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# Linearly Polarized Transmit-array Operating in cmWave Bands, Design, Optimization and Demonstration

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**Abstract**—This paper presents the design and optimization of a transmit-array (TA) operating at 10 GHz. This TA is based on a new unit-cell that allows to generate an easy phase rotation required for TA design, while keeping insertion losses to a minimum. The proposed unit-cell is a simple three metallic layer structure, in which two identical square patches are interconnected through an inner via. The optimized structure has a low profile with a total thickness of only 3.2 mm ( $0.1\lambda_0$ ), the simple design allows standard and low cost PCB printing. The unit-cell is designed with CST Microwave Studio and measured with a waveguide measurement system for S-parameters validation. The results show a working bandwidth of 900 MHz (9% relative bandwidth) and insertion losses of 0.3 dB at 10 GHz, full wave simulations show an unit-cell gain of 4.8 dBi making it a very suitable choice for TA design. To demonstrate its performance, a 1-bit transmit-array with  $20 \times 20$  cells is proposed, simulated and manufactured showing a high gain of 21.01 dBi and low side lobe levels (-20.93 dB). Finally, to reduce the overall profile of the TA, a multiple feed TA is conceived using an particle swarm optimization (PSO) algorithm to define the phase compensation distribution and allows a reduction of 50% of the focal length.

**Index Terms**—Transmit-array, unit-cell, linear polarization, low profile, multiple feed antenna, particle swarm optimization.

## I. INTRODUCTION

Transmit-Array (TA) antennas belong to the high gain antenna group, they present many attractive characteristics, such as beam-forming and beam-steering capabilities, that make them good solutions for many applications in the millimeter wave domain. A TA antenna consists of a focal source (primary source or feed), that can be a single antenna (such as horn antenna) or an antenna array, which illuminate(s) a first array of unit-cells (receiving side) interconnected to a second array of unit-cells (transmitting side) via passive or active control circuits, see figure 1. The unit-cells are designed to allow the control of the transmission phase by geometrical parameters or active components. The transmitted fields can therefore be recombined coherently in a certain direction, converting the incoming spherical wave into a planar phase front in that direction, thus highly increasing the directivity of the antenna.

The TA works in a similar way as a traditional phased array, its major advantage is that no feeding network is necessary, since the cells are excited through free space propagation leading to a high radiation efficiency.

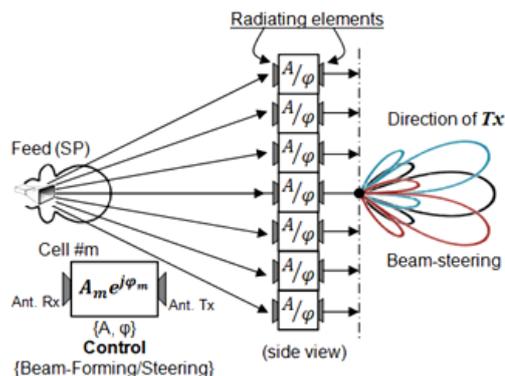


Figure 1. Working Principle of TA antenna [1]

TA research has greatly advanced in recent years, allowing this type of antenna to find applications in several fields, such as automotive [2], High Throughput Satellites (HTS) [3], Satellite on the move (SOTM) [4] and many other wireless high data rate communications. Usually unit-cells are developed in a receiver-transmitter configuration [5] [6], or using frequency selective surfaces (FSS) [4] [7] [8].

When compared to recent realizations, the proposed unit-cell has the advantage of having less layers and therefore a smaller profile, while not requiring complicated feed structures or multiple vias to generate the desired transmission phases.

A current problem in TA design is that the radiation performances of such antennas are majorly controlled by the position of the primary source that must be fixed with a compromise between the focal distance and aperture efficiency [9]. In order to reduce the overall profile of the proposed TA antenna, a multiple feed strategy [10] is applied to achieve a 50% reduction of the focal length.

This paper proposes a quick and effective way to optimize the phase distribution of the multiple feed TA by implementing a particle swarm optimization algorithm (PSO) [11]. Through the definition of straightforward cost functions, the algorithm is capable of searching the global best solution for a set of user defined goals for minimum acceptable gain and maximum side lobe levels (SLLs).

The rest of the paper is organized as follows. In section II

the concept and design of the unit-cell are detailed. The single and multiple feed TA are designed, simulated and measured in section III and finally in section IV conclusions are drawn.

