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A Tiled C-Band Dual-Polarized 1-Bit Transmitarray

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Abstract— An original structure of tiled transmitarray is presented, comprising a number of topologically similar unit cells arranged in arbitrary pattern within a planar array frame. Each unit cell represents a passive receiver-transmitter structure with integrated phase-shifter, fabricated in commercial 5-layer printed circuit board process, which can take either of two coding states corresponding to 0° or 180° phase shift imparted to the signal transmitting through the device. The unit cell design supports two orthogonal linear polarizations. An example of a 10x10 element 1-bit beam steering transmitarray operated in C-band is demonstrated by simulations and measurements. The proposed structure represents a cost-efficient solution for scalable transmitarrays and also for proof-of-concept experiments in research and education.

Index Terms—Antenna arrays, lens-array antennas, one-bit beamforming, transmitarrays

I. INTRODUCTION

High gain, high-efficiency and wideband antennas constitute the core enabling technology of the emerging millimetre-wave 5G wireless communications and surveillance systems, [1]-[2]. The beam-steering and beam-forming are also regarded as the essential functionalities of the 5G antennas. Phased antenna arrays provide the viable solutions to achieve the requirements of the emerging systems. However, alongside the fundamental trade-offs on their performance, e.g., gain versus bandwidth, there are other shortcomings of the conventional phased arrays, particularly, design complexity and power loss in the feed networks. To alleviate the later drawback, the alternatives to the traditional corporate feed networks have been proposed, including microwave lenses, e.g., Rotman lens, and spatial feed techniques. The latter can be implemented using dielectric lenses or transmitarrays, [3], also known as discrete lenses.

The primary function of the transmitarray structure is conversion, by means of the local phase adjustment, of the spherical wavefront emitted by the antenna feed positioned at the focal point, into the uniform plane wave propagating towards the intended recipient, thus directing the radiation of the low-gain antenna feed. Compared to the dielectric lens, transmitarray structures can be manufactured in a standard low-cost printed circuit board (PCB) technology and can be made arbitrary conformal and electrically reconfigurable. Multiple solutions have been proposed for the planar transmitarrays, which can be grouped into three design approaches, [3]: multi-layered frequency selective surfaces,

metamaterial/transformation optics slabs, and receiver-transmitter (RT) structures. The last approach requires two planar arrays of simple antenna elements connected via phase-shifters, which can be either passive transmission line structures or active devices.

Many RT structures have been proposed recently, [4]-[6], while their demonstrations were reported at low frequencies using the large multi-layer PCB structures. It has also been shown that a coarse 1-bit discretization of the phase-front adjustment can be feasible in many applications, [7]. The performance limitations inherent in the RT transmitarrays have been discussed, including the effects of the phase quantization, [8], and amplitude modulation due to oblique incidence toward the RT structure edges, [3].

In this paper, we report on the design, simulations and measurements of a 1-bit transmitarray operated in C-band. The device works with two orthogonal polarizations and, as such, can support polarization diversity communication schemes. The array is assembled manually from the identical building blocks (tiles) by arranging them in the prescribed pattern to steer the beam in the desired direction. The effects of the manual assembling are discussed. The main advantage of the proposed tiled construction is that large arrays of varying size can be assembled from identical unit cells. Moreover, the proposed structure represents a cost-effective and flexible solution for a range of demonstrations in the research and teaching on 5G antenna design.

Simulated and measured results of the unit cell are discussed in Section II. An example of a 10 × 10-element 1-bit beam steering transmitarray operated in C-band is demonstrated by simulations and measurements in Section III.

