Design of In-phase and Quadrature Two Paths Space-Time-Modulated Metasurfaces

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Abstract—Space-time-modulated metasurfaces can manipulate electromagnetic waves in space and frequency domain simultaneously. In this paper, an analytical design of space-time-modulated metasurfaces with modulation elements composed of two paths, In-phase (I) and Quadrature (Q), is proposed. The model is derived analytically, the space/frequency domain manipulations are achieved by designing the dimension and time sequence of I and Q paths. In the specular reflection direction, an objective frequency shift of the reflected first order harmonic can be obtained. While, in other directions, the opposite first order harmonic can be easily controlled by changing the dimension of I/Q paths and the objective first order harmonic remains unchanged. Furthermore, with a small dimension of I/Q paths, the first order harmonic can be used for beam scanning by pre-designing the start time of the modulation element. To realize the space-time-modulated metasurface with the required periodically time-varying responses, 2-bit unit-cells loaded with dynamically switchable pin diodes are employed as I/Q modulation. Both analytical and numerical results demonstrate that space and frequency domain manipulations of the reflected fields by the first order harmonics can be simultaneously obtained. The proposed designs have potential applications in wireless communications, radar camouflaging, and cloaking.

Index Terms—Metasurfaces, space-time modulation, analytical design.

I. INTRODUCTION

METASURFACES have obtained a great attraction for the manipulation of electromagnetic waves, due to their low cost fabrication and thin profile [1]-[3]. They have been widely used for numerous applications, such as beam steering

[4]-[7], absorption [8]-[10], focusing [11][13], imaging [14]-[17], etc. To achieve manipulation of the incident electromagnetic fields in the space domain [18]-[20], the design of the reflection/transmission responses of the metasurface at the frequencies of interest are required, and the responses do not change in time. Recently, dynamically reconfigurable metasurfaces can be achieved by using pin diodes [21], [22], varactors [23]-[25], MEMS [26], graphene [27], liquid crystal [28], etc.

To achieve the frequency modulation of the electromagnetic field interacting with a metasurface, the response of the metasurface itself must change in time. A time-modulated reflective metasurface producing a frequency shift with respect to the impinging radiation is proposed in [29]: the reflection phase of the whole metasurface changes linearly with time and an artificial Doppler effect for a non-moving electrically thin structure is realized. In [30], [31] and [32], 2-bit and 3-bit time varying phases are employed to match the linear phase change, respectively, and a frequency shift can be induced for different higher order harmonics. In [33], a transparent, time-modulated metasurface, which functions as a serrodyne frequency translator, is reported at X-band frequencies. With a simple biasing architecture, the metasurface provides electrically tunable transmission phase that covers 360° . A sawtooth waveform is used to modulate the metasurface, allowing Doppler-like frequency translation. In [34], time modulation engineered asymmetric photonic band gaps are proposed to generate optical isolation.

To manipulate the electromagnetic field in both space and frequency domains, digital space-time-coding metasurfaces have been proposed in [35]. In this case, the equivalent reflection amplitude A^m and phase ψ^m of the metasurface in frequency domain for the m th order harmonic frequency $\omega_c + m\omega_0$ is derived, and a binary particle swarm optimization (BPSO) algorithm is applied to design the space-time-coding sequences. In [36], joint multi-order harmonic manipulations based on optimization algorithm is proposed, which leads to much more sophisticated space-time coding. In [37], an N -path space-time-modulated metasurface is proposed to manipulate the first order harmonics in space domain using the time delay of each modulation path. The resulting space-time modulated metasurfaces exhibit unprecedented capabilities and may find applications in different operative scenarios, such as non-reciprocal structures [38]-[42], arbitrary multi-bit programmable metasurfaces [43], wireless communications [44]-[49], spread-spectrum radar camouflaging [50], etc.

Differently from using algorithms to optimize time sequence and space arrangement, in this paper, inspired by the concept of time-modulated phased arrays [51], an analytical design model

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for space-time-modulated metasurfaces with modulation elements composed of two paths, In-phase (I) and Quadrature-phase (Q), is proposed. Using this analytical model, the first order harmonics can be manipulated by designing the dimension and the time sequence of the I/Q paths. In the specular reflection direction, an objective frequency shift of the reflected first order harmonic can be obtained. Furthermore, with a small dimension of the I/Q paths, the first order harmonic can be used for beam scanning by pre-designing the start time of the modulation element. In non-specular directions, the opposite first order harmonic is manipulated by changing the dimension of the I/Q paths, keeping the objective first order harmonic unchanged.

An actual implementation of the I and Q two paths space-time-modulated metasurface is also proposed, making use of a 2-bit unit-cell exhibiting properly designed time-varying phases as I/Q modulation that can be dynamically switched by using pin diodes. Both analytical and numerical results demonstrate that the space and time modulation of the incident electromagnetic field can be accurately and effectively achieved with the proposed I/Q two paths space-time modulated metasurface.

Fig. 1. Geometrical sketch of a metasurface with modulation elements composed of I/Q two paths. The structure can manipulate the opposite first order harmonic (-1 or +1) by changing the dimension of the I/Q paths whilst the objective first order harmonic (+1 or -1) remains unchanged. The time sequences of the I/Q path of the n th modulation element are indicated as $I_n(t)$ and $Q_n(t)$, respectively, while the time sequences of the unit-cells for each of the two paths are $i_n(t)$ and $q_n(t)$, respectively.

