High Efficiency beamforming Based on Time-Modulated Programmable Metasurface

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

***Index Terms*—Programmable Metasurface, Time-Modulated Array, Single-Sideband.**

I. Introduction

Recently, metasurface have received wide attention due to its ability to manipulate electromagetic waves by controlling the polarization conversion, phase shift and amplitude response of electromagnetic waves. Many applications including beamforming, wireless communication, hologram and encryption have made great progress[...].

Focus on the area of metasurface beamforming, there are two kinds of metasurfaces: passive and active. Each unit of passive metasurface has only one response mode, so after periodic arrangement, the beam can only form on a specific direction. The active metasurface adds one or more switches on the metasurface structure, each switch brings two different states for active metasurface, and the formed wave can direct to many different directions. During this process, metasurface faces the trade-off between flexibility and efficiency, especially in beamforming. More states means that the beam direction can be adjusted by switches, but it also increases the harmonic waves, leading to the efficiency degradation.

So how to use active metasurface with less states to realize beamforming and suppress harmonics to ensure flexibility and efficiency at the same time becomes an important problem. In this context, beamforming achieved through the time-modulated array by exploiting time-domain signal processing techniques [1] becomes a potential solution. 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 [2].

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.

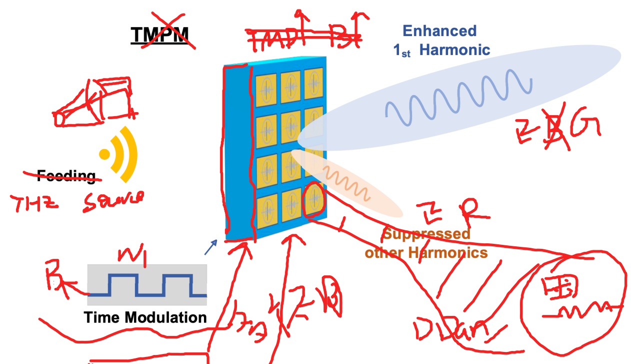

Fig. 1. Architecture of TMPM.

II. Design and Theory

A. Time Modulated Metasurface Principle

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

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

So the array factor can be written 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 written 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.

The control signal consists of square wave so that the control functions $U^{i}_{mn}(i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ can be further writtern 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.

For each unit structure, the four cells' time delay and τ can be written as

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

where

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

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

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

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

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

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. And the value of τ remains unchanged.

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

where $i = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$, (x_i, y_i) is the relative position of each unit cell, for example, $(x_1, y_1) = (\frac{\lambda}{4D}, \frac{\lambda}{4D})$.

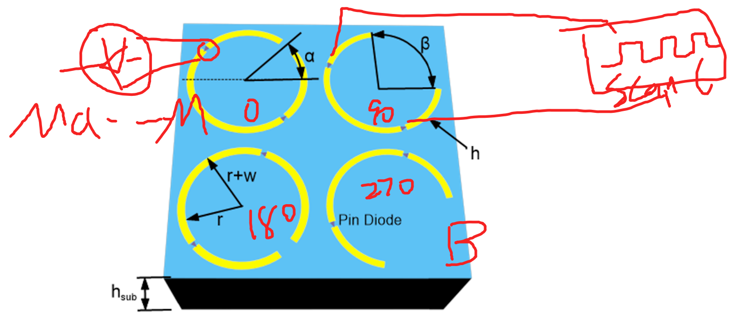

Fig. 2. Structure of C-shape metasurface unit structure with h={0.035, 0.018, 0.035, 0.018} mm, w={0.96, 0.84, 0.96, 0.84} mm, β={18, 108, 18, 108}°, α={45, 45, -45, -45}°, r=7.2 mm and h_{sub}=16 mm. Here the four parameters of all the data correspond to the unit cell perform 0,$\frac{\pi}{2}$,π,$\frac{3\pi}{2}$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

B. Unit Metasurface Structure Design

In this section, four 1-bit C-shape programmable metasurface unit cells 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.

