An Investigation on the Gain of Folded Reflectarray Antennas with Different *F*/*D*s

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Abstract — In this paper, an investigation on the effect of *F/D* ratio on gain for folded reflectarray antenna (FRA) is presented. Quantization phase errors which are the major contribution to losses of reflectarray are presented with different *F/D* ratios. In order to reduce the quantization phase error, a folded reflectarray antenna with high *F/D* ratio is preferred. A pair of FRAs with *F/D* of 0.5 and 1 is chosen to fabricated, measured and compared at 42GHz, respectively. A gain improvement of 0.8dB is achieved when the larger *F/D*, namely 1, is adopted to the antenna.

Index Terms — Folded reflectarray antenna, phase shifting surface, parabolic antenna, quantization phase error.

I. INTRODUCTION

Recently, millimeter-wave band has attracted more and more interests of wireless communications due to its abundant spectrum. China has proposed Q-LINKPAN as a high speed transmission standard proposal for both short-range and long-range millimeter-wave communications. For developing such short-range and point to point communication systems high gain antennas are most preferred.

Folded Reflectarray antenna (FRA) which was proposed in the 2000s [1]-[4], is attractive high gain antenna due to its low profile, low cross polarization and easily integrated with planar circuits. The antenna system consists of a primary source illuminating a polarizing grid which reflects the linearly polarized spherical wave toward the main reflectarray. The main reflectarray is designed to focus the beam and rotate the incident polarization by 90° to make sure the radiated wave can pass through the polarizer. Due to the folded wave trace, the FRA can reduce its depth by a factor of 2.

According to the reported research results on gain and loss mechanisms of folded reflectarray antenna in [5]-[6], phase errors are the major contributions to losses. For the reflectarray design, the phase distribution on the phase shifting surface (PSS) are often assumed to be continuous, but actually the PSS is compensated by tens of thousands of reflecting cells, so the phase distribution is discretized into many staircase sections, the quantization phase error [7] between the discretized phase cells and the continuous phase distribution on the reflecting surface will cause a lot of losses of the reflectarray antenna. In order to eliminate the quantization phase error, a size reduction of reflector element by choosing high permittivity substrate is adopted in [5], but the high permittivity substrate with high loss tangent also introduces extra dielectric loss, so the gain improvement is not significant. However, from another point of view, the quantization phase error is reduced with the decreased steepness of phase shifting curve. A high *F/D* ratio resulting in a smooth phase shifting curve will causes less phase errors. Thus, an appropriate choose of *F/D* will reduce the loss of folded reflectarray antenna.

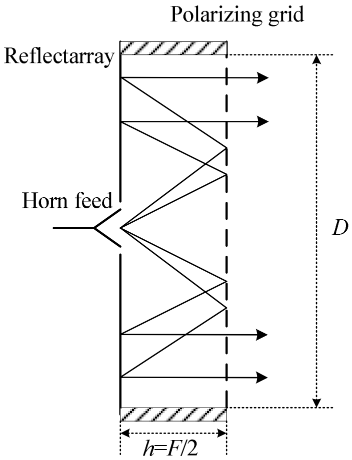

Fig. 1. Principle of FRA and the definition of focus *F* and reflecting surface diameter *D*.

In this paper, we present two FRAs with different *F/D*s for Q-LINKPAN application at 42GHz and investigate their gain performance. We firstly definite the quantization phase error and present the relationship between *F/D* and the quantization phase error. And then we study its effect on gain and 3dB beamwidth by simulating two pairs of FRAs and their corresponding parabolic antennas with different *F/D*s. By comparing the gains of these antennas, we study the loss reduction of FRA with the increase of *F/D*. Finally, we fabricate the FRAs with *F/D* of 0.5 and 1, and the experiment results are compared with Ref. 1 and Ref. 2.