The paper is organized as follows. In Sec. II, we derive the analytical model to design the I/Q space-time-modulated metasurface. In Sec. III, we present the implementation of the I/Q space-time-modulated metasurface through 2-bit unit-cells exhibiting the required periodically time-varying phases. In Sec. IV, we present the simulation results to verify the effectiveness of the proposed design of the I/Q space-time-modulated metasurface. Finally, in Sec. V, we briefly draw the conclusions of our work.

II. ANALYTICAL I/Q TWO PATH SPACE-TIME-MODULATED METASURFACE DESIGN

A. Background of I/Q space-time-modulation

The main purpose of this paper, is to propose a design method for the I/Q space-time modulated metasurface, as shown in Fig. 1. To this end, we follow the single side band (SSB) modulation method for time-modulated phased antenna arrays proposed in [51]. Without loss of generality, the metasurface is normally illuminated by a plane wave $E_i(t) = E_1 e^{j2\pi f_0 t}$; the reflected wave is given by

$$E_r(t) = E_i(t) \cdot \Gamma(t) \quad (1)$$

where $\Gamma(t) = a(t)e^{j\phi(t)}$ is the time varying reflection coefficient with amplitude $a(t)$ and phase $\phi(t)$. If we desire a modulated reflected wave as $E_r(t) = E_2 e^{j2\pi(f_0 \pm f_p)t} = E_2 e^{j2\pi f_0 t} \cdot e^{\pm j2\pi f_p t}$ in the specular reflection direction, we have to design the metasurface in such a way that the reflection coefficient $\Gamma(t)$ introduces the frequency shift $e^{\pm j2\pi f_p t}$. Considering the positive sign case, we can rewrite the frequency shift in the form of I and Q terms

$$\begin{aligned} e^{j2\pi f_p t} &= \cos(2\pi f_p t) + j \sin(2\pi f_p t) \\ &= \cos(2\pi \frac{t}{T_p}) + j \sin(2\pi \frac{t}{T_p}), \end{aligned} \quad (2)$$

where $\cos(2\pi \frac{t}{T_p})$ denotes the I term, $\sin(2\pi \frac{t}{T_p})$ denotes the Q term, T_p is the time period related to f_p . Since $\cos(2\pi \frac{t}{T_p}) = -\sin[2\pi(\frac{t}{T_p} - \frac{1}{4})]$, eq. (2) can be rewritten as

$$e^{j2\pi f_p t} = -\sin(2\pi \frac{t'}{T_p}) + j \sin(2\pi \frac{t}{T_p}) \quad (3)$$

where $t'/T_p = t/T_p - 1/4$. From the right hand part of (3), it is clear that the first term has a quarter-period delay with respect to the second term.

In order to introduce such a frequency shift, we consider the metasurface depicted in Fig.1, where the response of each column (in the y-direction) is the same. Then, we group the columns to define a “modulation element” consisting of a pair of I/Q paths, whose time variations of the reflection coefficient follow the two sinusoidal variations in (3) to introduce a frequency shift f_p to the reflected field.

The simplest implementation of this modulation scheme consists in adjusting the phase of the two paths according to the rectangular pulse signal whose amplitudes “+1” and “-1”, correspond to the phase “0” or “ π ”, respectively. In order to maximize the amplitude of the +1st or -1st order harmonics and suppress the unwanted higher order harmonics, proper time sequences of the rectangular pulse are needed, as shown in Fig. 2.

Fig. 2. Time sequences used to modulate the n th modulation element. (a) Real part of $e^{j2\pi f_p t}$, namely I path, (b) imaginary part of $e^{j2\pi f_p t}$, namely Q path, (c) and (d) rectangular pulses used to match the functions in (a) and (b).

$i_n(t)$ and $q_n(t)$ are the time sequences of the unit-cells for each of the two paths of the n th modulation element with period T_p matching the two time terms in (3), respectively. t_{1n}, t_{2n}, t'_{1n} , and t'_{2n} denote the start time of the “0” and “ π ” phase states, respectively, being τ the duration of both phase states. There is no scattering field during the other intervals of the modulation period. Since a “ π ” phase difference between the two paths of a modulation element is needed (see (3) and Fig. 2), and each path has two phase states with a “ π ” phase difference, a 2-bit unit-cell is required for the I/Q modulation of the metasurface.

In conclusion, the proposed approach is different from the well-established one based on the linear modulation of the reflection coefficient phase by modulating the single unit-cell element [29]. The latter method, in fact, which requires multi-bit phases to achieve a frequency conversion and is characterized by the same frequency spectra in every observation direction, results in designs based on the time dimension only. On the contrary, our proposed method exploits two paths to realize the I/Q distributions, and each path just needs 1-bit phases. Furthermore, the first order harmonics can be controlled by designing the dimension and the time sequence of the I/Q paths, resulting in designs based on both time and space dimensions.

