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A Ka-band Beam-Steering Transmitarray achieving Dual-Circular Polarization

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***Abstract*—This contribution describes a versatile and technologically simple approach for the design of polarization-agile beam-steering transmitarray antennas. The array interleaves two types of electronically reconfigurable unit cells which receive the same linear polarization but radiate horizontally and vertically polarized waves, respectively. The phase shift introduced by each cell can be varied with a resolution of about 90° (2-bit phase quantization) controlling the bias state of two pairs of p-i-n diodes. Dual-linear and dual-circular polarization can be obtained by enforcing the proper phase shift among orthogonally polarized cells. In order to validate this concept, a 24×24 dual-circularly polarized transmitarray is designed for Ka-band satellite communications. The experimental results prove the antenna beam-steering up to 60° and the polarization switching capability. An axial ratio < 1 dB is observed for the broadside beam over the operating band (29.5-31 GHz).**

***Index Terms*—transmitarray, beam-steering array, reconfigurable antennas, SatCom.**

I. Introduction

Novel electronically steerable and high-gain antenna solutions are essential to meet the challenging specifications required by future satellite communication (SatCom) systems at Ku- and Ka-bands. A two-dimensional scan range of at least 120° is often necessary for antennas mounted on mobile ground terminals to ensure a seamless communication with the satellites. Among the available compact antenna technologies, phased arrays [2] provide the finest control on beam-steering and a wide angular coverage. However, the numerous active devices and lossy feed networks that they comprise are not compatible with the strict constraints on the power consumption and costs targeted by commercial applications. Ultralow-profile reconfigurable metasurfaces leveraging on liquid crystal technologies [3], [4] have been intensively studied since a few years, but their losses are still prohibitive.

Though less compact than phased arrays and metasurfaces, space-fed architectures such as transmitarray antennas (TAs) [5], can achieve a higher efficiency at more affordable costs while preserving a good scanning performance.

Electronically steerable TAs [6]-[11] are generally implemented by integrating on the unit cells (UCs) electronic devices such as varactors [6], RF-MEMS switches [7] and p-i-n diodes [8]-[11]. Even if solutions based on varactors enable a continuous phase shifting and a higher aperture efficiency (up to 34% [6]), they require a high number of devices and bias lines. This hinders the realization of large arrays and degrade the bandwidth.

On the other hand, architectures relying on switches and p-i-n diodes are penalized by phase quantization losses, e.g. ≈ 3.5 dB for a 1-bit phase quantization [5],. However, they enhance the bandwidth and minimize the number of controls. In particular, only two and four switches are necessary to design a 1-bit [8]-[10] and 2-bit [11] reconfigurable UC, respectively.

An electronically beam-scanning dual-circularly polarized TAs has been demonstrated in [8] by implementing on the array aperture a specific sequential rotation scheme. This design relies on a 1-bit linearly polarized UC and requires only two p-i-n diodes. Although extremely simple, this solution attains a low aperture efficiency ($< 10\%$), due to the coarse quantization and the loss due to sequential rotation (3 dB).

In this paper, we propose and experimentally demonstrate a design achieving at the same time polarization agility, wide-angle electronic scanning and enhanced aperture efficiency. To this end, horizontally (H) and vertically (V) polarized 2-bit UCs are distributed in the TA aperture to generate circular polarization. Both UC types rely on the antenna-filter-antenna architecture reported in [11]. Each unit cell can provide four transmission phases, relatively shifted by 90°, and comprises four p-i-n diodes. Beam-steering and circular polarization switching are attained by opportunely phasing the two sets of UCs. As a proof of concept, a 24×24-element prototype is designed and characterized. Good scanning performance are experimentally demonstrated in a field of view of $\pm 60^\circ$. The estimated aperture efficiency is 19.2%. Since a directivity loss of 3 dB is due to the generation of circular polarization from H- and V-polarized UCs, the array operating in linear polarization attains an efficiency comparable to the values reported for TAs based on continuous phase shifting cells [6].

