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A New Hat Feed for Reflector Antennas Realized without Dielectrics for Reducing Manufacturing Cost and Improving Reflection Coefficient

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Abstract— The paper presents a new hat feed that is entirely made of metal without using dielectric material. Compared to the previous hat feeds where a piece of dielectric is used to support the hat on the waveguide, the new feed has lower manufacture cost and higher reliability. In addition, the new hat feed has low radiation along the feeding waveguide, which makes the vertex plate unnecessary. Therefore, the bandwidth over which the reflection coefficient is below -15 dB has increased. The feed has been optimized using Genetic Algorithm. A prototype has been manufactured, and measured results are presented to verify the numerical simulations.

Index Terms—Hat Feed, Reflector Antenna, Genetic Algorithm.

1 Introduction

Hat feeds are self-supported, rear-radiating feeds which consist of a waveguide (referred to as neck), a piece of dielectric material (head) and a corrugated brim (hat), as shown in Figure 1. Due to the geometry configuration, hat feeds eliminate the blockage caused by support struts and meanwhile make it possible to locate the transmitter and receiver at the rear side of the reflector. Therefore, hat feed reflector antennas have found many applications, such as in mini-link, satellite-communication terminals, gauge radar and so on.

Several types of hat feeds have been developed for different applications at Chalmers University of Technology and by other researchers worldwide since it was first introduced in 1987 [1]-[8]. Kildal presented the first patent-applied hat feed (Figure 1a) with low cross polarization and high efficiency in 1987 [1]. Then, a linearly polarized rectangular hat feed (Figure 1b) using soft and hard surfaces to improve the performance with broader bandwidth than the circular one in [1] was presented by Moldsvor *et al.* in 1993 [2] and an improved dual polarized circular hat feed was reported in [3]. The Chinese hat feed (Figure 1c) was developed by Yang and Kildal in 1998 [4], where the angle of the corrugated brim was changed to narrow the beam width so that shallow reflector antennas can be fed by it. As a variation of the Chinese hat feed, the parabolic hat feed (Figure 1d) was proposed by Yousefnia *et al.* in 2005 [5]. Denstedt *et al.* tripled the bandwidth of hat feed by using Genetic Algorithm in 2008 [6]. This contribution is considered as a breakthrough for designing wide band hat feed and the geometry is shown in Figure 1e. A further development of the parabolic hat feed in [5] was presented by Pirhadi *et al.* in 2008 [7] for having narrow beamwidth and use with Fresnel zone plate reflectors (planar structures). A hat feed without corrugated brim (Figure 1f) was presented by Slama *et al.* in 2008 [8].

The corrugated brims of all the hat feeds developed previously are supported by a piece of dielectric material (head) through gluing the three parts (hat, head and neck) together; see Figure 2 [9]. The gluing procedure requires high temperature treatment for strengthening the stability. The high temperature gluing procedure is time consuming and often causes unqualified products due to the difficult tolerance control for the head position.

For prime-focus reflector antennas, the reflection from the center of the reflector degrades the input reflection coefficient. By using vertex plate, the reflections from the vertex plate and from the rest of the center of the reflector can cancel each other in the feed [10]. However, the vertex plate is a narrow band solution. Therefore, in order to have broad band performance, it is desired that the hat feed has low radiation along the feeding waveguide so that there is no need to use the vertex plate.

This paper presents a new type of hat feed which is realized by pure metal structure without using dielectric material: the hat is supported by four metal tilted rods. In addition, in order to improve the performance under this pure-metal-structure constraint, a new technique is introduced, i.e., slits on the wall at the end of the waveguide. The new hat feed has low radiation along the feeding waveguide, which helps to increase the bandwidth of reflection coefficient by avoiding using a vertex plate. A prototype of the new hat feed has been manufactured. Simulated and measured performances of the new hat feed are presented in the paper for verifying the new design.

2 Characterization of Hat Feed

The hat feed is characterized by input reflection coefficient, aperture efficiency and co- and cross-polar radiation functions in this work. The aperture efficiency can be calculated by several sub-efficiencies [11] as

$$e_{ap} = e_{BOR1} e_{pol} e_{sp} e_{ill} e_{\phi} \tag{1}$$

where e_{BOR1} is the BOR$_1$ efficiency [11][12], e_{pol} the polarization efficiency, e_{sp} the spillover efficiency, e_{ill} the illumination efficiency and e_{ϕ} the phase efficiency. The BOR$_1$ (body of revolution) efficiency is the ratio of power in the n = 1 terms of the Fourier φ-series of the far field function of the antenna to the total power radiated by the antenna. It is well known that only the n = 1 term contributes to the axial radiation field (i.e. gain) of a rotationally symmetric reflector antenna, and that the higher order φ terms represent a power loss to the sidelobes [13]. It is also known that hat feed has a ring-shaped phase center and the phase efficiency can be improved to almost 100% by using a ring-shaped focus parabolic reflector [14]. e_{sp} and e_{ill} are mainly determined by the size of the hat brim of the hat feed and subtended angle of the reflector in use, and a good trade-off between e_{sp} and e_{ill} should be decided for different applications. Therefore, in the design and optimization of the new hat feed, we focus only on:

$$e_{opt} = e_{BOR1} e_{pol} \tag{2}$$

The co- and cross-polar radiation functions of BOR$_1$ antenna can be written as [11]:

$$\begin{aligned} G_{co}(\theta,\varphi) &= G_{co45}(\theta) - G_{xp45}(\theta)\cos(2\varphi) \\ G_{xp}(\theta,\varphi) &= G_{xp45}(\theta)\sin(2\varphi) \end{aligned} \tag{3}$$

Therefore, the radiation characterization of the feed is defined by the co- and cross-polar radiation functions in 45 degree plane: $G_{co45}(\theta)$ and $G_{xp45}(\theta)$.