B. Analytical model of the I/Q space-time modulation element

By assuming the time-modulation speed much smaller than the plane wave frequency. The field scattered by the I/Q modulated metasurface depicted in Fig 1, can be written using the array factor as

$$AF(\theta, t) = e^{j2\pi f_0 t} \sum_{n=1}^N [I_n(t) + jQ_n(t) e^{j\beta N_{sub} p \sin \theta}] e^{j\beta(n-1)d \sin \theta} \quad (4)$$

where β is the free space propagation constant at f_0 , θ the scattering direction from the metasurface, N the number of modulation elements, N_{sub} the number of unit-cells in the path,

p the period of the unit-cell, and $d = 2 \times N_{sub} \times p$ the distance between two modulation elements. As for the metasurface array, when we calculate the scattering field, we have to consider the spatial phase difference $e^{j\beta N_{sub} p \sin \theta}$ between the I and Q paths.

As shown in Fig. 1, $I_n(t)$ and $Q_n(t)$ are the time sequences of the paths, which, in turn, are obtained combining the time sequences of the unit-cells $i_n(t)$ and $q_n(t)$ as

$$I_n(t) = \sum_{i=1}^{N_{sub}} i_n(t) e^{j\beta(i-1)p \sin \theta} \quad (5a)$$

$$Q_n(t) = \sum_{i=1}^{N_{sub}} q_n(t) e^{j\beta(i-1)p \sin \theta} \quad (5b)$$

where $i_n(t)$ and $q_n(t)$ are given by

$$i_n(t) = \begin{cases} 1, & t_{1n} \leq t/T_p \leq t_{1n} + \tau \\ -1, & t_{2n} \leq t/T_p \leq t_{2n} + \tau \\ 0, & \text{others} \end{cases} \quad (6)$$

$$q_n(t) = \begin{cases} -1, & t'_{1n} \leq t'/T_p \leq t'_{1n} + \tau \\ 1, & t'_{2n} \leq t'/T_p \leq t'_{2n} + \tau \\ 0, & \text{others} \end{cases}$$

being T_p the modulation period, which corresponds to the +1st or -1st order harmonic frequency shift. Therefore, the time sequences of the I/Q paths pair constituting the modulation element can be expressed as

$$I_n(t) + j e^{j\beta N_{sub} p \sin \theta} Q_n(t) = \sum_{i=1}^{N_{sub}} [i_n(t) + j e^{j\beta N_{sub} p \sin \theta} q_n(t)] e^{j\beta(i-1)p \sin \theta} \quad (7)$$

The periodic time sequences of the unit-cells are decomposed by using the Fourier series to highlight the contribution of the different frequency harmonics as

$$i_n(t) + j e^{j\beta N_{sub} p \sin \theta} q_n(t) = \sum_{h=-\infty}^{+\infty} (a_{hn} + a'_{hn}) e^{j2\pi h f_p t}, h = 0, \pm 1, \dots, \pm \infty \quad (8)$$

where h is the order of the harmonics, n refers to the n th “modulation element”, $A_{hn} = a_{hn} + a'_{hn}$ are the coefficients of the Fourier series, whose expression is evaluated in (9).

In order to only keep the first order harmonic and suppress the unwanted higher order ones, we have to analyze each term of the coefficient A_{hn} in (9) and find the corresponding conditions. Considering the term

$$\sin(h\pi(t_{2n} - t_{1n})) e^{-j h \pi(t_{2n} + t_{1n} + \tau)} e^{j\pi/2} + \sin(h\pi(t'_{2n} - t'_{1n})) e^{-j h \pi(t'_{2n} + t'_{1n} + \tau)} e^{j\beta N_{sub} p \sin \theta} \quad (10)$$

when $t_{2n} - t_{1n} = t'_{2n} - t'_{1n} = 1/2$, all the even order harmonics are suppressed $|A_{hn}| = 0 \{h = 2k, k = \pm 1, \dots, \pm \infty\}$. For what

concerns the term $\frac{2}{h\pi} \sin(h\pi\tau)$, when $\tau = 1/3$, the h th ($h = 3k$, $k \in \mathbb{Z}$) harmonics can be suppressed, $|A_{hn}| = 0 \{h = 3k, k = \pm 1, \dots, \pm \infty\}$. Ideally, this case

results in the highest modulation efficiency. However, it is difficult to design a multi-functional unit-cell

$$\begin{aligned}
 A_{hn} &= a_{hn} + a'_{hn} = \frac{1}{T_p} \int_0^{T_p} [i_n(t) + j e^{j\beta N_{sub} p \sin \theta} q_n(t)] e^{-j2\pi h f_p t} dt = \\
 &= \left(\int_{t_{1n}}^{t_{1n}+\tau} e^{-j2\pi h f_p t} dt - \int_{t_{2n}}^{t_{2n}+\tau} e^{-j2\pi h f_p t} dt \right) + j e^{j\beta N_{sub} p \sin \theta} \left(- \int_{t_{1n}}^{t_{1n}+\tau} e^{-j2\pi h f_p t} dt + \int_{t_{2n}}^{t_{2n}+\tau} e^{-j2\pi h f_p t} dt \right) \\
 &= \begin{cases} 0 & h = 0, n \in [1, N] \\ \frac{2}{h\pi} \sin(h\pi\tau) \left\{ \sin[h\pi(t_{2n} - t_{1n})] e^{-jh\pi(t_{2n}+t_{1n}+\tau)} e^{j\pi/2} + \sin[h\pi(t_{2n} - t_{1n})] e^{-jh\pi(t_{2n}+t_{1n}+\tau)} e^{j\beta N_{sub} p \sin \theta} \right\} & h \neq 0, n \in [1, N] \end{cases} \quad (9)
 \end{aligned}$$

