High Efficiency beamforming Based on Time-Modulated Programmable Metasurface

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***Abstract*—In this paper, a time-modulated programmable metasurface structure and its corresponding control strategy is designed to achieve beamforming and undesired harmonics suppression.**

***Index Terms*—Beamforming, Harmonic Suppression, Programmable Metasurface, Time-Modulated Array.**

I. Introduction

Recently, metasurfaces have attracted significant research interests due to its capability of tailoring the electromagnetic characteristics such as polarization, phase and amplitude at ease allows for the realization of beamforming [1] and frequency-division multiplexing [2]. As for metasurface beamforming, to make the control of EM waves more flexible, the active metasurface adds one or more switches on the metasurface structure, each switch brings two different states for active metasurface. More states means that the beam direction can be adjusted by switches, but it also increases the harmonic waves, leading to the efficiency degradation. Therefore, active metasurface faces the trade-off between flexibility and efficiency, especially in beamforming.

On the other hand, beamforming is achieved through the time-modulated array by exploiting time-domain signal processing techniques [3]. To achieve a low sideband level (SBL), the switching sequence can be designed such that a combination of signals modulated by those pulses will lead to suppression of undesired harmonics [4]. Therefore, it is a possible solution to construct flexible and efficient metasurface by applying the time modulation technique.

In this paper, as shown on Fig. 1, a time-modulated programmable metasurface (TMPM) is designed to receive external time modulation pulse signals to control the fast switching of each switch independently, so as to achieve beamforming and harmonic suppression. Each unit structure has four "ON" states with phase shift $\phi = (0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ and one "OFF" state with low transmittance. To apply time modulation method, a unit structure of four 1-bit metasurface unit cells are implemented to provide different phase shifts, and then combine them together to form a metasurface array.

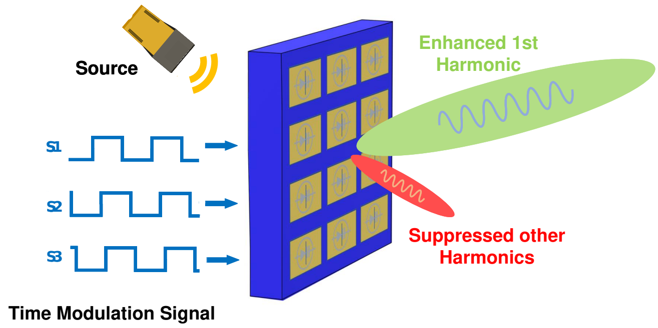

Fig. 1. Architecture of TMPM. Different time modulation signals are designed for each metasurface unit cell to achieve beamforming and suppress undesired harmonics.

II. Design and Theory

A. *Time Modulated Metasurface Principle*

To achieve high efficiency beamforming, time modulation control sequence for each switch should be designed. In this section, modulation sequence of metasurface with negligible inter-cell distance is first considered and then the impact of the distance is further calculated.

The length of each metasurface unit structure is defined as λ/D. As mentioned earlier, in ideal situation, each unit structure can be viewed as an array element which means that the distance $\lambda/2D$ between two unit cells vanishes. 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, then the position of the unit structure on the m^{th} row and n^{th} column under the ideal case can be defined as

$$d_{mn} = (m\lambda/D, n\lambda/D, 0). \tag{1}$$

Therefore, the array factor can be expressed as

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

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

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

where $U^0_{mn}(t)$, $U^{\frac{\pi}{2}}_{mn}(t)$, $U^{\pi}_{mn}(t)$ and $U^{\frac{3\pi}{2}}_{mn}(t)$ are control function on unit cell with different phases. Because those control functions consist of square wave, therefore $U^i_{mn}(i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ can be further expressed as

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

where T_p is the period of the switch control signal, τ is the time when the switch is on and t^i_{mn} is the time delay. The four cells' time delay and τ are designed as

$$\begin{cases} t^{\frac{\pi}{2}}_{mn} = t^0_{mn} + \dfrac{T_p}{4} \\ t^{\pi}_{mn} = t^0_{mn} + \dfrac{T_p}{2} \\ t^{\frac{3\pi}{2}}_{mn} = t^0_{mn} - \dfrac{T_p}{4} \\ \tau = \dfrac{T_p}{3} \end{cases} \tag{5}$$

where

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

To consider the impact of the interval between unit cells. A function $f_\Delta(x, y)$ can be defined to represent the time delay caused by the unit cell with position deviation (x, y) relative to the center of unit metasurface structures.