3 New Support Structure

In this design, thin metal rods with one end on the waveguide and another connected to the hat are chosen as support structure. As shown in [1], there are two modes in the aperture between the waveguide and the hat brim: φ-mode with only φ-directed E-field, and z-mode with z- and ρ-directed E-fields; see Figure 3. The φ-mode radiates only in the H-plane (since it is zero in the E-plane) and not along the waveguide because the E-field of the φ-mode vanishes at the surface of the metal waveguide. The z-mode radiates mainly in the E-plane and also strongly in the direction along the waveguide both in the E- and the H- planes because the ρ-directed E-field component is normal to the metal surface of the waveguide (as a hard surface), which supports the propagation of the field along the waveguide. The two tangential E-field components over the aperture of the slot can be expressed as [1]

$$E_z(z,\varphi) = [V_z + V_{z1} C \sin(\pi z/h)]\sin(\varphi) \tag{4}$$

$$E_\varphi(z,\varphi) = [V_{\varphi 1} + V_{z1}]\cos(\pi z/h)\cos(\varphi) \tag{5}$$

where, $C = k_p^2 az/\pi$ V_z, $V_{\varphi 1}$ and V_{z1} are complex coefficients representing the amplitudes and phases of TM$_{01}$, TE$_{11}$ and TM$_{11}$.

It can be seen that the z-mode field (including z- and ρ-directed E-fields) outside the aperture of the slot is proportional to E_z in

(4) and φ-mode field proportional to E_φ in (5). Therefore, from (4) and (5), the z-mode field reaches maximum in the E-plane where φ= π/2 but drops to zero in the H-plane where φ= 0. If two thin vertical metal rods at the aperture are used as the hat-support structure, the z-mode field will be affected strongly by the rods put in the E-plane but not at all by the rods put in the H-plane. The φ-mode field is perpendicular to the rods, and therefore is not affected by them. Consequently, the field distribution over the aperture will be much affected by the two metal rods vertically located in the E-plane but not by the two vertically located in the H-plane. Figure 4 shows the hat feed with 2 vertical metal rods and the simulated aperture efficiency, when it is located in a reflector of a diameter of 654 mm and a subtended angle of 105 ^{o}, by CST Microwave Studio [15] for the following three cases: no metal rods, two vertical thin round rods in the H-plane and the same two in the E-plane. It can be observed that the support structure of two metal rods in the H-plane makes almost no changes in the aperture efficiency, while the aperture efficiency is much degraded when two metal rods are in the E-plane. It can be concluded that two thin metal supports in the H-plane is the best solution to a single linearly polarized hat feed.

For dual polarized hat feeds, a support structure with four thin tilted metal rods in φ = 45 ^{o}, 135 ^{o}, 225 ^{o} and 315 ^{o} planes is proposed; see Figure 5.

The reasons for this proposal are as follows. First, the overall effect of the metal rods on the z-mode fields for dual polarization is minimum when they are located in φ = 45 ^{o}, 135 ^{o}, 225 ^{o} and 315 ^{o} planes. Second, it is desired to eliminate the radiation along the waveguide while the radiation in other directions remains. By using four titled metal rods as shown in Figure 5, the distance between rods at the waveguide end is small, often less than half wavelength of operating frequencies; while the distance between rods at the hat brim is much larger than half wavelength of operating frequencies. Therefore, the z-mode fields cannot propagate between the support rods near the waveguide end, and thereby the radiation along the waveguide will be reduced; while the z-mode fields propagate easily between the support rods close to the hat brim and are reflected by the corrugations towards the reflector. Third, four thin rods are mechanically very stable. In order to keep the manufacturing cost low and the structure compact, straight thin metal rods are used. It should be noted that thin tilted rods do not affect the φ-mode field and that the φ-mode field does not radiate along the outer surface of the metal waveguide.

All previous hat feeds have the maximum radiation in the direction along the feeding waveguide [1]-[8]. By introducing the new support structure, the radiation along the feeding waveguide has been reduced significantly; see the simulation in Figure 6. Note that $\theta=0^{o}$ is the direction of the center line of the feeding waveguide and θ from -10^{o} to 10^{o} is inside the waveguide. The radiation patterns for θ from -10^{o} to 10^{o} cannot be simulated accurately with the model in CST. Therefore, we have only plotted the pattern y outside $\pm10^{o}$ in Figure 6, and simply connect the 10^{o} pattern values on each side of θ = 0 by straight lines. The low radiation along the feeding waveguide of the new feed leads to a low reflected power level from the center area of the reflector. Therefore, the input reflection coefficient of the feed will not be affected when it is located in the reflector, which makes it unnecessary to use vertex plate. This is confirmed by Figure 7 which shows that when the new hat feed is mounted on the reflector, the reflector has almost no effect on the input reflection coefficient.

The new hat feed is not pure BOR antenna due to the new support structure, whereas all previous hat feeds have perfect BOR structure. Therefore, the BOR_1 efficiency of the new hat feed will be degraded. Consequently, optimization of the new hat feed configuration is applied to obtain an optimal BOR_1 efficiency; see Section 5.

