Spatial-temporal Programmable Metasurface for Single Channel Radiation

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***Abstract*—Exploiting the spatial-temporal relationship, a novel programmable metasurface architecture is proposed to suppress undesired harmonics for spectrally efficient communication. A single-bit metasurface array with four-element unit cells is proposed to allow dynamic beamforming of the information metasurface without the use of phase shifters. The proposed method achieves an array factor with a harmonic suppression ratio of more than 15 dB. The meta-element design operates at a center frequency of 4.3 GHz with a bandwidth of 200 MHz, which can be exploited further to suppress higher-order harmonics. Using a carrier frequency of 4.2 GHz with a 100 MHz modulation signal, the proposed metasurface transmitting a signal with 50 MHz bandwidth can achieve an adjacent channel power ratio of -14.38 dB, indicating the feasibility of spatial-temporal programmable metasurface in practical communication applications.**

***Index Terms*—space-time coding, beamforming, harmonic suppression, programmable metasurface, intelligent reflecting surface.**

I. Introduction

Recently, programmable intelligent surfaces attract increasing research interests due to their capability of tailoring the electromagnetic characteristics of wireless signals on the fly to allow a simplified realization of beamforming [1]. Thanks to the merits of programmable metasurfaces including low power consumption, the flexibility for installation, and low cost, extensive implementation of those surfaces can significantly enhance the quality of wireless communication channels by exploiting both the temporal and spatial domain multiplexing, and thus is considered a promising candidate for mmWave 5G communication.

Ideal beamforming requires the metasurface to present a continuously tunable phase, which greatly limits the number of feasible low-cost solutions. Nevertheless, metasurface suffers a tradeoff between phase granularity and radiation efficiency. A one layer metasurface with -1 dB transmission has phase limits of 54° [2]. On the other hand, although meta-element provides a discrete subset of amplitude and phase combinations, a meticulously-designed time-varying modulating sequence is applied to each meta-elements to facilitate granular beamforming [3]. Nevertheless, the adoption of time-domain modulation can be interpreted as a frequency domain convolution of the original narrowband signal with the Fourier sequences of the modulating pulses, which inevitably introduces frequency harmonics. Despite its potential applications in broadcasting and secured communication, frequency harmonics are in general undesired as they contaminate neighboring channels.

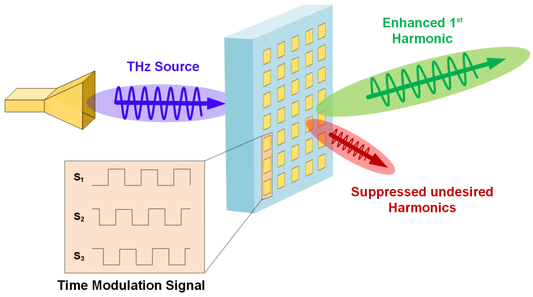


Fig. 1. Architecture of STPM. Different time modulation signals are designed for each unit cell to achieve beamforming and suppress undesired harmonics.

As shown in Fig. 1, we propose a Spatial-Temporal Programmable Metasurface (STPM) as a potential solution for intelligent beamformers that can achieve spectral and radiation efficiency simultaneously. The unit-cell design contains four programmable 1-bit meta-element whose switching patterns are designed to achieve beamforming and harmonic suppression at the same time.

II. STPM Array Principle and Unit-cell Design

A. Harmonic Suppression in a STPM

A classical method in signal processing to suppress harmonics is to exploit the property of Hilbert transformation by properly combining a signal with its quadrature duo. Inspired by this method, we design a unit cell that is capable of transmitting four different phases, and the modulating sequences are to be designed such that a combination of the transmissive electromagnetic waves modulated by the switching pulses leads to suppression of undesired harmonics [4]. We first consider the modulation sequences of metasurface with negligible inter-cell distance, and then the impact of a particular cell arrangement is further analyzed. The length of each meta-element is defined as D. We first assume that all four meta-elements are located at the center of the unit cell.

Suppose that the origin is defined at the center of the bottom left unit cell and the whole metasurface has M rows and N columns in total, then the coordinate of the unit structure on the m^{th} row and n^{th} column under the ideal case can be defined as

$$d_{mn} = (2mD, 2nD, 0). \tag{1}$$

Therefore, the array factor can be expressed as

$$AF(\theta, \phi, t) = f(t) \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} \cdot U_{mn} \cdot e^{j\frac{4\pi D}{\lambda} \sin\theta[(m-1)\cos\phi + (n-1)\sin\phi]}, \tag{2}$$

where θ and ϕ define the elevation angle and azimuth angle, $f(t)$ denotes the incident wave, I_{mn} and U_{mn} are the transmittance and modulation sequences for the unit cell on position d_{mn}. Because each unit cell contains four meta-elements, U_{mn} can be expressed as

