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► **To cite this version:**

Alessio Berto, Francesco Foglia Manzillo, Guido Valerio. Design of Huygens cells for transmit-reflect-arrays at 30 GHz. IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Jul 2023, Portland, United States. <10.1109/USNC-URSI52151.2023.10238310>. <cea-04211873>

**HAL Id: cea-04211873**

**<https://cea.hal.science/cea-04211873v1>**

Submitted on 20 Sep 2023

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# Design of Huygens' Cells for Transmit-Reflect-Arrays at 30 GHz

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**Abstract**—In this paper, it is demonstrated that Huygens' metasurfaces can achieve equi-amplitude reflected and transmitted waves and arbitrary phase shift in transmission, when illuminated by a normal plane wave. To exploit this property, a procedure for designing unit-cells of transmit-reflect-arrays is presented. First, the optimal surface parameters are analytically determined. Next, the design at 30 GHz of four cells with three patterned layers, compatible with printed circuit board technology, is presented. These cells operate with a maximum phase error of a  $10^\circ$  over a 5% relative bandwidth at the operating frequency, thus realizing a uniform 2-bit phase quantization in transmission and reflection.

## I. INTRODUCTION

Transmitarrays (TAs) and reflectarrays (RAs) are widely employed antennas for wireless communications due to their capability of forming high-gain beams without lossy feeding networks, by a careful design of their aperture phase profiles.

High-efficiency TAs and RAs can be designed using Huygens' metasurfaces (HMSs), which can precisely tailor the scattered waves [1]. Moreover, HMSs could also ease the realization of more advanced spatially fed antennas, such as transmit-reflect-arrays (TRAs). These arrays combine TA and RA functionalities, ensuring bidirectional coverage, and might be key for the development of future smart radio environments.

This paper presents a procedure to synthesize HMS cells with application to TRAs. The HMS constitutive parameters are determined to obtain an even power division of a normally incident wave into the reflected and transmitted ones. It is shown that, with these parameters, the full phase range is covered in reflection and transmission. Then, four sub-wavelength cells, enabling 2-bit TRAs, are designed at 30 GHz, using three impedance sheets to approach the optimal HMS parameters. The simulated scattering parameters of the four cells validate the proposed design.

## II. METASURFACE ANALYSIS AND DESIGN PROCEDURE

A lossless and non-chiral HMS illuminated by a normally incident plane wave polarized along  $\hat{y}$  is considered. The electric and magnetic surface currents are related to the average tangential electric and magnetic fields by the magnetic impedance  $Z_m$  and electric admittance  $Y_e$  [2]. Closed-form expressions for the transmission and reflection coefficients,  $\tau$  and  $\Gamma$ , respectively, as functions of  $Z_m$  and  $Y_e$ , have been reported in [1].

The cells of a TRAs must evenly split the power of the incident field into the transmitted and reflected ones. The HMS

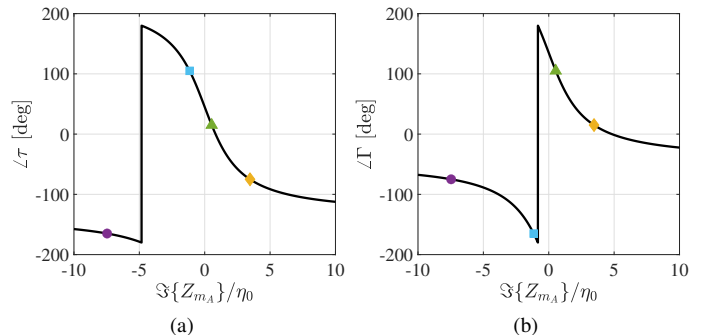


Fig. 1. Phase of (a) the transmission and (b) the reflection coefficients of the HMS under analysis, obtained for  $(Z_{m_A}, Y_{e_A})$ .

