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Dynamic Multi-Beam Control using Switched Feed with Shared Reflectarray Aperture

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Abstract: In this paper, a reflectarray based multi-beam gain-control structure is proposed for dynamically controlling the gain of each beam. In this structure, multiple array feeds are illuminating one shared reflectarray aperture. By carefully adjusting each array feed and aperture phase distribution, multiple beams with different gain status can be realized simultaneously, which can be helpful for full terminal coverage for next generation mobile communication.

Keyword: reflectarray antenna, beam control, array feed, reconfigurable antenna

1. Introduction

With the growing demands for high data rate, the use of millimeter-wave bands for the next generation wireless communication network such as the fifth generation (5G) mobile systems has generated much attention. In order to overcome the high path loss problem in mm-wave band, much effort has been paid to design effective highly directive multi-beam antenna systems. Many types of such antennas have been reported [1]. Multi-beam beam-scanning capability with same gain can be achieved for these antennas. However, few research works have been reported to realize gain control for multi-beam antennas. Gain control could be helpful for increasing the signal coverage for both near zone and far zone with high energy efficiency.

In this paper, a novel multi-beam gain-control architecture consisting of multiple array feeds with one shared reflectarray aperture is proposed to dynamically control the gain status for each beam. On one hand, due to multiple separated feeds, multiple channels can be supported for multi-user communication. On the other hand, the gain and beamwidth of each channel can be controlled dynamically by carefully adjusting excitation condition for each array feed. Based on this, a simple 2-feed 2-beam prototype with broadside beams is designed and simulated to validate this functionality. In addition, the capability of steering the main lobe direction can be simply realized by integrating RF switch such as PIN diode or MEMS into unit cell design.

This paper is organized as follow. The architecture of the proposed array feeds with reflectarray aperture is introduced in Section 2. Then, the design considerations of the array feed are presented in Section 3. In Section 4, the reflectarray unit-cell design is investigated. In Section 5, the system level aspects in the design is discussed. Finally, the simulation results are provided in Section 6, followed by a concise conclusion and future work in Section 7.

2. Architecture of the array feeds with reflectarray aperture

The architecture of the proposed system is shown in Fig. 1. It consists of two sets of 1x3 planar array feed and one shared reflectarray aperture. The two sets of array feed are positioned symmetrically in front of the reflectarray aperture with the focal distance of F and oblique angle of θ. By carefully controlling the excitation condition for each array feed, different incident beams with different beamwidth can be realized. Naturally, when illuminated by these two incident beams, the shared reflectarray aperture will be divided into two parts, each with different illumination area. Then, the reflectarray aperture is utilized to compensate the spatial phase delay in each area to get two collimated beams. Due to different effective illumination area, different beamwidth and gain of the two collimated beams will be achieved. The two different effective illumination area can be controlled by the excitation conditions of array feeds, resulting in dynamic gain control of the two output beams. Many considerations should be taken to determine the focal distance F and oblique angle θ together with reflectarray aperture size. This would be illustrated in Section V.

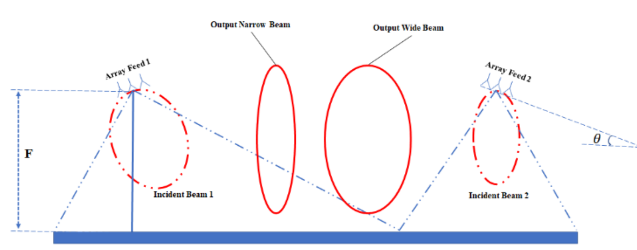

Fig. 1 Architecture of the proposed system

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3. Design Consideration of the planar array feed

3.1 Pin-Fed Rectangular Patch Antenna

In this paper, the pin-fed rectangular patch antenna is employed as an element of the linear array feed. The detail configuration of the patch antenna element is shown in Fig. 2. A small rectangular patch is printed on the CS3376C substrate with a thickness of 0.2 mm, a permittivity of 3.2, and a loss tangent of 0.006. The patch antenna element is designed resonant at 28GHz. Fig. 3(a) shows the simulated far-field radiation patterns, while the simulated reflection coefficient is depicted in Fig. 3(b).

