# A Broadband Reflectarray Based on Vivaldi Antenna Elements

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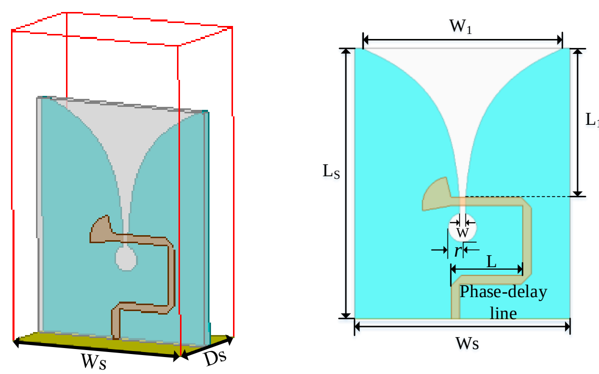
***Abstract*** **─** In this paper, a novel broadband reflectarray (RA) is presented. For achieving broadband performance, the unit cell is realized using Vivaldi antenna element, where the feeding line acts as phase delay-line for adjusting the reflection phase. By simply changing the length of phase delay-line, a full 360º phase coverage is obtained. Additionally, the phase response curves are nearly parallel within a broad bandwidth, leading to a wideband operation. To verify this design, a prototype consisting of 10×22 unit cells is designed, fabricated and measured. The measured results show that the maximum gain reaches 21.50 dBi with 20.15% 1-dB gain bandwidth and 30.38% 3-dB gain bandwidth, respectively. Simulated and measured results agree very well with the proposed design scheme.

***Index Terms*** **─** Broadband, high gain, reflectarray, Vivaldi antenna array.

## I. INTRODUCTION

Nowdays, it becomes more and more challenging to satisfy the ever-lasting capacity-growing and users-boosting demands in wireless networks. For example, many electronic devices in civil and military areas are preferred to be connected using wireless technology. To support these connections with high date rate, mobility and stability in wireless systems, antennas are highly required to have the properties of high gain, broad bandwidth and stable radiation characteristics [1-2]. In addition, for commercial applications, it is important to reduce the complexity of antenna structures and have low cost.

Reflectarrays (RAs) have been considered as promising alternative to traditional high-gain antennas because of their high gain, compact structure, lightweight, low cost, easy beam forming, etc. Compared to conventional antenna arrays and parabolic reflectors, RAs do not need complicated feeding network and have planar structure [3-5]. However, the RAs have a severe drawback of narrow bandwidth performance mainly due to the inherent narrow bandwidth for microstrip antenna unit cell and the differential spatial phase delay caused by different path lengths from feed source to each unit cell [6-7]. In recent years, many methods have been proposed to increase the bandwidth of the reflectarray, including the use of multilayer structures [8-10], subwavelength element [11], dual-frequency phase synthesis [12], and true - time delay technique [13]. In [14], a three-layer printed reflectarray with patches of variable size was designed, whose 1-dB bandwidth reaches to 10%. In [15], double-layer subwavelength elements with variable size were employed to enlarge the gain bandwidth of the reflectarray antennas. Besides, by employing tightly coupled technique, an ultra-wide-band reflectarray antenna was reported in [16].




(a) (b)

Fig. 1. The unit cell of this reflectarray: (a) periodic structure view; (b) front view.

As a kind of exponential tapered slot antenna, Vivaldi antennas provide a wide impedance bandwidth and stable gain. They are fabricated using low-cost planar fabricating technology. Hence, they are used in many applications which demand wide or ultra-wide bandwidth and directional radiation properties, such as ultra-wideband (UWB) imaging systems and emerging 5G systems [17]. However, one serious problem of Vivaldi antenna arrays is that it requires a complicated, bulky feed network consisting a number of power dividers, which will introduce significant losses at high frequency above X-band. Moreover, the perpendicular structure between Vivaldi array and feeding network

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improves the fabrication complexity seriously. These drawbacks extremely limit the applications of large Vivaldi antenna arrays.

Inspired by the concept of RAs and wideband property of Vivaldi antennas, a wideband unit cell based on Vivaldi antenna is proposed to enhance the bandwidth performance of reflectarray in this paper. The feeding line in the Vivaldi element is used as phase-delay line to control the reflection phase response. By varying the length of the delay line, a full 360° linear phase range within a broad bandwidth is obtained. Within its operating frequency, the reflection magnitude maintains above -0.5 dB. To verify the design, a wideband reflectarray consisting of 10×22 unit cells is designed, fabricated and measured. The maximum gain of the proposed reflectarray is approximately 21.50 dBi with the 1-dB gain bandwidth of 20.15% and 3-dB gain bandwidth of 30.38%, respectively.