II. QUANTIZATION PHASE ERROR

The main reflecting surface of the folded reflectarray antenna utilizes many radiation elements with different phase

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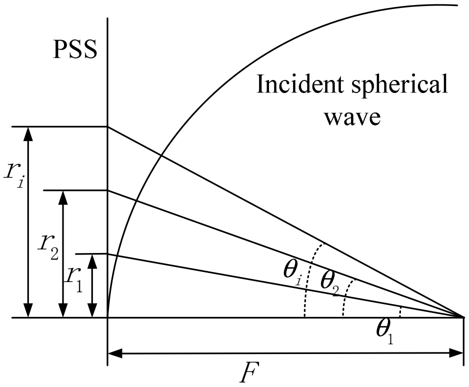


Fig. 2. Wave trace of the classic reflectarray antenna - definition of the phase shifting surface.

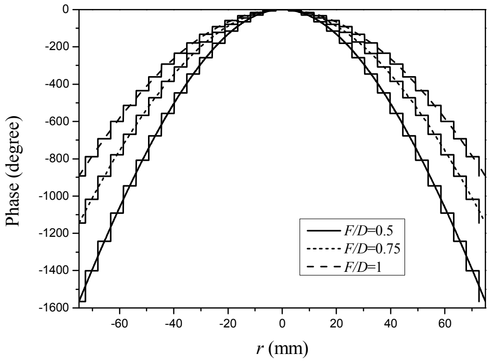


Fig. 3. The compensation phase distributions and the corresponding quantization phase distributions with different *F/D*.

shifting characteristics to compensate the phase delay from the feed to the reflecting plane by different wave paths. The operation is similar to a parabolic reflector to use its unique curvature to compensate the phase delay and form a planar phase front. The wave trace of the classic reflectarray antenna is shown in Fig. 2. The compensated phase function is determined by [8]:

$$\varphi_i = -k_0 F(1-\cos\theta_i)/\cos\theta_i \quad \text{for } i=1,2\ldots n \tag{1}$$

$$\theta_i = \tan^{-1}(r_i/F) \tag{2}$$

where φ_i is the compensated phase distribution; F is the focus distance; θ_i is the subtend angle from coaxial to the radiation element; r_i is the distance from center of the reflecting plane to the radiation cell; and k_0 is the propagation constant in vacuum.

Fig. 3 shows the required phase shifting on the reflecting surface and the counterpart quantization phase distribution. The root mean square (rms) quantization phase error is defined as:

$$\delta = \left(\frac{\int(\varphi_i-\varphi_0)^2 dS}{\pi(D/2)^2}\right)^{1/2} \tag{3}$$

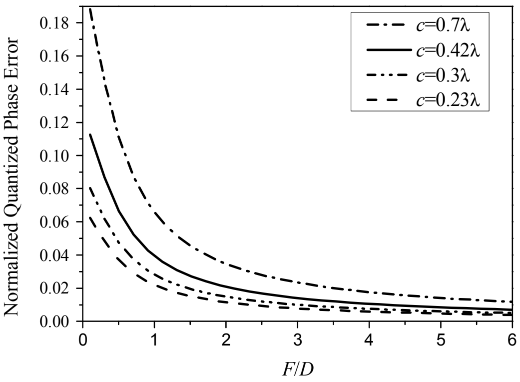


Fig. 4. The normalized phase errors versus *F/D* with different lengths of square reflecting cells *c*.

TABLE I

SIMULATED GAIN, BEAMWIDTH AND SIDE LOBE LEVEL OF THE LOSSLESS FRAS AND PARABOLIC ANTENNAS

	Gain (dBi) @42GHz		Beamwidth(°) @42GHz	Sidelobe(dB) @42GHz
	Parabolic antenna	FRA	FRA	FRA
F/D=0.5	34.41	32.86	3.3 ×2.9	-24.2
F/D=1	34.57	33.68	2.7×2.9	-20

where φ_0 is the continuous phase distribution function; and D is the diameter of the reflecting surface. The normalized quantization phase error can be obtain as $\varepsilon=\delta/2\pi$.

