Electronically-Steerable Transmitarray Antennas for Ka-Band

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***Abstract*—This paper reports the design and experimental validation of electronically-steerable transmitarrays at Ka-band. Two transmitarrays with 20×20 and 14×14 elements have been prototyped and full characterized, for an operation in switchable circular or linear polarization. They are based on 1-bit and 2-bit phase quantization tunable unit-cells, respectively. To control locally the transmission phase on the transmitarray aperture, two or four p-i-n diodes have been integrated on each unit-cell for the 1- or 2-bit designs, respectively. The measured broadside gain at 29 GHz of the 1-bit prototype is equal to 20.8 dBic with a 3-dB relative bandwidth of 14.6%. For the 2-bit architecture, the measured broadside gain at 29 GHz is equal to 19.8 dBi with a 3-dB bandwidth of 16.2%.**

***Index Terms*—transmitarray, discrete lens, electronically-steerable antennas, Ka-band, beam-steering.**

I. Introduction

In the Internet of Space (IoS) paradigm [1], satellite and satellite-on-the-move communication systems (SATCOM and SOTM) at Ka-band (17.7 – 21.2 GHz and 27.5 – 31.0 GHz, respectively for the downlink and uplink) are a key technology in the development of the future and high performance 5G and "beyond 5G" mobile networks. Thanks to their spatial feeding architecture, relatively low-cost, and the possibility to easily control the phase-shift on the array aperture, transmitarrays [2] and reflectarrays [3] are excellent antenna solutions for applications requiring high gain and efficiency, and wide field of view (> 60°) scanning capabilities.

We review here the main achievements on electronically-steerable transmitarrays studied at CEA-Leti in collaboration with IETR. Our latest results on circularly-polarized unit-cells and the demonstration of a 2-bit transmitarray with 2D beam-steering capabilities will be also presented and compared to the performance achieved with the previous 1-bit architecture [4].

The paper is organized as follows. We introduce in Section II the electronically-tunable unit-cells operating in linear and circular polarization with 1- or 2-bits of phase quantization. Then, in Section III, two electronically-steerable transmitarrays named respectively *Prototype #1* (1-bit circularly-polarized) and *Prototype #2* (2-bit linearly-polarized) are presented. Finally, conclusions are drawn in Section IV.

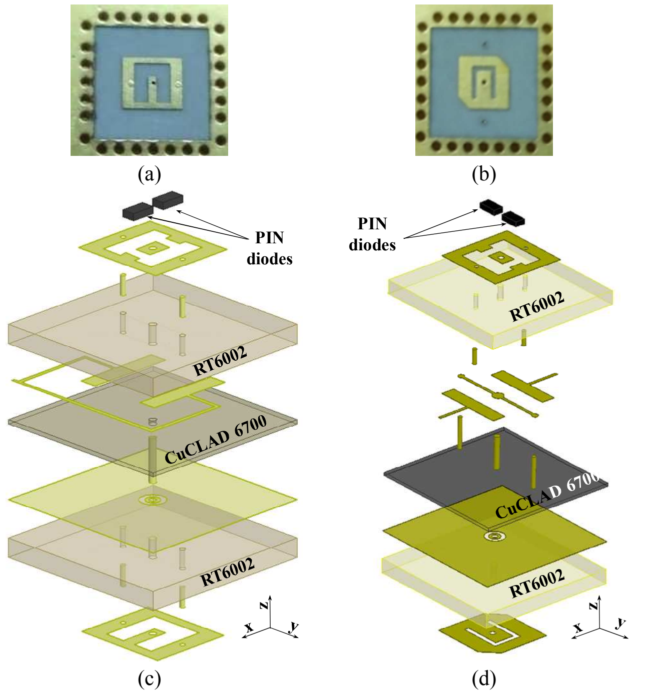


Fig. 1. Architecture of the 1-bit unit-cells. (a,b) Passive patch of the (a) linearly- and (b) circularly-polarized unit-cells. (c,d) Dielectric stuck-up of the (c) linearly- and (d) circularly-polarized unit-cells.