II. TILED TRANSMITARRAY DESIGN

A. Transmitarray model

In the transmitarray, the field amplitude received by each unit cell normalized to the transmitted power is given by

$$a_{nm} = \frac{\lambda e^{-jkR_{nm}}}{4\pi R_{nm}} F_{nm}^{fs} F_{nm}^{uc}, \quad (1)$$

where $n = 1, 2, \dots, N$ and $m = 1, 2, \dots, M$ are the row and column indexes of the array which determine the position of each unit cell with respect to the reference one, k is a free-space wavenumber, λ is free-space wavelength at the operating frequency, F_{nm}^{fs} is the complex radiation pattern of

the focal plane source in the direction of the unit cell (n, m) , F_{nm}^{uc} is the complex radiation pattern of the unit cell (n, m) in the direction of the focal plane source and R_{nm} is the distance between the focal plane source and the unit cell (n, m) .

The radiation pattern of the transmitarray, $F(\theta, \varphi)$, can be calculated as the vector sum of the fields radiated by each unit cell, while taking into account their scattering parameters:

$$F(\theta, \varphi) = F^{uc}(\theta, \varphi) \sum_{n=1}^N \sum_{m=1}^M b_{nm} e^{jkd(n \sin \theta \cos \varphi + m \sin \theta \sin \varphi)}, \quad (2)$$

where $F^{uc}(\theta, \varphi)$ is the radiation pattern of a unit cell in the periodic array, $b_{nm} = T_{nm} a_{nm}$ are the radiated fields and T_{nm} the unit cell transmission coefficients.

In conventional phased arrays, beam steering is achieved by changing the phase distribution of the radiated wave front across the array aperture. In the considered transmitarray, the ideal continuous phase distribution is discretized due to the 1-bit quantization of the unit cell phase shift, according to the following recipe:

$$\arg(T_{nm}^d) = \begin{cases} 0^\circ & \forall |\arg(T_{nm}^c)| \leq 90^\circ \\ 180^\circ & \text{otherwise} \end{cases} \quad (3)$$

where $\arg(T_{nm}^c)$ is the wrapped continuous phase shift of each unit cell required to implement the ideal phase distribution at the outward side of the transmitarray.

The effect of 1-bit phase quantization on radiation characteristics was analyzed in [6][9]. It has been shown that it results in the gain reduction of up to 4 dB, higher sidelobe level and an appreciable beam squint.

B. Dual Polarized Unit Cell Design

The proposed tiled transmitarray comprises a number of identical unit cells arranged at a half-wavelength distance in arbitrary pattern within a planar array frame, as shown in Fig. 1. The unit cell is implemented as a stacked 5-layer structure, Fig. 2(a). The receiving and transmitting antennas on each side of the unit cell are represented by the square ring microstrip elements. Due to the lengthening of the induced surface current path, a square-ring microstrip antenna has a smaller size compared to a patch antenna for the same

Fig. 1. Proposed 1-bit tiled transmitarray architecture.

resonant frequency, [9]. The proximity coupled (electromagnetic) feeds are employed using the open-ended half-wavelength semi-annular (U-shaped) microstrip loops in the layer beneath the ring antennas, which allows enhanced bandwidth when the feed and ring are properly aligned, [1]. The microstrip width of the square ring and feeding loops were optimized for the maximum return-loss bandwidth. The two resonators are connected to each other by a buried via hole. Using two resonators at the orthogonal arms of the square-ring patch allows a dual polarized unit cell design. The receiving and transmitting layers of the unit cell are decoupled by the ground plane placed in the middle layer. The metallic patterns are formed on 4 dielectric layers of 0.51 mm thick Rogers RO4003 material ($\epsilon_r = 3.5$, $\tan \delta = 0.0018$). The two layers of 0.1 mm bonding film Rogers RO4003C ($\epsilon_r = 3.38$) are used to attach the layers of RO4003 to each other. The size of the unit cell is 24 mm $\times$ 24 mm.

