Design and demonstration of Linearly-Polarized Transmit-Arrays in X-band

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Abstract—**This paper describes the design and demonstration of planar transmit-arrays operating in X-band with 1-bit phase quantization and based on wideband high efficiency unit cells. The unit cell consists of two identical square patch antennas loaded by C-loop slots and interconnected in their centers by a metalized via hole. The proposed transmit-array achieves a maximum directivity of 25.1 dBi and a gain of 22.8 dBi. Radiation efficiency of 56.3% is also obtained with a 1-dB gain bandwidth of up to 9.2% around 9.85 GHz and very low cross-polarization levels. The beam-steering up to 30° is achieved by tilting the focal source.**

Index Terms—**Antenna arrays, Transmit-array, Unit cell, Patch antenna, slot loaded patch, beam-steering, X-band.**

I. INTRODUCTION

Transmit-Arrays (i.e. discrete lens antennas) are based on similar concepts as for reflect-arrays [1-2], except that they operate in a transmission mode [3-4] rather than reflection. The typical configuration of transmit-arrays operating in transmission mode is schematized in Fig. 1. The transmit-arrays provide additional variables which can be used to control and shape the pattern of the radiation pattern. They are more versatile and can provide more symmetrical patterns with lower side lobes. In addition, they can be used to scan the main beam of the antenna toward any point in space. Transmit-arrays applications include tracking radar, search radar, remote sensing, automotive, high data rate wireless communication systems and imaging systems [5-7].

Transmit-arrays are particularly interesting due to their superiority over traditional lens antennas in terms of fabrication cost, planar geometry, low profile and efficiency.

A transmit-array consists of two antennas arrays (*Rx* and *Tx*) interconnected by a phase-shifter circuit and illuminated by a focal source [6-7]. By controlling the transmission phase introduced by each unit cell, the signal transmitted by the focal source can be focused and controlled (beam-forming and beam-steering).

In recent years, different configurations of transmit-arrays have been designed using various technologies (laminates, glass) from C- to K-band [8-10]. Reconfigurable transmit-arrays based on semiconductor or RF-MEMS switching components have also been proposed [11-13]. In [13], a reconfigurable transmit-array with four metallic layers has been demonstrated in X-band. This antenna is an extension of the transmit-array presented in [10], with two additional PIN diodes integrated to control the 1-bit transmission phase. In all these studies, the transmit-arrays performances were limited by the complexity of the unit-cell and the hard possibility to create an advanced version in the aim to design an active cell.

This work presents the design of transmit-arrays structured from 400 elementary cells. The major advantage and contribution is in the structure of the used unit cell [14], which is based on two identical square patch antennas that include C-loop slot and interconnected by a metalized via hole in the patches' centers and features design simplicity, low loss and small size. The cell structure also enables the upgrade to an electronic reconfigurable active cell, just by adding PIN diodes in the C-loop slot with the aim to modify the orientation of the electric field. The active version of the proposed unit cell can achieve real-time beam-steering by applying a specific aperture phase-shift distribution.

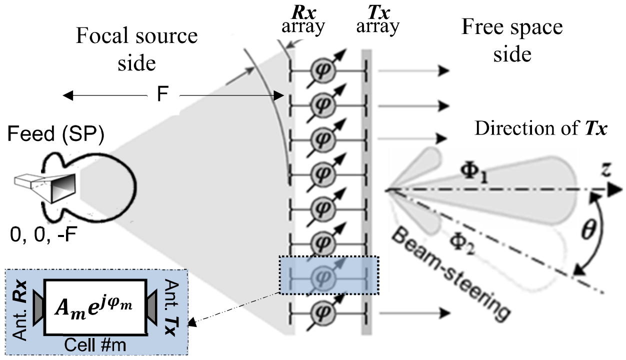
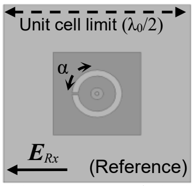


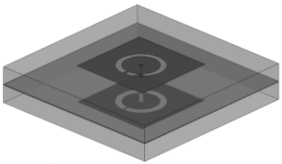
Fig. 1. Typical geometry and operation principle of a transmit-array operating in transmission mode [7].