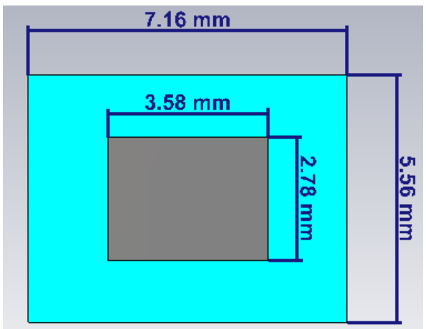


Fig. 2 Configuration of the patch antenna element

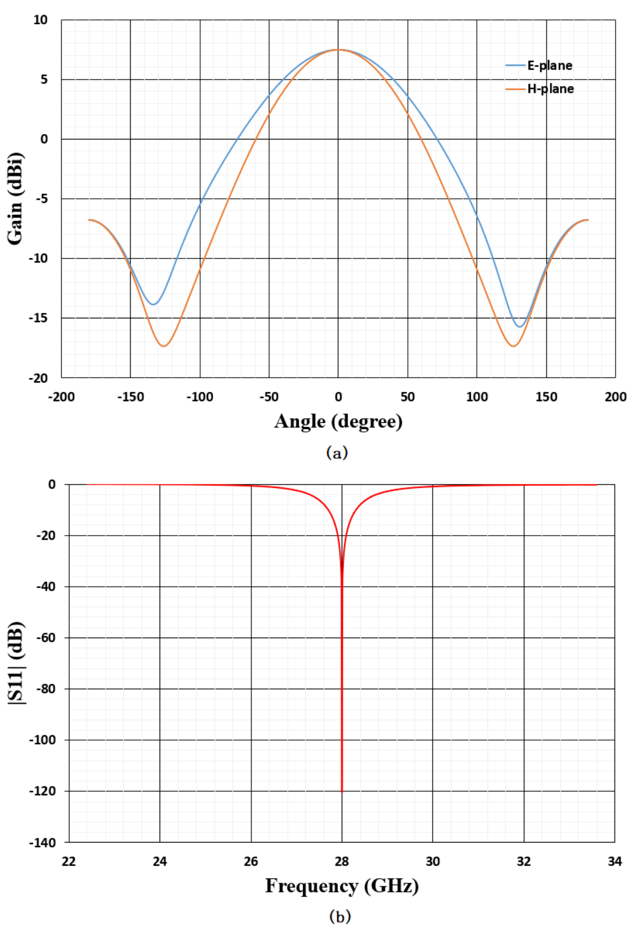


Fig. 3 (a) Radiation patterns@28GHz. (b) Simulated |S11|.

3.2 Configuration of the 1x3 Antenna Array

A series 1x3 patch array is deployed as the source feed of the reflectarray aperture. Fig. 4 shows the configuration of the array feed. The two sets of excitation conditions should be carefully designed to effectively illuminate the reflectarray aperture. For validation, two sets of beam states are chosen. The beams states together with the corresponding excitation conditions are shown in Table I.

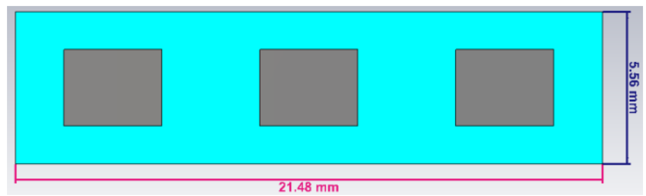
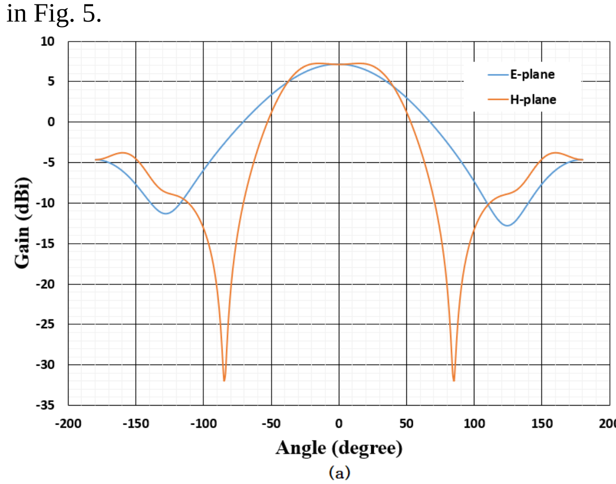


