A New Type of Reflective Reconfigurable Electronic Beam Squinting Feed

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***Abstract* –** With the development of highly integrated technology, a large number of satellites have been launched into synchronous orbit, saturating the number of satellites in these orbits. As a result, there has been a substantial increase in demand for near-Earth orbit satellites. However, due to their proximity to Earth, the location of these satellites rapidly drifts in free space. To maintain the received and transmitted signals within range, the ground antenna must track the satellites immediately. Therefore, near-Earth orbit satellite tracking has become a key technology in satellite communication research. In order to further improvement, we propose a new type of electronic beam squinting (EBS) tracking feed. In this paper, we will conduct both theoretical and experimental analyses of this EBS feed.

***Index Terms* –** electronic beam squinting(EBS) system, near earth orbit satellites tracking technology, reconfigurable EBS feed.

I. INTRODUCTION

The electronic beam squinting (EBS) technique [1] was investigated in the 1980s. By applying electronic switching technology, the EBS tracking system [2] could effectively perform real-time spatial measurements of the tracking signal [3]. This pseudo-real-time amplitude sensing system enables almost real-time derivation of the tracking error, and its accuracy is comparable to that of a single-pulse system. Additionally, only a simple single-channel tracking receiver is required to receive the signal.

In this work, we propose a reflective reconfigurable EBS feed to replace the traditional feed in the EBS system. The reflective EBS feed is a type of TE_{21} mode coupler typically employed in precision tracking [4-10]. To ensure the tracking sensitivity and accuracy, it is essential to extract the TE_{21} mode signal as efficiently as possible while suppressing the TE_{11} mode by at least 40 dB. A common design for achieving this is the application of a 48-holes or 32-holes Bessel distribution coupler. In our work, we select the 32-holes coupler to excite a porous coupling in the reflective reconfigurable EBS feed.

The theory of waveguide coupling was extensively researched by Miller in the 1950s [11, 12]. Choung and colleagues [13] analyzed the TE_{21} mode using the loose and tight coupling mode coupler theory, providing an empirical determination of the coupling aperture in the Ku band equation. In the original EBS system, a slot coupling technique was applied to excite the TE_{21} mode in the primary waveguide. This slot was positioned perpendicular to the primary waveguide, between the primary and secondary waveguides. By adjusting the width of the slot, the TE_{21} mode could be coupled from the secondary waveguide to the primary waveguide. However, in the reflective reconfigurable EBS feed, the slot coupler is replaced by a porous coupler, which allows for stronger coupling while minimizing the coupling of higher order modes. This adjustment simplifies the filter design and improves port isolation. In consideration of structure, the secondary waveguide is located along the primary waveguide, effectively reducing the feed's horizontal size. This miniaturization greatly simplifies the system.

The reflective reconfigurable EBS feed utilizes a reconfigurable secondary waveguide at the reflective surface to control the phase of the transmitted TE_{10} mode in the secondary waveguide [14, 15]. As a result, the phase of the TE_{21} mode in the primary waveguide changes, thus modifying the phase distribution over the aperture. So, beam direction could be changed in both the azimuth and elevation directions, meeting the requirements of the EBS system.

II. DESIGN OF REFLECTIVE RECONFIGURABLE EBS FEED

In the reflective reconfigurable EBS feed, a circular waveguide is applied as the primary waveguide, while four rectangular waveguides are applied as the secondary waveguides (shown in Fig. 1). By selecting appropriate dimensions for the primary and secondary waveguides, the equivalent phase constants of the TE_{21} mode in primary waveguide and the TE_{10} mode in the secondary waveguide are equal. The phases of the two modes are precisely aligned, resulting in wave superposition and achieving strong coupling as close as possible

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to 0 dB. For other modes in primary waveguide which have different equivalent phase constants compared to the TE_{10} mode, the energy cancels each other out when coupled to the secondary waveguide. However, there is a slight difference in the reflection coefficients between these two modes. This is because the TE_{21} mode in the circular waveguide is reflected by a smaller diameter, while the TE_{10} mode in the rectangular waveguide is reflected by reflective surface. To reduce these differences, it is necessary to adjust the size of each circular and rectangular waveguide. Additionally, if curved fading or step transformation is used for the circular waveguide aperture transformation, the length of the transformation section can be further reduced.

