Paneled Center-fed Reflectarray for Bandwidth Enhancement

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Abstract—**Regardless of the bandwidth of reflectarray (RA) elements, the RA bandwidth is narrower for many possible reasons. For a RA with small f/D, the ray path length varies as we move away from the center, which is compensated by the elements that are designed at the center frequency. However, as the frequency changes, the path length phase errors grows, as we move away from the center, at a more rapid rate than the element frequency phase variation. Therefore, the phase errors introduced as the frequency changes are so significant deteriorating the aperture phase distribution that causes very low aperture efficiency and in return limiting the gain bandwidth. In order to reduce the path length as we move away from the center, the RA is divided into annular planar panels centered with a small square sub-RA. The annular panels are displaced towards the feed position reducing the path length within each panel. A circularly polarized refectarray designed at 30 GHz with wideband cross Bowtie elements is used as an example. The RA size is $25.25\lambda \times 25.25\lambda$, which is corresponding to 101×101 elements. The performance of the antenna is compared with the original RA of the same diameter. The proposed method exhibits the maximum simulated aperture efficiency of 48 %, a 1-dB gain bandwidth of 16.9 %, and the 0.5-dB axial ratio bandwidth of 25.6 %.**

I. Introduction

Parabolic reflectors and array antennas have been used for decades for high gain applications. The wider bandwidth and higher aperture efficiency of the parabolic reflector antennas make them prominent, but the smaller beam scanning ability, makes array antennas more suitable, but the array antenna efficiency is low due to the corporate feeding network losses at millimeter wave frequencies. Reflectarray (RA) antennas are found to be alternative as they combine the advantages of reflectors and arrays. The RA is a planar structure, lightweight, and low cost, with wide scanning ability. However, the limited bandwidth of large reflectarray is the only disadvantage [1].

The RA consists of two main parts: the feed and the planar reflecting surface. The feed is placed away at the focal distance of the reflector, from where the waves with spherical wavefront are incident on RA surface and converted to planar wavefront after reflection. RA consists of an array of elements, which are subject to reflect a pre-adjusted phase accounted for the spatial delay in collimating the energy to a specified direction. The RA bandwidth is limited by two factors: the narrowband elements used for phase compensation, and the spatial delay [2]. To design wideband RA antenna, it is strongly recommended to use the elements holding wideband characteristics, in phase compensation. Recently, the RA bandwidth enhancement using novel broadband elements is presented [3], which exhibits that the spatial delay is the dominating degrading factor of the bandwidth.

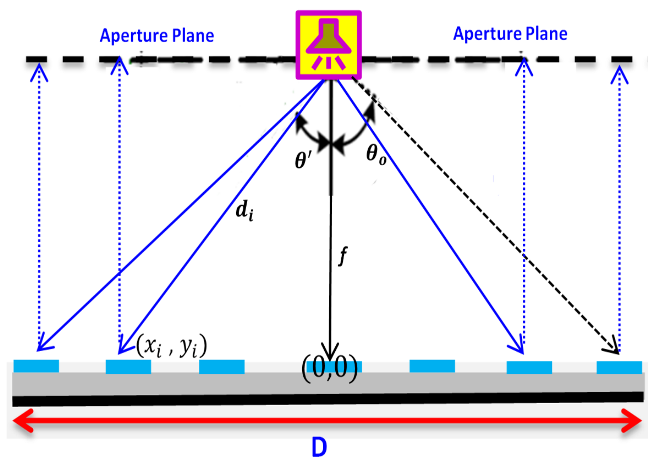

Figure 1. Ka-Band CP reflectarray designed with the conventional technique.

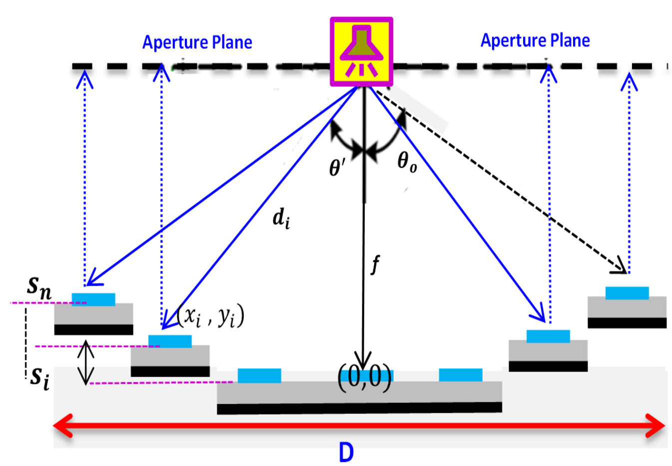

Figure 2. Ka-Band CP reflectarray designed with the proposed bandwidth enhancement technique.