In the proposed unit cell, a 180° phase shift is obtained by changing the feed point of the U-shaped resonator on the receiver side of the transmitarray, [6]. The state when the resonators at the receiving and transmitting sides are connected at the same end is referenced as the 0° state, because the currents flowing in the patches are codirectional. In the 180° state, when the resonators at the receiving and transmitting sides are connected at the opposite ends, the surface currents flow in the opposite directions. The full-wave

Fig. 2. Dual polarized 1-bit unit cell: (a) the unit-cell structure with the via connections corresponding to the 180° state and (b) simulated scattering parameters of unit cell for two orthogonal polarizations and the phase states of 0° and 180°. In (b), the solid and dashed curves for the magnitude correspond to the 0° and 180° phase states, respectively, whereas the solid and dashed curves for the differential phase correspond to the vertical and horizontal polarizations.

Fig. 3. Measured scattering parameters of the dual polarized 1-bit unit cell for the vertical polarization (solid lines of the magnitude correspond to 0° and the dashed lines to 180° phase states, respectively).

electromagnetic simulation (CST Microwave Studio) results for the unit cell with the Floquet periodic boundary conditions (FPBC's) are shown in Fig. 2(b). The dual polarized unit cell provides a 180° differential phase shift with the phase error less than $\pm 3^\circ$ for both polarizations in a frequency band 5.6 - 5.86 GHz (2.8 %).

To confirm the simulation results, the dual polarized unit cell prototype was fabricated and measured in a rectangular waveguide. The unit cell phase switching was verified by measuring two samples of stand-alone unit cells whose topologies differed by the excitation feed point of the U-shaped resonators. The simulation results are in a good agreement with the measurements, see Fig. 3. The experimental results exhibit a higher insertion loss due to unaccounted attenuation in the coaxial-waveguide junction, which was measured separately and amounted to about 1 dB. The transmission and reflection coefficients are very similar in both states with the minimum insertion loss being 1.7 dB and 1.9 dB for the phase states 180° and 0°, respectively. The passband at 10 dB return loss is 160 MHz. The phase error does not exceed $\pm 6^\circ$ for both polarizations within the operating bandwidth.

C. Tiled Transmitarray Design

The array of the unit cells mounted in the plastic holder, designed to provide half a wavelength spacing of the unit cells, was simulated using the CST Microwave Studio model with FPBC's, see Fig. 4. The frame dielectric was set as acrylonitrile butadiene styrene (ABS) with $\epsilon_r = 2.3$ and $\tan\delta = 0.0025$. The unit cell size was varied, while keeping the array period fixed. The differential phase error in Fig. 4 degrades considerably as the frame width increases, which can be attributed to the effect of the gaps in the ground plane.

A set of 120 topologically similar unit cells was fabricated, having the feeding loops arranged for either 0° or 180° phase states. The frame with 0.5 mm spacers was 3D-printed from the commercial ABS material. The unit cells were mounted in a plastic frame according to the specific phase modulation pattern across the transmitarray.

The array feed was designed as a linear-polarized slot-fed rectangular patch antenna with the simulated gain of 6-dBi at

Fig. 4. The effect of the frame spacer width on the differential phase shift of a unit cell.

5.8 GHz and a half-power beamwidth of 90° and it was fabricated in the multi-layer PCB technology. Fig. 5 shows the comparison of the simulated (CST MWS) and measured characteristics of the feeding antenna. It appears that the measured sample demonstrates about 1 dB gain reduction and a small shift of the operating bandwidth, which may have effect on the transmitarray bandwidth.

III. TRANSMITARRAY MEASUREMENTS

In order to demonstrate the beam-steering capabilities of the transmitarray, a 10×10 -unit cell transmitarray fed by the linearly-polarized printed patch antenna. The array was assembled manually using the pre-fabricated 0° and 180° unit cells by arranging them within the ABS frame in the prescribed phase distribution pattern to steer the beam in a given direction. The patch antenna feed was positioned at a distance of 2λ corresponding to the optimal efficiency and approximately equal to the focal length of the array. The antenna measurements were carried out in the far-field anechoic chamber using the transmitarray as the receive antenna and a standard dual-polarization horn as the transmit antenna. The measured H-plane radiation patterns for four beam scan angles (0°, 15°, 30° and 45°) at 5.75 GHz are shown in Fig. 6. The corresponding phase distributions obtained using (3) are shown in the insets. The measured results agree with full wave electromagnetic simulations (CST MWS). The measured gain at the broadside is 1.5 dB lower than expected from the simulations, which can be attributed to the gain loss of the feed antenna, see Fig. 6. A gain loss of

Fig. 5 Side view of the tiled transmitarray antenna in the anechoic chamber.