## II. PHASE ROTATION UNIT-CELL

### A. Working Principle

The unit cell of this transmit-array consists of two slotted square patches connected through an inner metallic via. The receiving patch (Rx side) faces the incident field from the feed and is linearly polarized in the  $y$  direction. Since the impedance at the center of a classic patch is zero, an excitation by the inner via at the center would cause a total reflection of the input power, that is  $S_{11} = 0$  dB. To work around this problem, a circular slot is placed in both patches allowing this configuration. The advantage of the inner via is that the coupling between the two sides is perfectly known. By properly designing the microstrip lines showed in figure 3, the unit cell can be adapted at the desired frequency. The equivalent transmission line model helps to better understand the adaptation problem in question.

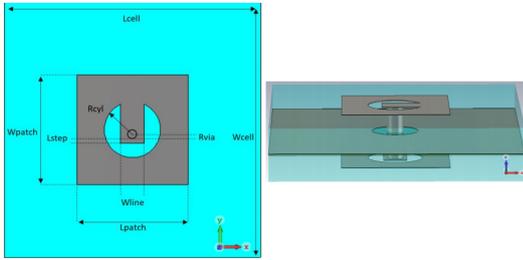


Figure 2. Geometry and design of the proposed Unit-Cell

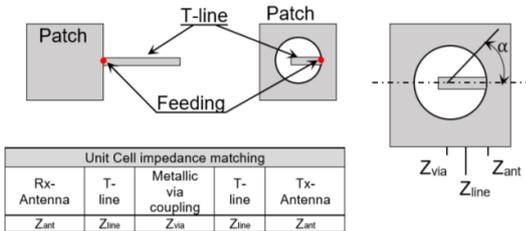


Figure 3. Unit cell T-line model for impedance matching control

Figure 3 shows the feeding of the patch and the impedances that must be matched. At the feed point, the patch presents its impedance  $Z_{ant}$ , thus, by neglecting the losses, the microstrip line presents an impedance at the inner via access given by:

$$Z_{via} = Z_{line} \frac{Z_{ant} + jZ_{line} \tan\left(\frac{2\pi L}{\lambda_g}\right)}{Z_{line} + jZ_{ant} \tan\left(\frac{2\pi L}{\lambda_g}\right)} \quad (1)$$

Where  $\lambda_g$  is the guided wavelength and  $L=R_{cyl}$  is the microstrip length. The challenge is therefore to match the impedance  $Z_{ant}$  to the one of the inner via excitation. A stub of length  $L_{step}$  was added as an additional optimization

parameter. By this analysis, the matching parameters are the lengths and widths of the microstrip lines and stubs, the patch length can also be modified to center the frequency band at the desired central frequency (10 GHz).

By rotating the upper patch by an angle  $\alpha$ , the transmitted electric field's phase is shifted by that same angle. As the impedance  $Z_{ant}$  presented to the transmission line is kept the same, the matching of the structure is not altered and therefore any transmission phase can be obtained for the circular polarization design. For this presented case (linear polarization), only two rotations are used.

### B. Design and Validation

The proposed unit-cell is designed and simulated with CST MicroWave Studio in a periodic environment and Floquet ports excitation, allowing to take into account the mutual coupling with adjacent cells. Both patches stand over a Rogers R04003C substrate (thickness of 1.524 mm, relative permittivity  $\epsilon_r = 3.55$  and a dissipation factor ( $\tan \delta$ ) of 0.0027), separated by a ground plane of  $18\mu\text{m}$  thickness copper, see figure 2. The simulated transmission and reflection coefficients are showed in figure 4, demonstrating a working bandwidth of 900 MHz centered at 9.8 GHz, which corresponds to a 9% relative bandwidth with an insertion loss limited to 0.3 dB. To verify these results, the manufactured unit-cells were measured with a WaveGuide Measurement System [1] to evaluate their reflection coefficient. Considering the inaccuracy in the alignment of the unit-cells with the waveguides, the response showed in figure 4 shows a good match, with a working band around 800 MHz centered at 9.8 GHz.

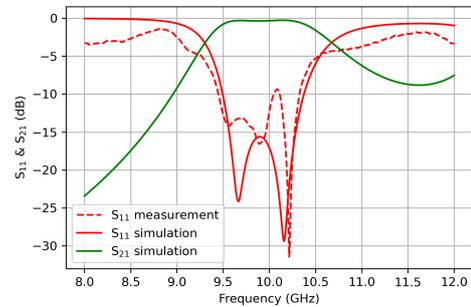


Figure 4. Simulated and measured unit-cell S-parameters

For its use in a TA, the cell must make it possible to produce, by rotations of the upper transmission line, accurate phase-shifts on the lens transmit array in-plane surface. As specified for example in [12], [13], the phase shift must be constant in frequency. Considering a one bit quantification, the two rotations ( $90^\circ$  and  $270^\circ$ ) must impose a  $180^\circ$  shift over the entire bandwidth. Figure 5 shows the validation by simulation of the phase shift of  $180^\circ$  on the useful frequency band. The use of the rotations  $90^\circ$  and  $270^\circ$  makes the TA a sort of polarizer, since the incident field will be converted into its perpendicular polarization.

