Optical Second Harmonic Generation in Amorphous Silicon Metamaterial

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***Abstract* – Second harmonic generation in centrosymmetric media is forbidden. However, mesoscopic structuring at the subwavelength scale can remove the center of inversion, creating nonlinear material with substantial second-order polarizability. We report efficient optical second harmonic generation in a 90 nm thick metamaterial fabricated from amorphous silicon that results from nanostructuring with a chevron pattern that simultaneously removes the center of inversion in the material and creates a closed mode optical resonance at the fundamental frequency that further enhances the metamaterial's effective second-order polarizability. The use of amorphous materials enables frequency converters on non-trivial platforms, such as the end-facet of optical fibres.**

I. INTRODUCTION

Second harmonic generation (SHG) is of key importance for converting the wavelength of optical signals, processing of optical information, and generation of non-classical states of light [1]. Efficient second harmonic generation typically requires optically thick non-centrosymmetric crystals with a strictly controlled orientation of the crystalline axes. These rigid requirements hamper the potential for miniaturization of photonic devices, which in turn limits the speed, efficiency and scalability of photonic technology. Photonic two-dimensional metamaterials, often referred to as metasurfaces, offer a great alternative to traditional bulk nonlinear optics, in cases where the small footprint of the nonlinear component is important.

Nano-structuring of electromagnetic materials has a drastic effect on the non-linear properties of resultant metasufaces. Indeed, second harmonic generation is forbidden at the electric dipole level in amorphous and centro-symmetric media [1]. However, by virtue of creating additional surfaces that break the (approximate) inversion symmetry of the sample, nano-structuring enables effective second harmonic generation in metasurfaces out of amorphous (and centro-symmetric) materials. For example, second harmonic generation has been demonstrated in L-shaped [2-4] metallic and dielectric nanostructures as well as in T-shaped [5] and triangular [3] metallic metasurfaces.

Despite the main motivation for seeking nonlinear response in metamaterials having been miniaturization, little effort has so far been dedicated to developing nonlinear photonic metamaterials on platforms suited for integration with guided light-waves. In this work, we investigate second harmonic generation in a low-loss metamaterial fabricated from centrosymmetric dielectrics - amorphous silicon on silica glass. The nonlinear response here arises as a result of inversion symmetry breaking at the surface of the metamaterial. Crucially, the use of amorphous media for nonlinear metasurfaces permits reliable fabrication on non-planar substrates, such as optical fibres. We demonstrate a high efficiency of the second harmonic generation (10^{-12}), for a layer of sub-wavelength thickness, and we show that such metamaterials can be integrated directly into optical fibre end-facets.

II. METAMATERIAL

The dielectric metamaterial consists of an array of chevron groove pairs milled into the core of a silica fibre (using focused ion beam milling) and subsequently coated with a 90-nm-thick amorphous silicon layer. The unit cell size is $1.1 \times 1.0\ \mu m^2$ and the overall metamaterial footprint is $22 \times 21\ \mu m^2$, see Fig 1(a). The chevron-shaped unit cell used here belongs to the D_1 symmetry point group, which allows for the following non-zero components of the effective second-order susceptibility tensor: $\chi^{(2)}_{yyy}$, $\chi^{(2)}_{yxx}$, $\chi^{(2)}_{xyx} = \chi^{(2)}_{xxy}$ (assuming plane-wave illumination incident along the z-axis). Due to a size difference of the chevrons contained in each unit cell, the metamaterial exhibits an asymmetric resonance with a quality factor of about 30 at 1500 nm wavelength (Fig. 1b), when illuminated with light polarized along the chevron symmetry axis (*y*-axis in Fig 1a). No resonance was observed with the orthogonal polarization (*x*-axis in Fig. 1a).

