On the Design of Reflectarrays and Transmitarrays Using 3-D Unit Cells

Ángel Palomares-Caballero[(1)], Carlos Molero[(2)], Pablo Padilla[(2)], María García-Vigueras[(1)], Raphaël Gillard[(1)]
[(1)]Institut d'Electronique et des Technologies du numéRique (IETR), UMR CNRS 6164, INSA Rennes, France.
[(2)]Department of Signal Theory, Telematics and Communications, Centre for Information and Communication Technologies (CITIC-UGR), University of Granada, 18071 Granada, Spain.
e-mail: Angel.Palomares-Caballero2@insa-rennes.fr

***Abstract*—This paper presents a guide to design unit cells for reflectarrays and transmitarrays based on unit cells with 3-D geometry. To explain the design process, a metal-only unit cell with basic 3-D geometry in a periodic environment is considered. The parts to be considered in the 3-D unit cell structure as well as their importance in the electromagnetic behavior in reflection are described. The inclusion of an impedance transformer at the interface between the 3-D unit cell and the free space is analyzed. Based on the design of the 3-D unit cell in reflection (for reflectarray design), its modification for transmitarray design is introduced. Finally, design strategies to modify the phase in transmission in 3-D unit cells are described and one of them based on meandered lines is assessed and discussed.**

I. Introduction

The reflectarray (RA) concept was first proposed by Berry *et al.* in 1963 [1]. This first design was composed of an array of waveguides illuminated by another square waveguide at a certain distance. Since this work, a large number of RA designs have been published in different technologies, frequency bands, different radiation patterns and polarizations [2].

A few years after the publication of the first RA design, in 1986, the array lens concept was introduced by McGrath [3]. Later, the name of this design was changed to transmitarray (TA) [4]. The TA can be seen as the transmissive version of the RA where the design processes of both are carried out in a similar way. This type of spatially fed antenna has also attracted a lot of attention over the last few years through many papers on a myriad of TA designs [5].

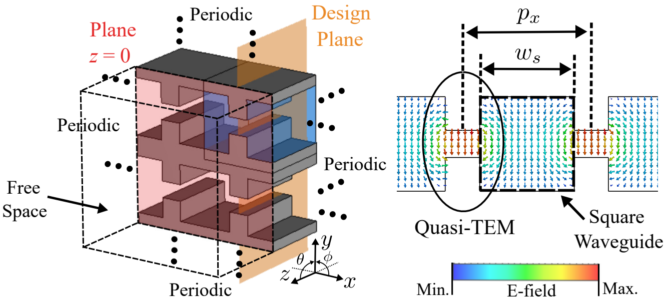
The merging of the above designs (RA and TA) into a single structure was first presented in [6]. It was later designated transmit-reflect-array (TRA) [7] or also called reflect-transmit-array (RTA). Although frequency selective surfaces (FSS) already naturally allow simultaneous transmission and reflection [8], the aim of the RTA is to be able to control the phase values in transmission and reflection. Right now, this is a topic that is getting a lot of attention from the scientific community [9]–[12] and where the electromagnetic limitations of having a structure with simultaneous transmission and reflection [13], [14] are being addressed.

Recently, the use of unit cells, which form periodic or quasi-periodic structures such as RA or TA, with three-dimensional (3-D) geometries are proposed [15]. The reason behind this trend is the advantage gained in the design process as they provide an additional spatial degree of freedom. In general, this allows the possibility of achieving a design with better electromagnetic performance or additional functionalities. Regarding periodic structures, the use of 3-D unit cells is employed in a spatial filter with dual polarization [16]. Also, it is introduced for the design of metal-only polarizers in transmission [17], [18] and in reflection [19]. Furthermore, 3-D unit cells are also used for the design of absorbers with the desired performance through a synthesis process [20]. On the other hand, concerning quasi-periodic structures, the design of RA unit cells with 3-D geometry is starting to be used as presented in the work [21]. There are more examples in the literature of 3-D unit cells for RA design where these can be either metallo-dielectric [22] or fully-metallic [23], [24], providing large bandwidth and orthogonal polarization control. The use of 3-D unit cells has also been proposed for TA design. In [25], a unit cell is presented by using coupled slotlines which generate a bandpass filter behavior with a phase in transmission determined by design. While in [26], the design of a metal-only unit cell supporting dual polarization and large bandwidth performance is introduced.