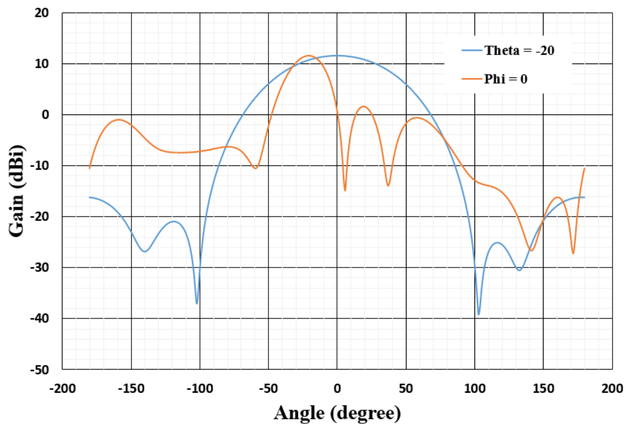
Fig. 4 Configuration of the array feed

Beam State	Illumination Area Ratio	Excitation condition for feed array 1	Excitation condition for feed array 2
1	1:1	(X, 0°, X)	(X, 0°, X)
2	2:1	(X, 0°, X)	(188°, 94°, 0°)

Table. 1 Beam states and corresponding excitation conditions, the excitation condition has the format of phase excitation in degree for each port, while X means no excitation.

Equal output beams are chosen for the beam state 1, which requires for the same excitation condition for the two sets of array feed. The format (A, B, C) for the excitation conditions in Table 1 demonstrates the excitation phase for each port, while the X in Table 1 means no excitation for the corresponding port. For beam state 2, the illumination area ratio of 2:1 is chosen. In this situation, the beam of array feed 2 should be scanned to illuminate the aperture efficiently. The incident radiation patterns for each beam state are shown in Fig. 5.





(b)

Fig. 5 (a) Radiation pattern for array feed 1 and 2 in beam state 1 and array feed 1 in beam state 2. (b) Radiation pattern for array feed 2 in beam state 2.

4. Reflectarray unit-cell design

In this design, a single layer variable-sized patch is selected as the unit cell of the reflectarray aperture. The geometrical model of the unit cell along with the design parameters are illustrated in Fig. 6. The width of each square element is P, the square patch length is L. The unit-cell periodicity, P=0.5 λ_0 , where λ_0 is the wavelength of free space electromagnetic wave at 28GHz. It is printed on a dielectric substrate with thickness T = 0.4 mm and relative permittivity of 3.2.

All elements are simulated by using periodic boundaries together with Floquet excitation mode. Fig. 7 shows that 330° can be obtained by varying the square patch length L from 0.1 mm to 5.3 mm, which is enough for most reflectarray designs.