Table 1: Optimized parameters of the Vivaldi antenna

| Parameter | $L_S$ | $W_S$ | W |
|---|---|---|---|
| Value (mm) | 18.6 | 15 | 0.4 |
| Parameter | *r* | $L_1$ | $W_1$ |
| Value (mm) | 1 | 7.3 | 14 |

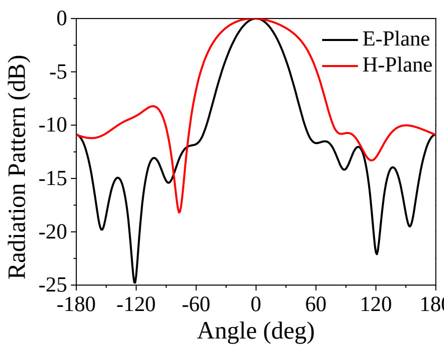



Fig. 2. The simulated radiation patterns of unit cell at 13GHz.

## II. DESIGN OF UNIT CELL

The geometry of the proposed unit cell is shown in Fig. 1, which is composed of a conventional taper-slot Vivaldi antenna and a metallic reflect plane. As can be seen, the taper-slot with a circle-end is printed on the ground of the Vivaldi antenna element. The phase-delay line beginning with a fan-shape is etched on the other side of the substrate for coupling electromagnetic (EM) signals through the taper-slot. This structure can provide a stable radiation patterns and good impedance matching over a wide frequency range. A metallic plane with the dimension of 15×6.8 $mm^2$ is placed at the end of the Vivaldi antenna element for reflecting EM signals. This proposed unit cell is printed on a 0.8 mm Rogers 4003C substrate with dielectric constant of 3.55 and loss tangent of 0.0027.

The operating principle of the proposed unit cell can be described as follows. The incident waves illumining the unit cell is received by Vivaldi antenna element and transmit through the delay line. Because the delay line is metallic ended, the waves will be reflected and radiated by the Vivaldi element. During this process, the functions of the delay line are signal transmitting and phase controlling. By varying the length of the delay line on each unit cell, the corresponding reflection phase can be simply controlled. It is worth noting that in order to obtain a more compact configuration and increase the length of the delay line, the delay line is bent and stretched. The unit cell has been optimized to operate at Ku-band. The optimized parameters are reported in Table 1.

To investigate the reflection coefficient of the unit cell, numerical simulations are carried out by using ANSYS HFSS software. The infinite array model is built by placing master- slave boundary around the unit cell with Floquet port excitation.

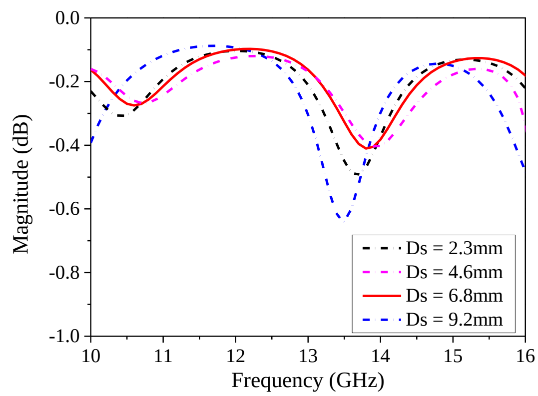



Fig. 3. The reflection magnitudes of the unit cell with different Ds.

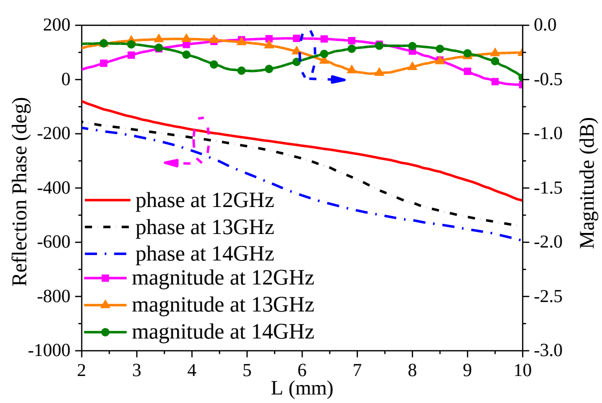



Fig. 4. Simulated element phase shifts and magnitudes at different frequencies.

