Nonlinear Dielectric Metasurfaces for Wavefront Control

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Abstract: We demonstrate Si-based metasurfaces for third-harmonic generation of an arbitrary wavefront. The nonlinear metasurfaces produce phase gradients within a full 0--2π phase range. We achieve 92% diffraction efficiency of the nonlinear wavefront control.
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1. Introduction

Metasurfaces, two-dimensional arrays of subwavelength resonators, became a new paradigm for functional flat optics, as they allow for high-precision control over the wavefront of light. In linear optics, we can reach a superior level of complexity for all-dielectric metasurfaces demonstrating near-unity efficiency [1]. The current research agenda goes beyond linear metasurface structures, and we foresee great opportunities provided by nonlinear metasurfaces in the rapidly developing field of multipolar nonlinear nanophotonics [2].

Several pioneering demonstrations of nonlinear metasurfaces for wavefront control have been demonstrated recently [3,4], however, those demonstrations of nonlinear phase-gradient metasurfaces are based on plasmonic designs. As a result, the efficiency of the nonlinear frequency conversion in plasmonic nanostructures remains small, being of the order of ~10^{-10}, despite the implementation of different strategies to boost the metasurface performance such as resonant coupling, three-dimensional geometries, and hybrid nanoantennas.

All-dielectric nanostructures have recently been suggested as an important pathway to enhance the nonlinear efficiency beyond any limits introduced by plasmonics. Indeed, more efficient third-harmonic generation (THG) in Si and Ge individual nanoresonators has been recently demonstrated by several groups, showing a huge enhancement of the conversion efficiency by optical pumping in the vicinity of the magnetic dipole Mie [5] or composite anapole resonances [6]. Conversion efficiencies of the order of 10^{-6} have been achieved experimentally in both individual dielectric nanoparticles and dielectric metasurfaces. These results clearly illustrate the potential of all-dielectric resonant nanostructures for nonlinear nanophotonics.

Here we design and fabricate a silicon metasurface that generates the third harmonic (TH) field. The metasurface is assembled from a set of 10 different elliptic nanopillar resonators, each of them providing similar conversion efficiency but different phase of the TH signal covering a full 0--2π range. Being assembled into a planar structure (a metasurface), the dielectric resonators allow for the creation of smooth phase gradients for the generation of the third harmonic field. As an example, we demonstrate a nonlinear beam deflector [see Figs. 1(a, b)] that generates a TH beam at an angle with respect to the direction of the pump.

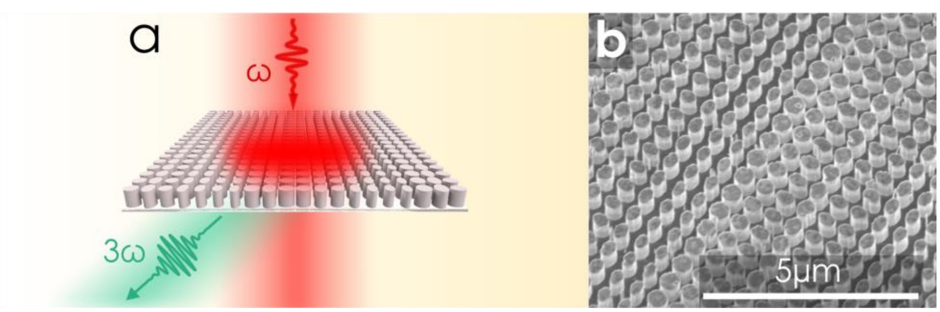

Fig. 1. Nonlinear dielectric metasurfaces for the third-harmonic beam control. (a) Concept image of a nonlinear beam deflector. (b) Scanning electron microscope image of the fabricated nonlinear beam deflector metasurface assembled from the set of ten elliptic nanopillar rods.