$$\begin{aligned}
 A_{hn} &= \frac{2}{h\pi} \sin\left(\frac{h\pi}{2}\right) \text{sgn}(h) \left[\sin\left(\frac{h\pi}{2}\right) e^{-jh\pi(t_{2n}+t_{1n}+\tau)} e^{j\frac{\pi}{2}} + \sin\left(\frac{h\pi}{2}\right) e^{-jh\pi(t_{2n}+t_{1n}+\tau)} e^{j\beta N_{sub} p \sin \theta} \right] \\
 &= \frac{2}{h\pi} \sin^2\left(\frac{h\pi}{2}\right) \text{sgn}(h) \left[e^{-jh\pi(2t_{1n}+\frac{1}{2})} e^{j\pi\frac{1-h}{2}} + e^{-jh\pi(2t_{1n}+1)} e^{j\beta N_{sub} p \sin \theta} \right] \quad (11)
 \end{aligned}$$

exhibiting the 2-bit phases and an absorption state to meet the required time sequences.

To simplify the implementation, we choose $\tau = 1/2$. This would cause the presence of the h th ($h = 3k, k \in \mathbb{Z}$) order odd harmonics, affecting, thus, the modulation efficiency. However, as will be demonstrated later by the numerical results, this choice leads to acceptable performances for the metasurface.

By substituting $t_{2n} - t_{1n} = t_{2n} - t_{1n} = 1/2$ and $\tau = 1/2$ into (9), we obtain formula (11), where $\text{sgn}(h)$ is the sign function. The coefficients of the first order harmonics are

$$A_{1n} = \frac{2}{\pi} \left[e^{-j\pi(2t_{1n}+\frac{1}{2})} + e^{-j\pi(2t_{1n}+1)} e^{j\beta N_{sub} p \sin \theta} \right] \quad (12a)$$

$$A_{-1n} = \frac{2}{\pi} \left[e^{j\pi(2t_{1n}+\frac{1}{2})} - e^{-j\pi(2t_{1n}+1)} e^{j\beta N_{sub} p \sin \theta} \right] \quad (12b)$$

If we aim at designing the metasurface to achieve a positive frequency shift (blue shift), only the +1st order harmonic is retained, and the -1st order harmonic must be suppressed. This can be obtained at $\theta = 0$ (the specular reflection direction) for $t_{1n} = t_{1n} - 1/4$ and $|A_{-1n}| = 0$, resulting in the largest amplitude for A_{1n} . With this assumption, the Fourier coefficients for each harmonic are given by

$$A_{hn} = \frac{2}{h\pi} \sin^2\left(\frac{h\pi}{2}\right) \text{sgn}(h) [e^{-jh\pi(2t_{1n}+\frac{1}{2})} (e^{j\pi\frac{1-h}{2}} + e^{j\beta N_{sub} p \sin \theta})] \quad (13)$$

As noted in [43], the Fourier coefficients of the harmonics in (13) can be also expressed by using the equivalent amplitude and phase. As a result, the field scattered by a single modulation element of the metasurface can be written as:

$$\begin{aligned}
 af_{hn}(\theta) &= \sum_{i=1}^{N_{sub}} [i_n(t) + j e^{j\beta N_{sub} p \sin \theta} q_n(t)] e^{j\beta(i-1)p \sin \theta} \\
 &= \frac{2}{h\pi} \sin^2\left(\frac{h\pi}{2}\right) \text{sgn}(h) (e^{j\pi\frac{1-h}{2}} + e^{j\beta N_{sub} p \sin \theta}) \\
 &\quad \cdot e^{-jh\pi(2t_{1n}+\frac{1}{2})} \sum_{i=1}^{N_{sub}} e^{j\beta(i-1)p \sin \theta} \quad (14)
 \end{aligned}$$

Similarly, for the case of a negative frequency shift (red shift), only -1st order harmonic is retained, and the +1st order harmonic is suppressed. In this case, with $t_{1n} = t_{1n} + 1/4$ and $|A_{1n}| = 0$, A_{-1n} has the largest amplitude and the Fourier coefficients of the harmonics are given by

$$A_{hn} = \frac{2}{h\pi} \sin^2\left(\frac{h\pi}{2}\right) \text{sgn}(h) [e^{-jh\pi(2t_{1n}+\frac{1}{2})} (e^{j\pi\frac{1-h}{2}} + e^{-jh\pi} e^{j\beta N_{sub} p \sin \theta})] \quad (15)$$

Accordingly, the field scattered by the individual modulation element is given by

$$\begin{aligned}
 af_{hn}(\theta) &= \sum_{i=1}^{N_{sub}} [i_n(t) + j e^{j\beta N_{sub} p \sin \theta} q_n(t)] e^{j\beta(i-1)p \sin \theta} \\
 &= \frac{2}{h\pi} \sin^2\left(\frac{h\pi}{2}\right) \text{sgn}(h) (e^{j\pi\frac{1-h}{2}} + e^{-jh\pi} e^{j\beta N_{sub} p \sin \theta}) \\
 &\quad \cdot e^{-jh\pi(2t_{1n}+\frac{1}{2})} \sum_{i=1}^{N_{sub}} e^{j\beta(i-1)p \sin \theta} \quad (16)
 \end{aligned}$$

Besides, as to the h th $\{h = (4k-1), k \in \mathbb{Z}\}$ harmonics, we have discussed the harmonics corresponding to $k = 0$ and $k = 1$, while for larger values of h , the amplitudes of the corresponding harmonics can be neglected, being more than 16.90dB lower than the first order harmonic, as shown in eq.(13) and (15).

