S21 出口 } f0+fs 最大带宽 f0 带外 4 Unit cell □
S11 入口 } f0 1 Meta-element C

Spatial-temporal Programmable Metasurface for Single Channel Radiation

ACPR

SB = 50M
MF = 0.16
|↔| = 200M, 0B

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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 4.205 GHz with a bandwidth of 50 MHz, which can be exploited further to suppress higher-order harmonics. Using a carrier frequency of 4.21 GHz with a 50 MHz modulation signal, the proposed metasurface transmitting a signal with 15 MHz bandwidth can achieve an adjacent channel power ratio of 33.4 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. For a double layer structure, a 50° of ~~flexibility on~~ phase shift reduces the transmission by at least 2 dB [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

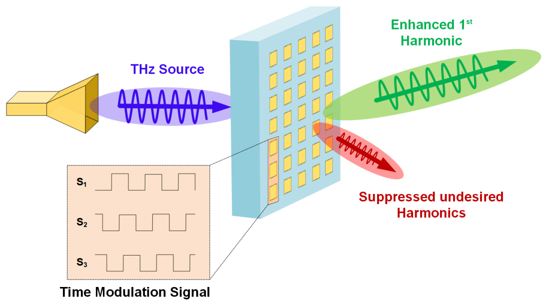

Fig. 1. Architecture of STPM. Different time modulation signals are designed for each ~~metasurface unit cell~~ to achieve beamforming and suppress undesired harmonics.

domain convolution of the original narrowband signal with the Fourier sequence of the modulating pulses, which inevitably introduces frequency harmonics. Despite its potential application in broadcasting and secured communication, frequency harmonics are in general undesired as it contaminates neighboring channels.

they ~~In this work,~~ as shown in Fig. 1, we propose a Spatial-Temporal Programmable Metasurface (STPM) architecture 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. In section II-A, the mathematical foundation of the proposed STPM array is presented to account for the physical arrangement of unit cells. In section II-B, the optimization of the unit cell design is presented. The frequency-dependent transmission features of the meta-element is further utilized to suppress high-order harmonics, and the collective effect of array synthesis and element design is presented in section III.

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 metasurface unit ~~array~~ that is capable of transmitting four different phases, and the modulating sequences are to be designed switching

such that a combination of the transmissive electromagnetic waves modulated by the modulating 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. 统一 The length of each meta-element is defined as D. We first simplify all four meta-elements are ~~at the same location~~ assume that located at. Suppose that the origin is defined at the center of the bottom left ~~unit structure~~ and the whole metasurface ~~totally~~ have 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

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

As shown on fig 2,... yinchu D

Therefore, the array factor can be expressed as

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

T → 2D   π/180

where θ and ϕ define the ~~target~~ angle for beamforming, $f(t)$ denotes the incident wave, I_{mn} and U_{mn} ~~is~~ are the transmittance and ~~control function~~ for the unit ~~structure~~ on position d_{mn}. Because each ME unit ~~structure~~ contains four ~~unit cells~~, U_{mn} can be further expressed as

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

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 MS ~~control functions~~ on ~~unit cell~~ with different phases. Since those modulating ~~waveforms~~ are composed of rectangular pulses with distinct switch-on time, $U^i_{mn}(i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ can be further expressed as

$$U_{mn,i}(t) = \mathrm{rect}\left(\frac{t-\tau/2-kT_p-t^i_{mn}}{\tau}\right), \quad (4)$$

τ

where T_p is the period of the ~~switch control signal~~, τ is the time length of the "ON" state, and t^i_{mn} is the ~~time delay~~ switch-on time. The ~~time delay~~ of the four ~~cells~~ ME and τ same 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

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

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

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

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 in time can be defined as negative. Therefore, $f_\Delta(x,y)$ can be reduced to

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

Then the equation for modifying the four t_{mn} functions ~~$(i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$~~ can be simplified into a more general form with the value of τ remains unchanged, i.e.,

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

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

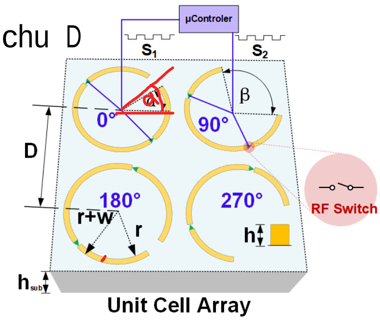

Fig. 2. ~~Structure of~~ C-shape ~~metasurface unit structure~~ ME with h={0.035, ~~0.018, 0.035, 0.018~~} mm, w={0.96, 0.84, 0.96, 0.84} mm, β={18, 108, 18, 108}°, α={45, 45, -45, -45}°, r = 7.2 mm, D = λ/4 and h_{sub}=16 mm. Here the four parameters of all the data correspond to the ~~unit cell~~ with perform 0, $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$ rad phase shift respectively. Each unit cell contains two ~~pin~~ PIN diodes controlled by the time modulation ~~signals.~~ seq