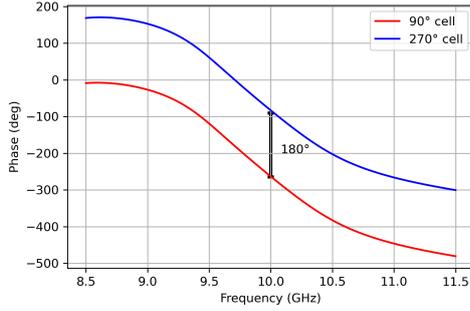


Figure 5. Constant phase shift of  $180^\circ$  between the rotations  $90^\circ$  and  $270^\circ$

### III. TRANSMIT ARRAY DESIGN

#### A. Single Feed TA

A  $20 \times 20$  transmit-array (TA) operating in the X-band and centered at 10 GHz is considered. It consists of 400 unit-cells of dimensions  $15 \text{ mm} \times 15 \text{ mm}$  populated with the two unit-cells previously described in section II. The in-plane dimension ( $D \times D$ ) of the array is then  $300 \times 300 \text{ mm}^2$  and the primary source is a rectangular 15 dB ATM 90-441-6(13971-D) horn operating between 8.2 and 12.4 GHz.

The design of the TA is optimized in terms of focal distance ( $F$ ) with a hybrid analytical/exact tool, initially developed in [9] and recently retrofitted in Python with an object-oriented strategy, to efficiently design transmit-arrays and obtain their performances.

The principle of a transmit-array is to associate with each unit-cell a phase gradient then allowing, once the array has been configured, to obtain a zenithal beam angle  $\alpha_0$  when the feed is at the central position ( $x=0, y=0$ ). Each unit-cell of the TA has been designed to provide a phase correction at position  $(x,y)$  defined by:

$$\Phi_{lens}(x, y) = k_0 \sqrt{x^2 + y^2 + F^2} - k_0 x \sin \alpha_0 \quad (2)$$

Where  $F$  is the TA focal distance. In order to reduce the complexity of the design, the phase distribution is often discretized in a  $n$ -bits configuration. For the sake of simplicity, the TA designed was of 1 bit quantification, that is 2 phase states ( $90^\circ$  and  $270^\circ$ ). If 2 or more bits are used, the sequential rotations of the unit-cell would generate a circularly polarized TA. Using the hybrid tool, the focal ratio is optimized in terms of axial gain, side lobe levels and aperture efficiency by realizing a parametric sweep study using the hybrid tool. The best compromise found was a focal ratio ( $F/D$ ) of 0.75.

In order to validate the results of the hybrid tool, a full wave simulation of the TA was realized using ONERA's FACTOPO Domain Decomposition Finite Element Tearing and Interconnecting (FETI) method in the frequency domain developed in [14]. Figure 6 shows the radiation patterns of the simulations, there is a good match between them with very close main beams and side lobe levels. The manufactured

prototype was therefore produced and measured showing remarkable agreement with simulations. The measured axial gain is 21 dB and the side lobe levels around -20 dB.

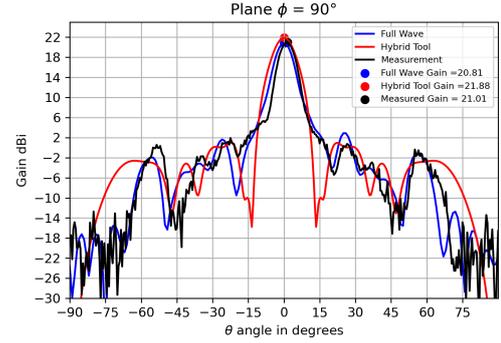


Figure 6. Measured and simulated gain pattern of the transmit-array for  $F/D=0.75$  (225 mm), H plane ( $\phi = 90^\circ$ )

#### B. Multiple Feed TA

In order to achieve high gain with reduced focal ratios, a multiple feed TA is designed with four sources placed at the center of each quadrant, as figure 7 shows. The source separation is chosen to be  $0.5D$ , since it has been shown that the maximal gain for multiple fed TA is obtained around this value [15]. By approaching the four sources to the unit cells, the illumination of the array becomes more uniform and thus higher directivities and gains can be obtained, since the four feeds will act as one equivalent source with a larger focal length. To avoid the use of bulkier sources like horn antennas, the optimization studies will be carried on using standard microstrip patch antennas.

