

Laser direct writing of nonlinear metasurfaces on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ for enhanced third harmonic generation

Lanpeng Guo, Haochong Liu, Shixin Gao, Ming Tang, Minghui Hong and Tun Cao*

Citation: Guo LP, Liu HC, Gao SX et al. Laser direct writing of nonlinear metasurfaces on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ for enhanced third harmonic generation. *Opto-Electron Technol* **2**, 260017 (2026).

<https://doi.org/10.29026/oet.2026.260017>

Received: 13 May 2026; Accepted: 29 June 2026; Published online: 16 September 2026

Related articles

Resonantly enhanced second- and third-harmonic generation in dielectric nonlinear metasurfaces

Ji Tong Wang, Pavel Tonkaev, Kirill Koshelev, et al

Opto-Electronic Advances 2024, **7**(5): 230186 doi: [10.29026/oea.2024.230186](https://doi.org/10.29026/oea.2024.230186)

High-efficiency infrared upconversion imaging with nonlinear silicon metasurfaces empowered by quasi-bound states in the continuum

Tingting Liu, Jumin Qiu, Meibao Qin, et al

Opto-Electronic Advances 2026, **9**(4): 250257 doi: [10.29026/oea.2026.250257](https://doi.org/10.29026/oea.2026.250257)

Non-volatile reconfigurable planar lightwave circuit splitter enabled by laser-directed Sb_2S_3 phase transitions

Shixin Gao, Tun Cao, Haonan Ren, et al

Opto-Electronic Technology 2025, **1**(1): 250002 doi: [10.29026/oet.2025.250002](https://doi.org/10.29026/oet.2025.250002)

Femtosecond laser maskless direct writing of dual-band crosstalk-free information for all-in-one high-security encryption metasurface

Hanmian Jiang, Zhuguo Li, Dongshi Zhang

Opto-Electronic Advances 2026, **9**(4): 250303 doi: [10.29026/oea.2026.250303](https://doi.org/10.29026/oea.2026.250303)

More related articles in Opto-Electronic Journals Group website



Laser direct writing of nonlinear metasurfaces on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ for enhanced third harmonic generation

Lanpeng Guo^{1†}, Haochong Liu¹, Shixin Gao¹, Ming Tang¹, Minghui Hong² and Tun Cao^{1*†}

Abstract: Nonlinear metasurfaces enable the precise nanoscale control of light–matter interactions and provide a promising route toward compact and multifunctional nonlinear optical devices by relaxing conventional phase-matching constraints. However, most reported nonlinear metasurfaces rely on materials with large intrinsic nonlinear coefficients, and their fabrication typically relies on complex and costly electron-beam lithography, raising the experimental barrier for nonlinear nanophotonics. A nonlinear metasurface fabricated by laser direct writing on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) is presented in this study. Experimental results show that the structured metasurface exhibits an approximately 13-fold improvement in third harmonic generation (THG) intensity relative to an unpatterned amorphous GST thin film. Notably, the observed THG enhancement is primarily dominated by multipole resonances supported by the metasurface, rather than being affected by laser-induced variations in the crystallization fraction. This work extends the laser direct writing fabrication to nonlinear photonics, providing a flexible approach toward laser-written nonlinear nanophotonic devices and indicating the potential for modulating nonlinear responses within a multipolar framework.

Keywords: metasurfaces; nonlinear optics; phase change materials; laser direct writing; third harmonic generation

DOI: [10.29026/oet.2026.260017](https://doi.org/10.29026/oet.2026.260017) | CSTR: [32419.14.oet.2026.260017](https://cstr.cn/32419.14.oet.2026.260017)

Citation: Guo LP, Liu HC, Gao SX et al. Laser direct writing of nonlinear metasurfaces on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ for enhanced third harmonic generation. *Opto-Electron Technol* 2, 260017 (2026).

1 Introduction

Nonlinear nanostructures enable efficient and compact nonlinear optical processes by enhancing light–matter interactions at the subwavelength scale, offering new physical pathways beyond conventional bulk nonlinear materials. Within this field, nonlinear metasurfaces have emerged as a prominent platform, where artificial nanostructures allow flexible control over nonlinear optical responses and exhibit distinctive advantages compared to traditional nonlinear crystals^{1–9}. Despite these advantages, the realization of nonlinear metasurfaces fundamentally relies on materials with strong intrinsic nonlinearities. Whether in plasmonic metasurfaces based on metals such as Au^{1,10–16}, or in dielectric metasurfaces employing materials including Si^{17–23}, Ge^{24,25}, TiO_2 ^{26,27}, GaAs^{28,29}, and AlGaAs^{30,31}, achieving strong optical field confinement and enhanced nonlinear interac-

tions typically relies on subtractive nanofabrication based on complex and costly electron-beam lithography techniques, which substantially raises the experimental limitation for nonlinear photonics research.

