Reflective FSS and an On-Air Frequency Mixer

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Abstract

In this paper a multi-functional metasurface is proposed which can work as a narrowband transmissive/reflective frequency selective surface (FSS) and an on-air frequency mixer based on its switching response. The metasurface is made up of unit cells with square and circular metallic loops connected by PIN diodes that are controlled by a biasing source. In contrast to typical wideband FSSs, the structure provides 0.55 GHz of narrow stopband (a fractional bandwidth of 22\%) at 2 GHz in the OFF state bias. The bandstop response can be adjusted by varying the reverse bias voltage. The metasurface alternates between its functionalities when in forward bias by providing a passband at the operational frequency. The structure is compact and operates as a transmissive/reflective surface under two different bias conditions (ON and OFF). The design is angularly stable and polarization-insensitive for both TE and TM polarisation. A prototype of the designed structure is developed and the measured results correlate well with the simulated responses. On-air frequency mixing for a wave propagating through the metasurface is experimentally demonstrated and effects of different parameters affecting the mixing are parametrically studied.
Multi-functional Metasurface as a Transmissive/Reflective FSS and an On-Air Frequency Mixer

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Index Terms—FSS, Metasurface, Mixer

I. INTRODUCTION

With the fast growth of wireless technology, the issue of electromagnetic interference (EMI) among neighboring electronic gadgets and electrical machinery in sensitive surroundings has emerged [1]. An FSS may be widely used to conceal such components and is an excellent solution for many applications because of its low cost, small profile, and ease of production. Furthermore, FSS can provide band-pass or band-stop responses and these structures are frequently used in microwave and millimeter-wave regimes as spatial filters, antenna reflectors, radomes, absorbers, artificial magnetic conductors, etc [2]. Reducing interference and wireless security between neighboring wireless local area networks (WLAN) have been the focus of extensive research in recent years [3], [4], [5].

Active FSSs, which can function as reflective and transmissive surfaces using diodes [6]–[8], have been recently developed to provide switchable frequency response. The frequency response can be varied with the control of the active devices incorporated into the periodic arrays. Active components, such as varactors and PIN diodes, enable high-speed and wideband tuning in a compact and low-cost package. The structure reported in [6] can function in various modes but is polarization-sensitive. In [7], an adjustable absorber is reported, but the structure has multiple layers. In [8], the structure operates in different states, but the structure is time-invariant. Varactor-driven adjustable structures have recently become popular in offering shielding and polarization-insensitive behaviors [9], [10]. However, in [9], the structure is complicated since it calls for layer modifications based on the type of application, and the structure in [10] is solely addressed for its shielding behavior. Therefore, it is necessary to develop a single structure without much complexity to achieve multiple functions such as various states (transmissive + reflective) as well as polarization insensitivity.

Metasurfaces are two-dimensional metamaterials that are artificially engineered to offer unique electromagnetic properties ("Meta" = beyond) [11], [12]. Time-engineered metamaterials/metasurfaces are metamaterials/metasurfaces whose constitutive parameters such as permittivity ($\epsilon$), permeability ($\mu$) or conductivity ($\sigma$) vary as a function of time [13]–[15]. The introduction of time-variation of media can lead to frequency translation and discrimination [16], [17], frequency mixing [15], [18] and non-reciprocity [19]. In [20], an analysis of a free-space N-path-modulated metasurface is presented. In [21], linear frequency conversion is demonstrated, and in [22], a serrodyne frequency translation is proposed using a time-modulated metasurface. Time-modulated metasurfaces have been proposed for electromagnetic cloaking and defense applications, such as, in [23], a time-modulated metasurface partially covering the targets is used to jam inverse synthetic aperture radar (ISAR) imaging and a target recognition based on Pseudorandom Noise sequence time-modulated metasurfaces in [24] and phase-induced frequency conversion and Doppler effect with time-modulated metasurface in [25]. The works in [23], [24], [24], [25] are based on reflective structure, while the works in [21], [22] are transmissive surfaces.

