Bandwidth response of a reflectarray antenna working as a Compact Antenna Test Range probe

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***Abstract*—A reflectarray antenna working at 28 GHz is proposed to replace the reflector antenna of a Compact Antenna Test Range (CATR) system. As a first approach, the quiet zone obtained using a far-field collimated reflectarray is analysed. Due to the size of this area is not large enough, the generalized Intersection Approach is employed to carry out an optimization of the near-field for both phase and amplitude in order to maximize the size of the quiet zone at one plane. Simulations are compared for the near-field before and after the optimization process, showing an important enhancement of the size of the quiet zone, especially in the main cuts. From the obtained phase distribution a design is carried out. The unit cell chosen is based on a two-layer stacked patch, having good agreement between optimization and design results. Finally, the bandwidth response of the designed reflectarray is analysed, in order to assess its performances as probe in a CATR system.**

I. Introduction

Compact Antenna Test systems (CATR) are widely known in the measurement of radiation pattern or Radar Cross Section (RCS), enabling to measure in far-field conditions the DUT within the near-field region of the probe. Thus, CATR presents a significant advantage regarding other systems that require the use of near-field to far-field transformations or larger distances in order to reach the far-field regions. The CATR working principle is based on the existence of a near-field area called quiet zone, wherein the near-field has a low ripple in both amplitude and phase so, this near-field behaviour mimics far-field conditions, allowing to measure the radiation pattern directly. The quiet zone is generally generated by a parabolic reflector which is illuminated by a feed, that is typically a horn. The incoming field provided by the feed is collimated by the parabolic reflector in a certain direction, where the quiet zone can be found.

Although CATR systems are really useful in antenna measurements, there are some drawbacks that should be borne in mind. Firstly, the size of the quiet zone is directly proportional to the equivalent aperture of the antenna, therefore, in many cases a large electrical reflector is required, having to lead with bulk antennas and structures[1]. On the other hand, the recent evolution of the technology whether for 5G, Internet of Things (IoT) or wireless power transfer has sparked in the need of using higher frequencies that are chiefly in the millimetre and sub-millimetre wave spectrum, particularly, the best efforts in 5G have been done at 28, 39 or 60 GHz. Within these frequencies, the reflectors present problems in terms of the antenna size and the manufacturing process since at high frequencies the manufacturing error in the surface has to be truly low. In the light of these disadvantages, the need of searching for an antenna replacement has become in a current topic. In [2] a hologram is proposed to replace the reflector, reaching a quiet zone but using a very large aperture. Another option is to replace the reflector by an antenna with a similar working principle, therefore, reflectarray antennas can be potentially good candidate. Nevertheless, this kind of antenna is not without drawbacks as it is shown in [3], where the quiet zone radiated by a reflectarray is assessed for being used as a probe of a CATR system. The main disadvantage lies on the taper of the amplitude of the incident field, since it is preserved in the reflected field thus, the near-field size is deeply affected by this factor. In addition, it is well-known that reflectarray antennas are narrowband unlike reflector antennas so, the quiet zone is also limited in terms of bandwidth.

Conversely, there are a lot of previous works where it is demonstrated that reflectarray antennas can be easily optimized. In [4] the far-field radiated by a reflectarray is synthesized in order to fulfil the requirement for space communications or, in [5] a reflectarray is optimized for DBS coverage. However, the majority of these works are focussed on the far-field optimization. Regarding the near-field, in [6] the generalized Intersection Approach is used to synthesize the amplitude of the field within the near-field region. Then, in [7] a reflectarray is improved for the deployment of efficient 5G near-field femtocells.

In this work, a reflectarray antenna is proposed for a CATR system working at a central frequency of 28 GHz, particularly suitable for the measurement of 5G antennas. The reflectarray is optimized with a Phase-Only Synthesis (POS) using the generalized Intersection Approach (IA) in order to fulfil the quiet zone requirements, both in phase and amplitude. Then, using the solution provided by the algorithm, a two-layer stacked patches design is carried out and, finally, the quiet zone bandwidth is studied in order to know if it is feasible to use only one reflectarray for the 5G band at 28 GHz, from 26 to 29 GHz.