$$\begin{aligned} f_\Delta(x, y) = &|(x-1)\sin\theta\cos\phi + (y-1)\sin\theta\sin\phi - \cos\theta| \\ &- |\sin\theta\cos\phi + \sin\theta\sin\phi + \cos\theta| \,. \end{aligned} \tag{7}$$

For the relative position of the four unit cells related to the center of the unit metasurface structure is fixed, the advance of time can be defined as positive and the delay of time can be defined as negative. Therefore, $f_\Delta(x, y)$ can be modified into

$$f_\Delta(x, y) = -x\sin\theta\cos\phi - y\sin\theta\sin\phi. \tag{8}$$

Then the equation for modifying the four $t_{mn,i}$ 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.

$$t^{i'}_{mn} = t^i_{mn} - f_\Delta(x_i, y_i) \tag{9}$$

where $i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$ and (x_i, y_i) is the relative position of each unit cell, for example, $(x_0, y_0) = (-\frac{\lambda}{4D}, \frac{\lambda}{4D})$.

B. Unit Metasurface Structure Design

In this section, four 1-bit C-shape programmable metasurface unit cells with different phase responses are designed and form a metasurface unit structure. The improved structure is shown on Fig. 2. On the top layer is four thin copper rings with height h, inner diameter r and thickness w. Under the ring is a substrate with thickness h_{sub}, side length λ/D and dielectric constant 3.66. Two MA4AGFCP910 pin diodes produced by MACOM are added on each metal ring to realize the programmable function, and FPGA is used to control the fast switch of each unit cell independently to realize the time modulation. Through the design of opening angle β and orientation angle α towards the x-axis, phase modulation can be realized. When just one unit cell is opened, the unit structure produces phase response corresponding to that of the unit cell. Therefore, four "ON" states with different phase shifts can be achieved by open one unit cell and through closing all the pin diodes, "OFF" state can be produced.

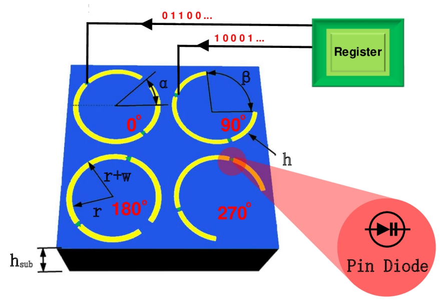

Fig. 2. Structure of C-shape metasurface unit structure with h={0.035, 0.018, 0.035, 0.018} mm, w={0.96, 0.84, 0.96, 0.84} mm, β={18, 108, 18, 108}°, α={45, 45, -45, -45}°, r=7.2 mm and h_{sub}=16 mm. Here the four parameters of all the data correspond to the unit cell perform 0, $\frac{\pi}{2}$, π,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

Simulation results performed through CST Microwave Studio is shown on Fig. 3(a) and Fig. 3(b), which show the transmittance and phase shift responses of the unit structure. At the operating frequency, 4.21GHz, the simulation results show that there exists about 45dB difference on transmittance difference between four "ON" states and the 'OFF', and four phases with separation of approximately $\frac{\pi}{2}$ in the four "ON" states.

III. Simulation Result

Simulation is performed to validate the TMPM method with T=4, targeted angle ...° and operating frequency 4.21GHz. In order to simulate the ability of the TMPM to form beam and suppress spurious bands, a binary image is modulated and transmitted through the time modulated metasurface.

