A Wide-Angle Series-Fed Active Metasurface

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***Abstract*—Wide-angle radiation capability allows antenna systems have wide-angle coverage and provide spectral and angular diversity desirable to many wireless communication systems. Previous schemes have aimed to achieve wide-angle beamforming with a microstrip patch array, but they add considerable complication to the fabrication, weight and cost to the antenna array. In this paper, we demonstrate wide-angle beamforming with a series-fed active metasurface, which is achieved by proper design and concatenation of sub-wavelength spaced series-fed microstrip patches. The demonstrated active metasurface consists of 14 patch elements and the center-to-center distance between adjacent elements is less than 0.3 λ. The currents on the elements are tapered in a Taylor distribution. The designed metasurface radiates at ±70° in the elevation plane with a 3 dB beamwidth of 35° and a sidelobe level (SLL) of -8.69 dB. These meritorious characteristics of the proposed design demonstrate that the series-fed active metasurface has good prospect to simplify the communication systems and keep the wide-angle function simultaneously.**

Keywords*—*Active metasurface, series-fed antenna, antenna array, microstrip antenna.

I. INTRODUCTION

Antenna arrays are useful in producing highly-directive beams and hence find many applications in radars and long-range, highly-efficient communication systems. The microstrip patch antenna has found particular popularity due to their compact form factor and desirable radiation characteristics. However, the wide-angle scanning performance of a microstrip antenna array is limited to ± 50° due mainly to several factors: (i) impedance mismatch at a wide scanning angle [1]; (ii) low gain at the wide scanning angle of the patch element [2]; and (iii) mutual coupling between array elements [3].

Researchers have expended much effort to increase the scanning angle of the phased array antenna. Firstly, the high impedance surface (HIS) has been proposed and demonstrated to broaden the scanning range of the phased array antenna [4][5]. The operation of the HIS is based on the electromagnetic image theory. The equivalent electric current generated by the patch antenna, placed in parallel and close to a magnetic wall implemented by a HIS substrate, radiates with a wide beam of around 180° in the elevation plane [1], which is hence useful for wide-angle scanning. Secondly, a pattern-reconfigurable element has been applied to replace the unit cell which has single radiation pattern [6][7]. The pattern-reconfigurable element is consisted of several modes, each of which cover a certain angular radiation space. Wide-angle coverage is achieved by the properly joining the modes. Thirdly, a decoupling

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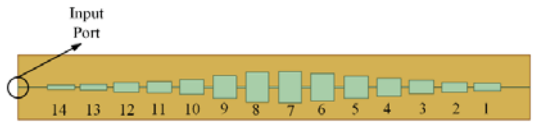

Fig. 1. The model of the series-fed metasurface

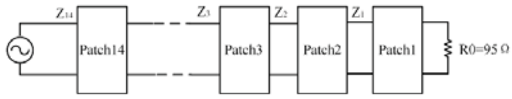

Fig. 2. The diagram of the series-fed metasurface

network has been used in the patch array system to improve the angular scan range to improve the impedance mismatch at wide angles caused by the mutual coupling between the patch elements [3]. Although the above methods can broaden the scanning angle to varying degrees, they introduce more complex structures which brings complications in design and fabrication. Further, the addition of the said structures would increase the size, weight and cost of the antenna. A simple route achieve wide-angle directive beamforming would be greatly desired.

We propose to achieve wide-angle directive beamforming with a series-fed active metasurface. We design sub-wavelength, resonant patches connected in a series-fed formation, but unlike previous works, we greatly reduce the distance between the elements to less than 0.3 λ. Each element is connected by microstrip line which provides the phase shift between adjacent elements. We successfully negotiated the geometric parameters and operated in a regime where mutual coupling effects remained manageable, despite the sub-wavelength separation between the patches. The series-fed architecture relieves the need for a complicated feeding network, which greatly simplifies the antenna.

II. THEORY AND METHODOLOGY

The radiation pattern of the phased array antenna is determined by the pattern of the elements and the array factor and follows the multiplicative theorem :

$$F = F_I \cdot F_a \tag{1}$$

where F is the pattern of the array antenna, F_I is the pattern of the element and F_a is the array factor. The beam pointing angle θ_B is determined by

$$\theta_B = \arcsin\left(\frac{\lambda}{2\pi d}\Delta\phi_B\right) \tag{2}$$

where λ is the working free-space wavelength, d is the center-to-center distance between the adjacent elements and $\Delta\phi_B$ is the phase shift between the excitation currents on adjacent elements.