II. Reflectarray working as a CATR probe

A. Quiet zone definition

A quite zone is defined as a volume wherein the near-field radiated has a behaviour virtually close to far-field conditions thus, it can be almost considered as an uniform plane wave. Generally, the near-field is assumed to be under this assumption provided that the amplitude ripple is lower than 1 dB and $10°$ for the phase ripple. Nevertheless, this is a theoretical consideration since previous literature [11] has developed operative working systems with less tight specifications. The antennas used in these works are reflectors and holograms, which are hardly optimizable. In this line, most of the improvements are achieved by the optimization of the feed [9], adjusting its position the taper of amplitude over the reflector can be significantly reduced thus, the amplitude of the reflected field will be flattener. On the other hand, the phase is automatically flat because of the geometry properties of the antenna.

In [3] a reflectarray was proposed as a potential candidate to replace the main reflector in CATR systems, since a reflectarray has the same working principle of the reflectors. Once again, the main drawback in the generation of the quiet zone is regarding the taper of amplitude imposed by the feed. However, reflectarray antenna can be optimized in an easier way, turning it in a perfect replacement. An example of a CATR system using a reflectarray is shown in Fig. 1, in this case, a horn is feeding the reflectarray and a DUT is placed within the near-field that satisfies the ripple requirements.

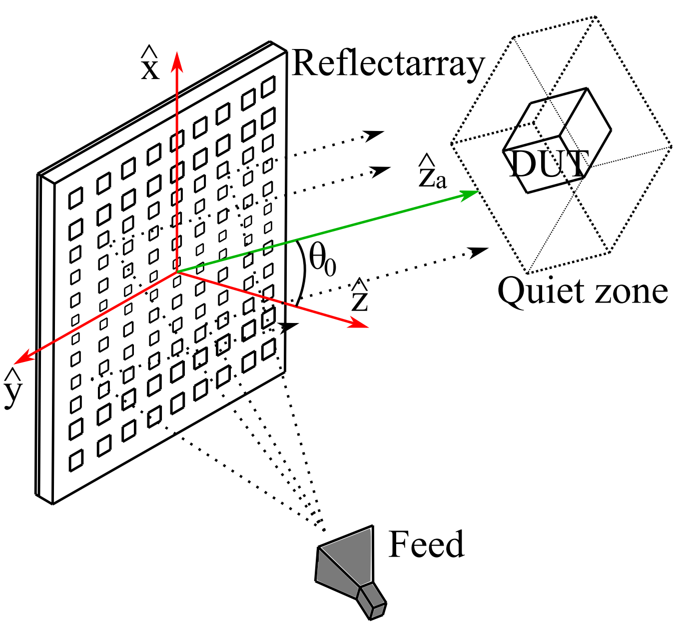


Fig. 1: Description of a CATR system based on a reflectarray antenna.

B. Far-field collimated reflectarray

In a first approach, a far-field focused reflectarray is considered, whereby the far-field radiation pattern is a pencil beam focused on a certain (θ_0, ϕ_0) direction. Assuming $\phi_0 = 0°$, the initial phase distribution can be easily calculated as follows:

$$\phi_{RA} = \phi_{in}(x_m, y_n) - k_0 x_i \sin\theta_0 \tag{1}$$

where $\phi_{in}(x_m, y_n)$ is the incoming phase of the incident field at the (m, n)-th element; k_0 is the vacuum wavenumber and θ_0 is the focusing direction. This equation provides the reflection coefficients for either the X or Y polarization but, considering the system depicted in Fig. 1, in this case they agree with the X polarization.

Furthermore, a planar reflectarray of 1936 elements in a 44×44 regular grid has been chosen. The periodicity in both, $\hat{x}$ and $\hat{y}$ direction is $4.29\times4.29\text{mm}^2$ thus, the equivalent aperture (D) is calculated using (2) at a central frequency of 28 GHz. Then, the feed is located at $(\hat{x}, \hat{y}, \hat{z}) = (-79.3, 0, 200.2)$ mm with regard to the centre of the reflectarray (see Fig. 1), and it is modeled as an ideal $\cos^q\theta$ function with a q-factor of 20.