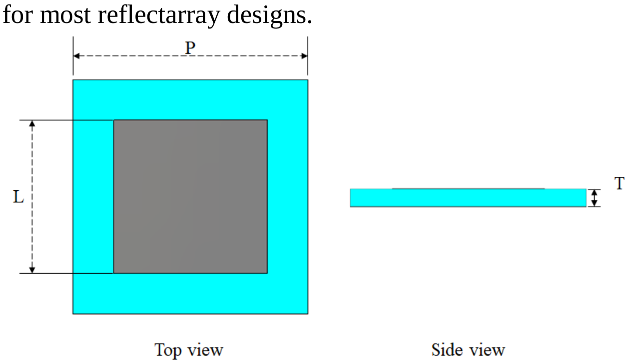


Fig. 6 Configuration of unit cell

5. System Level Design Consideration

As mentioned above, the focal distance F and oblique angle θ should be carefully determined, since they can deeply affect the aperture efficiency for the system. Taking actual radiation patterns of the array feed into considerations, optimization is executed to determine the focal distance F and oblique angle θ together with the reflectarray aperture size. The focal distance F=2.5λ_0 and oblique angle $\theta = 20°$. In order to illuminate the aperture effective, the aperture size is chosen as 10 X 20 ($5\lambda_0 \times 10\lambda_0$).

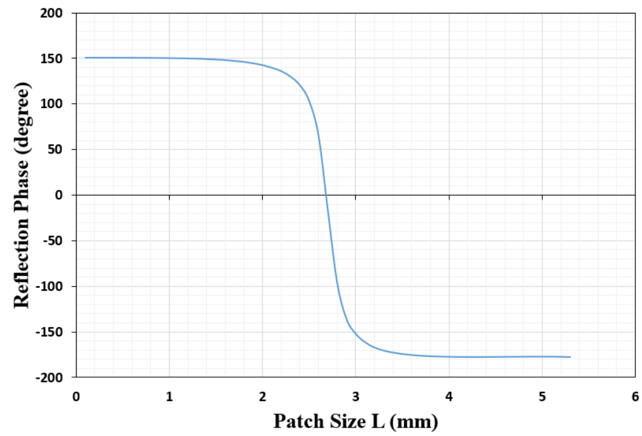


Fig. 7 Reflection phase response for the unit cell

6. Simulation Results

Full-wave simulations are carried out for both beam states to validate the feasibility. The excitation power for the two array feeds in both beam state is the same. For simplicity, the beam directions for both beam states are broadside.

Fig. 8(a) shows the radiation patterns for excitation of array feed 1 in beam state 1, while Fig. 8(b) shows the radiation patterns for excitation of array feed 2 in beam state 1. The radiation patterns for both array feed in beam state 1 are symmetrical due to equal illumination area. The gain of 20.89dB is obtained for both beams resulting in 39.1% aperture efficiency.

For beam state 2, the radiation pattern for excitation of array feed 1 is illustrated in Fig. 9(a). Fig. 9(b) presents the radiation pattern for excitation of array feed 2. For excitation of array feed 1, the gain of 22.17dB is achieved, while the gain of 18.38dB is obtained for excitation of array feed 2. The corresponding aperture efficiency are 40.4% and 31.4%, respectively. According to theoretical analysis, the two beams should have a 3dB gain difference, since the effective aperture size ratio is 2. However, a 4dB gain difference is observed from the simulation results. This sight difference between theoretical analysis and full-wave simulation is mainly caused by the beam scanning of the array feed, which should be further optimized.

7. Conclusion and Future Work

In this paper, a novel multi-beam gain-control antenna system that contains a shared reflectarray aperture fed by two sets of array feed has been proposed, designed and simulated. The dynamic gain control capability has been validated in the full-wave simulation. Next step is to design a reconfigurable unit cell to support both beam-scanning and gain-control. A prototype will be fabricated and measured in the future.

