POLARIZATION-CONTROLLED SECOND HARMONIC NORMAL EMISSION FROM SEMICONDUCTOR METASURFACES

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ABSTRACT

We experimentally demonstrate second harmonic generation with controlled polarization in a small solid angle around the zero-diffraction order, in AlGaAs-on-AlOx MOCVD-based monolithic metasurface. Polarization and diffraction features are decoupled by the interplay of single Mie-resonator scattering and the spatial periodicity of the metasurface.

KEYWORDS: *nanophotonics, metasurfaces, nonlinear optics.*

1. INTRODUCTION

Optical metasurfaces have recently shown their huge potential for engineering the polarization and phase of light both in the linear and the nonlinear regime. Their control on the phase of reflected and refracted light has led to Snell's law generalization, the demonstration of flat lenses, the development of holographic imaging, and harmonic generation.

All-dielectric metasurfaces are particularly effective in generating harmonic light thanks to the strong light coupling with both magnetic and electric resonances, bulk nonlinearities and negligible ohmic losses [1]. Among all phase encodings of the nonlinear wavefront, on-axis nonlinear emission would be of particular interest, [2] e.g. for intracavity applications. However, simultaneous control of highly polarized and on-axis second-harmonic (SH) generation, required in many applications such as nonlinear imaging, has yet to be demonstrated.

In this work, based on a metasurface made of AlGaAs nanostructures, we demonstrate the control of SH polarization and phase encoding into the zero-order diffraction. We achieve the former via the rotation of either the meta-atom or the pump polarization, and the latter via the array factor of the metasurface.

2. FABRICATION AND MATERIAL CHARACTERIZATION

Our fabrication process started from from metal-organic chemical vapor deposition of the epitaxial structure: (100) GaAs wafer; $Al_{0.98}Ga_{0.02}As$ layer to be oxidized (1 µm); GaAs interlayer (5 nm); $Al_{0.18}Ga_{0.82}As$ for the nanoantenna body (350 nm); and GaAs capping layer (5 nm). The AlGaAs metasurface eventually on an amorphous aluminum-oxide substrate via the selective oxidation of a MOCVD epitaxial heterostructure. $Al_{0.18}Ga_{0.82}As$ meta-atoms were defined with e-beam lithography and ICP-RIE, and then the $Al_{0.98}Ga_{0.02}As$ layer was selectively oxidized resulting in an amorphous layer of aluminum oxide (AlOx), whose low refractive index ≈1.6, ensures strong optical confinement in the nanoresonator (see Fig. 1).

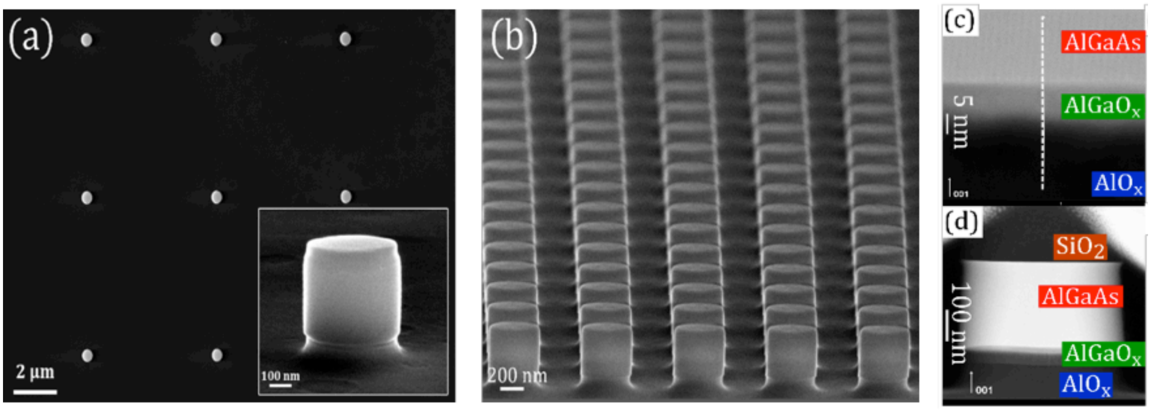

Figure 1. (a) SEM image of an array of widely spaced cylindrical nanoantennas with 215 nm radius; (b) SEM image of a square-lattice metasurface with period 940 nm; (c) HAADF-STEM image of AlGaAs/AlOx interface; (d) Same as c for a whole nanoantenna.

3. OPTICAL EXPERIMENTS AND DISCUSSION

To control the polarization of the SH radiated from a square-lattice metasurface, we followed the two approaches sketched in Fig. 2: a,b) 90° rotation of nanocylinders with elliptical basis, for a given linear polarization at the fundamental frequency (FF); and c,d) 45° rotation of FF linear polarization with circular nanocylinders. In the former case, by switching the semi-major and semi-minor axes of the ellipse, we excite orthogonally polarized SH modes through the same nonlinear current. In the latter, changing the FF polarization from horizontal to diagonal, we excite different nonlinear current components in each nanoantenna. Fig. 2e illustrates the experimental conditions; a pump beam at $\lambda_{FF} = 1550$ nm excites the metasurface, and the SH field at $\lambda_{SH} = 775$ nm in the backward direction is characterized in directivity and polarization. The optical measurements were carried out with a 160 fs, 1 MHz pulsed pump beam at 1550 nm from provided by a Mango (Amplitude), proper optics, and back-focal-plane imaging [3].