$$\begin{aligned} D = D_x \times D_y &= 188.76 \text{ mm} \cdot \cos\theta_0 \times 188.76 \text{ mm} \\ &= 177.37 \times 188.76 \text{ mm}^2 = 16.55\lambda \times 17.61\lambda \end{aligned} \tag{2}$$

Assuming a beam radiated in the $\hat{z}_a$ direction with $\theta_0 = 20°$, the phase distribution shown in Fig. 2 is calculated. Additionally, the near-field radiated at a plane $z_a = 500$ mm, perpendicular to $\hat{z}_a$ direction, is shown in Fig. 3, specially, the main cut that corresponds to $x = 0$ and $y = 0$ for both amplitude and phase. The quiet zone size is limited by the lower dimension wherein the ripple specifications are fulfilled, considering both phase and amplitude. Therefore, the limiting cut is the asymmetric one of the amplitude, which is the plane where the feed is placed.

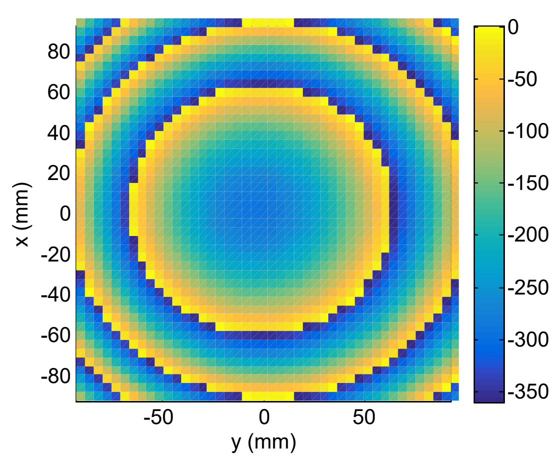
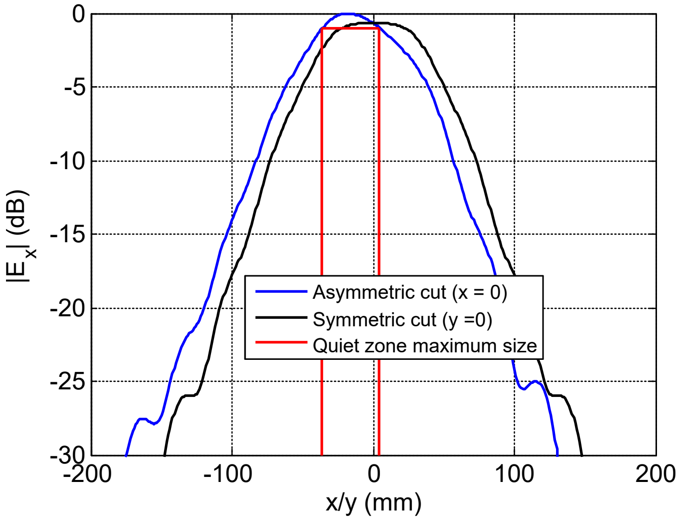
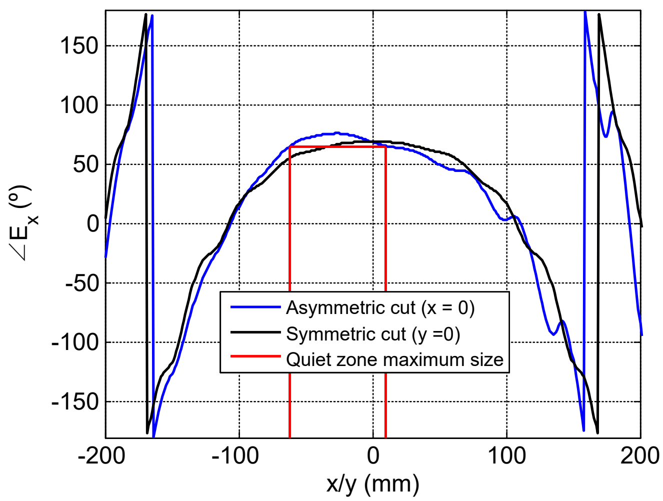


Fig. 2: Initial phase distribution for a far-field focused reflectarray on $(\theta_o = 20°, \phi_0 = 0°)$ direction.