In this work, a termination resistance of load (95 Ω) is connected to the terminal of the circuit. The width of the connecting microstrip transmission line is tuned to match with the input impedance of each section. Fig. 1 shows the model of our proposed series-fed active metasurface; Fig. 2 shows the equivalent circuit diagram. Z_n for ($n = 1$ to 14) are the characteristic impedances of the microstrip transmission lines before the corresponding patches.

In addition to controlling the phase of the current excitation, we also control the amplitude of the currents by tuning the size of the patches.Specifically, we aim to achieve a Taylor distribution of the currents which has been verified to reduce the SLL [7].

The design process is shown in Fig. 3. We first design the size of the first patch (closest to the terminal load), as shown in Fig. 3. (a). By tuning the width of the microstrip transmission line and the value of the load, it can be matched at the input port, as shown in Fig. 3. (c) . Then we add the second patch (Patch 2) on the "input" side of Patch 1, as shown in Fig. 3. (b). Here, we tune the width of patch 2 such that the current amplitude ratio on both patches are in approximate accordance to the Taylor distribution. Similarly, we tune the width of the transmission line before patch 2 to achieve impedance matching at the input as shown in Fig. 3. (d). We go on to repeat this procedure for the remaining antenna elements. The length of all the patches are close to 0.5 λ_g . However, due to the size difference of the patches, the length of the patches is slightly adjusted such that all patches radiate at resonance. Table I gives geometric parameters of the series-fed metasurface in detail.

In our proposed design, $f = 2$ GHz, $\lambda = 150$ mm , $d = 40$ mm. We used a Rogers RO3006 substrate with a dielectric constant of 6.15 and a thickness of $h = 3$mm.

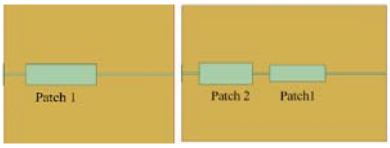

Fig. 3. (a) The model of the first (b) the second section.

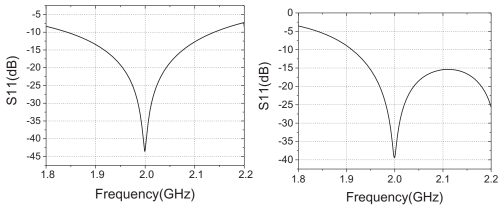

Fig. 3. (c) The S parameter of the first (d) the second section.

TABLE I. GEOMETRIC PARAMETERS OF THE SERIES-FED METASURFACE

No.i	Patch width/mm	Patch Length/mm	Line width/mm	Line Length/mm
1	10.0	32.7	1.0	8.0
2	12.5	31.4	1.3	9.1
3	16.5	30.6	1.5	10.0
4	22.0	29.6	1.7	10.6
5	27.0	29.3	1.9	12.1
6	34.0	28.5	2.2	11.6
7	38.0	28.4	2.2	11.6
8	37.0	28.5	2.2	11.5
9	28.0	28.6	2.2	11.0
10	18.0	29.6	1.8	10.2
11	14.0	30.2	1.6	9.6
12	12.0	30.8	1.4	8.2
13	7.5	33.0	0.8	7.9
14	6.0	33.3	0.7	

III. SIMULATION AND RESULTS

By tuning the size of the patches, we control the current in a tapered distribution which is close to Taylor distribution. As shown in Fig. 4, patch 7 and patch 8 have the maximum current values. Then from Patch 7 to Patch1 and from Patch 8 to Patch 14, the current value shows a decreasing trend, which closely approximates the Taylor distribution . Due to that the patches are matched well by using microstrip lines with varying width before them, we achieve impedance matching across a respectable S11 as shown in Fig. 5. At the design frequency of 2 GHz, the return loss is above 20 dB, which shows that excellent matching has been achieved.

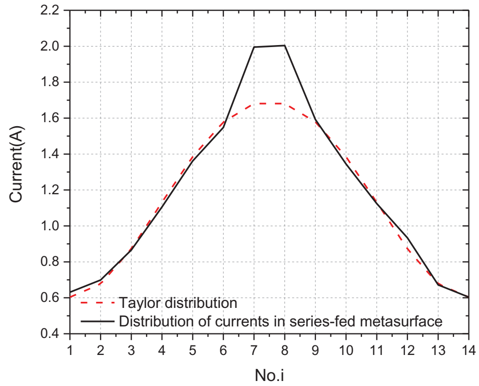

Fig. 4. The excitation current distribution.