Based on the above definition, the normalized phase errors versus *F/D* with different lengths of square reflecting cells *c* are illustrated in Fig. 4. The rms quantization phase error reduced with the increasing of *F/D* due to the decreasing steepness of the phase shifting curve as illustrated in Fig. 3. The quantization phase errors will contribute to the side lobes and further reduce the gains of the reflectarray antennas. Therefore, the folded reflectarray antenna with lower *F/D* ratio causes more loss due to quantization phase error.

In order to investigate the losses brought by the quantization phase errors with different *F/D*, the EM simulator of CST Microwave Studio (MWS) is adopted to simulate two pairs of parabolic antennas and FRAs with *F/D* equaling to 0.5, and 1, respectively. The materials of the simulated antennas are free from losses in order to guarantee the major gain differences between the FRAs and the corresponding parabolic antennas are only contributed by quantization phase errors. The gains, beamwidths and side lobe levels of these antennas are illustrated in table I. The losses caused by quantization phase errors are 1.55dB and 0.89dB, receptively corresponding to *F/D* of 0.5 and 1. Due to the better compensated phase distribution on the reflecting surface, the FRA with *F/D* of 1 has narrower beamwidths than the FRA with *F/D* of 0.5 which resulting in a gain increase of 0.82dB.

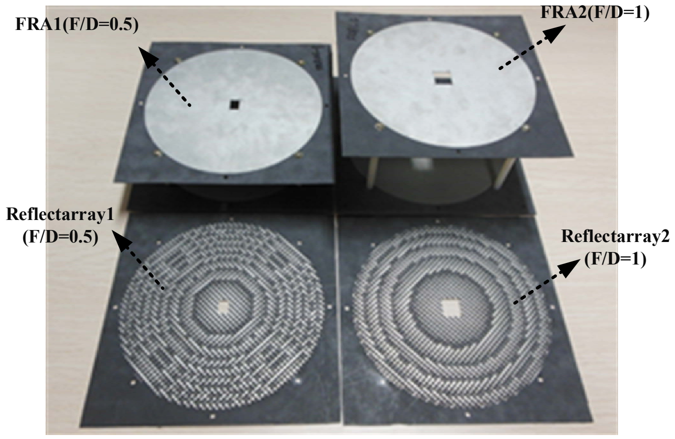
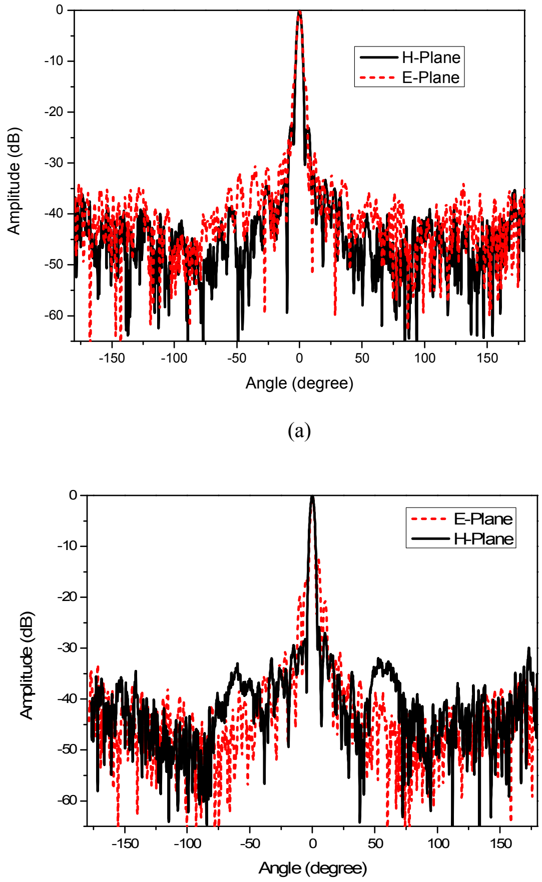


Fig. 5. The photograph of the folded reflectarray antennas.