The patch is designed to operate at 10 GHz following the steps described in [16] using the same substrate as the unit cells, afterwards it is simulated using CST Microwave Studio and the results show a maximal gain of 6 dBi. To properly place the sources, a  $2 \times 2$  array was designed using coaxial feeding and microstrip lines.

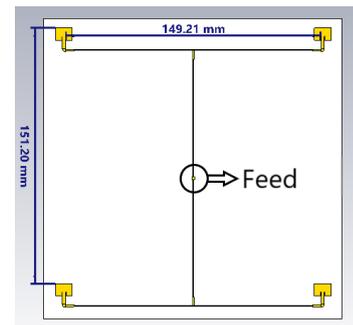


Figure 7. Square placement of the patch sources

It is worth mentioning that the simulations realized with the hybrid code include (in this case) 4 objects of the type "primary source" or "feed". That is, each source is treated as an independent antenna. Since the spacing between the

elements is large ( $5\lambda_0$ ), the coupling between elements is very reduced.

### C. PSO Optimizer

Considering the  $20 \times 20$  transmit-array, the optimization should find a 400 dimensional vector that satisfies the constraints of gain and SLL. This high dimensional problem would require a great effort to find the global maximum, which makes the use of gradient associated methods difficult due to the need of estimating a large gradient vector or an approximation to the Hessian matrix. Also, the search space of the multiple feed TA might not be differentiable, thus prohibiting the use of these methods.

A way around this problem is to consider only solutions in which the phase gradient is symmetric around the  $x$  and  $y$  axis. In doing so, the 400 dimensional problem becomes a 100 dimensional one. Even though this method reduces the computational efforts to find a solution, the gradient associated methods still took too much time to converge (if ever). An optimization technique that has been used in solving many EM problems, such as phased array synthesis [17]- [18], is the particle swarm optimization (PSO).

PSO is a stochastic population based optimization algorithm in which “particles”, or candidate solutions vectors, move around the optimization hyperspace to find the global maximum. We apply a standard PSO algorithm presented in detail in [11], in which to update the position of particle  $i$ , its velocity is defined as:

$$v_n^i = \omega v_{n-1}^i + c_1 \psi_1 (x_n^i - p_{best}^i) + c_2 \psi_2 (x_n^i - g_{best}) \quad (3)$$

$$x_n^i = x_{n-1}^i + v_n^i$$

Where  $x_n^i$  is a vector (position of particle  $i$ ) mapped as a phase distribution of the TA,  $p_{best}^i$  is the particle best position,  $g_{best}$  is global best position ever passed by any of the particles,  $\omega, c_1, c_2$  are coefficients controlling the impact of each term and  $\psi_1, \psi_2$  are random numbers between 0 and 1.

The simplicity of this method allows an easy adaptation of the routine, therefore making it capable of being applied to multiple transmit-array configurations with very little effort. Furthermore, it does not require differentiability (neither the approximation of derivatives) and it has the natural capacity of avoiding local minima by its random movements. Inspired by other array synthesis problems [11], [18] and [17], an optimization module was developed. The goal was to maximize the axis gain, and keep the SLL under a determined threshold level  $SLL_{min}$ , thus the cost function was defined as:

$$f(x) = -Gain(\theta = 0^\circ) + \Pi(SLL) \quad (4)$$

$$\Pi(SLL) = \begin{cases} 0 & \text{if } SLL \leq SLL_{min} \\ \gamma |SLL - SLL_{min}| & \text{else} \end{cases} \quad (5)$$

In which  $\Pi(SLL)$  is a penalty function only applied if the SLL is over the threshold level, the penalty can be controlled

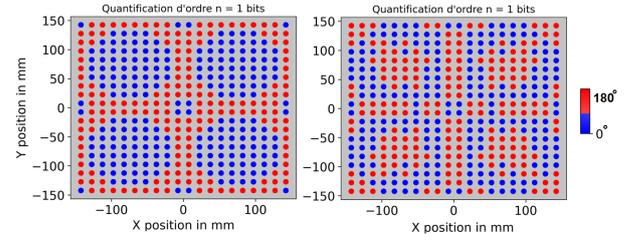


Figure 8. 1 bit phase gradient of the TA, initial guess (left) and final optimization result (right).

through the  $\gamma$  parameter. Each particle corresponds to a 100 dimensional vector that is mapped as a phase distribution on the array. For each position of the optimization hyperspace, the hybrid tool is used to obtain the performances of the TA. Based on the cost function, each position is then scored and used to update the particles’ velocities and position. To ensure better performances, the constriction factor proposed by [19], along with velocity clamping were applied. Upper and lower bounds for the positions were also used to ensure consistency with a 1 bit quantification.

