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Multifunctional Electronically Reconfigurable Electromagnetic Surfaces for Ka-band Antennas

Francesco Foglia Manzillo⁽¹⁾, Reda Madi⁽¹⁾, Samara Gharbieh⁽¹⁾, Ronan Sauleau⁽²⁾, and Antonio Clemente⁽¹⁾

⁽¹⁾ CEA-Leti, Univ. Grenoble-Alpes, F-38000 Grenoble, France (antonio.clemente@cea.fr)

⁽²⁾ Univ Rennes, CNRS, IETR – UMR 6164, FR-35000 Rennes, France (ronan.sauleau@univ-rennes1.fr)

Abstract—This paper presents the design and performance of two novel Ka-band reconfigurable unit-cells, using p-i-n diodes, for electronically controlled intelligent surfaces. The first cell operates in reflection or in transmission mode, by properly biasing its 4 diodes, and achieves a 1-bit and 2-bit phase quantization, respectively. The second cell comprises the first one, in transmitting mode, and a reconfigurable linear-to-circular polarization converter with 2 diodes, spaced by an air gap. It radiates a circularly-polarized wave with switchable handedness. The possibility of realizing wide-angle scanning and polarization-agile transmitarray antennas attaining limited phase quantization losses and enhanced aperture efficiency with respect to the state of the art is experimentally and numerically demonstrated.

I. INTRODUCTION

New communication paradigms based on the dynamic optimization of dense wireless networks are pushing the research on programmable electromagnetic (EM) surfaces [1]. These surfaces are large arrays of unit-cells (UCs) whose scattering properties can be electronically reconfigured to devise the reflected and transmitted waves. They are thus suitable for diverse applications, e.g. polarization manipulation, holography, and energy-efficient beam-forming [1]–[5]. Though a few EM surfaces performing multiple functions have been proposed [1], [2], the research on them is at an early stage. The reconfiguration technique is key to the surface performance. The existing methods, e.g. the use of tunable materials and devices, switches [3], achieve different trade-offs in terms of bandwidth, phase resolution and power consumption.

This paper presents novel multifunctional Ka-band cells and surfaces using p-i-n diodes, based on the designs in [3]–[5]. First, a linearly-polarized (LP) transmitting (Tx) and reflecting UC is discussed. It realizes a uniform 2-bit and 1-bit phase quantization in transmission and reflection, respectively, ensuring a finer resolution with respect to state-of-the-art switch-based designs [2]. This UC is co-optimized with the LP-to-circular polarization (CP) converter reported in [5]. In this way, a 2-bit UC radiating either a left-handed (LH) or right-handed (RH) CP is obtained. Two 24×24 beam-steering transmitarray antennas (TAs) are designed using these UCs. Measured and numerical results are presented. They cover relative 3-dB gain bandwidths exceeding 12%.

II. MULTIFUNCTIONAL CELLS USING P-I-N DIODES

The reconfigurable UCs of the LP EM surface and of the LP-to-CP converter with switchable handedness are shown in Fig. 1. The transmission and reflection coefficients (S_{21} and S_{11}) are obtained from full-wave simulations under normal

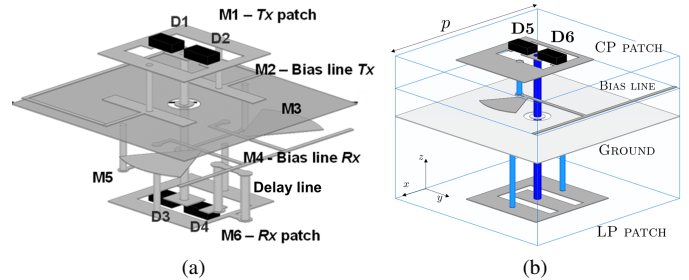


Fig. 1. View of the (a) LP cell operating in transmitting or reflecting mode; (b) the cell for LP-to-CP conversion with switchable handedness.

plane-wave incidence, with periodic boundary conditions, considering the equivalent circuits of diodes in their bias state.

A. Linearly Polarized Transmitting and Reflecting Cell

The LP UC (see Fig. 1a) comprises 6 metal layers, 3 substrate cores and 2 bonding layers (Isola Astra MT77). The radiating elements, on the outer layers, are referred to as receiving (Rx) patch, on the side of the primary source, and Tx patch. They share a common ground on M4 and are connected by a via. Each patch comprises an O-shaped slot and is loaded by a pair of p-i-n diodes in anti-parallel configuration. The diodes are controlled by the bias lines on M2 and M4. A 90° delay line, activated when D4 is on, is realized between M5 and M6. The operation and performance in transmission of a Ka-band square UC design, with period $p = 5.1$ mm are detailed in [3], [4]. The four transmission coefficients of the UC, obtained by forward biasing only one diode in each pair, are higher than -2 dB, in amplitude, and are shifted in phase approximately by multiples of 90° (2-bit quantization) in the 28–31.5 GHz band.

The same UC operates in reflection mode when both diodes on the Tx patch (D1 and D2) are reversed biased. This configuration determines a relevant mismatch between the patches, so that the incident wave is mainly reflected. Moreover, when D3 is off and D4 is active (State 180°), the Rx patch introduces a phase shift $\approx 90^\circ$ on the propagating wave, with respect to the opposite bias state (State 0° , D3 on, D4 off). Therefore, the relative phase of the reflected wave, after being shifting twice by the Rx patch, is approximately 180° . The simulation results in Fig. 2 confirm the principle of operation previously described. The reflection losses in the two states vary between 0.5 dB and 1.5 dB in the 29–31.3-GHz band. In the same frequency range, the relative phase shift is $125^\circ \pm 15^\circ$.