Several methods have been proposed to accomplish the phase compensation. For linear polarization, varying element size [4], stacked patches with variable length [5], multi-resonant

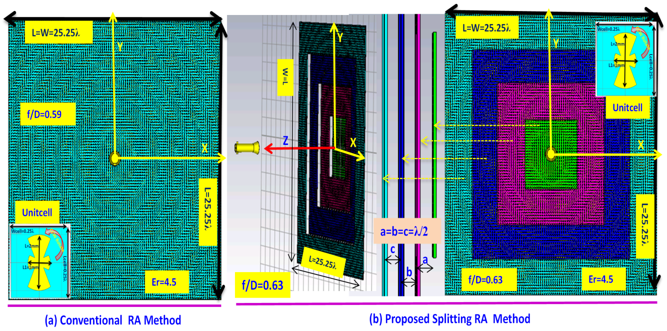

Figure 3. Ka-Band CP RAs with the original and proposed bandwidth enhancement technique.

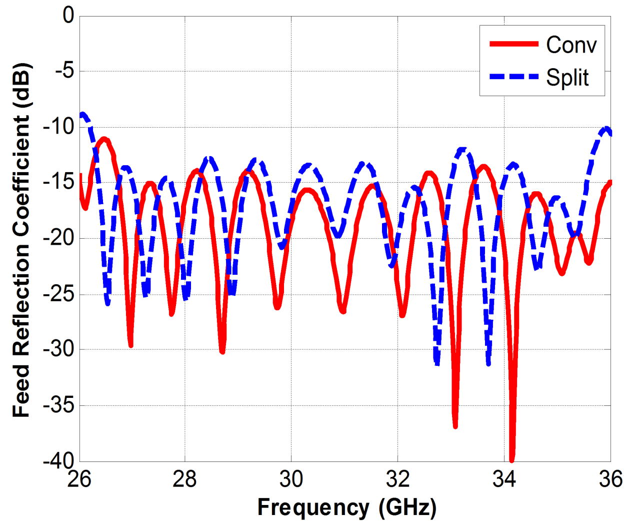

Figure 4. Simulated reflection coefficient comparison vs. frequency for the conventional and proposed split reflectarray.

dipoles [6], size varying multi-bowtie [7], disk elements attached to phase-delay lines [8], varying size slot loaded with dielectric resonator antenna [9], and size varying perforation in the dielectric [10], are used. For circular polarization, the element rotation technique is used in [11]. For the dual band, delay lines and circular rings [12] are implemented. Broadband circularly polarized RA (CP-RA) has been designed in [13], using cross-Bowtie elements while element rotation technique has been used for phase compensation.
In this paper, bandwidth enhancement technique is presented to reduce the spatial delay problem.

II. Reflectarray Model and Performance Comparison

The proposed method is implemented in a 101×101 CP RA design with an electrical size of $25.25\lambda \times 25.25\lambda$, using cross-Bowtie elements [13]. To achieve wider bandwidth, the elements used for phase compensation must hold wide band characteristics. The traditional patch elements utilized for this purpose resulted in a narrow band antenna performance due to the patch small bandwidth. The used sub-wavelength cross-Bowtie elements are designed to result in a wideband performance. In the first step, the RA antenna using cross-Bowtie elements [13], is designed and its performance is considered as a reference, as shown in Figure 1, and Figure 3 (a). In the second step, the proposed technique is implemented by splitting the RA into multiple sized annular shaped sub-RAs, which are lifted up a distance S_i, as shown in Figure 2, and Figure 3 (b).