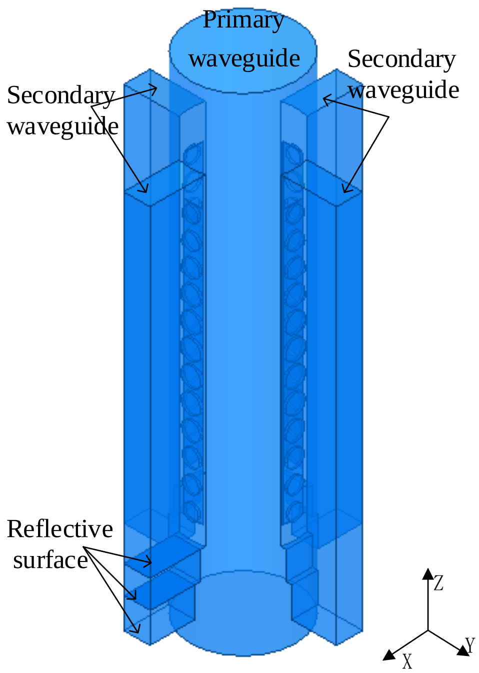

Fig. 1. Structure of feed.

Under the reciprocity theorem of transmission and reception, the feed can be considered as a transmission antenna. To generate phase differences for the purpose of shifting the phase center, a pair of coupling waveguides and primary waveguides can be utilized. The phase distributions of the TE_{11} mode and the TE_{21} mode along the Y-axis play a crucial role in achieving the desired phase center shifting. In Fig. 2, a pair of coupling waveguides and primary waveguides are applied to demonstrate how phase differences are generated to make phase center shifting.

When observing the phase distribution along the Y-axis for the TE_{11} mode (shown in Fig. 3), there is no difference in phase along the Y-axis. On the other hand, when observing the phase distribution along the Y-axis

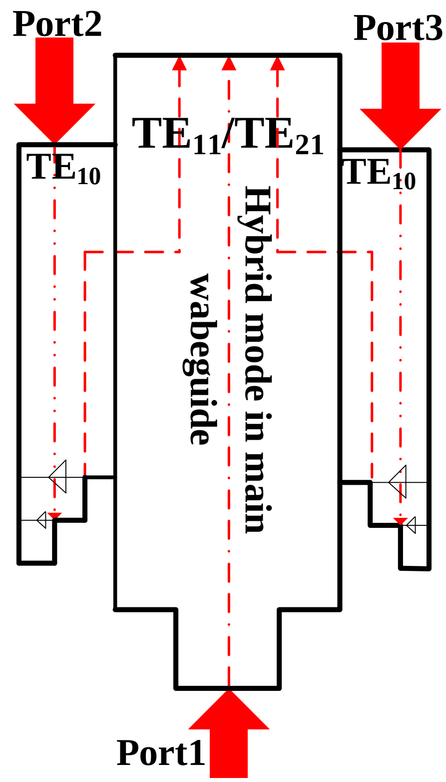

Fig. 2. Workflow of EBS feed.

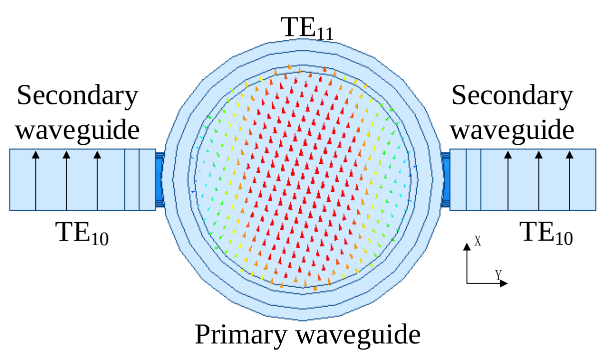

Fig. 3. Schematic of fields in both main/secondary waveguide (TE_{11}).

for the TE_{21} mode (shown in Fig. 4), it becomes apparent that the phase is exactly opposite along the Y-axis. This characteristic of the TE_{21} mode plays a critical role in achieving the necessary phase differences required for the phase center shifting. By using these phase differences in the TE_{21} mode, the phase center shifting can be effectively realized.