Multi-order harmonic manipulations based on an optimization algorithm [36] leads to much more sophisticated space-time coding. In our case of the I/Q two paths modulation method, we have proposed the analytical model for objective +1 or -1 harmonics, but it is also possible to design multi-order harmonics, resulting in similar expressions of the amplitudes of the harmonics in Eq. (9) and designing the time sequences for keeping the desired multi-order harmonics and suppressing the undesired ones.

C. Analytical model of the I/Q space-time metasurface

The field scattered by the entire array is the sum of the fields scattered by all the modulation elements and, thus, it reads

$$AF_h(\theta) = \sum_{n=1}^N af_{hn}(\theta) e^{j\beta(n-1)d \sin \theta} \quad (17)$$

Based on the above derivation, namely $t_{2n} - t_{1n} = t'_{2n} - t'_{1n} = 1/2$ and $\tau = 1/2$, for blue shift $t'_{1n} = t_{1n} - 1/4$, the scattered field of each order harmonics can be calculated using (14) and (17). And for red shift $t'_{1n} = t_{1n} + 1/4$, the scattered field of each order harmonics can be calculated using (16) and (17). The time variations of the phase $\phi(t)$ and $\phi'(t)$ corresponding to the time sequences $i(t)$ and $q(t)$, respectively, are shown in Fig. 3. Actually, when the modulation time sequence is a non-ideal rectangular pulse, such as trapezoidal or time-domain raised cosine waveforms, the equivalent circuit of the diodes would change in a period, leading to imperfect 2-bit phase of the unit-cell. This partially motivates the existing mismatch (even if slight) between analytical and numerical results [53]. A more accurate analytical model can be derived considering the non-ideal behavior of the diodes.

As to the efficiency of the harmonic patterns, the method reported in [54] is used to determine the order of the harmonics to be considered. When $h \geq 5$, by increasing the order the power efficiency of the first order harmonics remains almost constant. As a result, we choose $h = 5$ in our analysis.

Then we explore here, in the non-specular reflection observation directions, the opposite first order harmonic can be easily controlled by changing the dimension of I/Q paths, while the objective first order harmonic remains unchanged. Thus, the field scattered by the proposed metasurface depends on the dimension of the paths, which should introduce a spatial modulation. Let us first consider the $+1st$ or $-1st$ order harmonics. Without loss of generality, an 8×16 metasurface is considered with N_{sub} unit-cells in each path. For the blue shift, the scattered field of the $\pm 1st$ harmonics is given by

$$|AF_{+1}| = \frac{2}{\pi} \sum_{i=1}^{N_{sub}} e^{j\beta(i-1)p \sin \theta} \sum_{n=1}^{8/N_{sub}} (1 + e^{j\beta N_{sub} p \sin \theta}) e^{j\beta(n-1)2N_{sub} p \sin \theta} \quad (18a)$$

$$|AF_{-1}| = \frac{2}{\pi} \sum_{i=1}^{N_{sub}} e^{j\beta(i-1)p \sin \theta} \sum_{n=1}^{8/N_{sub}} (-1 + e^{j\beta N_{sub} p \sin \theta}) e^{j\beta(n-1)2N_{sub} p \sin \theta} \quad (18b)$$

Calculating the summations in (18), we obtain (19a) and (19b).

In (18a), we recognize that the summation in the scattered field of the $+1st$ order harmonic is a geometric series and, thus, it is independent of N_{sub} as in (19a). In contrast, in (19b), the summation in the scattered field of the $-1st$ order harmonic is an interleaved geometric series and, thus, it depends on N_{sub} as in (19b). Similarly, by using (14) and (17), we find that the scattering fields of the $-3rd$ and $+5th$ order harmonics are also geometric series, so that they do not depend on the path dimension, as it happens for the $+1st$ order harmonic. Instead, being the fields scattered by the $+3rd$ and $-5th$ order harmonics interleaved geometric series, they can be modulated by properly choosing the path dimension, as for the $-1st$ order harmonic. To sum up, when changing the dimension of the I/Q paths, the opposite first order harmonics can be easily controlled by changing the dimension of the I/Q paths, keeping the objective first order harmonic unchanged. This space-time

modulated character of the objective and its opposite first order harmonics would provide new approaches for space- and frequency-division multiplexing or secure communications [55].