As it was mentioned before, one of the advantages of using a reflectarray instead of a reflector is the chance to optimize its design by only adjusting the phase-shift response of the elements. Therefore, an optimization can be applied to reduce the amplitude taper of the near-field and, consequently improve the quiet zone performances.



(a)



(b)

Fig. 3: Main cut ($x = y = 0$) of the near-field radiated by the phase-distribution shown in Fig. 2 and the quiet zone generated. (a) Normalized amplitude (b) Phase.

III. Reflectarray synthesis and design

A. Optimization of the quiet zone size

The generalized Intersection Approach (IA) has been widely used in the optimization of reflectarray antennas, especially in far-field applications. Nevertheless, in [6] the algorithm is described to perform a Phase-Only Synthesis (POS) of the near-field radiated by a reflectarray, considering both phase and amplitude. Hence, the IA is chosen to carry out an optimization of the reflectarray defined in previous section in order to increase the size of the generated quiet zone. Although the strict definition of the quite zone establishes a maximum amplitude ripple of 1 dB, so as to facilitate the convergence of the algorithm due to the strong taper of the starting point, this specification is relaxed to 1.5 dB. Regarding the phase ripple is maintained in $10°$. These requirements are established within a circular area of radius 50 mm at a plane 500 mm far from the reflectarray center and perpendicular to the pointing direction defined by the vector $\hat{z}_a$ (see Fig. 1).

Once the optimization process is finished the phase distribution of Fig. 4 is obtained. Then, the main cuts of the optimized near-field radiated for both phase and amplitude are shown in Fig. 5, in which are compared with the starting point. These two cuts represent the largest dimension where the field has to be within the specifications since these requirements are established within a circular area. Thus, as it can be seen, both amplitude cuts have significantly improved and flattened the starting point while the phase is also slightly enhanced achieving to keep the whole phase within the boundaries.

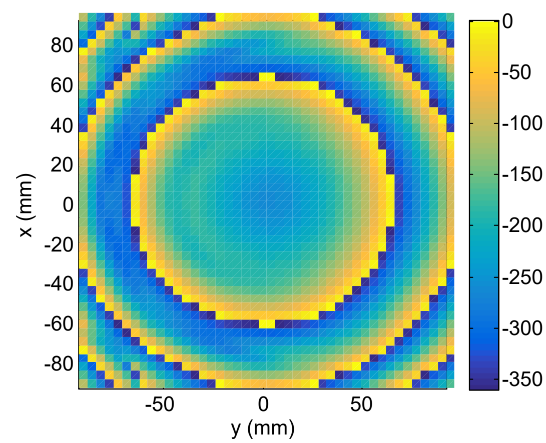


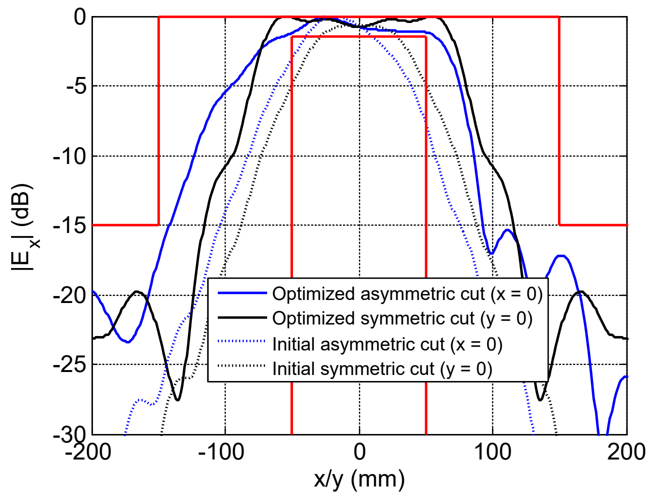
Fig. 4: Optimized phase distribution obtained after the synthesis process.

Considering the whole quiet zone in amplitude, Fig. 6 shows the ripple within this area for the starting point and after the optimization. The enlargement of the amplitude of the near-field is the major challenge since there is a strong taper because of the feeder but, after the synthesis this problem is solved and a solution that fulfil the requirements for the whole area is reached. On the other hand, the starting point for the phase is much better due to the reflectarray is properly collimating the incoming phase in the required direction.