In this paper, the authors have aimed to address some of the above-mentioned limitations by developing a single metasurface that can offer different functionalities based on its bias state. Fig. 1 illustrates the multiple functions the metasurface performs under different bias conditions. The proposed structure’s design is inspired by the work presented in [10], where the unit cell has been modified, and the varactors are replaced by PIN diodes. The proposed multi-functional metasurface was fabricated and successfully tested.
The proposed structure offers the following improvements over the earlier proposed FSSs:

- The proposed metasurface is simple in its design and easy of operation.
- It can function as a switchable transmission/reflection surface at the desired frequency.
- The structure offers an attenuation of more than 30 dB for a stop band of 0.55 GHz (22 % bandwidth), demonstrating its narrowband operation and tunability under different reverse bias voltages.
- The design exhibits fourfold symmetry, providing tunable characteristics for all polarization angles.
- The structure works as an on-air frequency mixer. An incident wave propagating through the metasurface undergoes frequency mixing with the modulating frequency of the metasurface.

The paper is organized as follows. Section II describes the design of the proposed structure. Section III presents the simulations and parametric analysis. In Section IV, the fabricated prototype of the metasurface and its measurement results are discussed. Section V discusses the designed metasurface structure for frequency mixing applications. Finally, the conclusion is presented in the last section.

II. METASURFACE STRUCTURE DESIGN

The metasurface structure is intended to function as a transmissive/reflective surface at 2 GHz. Designing the structure’s OFF state model at a frequency lower than 2 GHz can increase the structure’s tuning range as the switches employed are the BAP64-03 Silicon PIN diodes, from NXP Semiconductors, which can operate up to 3 GHz [26]. These diodes possess variable capacitance and resistance under reverse and forward voltages, respectively. Whenever the reverse bias of the PIN diode rises, the intrinsic layer’s depletion region widens, and the diode’s capacitance decreases due to which the frequency of operation increases.

Fig. 2 shows the array and unit cell shapes of the proposed multipurpose metasurface. A metallic square and circular loop design is printed in a regular pattern on a dielectric substrate for the top layer. Semiconductor switches that are diagonally arranged connect both square and circular loops. The dielectric substrate is FR4, with a relative permittivity ($\epsilon_r$) 4.4 and a loss tangent (tanδ) of 0.02. The top metallic patch is made of copper, with a conductivity of $5.8 \times 10^7$ S/m and a thickness of 0.035 mm. The unit cell for the optimally designed structure has geometrical dimensions: $l = 54$ mm, $a = 11$ mm, $r = 5.5$ mm, $w_1 = w_2 = 1.2$ mm, $g = 2$ mm, and $t = 1$ mm. The incident field directions are also shown in Fig. 2. The operating frequency of the unit cell is controlled by the cell size ($l = 54$ mm, inter-spacing between the loops) and the size of the loops (both $a$ and $r$). The frequency ($\lambda_g$) of reflection or absorption by an FSS relies on the perimeter of patch loops in such a way that $\lambda_g = 2\pi r$ (or $4a$), where $r$ is the radius of the circular loop and $a$ is the side of the square loop. The gap ($g = 2$ mm) is for placing the diode. In the absence of diodes, the air in this gap provides a low capacitance, which causes the structure to resonate at higher frequencies. The capacitance between the loops is varied by incorporating the PIN diodes in the gaps, which can offer lower capacitance ($\ll 1$ pF). The required resonant frequency of 2 GHz is attained by optimizing the above parameters.

III. SIMULATED RESULTS AND PARAMETRIC ANALYSIS

The unit cell of the proposed structure is modeled using periodic boundary conditions in the CST Microwave Studio. The following subsections provide more details on the different simulation outcomes based on various configurations.

A. Metasurface in the OFF state

The structure is simulated in the OFF state of the PIN diode, i.e., at ‘0 volt’ of biasing. The PIN diode offers a capacitance of 0.147 pF, found through characterization.

The transmission and reflection coefficients are shown in Fig. 3 and 4, respectively. The structure provides a stopband of 0.55 GHz, which is 22.22 % w.r.t. center frequency with a 10 dB attenuation level for the various reverse voltages. $|S_{21}|$ is observed to be nearly -40 dB at the operating frequency, which can be tuned by varying the reverse bias voltage.

Shielding effectiveness (SE), defined as the ratio of the transmitted field component ($E_t$) to the incident field component ($E_i$), can be used to assess the performance of a bandstop FSS suggested for shielding applications [1]. It is represented by

$$SE_{dB} = -20 \times \log \left( \frac{E_t}{E_i} \right) \quad (1)$$

Fig. 1. Illustration of multi-functionality of the proposed metasurface.

Fig. 2. Schematic diagram of the proposed switchable metasurface prototype (a) Perspective view, (b) Side view and (c) Top view of the unit cell.
The SE of the suggested structure is also shown in Fig. 5, demonstrating that at least 30 dB SE is attained by tuning the reverse bias voltage.

