High-Efficiency Spatial-Wave Frequency Multiplication Using Strongly Nonlinear Metasurface

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In the past decades, metasurfaces have opened up a promising venue for manipulating lights and electromagnetic (EM) waves. In the field of nonlinearity, second-harmonic generation (SHG) is a research focus due to its diverse applications. There have been many researches for realizing SHG in optical regime using nonlinear characteristics of optical materials, but its efficiency is low. In microwave frequencies, SHGs are basically studied in the guided-wave systems. Here, high-efficiency SHGs of spatial waves are presented in the microwave frequency using nonlinear metasurface loaded with active chips at the subwavelength scale. The nonlinear meta-atom is composed of receiving antenna, transmitting antenna, and active circuit of frequency multiplier, which can realize strongly nonlinear response and link the EM signals from the receiving to transmitting antennas. Correspondingly, to achieve the function of spatial-wave frequency multiplication, the working frequency of the transmitting antenna in the meta-atom should be twice as that of the receiving antenna, and hence the active chip is well matched to obtain the signal transforming with high efficiency. Good performance of the spatial-wave frequency multiplication is demonstrated in the proof-of-concept experiments with the best transform efficiency of 85.11% under normal incidence, validating the proposed method.

1. Introduction

Optical nonlinearities have been observed in natural media when interacting with light at high intensities, and such nonlinear microscopic properties are intimately related to an effectively macroscopic nonlinear polarization, resulting in power conversions from some frequencies to others.\(^1-^4\) Second-harmonic generation (SHG) is one of the most important nonlinear effects, and has been utilized to diverse applications, such as source generation,\(^5\) communication,\(^6\) imaging,\(^7\) and vital signs monitoring.\(^8,^9\) In the optical frequency, SHG is a nonlinear wave-mixing procedure where two same-fundamental-wavelength (\(\lambda_{FW}\)) incident photons acting together to generate a single photon with higher energy at the second harmonic wavelength (\(\lambda_{SH} = \lambda_{FW}/2\)).\(^10\) Traditionally, SHG can be desinged using a noncentrosymmetric crystal superlattice of bulk material with large nonlinear susceptibility,\(^11\) and more importantly, accurate phase matching is required for efficient frequency conversions in the conventional nonlinear-optical crystals.\(^12\)

The emergence of metamaterials and metasurfaces have opened up a promising venue for artificially manipulating the electromagnetic (EM) waves in the linear optical area at subwavelength scale.\(^13-^15\) Recently, investigations of optical metamaterials and metasurfaces exhibit some novel nonlinear properties and can relax the critical phase matching requirement, including phase-mismatch-free nonlinear generation,\(^16\) large nonlinear susceptibilities,\(^17-^19\) and new quasiphasematching capabilities,\(^17,^18\) which were not found in natural nonlinear buck optical crystals.\(^20,^21\) Therefore various optical metasurfaces have been proposed for enhancing SHG, and the intensity, phase, and polarization states of the induced SHG can be precisely manipulated by optimizing the sizes, shapes, and orientations of the metallic nanostructures.\(^10,^22-^30\)

The traditional optical buck metamaterial can generate second harmonic nonlinearity with efficient conversion by using phase matching techniques. The optical metasurfaces have exhibited novel nonlinear properties that were not found in the natural nonlinear buck optical crystals, and they provide a promising venue for enhancing and manipulate SHGs. However, in the microwave band, the above mentioned nonlinear properties are not found in natural materials.\(^31\) Actually, the passive meta-structures cannot contribute to the nonlinear design, and the passive resonance features of the metasurfaces cannot be directly employed for the generation of nonlinearity in the microwave frequency. After the composite materials created by arrays of wires and split-ring resonators (SRRs), also referred as
left-handed materials, were demonstrated to have property of negative refraction, researchers have theoretically and experimentally shown that left-hand materials constructed with varactor-loaded SRRs can exhibit dynamic tunability and self-induced nonlinearity.\cite{32-37} Therefore, in the past decade, the nonlinear metamaterials with active devices have been extensively investigated in the microwave frequencies.\cite{38-43} For instance, by inserting a varactor diode into the gap of SRR, the SHG intensity can be enhanced in quasiphase-matching configurations and double-resonant particles.\cite{17,38} However, these works have been analyzed to generate SHGs at low powers with low efficiency.\cite{39,40} Some plasmonic metamaterials with compact size and efficiency have been proposed.\cite{41-43} The ultrathin spoof surface plasmon polarization meta-waveguides loaded with a field effect transistor (FET)\cite{41} and varactor diodes\cite{42,43} can realize efficient SHGs. More importantly, these SHG works are limited to the guided waves.