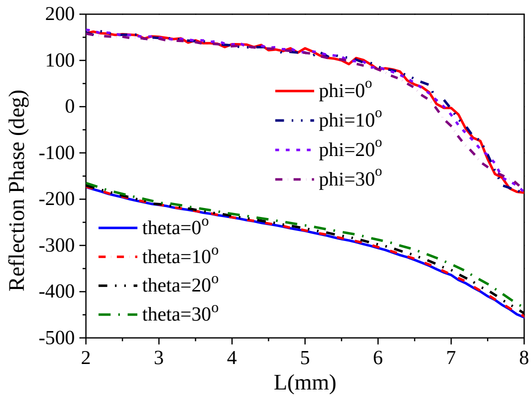
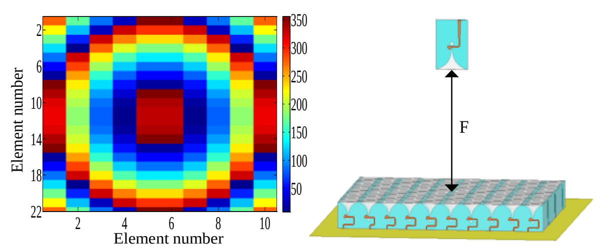



Fig. 5. The reflection phase of the unit cell with different oblique incidence.

Figure 2 shows the simulated radiation patterns of unit cell at 13GHz. The 3-dB beamwidth of the radiation pattern on the E-plane and H-plane is 28° and 49°, respectively. The simulated magnitudes of unit cell with different Ds is presented in Fig. 3. As can be seen, the unit cell has good reflection performance when Ds is 6.8mm (0.3 λ), whose magnitude is lower than -0.4dB within 10GHz to 16GHz. Therefore, the optimized Ds is finally chosen as 6.8 mm in this paper. Figure 4 shows the simulated reflection phase and magnitude for a normal incident wave at different frequencies. It can be observed that the reflection phase covers a full 360° phase range as the delay line varies from 2 mm to 10 mm. Besides, within 12 GHz to 14 GHz, the phase response curves maintain parallelism with each other, which imply that the unit cell has a good wideband response. The magnitude curves show a good reflection performance, whose values are above -0.5 dB in the operating band.




(a) (b)

Fig. 6. (a) The phase distribution of the reflectarray. (b) The 3-D structure of the reflectarray.

In general, most of the unit cells are not located in the center of the reflectarray and they are obliquely illuminated by the incident waves, so it is necessary to consider the performance of the reflection phase when the incident angle is different. Figure 5 simulated the phase response of the unit cell under different incident angles. It is clearly seen that compared to normal incident illumination, the unit cell illuminated by 30° (theta or phi) incident waves still can maintain a very stable performance with little phase variation. Hence, according to the above analysis, the proposed unit cell has the properties of broadband operation, high reflection magnitude, full phase range, low sensitive of incident angle, which is desired to constitute a wideband reflectarray.

## III. SIMULATION AND MEASUREMENT

To obtain high-gain performance, the reflection phase for each unit cell must be designed to compensate for different path lengths from the illuminating feed, and achieve a uniform phase on the array aperture. The required reflection phase $\varphi_i$ for the i$^{th}$ unit cell is calculated as:

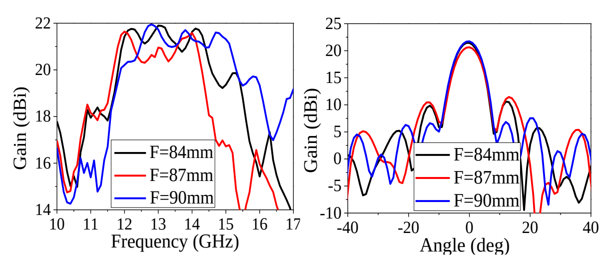
$$\varphi_i = k_0(R_i - \vec{r}_i \cdot \hat{r}_0) + \varphi_0, \qquad (1)$$

where $k_0$ is the propagation constant in free space, $R_i$ is the distance from feed antenna to the i$^{th}$ unit cell, $\vec{r}_i$ is the position vector of the $i^{th}$ unit cell, and $\hat{r}_0$ is the main beam unit vector. For generating the far-field at the broadside direction, $\vec{r}_i \cdot \hat{r}_0$ =0, where $\varphi_0$ is a phase constant that is selected to drive the reference phase at the aperture center phase to a certain value. Once the required phase at each unit cell is determined, the corresponding length of delay line in unit cell, namely the parameter of '$L$', can be obtained from Fig. 3.

