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Alessio Berto, Alessio Berto, Francesco Foglia Manzillo, Guido Valerio. Bianisotropic metasurfaces for bidirectional arrays with independent reflected and transmitted beams. AP-S/INC-USNC-URSI - 2024 IEEE International Symposium on Antennas and Propagation and ITNC-USNC-URSI Radio Science Meeting, Jul 2024, Florence, Italy. pp.85-86, <10.1109/AP-S/INC-USNC-URSI52054.2024.10687259>. <cea-05199244>

**HAL Id: cea-05199244**

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Submitted on 4 Aug 2025

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# Bianisotropic metasurfaces for bidirectional arrays with independent reflected and transmitted beams

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**Abstract**—This article proposes a method to engineer omega-type bianisotropic metasurfaces for the design of transmit-reflect-array cells. First, we prove that they can evenly split the power of a normally incident plane wave into a transmitted and a reflected wave and, at the same time, arbitrarily tailor their phase difference. Next, the metasurface constitutive parameters are determined to realize sixteen unit cells achieving a 2-bit phase quantization in transmission and reflection. Preliminary designs with three sheet impedances spaced by two dielectric slabs are analyzed. The numerical results confirm their suitability for the design of arrays with independent control of the propagation directions of the scattered waves.

## I. INTRODUCTION

Transmit-reflect-arrays (TRAs) are space-fed electromagnetic surfaces capable of shaping both the refracted and reflected fields. They represent a promising solution for enhanced intelligent surfaces in smart radio environments [1]. To date, TRAs have been essentially realized by full-wave optimization of particular unit-cell designs [2]. A more general approach optimizing Huygens' metasurfaces (HMSs) for the design of TRAs is presented in [3]. However, a HMS does not enable independent beam-forming of the transmitted and reflected fields, since their phases cannot be controlled separately. In this paper, we demonstrate that this limitation can be overcome by using omega-type bianisotropic metasurfaces (O-BMSs) [4], [5]. The scattering properties of a lossless O-BMS under plane-wave excitation are reviewed. We present a procedure for designing the O-BMS constitutive parameters to obtain transmitted and reflected fields with the same amplitudes and an arbitrary phase shift. Based on that, a set of 16 meta-cells achieving a 2-bit uniform phase quantization in both transmission and reflection is determined. The cells are preliminarily designed using 3 stacked ideal sheet impedances and their scattering parameters are numerically investigated.

## II. METASURFACE ANALYSIS FOR TRA DESIGN

We consider a planar, passive, non-chiral and lossless O-BMS in free space (impedance  $\eta_0$ ), illuminated by a normally incident monochromatic plane wave with an electric field  $E_y^i \hat{y}$ , as shown in Fig. 1. This analysis aims at evaluating the fields  $E_y^t \hat{y}$  and  $E_y^r \hat{y}$  which are transmitted and reflected. The O-BMS is described by an electric susceptance  $B_e$ , a magnetic reactance  $X_m$  and a real magneto-electric coupling factor  $R$  [5]. The boundary conditions on the surface are given by:

$$\begin{pmatrix} J_y^s \\ M_x^s \end{pmatrix} = \begin{pmatrix} jB_e & -R \\ R & jX_m \end{pmatrix} \begin{pmatrix} E_y^{\text{avg}} \\ H_x^{\text{avg}} \end{pmatrix}, \quad (1)$$

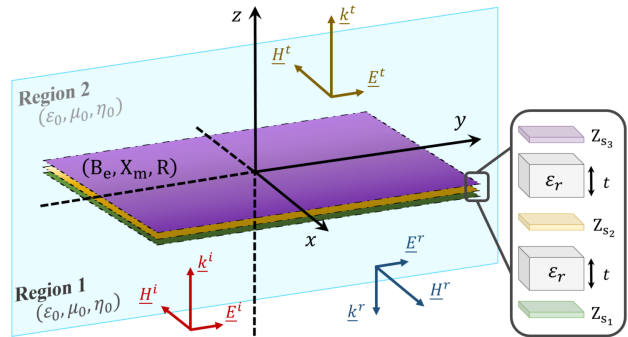


Fig. 1. Scattering from an infinite lossless O-BMS illuminated by a plane wave at normal incidence: main parameters and a possible design (inset).

