# Coherent all-optical steering of upconverted light by a nonlinear metasurface

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**Abstract.** In recent years a strong drive towards the miniaturization of nonlinear optics has been motivated by the functionalities it could empower in integrated devices. Among these, the upconversion of near-infrared photons to the visible and their manipulation is fundamental to downscale optical information. We propose a dual-beam scheme whereby a pulse at the telecom frequency $\omega$ (1550 nm wavelength) is mixed with its frequency-doubled replica at $2\omega$. When the two pump pulses are superimposed on a nonlinear, all-dielectric metasurface two coherent frequency-tripling pathways are excited: third-harmonic generation (THG, $\omega+\omega+\omega$) and sum-frequency generation (SFG, $\omega+2\omega$). Their coherent superposition at $3\omega$ produces interference, which we enable by filtering the k-space with the metasurface diffraction. The steering of the emission among diffraction orders, is sensitive to the relative phase between the two pumps. Therefore, by exploiting the phase as a tuning knob, the upconverted signal can be switched between diffraction orders with an efficiency >90%. The proposed approach can be envisioned as an all-optical method to reroute upconverted telecom photons.

## 1 Introduction

Optical signal upconversion is driven by nonlinear light–matter interactions, where more than two photons participate. We can consider either energy-degenerate photons, such as in second-harmonic and third-harmonic generation (THG), or photons with non-degenerate energies, such as in sum-frequency generation (SFG). Nonlinear upconversion of near-infrared photons to the visible range is strategical for information technology, as it can provide an alternative for the read out of telecom signals using efficient silicon-based detectors. Reaching also all-optical control on light can in principle push optical information encoding beyond the GHz speed. In this sense, optical metasurfaces are ultrathin multifunctional platforms that can shape and steer light [1]. In past works we devised metasurfaces for efficient nonlinear light generation and polarization-based steering [2,3]. Here we adopt a double-pump scheme to excite two frequency-degenerate nonlinear processes in a nonlinear metasurface. By exploiting their interference, we perform phase-controlled all-optical routing of the upconverted photons among different diffraction orders.

## 2 Coherent routing with a nonlinear metasurface

### 2.1 $\omega$ + $2\omega$ frequency tripling

The adopted dual-beam pump scheme is seeded by a single laser source delivering ultrashort pulses at the telecom frequency $\omega$ (wavelength $\lambda$ = 1551 nm), which are then partially duplicated in frequency ($2\omega$). The two pumps illuminate the sample, exciting THG ($\omega+\omega+\omega$) and SFG ($\omega+2\omega$), which are degenerate in energy at the frequency $3\omega$. In addition, SFG is sensitive to the relative phase between the pumps at $\omega$ and $2\omega$ (Fig. 1a). In principle, the frequency degeneracy along with the coherence of these two processes could enable the interference between them. Yet, symmetry plays a major role in enhancing/suppressing interference between SFG and THG. In the past, we applied this scheme on isolated nanostructures [4,5]. We obtained frequency tripling from single AlGaAs nanoresonators [4], which possess a strong second-order nonlinearity $\chi^{(2)}$ and, for a height of 400 nm, can support electric and magnetic dipole modes in the near infrared for radii between 200 and 250 nm. Yet, the expected interference between THG and SFG is cancelled by the overall cylindrical symmetry of the system (cylindrical shape of the resonators at normal illumination/detection). Symmetry breaking is then

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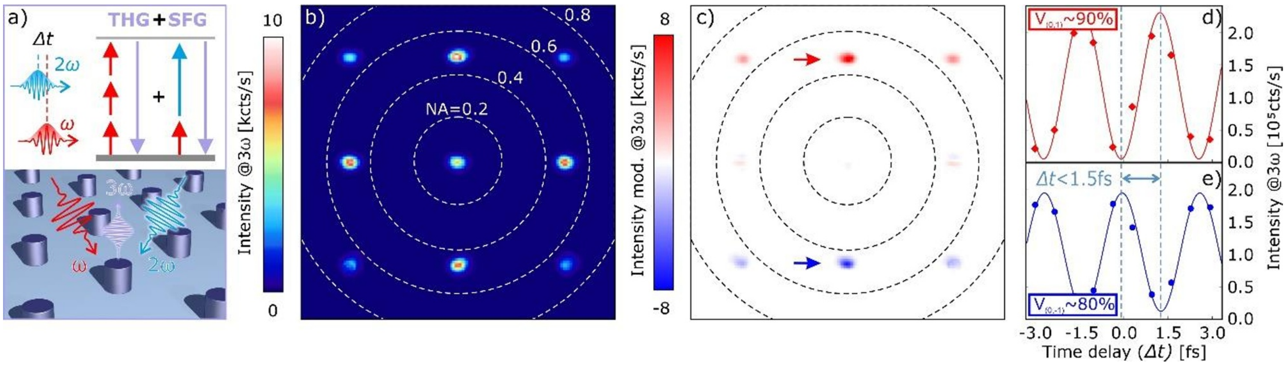