Fig. 3(c) gives a pictorial representation of the switch control signal of twelve metasurface unit cells at the posi-

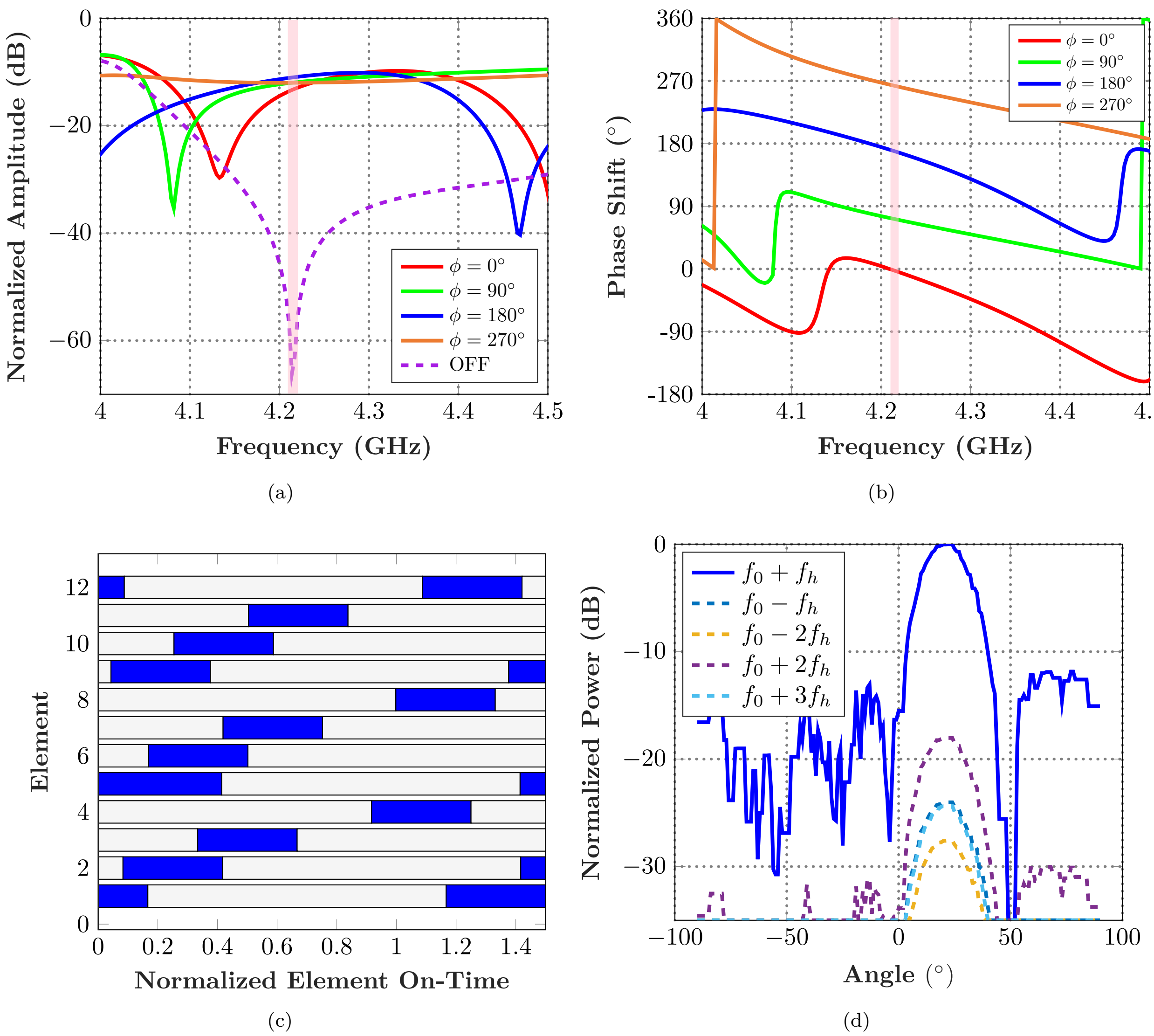

Fig. 3. Simulated characteristics of unit metasurface structure. (a) The S_{21} parameter of the five states. From 4.19GHz to 4.39GHZ, the S_{21} parameter for "ON" states is larger than -13dB and S_{21} parameter for the "OFF" state is less than -30dB. And the minimal amplitude response for "OFF" state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

tion d_{11}, d_{12} and d_{13}. 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 are all less than ...dB and the power of the 1_{st} harmonic reaches the maximum at our target angle.

IV. Conclusion

In this paper, a time modulated programmable metasurface structure and its corresponding 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 metasurface array is tested by MATLAB which shows accurate beamforming and effective harmonic suppression abilities.

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