4 Slits in the waveguide end (wire grid)

In order to have low cross polar radiation level, the hat feed should be designed in such a way that the z- and φ-modes are excited with correct amplitudes and phases to have the same E- and H-plane radiation functions [11]. For the previous hat feeds with dielectric support, this is achieved by adjusting the aperture size (distance between the hat and the waveguide end) and the shape of the dielectric support material inside the waveguide. In the present design, we introduce longitudinal slits at the end of the waveguide as shown in Figure 8 for adjusting the z- and φ-modes excitations independently from each other. If we have an infinite number of infinitely thin slits in the end of the waveguide, the slit waveguide wall becomes a wire grid that allow the φ-mode field to penetrate through this part of the wall so that the circumferential aperture between the hat and the end of the waveguide appear larger, whereas the z-mode field is unaffected by the wire grid and see a circumferential aperture that is unchanged by the slits. Therefore, the aperture size for the φ-mode field is *h1* longer than that for the z-mode field where *h1* is the length of the slits; see Figure 8. Thus, by changing the depth of the slits, we can adjust the φ-mode field without changing the z-mode field in the aperture.

It should be noted that the reflection coefficient at the waveguide input port is also affected by these slits so optimization is applied. In this design, sixteen slits are used.

5 Optimization

The geometry of the new hat feed is shown in Figure 8. Three corrugation rings on the hat brim are used in this design, and the support metal rods are configured with one end on the bottom of slits and other end on the most outer brim of the corrugation rings. The size of the cross section of the metal rods is determined by mechanical consideration as 2x2 mm^2. The inner diameter of the circular waveguide is determined by the operating frequency band of 10.7 – 12.7 GHz. The remaining 12 geometry parameters (*L1, L2, L3, W1, W2, W3, D1, D2, D3, h1, h2, T,* as shown in Figure 8) have be determined through the optimization.

Genetic algorithm, which has been proved as an efficient optimization scheme for hat feed [6], is used to optimize both the reflection coefficient and aperture efficiency of the new hat feed. The goal function is defined as

$$F = e_{BOR1} \cdot e_{pol} \cdot (|S_{11}|^{-\alpha} - 1) \tag{6}$$

where S_{11} is the reflection coefficient and α a number between 0 and 1. The larger α is, the more the reflection coefficient dominates in the value of F. In this optimization, α is set as 0.5. The goal of the optimization is to maximize the value of F.

The first generation in the optimization is created randomly with a population of 500 models under the condition that all corrugations must be wider than 2.5 mm for the convenience of manufacture. Then, an elite group of 6 models with the maximum F values is selected and two-point crossover is applied among the group for creating 60 new models for the next generation. Then, 440 new models are created randomly and crossover with the best 6 models. Among the best 6 models, better models have higher priority to crossover with newly introduced models. All genes are checked to see if they satisfy the manufacturability constraints. The whole procedure runs 5 generations to achieve convergence.

6 Simulated and Measured Results

A prototype of the optimized new hat feed realized without dielectrics was manufactured for verifying the design; see Figure 9.

Figure 10 shows that the decrease of the simulated BOR_1 efficiency caused by the 4 metal rods is smaller than 0.3 dB. Meanwhile the polarization efficiencies remains higher than -0.5 dB. Consequently, the deterioration caused by the 4 rods is acceptable.

Figure 11 shows the simulated and measured reflection coefficient of the hat feed reflector antenna with the new hat feed mounted in the reflector; see Figure 9. The reflector has a diameter of 654 mm and a subtended angle of 105°. Notice that there is no vertex plate in the new hat feed reflector antenna. The measured result shows that a 26% bandwidth with reflection coefficient below -15 dB is achieved.

The simulated and measured radiation patterns in $\varphi = 45^{\circ}$ plane of the new hat feed reflector antenna are shown in Figure 12. The measurements were done in the anechoic chamber at Chalmers. The radiation patterns almost meet the requirement of class 2 of ETSI EN 302 217-4-2 [16] (ETSI RIC2).

Figure 13 shows the calculated and measured aperture efficiency of the new hat feed reflector antenna. We used two methods to calculate the aperture efficiency based on the simulations by CST: 1) $e_{ap} = D_{0sim} - D_{max}$, where D_{0sim} is the directivity of the antenna simulated by CST, and D_{max} the theoretical maximum directivity; 2) using the definition of (1) and calculating all sub-efficiencies based on the simulated radiation patterns. The measured aperture efficiency is obtained by $G_{0mea} - D_{max}$, where G_{0mea} is the measured gain of the antenna. From the figure, the two calculated results are very close to each other. The measured values agree with the calculated ones quite well, within the measurement error. The results of aperture efficiency also show the property of a wide bandwidth.

Table 1 shows a comparison among three hat feeds: the new present design with support rods, the previous model in [17], and the wideband hat feed presented in [6]. The new hat feed achieves a wider bandwidth and higher aperture efficiency with a lower manufacturing cost than previous models of the hat feed. Although the wideband hat feed in [6] has the widest bandwidth of the reflection coefficient, the radiation performance does not satisfy the standard requirement of class 2 of ETSI EN 302 217-4-2. Therefore, the new design is very attractive.

7 Conclusions

A novel hat feed that is entirely made of metal has been successfully designed. The expensive dielectric support is replaced by a simple metal structure while good merits of the hat feed remain. A new technique - longitudinal silts located evenly around the waveguide end is used to improve the performance, and the vertex plate becomes unnecessary due to very low radiation along the waveguide for the new hat feed. The new hat feed reflector antenna exhibits a bandwidth of 26% with the reflection coefficient below -15 dB, the aperture efficiency is higher than -3dB, and radiation performance satisfies the requirement of class 2 of ETSI EN 302 217-4-2.