II. Electronically-Tunable Unit-Cells with PIN Diodes at Ka-Band

A. 1-bit linearly- and circularly-polarized unit-cell architectures

The proposed 1-bit (2 phase states with 180° phase difference) electronically tunable unit-cells have been designed to operate in linear [5] or in circular [6] polarization at Ka-band (27.5 – 31.0 GHz). Their size is 5.1×5.1 mm^2 ($\lambda_0/2\times\lambda_0/2$, where λ_0 is the wavelength in free space at 29.4 GHz). They have been designed on a dielectric stack-up formed by two identical substrates (Rogers Duroid

RT6002, thickness 508 µm, $\varepsilon_r = 2.94$), a bonding film (Arlon CuClad 6700, thickness 114 µm, $\varepsilon_r = 2.30$) and four metal layers (Fig. 1). The receiving (*Rx*) layer is composed of a rectangular patch loaded by an O-shaped slot and two p-i-n diodes; this active patch is linearly-polarized. In the transmitting layer (*Tx*), a rectangular patch loaded by a U-shaped slot is used for operation in linear polarization (Fig. 1a). Instead, a square patch loaded by a U-shaped slot with truncated corners is designed for the circularly-polarized unit-cell (Fig. 1b).

The active patch is connected to the passive one with a metallized via hole placed at the center of the unit-cell. A ground plane occupies one of the two intermediate metallic layers. The other inner layer, shown in Fig. 1, is used to route the DC bias network. For the linearly-polarized (LP) unit-cell, the ground connection is realized by using two metallized vias between the passive patch and the ground plane. Instead, in the case of the circularly-polarized (CP) unit-cell, the ground connection is realized with two symmetrical short-circuited quarter-wavelength stubs connected to the central via hole (Fig. 1d).

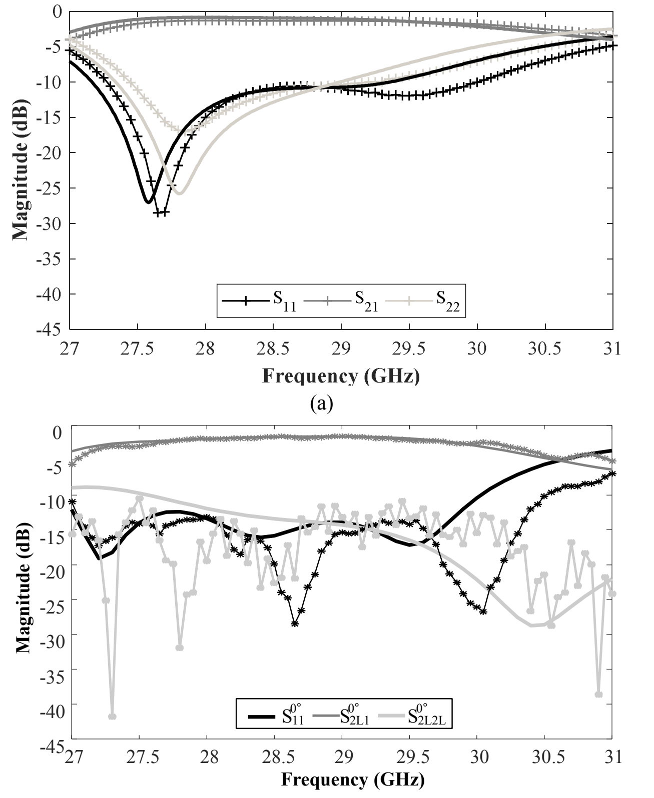
These unit-cells have been simulated and optimized using the commercial software Ansys HFSS with periodic boundary conditions and Floquet port excitations. More details on the simulation results and p-i-n diode models are available in our previous work [5]. These unit-cells have been realized and characterized by using specific waveguide simulators. Description of the detailed measurement setups is out of the scope of this paper, and more details are available in [5],[6].

The measured and simulated magnitude of the scattering parameters of the 1-bit LP and CP unit-cells are plotted in Figs. 2a and 2b, respectively. The measured transmission phase of the CP unit-cell is represented in Fig. 3. This plot shows that a relative phase shift of 180° with a maximum error of 13° and 17° is achieved on the frequency bands 27-30 GHz and 27-31 GHz, respectively.