(a)

(b)

Fig. 6. The measured radiation patterns in E-plane and H-plane of the FRAs with F/D 0.5 (a) and 1 (b) at 42GHz.

III. FOLDED REFLECTARRAY ANTENNA DESIGN AND MEASUREMENT

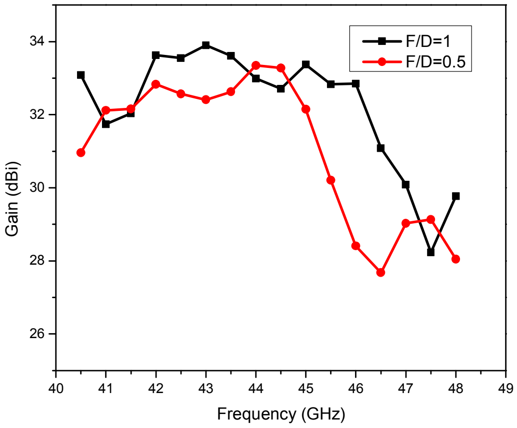


Fig. 7. Measured gains of the FRAs with F/D of 0.5 and 1.

TABLE II
THE COMPARISON OF VARIOUS REFLECTARRAY ANTENNAS

	F/D	Gain(dBi)	Aperture Efficiency
FRA1	0.5	32.8@42GHz	43.8%
FRA2	1	33.6@42GHz	52.6%
Ref. 1 in [6]	0.5	36.5@94GHz	29%
Ref. 2 in [4]	0.36	27.4@38.5GHz	33.9%

The main reflector consists of rectangle patches with various sizes. By varying the lengths and widths of the metal patches, the classic phase compensation as well as rotated electric field polarization by 90º is obtained. All the simulations of reflecting cells by CST are using Floquet boundary condition, which is assuming the unitary cell is surrounded by identical cells. The unit size is 3mm×3mm, and the reflecting surface diameter *D* is 150mm.

Pyramid horn antenna is adopted as the feed for the folded reflectarray antenna. Two sizes of pyramid horns are simulated by CST for the antenna designs of *F/D*=0.5 and *F/D*=1. The average edge amplitude tapers of the pyramid horns which are the average values of E-plane and H-plane are 10.3dB and 10.9dB at 42GHz respectively. Therefore, the folded reflectarry antennas theoretically can achieve amplitude taper loss (ATL) and spillover (SPL) efficiencies [9] of 78% and 80% respectively.

The reflecting planes and polarizing grids are all fabricated on Rogers5880 with the permittivity of 2.2 and loss tangent of 0.0009. Fig. 5 shows the photograph of the proposed FRA1 and FRA2, corresponding to *F/D* of 0.5 and 1 respectively. The measured radiation patterns of both antennas at 42GHz are shown in Fig. 6. From Fig. 6, it can be seen that the measured 3dB beamwidths in E-plane and H-plane are 3.5°×3.4° and 2.9°×3.3° for FRA1 and FRA2 respectively. Fig. 7 shows the measured gains of the FRAs with *F/D* of 0.5 and 1. The gains of the FRAs with *F/D* of 0.5 and 1 are 32.8 dBi and 33.6 dBi respectively at 42 GHz, and the 3dB bandwidths are 11.6% and 13.8% respectively. Table II illustrates the comparison of the proposed FRAs with some reported FRAs.

This comparison shows the both proposed folded reflectarray antennas have good gain and efficiency performances and a gain increase of 0.8dB as well as an efficiency increase of 8.8% is achieved when adopting FRA with *F/D* of 1 to replace the antenna with *F/D* of 0.5.

IV. CONCLUSION

In this paper, quantization phase error of folded reflectarray antenna is proposed and its effect on gain is analyzed and compared with different *F/D*s. The FRA with *F/D* equaling to 1 is preferred to reduce the quantization phase error, and a gain increase of 0.8dB is achieved when adopting FRA with *F/D* of 1 to replace the antenna with *F/D* of 0.5. The good measured results testify the ideas.

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