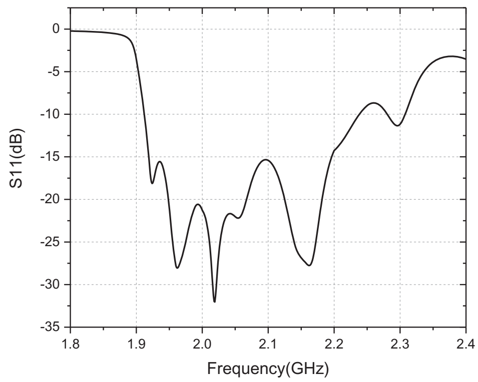

Fig. 5. The S parameter of the series-fed active metasurface.

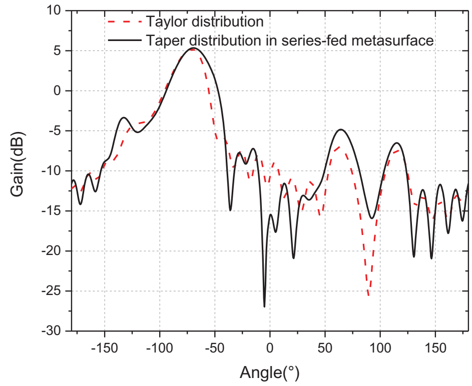

Fig. 6. The E-plane radiation pattern of the 1-D series-fed active metasurface and the radiation pattern of a corresponding antenna with the Taylor current distribution.

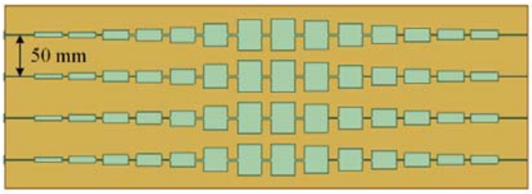

Fig. 7. The model of the 2-D series-fed metasurface.

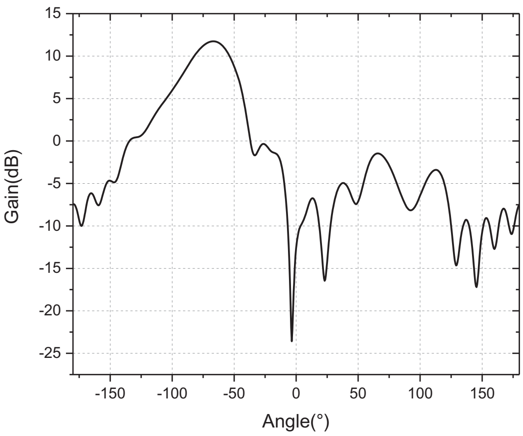

Fig. 8. The E-plane radiation pattern of the 2-D series-fed metasurface.

Fig. 6. gives the E-plane radiation pattern of the proposed series-fed active metasurface. The main beam is at 70° with gain of 5.33 dB, the SLL is -8.69 dB and the beam width of 3 dB is 35°. Although there is a small difference between the gain curve of our proposed work and the one when the currents are in ideal Taylor distribution, this difference is small and acceptable. In our ongoing work seek to further reduce the difference. We then duplicate the 1-D array 4 times to make it a 2-D metasurface. The center-to-center distance between 1-D array is 50 mm (λ/3), as shown in Fig. 7. We can see from Fig. 8 that the angle of the main beam is shifted to 67° but the gain is increased to 11.76 dB . The reduction of the angle is caused by the mutual coupling between the 1-D arrays. The proposed 2-D active metasurface has much more similar structure when compared to traditional phased array antennas, because that it does not introduce phase shifters and separate feeds for each elements. We will further work on the extension of the radiation angle not only in the E-plane but also in H-plane.

IV. Conclusion

This paper gives a design of the series-fed active metasurface which can radiate at ±70° from broadside. Compared with the existing researches which achieve wide-angle scanning by designing complex structures, our design has the advantage of simple structure. In addition, the distance between the center of the elements is less than 0.3 λ, which saves the space and the weight. So our proposed work has potential applications in greatly simplifying communication systems and optimizing their structures. Beyond antenna array applications, the series-fed active metasurface allows one to independently tune the phase and amplitude of a current distribution, with sub-wavelength precision across a multi-wavelength surface. It can thus be used for arbitrary waveform generation with applications in communication and imaging [8-10].

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