The proposed structure has a fourfold symmetrical design which makes it polarisation insensitive, i.e., it shows equal SE performance for all polarisation angles, as shown in Fig. 6.

The proposed metasurface is further examined for various oblique incidences of TE and TM polarisations. Fig. 7 and 8 show the SE for the TE and TM polarisations of the incident wave, respectively, demonstrating consistent stopband frequency responses up to 60° angle of incidence.

When an EM wave is incident on the top layer, the surface current flowing through the structure creates the equivalent inductance, and the diode provides inductance and capacitance, which together produce the resonance [2]. The capacitance value changes with the reverse bias, and the resonance frequency tunes within a particular frequency band. Frequency tuning can be observed in Fig. 3, as the reverse voltage increases from 0 to 4 V, the capacitance decreases, and the resonance frequency shifts from 2 to 2.2 GHz.

**B. Metasurface in the ON state**

The structure is simulated in the ON state of the PIN diode, i.e., at ‘1 volt’ of biasing, where the PIN diode has a resistance of 20 Ω as measured by characterization in the forward bias of the diode.
In Fig. 9, the corresponding transmission coefficient is presented, and at the targeted frequency of 2 GHz, the proposed metasurface achieves a transmission coefficient of about -1.8 dB. The PIN diode functions as a variable resistor, with the resistance inversely proportional to the forward bias voltage across the PIN diode.

IV. Prototype Fabrication and Measurement Results

The proposed metasurface, as stated in Section II, is fabricated and tested. DC biasing lines are introduced in the structure to control the biasing states of PIN diodes, as shown in Fig. 10. The structure has physical dimensions of 290 mm × 275 mm, which consists of 4 × 4 arrays of unit cells. The measurement result shows that the structure operates at 2 GHz, slightly deviating from the simulation results, which can be accounted for by fabrication tolerance.

Circular loops at the outer edges of the unit cell are connected to the left-side bias line, whereas square loops in the unit cell’s center are connected to the right-side bias line. PIN diode’s anodes and cathodes are connected to the right and left bias lines by connecting them across the diagonal gap between the loops. Murata Electronics LQG18HH10N00D inductors with 10 nH values are used in consecutive central square loops to achieve isolation and protect the biasing lines from EM interference. Bias lines allow direct current to flow continuously through PIN diodes. The resultant capacitance of the diodes about the DC bias voltage thus varies, leading to adjustable bandstop performance.

The measurement setup is shown in Fig. 11. It is organized by placing the testing structure between the two Vivaldi antennas facing each other. The metasurface is kept at the far field distance of the transmitting antenna. Both antennas are connected to the Vector Network Analyzer to estimate the structure’s reflection/transmission coefficient. At 2 GHz, when there is no obstruction, the power transmitted between the antennas is -31 dB from Fig. 12, which is close to the calculated value using the Friis Transmission formula.

The transmission coefficients are measured between the antenna system in the subsequent steps under various configurations of the metasurface, shown in 12. The transmission coefficient of the metasurface is first determined in its OFF state. It is observed that the transmission coefficient is -62 dB at the desired frequency. It should be noted that the attenuation level is 30 dB, which is in agreement with the simulated results.

The shielding performance can be tuned to higher frequencies
by varying the reverse bias voltage, as shown in Fig. 12. Shifting of shielding resonance to 2.06 GHz can be observed by applying a reverse bias voltage of 1 volt to the structure. Therefore, from the above observations, the structure is best suited for shielding applications in the open air at and above 2 GHz. Fabrication tolerances, parasitic capacitance, and inductance effects of PIN diodes account for the minor measurement discrepancies.

The metasurface’s ON state performance is measured at 2 GHz using the same approach as the OFF state, except that forward biasing is introduced into the structure. As seen in Fig. 12, the transmission coefficient is observed to be -33 dB. An attenuation of less than 2 dB is observed. This demonstrates the transmissive nature of the proposed structure.

Therefore, the proposed structure performs a good switching response at 2 GHz in both ON and OFF states. Hence, the proposed metasurface works as an active transmissive/reflective FSS at 2 GHz and above.