In this paper, some guidelines for the design of RA and TA using 3-D unit cells based on waveguide elements are presented. By describing and simulating the fundamental electromagnetic aspects, it is aimed to provide an understanding of the design process followed for this type of unit cells. Specifically, we are going to focus on metal-only unit cells.

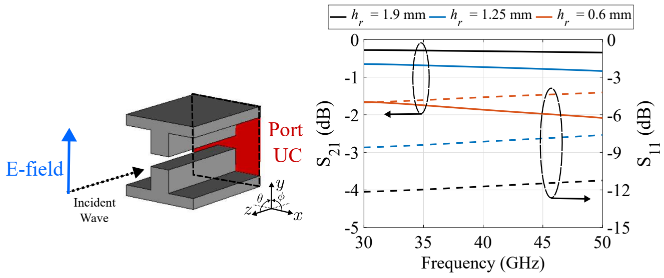
II. Reflectarray Design

In Fig. 1(a), an array of metal-only 3-D unit cells is illustrated. More specifically, only four unit cells are shown in the figure although in the analysis done, a periodic structure in the *x*- and *y*-directions is considered. This unit cell [see framed in blue in Fig. 1(a)] can be considered as the basic design of the unit cell (1) in [24] [see Fig. 1 of that work]. The excitation of this periodic structure is provided by a plane wave in the -*z*-direction and with the electric field (E-field) in the *y*-direction. It can also be seen in Fig. 1(a) two highlighted planes named *Plane z = 0* and *Design Plane*. The first one refers to the plane that determines the interface between the periodic structure and the free space. While the second one indicates the main design plane in 3-D unit cells where, in a general way, elements are introduced to provide the desired phase shift in reflection [24] or in transmission [17], [18]. It should be noted that in conventional planar unit cell designs for RA [27], the design plane is the *Plane z = 0*. Also note that the *Design Plane* can also be in the XZ plane and, in the case of the design in Fig. 1(a), having two orthogonal *Design Planes* and providing dual-polarization behavior to the unit cell [24]. However, for the sake of simplicity in the analysis, the unit cells are connected along this plane.



(a) (b)

Fig. 1. (a) 3-D view of a generic array of metal-only 3-D unit cells. (b) Electric field distribution on a transverse plane (XY plane) of two metal-only 3-D unit cells at the same y-position. The dimensions (in mm) are: p_x = 3.75 mm and, w_s = 2.75 mm.



(a) (b)

Fig. 2. (a) 3-D view of a single metal-only RA unit cell whose rear part is placed a port and in the front part is excited by a vertically polarized plane wave. (b) S-parameters in magnitude when the ridges spacing is modified.