A 50 particles population was considered, with a total of 10000 iterations. The algorithm presented an overall good speed of execution, being able to execute a full iteration, that is 50 executions, under 9 seconds. For the final results, a similar penalty regarding a minimum acceptable gain was also included on the cost function to avoid gain reduction. The gamma parameter impacts the overall evolution of the optimization in a sense that it may lead to a solution that favours the constraint function over the gain optimization. The best compromise found was to set  $\gamma_{SLL} = \gamma_{gain_{min}} = 3$ .

### D. Final Results

This optimization algorithm has been used to achieve a reduction of at least 50% on the focal ratio by using multiple feeds, the SLL threshold was set at -14 dB. The radiation pattern of the multifeed case is compared to the previously designed single feed TA (see figure 9).

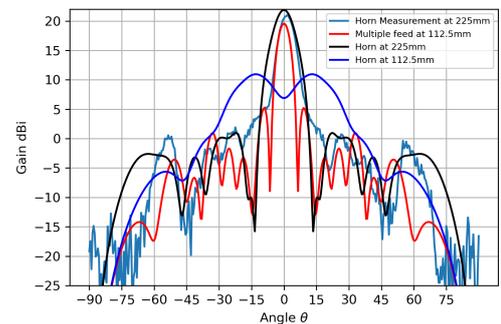


Figure 9. Radiation patterns of the multiple feed case compared to a single horn feed at multiple focal distances,  $\phi = 90^\circ$

When compared to the initially designed TA (black and red curves), the multiple feed presents smaller gain (19.55

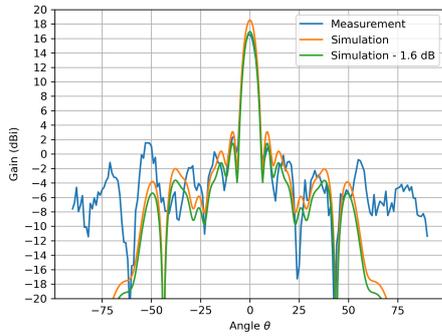


Figure 10. Measurement and Simulation of realized multiple feed TA,  $\phi = 90^\circ$

dB), higher SLLs (-14 dB) and smaller aperture efficiency. Nevertheless, in the case of a reduced focal ratio ( $F = 112.5$  mm) it has a much better performance than the horn (dark blue curve). In this case, the multiple feed presents a well defined main beam and a higher axial gain, justifying its use as a solution for focal length reduction.

In figure 10, it is possible to see a good match of the simulated and measured radiation pattern of the multiple feed TA, with side lobes well placed. As the manufactured source presented 1 dB of loss in the transmission lines, this impact was considered for the final simulation which led to a simulated realized gain of 18.55 dBi. The gain measurements show a difference of -1.6 dB when compared to the simulations, multiple tests did not show evidence of misalignment between the antennas and this reduction was therefore attributed to edge effects on the feeding patches, that could not be modeled in the hybrid code.

#### IV. CONCLUSION

A novel unit-cell working in X-band was presented. The simulations and measurements show a 900 MHz bandwidth and the capability of generating a  $360^\circ$  continuous phase shift, with a reduced profile of  $0.1\lambda_0$ . A transmit-array antenna composed of  $20 \times 20$  unit-cells was simulated, manufactured and measured showing a high gain of 21 dB and low SLLs of -20.93 dB with an 1 bit quantification. As the Unit-Cell is capable of generating more phase states, a higher number of bits would impose a higher gain and lower side lobes at the cost of manufacturing complexity. Finally, to reduce the overall profile of the TA antenna a multi-source strategy alongside with a PSO algorithm to find the optimal phase distribution was used. The simulation results showed promising results in terms of gain (19.5 dB) with a reduction of 50% on the focal length. The measurements show a -1.6 dB difference with the simulations, indicating that the primary source should be redesigned to reduce its losses.

#### ACKNOWLEDGMENT

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