Phase-change materials are characterized by pronounced optical contrast and tunable structural phases^{32–37}. Among them, $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST), as the extensively studied phase-change materials, has been widely applied across various research fields^{38–43}, and its nonlinear optical properties have also been investigated in several previous studies^{44–46}. As a centrosymmetric material, GST exhibits a strong third-order nonlinearity, which is comparable in magnitude to that of silicon⁴⁷, making it a promising candidate for nonlinear metasurface platforms. Laser direct writing, as an efficient and highly flexible fabrication technique, has become one of the available options for nanofabrication^{48–52}. In recent, the combination of laser direct writing and phase-change

Received: 13 May 2026

Accepted: 29 June 2026

Published online: 16 September 2026

¹School of Optoelectronic Engineering and Instrumentation Science, Dalian University of Technology, Dalian 116024, China; ²School of Intelligent Manufacturing (Pen-Tung Sah Institute of Micro-Nano Science and Technology), Xiamen University, Xiamen 361005, China.

[†]These authors contributed equally to this work.

*Correspondence: T Cao, E-mail: caotun1806@dlut.edu.cn

materials has attracted growing interest in linear photonics, as it offers a new paradigm for realizing nonvolatile and reconfigurable nanophotonic devices^{38,53–55}. This emerging approach also opens new opportunities for extending such concepts to nonlinear photonics, enabling alternative routes for the design and fabrication of nonlinear nanophotonic structures.

This work demonstrates a nonlinear metasurface fabricated by the laser direct writing on a GST thin film, leading to a significant enhancement of the THG signal. Specifically, a two-dimensional periodic array of circular crystalline regions is patterned within an amorphous GST film via laser direct writing, as shown in Fig. 1(a). This nonlinear metasurface supports strong Mie resonance, as shown in Fig. 1(b), which lead to an order of magnitude enhancement of the THG signal. Additionally, we observe that the fully crystallized GST film exhibits a weaker THG signal compared with the amorphous GST film. This finding suggests that the observed THG enhancement is primarily dominated by the Mie resonance rather than by laser-induced changes in the crystallization fraction. Such enhancement can be interpreted within a multipole decomposition framework, highlighting a promising route for nonlinear multipole engineering enabled by laser direct writing. This work experimentally demonstrates a laser direct written nonlinear metasurface based on phase-change materials, providing a new perspective for the nonlinear photonics.

2 Results and discussion

Figure 1(a) schematically illustrates the nonlinear metasurface investigated in this work. The nonlinear metasurface consists of circular crystalline regions periodically arranged in a square lattice, surrounded by an amorphous GST background. The advantage of adopting a circular geometry lies in its intrinsic formation during the laser direct writing process, eliminating the need for additional beam shaping. we have optimized the design parameters of the unit cell, such as lattice constant, diameter of the circular crystalline region, and the thickness of the GST film, which achieves

optimal near-field localization at the target pump wavelengths. The structural parameters of the unit cell are presented in Fig. 1(b). During sample preparation, an amorphous GST layer with a thickness of 50 nm is deposited onto a SiO₂ substrate and protected by a 30 nm Al₂O₃ layer. The oxidation of GST in ambient air is effectively suppressed by the Al₂O₃ capping film, thereby maintaining its long-term stability during operation⁵⁶ (see *Methods* for fabrication details). Local crystallization patterning is then performed using a home-built laser direct writing system, producing a periodic two-dimensional array of circular crystalline regions within the GST film. Figure 1(c) presents an optical microscopic image of the fabricated sample, while the inset displays a magnified view of an individual meta-atom. A pronounced optical contrast between the patterned regions and the surrounding amorphous GST film is observed, which is consistent with the significant refractive-index difference between crystalline and amorphous GST and provides evidence for the crystallization of the laser-written regions. Due to thermal diffusion and laser power fluctuation during the direct writing process, the crystalline regions exhibit minor morphological and positional deviations. Specifically, higher laser power and slower scanning speeds increase the thermal accumulation within the phase-change material, thereby enlarging the structural feature size. Additionally, the edge sharpness is correlated with the deposition of the GST thin film, rather than being solely dictated by the laser processing parameters. Nevertheless, these imperfections do not significantly affect the optical response, demonstrating that the targeted resonance is relatively tolerant to geometric imperfections. A detailed statistical analysis of the size distribution and positional deviations of the crystalline regions can be found in Section 2 of the Supplementary information.

2.1 Linear optical properties

To establish a clear physical picture for the observed THG enhancement, the reflection of the metasurface is characterized theoretically and experimentally. Figure 2(a) presents

