Design and Demonstration of 1-bit and 2-bit Transmit-arrays at X-band Frequencies

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Abstract—This article describes the design of new planar transmit-arrays at 10 GHz with 1-bit and 2-bit phase quantization and specific unit-cell designs in each case. The influence of the main design parameters are investigated numerically. The simulated directivity/gain values equal 26/23 dBi for the 1-bit design, and 31/28 dBi for the 2-bit design, respectively. In particular, the influence of the phase quantization is highlighted. Both designs are built on a two-layer printed circuit board assembly and operate in linear polarization in source focal side. In free space side, the 1-bit design operates in linear polarization and 2-bit design operates in circular polarization. Beam-steering characteristics up to \( \pm 30^\circ \) are investigated and compared by tilting the feed source and by changing the phase distribution across the array.

1. INTRODUCTION

At millimeter-wave frequencies, antenna arrays are generally implemented as lens-arrays or reflectarrays with free-space feeding schemes to minimize the inherent loss and parasitic radiation of the feed network. Transmit-arrays (double-array discrete lenses) are low-profile and low-cost planar alternatives to dielectric lens antennas \cite{1, 2} for millimeter-wave applications like automotive radars, high data rate wireless communication systems, imaging systems, and quasi-optical power combiners \cite{3–7}.

They typically consist of two planar arrays of printed antennas, whose elements are interconnected or coupled with a specific transmission phase in order to generate a uniform or linear phase distribution across the array (Fig. 1).

![Figure 1: General description of a transmit-array.](image-url)
Transmit-arrays are based on similar concepts as for reflect-arrays except that they operate in a transmission mode rather than in reflection [8]. In contrast to reflect-arrays, such configurations offer several advantages, such as reduction of blockage effects due to the focal array, and easier integration and mounting onto various platforms. On the other hand, transmit-arrays are more complex to design and optimize.

This paper is organized as follows. Section 2 presents several numerical results on the general performance of transmit-arrays as a function of element spacing, phase quantization and feed position. Then two different designs with 1-bit and 2-bit phase quantization are proposed and compared in Sections 3 and 4. The capabilities of both solutions for beam steering are investigated in Section 5. Conclusions are drawn in Section 6.

These prototypes are designed after a first 2-bit design [9] in order to improve his directivity, gain and efficiency. The elementary cell of the first 2-bit design consists of two patch antennas connected by a coplanar (CPW) transmission line. Both patches are coupled to the CPW line through a rectangular slot loop etched in the ground plane. The phase delay induced by each cell is proportional to the t-line length.

2. TRANSMIT-ARRAY DESIGN

An in-house CAD tool has been developed to design and compute the performance of transmit-arrays, starting from the electromagnetic characteristics of the elementary cell and the focal source. The radiation pattern of the feed is first used to determine the electric field distribution illuminating the first antenna array. The radiation patterns and S-parameters of each elementary cell are then used to compute the radiation pattern, gain and directivity of the transmit-array.

A preliminary study has been performed to investigate the influence of the main design parameters on the antenna performance. This study is done at 10 GHz and is based on a generic elementary cell with a gain of 5 dBi, which is a typical value for patch antennas. The total array area is fixed at $300 \times 300 \text{ mm}^2$, corresponding to a maximum directivity of 31 dBi. The feed is a 10-dBi horn antenna with 3-dB beamwidths of 52$^\circ$ and 49$^\circ$ in E- and H-planes, respectively. This feed is placed at 260 mm away from the array, which results in 1.8-dB spill-over loss.

The influence of the element spacing on the array directivity and gain is represented in Fig. 2 when varying the element spacing in the E-plane direction and keeping it fixed at $\lambda_0/2$ in the other one. As expected, minimizing the element spacing is desirable so as to collect the radiation from the feed source with maximum efficiency. Since we are limited by the patch antenna size, a typical element spacing of $\lambda_0/2$ will be considered in the following.

The main challenge in designing transmit-arrays is the ability to generate the appropriate phase-shift for each cell in order to transform the incoming spherical wave radiated by the focal source into a plane wave on the free-space side, i.e., to produce a nearly-flat phase distribution with a given phase gradient depending on the main beam direction. Since this phase compensation cannot be ideal, we have investigated the effect of phase quantization on the directivity and gain of the array (Table 1). A constant difference of 3.1 dB between directivity and gain is due to spill-over and reflection loss on the transmit-array. Insertion losses are very low. It is seen that a 1-bit (180$^\circ$ phase steps) or 2-bit (90$^\circ$ phase steps) design result in 4.3 dB and 0.8 dB loss, respectively, as compared to the ideal case (Table 1).
Finally, the best location of the feed horn for maximum gain was found to be at $7.6 \times \lambda_0$ (228 mm) from the array (Fig. 3). While the gain decreases slowly for longer focal lengths, the directivity increases and the side-lobe level decreases because of the ‘more uniform illumination’ of the array.

Based on these results, two designs of transmit-arrays are proposed and compared in the following, with 1-bit (Section 3.1) and 2-bit (Section 3.2) phase quantization.

3. ELEMENTARY CELL DESIGN

3.1. 1-bit Design

The elementary cell is represented in Fig. 4. It consists of a single ground plane, two substrate layers (Rogers RO4003, $\varepsilon_r = 3.38$, $h = 1.524$ mm) and two patch antennas connected by a via hole. The two transmission phase values with a 180° phase difference (1-bit) are obtained by flipping one of the patches with respect to the via connection. The patch and cell sizes equal $7.4 \times 7.6$ mm$^2$ and $15 \times 15$ mm$^2$ ($\lambda_0/2 \times \lambda_0/2$), respectively.

