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A Low Profile Highly Isolated Phased Array MIMO Antenna System for 5G Applications at 28 GHz

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Abstract—This paper presents a highly isolated phased array antenna system for 5G applications at 28 GHz. The antenna array is formed by 1x8 microstrip antipodal exponential tapered slot antennas each connected to CMOS phase shifters with wire bonds for electrical beam steering. At 28 GHz, the mutual coupling between the antenna elements are lower than -30 dB while the envelope correlation between the ports is less than 0.1. The single antenna array element was fabricated on 20 mil thick Rogers 4003 substrate and the phase shifter was fabricated in 22 nm FD-SOI CMOS. The simulated and measured results of the single antenna element along with the integrated phase shifter are presented together with the simulation results of the overall system.

Index Terms—5G, antennas, CMOS, electromagnetics, integrated circuits, millimeter wave, mutual coupling, phase shifter, phased arrays, silicon-on-insulator(SOI).

I. INTRODUCTION

Utilizing millimeter wave (mmWave) frequency bands for 5G promises higher data rate, reduced latency and higher capability [1]. At mmWave, the individual antenna size can be reduced and thus a large number of antennas can be integrated in a small area, in contrast with the systems that are operating at the sub 6 GHz frequency bands. With the increased number of antennas and combining with multiple-input multiple-output (MIMO) beamforming techniques, narrow beams can be formed to point to user directions objectively, that can reduce channel interference and improve power efficiency. However, this advantage comes with a new challenge: decreasing the distance between the antennas will result in increased mutual coupling between the adjacent antenna elements. Many efforts have been devoted on reducing the mutual coupling in phased arrays antenna systems [2]–[4].

The main focus of this paper is to propose a low profile, highly isolated phased array system that can be deployed in the front-end of 5G mmWave beamforming transceivers in massive MIMO systems at 28 GHz. The proposed design consists of 1x8 antipodal exponential tapered slot antenna array in which each antenna element is fed by 4-bit switched-filter phase shifter to introduce electrical beam steering capability to the design. The antenna array is fabricated on 20 mil thick Rogers 4003 substrate whereas the phase shifter is designed with GlobalFoundries 22FDX process. The designed array and phase shifter are integrated using wire bonds. The array system offers lower than -25 dB mutual coupling between the antenna elements between 1 GHz to 30 GHz. In the same bandwidth, the envelope correlation coefficient is less than 0.1 while the apparent diversity gain is close to 10 dB.

II. UNIT ANTENNA ELEMENT DESIGN

The antenna array consists of antipodal exponential tapered slot antennas which are designed on a 20 mil thick Rogers 4003 substrate ($\epsilon_r = 3.55$ $\tan\delta = 0.0027$ @10 GHz). The unit element of the array has a similar structure with the one presented in [5]. As it is shown in Fig. 1(a), the selected structure has exponential tapered wings on both sides of the substrate which in return offers wide return loss characteristic. Antenna is fed with a microstrip transmission line whose width is 1 mm which corresponds to approximately 50 Ω characteristic impedance at 28 GHz. The length of the transmission line is set 3.38 mm longer than the antenna elements of the designed array as shown in Fig. 6(a), in order to use Southwest connector for the measurement. Fig. 1(a) presents the the dimensions of the designed single antenna element.

The unit element was fabricated with standard PCB process. However, the final cutting was performed manually in the lab. This leads to different copper-free area at the top of the antenna wings, labeled as “d” in Fig. 1(a), in different antenna samples. During the design procedure, “d” is set to zero.

Fig. 2 provides the measurement and simulation S-parameter results of a unit antenna element for different “d” dimensions. As it is shown in Fig. 2, discrepancies between the simulation and measurement results decreases with the increase in dimension “d”. These results show that the discrepancies between the simulation and measurement results can be reduced with a sensitive fabrication. At 28 GHz, measured return loss is approximately 10 dB which corresponds to 90% power transmission.

Fig. 3 illustrates the normalized radiation pattern of the unit

Fig. 1. (a) Schematic view and (b) fabricated picture of the unit element.

Fig. 2. Comparison of the simulated and measured S_{11} of the unit element.

Fig. 3. Normalized E-plane ($\phi = 0^\circ$) radiation patterns of the unit antenna element at 28 GHz.

antenna element at 28 GHz. The gain of the unit element is approximately 1.4 dBi.

III. CMOS PHASE SHIFTER

In this phased array antenna system, each of the antenna elements is fed with a CMOS phase shifter which provides 22.5° phase resolution. The designed phase shifter is a 4-bit, switched-filter phase shifter and it was fabricated in GlobalFoundries 22FDX process. The micrograph of the chip is shown in Fig. 4. For all 16 states of the phase shifter, S-

Fig. 4. Chip micrograph of the fabricated 4-bit switched-filter phase shifter.