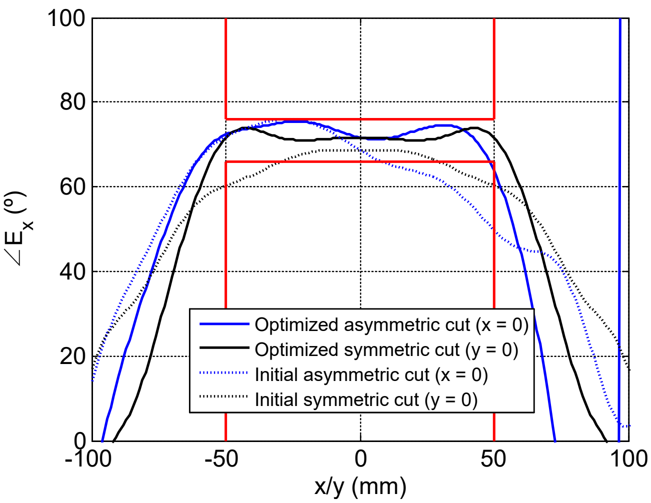
B. Reflectarray design

The synthesis results show that the near-field radiated by the optimized phase distribution totally satisfies the requirement within the desire area and therefore, the quite zone is improved. However, the optimization is based on a Phase-Only synthesis, which means that the elements of the reflectarray are modeled as an ideal phase-shifter without losses. Furthermore, the phase-distribution obtained is smooth enough to be implemented in a proper prototype, enabling to evaluate a more realistic quiet zone. In addition, the ideal $\cos^q \theta$ feed is replaced by a NARDA v637 horn, with a directivity of 15 dBi.

Then, a unit cell based on two-layer stacked patches backed by a ground plane has been chosen. The patches from the two layer have a fixed ratio of 0.80, placing the bigger patches on

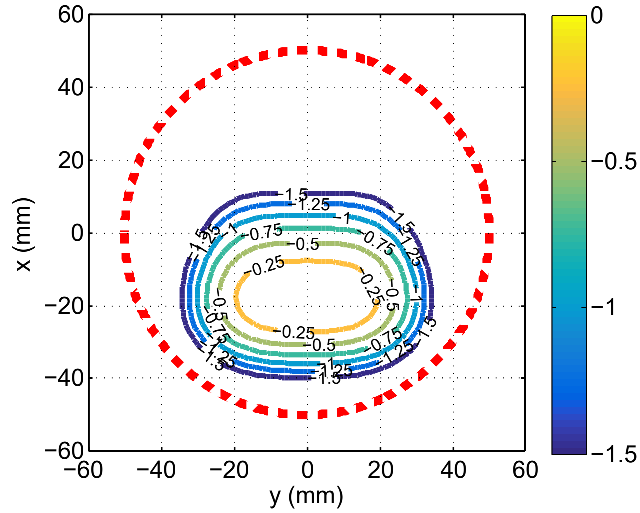


(a)

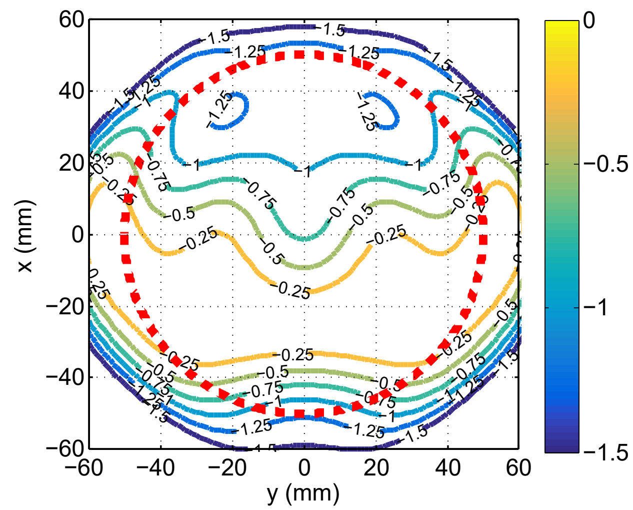


(b)

Fig. 5: Comparison between the (a) optimized and initial normalized amplitude and (b) optimized and initial phase normalized to the same point.