![Elementary cell for the 1-bit design](image-url)

Figure 4: Elementary cell for the 1-bit design, (a) side view, (b) front view.

![S-parameters of the elementary cell (1-bit design)](image-url)

Figure 5: $S$-parameters of the elementary cell (1-bit design).
This unit-cell was simulated with Ansoft-HFSS using periodic boundary conditions and Floquet port excitations [10, 11]. The $-10$ dB return loss bandwidth is $850$ MHz ($8.8\%$) (Fig. 5). The maximum directivity and gain are $5$ dBi and $4.8$ dBi in the broadside direction, respectively. The patches on both sides of the array are rotated by $90^\circ$, providing a natural polarization decoupling between the feed radiation and the array radiation.

### 3.2. 2-bit Design

The elementary cell of the 2-bit design is almost the same as the elementary cell of 1-bit design, in terms of dimensions and materials. For against in this case, we have 4 different elementary cells (Fig. 6), instead of 2 elementary cells, for achieve 2-bit phase quantization.

The 4 elementary cells have designed to reach $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ of transmission phase between the input and output signal of the array antennas.

The different transmission phase values are obtained by turning the patch in the free space side at $90^\circ$ against the other patch with respect to the via connection.

### 3.3. Discussion

An important advantage of these two designs is their simplicity with only two dielectric substrates and three metal layers. The two designs benefit from a small size, thus allowing a cell spacing of $\lambda_0/2$ in both directions. The 2-bit design, in contrast to the 1-bit design, permits an improved phase quantization.

![Cell no. 1 (\(\Phi = 0^\circ\))](image)

![Cell no. 2 (\(\Phi = 90^\circ\))](image)

![Cell no. 3 (\(\Phi = 180^\circ\))](image)

![Cell no. 4 (\(\Phi = 270^\circ\))](image)

Figure 6: Elementary cell for the 2-bit design, front view.

![Normalized gain, dB vs Angle \(\theta\), deg](image)

Figure 7: Radiation pattern simulated at $10$ GHz for the 1-bit design.
4. PERFORMANCE OF THE TRANSMIT-ARRAYS

4.1. 1-bit Design

The 1-bit design transmit-array comprises \(20 \times 20\) cells. The feed horn is placed at \(260\) mm (\(8.7 \times \lambda_0\)), which corresponds to an acceptable trade-off between the taper efficiency (7.5 dB) and spill-over efficiency (1.8 dB).

The simulated radiation patterns at 10 GHz show a directivity and gain of 26 dB and 23 dB, respectively, with side-lobe levels lower than \(-15\) dB (Fig. 7).

4.2. 2-bit Design

The 2-bit design is designed like the 1-bit design; the only difference is that the quantization phase is more important.

The simulated radiation patterns at 10 GHz show a directivity and gain of 31.2 dB and 28 dB, respectively, with side-lobe levels lower than \(-15\) dB (Fig. 8).

5. BEAM-STEERING

Beam-steering or beam-switching can be achieved via two methods. The first one relies on the feed horn that can be tilted at a specific angle from the main axis of the array. The second method consists in changing the phase-shift distribution across the array to produce a desired phase gradient to steer the beam, as done classically for antenna arrays. This second method is investigated here only for fixed-beam passive arrays. It is expected that tunable phase-shifter may be used in the future to achieve fully reconfigurable transmit-arrays [12].

5.1. Beam-steering by Tilting the Feed Horn

This method has been studied experimentally for the first 2-bit prototype with steering angles up to \(\pm 30^\circ\) [9]. A gain reduction of 2.8 dB was obtained experimentally for the maximum scan angle, which is due both to the increase of the spill-over loss and to the limited beamwidth of elementary cells.

The simulated radiation patterns for the 1-bit design are represented in Fig. 9 for 10\(^\circ\) and 30\(^\circ\)-scan angles. The corresponding gain values equal to 22.6 dB and 18.7 dB, respectively.

\[\text{Normalized gain, dB} \]
\[\text{Angle } \theta, \text{ deg}\]

\[\text{Figure 8: Radiation pattern measured at 10 GHz for the 2-bit design.}\]

\[\text{Figure 9: 1-bit design with tilted feed horn. Simulated radiation patterns at 10 GHz for two scan angles (10\(^\circ\) and 30\(^\circ\)).}\]
5.2. Beam-steering by Modifying the Phase-shift Distribution

Here the feed horn is placed along the main axis, and the phase gradient is tuned to steer the main beam at $30^\circ$ (Fig. 10). Compared to the previous method, this strategy provides better performance in terms of gain reduction and side-lobe level ($-14$ dB). The gain values are 23.5 dBi and 20.3 dBi at $10^\circ$ and $30^\circ$, respectively.

6. CONCLUSION

Passive transmit-arrays operating at X-band have been investigated numerically and experimentally. The numerical study has highlighted the impact of cell spacing, phase quantization and focal length upon the gain and directivity of the array. Two designs have been proposed, with 1-bit and 2-bit phase quantization. The first design provides a 23 dBi-gain, and the gain of the second one is equal to 28 dBi due to the phase quantization. The beam-steering capabilities of the 1-bit design have been studied for scan angles up to $30^\circ$.

REFERENCES