Recently, owing to the simultaneous manipulations of the EM waves in both space and frequency domains, the space-time-coding digital metasurfaces\cite{44-48} and time-domain digital coding metasurfaces\cite{49-51} have attracted growing interests and enabled efficient harmonics wave-manipulation capabilities in the microwave frequencies. However, the spatial-wave SHGs in the space-time-coding digital metasurfaces can only generate the second harmonics of the modulation frequency, instead of the carrier frequency of the incident waves.

Therefore, in the microwave band, it is possible to produce spatial-wave SHGs by integrating microwave active chips with dedicated design of meta-atom. In this paper, we present high-efficiency SHGs of the spatial waves and realize spatial-wave frequency multiplication in the microwave frequency using strongly nonlinear metamaterials loaded with active circuits of frequency multiplier at subwavelength scale. The nonlinear meta-atom is composed of a receiving antenna, a transmitting antenna, and an active chip. To achieve the second-harmonic generator, the operating frequency of transmitting antenna in the nonlinear metasurface should be designed as twice as that of receiving antenna. In addition, to make the EM signals transform with high efficiency, the active chip of frequency multiplier needs to be well matched with the transmitting and receiving antennas. According to the simulations and experimental measurements, the results demonstrate efficient frequency multiplications of incident spatial waves by the proposed nonlinear metasurface.

2. Results and Discussion

2.1. Design of Strongly Nonlinear Metasurface

Figure 1 illustrates a schematic diagram of SHG using nonlinear metasurface, which is composed of 2D lattices of subwavelength-scale meta-atoms. Each meta-atom is composed of a receiving antenna, a transmitting antenna, and an active chip. The active chip forms an active circuit of microwave frequency multiplier embedded on the bottom of the meta-atom, which can be considered as a bridge to link the electromagnetic signals from the receiving antenna to the transmitting antenna. The 3D structure of nonlinear metasurface unit is presented in the zoom-in inset of this figure. When the spatial incidence captured by the receiving antenna goes through the integrated nonlinear active chip, the second harmonic signal can be generated and radiated back again into space via the transmitting antenna.
is designed with a dielectric constant of 3.52 and thickness of 0.1 mm.

The receiving/transmitting antenna is composed of two patches. The rectangular inner patch is the receiving antenna and is used for receiving fundamental-frequency \( f_{\text{FF}} \) incident wave. The outer patch with an open loop fed at reversal direction is the transmitting antenna, which can be used for radiating second-harmonic-frequency \( f_{\text{SH}} \) reflected wave with the same polarization. The two patches are connected with the bottom layer by two \( \lambda/4 \)-transformers and two metal via-holes through the ground. The components in the bottom layer contain an active chip of frequency multiplier and a related peripheral circuit. Besides, the electronic circuit shares the same ground with the receiving/transmitting antenna, and ground signals in the active circuit can be directly connected to ground plane by metalized via-holes. Therefore, the second harmonics generation and transmitting route can be demonstrated by the topological structure clearly. The spatial EM wave of frequency \( f_{\text{FF}} \) is captured by the front receiving antenna and converted to the radio frequency (RF) signal. Then the RF signal transmits through one via-hole to the bottom nonlinear circuit layer and is converted to the RF signal of second-harmonic frequency \( f_{\text{SH}} \) by the active circuit of frequency multiplier. Finally, the output RF signal of \( f_{\text{SH}} \) is sent to the front transmitting antenna through another via-hole and is transformed into the reflective spatial EM wave radiating back again into space.