8 Acknowledgement

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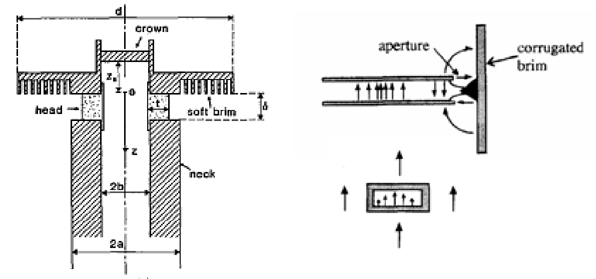
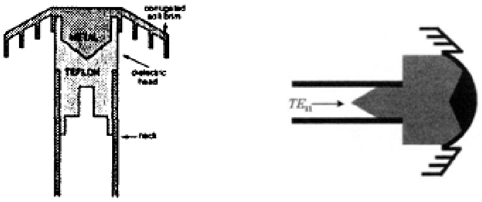
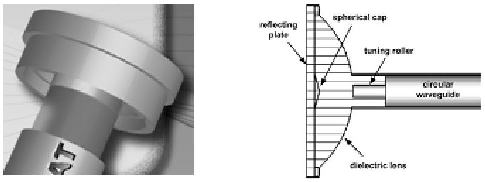


(a) The first hat feed [1] (b) Rectangular hat feed [2]



(c) Chinese hat feed [3] (d)Parabolic hat feed [4]



(e) Wideband hat feed [5] (f) The hat feed in [7]

Figure 1 Different versions of hat feeds

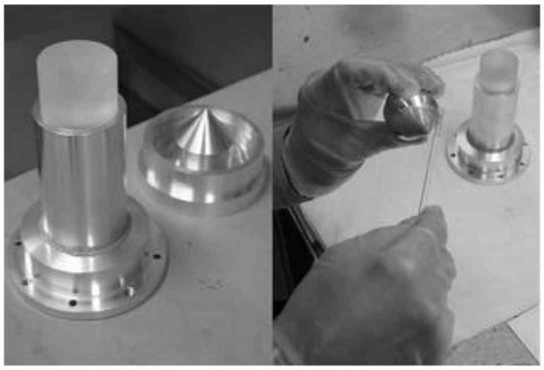
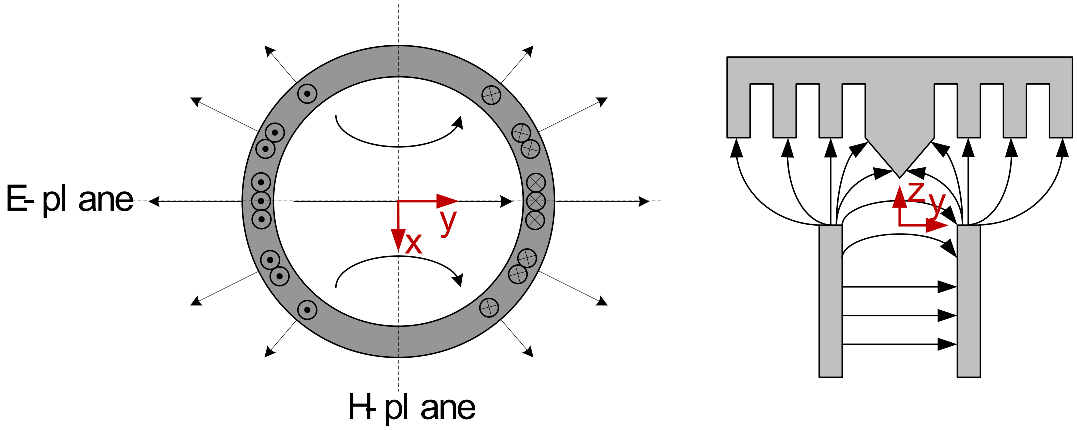
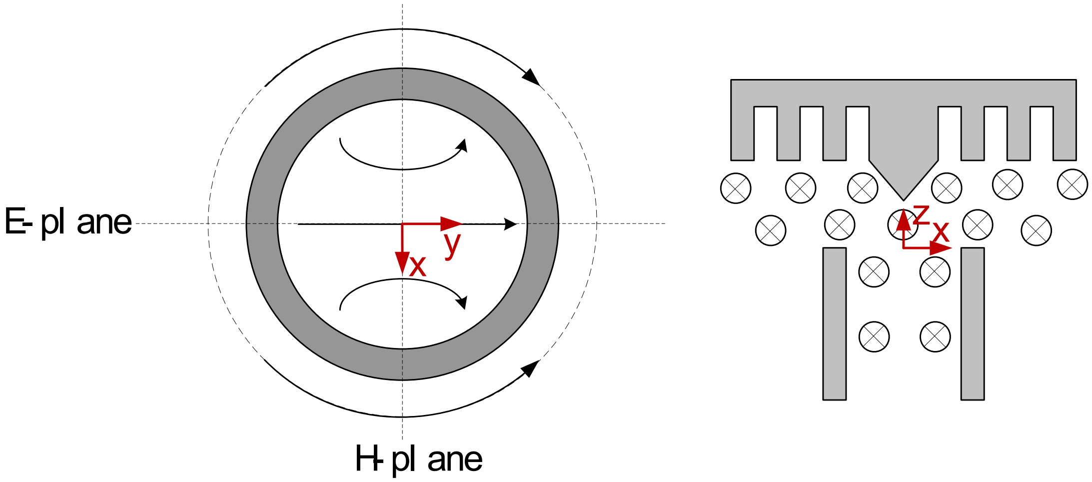