Reference

[1] W. Hong, Z. H. Jiang, C. Yu, J. Y. Zhou, P. Chen, Z. Q. Yu, H. Zhang, B. Q. Yang, X. D. Pang, M. Jiang, Y. J. Cheng, M. K. T. Al-Nuaimi, Y. Zhang, J. X. Chen, S. W. He, “Multibeam Antenna Technologies for 5G Wireless Communcations,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6231-6249, Dec. 2017

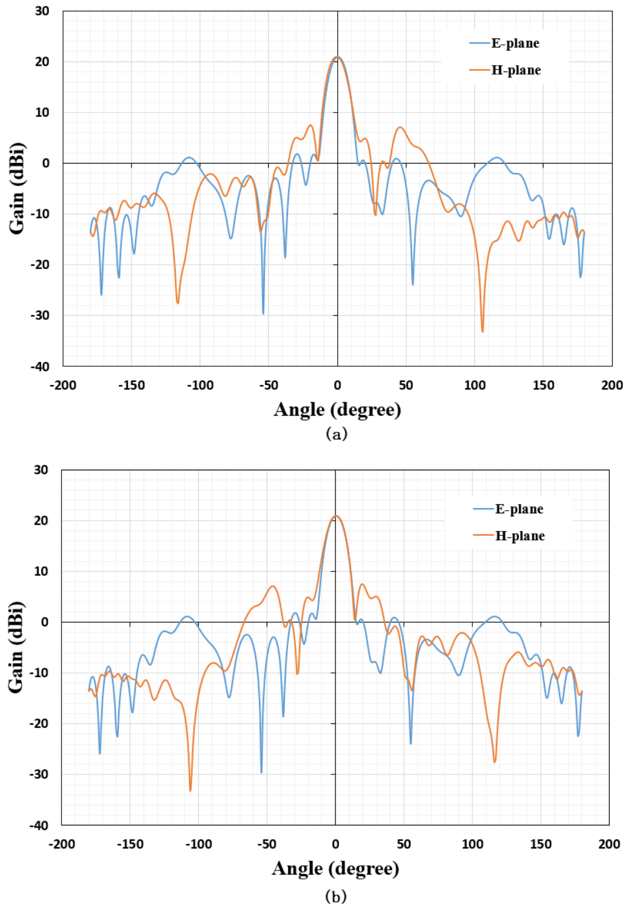


Fig. 8 Radiation pattern in beam state 1 for excitation of array feed (a) 1. (b) 2.

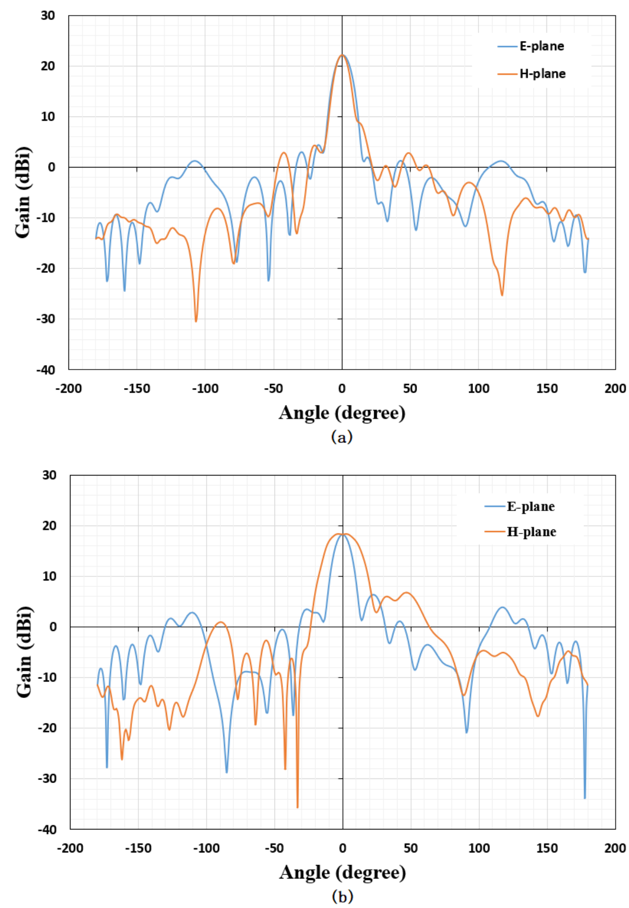


Fig. 9 Radiation pattern in beam state 2 for excitation of array feed (a) 1. (b) 2.