To realize the second-harmonic generator, the operating frequency \( f_{\text{SH}} \) of transmitting antenna in the nonlinear metasurface should be designed as twice as the \( f_{\text{FF}} \) of receiving antenna. The top view of receiving and transmitting antenna is shown in Figure 2b. For frequency \( f_{\text{FF}} \), the receiving antenna works in a higher-order mode, and the resonance is associated not only with the physical length in \( y \)-direction, but also with the length in \( x \)-direction. For frequency \( f_{\text{SH}} \), the transmitting antenna operates in the basic-order mode, and the response is mainly dependent on its physical \( y \)-direction length. Therefore, the key geometrical parameters of receiving/transmitting antenna are physical length in \( y \)-direction and can be first estimated by the empirical formula using effective dielectric constant under the certain condition of substrate thickness, receiving patch width and transmitting patch width. The \( \lambda_{\text{eff}} \) is the corresponding propagation wavelength in the equivalent medium for EM wave of frequency. In addition, two patches are matched to 50 \( \Omega \) using \( \lambda_{\text{eff}} /4 \)-transformers for impedance matching of operating point, and \( \lambda_{\text{eff}} /4 \)-transformer for the frequency \( f_{\text{FF}} \) is bent to 90° to minimize the unit size (as shown in Figure 2b). Simultaneously, in order to ensure good impedance matching, the geometries of the bottom nonlinear circuit layer are also required to be optimized carefully, as illustrated.
The simulated results of the scattering $S$ parameters of the second-harmonic meta-atom structure without the nonlinear active chip, in which the input ($RF_{in}$) and output ($RF_{out}$) of the frequency multiplier are replaced by Ports 2 and 3, and the Floquet Port 1 (with the oblique incidence $\theta$) is defined as the transmitting or receiving port of the spatial wave. a) Resonant features at 5 GHz (the fundamental frequency) with the oblique incidence of 10°. b) Resonant features at 10 GHz (the second-harmonic frequency) with the oblique incidence of 10°. c,d) $S_{21}$ and $S_{13}$ simulation results with different oblique incidences of $\theta = 5°$, 10°, 15°, 20°, and 30°, respectively.

Table 1. Detailed dimension parameters of the proposed nonlinear receiving/transmitting unit in millimeters.

| Parameter | $h_1$ | $h_2$ | $h_3$ | $D_x$ | $D_y$ | $L_1$ | $W_1$ | $g_1$ |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|
| Value     | 1.5   | 0.5   | 0.1   | 20    | 22    | 15.5  | 18    | 0.3   |
| Parameter | $h_1$ | $h_1$ | $h_1$ | $L_2$ | $W_2$ | $L_{x1}$ | $L_{y1}$ | $W_{x1}$ | $W_{y1}$ |
| Value     | 8.1   | 8.4   | 4.3   | 6.6   | 3.0   | 1.6   | 4.9   | 1.3   |
| Parameter | $L_{M1x}$ | $L_{M1y}$ | $W_{M1}$ | $W_{M2}$ |
| Value     | 7.05  | 7.55  | 1.4   | 6.08  | 1.4   |

in Figure 2c. Furthermore, the smooth conversion parts are also added between the microstrip and the input/output pads of the active chip to obtain the impedance matching between the connecting microstrip and the active chip. Finally, to implement the foregoing concept, the detailed meta-atom is designed at fundamental frequency ($f_{FF} = 5$ GHz) and second-harmonic frequency ($f_{SH} = 10$ GHz). We optimize the geometries of the meta-atom unit so as to cover the operating bandwidth of the nonlinear active chip. The detailed dimension parameters of the proposed nonlinear meta-atom are provided in Table 1.