Figure 2 Gluing procedure [9]



(*a*) E-plane Mode



(*b*) H-plane Mode

Figure 3 E-field Distributions of (*a*) z-mode (the E-plane mode) and (*b*) φ-mode (the H-plane mode) in the aperture between the hat and the waveguide

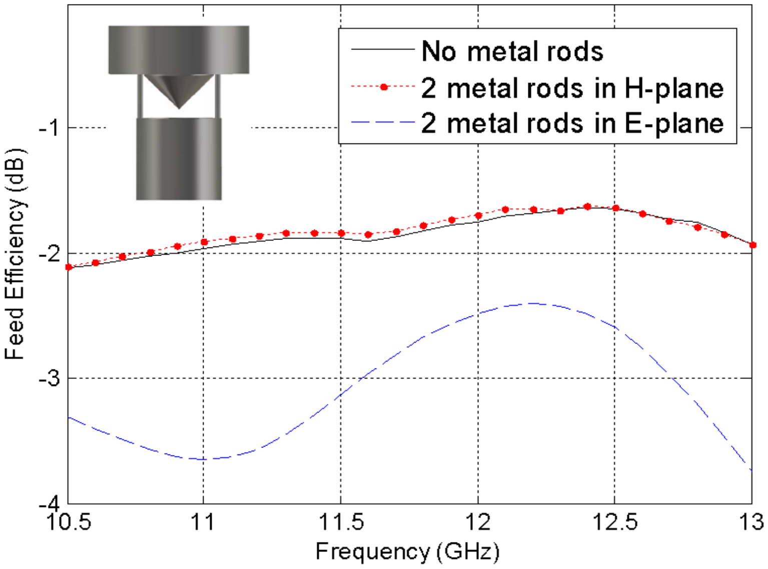


Figure 4 Simulated aperture efficiency with two vertical metal rods in the E-plane or in the H-plane

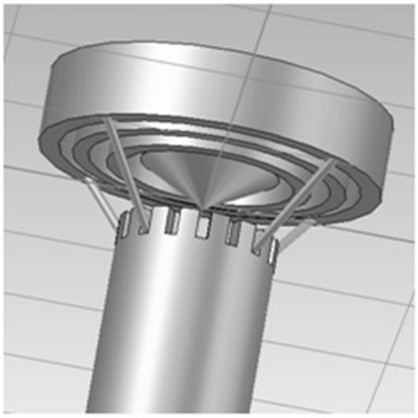


Figure 5 New hat feed with support structure of four tilted metal rods in φ = 45º, 135 º, 225 º and 315 º planes

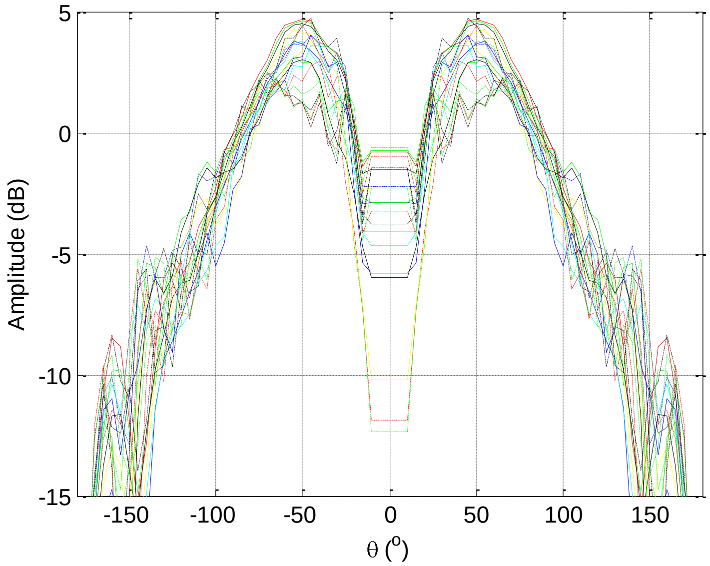


Figure 6 Simulated co-polar radiation patterns in φ=45° plane for the new hat feed from 10 to 14 GHz with a frequency step of 0.2 GHz

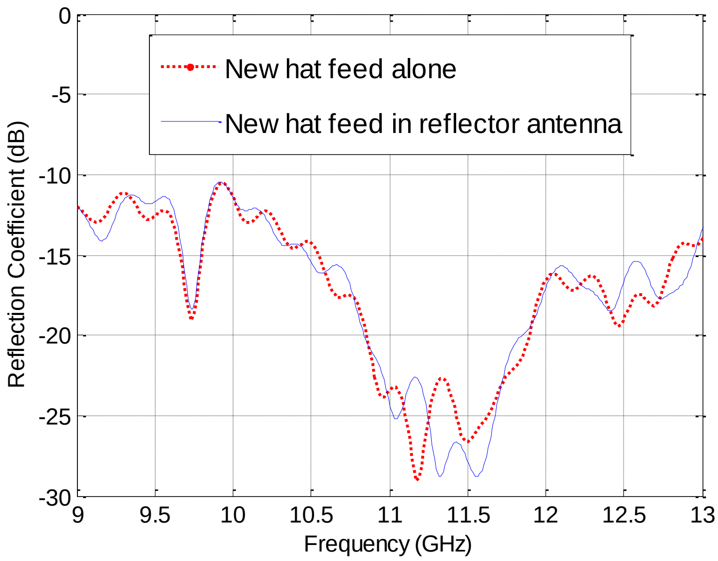


Figure 7 Simulated reflection coefficients of the new hat feed alone and when it is located in the reflector antenna of a diameter of 654 mm and a subtended angle of 105 °