parameters fulfilling this condition are determined by solving the following equation for  $Z_m$  and  $Y_e$ :

$$|\tau(Z_m, Y_e)| = |\Gamma(Z_m, Y_e)|. \quad (1)$$

Two solutions are found, each one defining a relation between the surface parameters  $Z_m$  and  $Y_e$ :

$$Y_{e_A} = \frac{2jZ_{m_A} + 4\eta_0}{2j\eta_0^2 + \eta_0 Z_{m_A}}, \quad (2)$$

$$Y_{e_B} = \frac{2jZ_{m_B} - 4\eta_0}{2j\eta_0^2 - \eta_0 Z_{m_B}}. \quad (3)$$

The phases of the transmission and reflection coefficients,  $\angle\tau$  and  $\angle\Gamma$ , obtained for these solutions, vary in the entire  $360^\circ$  range. For example,  $\angle\tau$  and  $\angle\Gamma$  when  $Z_m$  and  $Y_e$  fulfill (2) are plotted in Fig. 1(a) and Fig. 1(b), respectively. This property enables, in principle, the realization of TRAs with arbitrary transmission phase profiles. However, the difference between  $\angle\tau$  and  $\angle\Gamma$  is constant and equal to  $-90^\circ$  and  $90^\circ$ , for the first and second solution, respectively. This means that these two phases cannot be controlled separately. Thus, when the transmitted beam of a TRA is optimized, the shape of the reflected beam is automatically stipulated.

## III. TRA CELL DESIGN AT 30 GHz

To demonstrate the practical viability of the derived HMS parameters, four TRA cells implementing a uniform 2-bit quantization of the full phase range are designed at 30 GHz.

The HMS elements are designed as a cascade of three impedance sheets,  $Z_{s_1}$ ,  $Z_{s_2}$  and  $Z_{s_3}$ , interleaved by two

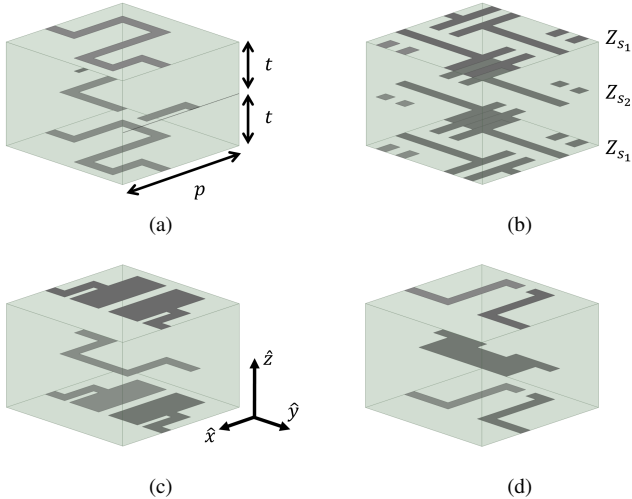


Fig. 2. TRA cells implementing at 30 GHz, in transmission, a phase shift of: (a)  $\phi_{\tau_1} = 15^\circ$ , (b)  $\phi_{\tau_2} = 105^\circ$ , (c)  $\phi_{\tau_3} = 195^\circ$  and (d)  $\phi_{\tau_4} = 285^\circ$ .

dielectric slabs of thickness  $t$  (see Fig. 2). As proved in [2], [3],  $Z_{s_1}$  and  $Z_{s_3}$  are equal for a HMS. The designed slabs have  $\epsilon_r = 2.2$  and  $t = \lambda_g/8$ , where  $\lambda_g = \lambda_0/\sqrt{\epsilon_r}$  and  $\lambda_0$  is the free-space wavelength at the design frequency  $f_0 = 30$  GHz.

First, four pairs  $(Y_{e_i}, Z_{m_i})$ , with  $i = 1, \dots, 4$ , are selected (see Fig. 1), using (2), so that the corresponding phases of the transmission coefficients are progressively shifted by  $90^\circ$ , starting from  $\phi_{\tau_1} = 15^\circ$ . Then, for each cell, the optimal values of the sheet impedances  $Z_{s_1}$  and  $Z_{s_2}$  are found analytically from the surface parameters previously determined and the slab properties, using the formulas reported in [2], [3].