In primary waveguide, the mode is mixed with TE_{11} and TE_{21} which are from port 1 and port 2/3, respectively. In this hybrid mode, the direction of the beam

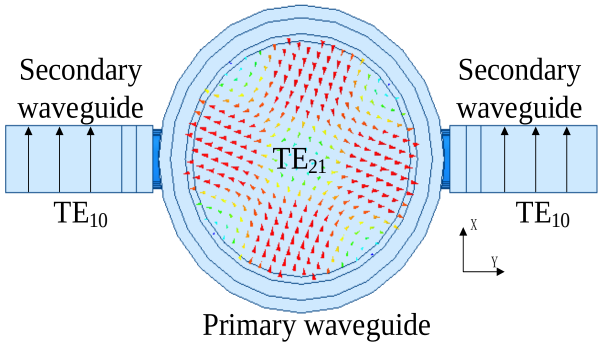

Fig. 4. Schematic of fields in both main/secondary waveguide (TE_{21}).

corresponds to the phase center. Therefore, if the phase center squints, the beam direction will also squint proportionally.

To control the phase differences between the TE_{10} modes in a pair of secondary coupling waveguides, different reflective surfaces are applied in each secondary waveguide. By adjusting the reflective surfaces, the phase distribution over the aperture can be adjusted to achieve desired phase center. After applying diodes in different reflective surfaces, the position of these reflective surfaces is reconfigurable, allowing for precise control of the phase differences. When the phase difference between the two secondary waveguides is 0°, the phase center over the aperture will be located at its geometric center, and the TE_{21} modes from both secondary coupling waveguides will cancel each other out. However, when the phase difference is ±180°, the phase center will be located at the maximum offset position, thus generating the desired beam squinting.

In 2010, Satish K. Sharma and Ashish Tuteja designed a 3-mode feed using slot coupling. This feed achieved a gain of about 14 dBi at the center frequency of 7.73 GHz, a maximum beam shift of ±24° in the azimuth and elevation direction, and a bandwidth of about 7.48-8 GHz for $S_{11} \leqq -10$ dB. However, in this work, a porous coupling is applied to replace the slot coupling. In this way, we could improve the isolation between each port and accuracy of phase center control. S-parameters are shown in Fig. 5.

From Fig. 5 we observed that significant improvements have been achieved compared to the 3-mode feed developed by Satish K. Sharma in terms of S_{11} and port isolation. The S_{11} parameter being less than -20 dB over the bandwidth range indicates good matching, while the port isolation exceeding 45 dB around the center frequency of 12.5 GHz demonstrates strong suppression of the reflected TE_{11} mode. The port isolation improvement is attributed to the strong coupling utilized in this antenna.

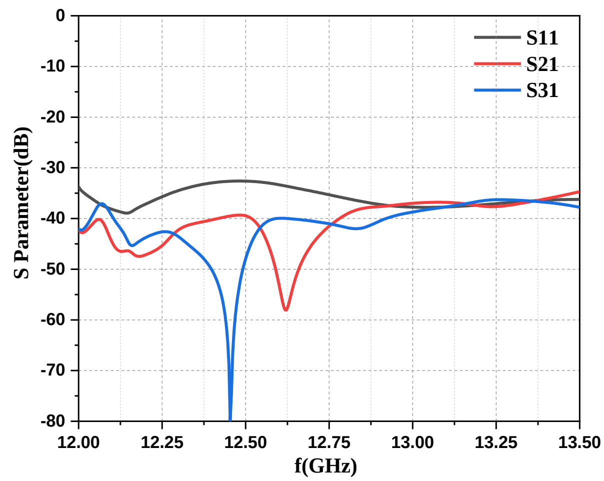

Fig. 5. Simulated S-parameter.