II. TRANSMIT-ARRAY ELEMENT

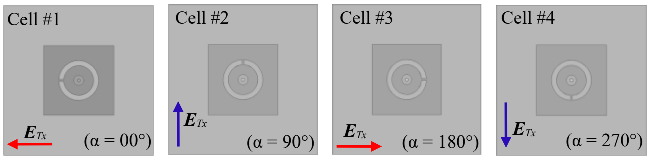
The concept, design and radiation performance of the transmit-array element (elementary cell) have been presented and discussed in detail in [14]. The schematic representation of the transmit-array element is shown in Fig. 2. This can be used in non-uniform array for transmit-arrays (TA), and can also be used in uniform array frequency selective surfaces (FSS) in Quasi-Optical applications. It is composed of two back-to-back microstrip patch antennas interconnected in their centers by a metalized via hole passing through a common ground plane placed in the middle of the substrate. They benefit from low loss and a small size, thus allowing a cell spacing of $\lambda_0/2$ in both directions.



(a) Bottom patch (*Rx*)



(b) 3D structure



(c) Top patch (*Tx*), different configurations

Fig. 2. Schematic representation of the proposed unit cell [14].

The different configurations of the unit cell permitting a 1-/2-bit phase quantization are obtained by orienting the direction of the electric field (i.e. by rotating the C-loop slot), as shown in Fig. 2c. The incident wave with the appropriate polarization is received by the first patch antenna in the input side (focal source side), passes through the via hole after the C-loop impact on the impedance and E-field, and reradiates from the second patch antenna (free space side) with same polarization (or the opposite/orthogonal polarization related to the C-loop slot orientation; i.e. related to the position of the C-loop gap). The bottom patches (reference patch, Fig. 2a) have the same positioning for all cells, while the top patch (free space side) is rotated by an angle α, providing therefore a polarization rotation and a transmission phase-shift, see Fig. 2. For linearly polarized transmit-arrays, the α-values are 00° and 180° (or 90° and 270°) for the two transmission phase values with 180° phase difference (1-bit phase quantization).

The dimension of the elementary cell is 15×15 mm^2 ($\lambda_0/2\times\lambda_0/2$ at 10 GHz). The two identical patch antennas (7×7 mm^2) are connected by a via hole (∅ = 150 µm) through the substrates and separated by a ground plane (thickness 17 µm). The top (free space side) and bottom (focal source side) substrates are Rogers RO4003 (ε_r = 3.38, tanδ = 0.0027, thickness 60 mils). A bonding film (thickness 2 mils) has been used between the ground plane and the bottom substrate.

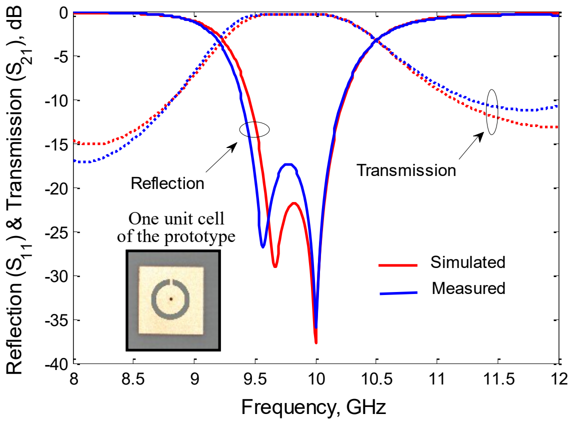


Fig. 3. S-Parameters of the reference unit cell; measurement versus simulation.

The simulated and measured S-parameters of the reference cell (#1) are presented in Fig. 3, which indicate a very good agreement between the simulations and experiments. The measurement results show a -10 dB return loss bandwidth of 870 MHz (8.8% around 9.85 GHz) and an insertion loss of 0.36 dB at 9.85 GHz. The transmission phase difference between the both couples of unit cells (cells 1&3 and cells 2&4) is constant (180°) [14]. This guarantees a perfect 1-bit/2-bit phase compensation for a linear/circular polarization.