TABLE I. MAIN FEATURES OF THE 1-BIT UNIT-CELLS (EXPERIMENTAL RESULTS)

	Phase state	LP unit-cell	CP unit-cell
N. of p-i-n diodes	-	2	2
Insertion loss	0°	1.09 dB	1.59 dB
	180°	1.29 dB	1.60 dB
3-dB bandwidth	0°	26.8 – 30.8 GHz	27.0 – 30.5 GHz
	180°	26.7 – 32.0 GHz	27.0 – 31.0 GHz

The main experimental features of both 1-bit unit-cells are compared in Table I in terms of insertion losses and 3-dB transmission bandwidth.



(b)

Fig. 2. Magnitude of the simulated (line) and measured (line and markers) scattering parameters of the 1-bit unit-cells: (a) LP, (b) CP.

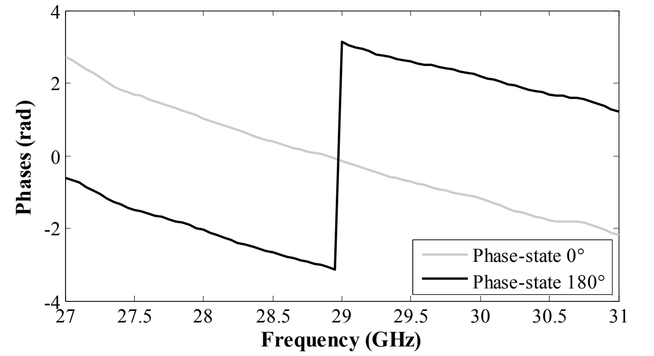


Fig. 3. Phase of the measured transmission coefficients of the 1-bit CP unit-cell.

B. 2-bit linearly- and circularly-polarized unit-cell architectures

As discussed in [7], the use of a 2-bit (4 phase states with a 90° phase difference) phase quantization allows increasing the directivity (and gain) of a 14×14 element transmitarray by 2-2.3 dB. Therefore, when the 1- and 2-bit unit-cell insertion losses are comparable, this directivity improvement corresponds to a 10% additional aperture efficiency. However, the architecture of a 2-bit unit-cell is more complex compared to the one of the 1-bit cell and requires the use of additional tunable devices to control electronically the transmission phase.

The proposed dielectric stack-up used to implement the LP and CP 2-bit unit-cells is depicted in Fig. 4. Here, three dielectric substrates (Rogers RT/Duroid 6002) and two bonding films (Arlon CuClad 6700) are used. The unit-cell size is 5.1×5.1×1.3 mm³ ($\lambda_0/2\times\lambda_0/2\times\lambda_0/8$ at 29 GHz, where λ_0 is the wavelength in free space at this frequency). Six metal layers (*Rx* patch, biasing layer of the *Rx* patch, DC connection, ground plane, biasing layer of the *Tx* patch, and *Tx* patch) and 4 p-i-n diodes (2 on each patch) are required to generate correctly the four phase states with 90° of relative phase-shift. As in the case of the 1-bit unit-cell, a CP patch antenna is used on the *Tx* side to radiate circular polarization. More details on the LP and CP unit-cell architectures are available in [7] and [8], respectively.

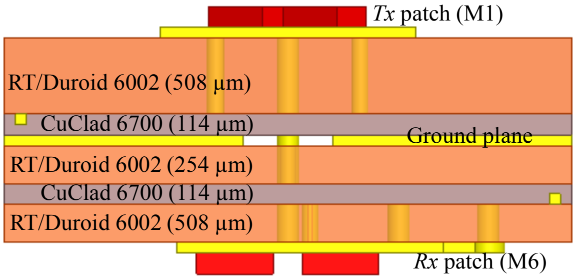


Fig. 4. Dielectric stuck-up of the LP and CP 2-bit unit-cells.