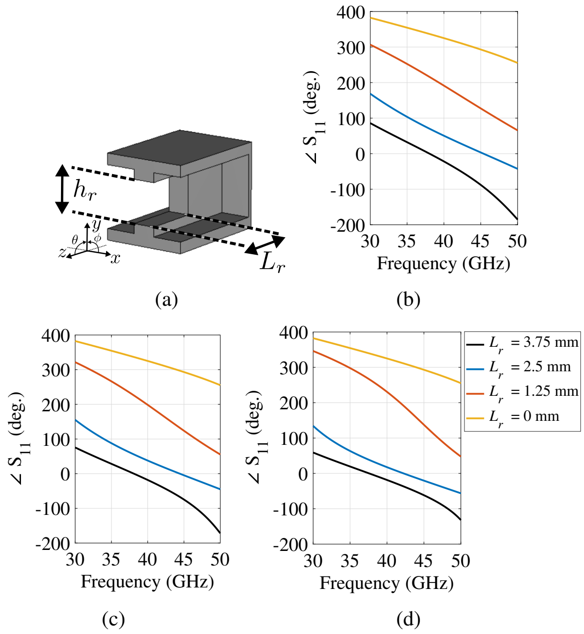


Fig. 3. (a) 3-D view of the metal-only 3-D unit cell whose rear part is a metallic plane.(b) Reflection performance, at normal incidence ($\phi = 0^o$, $\theta = 0^o$), of the RA unit cell when the L_r parameter is swept for: (b) h_r = 1.9 mm, (c) h_r = 1.125 mm and, (d) h_r = 0.6 mm.

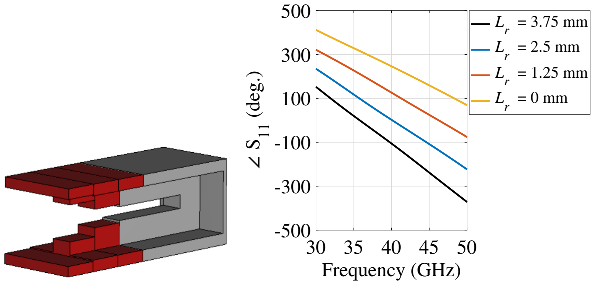
If a plane-wave excitation is performed from free space, the E-field distribution that appears inside the unit cell is illustrated in Fig. 1(b). In this figure, it can be seen the transverse plane (XY plane) of two unit cells at the same y-position. The main part of the E-field is concentrated between the two ridges providing a quasi-TEM mode. Depending on the type of structure that is introduced in the *Design Plane* to propagate the incident E-field, the unit cell will provide a narrowband [17] or broadband [18] performance. In the case of exciting a quasi-TEM mode, a large bandwidth free of higher-order modes can be ensured. In Fig. 1(b), it can be also observed a square waveguide region where no mode is deliberately excited (sufficiently small w_s). Thus, the E-field is concentrated between the ridges which gives greater control of the mode propagating along the *Design Plane*.

Once the unit cell design and the fundamental mode propagating in it have been presented, the behavior of the unit cell in terms of S-parameters is described. The design to be analyzed is depicted in Fig. 2(a). It consists of the unit cell of Fig. 1 where a plane wave is impinging. At the back of the unit cell, a port named *Port UC* has been placed to determine the power level reaching it depending on the separation between ridges h_r [see Fig. 3(a)]. Fig. 2(b) shows the transmission to the *Port UC* and the reflection of the incident plane wave. The greater the ridges separation (higher h_r), the lower the reflection and therefore, the higher the transmission reaching a maximum of -0.2 dB. On the contrary, increasing the height of the ridges (lower h_r) produces a higher reflection in the *Plane* $z = 0$. In this case, a transmission of approximately -2 dB and -4.5 dB in reflection (at the center frequency) are obtained.

In Fig. 3, the unit cell of Fig. 2 is analyzed but replacing the *Port UC* with a metallic plane to provide a reflection of the incident wave. In this way, depending on the value of L_r [see Fig. 3(a)], a 3D unit cell with an suitable range of reflected phase can be obtained directly for RA design. The geometrical value of L_r should control the reflected phase [24]. Figs. 3(b), 3(c) and 3(d) present the reflected phase over the frequency for different values of L_r and in the different cases of ridges separation h_r. It can be seen how for the case of higher ridges separation, the phase responses maintain some linearity over the frequency. This linearity is lost as the ridges spacing decreases since a non-negligible reflection occurs in the *Plane* $z = 0$ and cannot be controlled by the variation of L_r. This implies that an RA unit cell with broadband behavior (linear phase along the frequency) cannot be achieved by selecting a small ridges spacing. On the other hand, if a large ridges spacing is selected to obtain a better linearity, it may bring other drawbacks such as less degree of freedom in the design due to the lack of metal in the ridges.

