Design of Switchable SHG and THG using Metasurface-based Frequency Mixing System

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December 7, 2023

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Index Terms—Metasurface, second-harmonic, third-harmonic, frequency mixing

I. INTRODUCTION

Frequency mixing capabilities based on nonlinear metamaterials and metasurfaces have garnered significant attention due to their distinct advantages and promising applications in the artificial manipulation of electromagnetic (EM) waves at subwavelength scales [1]-[3]. Nonlinearity allows the second-harmonic generation (SHG) and third-harmonic generation (THG) in metasurfaces with applications spanning from source generation [4] and imaging [5],[6] to communication [7], vital signs monitoring [8], and live bioimaging [9].

At present, the efficiencies of SHG [10]-[12] and THG [13] by optical metasurface usually depend on the second-harmonic or third-harmonic nonlinearity of natural materials [14]-[16]. However, in the microwave band, the nonlinear properties mentioned above are not found in natural materials [17]. The nonlinear metamaterials with active devices have been in the microwave frequencies [18], due to the dynamic tunability and self-induced nonlinearity [19]-[21] obtained by varactor-loaded resonators. In spatial-wave SHGs and THGs domain, the space-time-coding digital metasurfaces [22] recently have attracted growing interests [23]. However, this metasurface can only generate harmonics of the modulation frequency, instead of the working frequency of the incident waves. Strongly nonlinear metasurfaces loaded with active circuits of frequency multiplier to achieve spatial-wave SHG is proposed in [24].

This letter presents a switchable SHG and THG using nonlinear metasurface-based system, able to capture, frequency mix and irradiate back an illuminating EM field at frequency $f_0$. The reflected EM field propagates at frequency $2f_0$ and $3f_0$, according to the desired order harmonic to be generated. To the best of authors’ knowledge, the switchable SHG and THG have not been reported in the microwave band, which is possible applied in harmonic radar [25] and advanced communication systems. The intensity of the reflected signals at the harmonic frequencies can be modulated for harmonic radar jamming. Both simulation and experimental results validate that the proposed system can implement two efficient frequency conversions of incident spatial waves.

II. OPERATIVE PRINCIPLE

The frequency mixing capability of the proposed metasurface-based systems is enabled by a frequency mixer.
connected to the metasurface elements via two microstrip networks. The metasurface sub-elements operating at fundamental frequency $f_0$ capture the EM field at the same frequency impinging normally to the metasurface plane. The fundamental frequency network guides the EM signal towards the mixer connected to a signal generator that can generate alternatively a continuous wave at $f_0$ or $2f_0$, such that the second or third harmonic is generated at the mixer output, respectively. Finally, the mixer output is connected to the SH/TH frequency network that guides the signal towards the metasurface sub-elements operating at $2f_0$ and $3f_0$.

As it is well known from signal theory, the mixing process is a product of signals in time-domain and a convolution of the corresponding Fourier spectra in frequency domain. In the case of SHG, the mixing between the incident wave and the signal from the signal generator realizes not only the second harmonic, but also a DC component that does not affect the operation of the metasurface, being not able to generate a propagating field. On the contrary, in the case of THG the mixing of fundamental frequency with a signal at double frequency will produce the third harmonic component, and a fundamental frequency component. However, the fundamental frequency is filtered out by the SH/TH frequency network that is highly mismatched at $f_0$. In addition, the third harmonic has a higher path loss compared to the second harmonic because of its higher frequency. These features all result in a lower generating efficiency for the third harmonic than for the second harmonic in the same setup. To compensate for the above conversion losses and suppress the undesired harmonic components, a low noise radio frequency (RF) amplifier and a filter are inserted between Port 2 and RF port (See Fig. 1) of the mixer when the sample is used to generate the third harmonic.