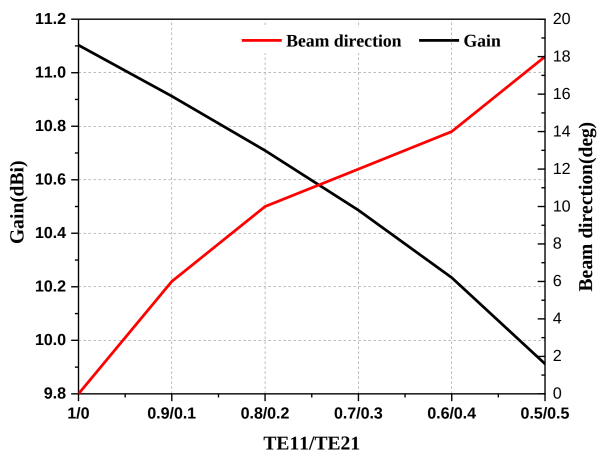

Fig. 6. Gain and beam direction.

For a comprehensive analysis of the hybrid mode in the transmission antenna, it is essential to quantitatively analyse the magnitudes in both coupling waveguides. By ensuring that the magnitudes in both coupling waveguides are the same, the beam direction and gain can be calculated separately for different hybrid mode ratios. The beam direction and gain are calculated separately in different hybrid mode ratios (shown in Fig. 6). By systematically evaluating the influence of varying hybrid mode ratios on these parameters, a thorough understanding of the antenna's performance under different configurations can be obtained.

As shown in Fig. 6, there is a direct relationship between the difference in mode ratio, beam direction, and gain. Specifically, the greater the difference in mode ratio, the greater the beam direction and the greater the drop in gain. This accentuates the importance of selecting an appropriate mode ratio to achieve a desirable balance between beam direction and gain. Since the beam

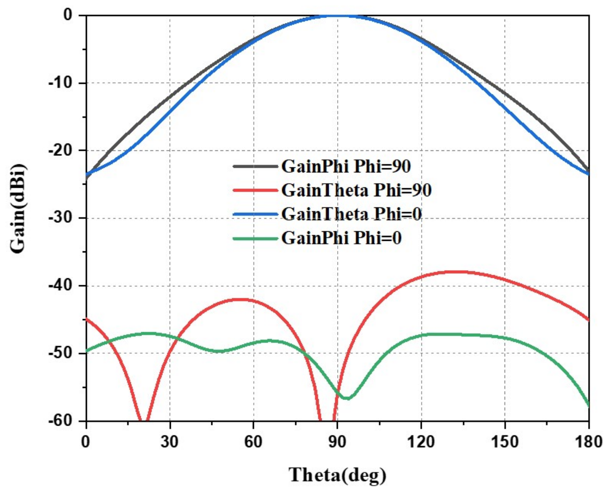

Fig. 7. Simulated radiation pattern in 0° phase difference.

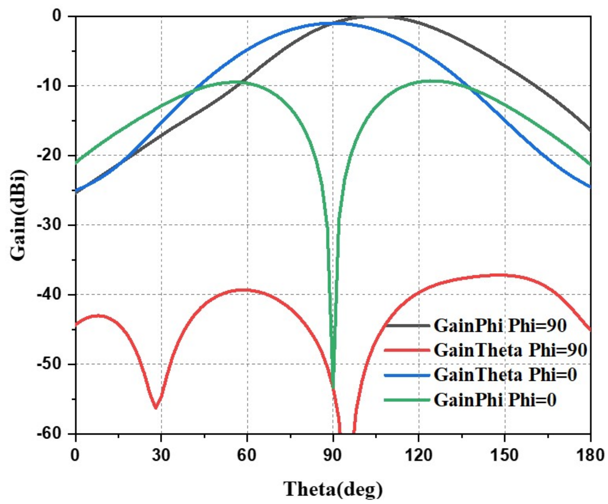

Fig. 8. Simulated radiation pattern in 180° phase difference.

direction corresponds to the phase center, when the beam direction is at its maximum degree, the phase center shifts to the maximum position. Therefore, it is critical to carefully consider the impact of different mode ratios on the phase center to avoid undesirable beam squinting.