The elementary cell presents a maximum gain of 4.7 dBi at 10 GHz and its gain radiation patterns show a 3-dB beamwidth of 98° and 96° in E- and H-planes, respectively [14].

III. TRANSMIT-ARRAY CONFIGURATION & DESIGN

The first array of receive patch antennas is illuminated by the focal source which consists of a 10 dBi linearly-polarized pyramidal horn antenna.

For obtaining the required wave transformation, the transmit-array must be designed to procure the needed phase delay at the operating frequency. This desired phase delay is a function of; the initial phase of the incident wave from the focal source, the wavelength at the design frequency, position of the focal source, and the special coordinates of each elementary cell.

The incident wave received by each elementary cell depends on the distance between it and the focal source (relative position), the complex radiation pattern of the focal source and the complex radiation pattern of the receive patch antenna of concerned elementary cell.

To study, design and simulate the performance of this kind of antennas (transmit-arrays), a numerical simulator has been developed, which starts from the electromagnetic characteristics of the elementary cell and the focal source. The radiation pattern of the focal source is first used to determine the distribution of the electric field illuminating the receive array. The complex radiation patterns and S-parameters of each elementary cell are then used to compute the radiation pattern, gain and directivity of the full transmit-arrays.

The radiation pattern of the full transmit-array $\vec{H}_{TA}(\theta,\varphi)$ is given by:

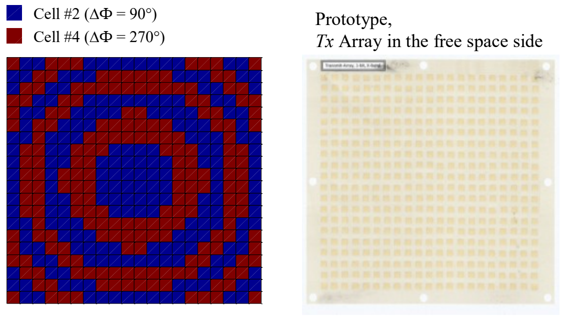
$$\vec{H}_{TA}(\theta,\varphi)=\sum_{n} S_{21}^{n}.\,a_{1}^{n}.\,\vec{H}_{2}^{n}(\theta,\varphi) \qquad (1)$$

Where a_1^n is the incident wave received by the n^{th} elementary cell in the array, S_{21}^n is it S-parameters and $\vec{H}_2^n(\theta,\varphi)$ is it complex radiation pattern on the free-space side [6].

According to the parametric studies done in the previous research works [6-7], the important design parameter of the transmit-array is the focal length (*F*, distance between the focal source and the array). For large focal lengths the spill-over loss increases monotonically while the power efficiency drops (i.e. the directivity increases while the gain decreases). For the applications of interest in X-band, *F* = *D*/2 is a good compromise between directivity and power efficiency (*D*, the side dimension of the array).

The full array area is composed of 400 unit cells which consists of a total physical area A_e equals to 300×300 mm² ($10\lambda_0 \times 10\lambda_0$), corresponding to a maximum directivity for an uniform aperture of 31 dBi. The selected focal length (150 mm) consists of a spill-over loss of 2.14 dB at 10 GHz.

This linearly-polarized transmit-array with 180° phase quantization (1-bit) is designed based on the two of the cells presented in the Fig. 2. It is possible to use the cell #1 and cell #3 for this design, but the other couple has been chosen (cell #2 and cell #4) for a perfect polarization decoupling between the feed source and the radiation. The 1-bit elementary cells' distribution carried by the numerical simulator is presented in the Fig. 4.



(a) (b)

Fig. 4. Elementary cells' distribution (a) for the designed transmit-array (b).

IV. TRANSMIT-ARRAY PERFORMANCES

A. *Broadside Beam*

The variation of the directivity and gain of the 1-bit designed transmit-array as function of frequency is presented in Fig. 5. The frequency response in gain is similar to the transmission coefficient of the elementary cell shown in Fig. 3. The variation of the aperture and radiation efficiencies is presented in Fig. 7. As shown in Fig. 5-6, the variation of the simulated directivity (max 25.3 dBi at 10.4 GHz) is relative to the variation of the aperture efficiency (max 27% at 10.4 GHz), while the variation of the gain is related to the variation of the radiation efficiency.