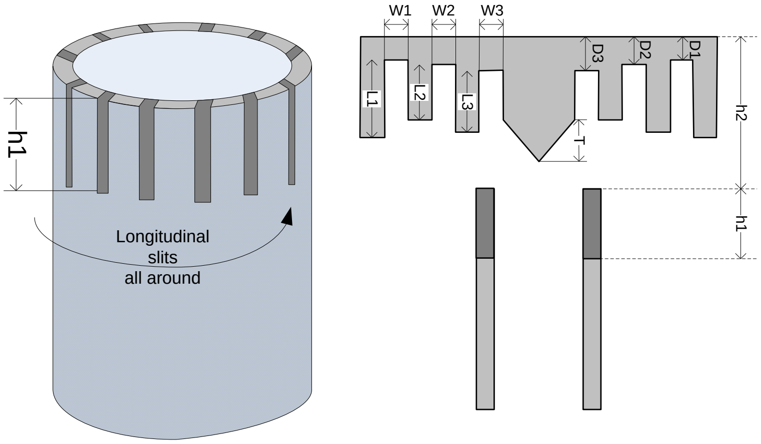


Figure 8 Slits around the waveguide wall and corrugations of different depths

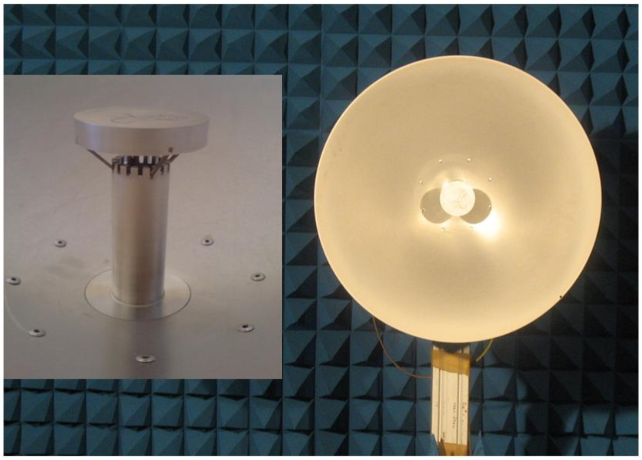


Figure 9 Prototype of the new hat feed reflector antenna under measurement

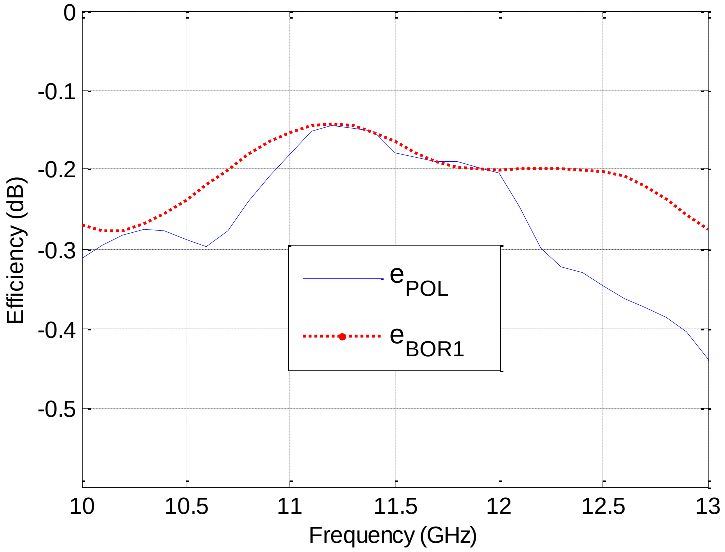


Figure 10 Simulated BOR$_1$ and polarization efficiency of the new hat feed