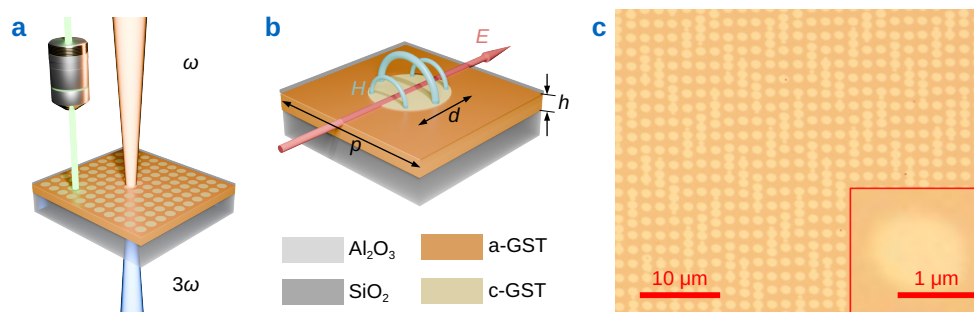


Fig. 1 | Nonlinear metasurface realized by laser direct writing. (a) Illustration of the metasurface together with the fabrication procedure. (b) Illustration of the Mie-resonance mechanism and the corresponding meta-atom geometry (period $p = 1.7 \mu\text{m}$, GST thickness $h = 50 \text{ nm}$, crystalline region diameter $d = 1 \mu\text{m}$). (c) Optical micrograph of the fabricated sample; the inset presents a magnified view of a single meta-atom.

numerical results of the reflection spectra for an amorphous GST film and the metasurface. While the unpatterned film exhibits a featureless profile, the metasurface shows a distinct resonance dip at 2.73 μm . It suggests the excitation of a strong resonance at this wavelength. The resonance is enabled by the refractive index difference created through laser-induced crystallization of GST. The optical contrast between the crystalline and amorphous ($\Delta n = 1.63$ at 2.73 μm)³⁴ leads to strong localization of the incident electric field within the crystalline regions. Correspondingly, the reflection spectrum measured by FTIR spectroscopy is shown in Fig. 2(b), exhibiting a resonance dip near 2.73 μm . Compared with the numerical simulations, the spectral broadening of the resonance is largely due to the fabrication imperfections. Additionally, several other experimental factors also contribute to this difference, including the finite size of the metasurface array, potential partial crystallization, surface roughness. The small ripples observed in the measured curves result from instrumental noise and environmental fluctuations during the FTIR characterization. Despite these minor spectral ripples, the overall resonant profile and the position of the dip are distinguishable and identical to the numerical prediction. Furthermore, the optical constants (n and k) used in the simulations were extracted from spectroscopic ellipsometry measurements of GST films crystallized under the same laser-writing conditions as those employed for the fabrication of the metasurface. The good agreement between the simulated and experimental reflection spectra therefore provides further evidence that the laser-written regions possess optical properties consistent with those of crystalline GST.

To clarify the physical mechanism responsible for the observed resonance, a multipole analysis based on finite-element simulations was carried out for the metasurface. Figure 3(a) schematically depicts the electric dipole resonance and the multipole contributions are shown in Fig. 3(b). The scattering power has a strong electric dipole resonance, while contributions from other multipoles are negligible. Consequently, the resonance in the proposed metasur-

face arises from this specific resonant mode. It is noteworthy that the proposed metasurface does not rely on a high-Q factor resonance, thereby providing inherent robustness against fabrication imperfections. The defects shown in Fig. 1(c) have a negligible influence on the excitation of the Mie resonance. Further information regarding the multipole decomposition approach is available in the Supplementary information. Figure 3(c) and 3(d) present the normalized electric and magnetic field distribution within GST layer. In Fig. 3(c), the electric field exhibits strong localized enhancement both inside and at the opposite ends of the crystalline GST, with its orientation aligned with the incident field (along x axis). In Fig. 3(d), the magnetic field forms a closed loop within the crystalline GST and exhibits localized enhancement on both sides of the resonator. Compared with the electric field, the magnetic-field enhancement is less pronounced. Similar features can also be identified from the current density distributions in Fig. 3(c) and 3(d).

2.2 Nonlinear optical measurement

The nonlinear response of the fabricated sample was characterized using the THG measurement system illustrated in Fig. 4(a). Femtosecond pulses were provided by an optical parametric amplifier (OPA) covering wavelengths from 2.4 to 2.9 μm and delivering pulses of 190 fs. A lens ($f = 15$ mm) was employed to focus the excitation beam onto the sample, producing a spot diameter of approximately 40 μm . The generated THG is collected by an objective 20 $\times$ with 0.45 numerical aperture (NA) and filtered by a short-pass filter before being coupled to a spectrometer. We emphasize that the laser peak power density applied to the metasurface is far below the crystallization threshold of GST³⁸ and is therefore insufficient to induce crystallization or cause damage to the metasurface during the measurement. Details of the optical setup can be found in the Methods and Fig. 4(a).

The metasurface enhancement factor is calculated as a ratio of the THG power generated by the sample to that of an unpatterned amorphous GST layer under the same