To demonstrate our design, we perform full-wave simulations using commercial EM software ANSYS HFSS 2018. The element simulation applies periodic boundary conditions and Floquet port excitation. The input ($RF_{in}$) and output ($RF_{out}$) of the frequency multiplier are replaced by Port 2 and Port 3 (marked in Figure 2c), and the Floquet Port 1 (oblique incidence of 10°) is defined as the transmitting and receiving port of the spatial wave. Figure 3 shows the simulated scattering $S$ parameters for the proposed whole structure without the active circuit of frequency multiplier. The reflection coefficient $S_{11}$ and transmission coefficient $S_{21}$ results are illustrated in Figure 3a. It is obviously seen that the bandwidth of $S_{21}$ is 0.42 GHz (8.4%) at $-3$ dB, covering from 4.79 to 5.21 GHz, and the center frequency is 5 GHz. While for the transmission coefficient $S_{13}$ result shown in Figure 3b, the bandwidth of $S_{13}$ is 0.49 GHz (4.9%) at $-3$ dB, covering from 9.71 to 10.2 GHz, and the center frequency is 9.96 GHz. In addition, the $S_{11}$ results show that the resonant frequencies in the two bandwidths are 5 and 10 GHz with very low reflection coefficient, respectively. Therefore, the simulation results indicate that this meta-atom has the largest receiving efficiency at fundamental frequency. While the structure has the greatest radiating efficiency at second-harmonic frequency, which can transfer the most generated second-harmonic energy into the space through the transmitting antenna.

It is well known that designing a high-quality frequency multiplier is a challenging task which requires nonlinear analysis, matching at the multiplier operating point, stability analysis, and heat dissipation considerations. Compared with diode-based frequency multiplier, transistor-based, especially FET, can provide better bandwidth with lower input power, DC power, and...
higher conversion efficiency (or gain).\textsuperscript{[52]} Therefore, a FET-based x2 active frequency multiplier (ADI HMC561LP3) is employed to integrate in our meta-atom. It is a commercially GaAs monolithic microwave integrated circuit (MMIC) with a broadband input frequency range from 4 to 10.5 GHz. The related application circuit of active frequency multiplier is provided in Figure 4. To guarantee pure DC power supply, the values of decoupling capacitors (C\textsubscript{1}–C\textsubscript{6}) for the active chip are 100 pF, 100 pF, 1 nF, 1 nF, 2.2 µF, and 2.2 µF, respectively. The bottom view of nonlinear metasurface unit sample is provided in Figure 4b.

According to the function diagram of the active chip illustrated in Figure 4c, the key elements are two balanced FETs. The output characteristics of two balanced FETs are determined and tuned by the DC bias voltage $V_g$, which is connected to the gates of FETs. After the electromagnetic signal goes through the input of chip, there are two complementary signals with 180° phase difference output from the preamplifier and fed as amplified input signal to the common gates. When the bias voltage $V_g$ is with the range from $-2$ to $-1.2$ V, which is higher than the turn-on-voltage of FET, then the FET can be turned on and the obtained drain current has rich harmonic components. Under the precondition of the $V_g$ keeping the same in the work process, the final output of the chip can be calculated as follows

$$V_{SH} = A_{post}(f_{SH}) \left[ \text{func}(V_g + A_{pre}(f_{FF}) V_{in}) + \text{func}(V_g - A_{pre}(f_{FF}) V_{in}) \right]$$

in which $V_{in}$ means the input signal voltage of electromagnetic signal and $\text{func}(\cdot)$ represents the voltage response function of FET. $A_{pre}(f_{FF})$ and $A_{post}(f_{SH})$ are the transmission-spectrum functions describing the linear response of preamplifier and postamplifier in the chip, respectively. Therefore, according to Ref. [52], the conversion efficiency can be obtained with the follow equation.