Simulation results performed through CST Microwave Studio is shown on Fig. 3, which shows 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 20° 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. **??** gives a pictorial representation of the switch control signal of twelve metasurface unit cells at the position d_{11}, d_{12} and d_{13}. The periodicity of the switch control signal and the offset between different unit structures can

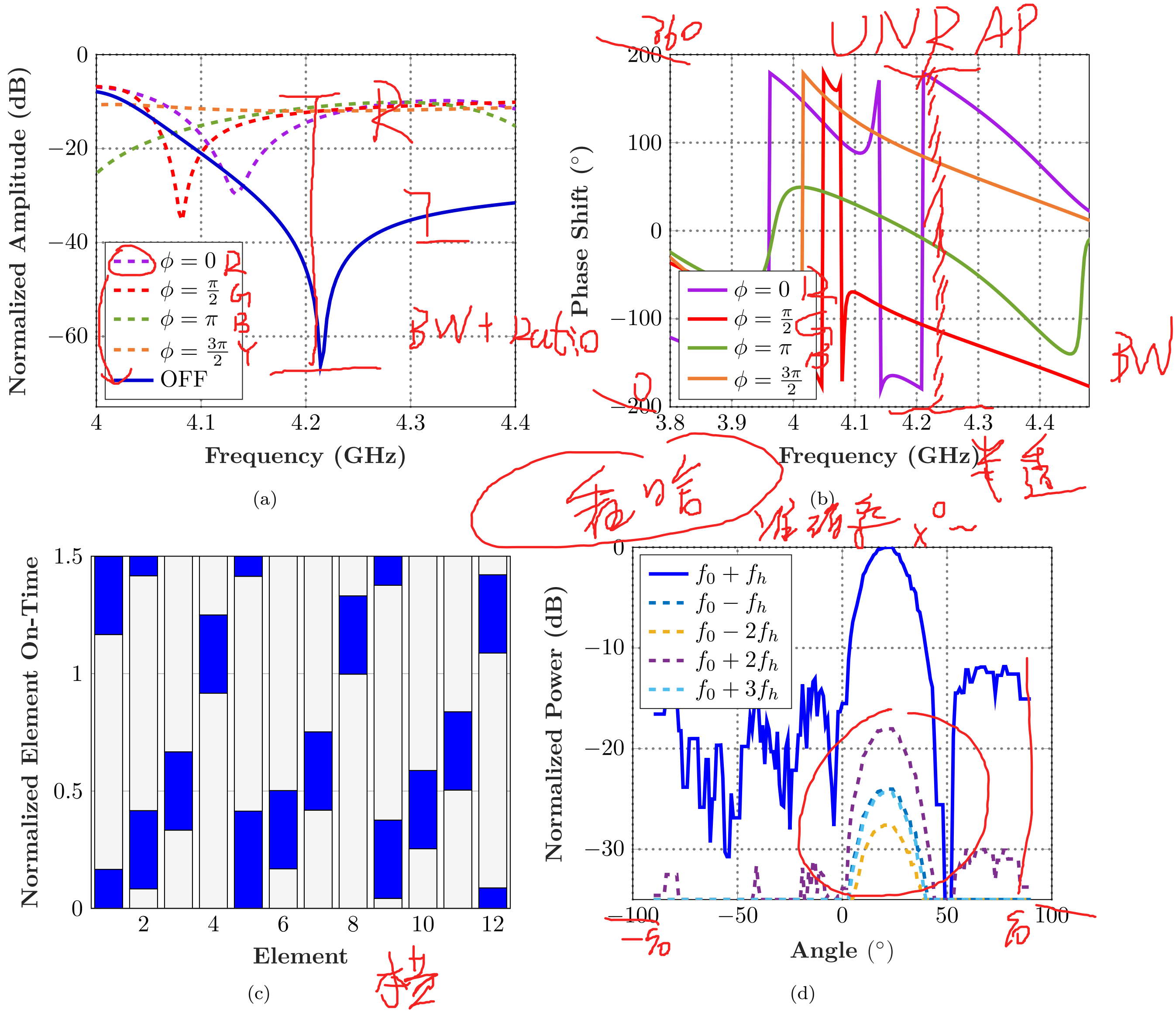

Fig. 3. Simulated characteristics of unit metasurface structure. (a) The S_{12} parameter of the five states. (b) The four different phase shift responses.

be clearly observed. Fig. **??** shows the normalized power on five different harmonics. The normalized power of the side band are all less than -18dB and the power of the 1_{st} harmonic reaches the maximum at our target angle.

IV. Conclusion

In this paper, a time modulated transmitive programmable metasurface structure and its corresponding control strategy is designed to achieve beamforming and spurious bands suppression. The CST simulation is provided to ensure the validity of the characteristic of the structure and the Matlab is used to test the control strategy of the metasurface array. Both the two simulation shows excellent results in line with our expectation.....be specificc Introducing time modulation into metasurface can ensure the flexibility and efficiency of beamforming, namely, use less states for each unit cell to perform more complex functions.to solve blabla problem, TM technique blabla

References

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