B. Unit Metasurface Structure Design

In this section, ME four 1-bit C-shape programmable ~~meta-surface elements~~ with different phase responses are designed, as shown in Fig. 2. The ~~unit cell structure~~ prog meta is designed to be fabricated on a Rogers printed circuit board with a top copper thickness h, a subtrate thickness of 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 4.23 GHz with a inner diameter r and 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 ~~unit cell~~ 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 ~~structure~~. Bandwidth is defined as the frequency range in which the "ON"-"OFF" ratio is greater than 20 dB and the relative phase error ~~angle~~ is less than 10°. At the ~~operating~~ center frequency, 4.213 GHz, the simulation results

transmittance

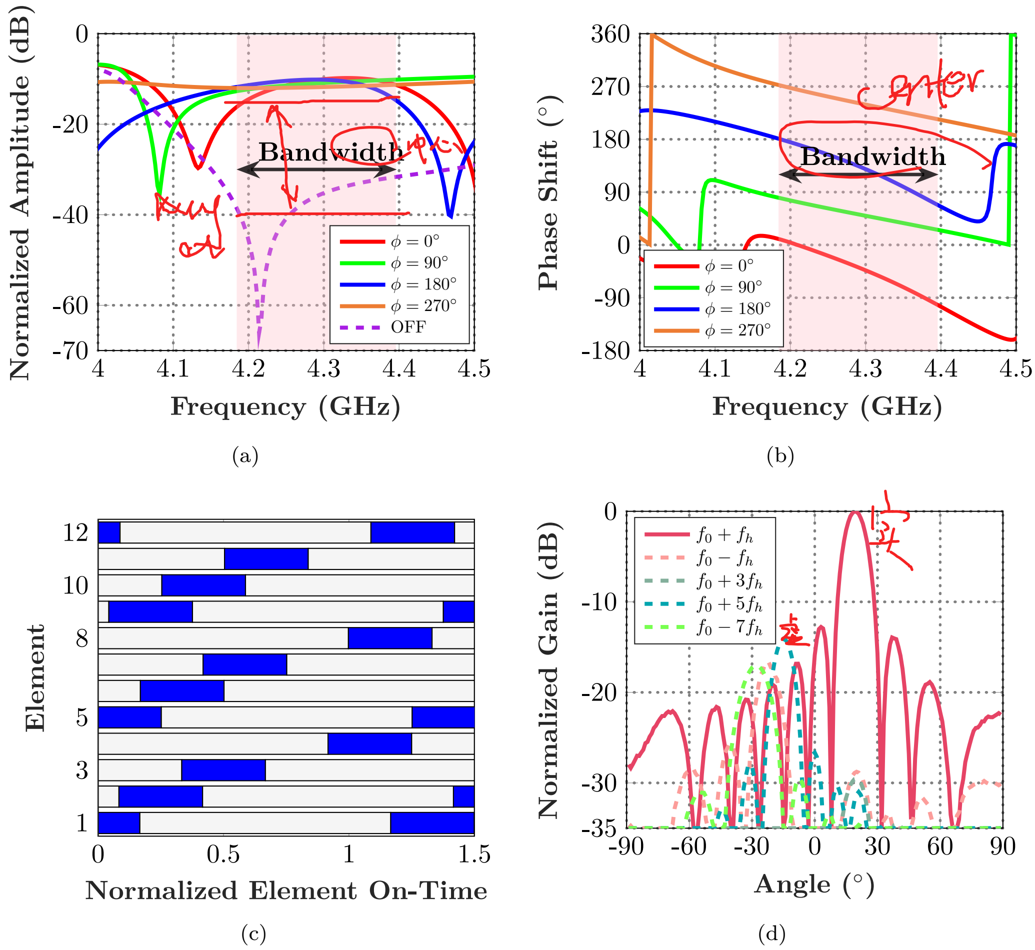

Fig. 3. Simulated characteristics of unit ~~metasurface structure~~. (a) The S_{21} parameter of the five states. From 4.19 GHz to 4.39 GHz, the S_{21} parameter for "ON" states is larger than -13 dB and S_{21} parameter for the "OFF" state is less than -30 dB. ~~And the minimal amplitude response for "OFF" state is -66 dB.~~ (b) The four different phase shift responses. ~~From 4.14 GHz to 4.35 GHz, the average relative error angle is less than 10°.~~ (c) The switch ~~control signal~~ MS for STPM unit cells at the position d_{11}, d_{12} and d_{13}, where blue means the ~~pin~~ PIN diode ~~is on~~ are switched. (d) Simulated radiation patterns for different harmonics generated by STPM at ~~the~~ a target angle of 20°.

show that within the bandwidth, the average "ON"-"OFF" ratio is 27.6 dB ~~and the average relative error angle for the phase shift of four "ON" states is less than 10°~~.

III. Simulation Result

Simulation is performed to validate the STPM method with D = $\lambda/4$, a targeted angle 20° and ~~operating~~ center frequency 4.2~~3~~ GHz. In order to simulate the ability of the STPM to form beam and suppress ~~spurious~~ undesired har bands, a ~~binary image~~ signal is transmitted through the time modulated metasurface. Fig. 3(c) ~~gives a pictorial representation of the switch control signal~~ illustrates a subset of MS of twelve metasurface ~~unit cells~~ ME at the position d_{11}, d_{12}, and d_{13}, where d_{mn} is defined ~~on~~ Eq. (1) ~~and the order of unit cells in the unit structure follows 0, $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$. The periodicity of the switch control signal and the offset between different unit structures can be clearly observed.~~ Fig. 3(d) shows the normalized power on five ~~different~~ harmonics. The normalized power of the ~~side band~~ harmonics containing the most power are all less than -15 dB and the power of the 1st harmonic reaches the maximum at our target angle.

Ref by (1)

IV. Conclusion

In this paper, a time modulated programmable metasurface structure and its control strategy is designed to ensure both flexibility and efficiency of beamforming and spurious bands suppression. The validity of the metasurface structure containing four "ON" states with different phase responses and one "OFF" state with low transmittance is shown by CST simulation and the control strategy of the STPM is tested by ~~MATLAB~~ which shows beamforming and undesired harmonic suppression abilities.

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