$$\eta_c = \frac{P_{SH}}{P_{FF}} = \frac{V_{SH}^2}{R_L} = \frac{R_i}{R_L} \cdot \left[ A_{post}(f_{SH}) \sum_{n=1}^{\infty} \frac{\text{func}(2n)(V_g A_{pre}(f_{FF}))}{n!} V_{in}^{n-1} \right]^2$$

According to Equation (2), the conversion gain of the HMC561LP3 is estimated with 7.94 from 4 to 10.5 GHz, and we can learn that the efficiency is related with input power and DC bias voltage $V_g$.

2.2. Measurement Results and Discussion

To validate our proposed concept and design, we fabricate and measure a sample of nonlinear active metasurface composed of $6 \times 6$ meta-atoms with same parameters illustrated in Table 1, as shown in Figure 5. The sample is manufactured with the size of 200 × 200 mm\textsuperscript{2}. The bottom and top views are shown in Figures 4a and 5, respectively. The biasing networks consist of biasing wires for the DC bias voltage $V_g$ and the ones for the 5V DC power supply voltage $V_d$, which can make the active chip work appropriately. All capacitors and the active chip are embedded on the bottom layer of metasurface sample with the use of surface mount machine soldering techniques, as shown in Figure 4b. The experiments are performed in the microwave
Figure 5. Photograph of the fabricated metasurface sample (top view) and experiment setup for the power spectrum measurements of SHG in the anechoic chamber.

Figure 6. The incident wave $f_{FF}$ varies from 4.7 to 5.3 GHz with a step of 0.1 GHz, and the output intensity of the signal generator for excitation is retained at a constant level of 10 dBm. It can be observed that for each incident wave with frequency $f_{FF}$, there is a distinct peak at corresponding second-harmonic frequency $2f_{FF}$ in the reflected spectrum. The three maximum induced SHG power are identified with $-21.3$, $-21.5$, and $-21.9$ dBm at the excitation frequency of 5.1, 5.2, and 5 GHz. As a typical example, the measured frequency spectrum at $f_{FF} = 5.1$ GHz is shown in Figure 6b. We can obviously observe an output peak power at 10.2 GHz, which is the second-harmonic frequency, accompanying with a weaker gain at fundamental frequency. For the convenient quantitative analysis, the results of the reflected intensity of fundamental frequency and SHG at broadband incident frequencies are compared with ones from the copper, as illustrated in Figure 6c. The measured bandwidth of efficient SHG has good consistency with simulation. Here, a copper plate with same size is placed in the same position of metasurface sample for the comparison. The measured results suggest that the detected fundamental frequency wave intensity reflected from copper keep nearly unchanged with incident wave $f_{FF}$ varies, maintaining at a constant level of $-20$ dBm when setting the signal generator output intensity at 10 dBm.

Then, the nonlinearity of SHG varying the incident power at the oblique incident angle of 5° is measured and shown in Figure 7a. The output power of the signal generator is adjusted from 0 to 10 dBm with the step of 2 dBm, and the frequency is selected as 5, 5.1, and 5.2 GHz. The red-circle points depict the
Figure 6. Measured results of the second-harmonic metasurface generator. a) Frequency-doubled wave reflecting from the nonlinear active metasurface. The reflective SHG spectra generated with a series of $f_{ex}$ incident wave from 4.7 to 5.3 GHz. The input power of incident wave is maintained at a constant level by setting the output intensity of the signal generator as 10 dBm. For each incident excitation wave with the frequency $f_{ex}$, there is a distinct peak at the corresponding second-harmonic frequency $2f_{ex}$ in the reflected spectrum. b) Measured frequency spectra of the second-harmonic metasurface generator at the excitation frequency of 5.1 GHz. c) Results of the reflected fundamental frequency and SH powers at a series of incident $f_{ex}$, compared with the reflected fundamental frequency intensity from the copper.

