Multilayer and Nonlinear Metamaterials

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Abstract: We demonstrate precise control of the phase and amplitude of nonlinear signals generated by plasmonic meta-atoms and fabricate nonlinear metasurfaces and 3D metamaterials that can simultaneously generate and control light beams. Implications to nonlinear holography and to achromatic optical elements are discussed.

Advances in nanofabrication techniques have enabled fast development of technologies for functional light control at the nanoscale. Two-dimensional metamaterials, also known as metasurfaces, have been proposed as ultrathin optical elements that can potentially replace the relatively large bulk optical devices used nowadays.

The majority of metasurface optical elements demonstrated so far (lenses, waveplates, holograms, etc.) are passive elements that can shape light beams but not alter their frequency. We have recently demonstrated a novel class of metamaterials and metasurfaces that can not only manipulate the amplitude and phase of light beams, but can also change the frequency of the incoming radiation through nonlinear frequency conversion [1,2]. Plasmonic meta-atoms are used as the building blocks of the nonlinear devices. Controlling their shape and therefore their optical resonances (Fig.1a), we can impart up to 2π radians phase shift to the nonlinear signals generated by the meta-atoms (Fig.1b). This complete and continuous control of the phase of the nonlinear susceptibility allows us to fabricate metasurfaces that can mold the wavefront of the nonlinear radiation to achieve light focusing (Fig. 1c,d), and give rise to a new phase matching condition in nonlinear optics, where the signal generated in a collinear four-wave mixing scheme is non-collinear [2].

Using this precise nanoscale nonlinear phase control, we demonstrate a new type of computer-generated holograms [3], where the holographic images are reconstructed at the third-harmonic frequency of the input beam (Fig. 1e). These polarization-multiplexed holograms are fabricated by multilayer e-Beam lithography (Fig. 1f) and form different images depending on the input polarization. On the linear side, this multilayer approach enabled us to design (Fig. 1g) and fabricate [4] achromatically corrected RGB lenses, where all three wavelength were focused into a sigle focal spot.

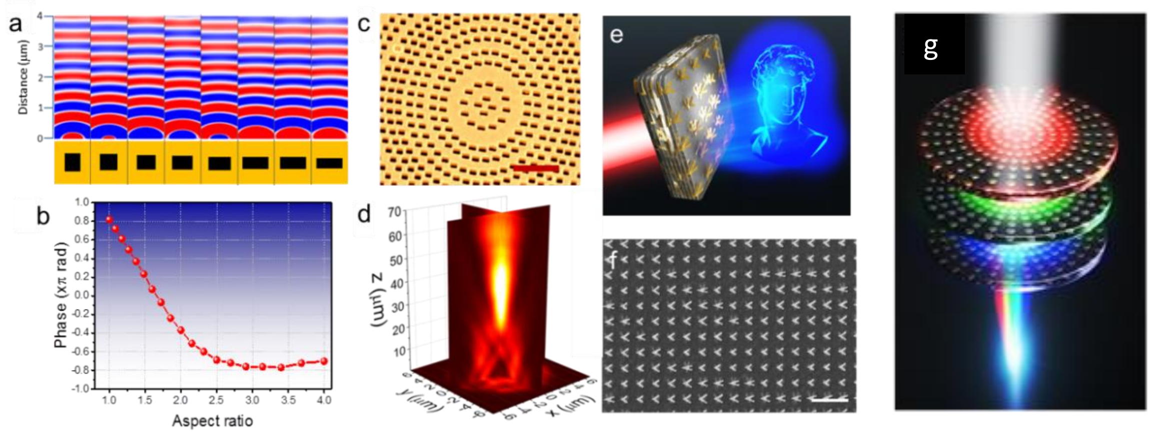

Figure 1 – Digital nonlinear metamaterials. a) Calculated electric field of the four-wave mixing (FWM) signal generated by single metallic nanocavities of varying aspect ratios in a free-standing gold film. Two input femtosecond laser beams centered at λ_1=800nm and λ_2=1266nm are mixed to generate a FWM signal at λ_3=633nm. b) Phase variation of the FWM signal. c) Scanning electron microscopy (SEM) image of a nonlinear metalens and the FWM signal (d) around the focal point. e) Artist's depiction of nonlinear hologram. f) SEM of a dual layer digital nonlinear metamaterial (g) Illustration of an achromatically corrected RGB metalens

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[2] E. Almeida, G. Shalem and Y. Prior. Nature Communications **7**, 10367 (2016);
[3] E. Almeida, O. Bitton and Y. Prior. Nature Communications **7**, 12533 (2016).
[4] O. Avayu, E. Almeida, Y. Prior and T. Ellenbogen, Nature Communications, 8:14992 | DOI: 10.1038/ncomms14992 (2017)