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High-efficiency sum frequency generation from inverse designed metasurfaces

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ABSTRACT

Sum frequency generation is the process in which two incoming photons are converted into an outgoing photon of higher energy. This process is highly inefficient, and therefore requires either large interaction distances in bulky crystals, or large field concentrations in the non-linear materials. Metasurfaces are one such platform to generate extreme field enhancements with resonant processes. In this work, we use topology optimisation to design metasurfaces that exhibit increase high efficiency sum frequency generation, as well as the ability to tailor the generated polarisation.

1. INTRODUCTION

Sum-frequency generation (SFG) is a fundamentally important second-order nonlinear process with many applications ranging from wavelength conversion of optical sources to spectroscopy. Recent advances in nanotechnologies have facilitated the development of ultra-thin single layer dielectric metasurfaces, where optical resonators can enhance and tailor nonlinear interactions with functionalities beyond the capabilities of traditional bulky crystals.[1,2] The metasurface designs were often obtained semi-analytically in the limiting cases of localised Mie-type modes for individual nanoresonators or nonlocal lattice resonances. We demonstrate that the largely unexplored intermediate regime may offer more flexibility in enhancing the SFG process. Furthermore, nano-structured materials provide an opportunity to control the wavefront and directionality of the SFG emission in ways that are impossible in bulk crystals.

2. METHODOLOGY

We develop an inverse-design method for optimisation of high-efficiency polarised SFG by non-trivially generalising the inverse-design approach previously applied to the case of second-harmonic generation.[3,4]

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The algorithm is based on freeform topology of the metasurface, where the gradient of the figure of merit is efficiently calculated through a series of adjoint simulations. We show a representative example of SFG optimisation for incoming photons with wavelengths of 860 nm and 1550 nm (Fig. 1a). The nonlinear material is gallium arsenide (GaAs) which is 300 nm thick. A quality factor limit to the metasurface is imposed by introducing an artificial loss during the optimisation, which is removed at the end. This process tends to enable the convergence of the optimisation to a final design that exhibit quality factors that can be feasibly measured in our experimental setup.

3. RESULTS

We show in Fig. 1b a 2-by-2 unit cell of our final optimised metasurface, with white regions representing the non-linear material and shaded representing air. Because the algorithm is agnostic to the underlying physics for high efficiency, e.g. quality factor, phase matching conditions, and mode overlap, the structures that emerge from the optimisation are highly non-trivial. Our optimised metasurface has an SFG generation efficiency of $1 \times 10^{-3}\,\mathrm{cm}^2\,\mathrm{GW}^{-1}$ (Fig. 1c), representing one order of magnitude enhancement over an unpatterned GaAs film of the same thickness. More interestingly, this metasurface crucially can generate horizontally polarised light from two horizontally polarised input beams, a SFG process which is impossible in bulk crystals of GaAs.

4. DISCUSSION AND CONCLUSION

We observe that the algorithm has converged to structures that peaks in SFG efficiency around the input wavelengths 1550 nm and 860 nm (Figs. 1d,e) as intended. The estimated quality factor is ~ 500 and ~ 40 around the resonant operating wavelengths of 1550 nm and 860 nm respectively. It is noted that at 860 nm, the GaAs non-linear material has some loss and therefore limits the maximum quality factor attainable. We are currently investigating non-linear materials that have minimal loss at both input wavelengths, and the SFG wavelength which should, in principle, greatly increase the SFG efficiency. We generalise our topology optimisation so that the resulting metasurface can generate arbitrarily desired polarisation state for the SFG, from any polarisation states of the input beams. Furthermore, our optimisation framework can be extended so that the directionality of the SFG light can be tailored. We anticipate that inverse-designed metasurfaces may find future applications for SFG-based polarisation-independent up-conversion imaging across the infrared spectrum.

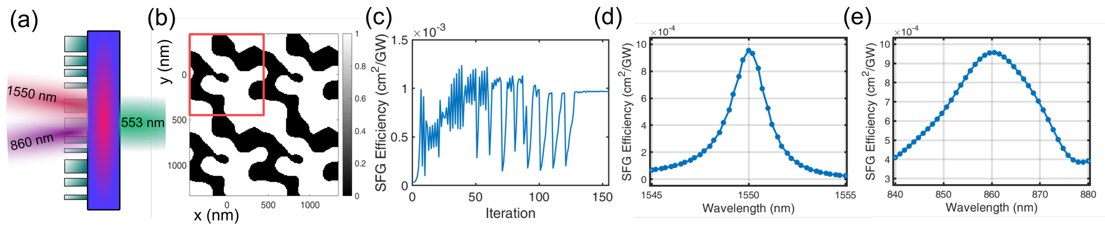

Figure 1. (a) Scheme of SFG inputs and output. The input wavelengths are 1550 nm and 860 nm, which generates 553 nm SFG light. (b) Top down view of final optimised pattern; GaAs is represented as white and air as black. A Red box outlines one unit cell as a visual guide. (c) Iterative increase of conversion efficiency over the course of the topology optimisation converging to the final state. (d,e) SFG efficiency as a function of input wavelengths 1550 nm and 860 nm respectively. For each respective wavelength sweep, the other wavelength is fixed at the central wavelength.

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