(a)

(b)

Fig. 5. Measured (a) phase difference and (b) percentage phase error for all 16 states of the phase shifter.

parameters were measured with Cascade Microtech Summit 9000 Analytical Probe Station and MPI T40A GSG-100 wafer probes connected to Agilent E8361A PNA directly. On-wafer calibration was done with AC-2 calibration substrate.

At 28 GHz, the measured RMS phase error is 3.45° with insertion loss 13.5 ± 2.5 dB, including GSG pads, and return loss is lower than 7 dB. Furthermore, Fig. 5 illustrates the phase difference and percentage phase error for all of the states. As it can be seen in Fig. 5(b), State 8 has the maximum percentage phase error at 28 GHz which increases the RMS phase error of the phase shifter. Nevertheless, the designed phase shifter offers percentage phase error lower than 15% for all states between 26 GHz and 30 GHz.

IV. ANTENNA ARRAY DESIGN

Based on the fabricated single antenna element mentioned in Section II, a 1×8 antenna array is designed with $0.54 \times \lambda_0$ spacing between the antennas. The antenna spacing is optimised for minimum side lobe level (SLL) at E-plane. For further decreasing the SLL and increasing the gain of the antenna, half-circular shapes can be cut off from each side of the antenna similar to the one presented in [6]. Fig. 6(a)

Fig. 6. Schematic representation of (a) the 1×8 antenna array and (b) the cross section of the proposed system.

shows the schematic of the array. Because of the fact that the proposed array is in one dimension, radiation performance is improved in only one plane. As Fig. 7 points out, the beam width decreased significantly in E-plane while there is no obvious change in H-plane.

Fig. 6(b) illustrates a section from the proposed phased array system where each antenna element is fed with a phase shifter. The connection between the unit elements and the phase shifters are established with wire bonds. When there is no phase difference, the main beam angle, θ_M , equals to zero. In order to reduce SLL, the progressive phase shift values are limited between $\pm 112.5^\circ$. With this configuration θ_M can be shifted up to $\pm 15^\circ$ with 1° resolution. Furthermore, as Fig. 8 indicates, active S-parameters of each antenna element is lower than -10 dB for both broadside, $\theta_M = 0^\circ$, and maximum angle steering, $\theta_M = 15^\circ$, radiation cases.

Fig. 7. Normalized E-plane ($\phi = 0^\circ$) radiation patterns for broadside radiation ($\theta_M = 0^\circ$) and for maximum angle steering ($\theta_M = 15^\circ$) cases at 28 GHz.

Fig. 8. Active S-parameters (a) for broadside ($\theta_M = 0^\circ$) and (b) maximum angle steering ($\theta_M = 15^\circ$) radiation cases.

Reduced mutual coupling is one of the advantages of the proposed design. This high isolation between the array elements has been achieved by optimising the distance between

Fig. 9. Mutual coupling between the antenna elements.

Fig. 10. Calculated envelope correlation coefficient and apparent diversity gain of the proposed design.

the array elements and fine tuning the various design parameters related to each antenna element based on the simulations carried out using Ansys High Frequency Structure Simulator (HFSS). As shown in Fig. 9, mutual coupling between the antennas are lower than -30 dB at 28 GHz. Between 1 GHz and 30 GHz, the proposed system offers lower than -25 dB mutual coupling. Again at 28 GHz, the efficiency of the array for the broadside radiation is about 96% and the gain is 6.99 dBi.

In order to visualise the diversity performance of the proposed design, envelope correlation coefficient (ρ_e) and apparent diversity gain (G_{app}) are calculated. For the calculation of ρ_e , the S-parameter approach presented in [7] is adopted. As the results presented in Fig. 10 indicate, ρ_e is less than 0.1 while G_{app} is almost 10 dB in a very large bandwidth.

V. CONCLUSION

This paper presents a 1×8 low profile, highly isolated phased array system for 5G mmWave beam forming transceivers in massive MIMO systems. The unit elements of the array are antipodal exponential tapered slot antennas which are fed by 4-bit switched-filter phase shifters. The mutual coupling between the antenna elements are lower than -30 dB at 28 GHz while the efficiency of the array for the broadside radiation is about 96% and the gain is 6.99 dBi. Furthermore, lower than -25 dB mutual coupling and envelope correlation coefficient less than 0.1 can be achieved between 1 GHz to 30 GHz. The active S-parameters of each element is lower than -10 dB for both broadside and maximum main beam steering case. The unit antenna element and the phase shifter were fabricated with standard PCB process and GlobalFoundries 22FDX process respectively. The integration of the array elements with the CMOS phase shifters will be carried out and the overall performance will be presented at the conference.

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