Therefore, the final output of SHG and THG can be calculated as follows:

$$P_{SH} = \frac{P_r(f_0)G_{am1}}{I_{loss}(2f_0)I_L(2f_0)}$$

$$P_{TH} = \frac{P_r(f_0)G_{am1}}{I_{loss}(3f_0)I_L(3f_0)} \cdot G_{am2} \cdot I_{filter}$$

where $P_{SH}$ and $P_{TH}$ represent the power of SHG and THG, respectively. $P_r(f_0)$ represents the power received by the metasurface when the fundamental frequency is $f_0 \cdot I_{loss}(f)$ represents the insertion loss of mixer at the generic frequency $f$. Similarly, $I_L(f)$ represents the insertion loss of the metasurface as a function of RF. $G_{am1}$ and $G_{am2}$ represent the gain of two RF amplifiers, respectively. $I_{filter}$ represents the insertion loss of filter, that is very small in the passband.

### III. Metasurface for Second/Third Harmonic Generation

In this section, we first describe the overall metasurface-based system in Section III-A. Then, in Sections III-B and III-C, we describe in detail the design and performances triband metasurface element and the network, respectively.

#### A. Overview of the metasurface-based system

Fig.1 shows the exploded view of the proposed tri-band metasurface with its impedance matched network. The metasurface consist of two printed circuit boards (PCBs) separated by a foam spacer and connected by copper needles. The top PCB is a three-copper-layer board with two different substrates separated by a common ground plane. The tri-band metasurface elements are printed on the top side, whereas the SH/TH frequency network on the bottom side. The substrates are made of F4B with dielectric constant $\varepsilon_r = 2.65$ and loss tangent $\tan \delta = 0.02$, and Rogers RT5880 with dielectric constant $\varepsilon_r = 2.2$ and loss tangent $\tan \delta = 0.009$, respectively. On the contrary, the bottom PCB is a two-copper-layer board with substrate Rogers RT5880. The top side is left as ground plane, whereas the fundamental frequency network is printed on the bottom side. With reference to Fig. 1, the thicknesses of four substrates are: $h_1 = 3\text{mm}, h_2 = 0.5\text{mm}, h_3 = 3.5\text{mm}, h_4 = 0.5\text{mm}$. The fundamental frequency network collects the signals from the metasurface elements and makes it available at the port 1 (see Fig. 1), that in turn is connected to the intermediate frequency (IF) port of mixer module DC2310A ($I_{loss}(f)$ are about 8 dB at 6 GHz and 10 dB at 9 GHz) using the chip LTC5549 [26]. Such a mixer also receives the signal from the local oscillator (LO) port to be frequency mixed with the ones collected by the metasurface. The second/third harmonic signal in output from the RF port are forwarded towards the metasurface elements via the SH/TH frequency network accessible thanks port 2 (see Fig.1). There is a power amplifier ($G_{am1}$ is about 25 dB) between port 1 and mixer to increase frequency conversion efficiencies. In case of THG, we add a low noise amplifier ($G_{am2}$ is about 15 dB) and a filter ($I_{filter}$ are about 0.6 dB at 8-13 GHz and above 10dB at 2-7 GHz) between RF port and port 2.

#### B. Triband metasurface Element

The proposed triband metasurface element is shown in Fig. 2(a). The square sub-element is designed to operate at $f_0$ when a y-polarized incident wave impinges in normal direction, i.e., negative z-direction. It is connected to the fundamental frequency network by a metal via-hole through the ground. The two circle sub-elements are designed to operate at $2f_0, 3f_0$, and connected to the SH/TH frequency network by another metal via-hole through the ground. The design dimensions of the metasurface element are reported in Table I.