The maximum value of the aperture efficiency (27%) corresponds to difference (5.7 dB) between the theoretical directivity (31 dBi) and the maximum value of the simulated directivity (25.3 dBi).

The 1-dB gain bandwidth is 900 MHz (9.2%) around 9.85 GHz. The total power (radiation) efficiency is more than 50% between 9.35 GHz and 10.2 GHz (up to 60.3% at 9.6 GHz).

The radiation patterns of the transmit-array are presented in Fig. 7-9, and shows a maximum gain of 22.6 dBi. This radiation pattern (broadside beam) is not perfectly symmetric due to the impact of the radiation pattern of the elementary cells [14]. The important effect is of the 32 cells placed in center of the array, as shown in the unit cells' distribution, Fig. 4.

The main features and power budget are summarized in Table I. As mentioned in the Section III, the spill-over loss has a significant impact on the transmit-array power budget and is related to the position of the focal source. The taper loss is due to the non-uniform field distribution on the receiving array (focal source side) and the quantization loss is due to the 180° phase quantization (1-bit) compared to the ideal case.

The Fig. 7 also shows the effect of the focal source misalignment (consisting of a 10-mm source drift along x-axis) on the radiation pattern, which results in a 4.5° beam-steering.

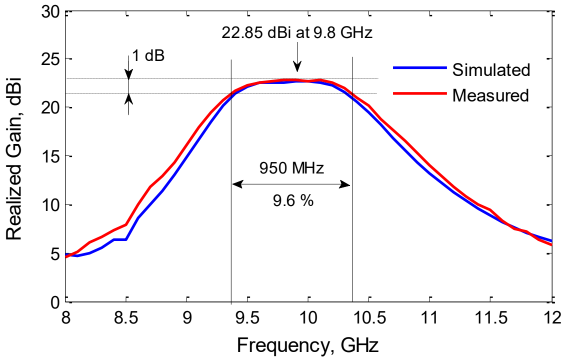


Fig. 5. Varaition of the directivity and gain of the 1-bit designed transmit-array.

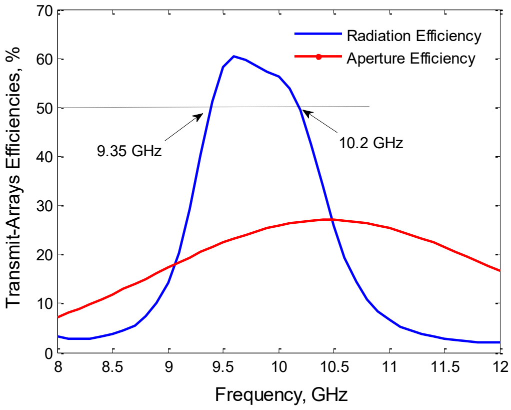


Fig. 6. Variation of the efficiencies of the 1-bit designed transmit-array.

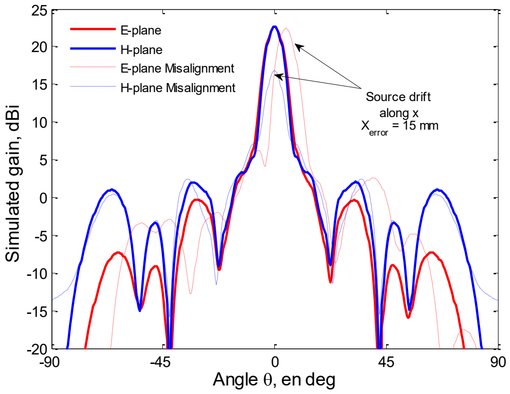


Fig. 7. Simulated radiation pattern of the linearly-polarized transmit-array computed at 10 GHz.

B. *Offset Beam (Beam-Steering)*

In the order to demonstrate the bean-steering capabilities of the linearly-polarized transmit-array (Section IV.A), the radiation performances have been simulated as function of tilting (scanning) angle in the H-plane, Table I.