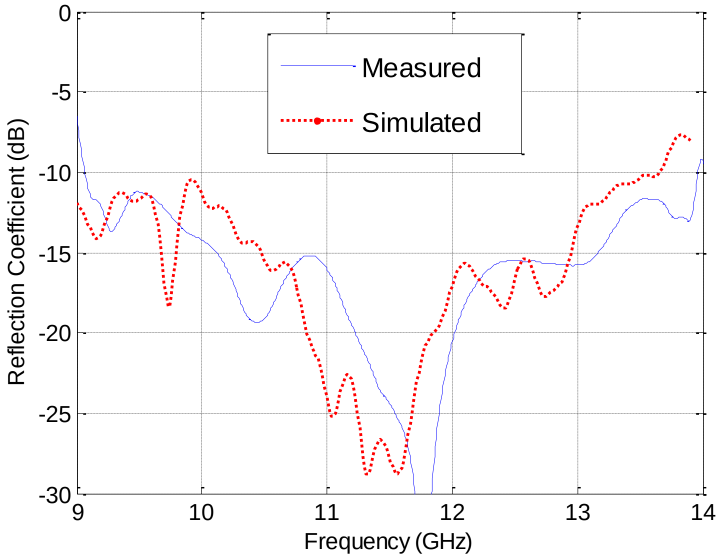
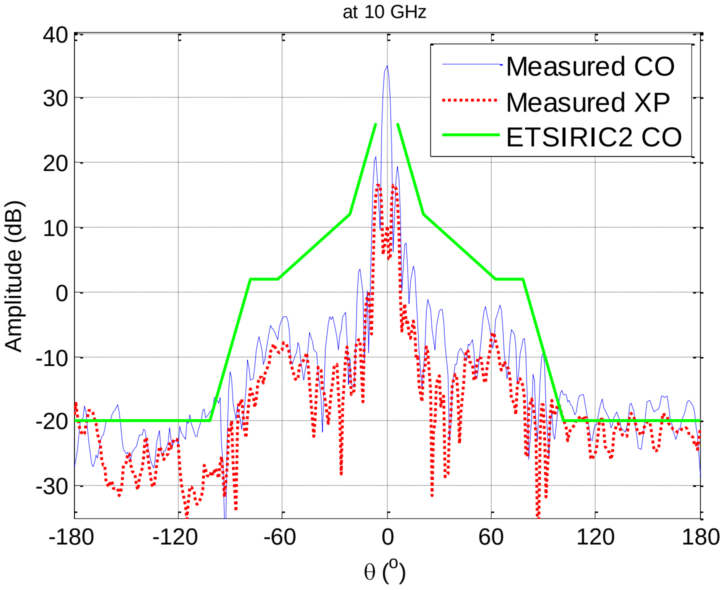
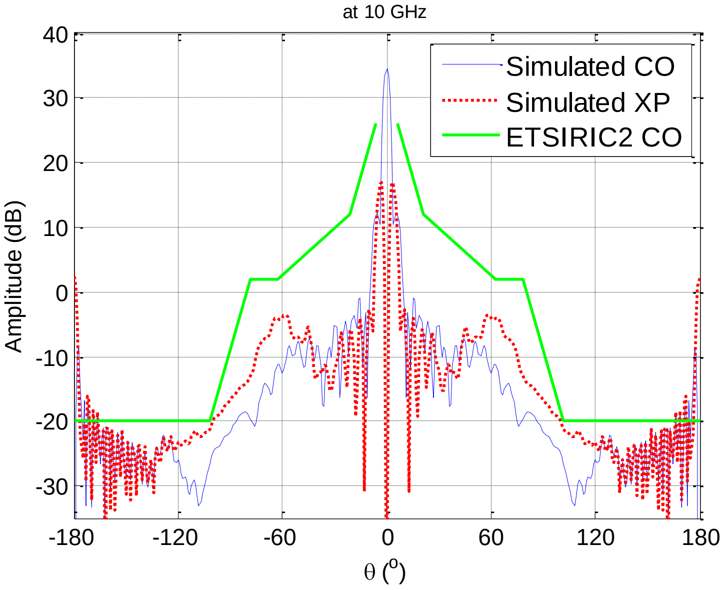


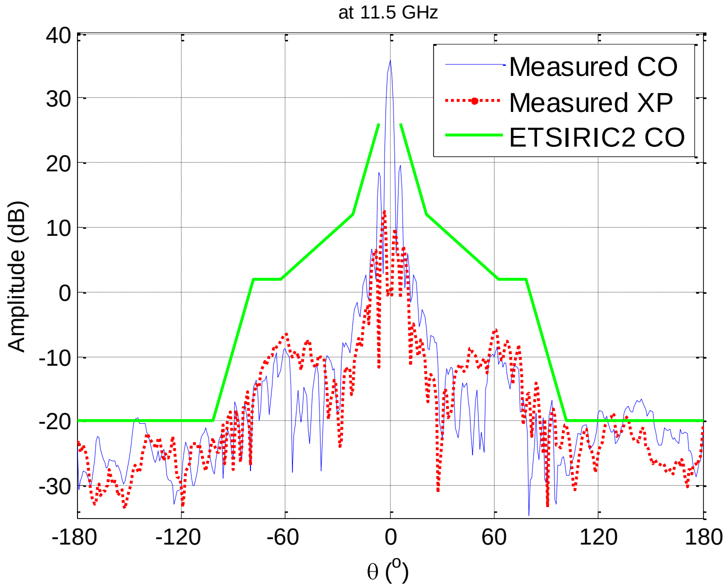
Figure 11 Simulated and measured reflection coefficient of the new hat feed mounted in the reflector



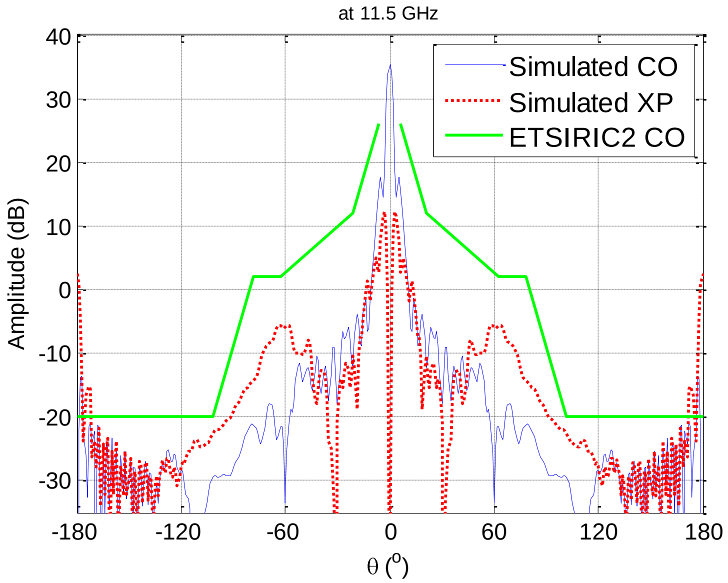
(a) Measured radiation patterns in φ=45° plane at 10 GHz