$$|AF_{+1}| = \frac{2}{\pi} \left| \frac{\sin(\frac{\beta N_{sub} p \sin \theta}{2})}{\sin(\frac{\beta p \sin \theta}{2})} \right| \left| \frac{\sin(\beta 8 p \sin \theta)}{\sin(\frac{\beta N_{sub} p \sin \theta}{2})} \right| \quad (19a)$$

$$= \frac{2}{\pi} \left| \frac{\sin(\beta 8 p \sin \theta)}{\sin(\frac{\beta p \sin \theta}{2})} \right|$$

$$|AF_{-1}| = \frac{4}{\pi} \left| \frac{\sin(\frac{\beta N_{sub} p \sin \theta}{2})}{\sin(\frac{\beta p \sin \theta}{2})} \right| \left| \sin \frac{\beta N_{sub} p \sin \theta}{2} \right| \left| \frac{\sin(\beta 8 p \sin \theta)}{\sin(\beta N_{sub} p \sin \theta)} \right|$$

$$= \frac{4}{\pi} \left| \frac{\sin^2(\frac{\beta N_{sub} p \sin \theta}{2})}{\sin(\frac{\beta p \sin \theta}{2})} \right| \left| \frac{\sin(\beta 8 p \sin \theta)}{2 \sin(\frac{\beta N_{sub} p \sin \theta}{2}) \cos(\frac{\beta N_{sub} p \sin \theta}{2})} \right|$$

$$= \frac{2}{\pi} \left| \tan(\frac{\beta N_{sub} p \sin \theta}{2}) \right| \left| \frac{\sin(\beta 8 p \sin \theta)}{\sin(\frac{\beta p \sin \theta}{2})} \right| \quad (19b)$$

Fig. 3. The time-varying phases to achieve a (a) blue shift and (b) red shift in a modulation period. $\phi(t)$ and $\phi'(t)$ correspond to $i_n(t)$ and $q_n(t)$, respectively.

Finally, in order to check the scanning properties of the beam scattered by the metasurface, let us consider the $+1st$ order harmonic (similar considerations hold for the $-1st$ order one). From (14) and (17), we observe that some terms of the expression do not depend on n and some others depend on n and, thus, determine the superposition of the fields scattered by the “modulation elements” and, in turn, are responsible for the beam scanning. The term $e^{-j\pi(2t_{1n} + \frac{1}{2})}$ is determined by the start time of the first periodic time sequence of the n th “modulation element”: when the start time of the periodic time sequence varies within a period $t_{1n} \in [-1/4, 3/4]$, the corresponding phase $-\pi(2t_{1n} + 1/2)$ covers the 2π range. Therefore, by properly designing the start time of the sequences t_{1n} , it is possible to achieve high efficiency beam scanning of the $+1st$ order

harmonic. Thus, to achieve a blue shift with pre-designed scanning angle $\theta = \theta_{scan}$, using the other term $e^{j\beta(n-1)d \sin \theta}$, we find the expression for t_{1n} as

$$t_{1n} = \frac{1}{2} \left[\frac{\beta(n-1)d \sin \theta_{scan}}{\pi} - \frac{1}{2} \right] \quad (20)$$

III. I/Q SPACE-TIME-MODULATED METASURFACE IMPELEMENTATION WITH 2-BIT UNIT-CELLS

To implement the space-time modulated metasurface, the 2-bit unit-cell originally proposed in [52] for other purposes is employed to match the time sequences reported in Fig. 3. The unit-cell with small electrical size is chosen to achieve the functionality of manipulating the opposite first order harmonic frequency by changing the dimension of I/Q paths. Thus, large range of I/Q paths dimensions composed of smaller unit-cells would produce diverse modulation. The unit-cell has been designed to exhibit the 2-bit phase response at 3.15 GHz with a reflection amplitude larger than 0.9. Four different phase responses, denoted as “0”, “ $\pi/2$ ”, “ π ”, “ $3\pi/2$ ” can be obtained by switching the ON/OFF states of three PIN diodes.

Considering the case of the blue shift, the corresponding implemented metasurface is shown in Fig. 5. According to the derived time varying phases of the modulation elements, it can be seen that the states of the entire array have been switched four times in a modulation period, that is, a quarter of a period corresponds to a phase state of the modulation element. The time variations of the reflection phases for the two I/Q paths constituting the modulation element are expressed as

$$\{\varphi(t), \varphi'(t)\} = \begin{cases} \{0, \pi/2\}, t \in [0, \frac{T_p}{4}) \\ \{\pi, \pi/2\}, t \in [\frac{T_p}{4}, \frac{T_p}{2}) \\ \{\pi, 3\pi/2\}, t \in [\frac{T_p}{2}, \frac{3T_p}{4}) \\ \{0, 3\pi/2\}, t \in [\frac{3T_p}{4}, T_p) \end{cases} \quad (21)$$

For the simulation, we used a similar procedure as in [29], based on a co-simulation between CST Studio Suite and Advanced Design System (ADS). In [30], however, being the time sequences of all the unit-cells the same, the authors simulated the frequency spectrum of the reflected field by considering a single unit-cell with periodic boundary conditions. In our design, instead, the reflection responses of the two I/Q paths in the modulation element are different. So, we considered the diode equivalent circuit and the phase states of the metasurface shown in Fig. 4, and performed the frequency domain simulations. Then, we have used CST full-wave simulations to compute the field reflected by the array within each quarter of the period and combined such results to analyze the corresponding frequency spectrum. In particular, we have used the CST post-processing tools to perform the Fourier analysis of the reflected field time sequences needed to eventually obtain the frequency spectra.

The case of the red shift can be studied in a similar way, starting with the different time-varying phases shown in Fig.