$$U_{mn} = U^0_{mn}(t) + jU^{\frac{\pi}{2}}_{mn}(t) - U^{\pi}_{mn}(t) - jU^{\frac{3\pi}{2}}_{mn}(t), \tag{3}$$

where $U^0_{mn}(t)$, $U^{\frac{\pi}{2}}_{mn}(t)$, $U^{\pi}_{mn}(t)$ and $U^{\frac{3\pi}{2}}_{mn}(t)$ are the modulation sequences on meta-elements with different phases. $U^i_{mn}(i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ can be further expressed as

$$U_{mn,i}(t) = \text{rect}(\frac{t - \tau/2 - kT_p - t^i_{mn}}{\tau}), \tag{4}$$

where T_p is the period of the modulation sequence, τ is the time length of the "ON" state and t^i_{mn} is the switch-on time. The switch-on time of the four meta-elements and the time length of the "ON" states are optimized as $t^{\frac{\pi}{2}}_{mn} = t^0_{mn} + \frac{T_p}{4}$; $t^{\pi}_{mn} = t^0_{mn} + \frac{T_p}{2}$; $t^{\frac{3\pi}{2}}_{mn} = t^0_{mn} - \frac{T_p}{4}$ and $\tau = \frac{T_p}{3}$, where

$$t^0_{mn} = \{\frac{2\sin\theta D}{\lambda}[(m-1)\cos\phi + (n-1)\sin\phi] - \frac{1}{6}\}T_p. \tag{5}$$

We further consider the impact of the displacement between meta-elements. One realization of the unit cells is illustrated in Fig. 2. Here we analyze the effect of element spacing D between adjacent meta-elements. We introduce a function $f_\Delta(x, y)$ to represent the time delay contributed by the relative location of the meta-element with position deviation (x, y) to the center of the unit cell which can be expressed as

$$\begin{aligned} f_\Delta(x, y) =& \frac{1}{c}(|(x-1)\sin\theta\cos\phi + (y-1)\sin\theta\sin\phi - \cos\theta| \\ &- |\sin\theta\cos\phi + \sin\theta\sin\phi + \cos\theta|). \end{aligned} \tag{6}$$

If the relative positions of the four elements related to the center of the unit cell are fixed, the advance in time can be defined as positive and the delay can be defined as negative. Therefore, $f_\Delta(x, y)$ can be reduced to

$$f_\Delta(x, y) = -\frac{1}{c}(x\sin\theta\cos\phi + y\sin\theta\sin\phi). \tag{7}$$

Then the equation for modifying the four t^i_{mn} functions can be simplified into a more general form with the value of τ remains unchanged, i.e.,

$$t^{i'}_{mn} = t^i_{mn} - f_\Delta(x_i, y_i), \tag{8}$$

where (x_i, y_i) is the relative position of each unit cell.

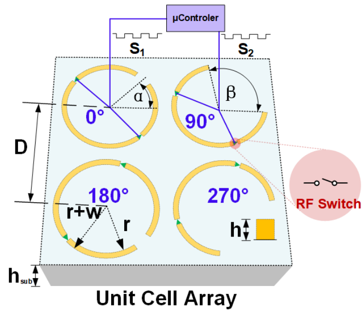


Fig. 2. C-shape unit cell with h= 0.035 mm, w={0.96, 0.84, 0.96, 0.84} mm, β={18, 108, 18, 108}°, α={45, 45, -45, -45}°, r = 7.2 mm, D = $\lambda_{air}/4$ and h_{sub}=16 mm. Here the four parameters of all the data correspond to the meta-elements with 0, $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$ phase shift, respectively. Each unit cell contains eight PIN diodes controlled by the time modulation sequences.

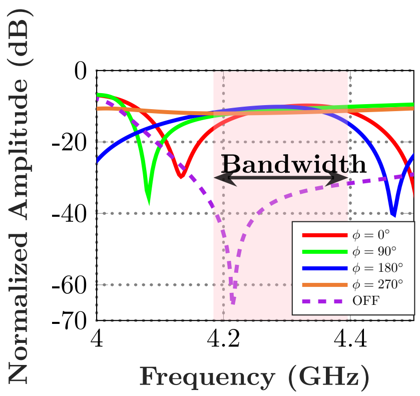
B. Unit Metasurface Structure Design

In this section, four 1-bit C-shape programmable meta-elements with different phase responses are designed, as shown in Fig. 2. The metasurface is designed to be fabricated on a Rogers printed circuit board with a top copper thickness h, a subtrate thickness h_{sub}, and a dielectric constant of 3.66. The split-ring-resonator (SRR) inspired meta-elements are designed to operate at a center frequency of 4.3 GHz with a inner diameter r and a thickness w. Chosen parameters can be found in the caption of Fig. 2. Two PIN diodes controlled by a micro-controller are added to each SRR to realize fast and independent element modulation. Through the design of opening angle β and orientation angle α, different phase modulation values can be realized. Four "ON" states with different phase shifts can be achieved by turning on the corresponding meta-element while turning off the reminders, and the "OFF" state can be produced by turning off all PIN diodes.