As summarized in Table I and shown in Fig. 8, when the tilting angle increases, the directivity and gain decrease while the side lobes increase. The scan angle up to 30° can be achieved in H-plane with only a 4.6-dB gain reduction.

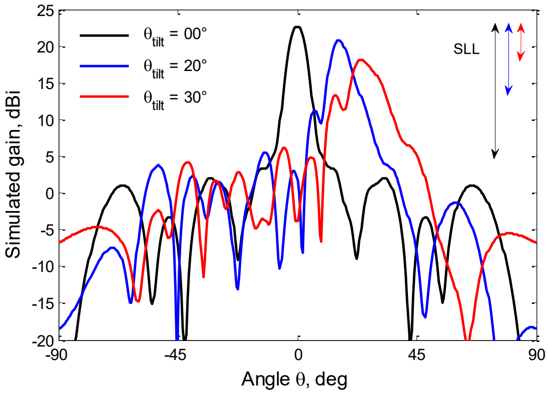


Fig. 8. Simulated radiation patterns of the linearly-polarized transmit-array with tilted beam in H-plane.

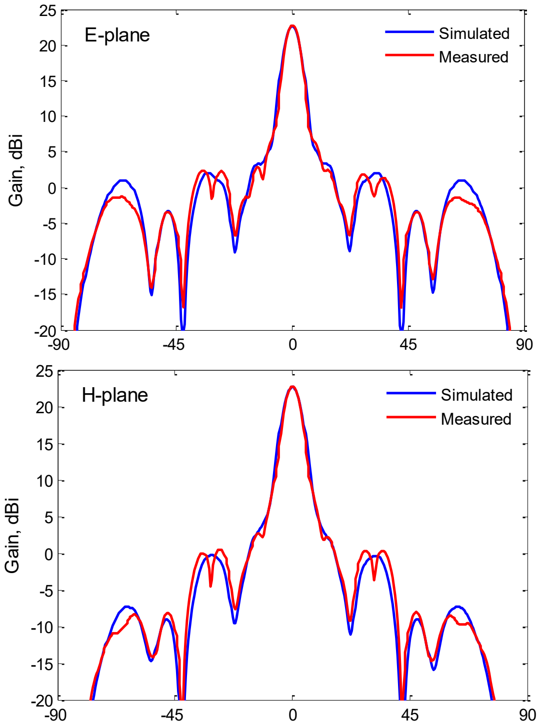


Fig. 9. Gain variation of the linearly-polarized transmit-array; simulation versus measurement. The cross-polarization is not shown (it is lower than -45 dB with respect to the main lobe).

Table 1. Power budgets of the Transmit-Arrays at 10 GHz

Transmit-Arrays	Broadside	Offset (20°)	Offset (30°)
Maximum Directivity for Uniform Aperture (dBi)	31	31	31
Quantization loss (dB)	3.89	4.17	4.59
Taper loss (dB)	1.97	3.32	5.31
Spill-over loss (dB)	2.14	2.37	2.66
Insertion loss (dB)	0.35	0.35	0.35
Directivity (dBi)	25.14	23.51	21.1
Gain (dBi)	22.64	20.78	18.08
SLL E-/H-plane (dB)	23 /20.6	-- / 9.57	-- / 4.74
Power Efficiency (%)	56.31	53.4	50
Aperture Efficiency (%)	25.93	17.82	10.24

V. CONCLUSION

A 400-element linearly-polarized transmit-array has been designed and demonstrated in X-band based on an attractive wideband unit cell with only three metallic layers. The 1-bit transmit-array presents good radiation performances (25.1/22.8 dBi maximum directivity/gain and 56.3% peak power efficiency at 9.85 GHz that up to 60.3% for 9.6 GHz, 1-dB gain bandwidth of 9.2% around 9.85 GHz). The beam steering has been demonstrated with just tilting the focal source. The scanning angle up to 30° can be achieved with only 4.6-dB gain reduction. The promising characteristics, in addition to the low cost and light weight, qualify the designed transmit-array to be an excellent candidate for satellite applications in the X-Band.

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