To solve the above problems of the RA unit cell with smaller h_r, the introduction of an impedance transformer between the free space and the RA unit cell is proposed. Classical transmission line theory can be used to design the desired impedance transformer [28]. For this, it is needed to know the dependence of the characteristic impedance of the double ridge waveguide with respect to the separation between ridges h_r. Such a relation (between the characteristic impedance and the ridges separation) can be obtained through a simple simulation and a comparison with a symmetric circuit model composed of three transmission lines. The details can be found in [18].

As an example, a three-section impedance transformer is



(a) (b)

Fig. 4. (a) 3-D view of the metal-only RA unit cell of Fig. 3(a) with a broad-band impedance transformer (highlighted in red).(b) Reflection performance, at normal incidence ($\phi = 0^o$, $\theta = 0^o$), of the RA unit cell when the L_r parameter is swept for $h_r = 0.6$ mm.

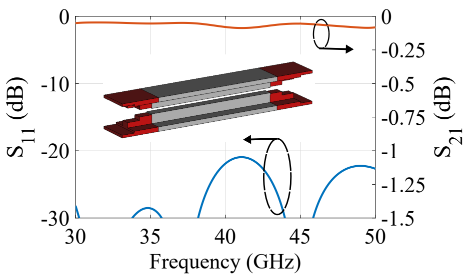


Fig. 5. S-parameters of the metal-only 3-D unit cell for TA design.

designed and introduced to obtain maximum power transfer between the free space and the double ridge waveguide in the RA unit cell. The design is presented in Fig. 4(a), where the impedance transformer is highlighted in red. Fig. 4(b) shows the reflected phase for different values of L_r. A large improvement in the phase linearity can be observed along the frequency even better than that produced for the case of the RA unit cell with the bigger h_r [see Fig. 3(b)]. Therefore, for the design of 3-D RA unit cells with large bandwidth, the use of impedance transformers is advised to achieve the best phase linearity. It should also be mentioned that the magnitude of the reflection coefficients (S_{11}) for the analyzed RA unit cells has not been shown since in all of them it is very high (close to 0 dB). It is due to the conductivity selected in the simulations ($\sigma = 3.56 \cdot 10^7$ S/m) and the almost negligible excitation of cross-polar reflection (lower than -60 dB).

III. Transmitarray Design

To design a 3D unit cell for TA, it can be based on the previously described 3-D RA unit cell. It is only necessary to remove the metallic plane (or short-circuit) located at the rear part of the RA unit cell and perform a mirror symmetry of the resulting unit cell. The design can be seen in the inset of Fig. 5. This design can be seen as the 3-D version of the conventional unit cell for TA [3]. In our case, the 2-D layers in [3], where patch antennas are implemented, are replaced by 3-D unit cells with the impedance transformers. The transmission and reflection coefficients of the 3-D unit cell for TA are shown in Fig. 5. Thanks to the use of the large bandwidth impedance transformers, a transmission greater than -0.1 dB is achieved with a reflection below -20 dB from 30 GHz to 50 GHz (50% relative bandwidth).

Now it is necessary to introduce some elements or structures that provide some geometrically adjustable phase shift in the *Design Plane* [see Fig. 1(a)]. There are several design strategies to implement this type of phase-shifting elements. In [29], a periodic structure based on corrugations is introduced where depending on the depth of corrugations, a certain phase shift is achieved in the TA unit cell. Another example in a different technology is presented in [25]. Through the length of the coupled lines that form the transmission path, a phase shift is implemented among the unit cells that form the TA. Alternatively and using metal only 3-D unit cells, in Fig. 6(a) is presented another phase-shifting structure based on meandered lines [30]. The use of this type of lines in 3-D unit cells brings benefits since through a single parameter (named A), the phase shift can be modified while preserving the good impedance matching of the transmitted wave. This parameter is found in equation 8 of [30], which models the path of the meandered line. Additionally, this type of line is more robust to ridges spacing compared, for example, to the 3-D unit cell with corrugations presented in [29], which alleviates fabrication complexity.