To compensate the spatial delay from the feed by the elements on the sub-RAs surfaces, reflected wave phase curve is obtained by anticlockwise Bowtie rotation when a left-hand circularly polarized (LHCP) is incidence. The RA principle is to convert incident spherical waves to planar wavefront, in transmit mode, while converting back the planar wavefront to the spherical wavefront in the receiving mode based on the principle of focusing energy to the focal point of the reflector. The feed is a circularly polarized feed used in [13]. Using the proposed split and displace concept of the sub-RA design to minimize the spatial delay phase errors from the center to the edge elements, especially for large reflectors where these errors dominate the bandwidth reduction. Whenever the ray path phase increased by 2π, raise the sub RA by a $\lambda/2$. Each of the followed displaced sub-RA with a diameter D_i is larger in size than the previous one, and their subtraction makes an annular shaped sub-RA displaced attaining a proper focal distance f_i. The RA is sub-divided into the sub-arrays as follows: 25×25, 51×51, 75×75, and 101×101. Due to the different sub-RA size and different F/D, the edge tapering changes at each level and requires to be optimized. The edge tapering in this environment is optimized on the last sub-RA D_n, which in the presented work is -9 dB where the F/D is 0.63. The phase of the element i, $\phi(x_i, y_i)$, in the X-Y plane, to provide the radiation pattern primary beam in the direction (θ_0, ϕ_0), can be obtained from Equations (1) and (2). k_0 is the free space wavenumber, and d_i is the distance from feed to individual elements at (x_i, y_i) [1]. For the main beam to be at (0,0), the aperture phase distribution must be uniform, which is only possible if the proper phase compensation to each element is made on RA surface.

$$\phi(x_i, y_i) - k_0(d_i - sin\theta_0(x_i cos\phi_0 + y_i sin\phi_0)) = 2\pi N \quad (1)$$

$$d_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_f)^2} \quad (2)$$

The performances of the original RA antenna, and the proposed technique are compared. The simulated reflection coefficients for both antennas are shown in Figure 4, indicating the wide matching bandwidth. The simulated gain and their corresponding aperture efficiency are also compared, as shown in Figure 5, depicting the maximum gain of 36.7 dB are achieved from the original RA with an aperture efficiency of 58 %, but the 1-dB gain bandwidth is 6.8 %. On the other hand, the maximum achieved gain of the proposed antenna is 35.85 dB, with an aperture efficiency of 48 %, where the 1-dB gain bandwidth is 16.9 %. This bandwidth enhancement is due to the error reduction generated mainly by the spatial delay.

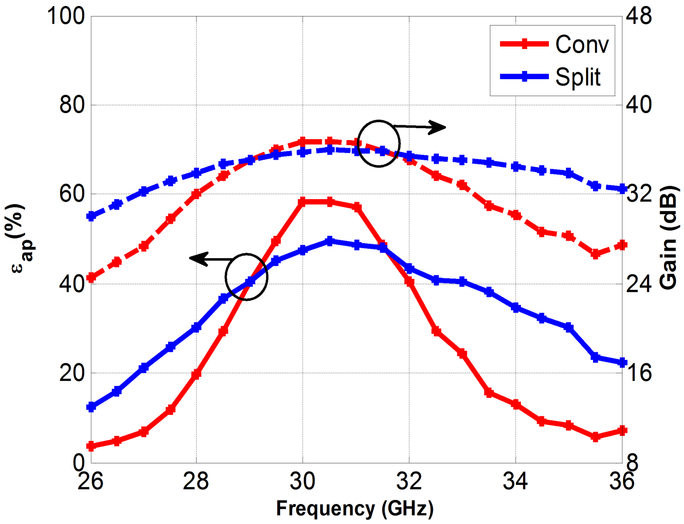

Figure 5. Simulated gain and aperture efficiency comparison vs. frequency for conventional and proposed split reflectarray.

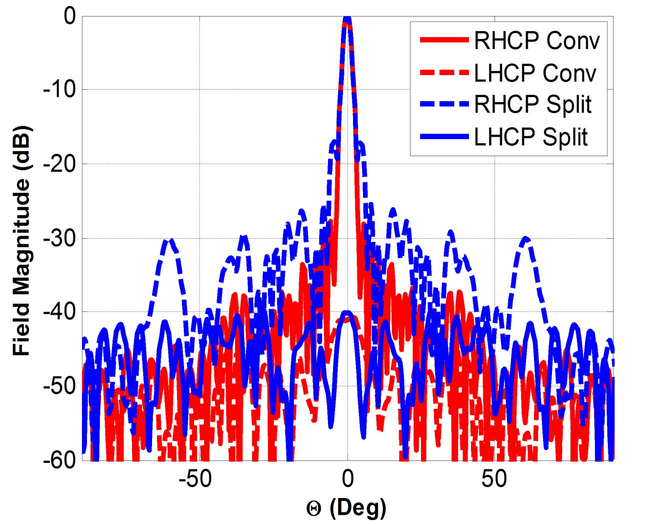

Figure 7. Comparison between the simulated radiation pattern at $\phi = 90$ for the original and proposed split RA at 30 GHz.

