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High-Resolution Quartz Transmitarray Antenna for Sub-THz Applications

Orestis Koutsos(1), Francesco Foglia Manzillo(1), Antonio Clemente(1) and Ronan Sauleau(2)
(1) CEA-Leti, Univ. Grenoble-Alpes, 38054 Grenoble, France
({orestis.koutsos, francesco.fogliamanzillo, antonio.clemente}@cea.fr)
(2) Univ Rennes, CNRS, IETR – UMR 6164, 35000 Rennes, France (ronan.sauleau@univ-rennes1.fr)

***Abstract*—A high resolution (4-bit) anisotropic transmitarray (TA) for sub-THz applications is presented here. A simple numerical model is employed to design efficiently the TA unit-cell. A 50×50 element TA optimized at 280 GHz is designed. The antenna achieves a peak gain of 28.0 dBi with 53.7% aperture efficiency at 290 GHz. The effectiveness of the design methodology demonstrates only 0.5 dB of gain loss compared to an ideal lens used for the same scenario.**

I. INTRODUCTION

Sub-THz wireless systems for imaging and high data-rate applications have been undergoing rapid development in recent years. A basic premise to support effectively such systems is to deploy high-gain antennas with high radiation efficiency and beamforming capabilities. Among the proposed antenna technologies, transmitarray (TA) antennas have been showing an increased interest. However, the realization of high-performance TAs is rather challenging at sub-THz frequencies, especially for high phase-resolution (> 2-bit) designs. The gravity of this problem is determined by the geometry of the selected unit-cell (UC) and the constraints imposed by the fabrication process. To this end, anisotropic TAs comprising three layers and no vias [1],[2] have showed enhanced performance, i.e. low insertion loss (IL) in a relatively large bandwidth. Moreover, by optimizing only the middle layer, called rotator, the structure can achieve high phase-resolution.

This paper presents a preliminary design of a 4-bit anisotropic TA antenna for sub-THz systems. The proposed UC is compatible with quartz-based lithography process to enable higher accuracy. The quartz glass substrate does not introduce substrate waves, thanks to the low dielectric constant, leading to some high-gain and cost-efficient antennas [3]. In addition, this level of phase accuracy not only improves the antenna gain, but it can also enable a more accurate pattern synthesis in the case of more complicated scenarios, such as synthesizing focused beams with reduced sidelobe levels (SLLs) [4]. Moreover, the proposed UC exhibits a subwavelength periodic size, which makes the TA less sensitive to the illumination angle of incidence. Finally, a TA antenna is synthesized and presented, demonstrating high gain and high aperture efficiency. The radiation performance is further highlighted by comparing the antenna to an ideal TA.

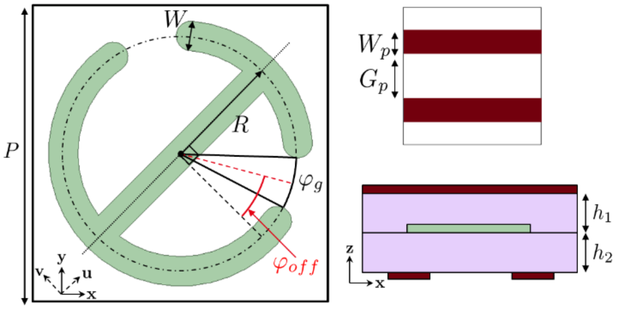


Figure 1. Proposed unit-cell design. The two grid polarizers, depicted in dark color, are orthogonally oriented; they are assumed identical (top right). The rotator (left), depicted in green color, is placed between the polarizers, as shown in the stack-up (bottom right).

II. UNIT-CELL DESIGN

A. Theoretical model

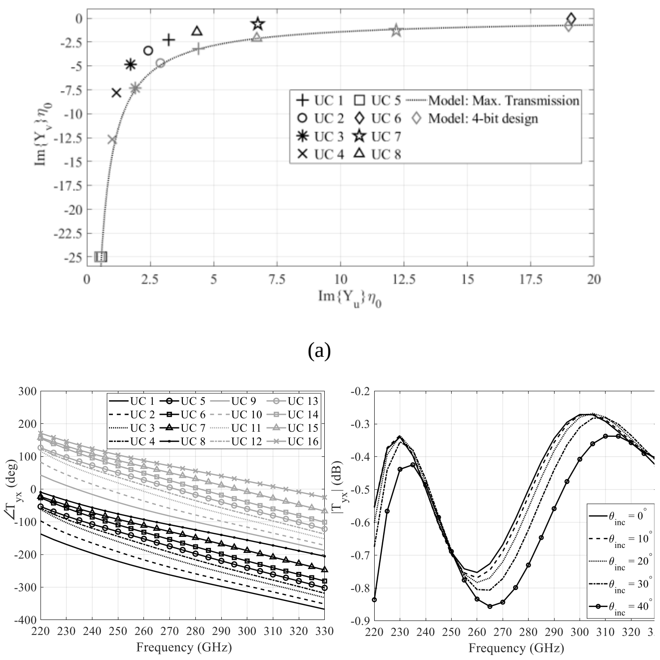
The proposed UC architecture is represented in Fig. 1. The selected rotator is a combination of a dipole and a split circular ring, and is sandwiched by two orthogonal grid polarizers. The phase of transmission is tuned by controlling the opening, φ_g, and the orientation, φ_{off}, of the two splits.