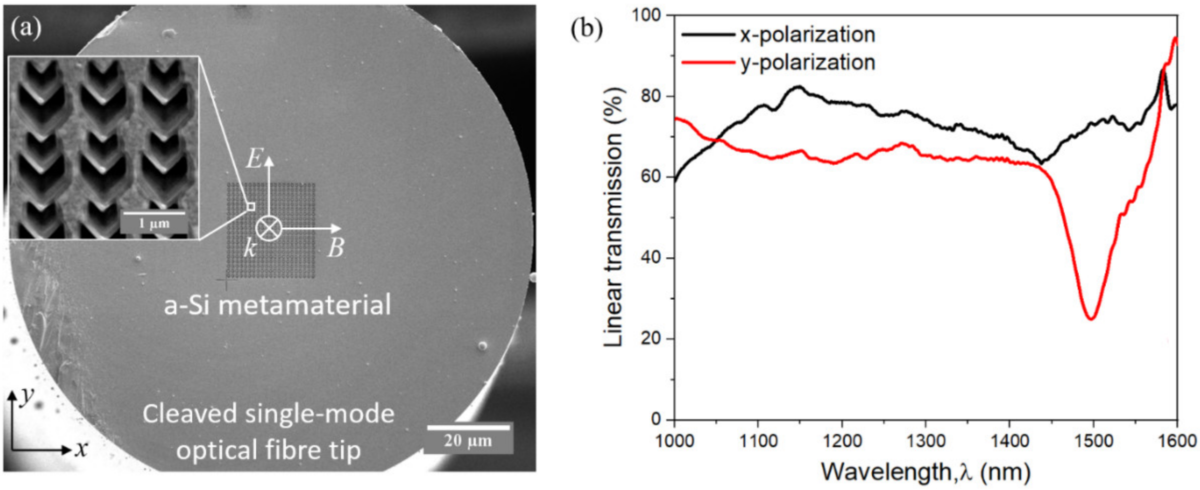

Fig. 1. (a) Metamaterial fabricated from amorphous silicon. The structure covers the core of a cleaved optical fibre and consists of pairs of chevron grooves in silica coated with an amorphous silicon layer of 90 nm thickness. (To prevent charging, SEM imaging took place with an additional gold coating that was subsequently removed.) (b) The metamaterial's transmission as a function of wavelength for *x* (black) and *y* (red) polarization.

III. Nonlinear experiments

The second-order nonlinear response of the metamaterial has been characterized by illuminating it with linearly polarized 200 fs optical pulses with 25 mW average power and 80 MHz repetition rate from an optical parametric oscillator (OPO). The centre wavelength of the pulses was tuned from 1440 nm to 1610 nm with a pulse bandwidth of about 5 nm. The light was focused onto the fibre-tip from free-space. The peak intensity at the metamaterial surface was about 6.25 GW/cm^2. The radiation coupled into the fibre was then filtered to remove the pump as well as any third harmonic signal, and then detected using a polarization-insensitive photomultiplier tube.

Strong second harmonic emission was observed for *y*-polarized pump light at 1510 nm. The second harmonic emission peak (Fig. 2) coincides with the metamaterial's resonance (Fig. 1b), indicating that the nanostructure's resonance enhances the effective second order nonlinear response of the metamaterial. Analysis of symmetry-allowed components of the $\chi^{(2)}$ tensor for our case shows that second harmonic signals could be generated for both *x*- and *y*-polarized pump (see Fig. 1a). Probing the metamaterial's nonlinear response with three pump polarizations, e.g. *x*, *y*, and *xy* (at 45° to both *y*- and *x*-axis), and detecting the second harmonic with a polarization-insensitive detector, provides sufficient information to determine the (relative) strengths of the three symmetry-allowed $\chi^{(2)}$ components (Fig. 2). A progressive decline in the level of second harmonic signal is observed as the polarization of the pump is turned from the y-axis towards the x-axis. Our observations indicate that the $\chi^{(2)}_{yyy}$ is at least 4 times larger the other $\chi^{(2)}$ components.

About 60 fW second harmonic power has been observed for 32 mW *y*-polarized average pump power, which corresponds to a peak pump intensity of 8 GW/cm^2. We estimate that the second harmonic generation efficiency is about 10^{-12} and that the peak nonlinear coefficient [6] is about 10^{-15} W/W^2 .

Whilst of secondary importance, the metasurface also exhibited third harmonic generation (THG). Preliminary experiments on a simpler metamaterial structure indicate that THG efficiency could be about 10^{-10}, more than 100× stronger than THG on a reference optical fibre without the metamaterial layer.

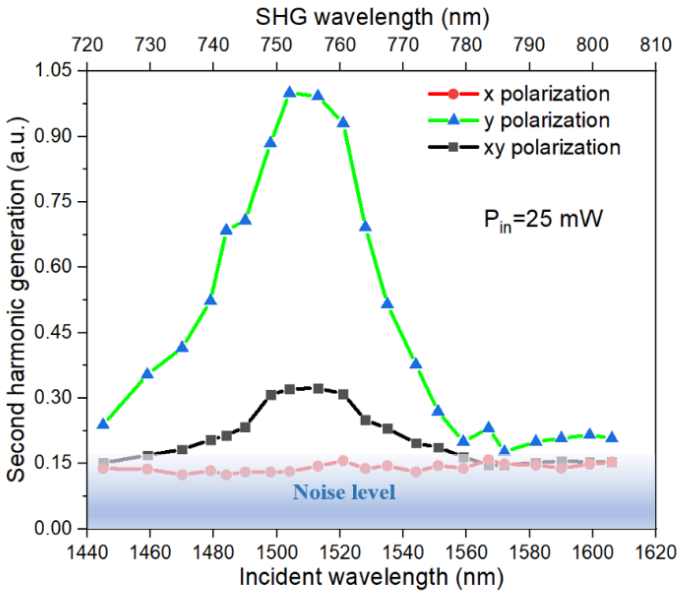

Fig. 2. Second harmonic generation by the metamaterial with 25 mW *x*-polarized (red), *xy*-polarized (black) and *y*-polarized (green/blue) pump beams.

IV. Conclusion

We have demonstrated that nanoscale structuring, with a suitable choice of point group symmetry, enables the fabrication of nonlinear metamaterials on complex non-planar platforms, such as end-facets of optical fibres. We have observed resonantly enhanced optical second harmonic generation in a fibre-tip metamaterial fabricated from amorphous, approximately centrosymmetric, media. Our work breaks the ground for miniaturization of nonlinear photonic devices.

Acknowledgement

This work is supported by the UK's Engineering and Physical Sciences Research Council (grant EP/M009122/1) and the MOE Singapore (grant MOE2016-T3-1-006).

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