(a)



(b)

Fig. 6: Evaluation of the amplitude ripple within the optimization area for (a) before (b) after the optimization.

the lower layer. The chosen substrate is ARLON 25N, with $\epsilon = 3.38$, $\tan\delta = 0.003$ and thickness 30 mills for both layers. As Fig. 7 shows, this topology provides more than $360°$ phase-shift to perform the design using a zero-finding routine [10]. Then, the near-field radiated by this design is computed using the Method of the Moments, assuming local periodicity, and it is compared with the previous results, Fig. 8. As it can be seen, the amplitude and phase matches perfectly at 28 GHz and only bare differences can be appreciated.

IV. Bandwidth Respone of a Reflectarray Probe

In spite of having a reflectarray properly designed and obtaining high agreement between the synthesis results and the MoM analyse, it should be borne in mind that the reflectarray is only optimized for only one frequency, particularly, 28 GHz. This fact deserves to be highlighted since a reflectarray is a narrow band antenna so, the quiet zone is supposed not to have a broadband behaviour. Even so, it is important to study the bandwidth response due to this reflectarray intends to work as a probe in a measurement system. Therefore, the quiet zone performances are evaluated for different frequencies from 26 to 29 GHz, regarding that this in one of the operation band of 5G.

In the light of the results shown in Fig. 9, the amplitude satisfies the 1.5 dB specification in the whole studied band. Conversely, the phase presents a stronger ripple regarding the results at 28 GHz, with a variation of almost $20°$. Therefore, when it comes to analyse the quiet zone bandwidth response, the phase seems to be the factor that limits the size of it. However, a deeper study is required since literature demonstrates that there are systems working with higher ripples, particularly in the near-field phase as it happens in [11].

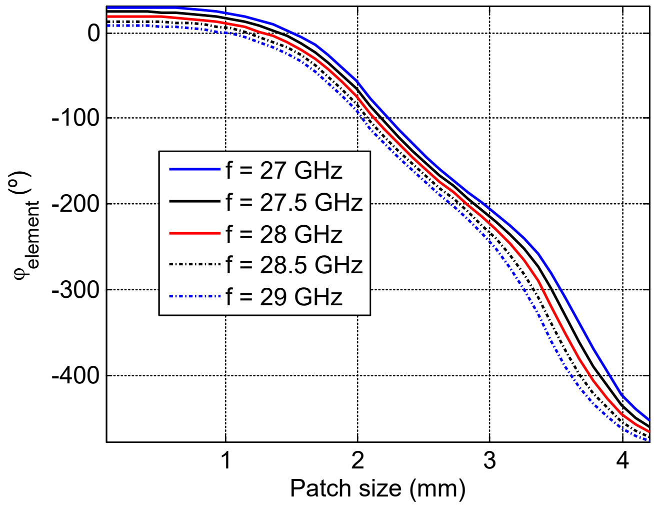


Fig. 7: Response of the two-layer stacked patch used for normal incident and different frequencies.

V. Conclusions

In this work, a reflectarray antenna working at 28 GHz is proposed to be used as a CATR probe, replacing the traditional parabolic reflector, for the radiation of a quiet zone area. A far-field focused reflectarray is fed by a single-offset feed, which generates a strong amplitude taper over the reflectarray surface so, both near-field and quiet zone are deeply affected by this factor. Then, the generalized Intersection Approach is employed to reduce this effect by carrying out a POS synthesis of both amplitude and phase of the near-field radiated. The optimizations results show a great improvement and a larger quiet zone is reached. At the sight of these results a design using the optimized phase distribution is carried out, using a two-layer of stacked patches unit cell. The comparison between the near-field obtained in the synthesis process and the design shows a high agreement between both. Finally, a bandwidth response study is carried for the designed reflectarray, covering the band of 5G communications at 28 GHz. This study shows a better bandwidth behaviour of the amplitude rather than the phase. The designed reflectarray can be improved with an in-band optimization.