**Fig. 1.** a) Frequency-tripling process based on $\omega + 2\omega$ pumping scheme producing THG ($3\omega = \omega+\omega+\omega$) and SFG ($3\omega = \omega+2\omega$). b) Back focal plane (BFP) map of the signal at $3\omega$ emitted by the metasurfaces, showing the first and second diffraction orders. The first-order diffraction lobes appear at a numerical aperture NA = $(\lambda/3)/p$ = 517 nm/1100 nm = 0.47, where $p$ is the array periodicity. c) Modulation of the upconverted signal at $3\omega$, evaluated as the difference between the BFP maps acquired at a delay $\Delta t$ between the $\omega$ and $2\omega$ pumps of about $\Delta t$ = 1.3 fs between the pump pulses (see dashed lines in panels d and e). d,e) Upconverted power of the (0,+1) and (0,−1) orders of the metasurface (red and blue arrows, respectively) as a function of $\Delta t$, demonstrating switching with visibility ($V$) larger than 90%.

needed to enable it. This was obtained in a system of single, asymmetric gold nanoantennas, where the $3\omega$ signal showed sizable interference [5]. Here, instead, we report about a dielectric nonlinear metasurface, designed to lift symmetry constraints in the emission pattern of the $3\omega$ signal, enabling the coherent control of the upconverted light.

### 2.2 Interferential routing in the Fourier space

We investigated a 2D array of AlGaAs nanocylinders excited within the $\omega + 2\omega$ pumping scheme. By arranging the meta-atoms in a square array of pitch $p$ ranging from 900 nm to 1500 nm, we reach a total upconversion figure of merit $\beta^{SFG} = P^{3\omega}/P^{2\omega}P^{\omega} > 10^{-5}$ W$^{-1}$ and $\beta^{THG} = P^{3\omega}/(P^{\omega})^3 > 10^{-7}$ W$^{-2}$ at relatively low $\omega$ and $2\omega$ pump peak intensities (10 MW/cm$^2$). The radiation at $3\omega$ is redirected into diffraction orders that lie within the numerical aperture of the objective used for the detection ($NA_{obj.}$ = 0.85, see Fig. 1b). Since each order corresponds to a specific **k** vector, each of them corresponds to non-normal detection (except for the zeroth order). In this way, the symmetry breaking condition necessary to observe interference between THG and SFG is achieved. Interference enables switching the power between selected couples of diffraction orders (Fig. 1c). Indeed, by monitoring the power emitted by a couple of diffraction orders, *e.g.* (0,±1), as a function of the relative phase between the $\omega$ and $2\omega$ pumps, we observe a strong power modulation with oscillations in antiphase (Fig. 1d). The interference time period is $T_{int}=2\pi/2\omega$. A complete switching takes place after delaying either pulse by half $T_{int}$, *i.e.* $\Delta t$ = 1.3 fs. Notably, we reach a visibility $V = (P_{max} - P_{min})/(P_{max} + P_{min})$ of the modulation up to 90% within selected diffraction orders. This is attained by engineering the far-field pattern of the individual meta-atoms along with the metasurface diffraction to maximize the interference between SFG and THG in specific $k$-space directions. Therefore, the power can be efficiently re-routed into specific directions by using the relative phase between pumps as a tuning knob. The polarization state of the pumps can be used as an additional degree of freedom reconfigure the steering behavior.

## 3 Conclusion and outlook

We exploited the frequency degeneracy between two nonlinear processes to shape and coherently control the directionality of emitted radiation. The proposed approach can be envisioned as an all-optical method to reroute telecom photons upconverted in the visible range between different $k$-space directions Notably, the instantaneous nature of the involved nonlinear processes could enable an ultrafast reconfigurability of the metasurface. This can pave the way to GHz modulation of a signal for optical information multiplexing and encoding.

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