Different geometries have been investigated to physically realize these sheet impedances at 30 GHz, considering all square cells, with a period  $p = 0.12\lambda_0 = 1.2$  mm. Meander lines have been employed to obtain positive sheet reactances, while either dog-bones or meander lines with discontinuities have been optimized to achieve negative sheet reactances. Each layer has been designed individually. The corresponding sheet impedance has been evaluated using the  $S$ -parameters obtained from a two-port full-wave simulation of the sheet, under normal incidence and using periodic boundaries, as described in [4]. The optimized geometries are shown in Fig. 2, and achieve at 30 GHz sheet impedances close to the optimal values, for all cells, as it can be observed in Table I.

The simulated amplitudes of the reflection and transmission coefficients of the four designed cells are plotted in Fig. 3(a) and Fig. 3(c) as functions of frequency, respectively. They

TABLE I  
SHEET IMPEDANCES OF THE TRA CELLS AT 30 GHz

		$\phi_{\tau_1}$	$\phi_{\tau_2}$	$\phi_{\tau_3}$	$\phi_{\tau_4}$
$\Im(Z_{s_1})$ [ $\Omega$ ]	Theoric	167.52	-117.17	-215.13	-415.87
	Designed	172.58	-114	-218.50	-421.41
$\Im(Z_{s_2})$ [ $\Omega$ ]	Theoric	-2128.53	-82.31	123.76	50.61
	Designed	-2196.76	-97.09	121.39	56.11

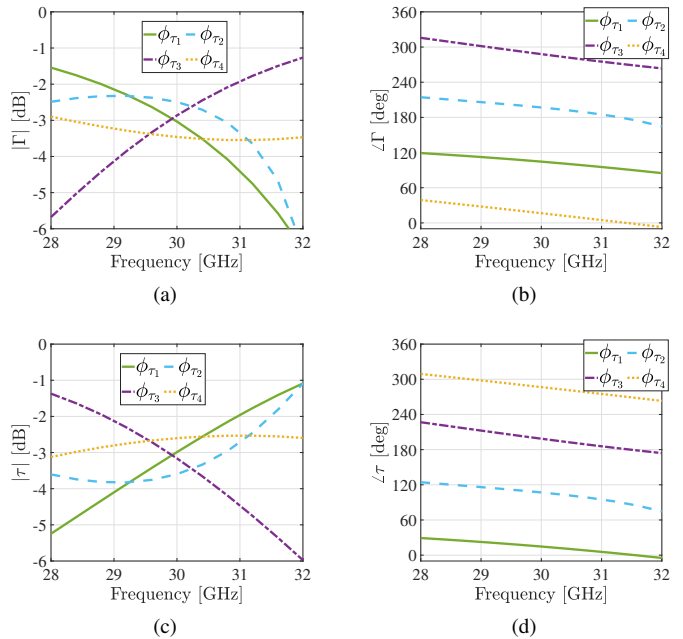


Fig. 3. Simulated reflection and transmission coefficients of the TRA cells: (a) magnitude of  $\Gamma$ , (c) magnitude of  $\tau$ , (b) phase of  $\Gamma$  and (d) phase of  $\tau$ .

are all very close to -3 dB at 30 GHz, as prescribed by the design procedure. In a 5% relative bandwidth centered at 30 GHz, they are all between -4 dB and -2 dB. The bandwidth is mainly limited by the frequency variation of the designed sheet impedances. In the same band, the relative phase shifts introduced by different cells, in transmission and reflection, are approximately multiples of  $90^\circ$ , as shown in Fig. 3(b) and Fig. 3(d), respectively.

#### IV. CONCLUSION

An approach to designing HMS cells of efficient TRAs has been described, from the analytical determination of the equivalent surface parameters to their synthesis using cascaded impedance sheets. Four sub-wavelength cells comprising three patterned layers and two dielectric substrates have been optimized at 30 GHz. Simulations show that the cells enable a 2-bit uniform quantization in both transmission and reflection with an amplitude imbalance of  $\pm 1$  dB in the 29 – 31 GHz band and a phase error  $< 5^\circ$  at 30 GHz. These results make the proposed design attractive for the realization of Ka-band TRAs in low-cost printed circuit board technology.

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