Acknowledgement

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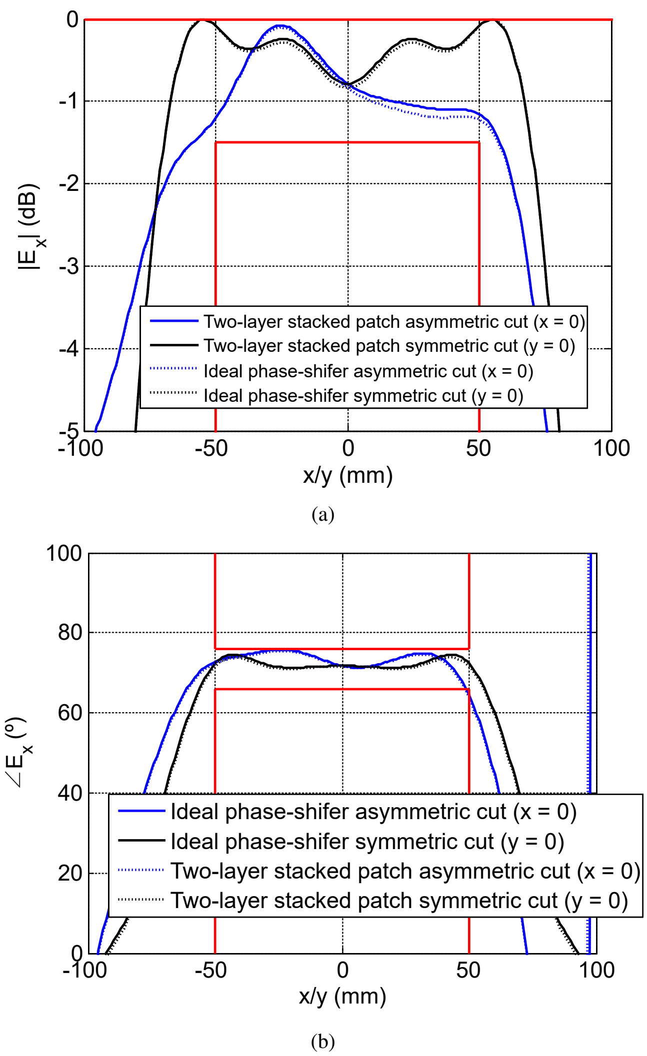

Fig. 8: Comparison of the (a) normalized amplitude and (b) normalized phase between the ideal phase-shifters and the two-layer stacked patches.

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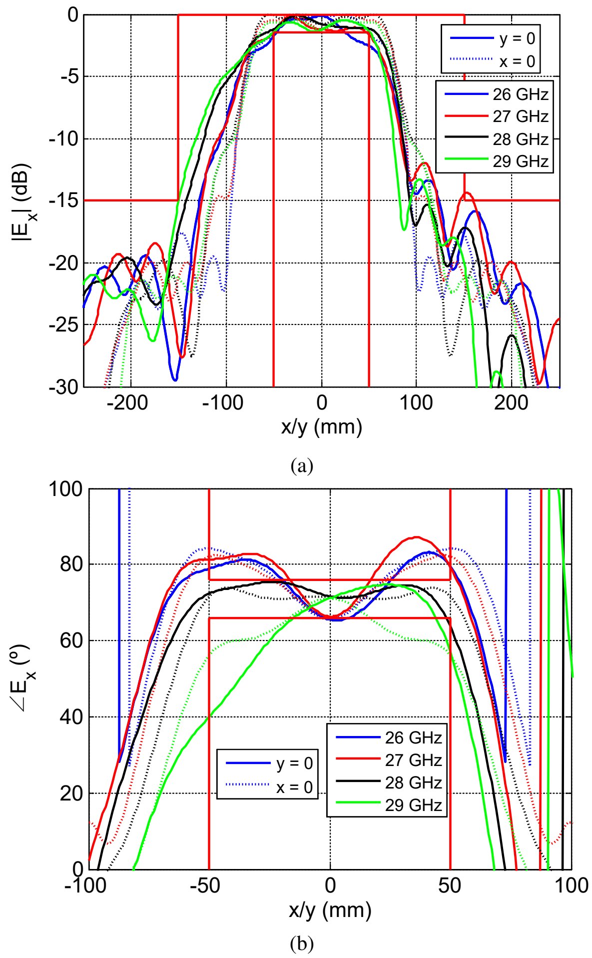

Fig. 9: Bandwidth response of the reflectarray design from 26 to 29 GHz for the normalized (a) amplitude and (b) phase.

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