3(b).

Fig. 4. The four modulation schemes of the metasurface for each quarter of the period of the time sequence to achieve a blue shift. Phase states within (a) the first quarter of the period (“0” and “ π ”), (b) the second quarter of the period (“ π ” and “ $\pi/2$ ”), (c) the third quarter of the period (“ π ” and “ $3\pi/2$ ”), (d) the fourth quarter of the period (“0” and “ $3\pi/2$ ”).

IV. RESULTS AND DISCUSSIONS

A. Blue and red shifts in the specular reflection direction

In order to demonstrate the blue and red shifts using the proposed I/Q space-time-modulated metasurface, a time-domain simulation is implemented considering an 8×16 array. The designed frequency shift is $f_p = 1/T_p = 2$ MHz and the number of cells for each path $N_{sub} = 8$. The simulated frequency spectra of the normal reflected fields are shown in Fig. 5. An excellent agreement of the frequency shift can be found between the simulated and the analytical results obtained from (18). Besides the $\pm 3rd$ order harmonics, as noted in Sec. II-B,

Fig. 7. Comparison between the normalized scattered fields of the different harmonics evaluated with far field superposition (dashed line) and analytical (solid line) methods, ((a)-(d) +1, +5, -3 harmonics, (e)-(h) +3, -1, -5 harmonics) for the blue shift case when the beams scan at (a) (e) $\theta_{scan} = 0^\circ$, (b) (f) $\theta_{scan} = 12^\circ$ (g) $\theta_{scan} = 24^\circ$ and (d) (h) $\theta_{scan} = 32^\circ$, respectively.

Fig. 8. Comparison between the normalized scattered fields of the different harmonics evaluated with full-wave simulation (dashed line) and analytical (solid line) methods, ((a)-(d) +1, +5, -3 harmonics, (e)-(h) +3, -1, -5 harmonics) for the blue shift case when the beams scan at (a) (e) $\theta_{scan} = 0^\circ$, (b) (f) $\theta_{scan} = 12^\circ$ (g) $\theta_{scan} = 24^\circ$ and (d) (h) $\theta_{scan} = 32^\circ$, respectively.

there is the fundamental frequency component at 3.15 GHz, which is due to the imperfect 2-bit phase of the designed metasurface unit-cell. As a result, the modulation efficiency would be, in turn, affected. However, as shown in Fig. 5, the amplitude of the unwanted fundamental frequency component is 18.05 dB lower than the ones of the desired $\pm 1st$ order harmonics, thus the influence on the frequency shift can be considered as negligible.

For the blue shift, the amplitude of the +1 st order harmonic is 9.54 dB higher than the one of the -3 rd order harmonic and 13.98 dB higher than the one of the +5 th order harmonic, which results in a higher modulation efficiency. For the red shift, the same modulation efficiency is found for the -1 st order harmonic. Comparing our method with the 2-bit linear time varying phase modulation one [32], both methods result in the same theoretical harmonic efficiency, whilst in the numerical results,

the amplitude of the fundamental component obtained with the linear modulation phase method is about 2dB lower than by using our method (see Fig. 5).

From these results, it is clear that the highest modulation efficiency can be obtained by matching in the most accurate way possible the 2-bit phase. To this end, the unit-cell should exhibit a wide-angle response and reduced mutual coupling among the elements. Theoretically, if we could design a multi-functional metasurface with both 2-bit phases and absorption states, then we would completely eliminate the hth ($h = 3k, k \in \mathbb{Z}$) order odd harmonics, in agreement with the theory presented in Sec. II-B. Ideally, when $\tau = 1/3$, the designed I/Q modulation model can achieve the highest modulation efficiency, being the amplitude of the first order harmonic 13.98 dB higher than the amplitude of any other unwanted harmonic.

Fig. 5. Normalized reflection spectrum analytically calculated through the formulas and numerically computed through simulations of the I/Q modulation (a) blue and (c) red shifted, the 2-bit linear time varying phase modulation (b) blue and (d) red shifted reflected electromagnetic fields at $\theta = 0$.

Besides, as for $(4k-1)th$ ($k \in \mathbb{Z}$) harmonics, when $k = 0$ and $k = 1$, we have discuss the corresponding harmonics, and if h becomes larger, the corresponding harmonics is more than 16.90dB difference from the first order harmonic. So they can be neglected.

B. Opposite first order harmonic modulation by the dimension of I/Q paths

In order to analyze the opposite harmonic modulation performances with the variation of the I/Q paths dimensions in the non-specular reflection directions, we simulate a metasurface for blue shift case with 8×16 unit-cells imparting a frequency shift $f_p = 1/T_p = 2$ MHz with a different number of the unit-cells in the path, namely $N_{sub} = 2, 4$ and 8 . The analytical (evaluated through (21)) and full-wave simulation results are shown in Fig. 6. As expected, in the non-specular reflection direction, with the increase of the I/Q paths dimension, the fields of the $-1st$, $+3rd$ and $-5th$ order harmonics are modulated, while the scattering fields of the $+1st$, $-3rd$, $+5th$ order harmonics maintain unchanged. And $-1st$, $+3rd$, $-5th$ order harmonics have the same scattering fields but with constant difference according to eq. (18). $+1st$, $-3rd$, $+5th$ order harmonics also have the same relation between each other.