In this work, in case the gain is too low, it is advisable to select a mode ratio of 6:4. Additionally, the simulated radiation patterns in different phases are shown in Figs. 7–9 in the horizontal plane.

Figure 7 shows the results of 0° phase difference in both E and H plane with cross-polarization. It can be observed from Fig. 7, E plane and H are equalized well. Figure 8 also shows the results of 180° phase difference in E and H plane with cross-polarization. The main beam in H plane is 14°. Figure 9 shows the results of -180° phase difference in E and H plane with cross-polarization. The main beam in H plane is $-14°$.

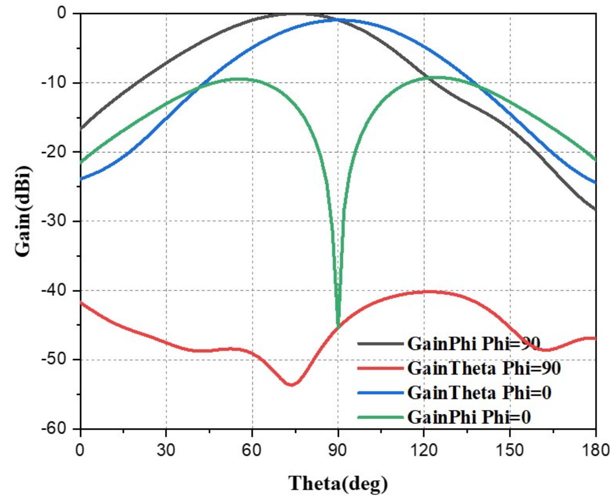

Fig. 9. Simulated radiation pattern in -180° phase difference.

The cross-polarization isolation is greater than 40 dB in all three radiation patterns shown in Figs. 7–9, indicating that cross-polarization has minimal influence on tracking accuracy.

Furthermore, it is evident from the results that by controlling the phase of the reflective reconfigurable EBS feed, electronic beam shifting within $\pm 14°$ can be achieved. However, to achieve a larger beam shift degree, a larger aperture may be needed, which could lead to a decrease in aperture efficiency.

Under the reciprocity theorem of transmission and reception, if the transmission antenna can achieve a certain angle of beam squinting, it can also receive signals within $\pm 14°$. Table 1 provides information on other phase differences that result in beam squinting.

Table 1: Phase difference and beam squinting

Phase Difference	Beam Squinting	Phase Difference	Beam Squinting
30°	4°	30°	$-4°$
60°	8°	60°	$-8°$
90°	12°	90°	$-12°$
180°	14°	180°	$-14°$

III. RESULTS AND EXPERIMENTAL VALIDATION OF REFLECTIVE RECONFIGURABLE EBS FEED

After the simulation, it is necessary to validate the performance of the reflective reconfigurable EBS feed. To accomplish this, the Voltage Standing Wave Ratio (VSWR) of the antenna is measured using a vector network analyzer. Additionally, the radiation patterns of the antenna at ±180° phase differences are measured in a microwave measurement darkroom at Xi'an University of Electronic Science and Technology. The antenna far field measurement system used for this purpose was XD-2. For reference, a photograph of the reflective reconfigurable EBS feed is shown below. The photograph of the processed antenna and the measurement environment are shown in Figs. 10 and 11, respectively.