2. Nonlinear metasurface beam deflector

We used silicon nano-cylinders as building blocks for the metasurface. The cylinders support both electric and magnetic Mie resonances dominated by the magnetic dipole. We identified the condition of interplay between the Mie resonances that allow for a full 2π phase coverage at the TH. We backed our analytical considerations with fullwave nonlinear simulations of nanocylinders in COMSOL Multiphysics. In our design, we optimized the performance for a wavelength of 1600 nm. The cylinder height was fixed at 620 nm, and the pillars arranged in square arrays with 550 nm period. To achieve the desired phase coverage at the THG while maintaining nearly-unchanged amplitude we introduced two geometric parameters: we considered the pillars with elliptical cross-section with the semi-axes values ranging between 320 nm and 535 nm. To demonstrate the capabilities of nonlinear wavefront control we designed a nonlinear beam deflector: a metasurface that generates a beam of light at third harmonic wavelength propagating at 5.5º from normal. For this we arranged the 10-pillar set into a supercell that creates a linear phase gradient at the TH wavelength. The supercell is then used for a periodic array [see Fig. 1(a)]. Such a metasurface creates a phase profile for the generated TH that is conceptually similar to a blazed diffraction grating optimized for the first diffraction order. In this analogy, the full length of the 10-pillar supercell is equivalent to the grating period.

We fabricated this nonlinear metasurfaces from silicon on a glass substrate using the electron beam lithography. An electron microscope image of the fabricated metasurface is shown in Fig. 1(b). We optically pumped the metasurface with femtosecond pulses from an optical parametric amplifier tunable in the spectral range of 1330-1750 nm. We measured the directionality of the TH [see Figs. 2(a, b)], and retrieved the nonlinear wavefront control efficiency across the spectrum [see Fig. 2(c)]. The nonlinear diffraction efficiency reaches 92% at 1615 nm, e.g. 92% of forward-generated TH is directed into 1st diffraction order.

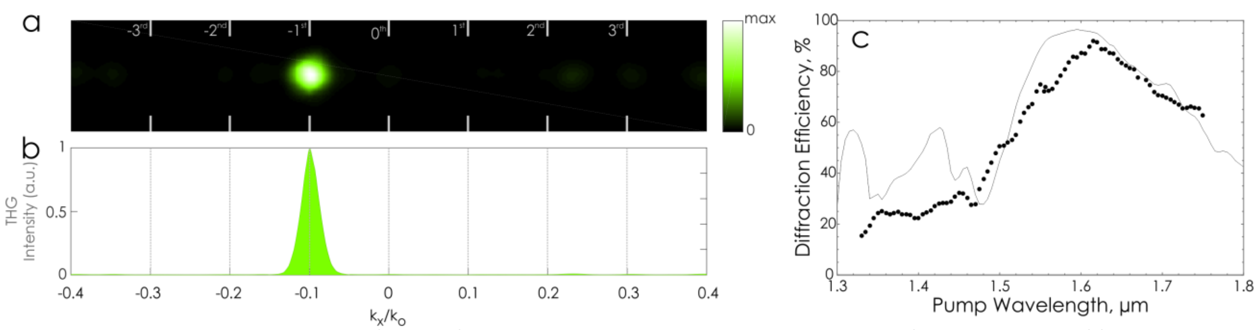

Fig. 2. Nonlinear optical characterization of metasurfaces. (a) Experimental directionality diagram (back-focal plane image) of forward-generated third harmonic at an optimal wavelength of 1615 nm. 92% of THG is deflected into 1-st diffraction order at the angle 5.5º. (b) Integral cross section of experimental back-focal plane image. (c) Experimentally measured and theoretically calculated nonlinear diffraction efficiency of the metasurface vs pump wavelength.

3. Conclusion

We have presented an experimental platform for nonlinear wavefront control with efficient nonlinear dielectric metasurfaces. Our approach allows for creating continuous phase gradients via nonlinear excitation of electric and magnetic Mie multipoles. We have demonstrated experimentally a nonlinear all-dielectric metasurface that generates the third harmonic signal with 92% precision of its wavefront control.

4. Acknowledgements

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5. References

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