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, the possibility for metasurface to engineer electromagnetic (EM) space and manipulate the EM wave propagation by tailoring permittivity and permeability arbitrarily has received wide attention. The application of metasurface spreads among beamforming [1] and communication [2]. then? may be focus on the advantages for Meta to achive beamforming However, metasurface faces the trade-off between flexibility and efficiency, especially in beamforming. The less states a metasurface cell has, the higher its energy efficiency and accuracy, but in this case the direction of the formed beam is limited. On the other hand, too many states will increase the harmonic waves, leading to the efficiency degradation and the crosstalk problem. grammar? will cause a increase of undesired harmonics, leading to blabla 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].

In this paper, as shown on Fig. 1, a time-modulated programmable metasurface (TMPM) is designed to apply the time modulated method on metasurface to achieve both flexibility and efficiency on beamforming grammar. Each unit structure has four on state with phase shift $0,\frac{\pi}{2},\pi,\frac{3\pi}{2}$ and one off state with low transmittance. connection? talk about your design for the "flexibility and efficiency" discussed in the first para

II. Design and Theory

A. Unit Metasurface Structure Design

A metasurface structure with five states which is on state with $\phi=(0,\frac{\pi}{2},\pi,\frac{3\pi}{2})$ phase shift and an off state need

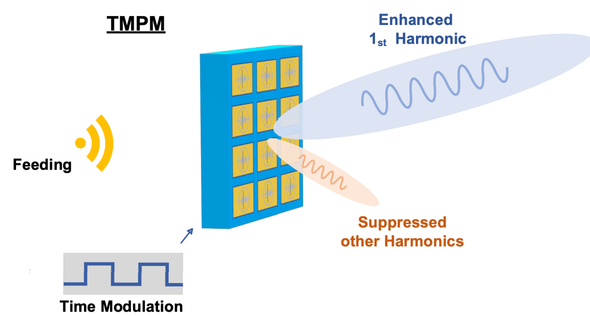


Fig. 1. Architecture of TMPM.

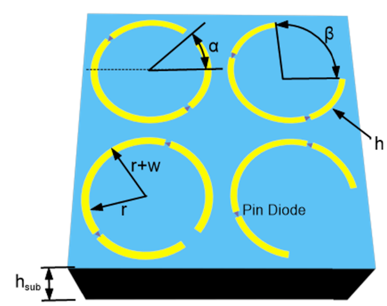
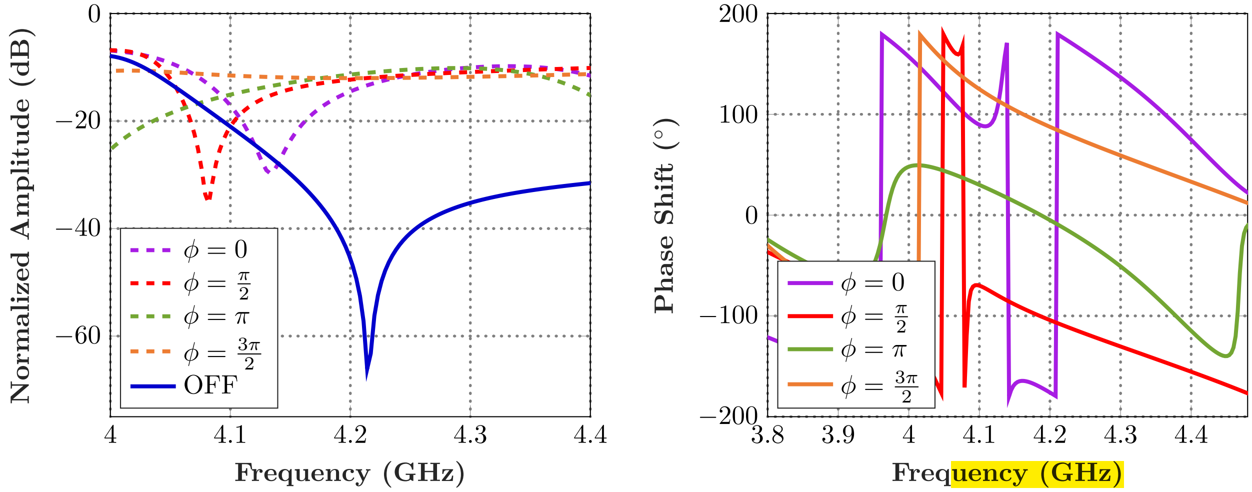