II. Transmitarray Design

A. Unit cells

The array operation relies on two reconfigurable UCs, namely V- and H-polarized UCs, shown in Fig. 1a and Fig. 1b. Both UCs share the same six-layer architecture comprising O-slotted patches as receiving *Rx* and *Tx* elements. The patches are connected by a through-via. On each patch, a pair of p-i-n diodes (Macom MA4AGP907) controls the current flow around the slot. Only one diode at a time is forward biased,

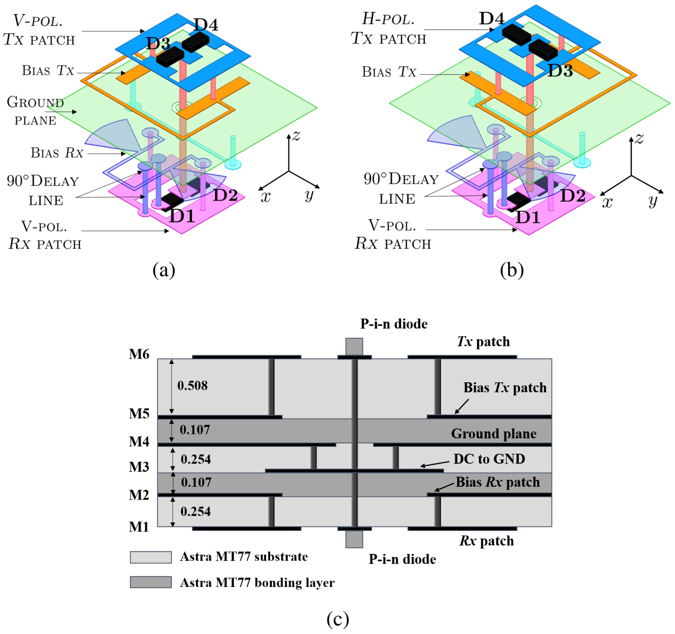


Fig. 1. View of (a) V-polarized and (b) H-polarized unit cells, and of (c) their common stack-up. The thicknesses of the substrate layers are in millimeters.

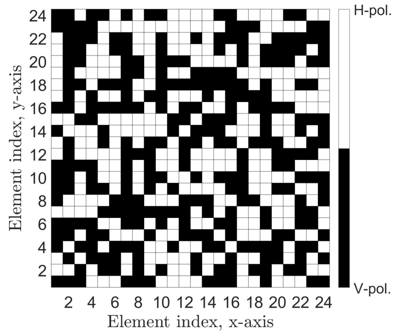


Fig. 2. Arrangement of H-polarized and V-polarized UCs in the designed 24×24 transmitarray.

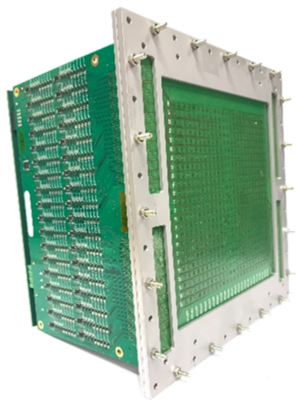


Fig. 3. Photograph of the assembled antenna prototype.

so that a single control line per pair is required. Thanks to the 90° delay line realized in layers M1 and M2, the phase of the transmitted wave is offset by 90° when the states of the diodes D1-D2 is swapped. On the other hand, an inversion of the states of diodes D3-D4 changes the sense of rotation of the current, providing either a 0° or a 180° shift. Therefore, the UC achieves four transmission phases, shifted by 90°, by reconfiguring the states of the diodes. Note that the two UCs only differ for the orientation of the *Tx*-patch and related bias line. In the H-polarized cell, the latter is rotated by 90° with respect to *Rx*-patch. The selected stack-up is shown in Fig.1c. It comprises three Isola Astra MT77 substrates ($\epsilon_r = 3, \tan\delta = 1.7 \times 10^{-3}$) and two bonding films with very similar dielectric properties.