Fig. 6 Simulated and measured radiation patterns of the tiled 1-bit transmitarray for several scan angles: (a) $\theta_0 = 0^\circ$, (b) $\theta_0 = 15^\circ$, (c) $\theta_0 = 30^\circ$, (d) $\theta_0 = 45^\circ$ at $f = 5.75\text{GHz}$.

about 4 dB has been measured between the broadside and 45° patterns at 5.75 GHz. The symmetrical phase pattern at the broadside features significantly stronger back radiation in the experiment, as compared to the electromagnetic simulations.

The above results confirm the feasibility of tiled transmitarray architecture. More results concerning the aperture efficiency, operating bandwidth and circuit analysis will be reported in a future publication.

IV. CONCLUSIONS

An original structure of the tiled dual-polarized transmitarray has been presented. The 1-bit beam steering has been demonstrated with simulations and measurements. It has been shown that the proposed structure can achieve better than 15 dBi gain and lower than 7 dB sidelobe level for the scan angles up to 45° within the 2.5% operating bandwidth. The proposed structure can be easily scaled for higher frequency bands and represents a cost-efficient and flexible solution for a range application, including 5G small-cell networks and as an educational platform for the antennas and communication courses.

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REFERENCES

- [1] A. H. Naqvi and S. Lim, "Review of recent phased arrays for millimeter-wave wireless communication," *Sensors*, vol. 18, 3194; pp. 1-31, 2018.
- [2] M. H. Dahri, et al., "A review of high gain and high efficiency reflectarrays for 5G communications," *IEEE Access*, vol. 6, pp. 5973-5985, 2018.
- [3] A. Abdelrahman, et al., *Analysis and Design of Transmitarray Antennas*, ser. Synthesis Lectures on Antennas. Morgan&Claypool, 2017.
- [4] H. Kaouach, L. Dussopt, R. Sauleau, et al., "Design and demonstration of 1-bit and 2-bit transmit-arrays at X-band frequencies," *PIERS Online*, vol. 5, no. 8, pp. 731-736, 2009.
- [5] J. Y. Lau and S. V. Hum, "Reconfigurable transmitarray design approaches for beamforming applications," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5679-5689, Dec. 2012.
- [6] I. Munina, P. Turalchuk, A. Verevkin, V. Kirillov, D. Zelenchuk, A. Shitvov, "A Study of C-band 1-bit reconfigurable dual-polarized transmitarray," in *Proc. Europ. Conf. Antennas Propag.*, 2019, pp. 1-4. (accepted)
- [7] F. Diaby, et al., "Design of a 2-bit unit-cell for electronically reconfigurable transmitarrays at Ka-band," in *Proc. Europ. Radar Conf.*, 11-13 Oct 2017, Nuremberg, Germany, pp. 473-476.
- [8] A. Shitvov, et al., "Phase interpolation Fourier transform beamforming for spatial division applications," *IET Microw. Antennas Propag.*, vol. 13, no. 1, pp. 9-15, 2018.
- [9] J. S. Row, "Design of square-ring microstrip antenna for circular polarization," *Electron. Lett.*, vol. 40, no. 2, Jan. 2004.
- [10] D. M. Pozar and B. Kauffman, "Increasing the bandwidth of a microstrip antenna by proximity coupling," *Electron. Lett.*, vol. 23, no. 8, pp. 368-369, 1987.