A new 1-bit configurable phase array antenna based on ‘ancient coin-like’ metasurface

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Abstract: Due to the low price, high efficiency and flexible manipulations, the metasurface has attracted more attentions. This paper proposes a new 1-bit configurable reflection array antenna with 11*11 unit cells. The unit cell in the metasurface, which is integrated with one PIN diode, shaped as ‘ancient coin’ can generate reflection phases between 165°-195° (180°±15°). The new phase array antenna can realize flexible manipulations to EM (electromagnetic) waves.

1. INTRODUCTION
When Professor Cui Tiejun put forward the programmable metasurface in 2014[1], this new method had attracted more attention. Compared with the traditional phase array antenna, which has complex servomechanism and high cost, the new phase array antenna with metasurface has some advantages in low price, high efficiency and lightweight. To realize the configurable technology, PIN diode is used to control phases usually. One PIN diode has two digital states ‘off’ and ‘on’ with 180° phase differences. By analogy, N PIN diodes will get 2^N digital states. One diode corresponds to one bit. In recent years, much attention has been paid on the study of 1-bit [2-5] and mutil-bit [6-8] metasurfaces. When electromagnetic waves illuminate to the metasurface, according to the digital state of each unit, the generated field intensity forms pattern in the far field. Different digital state distribution presents different pattern and different beam pointing. In this way, high gain and low side lobe beam can be achieved [9-11].

2. DESIGN OF UNIT CELL
2.1 Theoretical analysis
When EM waves illuminate to the metasurface, in order to achieve the specific beam, phase compensation should be made. The horn antenna \( H \) illuminates to the arbitrary unit cell \( E(p,q) \) on metasurface, an equal phase plane should be formed with the vertical plane of the specific direction, named \( u \) and \( u^* \), as figure 1 shows [12].
The following equation can be used to describe the relationship above:

\[-k \cdot D + \varphi_{pq} + k \cdot \vec{u} \cdot \vec{r}_{pq} = -k \cdot d + \varphi_{mn} + k \cdot \vec{u} \cdot \vec{r}_{mn}\]  \hspace{1cm} (1)

In the equation (1), $k$ is the propagation constant. $D$ and $d$ are the distance between the horn antenna $H$ and arbitrary unit cell $E(p,q)$ and between the horn antenna $H$ and unit $O(m,n)$, respectively. $\varphi_{pq}$ and $\varphi_{mn}$ are the phases of $E(p,q)$ and $O(m,n)$ respectively. $\vec{u}$ is the beam direction. $\vec{r}_{pq}$ and $\vec{r}_{mn}$ are the position vector of the unit. Because of $O(m,n)$ is original point, thus, equation (1) also can be written as

\[-k \cdot D + \varphi_{pq} + k \cdot \vec{u} \cdot \vec{r}_{pq} = -k \cdot d \]  \hspace{1cm} (2)

Therefore, the phase of arbitrary unit cell $E(p,q)$ is:

\[\varphi_{pq} = -k \cdot d + k \cdot D - k \cdot \vec{u} \cdot \vec{r}_{pq}\]  \hspace{1cm} (3)

2.2 Structure of the unit cell

The new 1-bit configurable unit cell is proposed in this paper as shown in figure 2:

| Dielectric layers | Materials | Dielectric constant | Thickness(mm) |
|-------------------|-----------|---------------------|---------------|
| 1                 | F$_2$BTM-1/2 | 4.4                 | 1.58          |
| 2                 | F$_2$BM220  | 2.2                 | 0.5           |
| 3                 | F$_2$BM220  | 2.2                 | 0.5           |
There is a voltage difference between the metal ground and bias circuit. By working on the digital state of 'off' and 'on', the PIN diode can provide 180° phase difference. $D$ and $R$ are the edge length of hexagon and the radius of the circle on the metasurface, respectively. The periodic length of unit cell is 7.8mm.

Simulation environment is HFSS, and the Floquet port is used to set as excitation. By optimizing the $D$ and $R$ at 14GHz, the simulation results are as follows (rectangular shadow range from 165°-195°):

| Parameters     | $D=1.5/R=2.8$ | $D=1.6/R=2.6$ |
|----------------|----------------|----------------|
| Bandwidth (GHz)| 2.5            | 2.2            |
| Reflection phase (deg) | 182            | 179            |
| Reflection loss (on)    | 0.69-0.85      | 0.43-0.99      |
| Reflection loss (off)    | 0.10-0.28      | 0.13-0.29      |

From the table II, both bandwidth are more than 2GHz, and reflection phases are 182°and 179°at 14GHz, respectively. Both reflection loss in 'off' are nearly zero, that means the EM waves has been reflected almost, rather than penetrated. It can meet the total reflection requirement of the unit cell on the phase array antenna.

3. DESIGN OF ARRAY

According to the result of II.B, both unit cells (Fig.4) have their advantages. The former (named E1) has wide bandwidth at the cost of reflection loss. Moreover, the later (named E2) does better in reflection loss and reflection phase differences, however, bandwidth is narrower than the former’s.
From the Fig.6, it can be shown that A1 is better than A2 in terms of reflection loss and reflection phase differences. In Fig.6 (a), A1-OFF and A1-ON are two smooth curves from zero to one. In Fig.6 (b), the reflection phase of A1 between 165°~195° is from 13GHz to 14.9GHz. The bandwidth reduces due to the coupling between the cells mainly.

According to the comparison above, the new metasurface sample is fabricated with 11*11 E1 unit cells shown in Fig.7.

The size of this new reflection array is 85.8mm*85.8mm. A horn antenna which working bandwidth is from 11.8 to 18GHz is employed as the feeding antenna to generate the EM wave to the coding metasurface. The simulation result of beam scanning at 14GHz is shown in Fig.8. Fig.9 shows the 3-dimension pattern of 0 degree and minus 30 degree beam pointing of the reflection array respectively. Both show good performance. The digital state distribution of minus 30 degree shows in Fig.10. (Black for “0”and white for “1”)

Figure 5 4*4 array antenna

Figure 6 Comparison of A1 and A2 (a) Reflection loss (b) Phase difference
4. CONCLUSION
This paper proposes a new reflection unit cell to achieve phase difference through PIN diode at 14GHz. This unit cell can meet requirement of reflection array well. From the 11*11-array antenna, the beam pointing increases accuracy and flexibility than traditional phase array antenna. In this paper, the new 1-bit phase array antenna can manipulate the beam flexibly to arbitrary direction. In addition, if there are more unit cells, the digital state distribution will be more smoothly. Meanwhile, it is easier to process the large antenna than the small one. In a word, it is of great significance to improve the traditional phase array antenna and has better prospects.

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