When feed antenna non-uniformly illuminates the reflectarray consisting of M×N unit cells, the reradiated field from the array in an arbitrary direction can be represented by:

$$\vec{E}(\vec{u}) = \sum_{i=1}^{n}\sum_{j=1}^{m} F_f(\vec{R}_{ij}\cdot\vec{R}_f)F(\vec{R}_{ij}\cdot R_0)F(\vec{R}_0\cdot\vec{R})F(\vec{R}_0\cdot\vec{R}) \cdot \exp\left\{-jK_0\left[\left|\vec{R}_{ij}-\vec{R}_f\right| - \vec{R}_{ij}\cdot\vec{R}\right] + j\varphi_{ij}\right\}, \qquad (2)$$

where $F_f$ is the radiation pattern function of the feed antenna, F is the radiation pattern function of the Vivaldi element, $\vec{R}_{ij}$ is the position vector of the $ij_{th}$ element, $\vec{R}_f$ is the position vector of the feed, $k_0$ is the free-space wavenumber, and $\varphi_{ij}$ is the required phase delay of the $ij_{th}$ element.




(a) (b)

Fig. 7. (a) The bandwidth of the RAs with varying F at the broadside direction; (b) the radiation pattern of the RAs with varying F at the broadside direction.

Table 2: Simulated results with different F

| Focal Length | 84mm | 87mm | 90mm |
|---|---|---|---|
| Unit numbers | 10*22 | 10*22 | 10*22 |
| Maximum gain/dBi | 21.90 | 21.64 | 21.94 |
| 1-dB bandwidth | 17.7% | 17.3% | 20.7% |
| 3-dB bandwidth | 29.6% | 22.7% | 33.4% |

According to function (1), the phase distribution for generating narrow beams along broadside direction is presented in Fig. 6 (a). As can be seen, the phase distribution shows a symmetric distribution around the array center. To validate the wideband performance of the reflectarray unit cell, a reflectarray antenna operating at 13 GHz is designed and simulated. This reflectarray consists of 10×22 unit cells with the dimension of 150×149.6mm$^2$. Based on the calculated phase distribution, the proposed wideband RA is built and shown in Fig. 6 (b).

Three different focal lengths are chosen to study the effects of F/D on gain performance, where *D* is the aperture size of the proposed reflectarray. Figure 7 presents the antenna gain and radiation patterns by changing F with fixed aperture dimension. It can be seen that the proposed reflectarray can successfully generate high-gain radiation patterns, where all of the maximum gain with different F/D are above 20 dBi. Meanwhile, the value of F/D impacts on the gain performance and gain bandwidth. Both of the maximum gain and gain bandwidth show growth trend with the increase of F/D. Table 2 reports the maximum gain, 1-dB gain bandwidth and 3-dB gain bandwidth with different focal lengths. According to the results, the focal length is finally chosen as 90 mm.

The simulated radiation pattern at 13 GHz is plotted in Fig. 8. The focusing pencil beam is produced successfully. With accurate phase distribution, the reflectarray has a high gain performance, whose maximum gain reaches 21.73 dBi at 13GHz. Figure 9 shows the side view of E-fields. As we can see, the proposed reflectarray has good focusing effects on EM waves. The incident spherical wave generated by the feed antanna is transmitted through the Vivaldi elements and reflected by the metallic plane, which is converted into plane wave. To verify the design, a prototype is fabricated, assembled and measured, as shown in Fig. 10. The overall dimension of the reflectarray is 220×220 mm$^2$ with the effective area of 150×180mm$^2$, which is covered by 10×22 unit cells. To assemble the proposed reflectarray and feed antenna, a frame and two supporters are designed, which are also considered during the simulations.

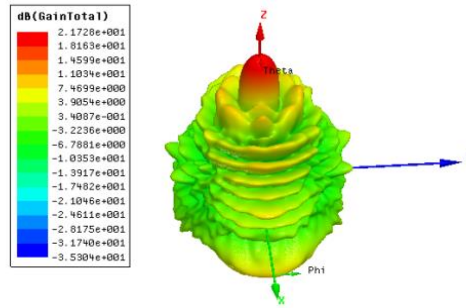



Fig. 8. The simulated radiation pattern at 13 GHz.

