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Hybrid Metasurface for Efficient & Broadband Second Order Nonlinear Processes

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Abstract: Second harmonic generation (SHG) is one of the most studied nonlinear optical phenomenon thanks to the its extensive practical applications. Efficient SHG can be achieved by either improving light-matter interaction or searching for materials with higher nonlinear susceptibility values. Together with nonlinear process efficiency, low losses and damage thresholds are desirable, as well as large operating bandwidth, scalability, integrability and ease of fabrication. We demonstrate that a hybrid approach that combines dielectric metasurfaces with semiconductor quantum well can satisfy all the aforementioned conditions, paving the way for novel designs of low loss, broadband and efficient ultrathin nonlinear optical devices.

Since the advent of laser, SHG has been extensively studied for numerous applications [1]. Because of the typically weak nonlinear response of materials, efficient SHG can be achieved only under phase matching conditions and using high power lasers. However, there is still a need to achieve efficient SHG at moderate pump intensities using ultrathin nonlinear optical devices [2]. Several approaches have been proposed, such as the use of two-dimensional transition metal dichalcogenides [3-6] and multi-quantum-well (multi-QW) semiconductor heterostructures [7-9]. In fact, ISTs allow to engineer extremely large $\chi^{(2)}$ values [10] and therefore can be used as nonlinear media for SHG in ultrathin nonlinear devices where phase matching conditions are not required. Nonlinear processes can be also boosted increasing light-matter interactions, i.e. confining electromagnetic fields to subwavelength volumes using resonators, metasurfaces or photonic crystals [11-18]. So far, the highest nonlinear response for SHG (normalized by length) by a nanostructure has been obtained at mid-infrared wavelengths using a hybrid approach which couples plasmonic metasurfaces to ISTs of semiconductor QWs [10, 19-21]. Although efficient, this approach suffers from the use of plasmonic nanostructures for coupling the pump light to the ISTs and out-coupling the second-harmonic (SH) light, which have high dissipative losses that induce heating effects and lowering of damage thresholds. Another possible strategy involves the use of Mie-like resonances in all-dielectric metasurfaces fabricated from nonlinear crystals such as GaAs [13-16]. This method solves the problems of metal absorption but they have intrinsically low $\chi^{(2)}$ and sustain only modest field enhancement. High field enhancement in all-dielectric metasurfaces can be attained by exploiting resonances with higher quality factors (Q) such as Fano resonances and bound states in the continuum. However, a higher Q significantly reduces the spectral bandwidth of the nonlinear device. The inverse relation between Q and spectral bandwidth is a fundamental limitation that dictates the bandwidth of SHG in a nonlinear device.

Here we experimentally demonstrate a new hybrid approach for high efficiency SHG that overcomes the limitations described above by combining the advantages of IST nonlinear metasurfaces and all-dielectric nonlinear metasurfaces. Our method uses high-Q leaky mode resonances (LMRs) [22-24] in dielectric nanostructures coupled to ISTs of semiconductor QWs. Our all-dielectric device has small dissipative losses and therefore a high damage threshold. Furthermore, since the LMR wavelength can be varied by changing the period of the grating, the high Q resonances can be tuned to fit the wavelength needs of a wide range of applications. Moreover, our approach allows us to achieve high Q resonances over a large bandwidth by tuning the incident angle of the pump light. The combination of a giant χ^2 within the IST band and high Q photonic resonances far from the IST band allows to achieve a large bandwidth of SHG. Fig. 1(a) shows a sketch of the fabricated structure, while Fig.1 (b) and (c) show the efficiency of the reflected SH simulated and measured, respectively. Although demonstrated for mid-infrared wavelengths, our approach of using LMRs coupled to ISTs can be scaled to both longer and shorter wavelengths. Finally, our device can operate in both reflection and transmission mode, is monolithically integrable, and easy to fabricate. Thus, this new system is well-suited for practical applications.

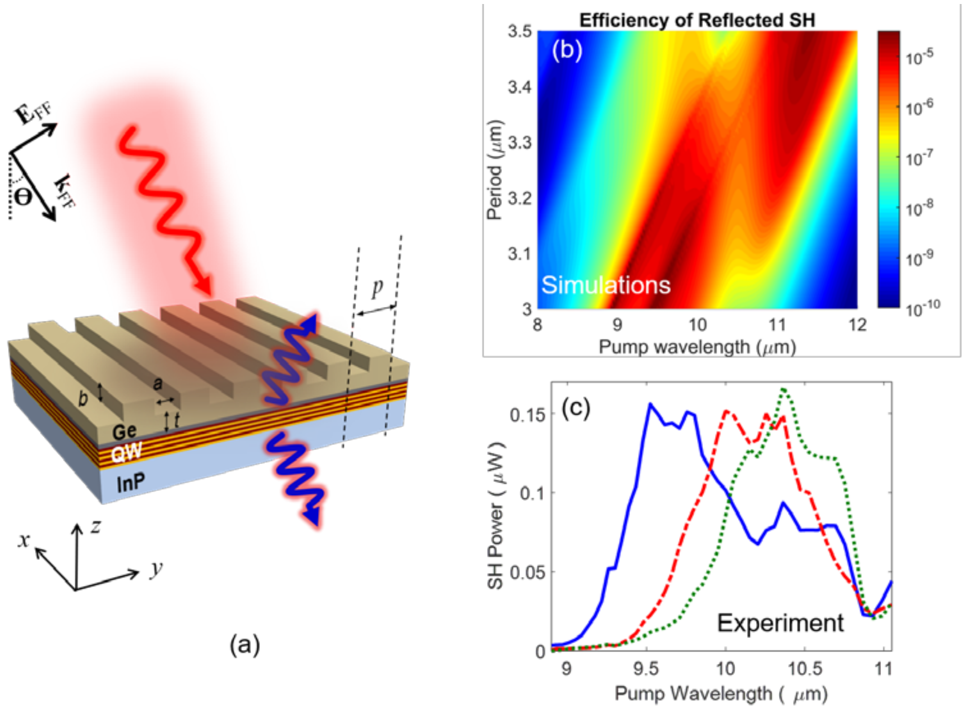

Fig. 1 (a) Sketch of the device and illumination scheme. The geometrical parameters of the fabricated devices are a = 1070 nm, b = 1200 nm, t = 500 nm, and p = 3150, 3250, and 3350 nm (for different structures tested). The thickness of multi-QW layer is 656 nm; (b) Efficiency of reflected SH (in log 10 scale) as a function of pump wavelength and period p. Incident pump intensity is 10 kW/cm^2; (c) Measured reflected SH power at normal incidence as a function of pump wavelength from structures with p = 3.15 μm (blue solid line), 3.25 μm (red dashed line), and 3.35 μm (green dotted line) at the incident pump intensity of approximately 3.3 kW/cm^2.

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