahertz frequencies, allowing a huge reduction in the required input intensities.