Fig. 6(b) shows the reflection and transmission parameters in magnitude of the TA unit cells displayed in Fig. 6(a). For all TA unit cell designs, a reflection below -20 dB is achieved over the entire frequency band in addition to a transmission performance close to 0 dB. It should be noted that for this type of metal-only 3-D unit cell, good conductivity is required to reduce ohmic losses and maintain high transmission. Finally, Fig. 6(c) shows the transmitted phase over the frequency for different values of A. It can be seen how the phase in all cases is quite linear with frequency, in addition to the fact that as A increases, the phase shift is more negative (behaves as a delay line). All the previous characteristics are quite beneficial to obtain TA designs with large bandwidth.

Finally, we can discuss about the 3-D unit cells for designing RTA. Since 3-D unit cells can have two *Design Planes* (one in each polarization plane), this can be used to assign in each a structure in reflection and in transmission, respectively, as can be found in [29]. Another strategy to design RTA with 3-D unit cells can be seen in [11] where both *Design Planes* are connected and thus, it is only necessary to have the excitation in one polarization. It is important to point out that 3-D unit cells for RTA are suitable to obtain independent transmission and reflection behavior.

IV. Conclusions

A guideline to obtain 3-D unit cells for RA and TA designs is presented. In order to point out the different things to take into account in the design process, a metal-only 3-D unit cell, which allows propagation of a quasi-TEM mode in it, is considered. Firstly, an analysis of the 3-D unit cell in reflection has been carried out, showing the importance of having a good impedance matching between the free space and the unit cell. If a good match is not achieved, the reflected phase, through the modification of the tuning element, worsens its linearity over the frequency. This makes it difficult to design reflectarrays with large bandwidth. By using a three-section impedance transformer, the 3-D unit cell can provide a fairly linear phase shift even for reduced ridges

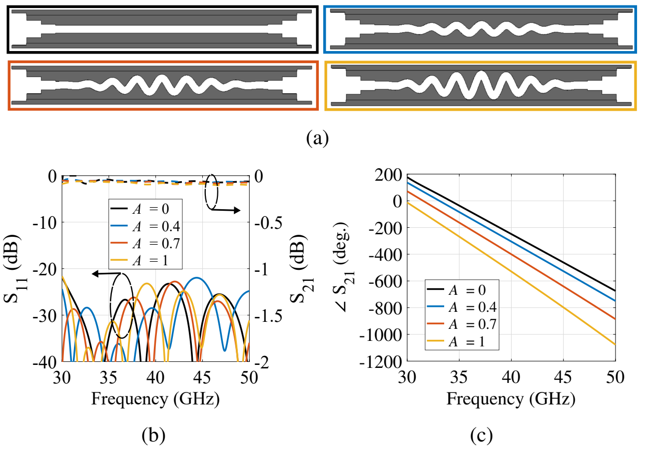


Fig. 6. (a) Side view of 3-D TA unit cells based on meandered lines for different values of A. (b) S-parameters, at normal incidence ($\phi = 0^o$, $\theta = 0^o$), of 3-D TA unit cell for different values of A: (a) in magnitude and, (b) in phase.

spacing. To achieve a 3-D unit cell design for TAs, the metal plate in the rear part the 3-D RA unit cell is removed and then, a mirror symmetry is applied to obtain a 3-D TA unit cell, which is symmetrical regarding its center. Thanks to the use of broadband impedance transformer, the 3-D TA unit cell has a high transmission level over a large bandwidth. Finally, different design strategies to introduce certain transmission phase shift have been described, where the simulated results of one of them based on meandered lines have been presented and discussed.

Acknowledgements

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