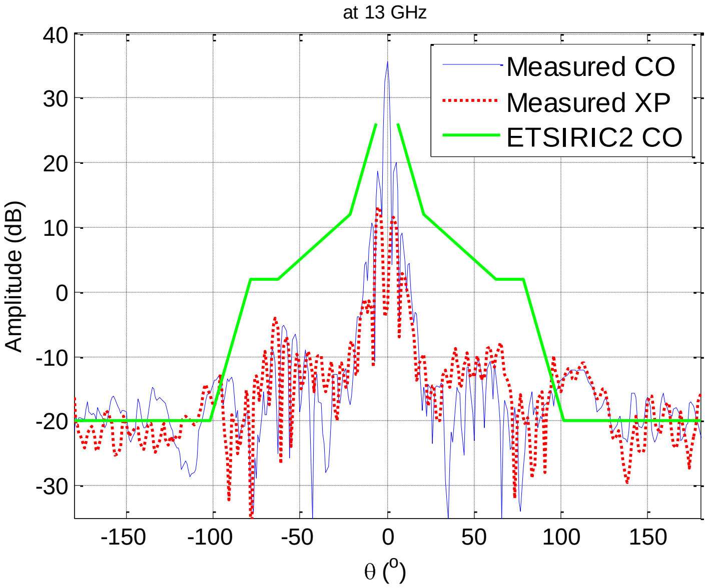
(b) Simulated radiation patterns in φ=45° plane at 10 GHz using CST



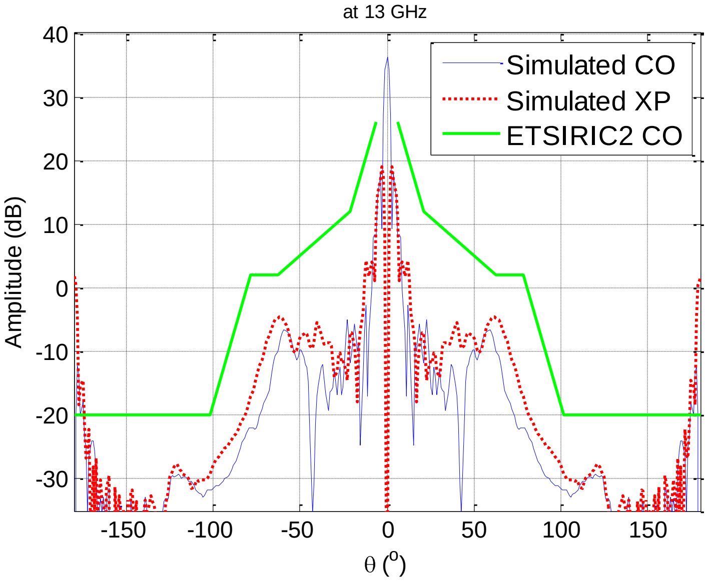
(c) Measured radiation patterns in φ=45° plane at 11.5 GHz



(d) Simulated radiation patterns in φ=45° plane at 11.5 GHz using CST



(e) Measured radiation patterns in φ=45° plane at 13 GHz



(f) Simulated radiation patterns in φ=45° plane at 13 GHz using CST

Figure 12 Measured and simulated co- and cross polar radiation patterns of the new hat feed reflector antenna in φ=45 ° plane at 10, 11.5 and 13 GHz

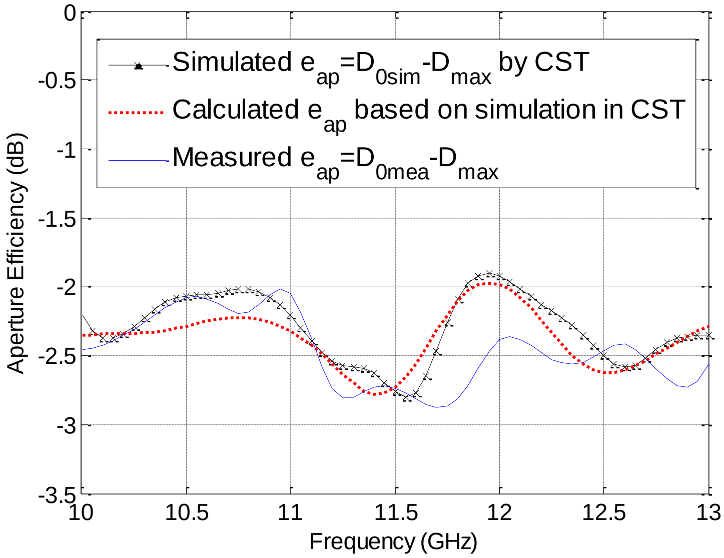


Figure 13 Calculated and measured aperture efficiencies of the new hat feed reflector antenna

Table 1 Comparison of three hat feeds

	Bandwidth for S_{11} below -15 dB	Aperture efficiency	European Standard Class 2 ETSI EN 302 217-4-2
The new hat feed	26%	-1.96 ~ -2.81 dB	Satisfied
Traditional hat feed[17]	14%	-2.43 ~ -2.95 dB	Satisfied
Wideband hat feed [6]	36%	-1.94 ~ -2.54 dB	Not satisfied