The UCs were optimized for operating between 29.5 GHz and 31 GHz, assuming periodic boundary conditions. To this end, full-wave simulations (Ansys Electronic Desktop 2018) and equivalent circuits for the diodes were employed. The final UC size is $5.1 \times 5.1 \times 1.23$ mm^3. In the design band, the simulated insertion loss under normal incidence is less than 2 dB, for all four states. The maximum deviation of the relative phase shifts from the nominal values is 15°. Since the UC was designed to minimize the impact of the bias circuits on the performance, H- and V-polarized UCs exhibit, for homologous states, very similar transmission coefficients.

B. Array design

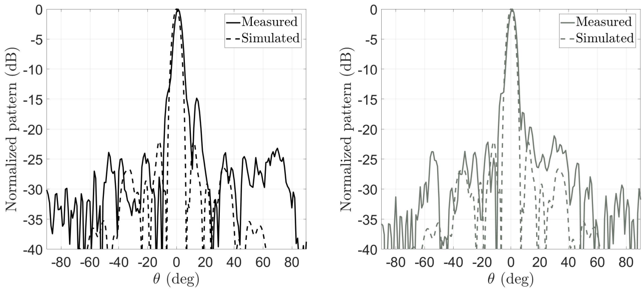
Three challenging objectives drove the TA design. First, the need to radiate nearly pure circular polarization and dynamically switch its handedness. Secondly, the coverage of a scan range of ±60° for all azimuth planes. Finally, the achievement of a broadside gain greater than 25 dBi.

The solution we propose to radiate dual-circular polarization consists in distributing in the aperture the same number of H- and V-polarized UCs and enforcing a ±90° relative phase shift. The possibility to stipulate such a phase shift is enabled by the designed 2-bit reconfigurable UCs.

To the best of our knowledge, the presented approach is the first in the literature allowing one to realize dual-circular polarization-agile transmitarrays based on p-i-n diodes. On the other hand, it inherently reduces the aperture efficiency. Indeed, the use of two interlaced linearly-polarized arrays to generate a circular polarization halves the effective radiating aperture. Moreover, two phase-shifting states of the UCs are employed to enable the reconfiguration of the polarization handedness (RHCP/LHCP).

Therefore, once the phase shift among H- and V-polarized cell is set, the remaining two phase states, i.e. a 1-bit of phase quantization, are used to collimate the wave impinging on the lens and focus the radiated beam. With the aid of the design tool presented in [12], the size of the transmitarray was set to 24×24 elements in order to attain a broadside gain of 25.5 dBi using a 10-dBi V-polarized horn as a feed. The length of the edge is $D = 122.4$ mm. A focal distance $F = 70$ mm was selected as a good trade-off between bandwidth and antenna compactness ($F/D = 0.57$)

The coarse phase quantization and a periodic arrangement of



(a) (b)

Fig. 4. Measured and computed radiation patterns (cut in $\phi = 0°$) of the broadside array at 30.25 GHz: (a) RHCP and (b) LHCP beam.

TABLE I
MEASURED AXIAL RATIO FOR THE BROADSIDE BEAM

Polarization	29.50 GHz	30.25 GHz	31.00 GHz
RHCP	0.70 dB	0.71 dB	0.24 dB
LHCP	0.40 dB	0.04 dB	0.88 dB

H- and V-polarized UCs generally lead to the onset of grating lobes [13] and spurious cross-polarized lobes [8] in several azimuthal planes, significantly degrading the antenna scanning performance. To mitigate this issue, the orthogonally polarized UCs were randomly distributed in the array. The final UC distribution is shown in Fig. 2. It was optimized to achieve at 30.25 GHz a field of view of 120° in all scan planes and an axial ratio lower than 0.5 dB for the broadside beams.

III. Antenna Performance

The fabricated prototype is shown in Fig.3. The array comprises 2304 diodes. Two boards on the lateral sides of the antenna panel provide the bias signals. Another board on the backside of the antenna system embeds the supply unit and the micro-controller which enables to select the beam steering angle via computer.

Figure 4 presents the radiation patterns at 30.25 GHz, in the plane $\phi = 0°$, when the transmitarray is configured to radiate either RHCP or LHCP broadside beams. The measured data are in satisfactory agreement with the numerical results obtained using our in-house analysis tool [12]. The latter uses the full-wave simulated performance of each UC under oblique incidence, in an infinite array environment. Further discrepancies might be attributed to the impact of the bias boards and to some faulty diode connections.