measured reflected second-harmonic intensity at $f_{ex} = 5.1$ GHz. The red solid line is the corresponding fitting curve, representing the relationship between input and output intensity. Compared with the linear relationship between the measured input and output intensity of reflected fundamental frequency wave from copper, the active metasurface sample shows a significant nonlinearity at input frequency of 5.1 GHz. Simultaneously, the weaker nonlinearities are observed at $f_{ex} = 5$ and 5.2 GHz. This is mainly because in the fabricated sample, the structure has the largest receiving and radiating efficiency at 5.1 and 10.2 GHz, and has better matching with frequency multiplier, which has a little frequency offset with the simulations. We can also verify this analysis from the measured results of reflected fundamental frequency wave intensity illustrated in Figure 6c, in which a minimum fundamental power reflected from metasurface is identified at $f_{FF} = 5.1$ GHz.

Finally, the quantitative evaluation is carried out. Owing to the conversion efficiency of spatial SHG produced by proposed metasurface cannot be directly calculated by traditional equation based on the above experimental setup in Figure 5, a relative efficiency is provided for estimating the overall conversion efficiency

$$\eta_{r} = \frac{P_{SHR}}{P_{FFR}} \times 100\%$$

in which $P_{SHR}$ reflects the power of second-harmonic obtained by the receiving horn, while $P_{FFR}$ represents the power of received fundamental frequency reflected from copper under the condition of same size and input excitation power. Thus, when the incident frequency varies from 4.7 to 5.3 GHz with a step of 0.1 GHz, and the excitation power varies from 0 to 10 dBm with a step of 2 dBm, then the relative efficiency of the SHG is measured and calculated, as shown in Figure 7b. It can be observed that a peak value (pink diamond point) of $\eta_{r} = 85.11\%$ at $f_{ex} = 5.1$ GHz with input intensity of 8 dBm, where the reflected power of waves are $P_{SHR} = -22.7$ dBm and $P_{FFR} = -22$ dBm, respectively. It means that a reflective spatial second-harmonic generator with high efficiency and gain can be implemented using our proposed nonlinear active metasurface. In addition, according to the curves at $f_{ex} = 5.1$ GHz with input intensity of 10 dBm in Figure 7, the output SHG power increases, while the efficiency decreases compared with input power of 8 dBm. This is owing to the input characteristics of used active chip in each meta-atom, whose maximum input-driven power is 6 dBm. Therefore, when the input power exceeds this threshold, it will cause saturation in the output power of SHG.

The conversion performance under different oblique incidences has been measured (see the Supporting Information S1). Figure S1 (Supporting Information) demonstrates the photograph of power spectrum measurements of SHGs under different oblique incidences ($\theta = 10^\circ$, $15^\circ$, $20^\circ$, $30^\circ$) in the microwave anechoic chamber. The measured output intensities of the reflected waves at the fundamental frequency and second harmonic from the metasurface sample and copper plate at different oblique incident angles are shown in Figure 7c; and Figure S2a–c (see the Supporting Information S1). We observe that the output intensities of the reflected second-harmonic waves keep nearly stable when the incident angle varies except at $\theta = 20^\circ$. Figure 7d illustrates the calculated relative conversion efficiencies of SHGs under different oblique incidences. The red circle points
Figure 7. The nonlinearity of SHG in the proposed metasurface. a) Relationship of the measured input and output intensities of the reflected waves at the fundamental frequency and second harmonic from the proposed metasurface sample and copper plate. b) The relative conversion efficiencies of SHGs at a series of frequencies and intensities of the incident fundamental waves. c) The measured output intensities of the reflected second-harmonic waves from the metasurface sample under different oblique incidences with the excitation frequency of $f_{FF}=5.1$ GHz. d) The calculated relative conversion efficiencies of SHGs at different oblique incidences ($\theta=5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, and $30^\circ$) with the constant input power of 10 dBm.