Fig. 2. Structure of C-shape metasurface unit structure with h={0.035, 0.018, 0.035, 0.018}mm, w={0.96, 0.84, 0.96, 0.84}mm, β={18, 108, 18, 108}°, α={45, 45, -45, -45}°, r=7.2mm and h_{sub}=16mm. Here the four parameters of all the data correspond to the unit cell perform $0,\frac{\pi}{2},\pi,\frac{3\pi}{2}$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

to be designed. After applying time modulated method, we do not need to design the complex 3-bit metasurface structure which is hard to ensure efficiency. But only need to design four 1-bit metasurface unit cells to provide different phase shifts, and then combine them together to form a unit structure. move those description in the into? till now, readers do not know that is time modulation

Here, we design four different C-shape programmable metasurface unit cells, and form a metasurface unit structure. do not use we The improved structure is shown on Fig. 2. On the top layer is four thin copper rings with



(a) (b)

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

height h, inner diameter r and thickness w. Under the ring is a substrate with thickness h_{sub}, side length λ/D and material Rogers RO4350B. 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.

Then Remove then the simulation results of our structure are given by CST Microwave Studio. Fig. 3 shows the transmittance and phase shift responses of the unit structure. combine them into a sentence At the operating frequency which is 4.21GHz .....grammar, the simulation results show an obvious transmittance difference between the on and off states, and four phases with separation of approximately $\frac{\pi}{2}$ in the four on states "ON" states.

B. Time Modulated Metasurface Principle

what's out goal 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. ? I don't get that

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 m^{th} row and n-th column under the ideal case can be defined as remove imperative sentence

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

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 writtern as

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

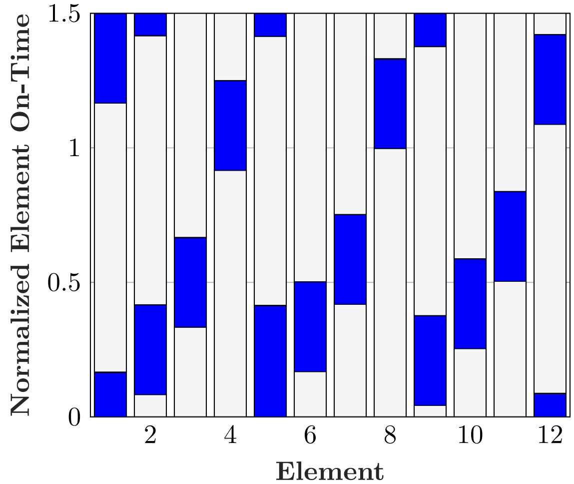


Fig. 4. The switch control signal for TMPM

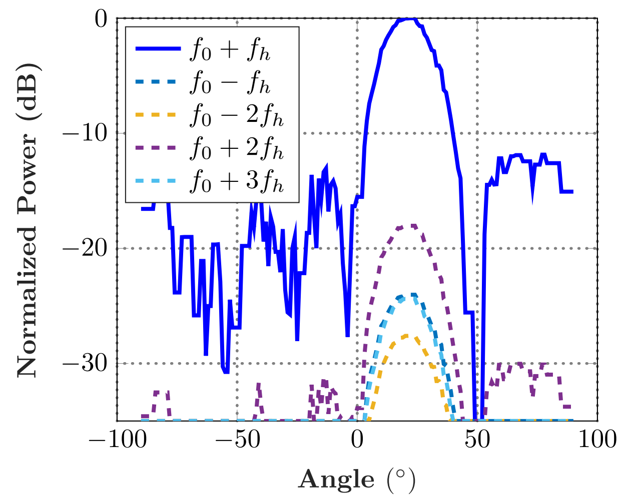


Fig. 5. Simulated radiation patterns for different harmonics generated by TMPM

where

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

Then the interval between unit cells can be considered. We can define a function $f_\Delta(x, y)$ to represent the time delay caused by the unit cell position deviation (x, y). then.... we....

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

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 ([?]) can be modified into

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

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.

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

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, $(x_1, y_1) = (\frac{\lambda}{4D}, \frac{\lambda}{4D})$.

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. 4 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 be clearly observed. Fig. 5 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

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