A simple and rigorous theoretical model based on the transfer-matrix method is used for the study and the design of the UC. Each metal layer is modelled as a 2×2 admittance matrix. In the case of the rotator, the matrix is non-diagonal to account for the anisotropy. This matrix can be simplified by applying a convenient rotation transformation between the UC reference system (*x*,*y*) and the rotator crystal system (*u*,*v*), as shown in Fig. 1. Eventually, the transmission coefficient of the entire UC is calculated as a function of two admittance values, namely Y_u and Y_v, which describe the rotator in the crystal system. A more detailed description of this method is reported in [2], which is omitted here for brevity.

Solving the problem for maximum transmission, the following condition is derived

$$Y_u Y_v = (\varepsilon_r/\eta_0)^2, \tag{1}$$

where η_0 is the free space impedance and ε_r is the relative permittivity of the two substrates. As long as the admittance values are defined by Eq. (1), the UC will exhibit zero IL and cover all the phase of transmission (360º). This condition also explains the dipole-like geometry of the rotator.



(a)

(b) (c)

Figure 2 (a) Synthesis procedure of the 4-bit TA at 300 GHz. The dotted curve represents the expression (1). (b) Phase of transmission in full-wave simulation. The mirrored case is shown in gray color. (c) Magnitude of transmission in full-wave simulation, with variable angle of incidence for a rotator element with $\varphi_g = 20°$, $\varphi_{off} = 60°$.

B. 4-bit transmitarray in quartz

The design of a 4-bit TA is presented here. The properties of the spacers and the polarizers are optimized to minimize the IL and maximize the frequency bandwidth. The optimization process is based on the previous model, considering a realistic scenario. In particular, the permittivity of the quartz is set to 3.78 and the substrate thicknesses are fixed to $h_1 = h_2 = 144$ µm. The filling factor of both polarizers, $W_p/(W_p+G_p)$, is fixed to 0.3. The periodic size, P, is 200 µm, which is equal to 0.2λ at 300 GHz. The radius of the circular ring and the metallic width are set to 80 µm and 20 µm, respectively, for all rotator designs. Eight different rotator topologies are designed, with the opening, φ_g, and the orientation, φ_{off}, varying from 20° to 45° and from 20° to 60°, respectively. By virtue of symmetry, 16 UCs are derived, resulting in a 4-bit TA. The 8 UC topologies, described as a function of the rotator admittance pairs (Y_u,Y_v), are shown in Fig. 2(a). The final designs are compared to a theoretical 4-bit TA with minimum insertion loss. The agreement between theoretical and designed UC values validates the effectiveness of the model. All UCs demonstrate less than 11° absolute relative phase error, as shown in Fig. 2(b), and a wideband performance, which for 1-dB IL is higher than 40% of relative bandwidth, as shown in Fig. 2(c). Thanks to the subwavelength design, the UC is not very sensitive to the angle of incidence.

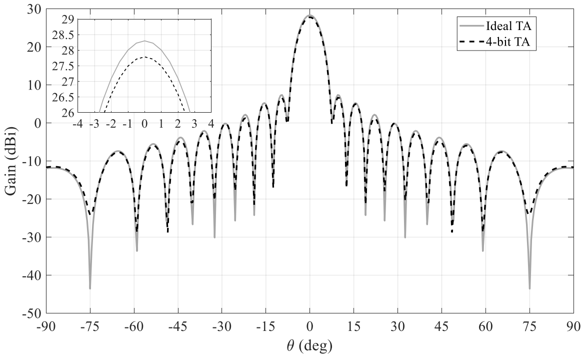


Figure 3. Comparison of the E-plane radiation pattern between the 4-bit TA design and the ideal TA (reflection-less with perfect phase compensation) at 280 GHz.

III. ANTENNA DESIGN

A 50×50 elements (10×10 mm^2) TA has been proposed. A standard pyramidal horn with 10 dBi gain is used as a focal source. The antenna system is realized using a hybrid (full-wave and numerical) simulation tool [2]. The focal-to-distance (F/D) ratio for maximum efficiency is calculated at 0.55, for a center frequency of 280 GHz. The corresponding gain is 27.8 dBi with 55% aperture efficiency. The peak gain is 28.0 dBi at 290 GHz with 53% aperture efficiency. Fig. 3 shows the radiation pattern for the E-plane. The sidelobe level is higher than 21 dB. Compared to an antenna comprising an ideal TA, i.e. reflection-less with perfect phase compensation, the gain loss is only 0.5 dB.

IV. CONCLUSION

A 4-bit transmitarray antenna with high gain and efficiency is presented in this paper. A theoretical model is employed for the efficient design of the three-layer structure. Thanks to the low insertion loss and the high phase-resolution, the antenna achieves a near-optimal radiation pattern, compared to the ideal scenario.

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