where  $E_y^{\text{avg}} \hat{y}$  and  $H_x^{\text{avg}} \hat{x}$  are the average electric and magnetic fields tangent to the surface,  $J_y \hat{y}$  and  $M_x \hat{x}$  are the equivalent magnetic and electric surface currents. The transmission coefficient  $\tau = E_y^t / E_y^i$  and the reflection coefficient  $\Gamma = E_y^r / E_y^i$  are found using their definitions and (1), yielding:

$$\tau = \frac{\eta_0(4 + B_e X_m - R^2)}{(\eta_0 R^2 - \eta_0 B_e X_m + 4\eta_0) + 2j(\eta_0^2 B_e + X_m)}, \quad (2)$$

$$\Gamma = \frac{2j(X_m - \eta_0^2 B_e) - 4\eta_0 R}{(\eta_0 R^2 - \eta_0 B_e X_m + 4\eta_0) + 2j(\eta_0^2 B_e + X_m)}. \quad (3)$$

Thus, the difference of the phases of these coefficients is:

$$\angle \tau - \angle \Gamma = \begin{cases} -\angle g(B_e, X_m, R) & \text{if } 4 + B_e X_m > R^2 \\ \pi - \angle g(B_e, X_m, R) & \text{if } 4 + B_e X_m < R^2 \end{cases} \quad (4)$$

where  $g(B_e, X_m, R) = -4\eta_0 R + 2j(X_m - \eta_0^2 B_e)$ . It is clear from (4) that if  $R = 0$ , i.e. in the particular case of HMSs, the phases of  $\tau$  and  $\Gamma$  are shifted by either  $\pi/2$  or  $-\pi/2$ , for all values of  $B_e$ ,  $X_m$ , as observed in [3]. Next, we enforce the equality of the amplitudes of the transmitted and reflected fields and study the achievable values of their phase difference under this condition. To this end, we first solve for  $B_e$ :

$$|\tau(B_e, X_m, R)| = |\Gamma(B_e, X_m, R)|, \quad (5)$$

using (2) and (3). Two solutions are found:  $B_{eA}(X_m, R)$  and  $B_{eB}(X_m, R)$ . For each of them,  $\angle \tau - \angle \Gamma$  is plotted as a function of the other two constitutive parameters in Fig. 2. The white areas represent loci which do not fulfill (5). For both solutions, any phase shift between  $\tau$  and  $\Gamma$  can be obtained, in a range of  $360^\circ$ , by properly selecting the values of  $X_m$  and  $R$ .

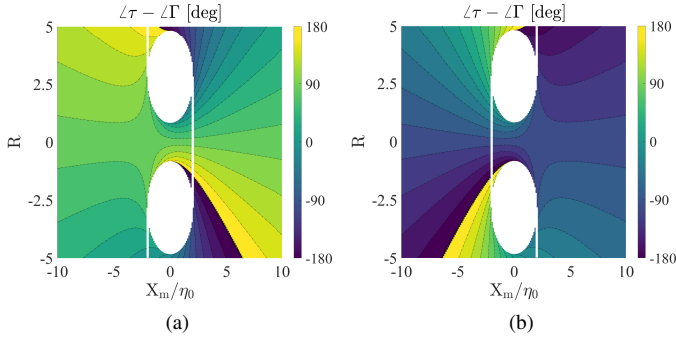


Fig. 2. Difference of the phases the transmission and reflection coefficients, as a function of  $X_m$  and  $R$ , for the solutions of (5): (a)  $B_{e_A}$  and (b)  $B_{e_B}$ .

### III. PRELIMINARY DESIGN OF 2-BIT TRA CELLS

The usefulness of the independent control on  $\angle\tau$  and  $\angle\Gamma$  for the design of TRAs is demonstrated through the preliminary design of sixteen unit cells enabling a 2-bit uniform quantization of the full phase range in both reflection and transmission. For each transmission (reflection) state, four cells are designed to achieve the same value of  $\angle\tau$  ( $\angle\Gamma$ ) and four values of  $\angle\Gamma$  ( $\angle\tau$ ) spaced by  $90^\circ$ . The constitutive parameters of each O-BMS cell were determined, with the aid of Fig. 2, to fulfill (5) and obtain the desired phase states  $\phi_\tau$  and  $\phi_\Gamma$  in transmission and reflection. They are reported in Table I. We analyzed a possible realization of these cells (see Fig. 1) with three stacked sheet impedances [4], spaced by two substrates of relative permittivity  $\epsilon_r = 2.2$  and thickness  $t = \lambda_g/8$ , where  $\lambda_g = \lambda_0/\sqrt{\epsilon_r}$  and  $\lambda_0$  is the free-space wavelength at the design frequency  $f_0 = 30$  GHz. The impedances  $Z_{s_1}$ ,  $Z_{s_2}$  and  $Z_{s_3}$  were found from the optimized surface parameters, as in [4]. The scattering parameters of the designed cells were computed using the transfer-matrix approach and considering that the sheet impedances are frequency independent. The targeted phase states are achieved. For instance, Fig. 3 shows the phase responses of the four cells with transmission phase state  $\phi_\tau = 90^\circ$ . In the 28-32-GHz band, the phases  $\angle\Gamma$  of these cells are subsequently spaced by  $90^\circ \pm 10^\circ$ . The phases  $\angle\tau$  are  $90^\circ$  at  $f_0$  and almost equal in the entire band. Fig. 4 shows that a similar wideband behavior is observed for the four cells characterized by the reflection phase state  $\phi_\Gamma = 105^\circ$ . The maximum variation of  $|\tau|$  and  $|\Gamma|$  is  $\pm 1$  dB around  $-3$  dB.