Here we first compute the performances of the triband metasurface element in stand-alone configuration (i.e., without the networks). We use two 50-ohm lumped ports, identified as Port A and Port B in Fig. 2(a), directly connected to the sub-elements by the via-holes. A Floquet port (Port C) is defined as the port for the propagating EM field (see Fig. 2(a)). The numerically computed performances of the proposed triband metasurface element in terms of scattering parameters are reported in Fig. 2(b)-(d). Specifically, Fig. 2(b) reports the...
scattering parameters $S_{AC}$, $S_{CB}$, i.e., a measure of the ability of the element to capture the illuminating field at $f_0$ and to radiate the fields at $2f_0$, $3f_0$, respectively, under normal incidence illumination condition. The -3dB-bandwidth of $S_{AC}$ is 0.98 GHz (33.7%), covering from 2.45 to 3.43 GHz, and the center frequency is 2.91 GHz. The $S_{CB}$ exhibits two operative bands: the first one extends for 1.18 GHz (19.9%), covering from 5.35 to 6.56 GHz, and the center frequency is 5.94 GHz, and the second one for 0.67 GHz (7.7%), covering from 8.23 to 8.9 GHz, and the center frequency of 8.74 GHz.

C. Design of the metasurface networks

The fundamental frequency network and the SH/TH frequency network are shown in Fig. 3(a) and Fig. 3(b), respectively. All dimensions in Fig. 3 are in mm. Besides, the dimensions of vias and clearance holes are 0.6mm and 1.2mm, respectively. To match the networks to the corresponding metasurface sub-elements, single-section and two-section quarter wave impedance transformer is embedded in the network [27], to achieve the necessary 50 $\Omega$ impedance matching condition.

The two networks have been designed separately and then combined with 64 (8x8) metasurface elements to realize the frequency mixing metasurface shown in Fig. 1. The numerical simulations have been performed connecting two waveguide ports at Port 1 and Port 2 of the fundamental frequency and SH/TH frequency networks, respectively, and again a Floquet port (named now Port 3) for the propagating EM field.

The simulation results are shown in Fig. 4. The presence of the network affects the original performances of the metasurface elements, slightly red-shifting the operating frequencies. The simulation results indicate that the highest capturing efficiency within the fundamental bandwidth is now at $f_0 = 2.9$ GHz, whereas the highest radiating efficiencies are achieved at 5.8 GHz (SH frequency) and 8.7 GHz (TH frequency). The scattering parameters at these frequencies are about -1.41 dB, -2.34 dB and -3.32 dB, respectively.

Moreover, the scattering parameters $S_{AC}$ and $S_{CB}$ with different angles of illuminations on the azimuthal plane ($x$-$z$ plane), i.e., TE illumination, within the angular range $\pm 20^\circ$ have been computed, and reported in Fig. 2(c)-(d) (for symmetry the metasurface exhibit similar performances for negative angles). The results indicate that $S_{AC}$, $S_{CB}$ are little affected by the incidence angle, especially at the fundamental and second harmonic operative bands. On the contrary, within the third harmonic band, $S_{CB}$ for $\theta = 20^\circ$ is reduced up to 1.3 dB relative to the normal incidence case.

The simulation results indicate that the metasurface element has the highest capturing efficiency within the fundamental bandwidth at $f_0 = 2.95$ GHz, and the highest radiating efficiency at 5.9 GHz and 8.85 GHz, that corresponds to the SH/TH frequencies.

### TABLE I

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The proposed triband metasurface is fabricated, it consists of 64 metasurface elements with an overall surface of $432 \times 224$ mm$^2$. A photograph of the fabricated sample and the measurement setup of testing the SHG/THG capabilities are shown in Fig. 5.

Before testing the SHG/THG capabilities, we have measured the realized gain of metasurface using the gain-comparison method. Three sets of measurements are performed. In set-1, we connect one of the two VNA ports to the metasurface (Port 1),
and another port to RX horn antenna (Port 4) placed in front of the metasurface and. In set-2, we connect one port to the metasurface (Port 2), and another port to RX horn antenna (Port 4). In set-3, we connect one port to TX horn (Port 3), and another port to RX horn (Port 4). In above sets, we measured the amplitude of $S_{11}, S_{21}$ and $S_{41}$, respectively. Then, according to the gain standard of horn antennas which operate with a bandwidth of 1-12 GHz and have a gain of 6-15 dBi, we get the realized gain of metasurface as shown in Fig. 6. The gain excited by Port 1 (red line) indicates the capability of the metasurface to capture the signal at the fundamental frequency, and the gain excited by Port 2 (blue line) indicates indicating the capability of the metasurface to radiate the signal at the SH/TH frequencies. We can observe that the gain of the sample excited by Port 1 is above 23 dBi in the frequency range of 2.6 to 3.45 GHz, and the gain of the sample excited by Port 2 is above 23.9 dBi in the frequency range of 5.58 to 7.08 GHz and above 22 dBi in the frequency range of 8.5 to 9.14 GHz. The results indicate that the sample have a good ability to capture the signal at the fundamental frequency and radiate the signal at the SH/TH frequencies.