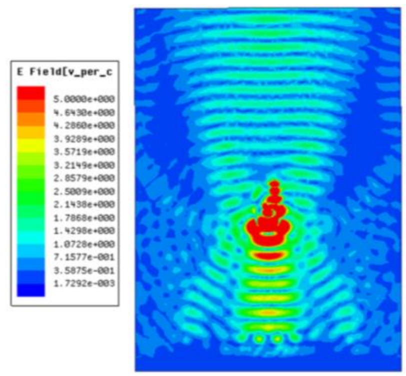
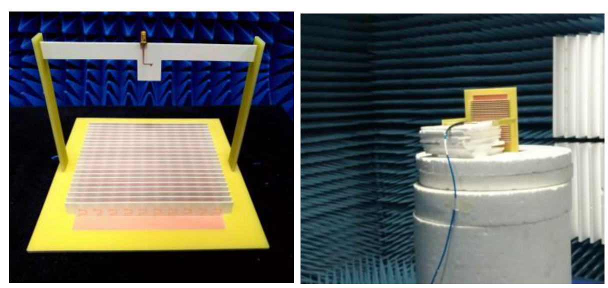


Fig. 9. The side view of E-fields.



(a) (b)

Fig. 10. The fabricated prototype: (a) the proposed reflectarray; (b) the E-field measurement in microwave chamber.

Vivaldi antenna is also selected as the feed antenna. It is placed above the reflectarray surface at the distance of 90 mm. Figure 11 (a) shows the simulated radiation patterns of feed antenna at 13GHz. The measured S parameters of the feed antenna is plotted in Fig. 11 (b), showing that the proposed feed antenna can work from 10 GHz to 18 GHz.

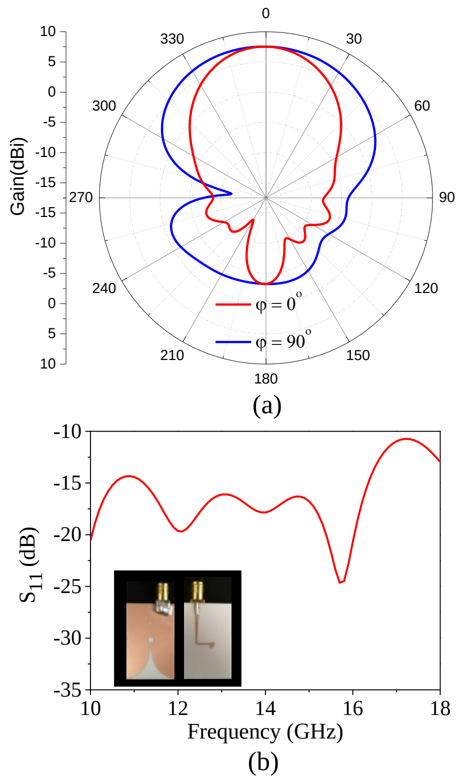



Fig. 11. The measured S parameter of the feed antenna.

Radiation patterns are measured in anechoic chamber. Figure 12 presents the measured E-plane and H-plane radiation patterns at 12 GHz, 13 GHz and 14 GHz, respectively. The simulated radiation patterns are also plotted as comparison. It can be observed that the simulated and measured results show a good agreement. Due to outstanding focused effects, pencil beams are generated. The 3-dB beamwidth of the radiation patterns is around 5°. Meanwhile, good cross-polarization lower than -20 dB is also achieved. Most of the side lobe level (SLL) are below -13 dB. Some measured SLL are slightly higher compared to these of the simulation. This can be the result of manufacturing tolerances and the manipulation setup. The measured gain is plotted in Fig. 12 to showing that the 1-dB gain bandwidth is 20.15% from 12 GHz to 14.6 GHz and 3-dB gain bandwidth is 30.38% from 11.54 GHz to 15.48 GHz, respectively. The measured maximum gain reaches to 21.5 dBi at 12.7 GHz. Clearly, the proposed reflectarray antenna is with outstanding high-gain and wideband characteristics. Moreover, the gain of feed antenna and the measurement results for aperture efficiency are also shown in Fig. 13. As we can see, the gain of feed antenna is stable at Ku-band, which is higher than 7.5dBi from11GHz to18GHz. The maximum aperture efficiency by the measurement is 23.1% at 12.6GHz.

Table 3 compares the proposed reflectarray based on Vivaldi antenna elements with other reported reflectarrays. The comparison mainly focuses on center frequency, maximum gain, aperture efficiency, 1-dB gain bandwidth and 3-dB gain bandwidth. As we can see, the proposed reflectarray based on Vivaldi antenna elements shows the superiority of wide gain bandwidth compared to those reported reflectarrays.