V. TIME-MODULATED METASURFACE FOR ON-AIR FREQUENCY MIXING

The proposed metasurface performs on-air frequency mixing when the metasurface is modulated with time. Fig. 13 depicts frequency mixing where the incident wave of frequency $f_i$ is modulated by the metasurface operating at $f_m$. The reflected and transmitted waves contain new frequency components at $f_i \pm nf_m$ where $n = 1, 2, 3, \text{ and so on.}$

The variation of capacitance offered by the PIN diodes with time varies the surface impedance ($\eta_m$) of the metasurface with time, leading to a time-varying reflection coefficient ($\Gamma_m$) at the metasurface.

$$C_d \rightarrow C_d(t) \implies \eta_m \rightarrow \eta_r(t)$$

$$\implies \Gamma_m \rightarrow \Gamma_m(t) = \bar{f}_t\{\eta_r(t)\}$$

$$& T_m \rightarrow T_m(t) = \bar{f}_t\{\eta_r(t)\}$$

Then the transmitted wave is given by

$$E_t(z, t) = \bar{f}_t\{T_m(t), E_i(z, t)\}.$$  \hfill (5)

Moving to the frequency domain, we get

$$E_t(z, t) \xrightarrow{\text{Fourier Transform}} E_t(z, \omega)$$ \hfill (6)

Hence, (6) suggests that we will observe frequency mixing between the incident wave and the metasurface modulation frequency.

A. Measurement setup and results

Fig. 14 shows the measurement setup for demonstration of on-air mixing in an indoor scenario. A signal source from LibreVNA operating at $f_i$ is connected to antenna 1. The metasurface is biased using a Sigilent Function Generator to provide a modulating bias signal of bias voltage $V_B$ at frequency $f_m$. The receiver antenna 2 is connected to a Tektronix Real-time Spectrum Analyser. The metasurface is placed in the far field of the transmitting antenna for plane wave incidence while the receiving antenna is placed closer to the metasurface to reduce path loss in the measurement setup.

The frequency of the incident wave ($f_i$) on the metasurface is 2.4 GHz, and the spectrum of the received signal is shown in Fig. 15 when the modulation frequency of the metasurface $f_m$ was maintained at 10 MHz. The bias voltage $V_B$ of the metasurface is 2 Vpp, and the power of the incident wave at the source is 0 dBm.

B. Parametric Analysis

The on-air frequency mixing using time-modulated metasurface demonstrated in Fig. 15 is further analyzed using square wave and sinusoidal modulation of the metasurface via parametric analysis of the following parameters:

1) Variation of duty cycle (DC): For modulation of metasurface via a square wave of frequency 5 MHz, the duty cycle of the wave was varied from 25% to 75%, thereby varying the transmission to blocking duration ratio. It is observed that the power of the received wave at incident frequency 2 GHz...
increases with an increase in the duty cycle as ON-state favors transmission, but the power in the modulated peaks initially increases with the duty cycle, achieving a maximum around 50-60% and then decrease with further increase in duty cycle.

Fig. 16. Spectrum for the received signal for variation of duty cycle (DC).

2) **Variation of incident frequency** \((f_i)\): The frequency of the incident wave \(f_i\) on the metasurface was varied, keeping \(f_m = 10\, \text{MHz}\), \(V_B = 2\, \text{V}_{pp}\) and transmitted power at the incident frequency \(|P(f_i)| = 0\, \text{dBm}\) and the spectrum of the received signal is shown in Fig. 17. It is observed that the newly generated frequencies correspond to \(f_i \pm nf_m\), and the power at the incident frequency \(f_i\) is minimum near the resonance of the metasurface while the power at the new modulated frequencies does not vary with the change of \(f_i\).

Fig. 17. Spectrum for the received signal for variation of incident frequency \((f_i)\).

3) **Variation of metasurface modulation frequency** \((f_m)\): Similarly, the metasurface modulation frequency \(f_m\) was varied keeping \(f_i = 2.4\, \text{GHz}\), \(|P(f_i)| = 0\, \text{dBm}\) and \(V_B = 2\, \text{V}_{pp}\). It is observed that the newly generated frequencies correspond to \(f_i \pm nf_m\), where \(n = 1, 2, 3, \ldots\) and the power in the new frequencies and their harmonics decrease as we move away from \(f_i\). It was also observed that in the case of modulation of metasurface via square wave, the power received at the incident frequency \(f_i\) decreases with an increase in modulation frequency \(f_m\) while for a sinusoidal modulation, it showed negligible variation as shown in Fig. 19.

Fig. 18. Spectrum for the received signal for variation of metasurface modulation frequency \((f_m)\).