represent the conversion efficiencies at $f_{FF}=5.1$ GHz with the input intensity of 10 dBm, where $\eta_i=74.13\%$, $75.85\%$, $83.17\%$, $144.54\%$, and $91.20\%$ for $\theta=5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, and $30^\circ$, respectively. The conversion efficiencies at $f_{FF}=5.2$ GHz also behave similar performance with the variation of incident angle. The transform efficiencies under different oblique incidences with the input powers from 0 to 8 dBm are shown in Figure S2d–h. We observe that the proposed metasurface can achieve the relative conversion efficiencies above 60% at different oblique incidences under the conditions of input excitation powers 8 and 10 dBm with the fundamental frequencies 5.1 and 5.2 GHz. Hence the same meta-atom can achieve efficient SHG conversions at multiple incident angles.

We remark that the transform efficiency has significant changes at the incident angle of $20^\circ$, as shown in Figure 7d, in which $\eta_i=144.54\%$ (red circle points) at $f_{FF}=5.1$ GHz and $\eta_i=120.22\%$ (blue triangle points) at $f_{FF}=5.2$ GHz. In order to investigate the reason for the significant change, numerical simulations are carried out. Figure 3c,d illustrates S21 and S13 results under different oblique incidences, respectively. From Figure 3c, we notice that the power transmissions from the incident wave to the input pin ($RF_{in}$) of the active chip (S21) keep nearly the same under different incident angles. However, according to the simulation results of S13 in Figure 3d, a frequency shift (the green dashed dots) occurs in the power transmissions frequency from the active chip output pin ($RF_{out}$) to the free space at $\theta=20^\circ$, which is consistent with the measurement result. Therefore, the transform efficiencies have significant changes at the incident frequencies of 5.1 and 5.2 GHz at the incident angle of $20^\circ$.

In the current experiments, a DC source is used to connect our designed metasurface sample during the measurements. In the future study, it can be replaced by the onboard power supply circuit module to make the metasurface more integrated and modular. Simultaneously, how to reduce the total cost should also be considered to enhance the application potentials and extend the application scope.

3. Conclusion

We propose a strongly nonlinear metasurface to realize the frequency multiplication of the spatial waves at the microwave frequencies. By integrating the active circuit of frequency multiplier as the bridge to link the receiving antenna and transmitting antenna and making perfect impedance matching with the active chip, a high conversion efficiency of the second harmonic is achieved. A metasurface sample with $6 \times 6$ meta-atoms is designed, fabricated, and measured. The experimental results have good agreements with numerical simulations. For the input fundamental frequency of 5.1 GHz, a maximum relative conversion efficiency of 85.11% is realized under normal incidence, which demonstrates a great nonlinear performance of our design. We also show that high conversion efficiencies of
SHGs can be achieved under different oblique incidences. It is expected that the proposed metasurface has latent abilities in spatial spectrum shifts, new EM stealth technology, and advanced radar and communication systems.

4. Experimental Section

The setup for measuring the power spectrum of SHG is shown in Figure 5. To measure the reflective spectral power distributions, two linearly polarized (LP) horn antennas were mounted on two supporting tripods. The right rectangular horn antenna (blue horn in Figure 5) working from 4.6 to 7 GHz was alternated as transmitting horn and was connected to a microwave signal generator (Agilent E8257D). While the left rectangular horn antenna (white horn in Figure 5) working from 8 to 12 GHz was receiving horn and was connected to a spectrum analyzer (Agilent E4447A). The microwave signal generator and spectrum analyzer are not shown in the picture. In order to accurately measure the reflective spectrum, the two horns were all placed as close as possible and 1.5 m away from the metasurface sample. Two DC power sources were utilized to provide voltage sources $V_g$ and $V_{f1}$ for the frequency multipliers in the metasurface. The $V_g$ for chip was set as 5 V.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

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