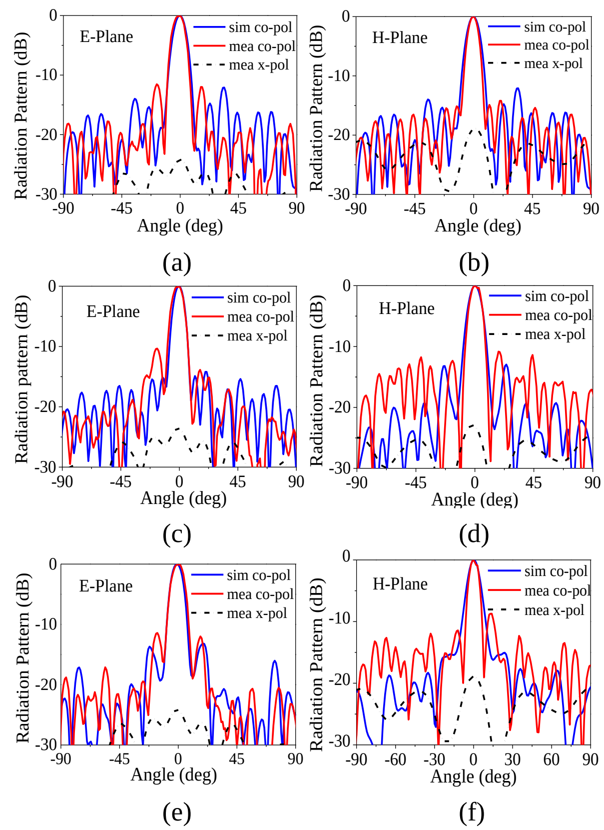



Fig. 12. The simulated and measured radiation patterns at: 12GHz (a), (b); 13GHz (c), (d); 14GHz (e),(f).

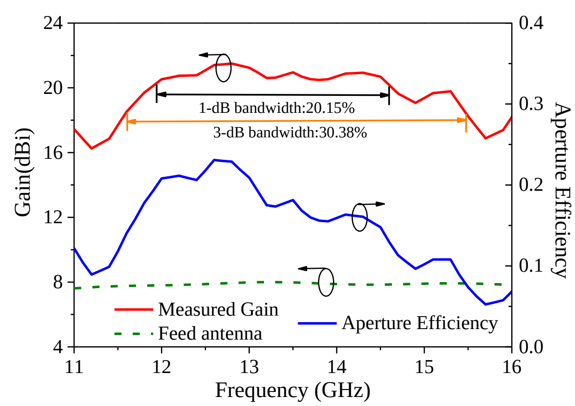



Fig. 13. The measured gain, aperture efficiency at the broadside direction and feed antenna gain.

Table 3: Comparison with other reported reflectarray

| Ref. | [5] | [7] | [10] | This Work |
|---|---|---|---|---|
| Center frequency (GHz) | 42.5 | 10 | 13.5 | 13 |
| Maximum gain (dBi) | 32.83 | 26.38 | 32.76 | 21.5 |
| Aperture efficiency | 51.11% | 51.3% | -- | 23.1% |
| 1-dB Gain bandwidth | 12.94% | 20% | 14.8% | 20.15% |
| 3-dB Gain bandwidth | 16% | 28% | -- | 30.38% |

## IV. CONCLUSION

In conclusion, a wideband reflectarray operating at Ku-band is designed by employing Vivaldi unit cells. By adjusting the delay lines, the required phase compensation can be simply achieved for producing high-band pencil beams. Arranging unit cells with different delay line length according to the calculated phase distribution, we have designed a reflectarray radiating along broadside direction with a focal distance of 90 mm. The measured results are in a good agreement with the simulated ones, which demonstrates a 20.15% 1-dB gain bandwidth and a 30.38% 3-dB gain bandwidth, respectively, with maximum gain of 21.5 dBi.

## ACKNOWLEDGMENT

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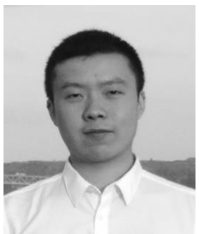

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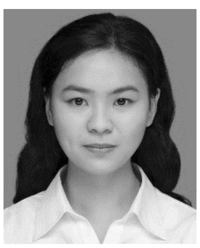

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