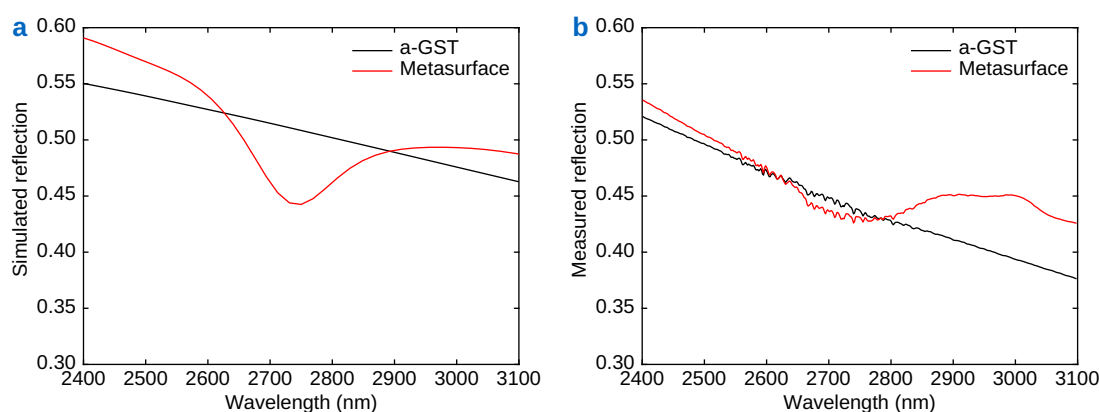


Fig. 2 | Simulated (a) and measured (b) reflection spectra of amorphous GST and the metasurface.

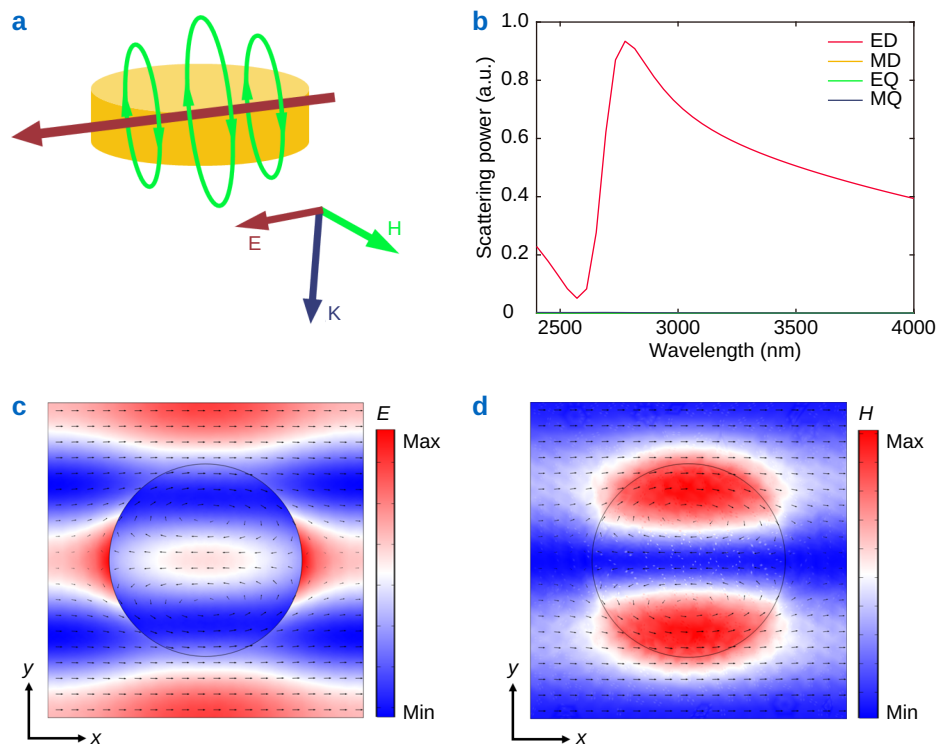


Fig. 3 | Electric dipole resonance supported by the metasurface. (a) Schematic illustration of an electric dipole resonance in metasurface. (b) Multipole contributions of the metasurface. (c) Electric and (d) magnetic field distributions within the GST layer, and the arrows show current density distribution.

conditions. In Fig. 4(b), the THG enhancement spectrum agrees well with the far-field reflectance dip induced by the electric dipole resonance. Under excitation at 2.73 μm , the metasurface provides a maximum enhancement factor of 13. The reported THG efficiency includes only the forward-emitted signal, while THG radiation is generated in both forward and backward directions. Figure 4(c) shows the simulated THG enhancement factor. In the calculation, the third-order susceptibilities for amorphous and crystalline GST are taken as $\chi_{\text{a-GST}}^3 \approx 8.25 \times 10^{-19} \text{ m}^2/\text{V}^2$ and $\chi_{\text{c-GST}}^3 \approx 9.9 \times 10^{-18} \text{ m}^2/\text{V}^2$, and the third-order susceptibilities of the SiO_2 substrate and Al_2O_3 protective layer are negligible. It is observed that the simulation and experimental results are consistent.