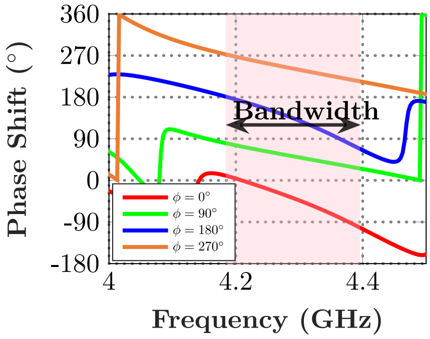
Simulation results performed through CST Microwave Studio are shown in Figs. 3(a) and 3(b), which show the cross-pol transmittance and phase shift responses of the unit cell. Bandwidth is defined as the frequency range in which the "ON"-"OFF" ratio is greater than 20 dB, the transmittance is greater than -12 dB and the relative phase error is less than 10°. At the center frequency, 4.3 GHz, the simulation results show that within the bandwidth, the average "ON"-"OFF" ratio is 27.6 dB.

III. Simulation Result

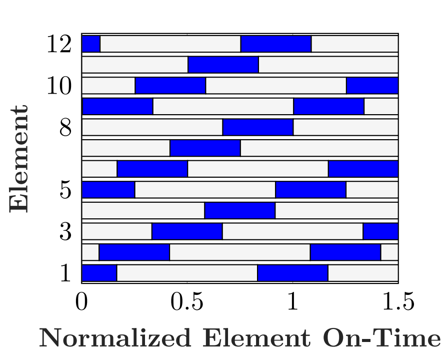
Simulation is performed to validate the STPM method with D = $\lambda/4$, a targeted angle 20° and center frequency 4.3 GHz. In order to simulate the ability of the STPM to form beam and suppress undesired harmonics, a signal is transmitted through the time modulated metasurface.



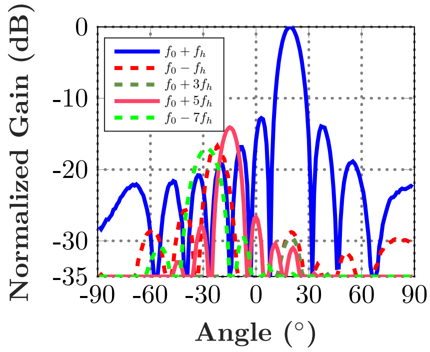
(a)



(b)



(c)



(d)

Fig. 3. Simulated characteristics of unit cell. (a) The S_{21} of the five states. From 4.19 GHz to 4.39 GHz, the S_{21} for "ON" states is larger than -13 dB and S_{21} parameter for the "OFF" state is less than -30 dB. (b) The four different phase shift responses. (c) The switch modulation sequences for STPM unit cells at the position d_{11}, d_{12} and d_{13} (definition of d_{mn} is provided by Eq. (1)) where blue means the PIN diodes are switched on. (d) Simulated radiation patterns for different harmonics generated by STPM at target angle 20°.

Fig. 3(c) illustrates a subset of modulation sequences of twelve metasurface unit cells at the position d_{11}, d_{12}, and d_{13} where d_{mn} is defined on Eq. (1). Fig. 3(d) shows the normalized power on five harmonics containing the most power. The normalized power of the harmonics are all less than -15 dB and the adjacent channel power ratio reaches -14.38 dB which is calculated by ACPR $= \Sigma p_5 / \Sigma p_1$ where Σp_i is the i^{th} harmonic. Moreover, the power of the 1^{st} harmonic reaches the maximum at our target angle.

IV. Conclusion

In this paper, a time modulated programmable metasurface architecture and its modulation sequences are designed to ensure both flexibility and efficiency of beamforming and undesired harmonics suppression. The metasurface unit cell contains four "ON" states with 0, $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$ phase shift and one "OFF" state with average transmittance -38.87 dB. Within the bandwidth, the average "ON"-"OFF" ratio is 27.6 dB. Moreover, the simulation results for the metasurface array applying the modulation sequences shows a harmonic suppression ratio of more than 15 dB and adjacent channel power ratio less than -14.38 dB. All these results prove the ability of the STPM to achieve high efficient beamforming and undesired harmonic suppression, indicating the potential for applying in practical communication applications.

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