Fig. 19. Comparison of square modulation v/s sinusoidal variation of modulating signal \((f_m)\).

4) **Variation of metasurface bias voltage** \((V_B)\): The amplitude of the biasing voltage \(V_B\) of the metasurface at frequency \(f_m\) was varied. The variation of bias voltage affects the range of impedance change (\(\eta_{m2}/\eta_{m1}\)) offered by the metasurface, where \(\eta_{m1}\) is the minimum surface impedance while \(\eta_{m2}\) is the maximum. From Fig. 20, it is observed that with an increase in \(V_B\) the received power at the newly generated frequencies \(f_i \pm f_m\) increases rapidly initially and then gradually saturates, while power at \(f_i\) remains almost constant.

5) **Variation of power of incident frequency** \(|P(f_i)|\): Fig. 21 shows the plot for variation of received power at \(f_i = 2.4\, \text{GHz}\), \(f_i - f_m = 2.31\, \text{GHz}\) and \(f_i + f_m = 2.41\, \text{GHz}\) with the power of incident wave at \(f_i\) at the source. The power at the source was varied from -20 \(\text{dBm}\) to 0 \(\text{dBm}\) while keeping \(V_B = 2\, \text{V}_{pp}\). It is observed that power at \(f_i\) and \(f_i \pm f_m\) vary linearly with the increase in incident power.

VI. CONCLUSION

This work proposes an active multifunctional metasurface with a tuneable narrowband reflective/transmissive response
TABLE I
COMPARISON OF PROPOSED METASURFACE WITH RECENT LITERATURE

<table>
<thead>
<tr>
<th>Reference</th>
<th>Operating Frequency (in GHz)</th>
<th>Mode</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>[21]</td>
<td>2.3, 3.3, and 5</td>
<td>Transmissive</td>
<td>Spurious-free and linear frequency-conversion</td>
</tr>
<tr>
<td>[20]</td>
<td>10</td>
<td>Reflective</td>
<td>Analysis of a free-space N-path-modulated metasurface</td>
</tr>
<tr>
<td>[23]</td>
<td>10</td>
<td>Reflective</td>
<td>Jamming of inverse synthetic aperture radar (ISAR) imaging with time-modulated metasurface partially covered on targets</td>
</tr>
<tr>
<td>[24]</td>
<td>2.4</td>
<td>Reflective</td>
<td>Target recognition based on Pseudorandom Noise sequence time-modulated metasurfaces</td>
</tr>
<tr>
<td>[22]</td>
<td>10</td>
<td>Transmissive</td>
<td>Serrodyne frequency translator</td>
</tr>
<tr>
<td>[25]</td>
<td>1.5</td>
<td>Reflective</td>
<td>Phase-induced frequency conversion and Doppler effect</td>
</tr>
<tr>
<td>This work</td>
<td>2</td>
<td>Reflective + Transmissive</td>
<td>Narrowband transmissive/reflective FSS and on-air frequency mixing</td>
</tr>
</tbody>
</table>

Fig. 20. Received signal power v/s metasurface bias voltage ($V_B$) at incident frequency ($f_i$) and achieved modulated frequencies ($f_i \pm f_m$).

Fig. 21. Received signal power v/s Incident power on the metasurface bias voltage ($P_{in}$) at incident frequency ($f_i$) and achieved modulated frequencies ($f_i \pm f_m$).

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and demonstrates on-air frequency mixing. The proposed metasurface prototypes are fabricated and tested. The simulated and measured results show that the metasurface has a switchable performance between nearly transparent and total reflection. Furthermore, the reported reflective/transmissive surface demonstrated narrowband absorption with a -10 dB bandwidth of up to 0.55 GHz in the vicinity of 2 GHz. The structure suggested can provide a wide tuning range for similar bandstop responsiveness as a function of reverse bias voltage. Furthermore, the structure has the advantages of reduced geometry, polarisation insensitivity, and angular stability. Also, obtaining a significant degree of agreement between simulation and experimental results. The concept has been expanded to demonstrate on-air frequency mixing. Additionally, the effect of parameters such as incident frequency, metasurface modulation frequency, bias voltage, and incident power on the frequency mixing have been analyzed via parametric study. To the authors’ knowledge, no singular structure demonstrating multi-mode operation as an electromagnetically transparent, opaque, and on-air frequency mixer using a transmissive-type metasurface has been reported in the literature.