Subsequently, the THG conversion efficiency, defined as $\eta_{\text{THG}} = P_{\text{THG}}/P_{\text{pump}}$ (where P_{THG} is the forward-emitted THG power and P_{pump} is the incident pump power), is evaluated at 2.73 μm . Figure 4(d) shows that the conversion efficiency is proportional to the square of the pump intensity. Because the THG intensity follows a cubic relationship $P_{\text{THG}} \propto (P_{\text{pump}})^3$, the conversion efficiency scales quadratically $\eta_{\text{THG}} = P_{\text{THG}}/P_{\text{pump}}$, resulting in a theoretical slope of 2 in the log-linear plot. At an excitation wavelength of 2.73 μm , the conversion efficiency of the metasurface reaches 2.3×10^{-10} at a pump power of 6.7 mW. It should be noted that the aforementioned results alone cannot completely rule out an alternative explanation, namely whether the observed THG

enhancement originates from an increased fraction of crystalline GST induced during the laser direct writing process. To address this issue, we further compare the THG power of unpatterned crystalline and amorphous GST films, with the results presented in Fig. 4(e). Despite the theoretically larger χ^3 of crystalline GST, which exceeds that of amorphous GST by roughly one order of magnitude⁵⁷, the experimentally observed THG intensity from the amorphous film is more than two times stronger than that from the crystalline counterpart. This behavior can be attributed to the significantly higher optical loss of crystalline GST in the pump wavelength range, which suppresses efficient nonlinear conversion despite its larger intrinsic χ^3 . These experiments clearly show that the observed THG enhancement is primarily governed by the electric dipole resonance supported by the metasurface, rather than being influenced by the crystallization fraction introduced during laser writing.

3 Conclusions

We have demonstrated a laser-written nonlinear metasurface based on GST, which improves the THG conversion efficiency by a factor of 13. In particular, we utilize the laser direct writing to pattern periodically arranged circular crystalline domains on the amorphous GST film, which supports electric dipole resonances to achieve THG enhancement. This strategy can be further implemented in phase-change