![Fig. 5. (a) Photograph of the fabricated metasurface. (b) Measurement setup of testing the SHG/THG capabilities.](image)

Fig. 6. The measured gain of metasurface sample using gain-comparison method.

The capability to generate the second/third harmonic for spatial wave has been first experimentally verified under normal incidence. The measured results are reported in Fig. 7(a)–(b), where the power of the second and third harmonic is received by the RX horn antenna when the TX horn antenna is radiating a monochromatic EM field at different fundamental frequencies, ranging from 2.7 to 3.3 GHz with a step of 0.1 GHz. During the measurements, the output intensity of the VNA feeding the TX horn and the signal generator for LO port of mixer is set at a constant level of 0 dBm. In addition, the reflected spectrum of isometrical copper under the same conditions is added as a comparison in Fig. 7. In Fig. 7(a), it can be seen that there is an obvious peak in the amplitude of the second harmonic when the frequency of the incident plane wave is 3 GHz. The same response is also observed in Fig. 7(b) for the third harmonic. The fully operativity of the metasurface as frequency mixing system is demonstrated by the minimum value of fundamental frequency reflected by metasurface at 3 GHz. We observe a little frequency offset with respect to the simulated results in Sec III, which is primarily due to the fabrication imperfection of the metasurface sample.

Two relative efficiencies are defined for estimating the overall conversion efficiency: $\eta_{sh} = P_{sh}/P_0$ and $\eta_{th} = P_{th}/P_0$, where $P_{sh}$ and $P_{th}$ are the received powers of second-harmonic and third-harmonic at the RX horn terminals, respectively, and $P_0$ is a reference received power obtained considering a copper plate in substitution to the metasurface and of same size. The measured efficiencies are $\eta_{sh} = 55.5\%$ and $\eta_{th} = 42.6\%$ for illumination at $f_0 = 3$ GHz with input intensity of 0 dBm, where the reflected power of waves are $P_{sh} = -42.66$ dBm, $P_{th} = -43.81$ dBm and $P_0 = -40.1$ dBm, respectively. Then the reflective SHG and THG intensity with different oblique incidences at $f_0 = 3$ GHz is measured and shown in Fig. 7(c) and Fig. 7(d). It is observed that $P_{sh}$, $P_{th}$ and $P_0$ decreases as the incidence angle increases. Compared with [24], although the efficiency of SHG is slightly lower, the design of switchable SHG and THG has a wider application prospect.

![Fig. 7. Measured results of the switchable SHG and THG. (a) SH powers and (b) TH powers at a series of incident $\theta$. (c) SH powers and (d) TH powers with different oblique incidences of $\theta = 5^\circ, 10^\circ, 15^\circ$ and $20^\circ$, respectively.](image)

**V. CONCLUSION**

A metasurface-based frequency mixing system is proposed to realize switchable SHG and THG of the spatial waves at the microwave frequencies through the mixing scheme in this letter. A metasurface sample with designed elements and microwave networks is fabricated and measured. The experimental results have good agreements with numerical simulations. For the input fundamental frequency of 3 GHz, two relative conversion efficiencies of 55.5% and 42.6% are realized under normal incidence. The feature of switchable
second and third harmonic generation of proposed metasurface make it a good application prospect in spatial spectrum shifts, EM stealth and deception technology.

REFERENCES