A very low axial ratio is attained for both beams. The measured values at the central and edge frequencies of the band are reported in Table I. The 1-dB axial ratio bandwidths span from 28.9 GHz to 32 GHz for the RHCP beam and from 28.6 GHz to 31.2 GHz for the LHCP beam.

The measured patterns of three RHCP scanned beams in the plane $\phi = 0°$ at 30.25 GHz are shown in Fig. 5. The beam is well formed and the desired pointing direction is obtained up to 60°. The scan loss is 1.1 dB at 30° and 4.6 dB at 60°. The half power beamwidth increases with scan angle: from $5.5°$ for the broadside beam to $9.5°$ for the beam pointing at $60°$.

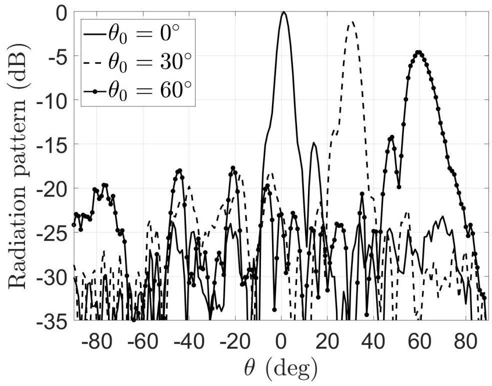


Fig. 5. Measured radiation patterns of several RHCP beams scanning in the plane $\phi = 0°$ at 30.25 GHz.

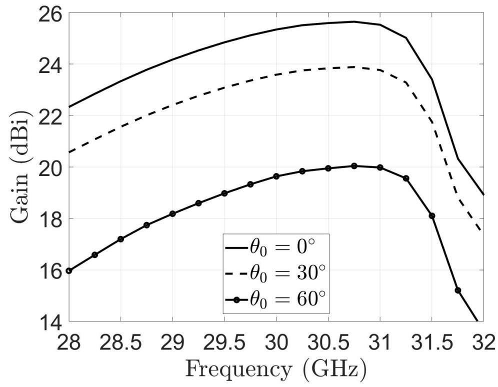


Fig. 6. Simulated gain when the antenna beam (RHCP) is steered in the plane $\phi = 0°$, for three different scan angles.

The scanning performance is consistent for both polarizations and in all azimuthal planes. The simulated gain values of RHCP beams scanning at the same elevation angles, but in the other principal plane ($\phi = 90°$), are plotted against frequency in Fig. 6. The scan losses are very close to those measured in the plane $\phi = 0°$. For the broadside beam, the fractional gain bandwidths evaluated at -1 dB and -3 dB with respect to the peak value are 6.4% and 10.4%, respectively. As per simulations, the peak broadside gain is 25.6 dB at 30.75 GHz, corresponding to an aperture efficiency of 19.2%. This efficiency is about twice that attained by dual-circular polarized transmitarray presented in [8].

IV. Conclusion

The design and experimental characterization of a 24×24 polarization-agile beam-steering transmitarray based on p-i-n diodes has been presented. Dual-circular polarization is attained by using a linearly-polarized feed and two even sets of 2-bit reconfigurable UCs radiating orthogonal linear polarizations. Each UC comprises only four p-i-n diodes and two bias lines, reducing both the layout complexity and the costs in the realization of large beam-steering arrays. The UCs are randomly distributed to enhance the scanning performance. Beam steering up to 60° has been proved. For both RHCP and LHCP broadside beams, the measured axial ratio is less than 1 dB between 28.9 GHz and 31.2 GHz. The simulated gain of each beam varies less than 1 dB between 29.5 GHz and 31.0 GHz. In terms of peak aperture efficiency (19.2% as per simulations), the proposed solution outperforms state-of-the-art polarization-reconfigurable 1-bit transmitarrays. The antenna performance, the simplicity and reduced number of reconfigurable elements (p-i-n diodes) make the presented concept and technology attractive for satellite ground and airborne terminals.

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