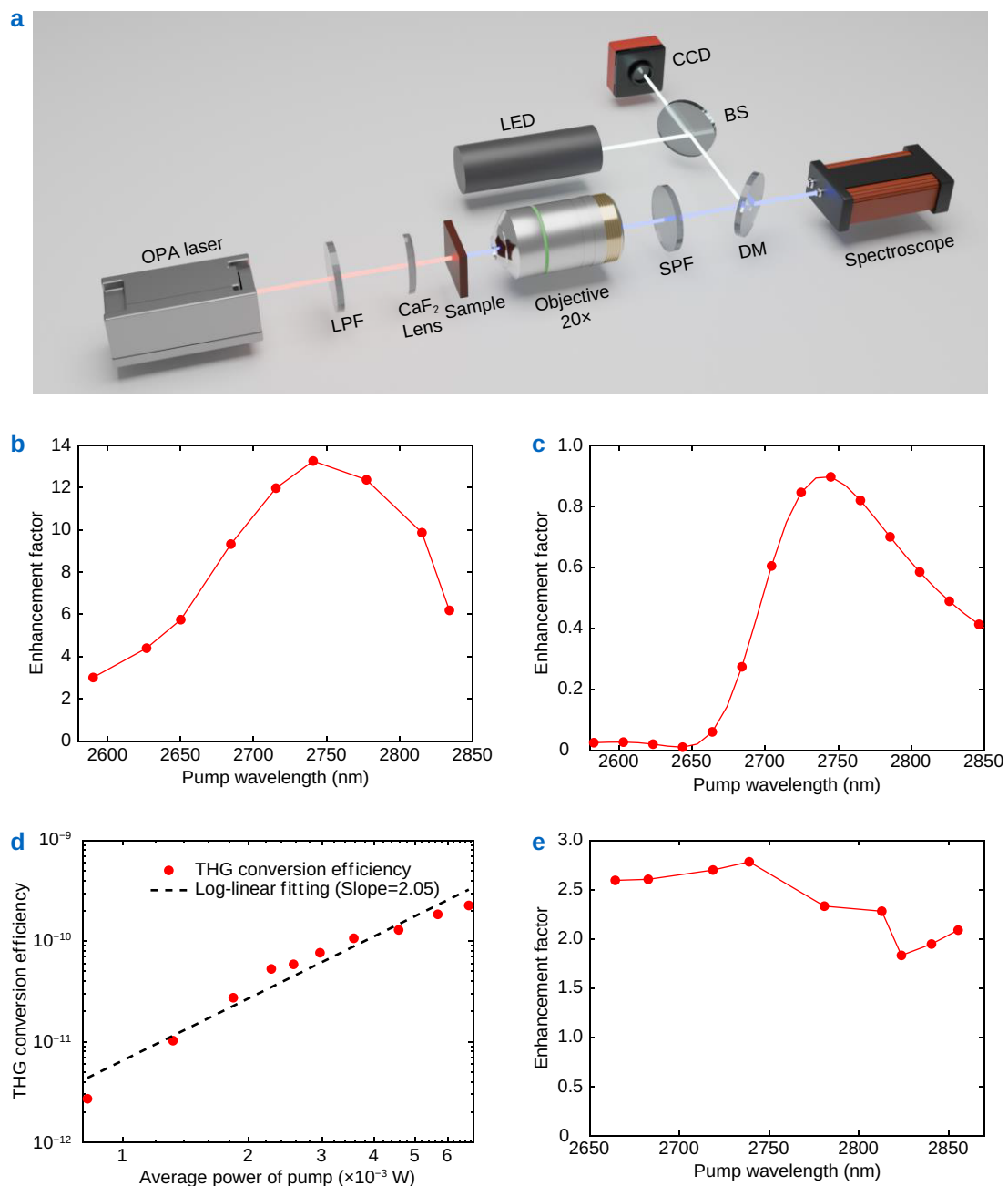


Fig. 4 | THG measurement of the metasurface. (a) Experimental configuration for THG measurements. LPF: long-pass filter; SPF: short-pass filter; DM: dichroic mirror; BS: beam splitter. (b) THG enhancement factor of the metasurface (with respect to an unpatterned amorphous GST film) measured at 0.8842 GW/cm². (c) The corresponding simulated THG enhancement factor of the metasurface. (d) Measured conversion efficiency (on a logarithmic scale) of the metasurface under excitation at 2.73 μm as the average pump power varies. (e) Measured THG enhancement factor of the amorphous GST film (with respect to an unpatterned crystalline GST film) under the same measurement condition.

materials exhibiting stronger nonlinear responses and lower optical losses, such as GSST and IST, combining with carefully designed crystallization patterns that could support high-order Mie resonance, which may allow further enhancement and control of the nonlinear response. Overall, this work highlights the potential of laser direct writing in nonlinear photonics, providing a flexible approach toward laser-written nonlinear nanophotonic devices and

indicating the potential for modulating nonlinear responses within a multipolar framework.

4 Methods

Nonlinear metasurface fabrication: The SiO₂ substrates are first ultrasonically cleaned in isopropanol and deionized water for 15 min each, followed by nitrogen drying. The

cleaned SiO₂ substrates are subsequently coated with a 50 nm GST layer using an AJA magnetron sputtering system, where the deposition rate is maintained at 0.1 nm/s. The deposited film remained in the amorphous state. Subsequently, a 30 nm Al₂O₃ protective layer is deposited on the GST surface using the same sputtering system at a deposition rate of 0.01 nm/s. Local crystallization is performed with a home-built laser direct writing system. Additional information on the laser direct writing system can be found in the Supplementary information.

FTIR measurements: Reflection spectra are recorded using a Bruker Vertex 70 Fourier-transform infrared spectrometer integrated with a Bruker Hyperion 2000 microscope. Measurements are carried out using a 15× grazing-incidence objective (NA = 0.4). For each measurement, 100 scans are accumulated with a resolution of 4 cm⁻¹.

THG measurements: The samples are excited by a tunable femtosecond source using a Pharos Yb:KGW amplifier and an Orpheus OPA, producing pulses of approximately 190 fs, repetition rate is 800 kHz. The THG spectra are collected with a spectrometer (Teledyne Princeton Instruments, HRS-500) equipped with a cryogenically cooled CCD camera (Teledyne Princeton Instruments, PyLoN).

Numerical simulations: The frequency-domain finite-element method (FEM), implemented in COMSOL Multiphysics, is employed for all numerical simulations. The complex refractive index of SiO₂ are obtained from the COMSOL database, while the complex refractive index of GST is measured by spectroscopic ellipsometry (J.A. Woollam Co, IR-VASE Mark II) from GST films crystallized under the same laser-writing conditions as those employed for the fabrication of the metasurface. A plane wave is used as the excitation source. Periodic boundary conditions are imposed along the *x* and *y* axes, while perfectly matched layers (PML) were defined in the *z* direction. The mesh resolution is refined to a minimum size of 5 nm. Details of multipole decomposition and nonlinear calculations are available in the Supplementary information.