TABLE I  
OPTIMIZED VALUES OF  $(B_e\eta_0, X_m/\eta_0, R)$  OF EACH TRA CELL

$\phi_\Gamma \backslash \phi_\tau$	$15^\circ$	$105^\circ$	$195^\circ$	$285^\circ$
$0^\circ$	(-0.2, 0.2, -0.8)	(-0.8, 0.8, 0.2)	(0.2, -0.2, 0.8)	(0.8, -0.8, -0.2)
$90^\circ$	(-0.9, -4.8, -0.5)	(-3.4, -2.3, -1.9)	(-4.8, -0.9, 0.5)	(-2.3, -3.3, 1.9)
$180^\circ$	(-1.3, 1.3, -4.7)	(-4.7, 4.7, 1.1)	(1.3, -1.2, 4.7)	(4.7, -4.7, -1.1)
$270^\circ$	(0.9, 4.8, 0.6)	(3.4, 2.3, 1.9)	(4.8, 0.9, -0.5)	(2.4, 3.3, -1.9)

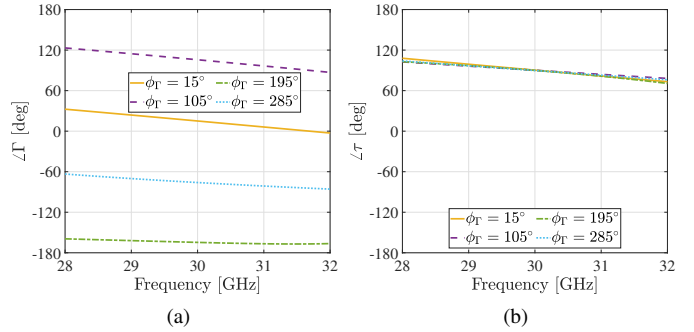


Fig. 3. Phases of the (a) reflection and (b) transmission coefficients as functions of frequency of four cells with  $\angle\tau = 90^\circ$  at 30 GHz.

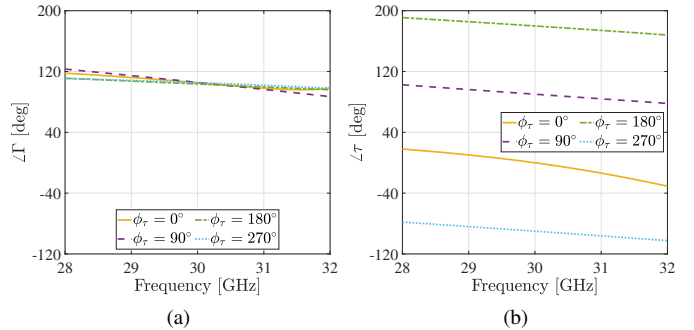


Fig. 4. Phases of the (a) reflection and (b) transmission coefficients as functions of frequency of four cells with  $\angle\Gamma = 105^\circ$  at 30 GHz.

### IV. CONCLUSION

We demonstrated that O-BMSs can be effectively employed for the design of TRAs achieving independent beam-forming in transmission and reflection. We showed how to numerically determine the constitutive parameters of an O-BMS impinged by a normal plane wave to equal the powers of transmitted and reflected fields and freely choose their phase difference. As a proof of concept, a set of 16 cells was designed. It enables a 2-bit uniform quantization of two arbitrary phase profiles in transmission and reflection. A preliminary 3-layer cell design was analyzed in a 13% relative bandwidth. The computed scattering parameters validate the proposed approach.

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