Second Harmonic Generation by Silicon Metamaterial on a Fibre Tip

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Second-order nonlinear optical response provides an opportunity for control of light with light, which is essential if photonics should ever provide an answer to the exponential growth of the world's data processing requirements. Silicon-based photonics is driving the miniaturization and integration of optical circuits, but bulk silicon lacks second-order optical nonlinearity. We demonstrate second harmonic generation (SHG) by an amorphous silicon metamaterial. The nanostructure was fabricated on the tip of an optical fibre that collects and guides the generated light. The silicon metamaterial is a double chevron array that supports a closed-mode resonance. The metamaterial's normalized second harmonic conversion efficiency is $\eta/(IL^2)$~10^{-11}/W , where η is absolute conversion efficiency, I is intensity and L is interaction length. The observed normalized and absolute conversion efficiencies exceed earlier silicon metamaterial [1] by 2 and 4 orders of magnitude, respectively.

The silicon-on-silica metamaterial (Fig.1a,b) consists of an array of pairs of V-grooves. Due to the different groove sizes, the structure supports a closed-mode (Fano-type) resonance, characterized by an anti-symmetric excitation (Fig. 1c). The resonance at λ_0=1.5 µm wavelength has a quality factor of 30 (Fig.1d). The metamaterial was fabricated by milling 256-nm-deep grooves into a cleaved silica fiber tip and then depositing a 90-nm-thick CVD-silicon film on the structured fiber tip, resulting in a metamaterial thickness of L = 346 nm.

SHG by the metamaterial was characterized by pumping the nanostructure with normally incident 200 fs laser pulses of up to 9 GW/cm^2 peak intensity, see Fig.1a. Strong SHG from the metamaterial is observed for y-polarized pump light at 1510 nm wavelength, Fig. 1d, while no second harmonic above the noise level is detected from unstructured reference samples (bare fibres with/without unstructured CVD-silicon). A quadratic power dependence of the metamaterial's SHG is confirmed, Fig. 2b. The SHG spectral peak coincides with the metamaterial's resonance, indicating that SHG is enhanced by the metamaterial's closed-mode excitation.

The SHG power conversion efficiency is η=0.8×10^{-10} (comparable to metallic structures) and exceeds previously reported silicon metamaterial by 4 orders of magnitude [1]. Considering that phase-matched SHG conversion efficiency increases linearly with pump peak intensity I and quadratically with interaction length L, the corresponding normalized efficiency is $\eta/(IL^2)$=8×10^{-3}/GW, that is $\chi_{yyy}^{(2)}$~0.3 pm/V, (comparable to KDP). The normalized efficiency exceeds previous silicon metamaterial [1] by 2 orders of magnitude. This improvement is largely due to resonant SHG enhancement at the closed-mode resonance of the double chevrons.

In summary, we report a fiberized silicon-on-silica metamaterial that offers a four orders of magnitude improvement in power efficiency of SHG over previously reported results. The frequency converter is the first example of integration of all-dielectric second-order nonlinear metamaterial with fiber optics.

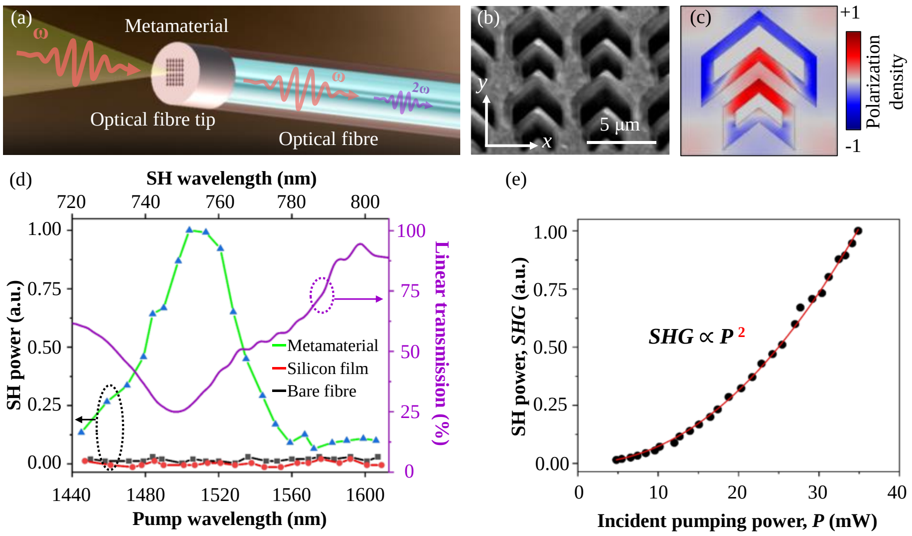

Fig. 1 Nonlinear silicon metamaterial on a fibre tip. (a) Artistic impression illustrating second harmonic generation by the resonant metamaterial. (b) SEM image of a fragment of the nonlinear metamaterial consisting of pairs of chevron grooves in silica coated with 90-nm-thick amorphous silicon. (c) The y component of the linear polarization density at the metamaterial's closed-mode resonance excited by y-polarized light at 1510 nm wavelength. (d) Detected spectral dependence of second harmonic (SH) emission by metamaterial (green), unstructured silicon film (red) and unstructured bare fibre (black) on a cleaved fibre alongside the metamaterial's linear transmission spectrum (purple). (e) Power dependence of second harmonic generation of the metamaterial (black dots) with a quadratic fit (red line) at 1510 nm pump wavelength. Incident (pump) light is y-polarized in all cases.

[1] J. Bar-David and U. Levy, "Nonlinear diffraction in asymmetric dielectric metasurfaces," Nano Lett. **19,** 1044-1051 (2019).