The results shown in Fig. 12 indicate that the S-parameter measurements of the feed are close to the simulation results. The reflection coefficient for port 1 (S_{11}) is less than -20 dB across the bandwidth. Moreover, the port isolation (S_{21} and S_{31}) is measured to be greater than -40 dB, indicating effective isolation between port 1 and port 2, as well as between port 1 and port 3. It is noted that the porous coupler has a positive impact on improving the port isolation, which is an important factor in ensuring minimal interference and efficient functioning of the feed. These results validated the effectiveness of the feed design and its ability to maintain good matching and isolation characteristics, as verified through the S-parameter measurements.

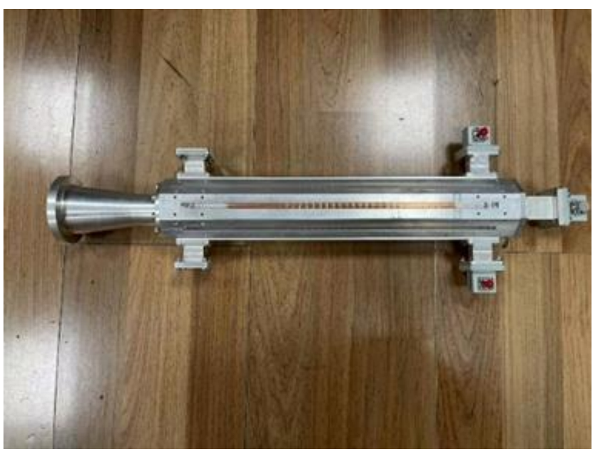

Fig. 10. Photograph of processed antenna.

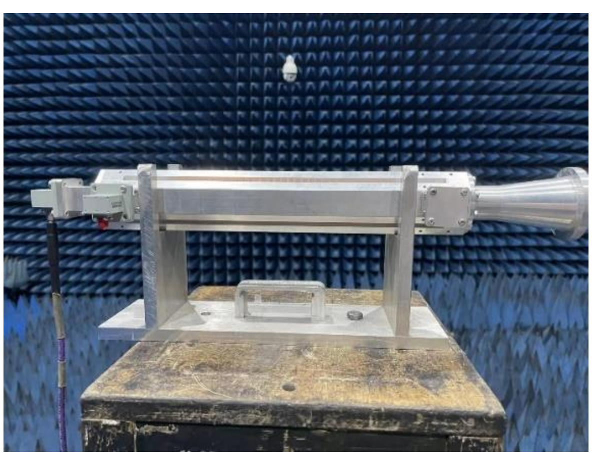

Fig. 11. Photograph of measuring the processed antenna.

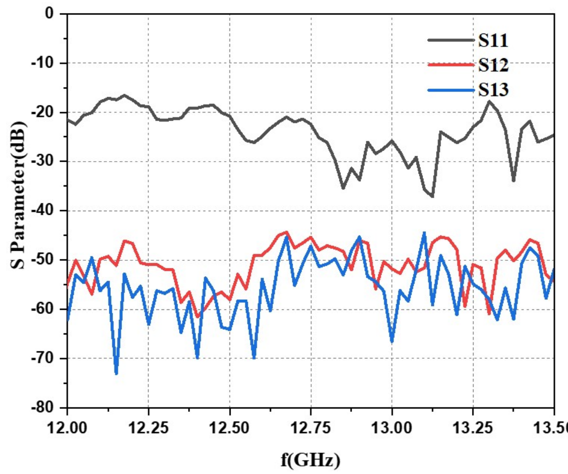

Fig. 12. Measured S-parameter.

For the accuracy of the main and cross-polarization, phase center of both measure and measured antenna should be aligned. The measured radiation patterns of reflective reconfigurable EBS feed are shown in Figs. 13 and 14.

In Fig. 13, with a 180° phase difference, the results show the cross-polarization and beam squinting in both the E and H planes. The maximum beam squinting is 13°. Similarly, Fig. 14 shows -180° phase difference results in both planes. Notably, the main beam is -13°.

In this case, the beam squint is from -13° to 13° and the cross-polarization isolation is larger than 30 dB. Table 2 provides further details on the measured radiation patterns under various phase differences.