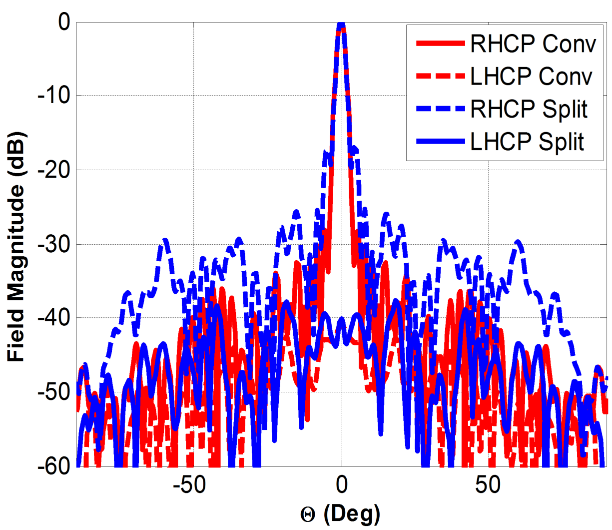

Figure 6. Comparison between the simulated radiation pattern at $\phi = 0$ for the original and proposed split RA at 30 GHz.

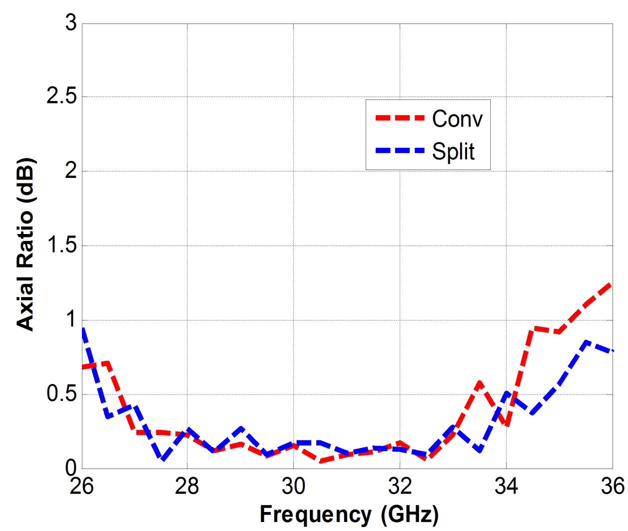

Figure 8. Simulated axial ratio for the original and proposed split RA.

The radiation pattern in the XZ ($\phi = 0$) and YZ ($\phi = 90$) plane for RHCP and LHCP, are compared with those from the original RA as shown in Figure 6, and 7, respectively. The proposed antenna provides 0.5 dB axial ratio bandwidth of 25.6 %, and compared results are shown in Figure 8. The proposed antenna performance compares with the previously published work in the literature as provided in Table I. The RA is designed using the proposed technique, provides much better bandwidth than the others.

Table I
COMPARISON B/W PREVIOUS RA PERFORMANCE WITH PROPOSED

RA in	[11]	Original	Proposed
Freq. Band (GHz)	30 - 34	26 - 36	26 - 36
Design Freq. (GHz)	31.75	30	30
Diameter D (mm)	506	252	252
Max Gain (dB)	41.5	36.7	35.85
Gain BW 1-dB (%)	3.5	6.8	16.9
AR BW 0.5-dB (%)	3.1	22.3	25.6
X-pol (dB)	< 40	< 40	< 40
$\varepsilon_{ap}(\%)$	50	58	48

III. CONCLUSION

In this paper, the bandwidth of the RA antenna has been enhanced by resolving the spatial delay problem. Spatial delay problem dominates the bandwidth degradation, especially when the RA f/D is relatively small. It limits the overall antenna bandwidth regardless of the elements potential bandwidth. A split of the regular planar RA to several planar sub-RA has been proposed that minimizes the spatial delay effect by displacing the annular sub-RAs towards the feed enhances the RA bandwidth. A CP-RA has been designed with wideband cross-Bowtie elements. The performances have been evaluated at 30 GHz. The RA size is $25.25\lambda \times 25.25\lambda$, which is corresponding to 101×101 elements. The performance of the antenna has been compared with some of the conventional designs, presented in the literature. The proposed antenna exhibits the maximum simulated aperture efficiency of 48 $\%$, a 1-dB gain bandwidth of more than 16.9 $\%$, and the 0.5-dB axial ratio bandwidth of 25.6 $\%$.

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