For the LP unit-cell, the simulated minimum insertion loss at 29 GHz is lower than 1.0 dB, and the 3-dB transmission bandwidth varies between 9.6% and 16.5% depending on the considered phase state. The phase difference between the four states is around 90° with a maximum error of 30° in the bandwidth. Similar results are obtained in CP [8], with insertion loss lower than 1.3 dB and a 3-dB transmission bandwidth in the range 10.3 – 13.1%. The experimental performance of both 2-bit unit-cells are reported in Table II.

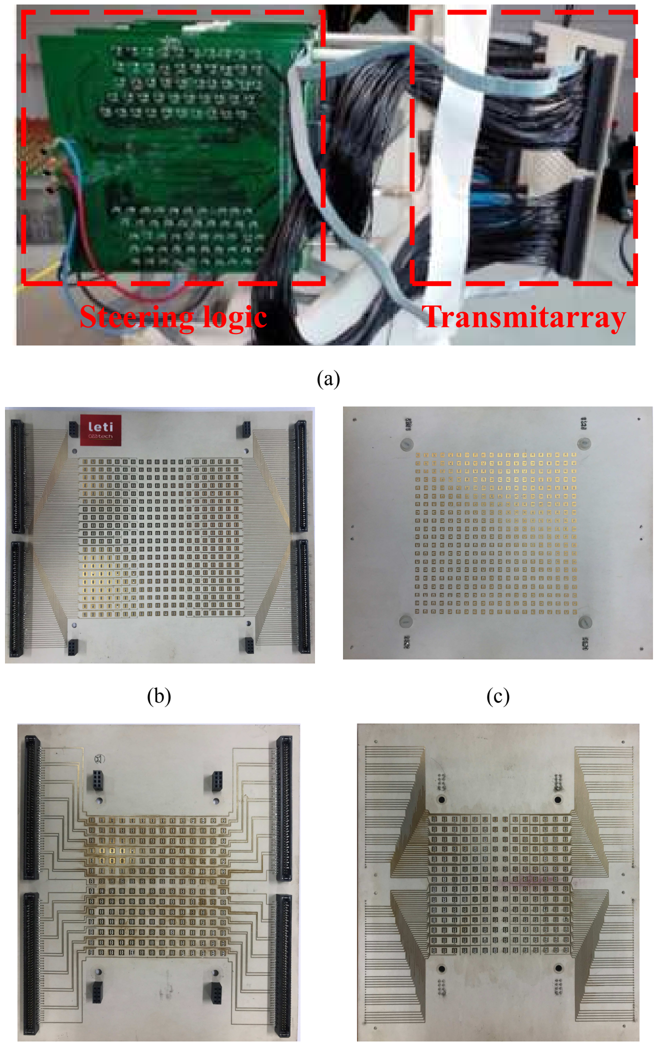
TABLE II. MAIN FEATURES OF THE 2-BIT UNIT-CELLS (EXPERIMENTAL RESULTS)

	Phase state	LP unit-cell	CP unit-cell
N. of p-i-n diodes	-	4	4
Insertion loss	0°	1.0 dB	1.30 dB
	90°	0.80 dB	1.10 dB
	180°	1.0 dB	1.30 dB
	270°	0.80 dB	1.20 dB
3-dB bandwidth	0°	27.6 – 30.4 GHz	27.7 – 30.7 GHz
	90°	26.2 – 31.0 GHz	27.3 – 30.9 GHz
	180	27.3 – 30.8 GHz	27.3 – 30.9 GHz
	270°	26.5 – 31.0 GHz	27.4 – 30.9 GHz

III. ELECTRONICALLY-STEERABLE TRANSMITARRAYS

We describe here the performance of two electronically-steerable transmitarrays operating in Ka-band using 1- or 2-bit unit-cells described in Section II. The architecture of both transmitarrays is very similar and is presented in Fig. 5a. An *in-house* steering logic used to bias the p-i-n diodes flip-chipped on the transmitarray aperture is connected with four DC ribbon cables and is placed behind a 10-dBi standard gain horn antenna used as a focal source.

Prototype #1 is made of 20×20 1-bit unit-cells and operates in circular polarization with polarization switching capabilities. In this case, the circular polarization is achieved from the linear polarization by using a specific sequential rotation scheme [4]. 800 p-i-n diodes are flip-chipped on the radiating aperture to control the transmission phase.