References

- Kauranen M, Zayats AV. Nonlinear plasmonics. *Nat Photonics* **6**, 737–748 (2012).
- Vabishchevich P, Kivshar Y. Nonlinear photonics with metasurfaces. *Photonics Res* **11**, B50–B64 (2023).
- Li GX, Zhang S, Zentgraf T. Nonlinear photonic metasurfaces. *Nat Rev Mater* **2**, 17010 (2017).
- Krasnok A, Tymchenko M, Alù A. Nonlinear metasurfaces: a paradigm shift in nonlinear optics. *Mater Today* **21**, 8–21 (2018).
- Grinblat G. Nonlinear dielectric nanoantennas and metasurfaces: frequency conversion and wavefront control. *ACS Photonics* **8**, 3406–3432 (2021).
- Chen Y, Jiang MN, Zhang F et al. Global selection rules and giant enhanced harmonic generations in LiNbO₃ nonlinear meta-optics. *Laser Photonics Rev* **19**, 2400991 (2025).
- Nan T, Zhao H, Guo JY et al. Generation of structured light beams with polarization variation along arbitrary spatial trajectories using tri-layer metasurfaces. *Opto-Electron Sci* **3**, 230052 (2024).
- Liu TT, Qiu JM, Qin MB et al. High-efficiency infrared upconversion imaging with nonlinear silicon metasurfaces empowered by quasi-bound states in the continuum. *Opto-Electron Adv* **9**, 250257 (2026).
- Liu TT, Qin MB, Qiu JM et al. Polarization-independent enhancement of third-harmonic generation empowered by doubly degenerate quasi-bound states in the continuum. *Nano Lett* **25**, 3646–3652 (2025).
- Li GX, Chen SM, Pholchai N et al. Continuous control of the nonlinearity phase for harmonic generations. *Nat Mater* **14**, 607–612 (2015).
- O'Brien K, Suchowski H, Rho J et al. Predicting nonlinear properties of metamaterials from the linear response. *Nat Mater* **14**, 379–383 (2015).
- Tymchenko M, Gomez-Diaz JS, Lee J et al. Gradient nonlinear pancharatnam-berry metasurfaces. *Phys Rev Lett* **115**, 207403 (2015).
- Almeida E, Bitton O, Prior Y. Nonlinear metamaterials for holography. *Nat Commun* **7**, 12533 (2016).
- Almeida E, Shalem G, Prior Y. Subwavelength nonlinear phase control and anomalous phase matching in plasmonic metasurfaces. *Nat Commun* **7**, 10367 (2016).
- Ye WM, Zeuner F, Li X et al. Spin and wavelength multiplexed nonlinear metasurface holography. *Nat Commun* **7**, 11930 (2016).
- Deng JH, Tang YT, Chen SM et al. Giant enhancement of second-order nonlinearity of epsilon-near-zero medium by a plasmonic metasurface. *Nano Lett* **20**, 5421–5427 (2020).
- Shcherbakov MR, Neshev DN, Hopkins B et al. Enhanced third-harmonic generation in silicon nanoparticles driven by magnetic response. *Nano Lett* **14**, 6488–6492 (2014).
- Yang YM, Wang WY, Boulesbaa A et al. Nonlinear Fano-resonant dielectric metasurfaces. *Nano Lett* **15**, 7388–7393 (2015).
- Gao YS, Fan YB, Wang YJ et al. Nonlinear holographic all-dielectric metasurfaces. *Nano Lett* **18**, 8054–8061 (2018).
- Wang L, Kruk S, Koshelev K et al. Nonlinear wavefront control with all-dielectric metasurfaces. *Nano Lett* **18**, 3978–3984 (2018).
- Reineke B, Sain B, Zhao RZ et al. Silicon metasurfaces for third harmonic geometric phase manipulation and multiplexed holography. *Nano Lett* **19**, 6585–6591 (2019).
- Kruk SS, Wang L, Sain B et al. Asymmetric parametric generation of images with nonlinear dielectric metasurfaces. *Nat Photonics* **16**, 561–565 (2022).
- Tripathi A, Ugwu CF, Asadchy VS et al. Nanoscale optical nonreciprocity with nonlinear metasurfaces. *Nat Commun* **15**, 5077 (2024).
- Connell GAN, Temkin RJ, Paul W. Amorphous germanium III. Optical properties. *Adv Phys* **22**, 643–665 (1973).
- Amotchkina T, Trubetskov M, Hahner D et al. Characterization of e-beam evaporated Ge, YbF₃, ZnS, and LaF₃ thin films for laser-oriented coatings. *Appl Opt* **59**, A40–A47 (2020).
- Siefke T, Kroker S, Pfeiffer K et al. Materials pushing the application limits of wire grid polarizers further into the deep ultraviolet spectral range. *Adv Opt Mater* **4**, 1780–1786 (2016).
- Semmlinger M, Zhang M, Tseng ML et al. Generating third harmonic vacuum ultraviolet light with a TiO₂ metasurface. *Nano Lett* **19**, 8972–8978 (2019).
- Papatryfonos K, Angelova T, Brimont A et al. Refractive indices of MBE-grown Al_xGa_(1-x)As ternary alloys in the transparent wavelength region. *AIP Adv* **11**, 025327 (2021).
- Vabishchevich PP, Liu S, Sinclair MB et al. Enhanced second-harmonic generation using broken symmetry III-V semiconductor Fano metasurfaces. *ACS Photonics* **5**, 1685–1690 (2018).
- Camacho-Morales R, Rahmani M, Kruk S et al. Nonlinear generation of vector beams from AlGaAs nanoantennas. *Nano Lett* **16**, 7191–7197 (2016).
- Coudrat L, Bouliard G, Gérard JM et al. Unravelling the nonlinear generation of designer vortices with dielectric metasurfaces. *Light*