As to this functionality, we can assume a wireless communication scenario. In the specular reflection direction, the $+1st$ order harmonic is unchanged resulting, thus, in a constant transmission. In the other directions, instead, by changing the dimension of the I/Q paths, we can select the communication directions using the $-1st$ order harmonic. Combining this with the red shift case, a simultaneous BFSK (Binary Frequency Shift Keying) transmission to multi-point communication with reverse frequency coding can be performed. This unique functionality may provide new approaches for space- and frequency-division multiplexing communications.

Since the 2-bit linear time varying phase modulation method

does not involve I/Q paths phase difference and the subarray concept, only the objective first order harmonic is generated. On the contrary, by using our method, the opposite first order harmonic can be easily manipulated by changing the dimensions of the I/Q paths, whilst the objective first order harmonic remains unchanged.

Fig. 6. Normalized scattering fields for the blue shift case: comparison between analytical (anal.) and full-wave simulations (sim.) when (a) $N_{sub} = 2$, (b) $N_{sub} = 4$, and (c) $N_{sub} = 8$.

C. $+1st$ or $-1st$ order harmonic beam scanning

In order to reflect the beam back to a specific scanning angle, the needed analytical start time is derived by using formula (20) and the corresponding scattering fields are calculated through (17). Considering the example of the blue shift, in order to achieve a narrower beam and low $-1st$ order harmonic lobes, we have designed a metasurface with 8×32 unit-cells imparting a frequency shift $f_p = 1/T_p = 2$ MHz with $N_{sub} = 2$ unit-cells for each path. We provide a comprehensive comparison between our proposed analytical model and both the full-wave simulation method in Sec. III and the far field superposition method (considering the scattering field of the designed unit-cells). In order to easily deal with the time varying scattering fields with an FFT code using the full-wave

simulation method, a time delay of 0, 1/8, 1/4 and 1/3 of the period is chosen between two adjacent modulation elements, corresponding to scanning angles of 0°, 12°, 24° and 32°, respectively.

As shown in Fig. 7, a good agreement between the proposed analytical method and the far field superposition without considering the mutual coupling can be found. In Fig. 8, instead, we observe a mismatch between analytical and full-wave simulation results. As explained in Sec. II-B, for blue shift scanning, the +1st harmonic is the objective scattering field retained by start time of I/Q paths design, the -1st harmonic is the undesired scattering field produced by the spatial phase difference between I/Q paths, ± 3 th and ± 5 th are undesired harmonics. When the +1st harmonic beam scans at different angles, as in Fig. 8, the analytical results for the +1, +5, -3 harmonics always agree well with the full-wave simulations. An expected mismatch is found for the +3, -1, -5 harmonics in the range $[-10^\circ, 10^\circ]$, but the amplitudes are smaller than -20dB, having a weak influence on the +1st harmonic scanning performance. It should be noted that, increasing the scanning angle of the +1st harmonic, as expected, the side lobe level of the -1st harmonic is higher and the agreement improves.

The comparisons shown in Figs. 7 and 8, reveal that the mismatch is mainly caused by the mutual coupling. To reduce the mismatch, we can increase the dimension of the I/Q paths, but this will deteriorate the +1st harmonic beam scanning performance due to the increased side lobe of the -1st harmonic beam. An alternative optimization method, such as the space mapping [56], can be used to enhance the scanning performance considering the mutual coupling.

In the design beam scanning angles, the resulting isolation of the +1st order harmonic from other harmonics is beyond 9.54 dB. But when increasing the scanning angle, the maximum amplitude of the -1st harmonic increases at opposite angles and a grating lobe appears, deteriorating, thus, the beam scanning performance of the objective harmonic. To deal with this problem, we can use an optimization algorithm to suppress the side lobe level considering as a good initial value the one coming from the proposed analytical formulation [43].

Similar periodic time series can be designed analytically for red shift case. It should be noted that the design beam scanning angle is only dependent on the normalized time period, while the frequency shift is determined by the time period. As a result, thus, the proposed I/Q space-time modulated metasurface can manipulate the reflected fields in both space and frequency domain simultaneously.

For what concerns the beam scanning performance, our method and the 2-bit linear time varying phase modulation method give similar results. At the scanning angle, the +1st harmonic beam of both methods has similar isolation with other harmonics. At other angles, the maximum side lobe levels are similar, whilst the maxima of the side lobes appear at different angles.

V. CONCLUSION

In this paper, an analytical design of I/Q two path

space-time-modulated metasurface is proposed. Compared to the 2-bit linear phase modulation method, in the specular reflection direction, the spectrum components of both methods are the same, the power ratio of the objective first order harmonic to the total harmonics is 81.1%. Since the 2-bit linear phase modulation method does not involve I/Q path phase difference and the subarray concept, only the objective first order harmonic is generated. By using our method, instead, the opposite first order harmonic can be easily manipulated by changing the dimensions of the I/Q paths, keeping the objective first order harmonic unchanged. For what concerns the beam scanning performance, the 2-bit linear phase modulation method and our method show similar performance. In particular, by using the two methods, at the scanning angle, the +1st harmonic beams have similar isolation with other harmonics. At other angles, the maximum side lobe levels are again similar by using the two methods, while the maxima of the side lobes appear at different angles.

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