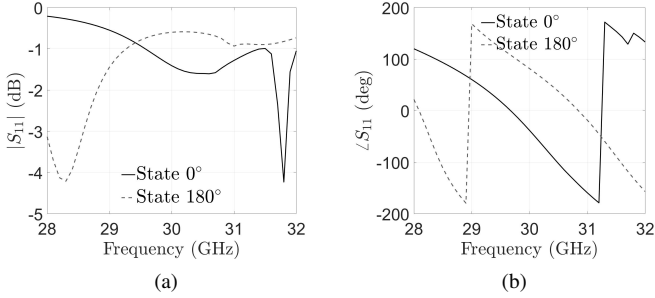


Fig. 2. Simulated (a) amplitude and (b) phase of the reflection coefficient of the cell in Fig. 1a, configured in reflecting mode.

B. A 2-bit LHCP/RHCP Transmitting Cell

The design at Ka-band and preliminary results of the reconfigurable LP-to-CP converter, of period p , shown in Fig. 1b, have been reported in [5]. The UC comprises 4 metal layers. The U-slotted LP patch on the bottom layer is connected by a via to a second square patch, on the top layer, which comprises an O-shaped slot, loaded by two diodes (D5, D6). The via is aligned with respect to the center patch but is displaced with respect to that of the top one. The asymmetric excitation and the shape of O-slot makes the top patch radiate a CP, when the two diodes are biased in opposite states. The handedness of the CP can be switched by swapping the bias states of the diodes, which reverses the current flow on the patch [5].

A 2-bit polarization-agile (RHCP/LHCP) UC can be realized by stacking the LP-to-CP converter UC on the 2-bit LP UC of Fig. 1a. The impact of the distance d , between the T_x LP patch and the converter, on the bandwidth and insertion loss of the overall UC has been studied via parametric full-wave simulations. The results in Fig. 3a, obtained for an LHCP UC with a phase shift of $\approx 0^\circ$ at 30 GHz, show that distances close to a quarter free-space wavelength enhance the bandwidth. A slightly higher value, $d = 4$ mm, is selected to ease the assembly and maximize $|S_{21}|$. The UC insertion losses are between 2 dB and 4 dB in the 28-31-GHz band. The phase responses of the four LHCP states are plotted in Fig. 3b.

III. APPLICATION TO BEAM-STEERING TRANSMITARRAYS

The performances of two 24×24 beam-steering TAs based on the proposed 2-bit UCs are presented. Both TAs are fed by a LP 10-dBi horn, aligned to their centers, at a focal distance $F = 70$ mm. The first TA comprises only 2-bit LP UCs, while the second one includes also the LP-to-CP converter. The phase profiles to steer the antenna beam and the gain patterns were numerical determined via an *ad-hoc* tool [4]. A prototype of the LP TA was realized and tested. It comprises 2304 diodes and 1152 bias lines, which are driven by dedicated control boards. The power consumption due to the diodes on the TA aperture is 14.4 W. The measured patterns of three beams with different scan angles in the E-plane are plotted in Fig. 4a. The scan loss at 40° is 1.6 dB. The simulated gain of the broadside LP TA is compared in Fig. 4b to that of the second TA. The maximum gain difference is 1.7 dB, due to

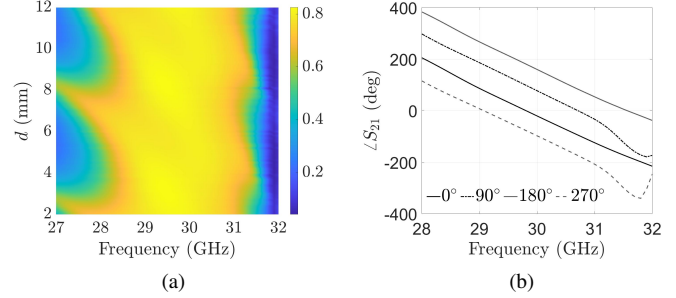


Fig. 3. (a) Simulated $|S_{21}|$ of the LHCP transmitting cell (phase shift 0° at 30 GHz) as a function of frequency and of distance d of the polarization converting cell. (b) Simulated phase responses of the 2-bit LHCP cell.

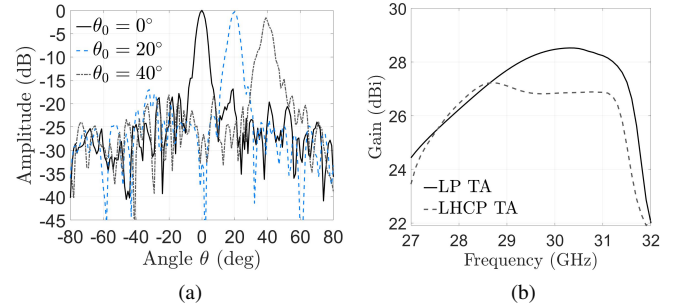


Fig. 4. (a) Measured radiation patterns (E-plane) at 30 GHz, for three scanning angles, and (b) simulated broadside gain of the 24×24 TAs.

the LP-to-CP converter. The aperture efficiency of the TAs are 38.5% and 24.8% at 30.75 GHz. The simulated gain of the RHCP/LHCP TA is 1.4 dB higher than that of the TA in [4], which has the same size, F and feed, but attains polarization agility by interlacing orthogonally LP 2-bit UCs.

In conclusion, solutions for controlling the reflection and transmission coefficients, and polarization of energy-efficient EM surfaces using p-i-n diodes have been presented. The suitability of the proposed UCs for high-gain wide-angle scanning antennas, with application to satellite terminals, has been demonstrated with preliminary experimental results.

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