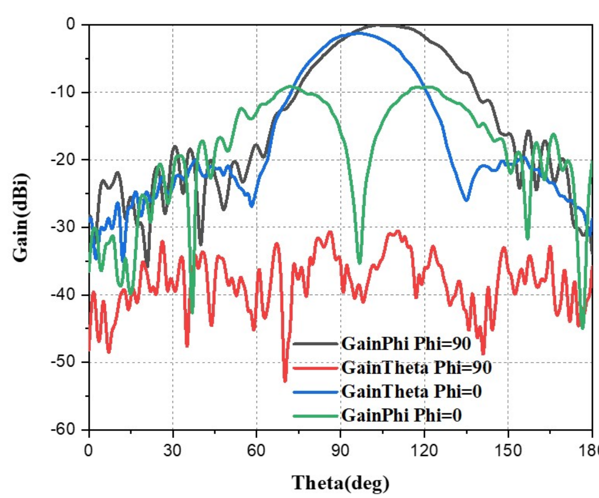

Fig. 13. Measured radiation pattern in 180° phase difference.

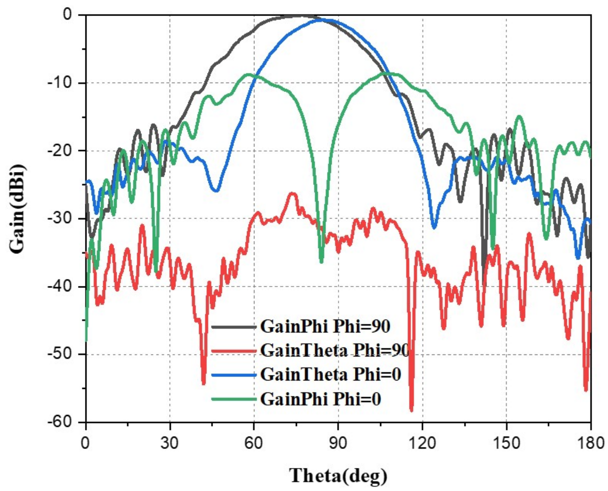

Fig. 14. Measured radiation pattern in -180° phase difference.

Table 2: Experiment result of phase difference and beam squinting

Phase Difference	Beam Squinting	Phase Difference	Beam Squinting
30°	3°	30°	-3°
60°	6°	60°	-6°
90°	9°	90°	-9°
180°	13°	180°	-13°

Considering the measurement errors, when compared with the simulation results, the experiment results are close to simulation results. This agreement between the measured and simulated results further strengthens the dependability of the experimental results.

By validating the experiment against the simulation, it verifies that the antenna's performance matches the anticipated performance. This enhances our confidence in the reliability and accuracy of the experimentally obtained radiation patterns and the overall performance evaluation of the reflective reconfigurable EBS feed.

IV. CONCLUSION

In this paper, reflective reconfigurable EBS feed is proposed. The application of porous coupling improves the port isolation, demonstrating an effective way to improve the antenna's performance. Furthermore, the separation of the primary and secondary waveguides enables control of the phase and manipulation of the main beam direction.

To ensure accurate phase control in the secondary waveguide, minimizing the leakage from the primary waveguide is crucial. As such, the authors have simplified the structure by removing corrugations or chokes and applying the porous coupler to increase port isolation.

This EBS feed could achieve beam squinting in horizontal plane within $\pm 14°$ without reflector and higher aperture efficiency (85%). By adjusting reflective surface with diodes, the reaction time is reduced, enabling faster adjustments to meet changing requirements. Moreover, the application of the secondary waveguide located along the main waveguide enables miniaturization of the feed, making it more compact and easier to integrate into various systems.

Overall, the proposed reflective reconfigurable EBS feed offers several advantages over traditional designs, including improved port isolation, accurate phase control, and high aperture efficiency. These characteristics make it a valuable addition to satellite communication that require accurate tracking and rapid response.

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