Our design for amplitude and directivity of the SH radiation from metasurfaces relies on the Bragg scattering of its constituents. As in this case the far-field response can be studied as the product between the far field of a single nanocylinder and the 2D array factor, we start our study with a focus on the SH of the isolated metasurface constituents [2,3]. In our first approach (Fig. 2a,b), we fix the FF polarization at 1550 nm along the crystalline axis [100] and rotate the orientation of an elliptical nanocylinder with semi-axes $a = 240$ nm and $b = 200$ nm by 90°.

By 90° rotation of the nanocylinder, the main nonlinear polarization component remains unchanged, with pump field distributions dominated by electric dipole (ED) and magnetic dipole (MD) resonances, and the effective nonlinearity dominated by the $\chi^{(2)}_{yzx}$ tensor element. However, as a result of the nanocylinder rotation (horizontally and vertically oriented resonator elliptical bases in the top and bottom panels of Fig. 3), the nonlinear polarization couples to orthogonal SH modes, oriented along [110] and [1$\bar{1}$0], respectively (see Fig. 3b). In Fig. 3c, which shows the calculated and measured SH far-field intensity within a numerical aperture NA=0.8, we can appreciate that the SH main lobes are at around 45° from the normal for both ellipse orientations. Please notice that SH multipolar decomposition shows that MD and electric quadrupole (EQ) dominate. Furthermore, Fig. 3d reports the inclination of the linearly polarized SH field, highlighting the possibility to obtain a mainly horizontal or vertical SH polarization from a single elliptical nanocylinder, according to its orientation. However, such polarization control is not very practical because of the angular separation of the two lobes. This motivates us to consider a periodic array in order to exploit the constructive interference in the far-field region and engineer SH polarization in the zero-diffraction order.

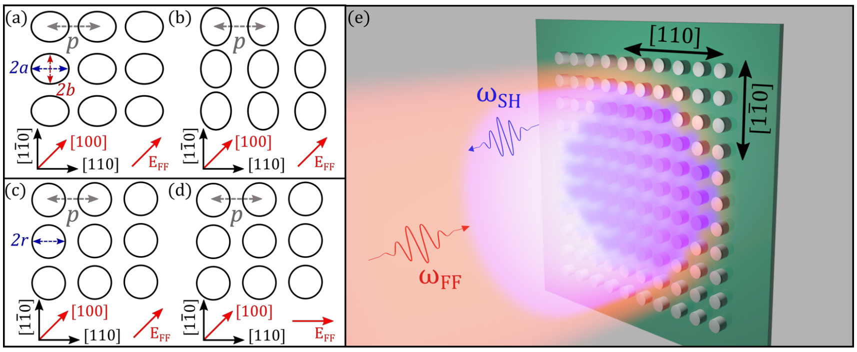

Figure 2. a,b) Control scheme with fixed FF pump polarization and elliptical-basis meta-atoms rotated by 90°. c,d) Control scheme (not discussed here) with fixed circular meta-atoms and pump polarization rotated by 45°. e) Artist's view of SHG by a metasurface.

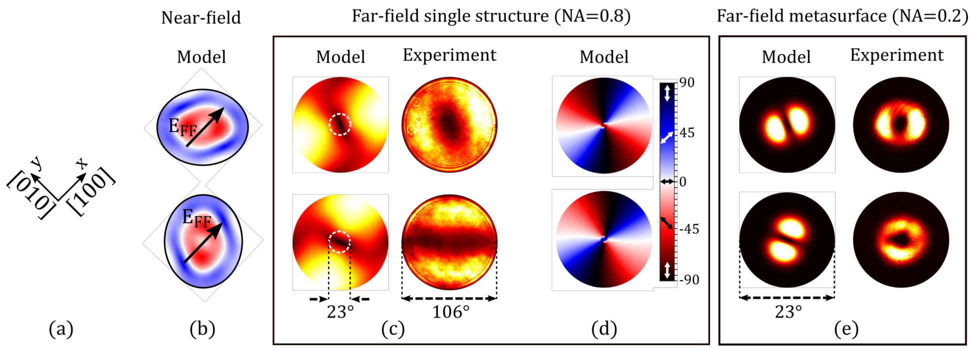

Figure 3. SH distributions (simulations and measurements) for horizontally (top) and vertically (bottom) oriented elliptical nanocylinders. (a) Reference system, corresponding to AlGaAs axes. (b) Near-field distribution of the mainly excited SH mode, with the indication of FF polarization. (c) SH radiation pattern of a single element within NA = 0.8. White dashes correspond to NA = 0.2 (d) SH polarization inclination for a single element. (e) Back focal plane imaging of SH generated by a metasurface with the same constitutive elements as in c, p = 940 nm, and collection within NA = 0.2.

Conclusion

We have demonstrated that the polarization of the SH generated by an all-dielectric metasurface can be effectively controlled by the scattering properties of its Mie-resonator constituents. By exploiting the AlGaAs-on-AlOx platform, we have overcome two intrinsic limitations of SHG from single (100) nano-resonators: tight pump focusing and off-axis emission. We have proved redirection of the radiated power within an angle of about 6° from the normal, which is compatible with quasi on-axis imaging applications. These results, achieved with MOCVD-based epitaxial structures, open the way to the use of nonlinear metasurfaces in quasi-on-axis devices like for example monolithic optical cavities.

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