(a)

(b) (c)

(d) (e)

Fig. 5. Photographs of the (a) electronically-steerable transmitarray with its steering logic, *Rx* and *Tx* layers of the (b)-(c) 1-bit CP and of the (d)-(e) 2-bit LP transmitarrays.

Prototype #2 is a 14×14 array of 2-bit unit-cells operating in linear polarization with 784 p-i-n diodes.

The measured gain frequency response at broad side is plotted in Fig. 6 for both prototypes. A maximum gain of 20.8 dBic is achieved for Prototype #1 with a 3-dB bandwidth of 14.6%. The 3 dB of directivity loss are due to the use of LP unit-cells in the sequential rotation scheme. For Prototype #2, the maximum measured gain is equal to 19.8 dBi with a 3-dB gain bandwidth of 16.2%. The characteristics and performance of both prototypes are summarized in Table III. The scanning capability in the E-plane of *Prototype #1* is also presented in Fig. 6.

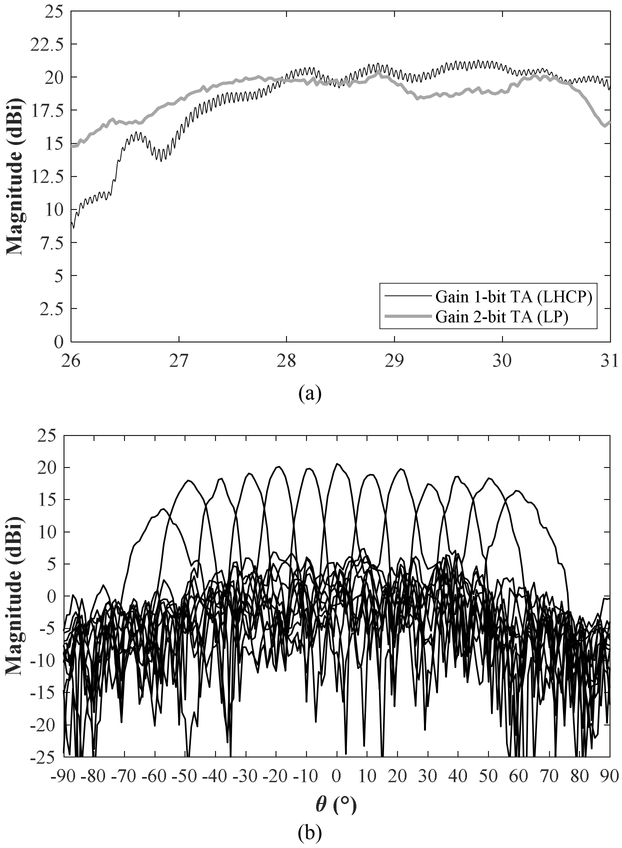


Fig. 6. Measured results of the electronically-steerable transmitarrays. (a) Broadside gain as a function of frequency for the 1-bit CP and the 2-bit LP transmitarrays. (b) Gain radiation patterns as a function of the steering angle of the 1-bit CP transmitarray.

TABLE III. MAIN CHARACTERISTICS OF THE ELECTRONICALLY-STEERABLE TRANSMITARRAYS

	Prototype #1	***Prototype #2***
N. of elements	400 (20×20)	196 (14×14)
Phase quantization	1 bit	2 bits
N. of p-i-n diodes	800	784
Polarization	CP (switchable)	LP (single)
Measured gain (dBi)	20.8	19.8
Measured aperture efficiency (%)	9.5	25.3
Measured 3-dB bandwidth (%)	14.6	16.2

IV. CONCLUSIONS

In this contribution, the current state-of-the-technique of the CEA-Leti and IETR activities on electronically-steerable transmitarrays at Ka-band has been presented. Linearly- and circularly-polarized unit-cell architectures with 1- and 2-bits of phase quantization have been detailed. Eventually, the experimental results of two electronically-steerable transmitarrays show the operation principle of a 1-bit circularly-polarized and a 2-bit linearly-polarized transmitarrays.

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