Design and optimization of holographic nonlinear metasurfaces

David Hähnel[1,*], Jens Förstner[1], and Viktor Myroshnychenko[1]

[1]Theoretical Electrical Engineering, Paderborn University, Paderborn, Germany
*corresponding author, E-mail: hdavid@mail.upb.de

Abstract

We present the design and optimization of all-dielectric nonlinear metasurfaces using a simple but effective sampling method combined with Monte Carlo simulation and demonstrate that the use of sophisticated optimization methods is not necessary. We apply this approach for the optimization of metasurface composed of silicon disks, which operates as a third harmonic beam deflector at a defined angle. Our results demonstrate a significant enhancement of radiated third harmonic intensity in the first diffraction order compared to that reported in literature.

1. Introduction

Various efficient methods for the design and optimization of linear metasurfaces have already been developed and reported in the past [1]. Among them, the most popular methods are gradient descent method, evolutionary and machine learning algorithms. Currently, attempts are being made to apply these techniques also for the design and optimization of nonlinear metasurfaces. However, this is quite a complex task due to the many degrees of freedom involved, the nontrivial functional dependencies, and complexity of the nonlinear processes. Many works in the literature employ sophisticated optimization algorithms for these purposes [2].

Here, we present a simple yet powerful sampling method in combination with the Monte Carlo simulation for the design and optimization of holographic nonlinear metasurfaces. The metasurfaces consist of silicon nanodisks of elliptical cross section deposited on a silicon dioxide substrate. The wavefront of the third harmonic signal is shaped through adjustment of the nanodisk's lateral dimensions. The robustness of our approach is illustrated through the design and optimization of a nonlinear beam deflector that directs the incoming linear polarized plane wave at the fundamental frequency into the first diffraction order at the third harmonic frequency. We reveal a capability of our approach to solve dynamic problems with a varying number of optimization parameters that are unknown in advance.

2. Results

Our metasurface is composed of silicon elliptical disks placed on a silicon dioxide substrate and generates a third harmonic signal under external illumination. To design the metasurface which produces a nonlinear beam deflection, a set of resonators with the required smooth phase gradient and constant amplitude has to be firstly found (Fig. 1).

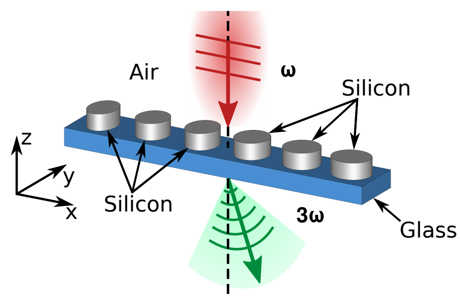

Figure 1: Sketch of the nonlinear beam deflection by a dielectric metasurface, illustrating the generated third harmonic beam deflection in transmission direction.

For this purpose, the phase and intensity maps of the third harmonic (TH) signal is calculated as a function of the disk's ellipse diameters. This is done independently for each resonator by modeling a unit cell with periodic boundary conditions and calculating the electromagnetic fields using COMSOL Multiphysics. The height of the resonators and periodicity are fixed and chosen to be $h = 285\,\text{nm}$ and $p = 916.67\,\text{nm}$, respectively. The corresponding phase map (color map) and the third harmonic intensity contour (black and white dashed lines) are shown in Fig. 2(a). By employing the sampling method, we then select six different resonators with equally spaced phase values and constant intensity in the parameter space. The disk parameters are determined by the intersections (white dots) of a predefined number of phase contours (solid black lines) with an intensity contour (dashed lines) that discretely covers the 2π phase range, as in [3]. We note that an arbitrary number of resonators with specified phase and constant intensity can be picked from the map, which provides the convenient flexibility to this method, especially, when the final number of resonators in the optimized application is unknown.

Finally, the diffraction spectrum for the presented parameter selection (Fig. 2(a)) is calculated and shown in Fig. 2(b). For orientation, the angle calculated with the equation of Bragg's law is inserted at the first diffraction order bar. The TH radiation of the first diffraction order is the maximum in the spectrum and in the near vicinity a suppression of about 80% can be achieved.

Aiming to further improve the TH radiation, we apply Monte-Carlo simulation to optimize the parameters of the individual resonators, by searching over a four-dimensional parameter space including resonator height, x- and y-diameters, and periodicity. In comparison to Fig. 2(b), the enhanced TH radiation at the first positive diffraction order by a factor of 250 is achieved for the optimized parameter selection (not shown here).

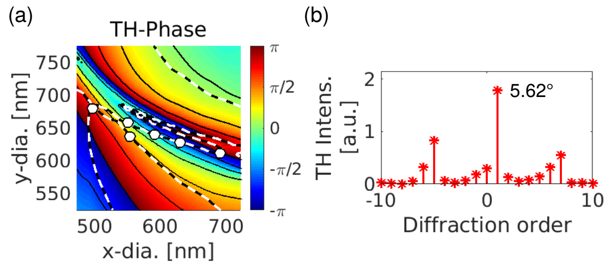

Figure 2: (a) Calculated third harmonic phase map with third harmonic intensity contour (black and white dashed lines). The resonators with selected parameters are marked by white dots. (b) Corresponding discrete diffraction spectrum of the radiated third harmonic intensity for the unit cell model composed of the selected six resonators and shown in Fig. 1.

3. Conclusions

In summary, we have shown that the proposed combination of the sampling method and Monte-Carlo simulation can be effectively used in the design and optimization of holographic nonlinear metasurfaces. We exemplarily use this approach to design and optimize a dielectric metasurface composed of silicon nanodisks for the nonlinear beam deflection application. The required phase gradient with a constant amplitude is engineered by varying the lateral dimensions of the nanodisks and thus exciting different electric and magnetic resonances. The selected set of the optimized resonators demonstrates a significantly enhanced intensity of the third harmonic beam radiated in the first diffraction order. Our approach can be used to design metasurfaces with other different functionalities.

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