- Sci Appl* 14, 51 (2025).
32. Wuttig M, Bhaskaran H, Taubner T. Phase-change materials for non-volatile photonic applications. *Nat Photonics* 11, 465–476 (2017).
 33. Abdollahramezani S, Hemmatyar O, Taghinejad H et al. Tunable nanophotonics enabled by chalcogenide phase-change materials. *Nanophotonics* 9, 1189–1241 (2020).
 34. Cao T, Wang RZ, Simpson RE et al. Photonic Ge-Sb-Te phase change metamaterials and their applications. *Prog Quantum Electron* 74, 100299 (2020).
 35. Wang RZ, Su Y, Fan HJ et al. Tunable vertical cavity microlasers based on MAPbI₃ phase change perovskite. *Opto-Electron Adv* 8, 240220 (2025).
 36. Li X, Liao XY, Zeng JX et al. Non-volatile tunable multispectral compatible infrared camouflage based on the infrared radiation characteristics of Rosaceae plants. *Opto-Electron Adv* 8, 250031 (2025).
 37. Gao JN, Vincenti MA, Frantz J et al. Near-infrared to ultra-violet frequency conversion in chalcogenide metasurfaces. *Nat Commun* 12, 5833 (2021).
 38. Wang Q, Rogers ETF, Gholipour B et al. Optically reconfigurable metasurfaces and photonic devices based on phase change materials. *Nat Photonics* 10, 60–65 (2016).
 39. Cao T, Zhang XY, Dong WL et al. Tuneable thermal emission using chalcogenide metasurface. *Adv Opt Mater* 6, 1800169 (2018).
 40. Cao T, Zhang L, Simpson RE et al. Mid-infrared tunable polarization-independent perfect absorber using a phase-change metamaterial. *J Opt Soc Am B* 30, 1580–1585 (2013).
 41. Ríos C, Stegmaier M, Hosseini P et al. Integrated all-photonic non-volatile multi-level memory. *Nat Photonics* 9, 725–732 (2015).
 42. Ríos C, Hosseini P, Taylor RA et al. Color depth modulation and resolution in phase-change material nanodisplays. *Adv Mater* 28, 4720–4726 (2016).
 43. Gao SX, Ren HN, Pang JZ et al. Reconfigurable free form silicon photonics by phase change waveguides. *Adv Opt Mater* 13, 2402997 (2025).
 44. Cao T, Liu K, Tang YT et al. A high-index Ge₂Sb₂Te₅-based Fabry-Perot cavity and its application for third-harmonic generation. *Laser Photonics Rev* 13, 1900063 (2019).
 45. Abdelraouf OAM, Anthur AP, Dong ZG et al. Multistate tuning of third harmonic generation in Fano-resonant hybrid dielectric metasurfaces. *Adv Funct Mater* 31, 2104627 (2021).
 46. Zhu ML, Abdollahramezani S, Li CT et al. Dynamically tunable second-harmonic generation using hybrid nanostructures incorporating phase-change chalcogenides. *Nanophotonics* 11, 2727–2735 (2022).
 47. Korolev V, Sinelnik AD, Rybin MV et al. Tunable high-order harmonic generation in GeSbTe nano-films. *Nanophotonics* 13, 3411–3419 (2024).
 48. Selimis A, Mironov V, Farsari M. Direct laser writing: principles and materials for scaffold 3D printing. *Microelectron Eng* 132, 83–89 (2015).
 49. Jia YC, Wang SX, Chen F. Femtosecond laser direct writing of flexibly configured waveguide geometries in optical crystals: fabrication and application. *Opto-Electron Adv* 3, 190042 (2020).
 50. Pinheiro T, Morais M, Silvestre S et al. Direct laser writing: from materials synthesis and conversion to electronic device processing. *Adv Mater* 36, 2402014 (2024).
 51. Gao SX, Cao T, Ren HN et al. Non-volatile reconfigurable planar lightwave circuit splitter enabled by laser-directed Sb₂S₃ phase transitions. *Opto-Electron Technol* 1, 250002 (2025).
 52. Fu JC, Jiang MT, Wang Z et al. Supercritical metalens at h-line for high-resolution direct laser writing. *Opto-Electron Sci* 3, 230035 (2024).
 53. Dong KC, Hong S, Deng Y et al. A lithography-free and field-programmable photonic metacanvas. *Adv Mater* 30, 1703878 (2018).
 54. Wu CM, Deng HQ, Huang YS et al. Freeform direct-write and rewritable photonic integrated circuits in phase-change thin films. *Sci Adv* 10, eadk1361 (2024).
 55. Conrads L, Bontke F, Mathwieser A et al. Infrared beam-shaping on demand via tailored geometric phase metasurfaces employing the plasmonic phase-change material In₃SbTe₂. *Nat Commun* 16, 3698 (2025).
 56. Raoux S, Welnic W, Ielmini D. Phase change materials and their application to nonvolatile memories. *Chem Rev* 110, 240–267 (2010).
 57. Liu HL, Zhang ZB, Shang ZC et al. Dynamically manipulating third-harmonic generation of phase change material with gap-plasmon resonators. *Opt Lett* 44, 5053–5056 (2019).

Acknowledgements

This work was supported by the National Natural Science Foundation of China (U24A20309).

Author contributions

L.P.G and T. Cao proposed the idea. L.P.G performed theoretical analyses and numerical simulations. L.P.G, H.C.L and S.X.G performed experimental measurements. L.P.G. evaluated the experimental and numerical results. L.P.G. and T.C. wrote the manuscript. M. T. contributed valuable comments and suggestions to the revision and improvement of the manuscript. T.C. and M.H.H. guided the research.

Competing interests

Minghui Hong serves as an Executive Editor-in-Chief for the Journal, and no other author has reported any competing interests.

Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplementary information

Supplementary information for this paper is available at <https://doi.org/10.29026/oet.2026.260017>



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>

©The Author(s) 2026.
Published by Editorial Office of *Opto-Electronic Technology*, Institute of Optics and Electronics, Chinese Academy of Sciences.



Scan for Article PDF