A 4 by 10 Series 60 GHz Microstrip Array Antenna Fed by Butler Matrix for 5G Applications

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***Abstract*—This paper presents a low-cost, beam-steerable 4×10 antenna array system operating at 60 GHz. The proposed antenna system is fed by a 4×10 Butler Matrix network designed using microstrip line (ML) structure. Chebyshev tapered microstrip antenna arrays with 10 series-fed elements are connected to four output ports of the feed network. Four steerable beams with maximum 16.5 dBi system gain and 1GHz bandwidth(BW) satisfy the requirements of millimeter wave propagation study and handset application for 5G communication.**

***Keywords*—5G, antenna array, Butler Matrix, Beam Steering, mmWave**

I. Introduction and Related Work

In the next decade, the demand on wireless communication traffic is expected to expand by a hundred times or more. This growing demand exceeds the channel capacities of 4G and LTE (Long Term Evolution) [1]. Therefore, researchers are turning to use higher frequencies with available unlicensed, large bandwidth and smaller antenna aperture size. They are also exploring the use of new technologies such as high gain antenna arrays, beam-forming algorithms, Massive MIMO, etc. in order to overcome high propagation attenuation rate in mmWave bands. Due to the complexity of 5G communication system and different propagation characteristics compared to lower frequencies, researchers need a low cost but high-gain and steerable antenna system prototype with moderate performance in order to study new challenges [2]. This paper addresses this requirement by proposing a microstrip line (ML) structure on RO4003C™ substrate based on an economical Printed Circuit Board (PCB) process in order to reduce prototyping cost. The small formfactor make it possible to fit this antenna system on a mobile device.

The use of both a series microstrip antenna array and Butler Matrix for mmWave communication has been investigated intensively recently. Some papers discussed only the antenna array design, the work in [3] introduced a 77 GHz 4×9 microstrip antenna array and [4] designed an 8×8 series patch phased array. The former antenna array does not have the beam-steering capability, while the latter phased arrays require 8 transceivers in order to perform Beamforming. The work in [5] focused on the feed network by designing an Substrate Integrated Waveguide (SIW) 4×4 Butler Matrix systematically. Other papers [6], [7] discussed the design of a Butler Matrix for a feed network integrated with either patch or slot antenna arrays. However, because of the limited number of array elements, the overall gain is below 15 dBi.

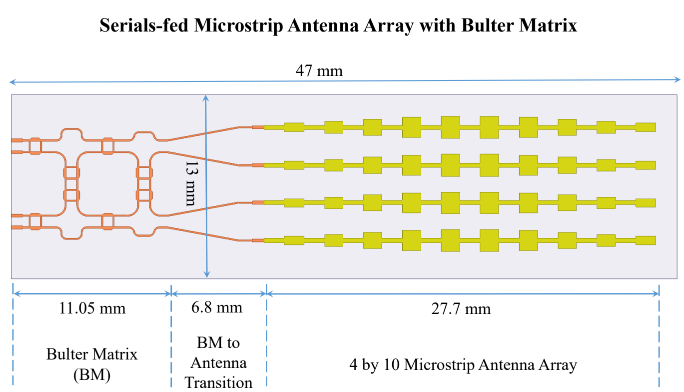

Fig. 1. Outline dimensions of the proposed antenna system

The contribution of this paper is a low-cost but high-gain microstrip antenna array system shown in Figure 1 fed by Butler Matrix network. Here are some key aspects of the new design:

- The whole design is based on low-cost 2-layer PCB process without any vias. Single Pull Double Through (SPDT) switches or Single Pull Four Through (SP4T) switches can be easily integrated on the same substrate. End-launch 1.85 mm RF connectors can also be applied for the interconnection with transceivers.
- Butler Matrix enables four configurations of output phase increment, therefore the whole system is capable of steering its beam with Half Power Beam Width

(HPBW) of about 25° covering from $-50°$ to $+50°$ in four steps(Figure 9).

- A Chebyshev tapered series-fed antenna with 10 elements was designed to limit the level of side lobes and resulted in a gain that is greater than 20 dBi for the 4×10 antenna array only.

The rest of the paper is organized as below: Section II shows the 4×4 Butler Matrix design. Section III describes the antenna modelling and the performance of the series patch antenna arrays. Section IV demonstrates the results of the antenna array system integrated with Butler Matrix. Section V concludes this work.

II. 4×4 Butler Matrix Design

A Butler Matrix is a beam-forming network composed of 90° hybrids, cross-overs, and phase shifters. By selecting different input ports, the phase increment between the outputs has N different configurations depending on which input ports are used, where N is size of the matrix.

There are two commonly used structures: one is based on ML and the other uses SIW structure. Unlike with SIW, designing ML Butler Matrix can avoid the use of vias, reducing manufacturing cost significantly. However, ML can bring 1.5-2.5 dB more insertion loss than SIW transmission. Another drawback is that a ML Butler Matrix is narrow band, while its SIW counterpart is broadband. Compromise must be made, considering the advantages of cost, simplicity, sufficient bandwidth and moderate performance. We decided to use ML Structure based on this criteria. RO4003C™ substrate was selected for cost consideration although RO5880 has lower dielectric loss and smaller dielectric constant. Thickness of the substrate was also important. One reason is that ML built on thick substrates tends to be too wide compared to wavelength in the mmWave band. The other reason is that unexpected surface waves can be generated in thick substrates. On the other hand, thin substrate will reduce the bandwidth and mechanical strength. Therefore, we chose 0.2 mm thickness RO4003C™ material.

A. 90° Hybrid Coupler and Cross-over

One of the most critical components of Butler Matrix is the 90° hybrid coupler. At 60 GHz, we are not able to use a Z_o = 50 Ω impedance system as it necessitates a ML of around 0.45 mm width which is too wide compared to a quarter wavelength (which is about 0.78 mm). Alternatively, we used 100 Ω for Z_o similar the work in [7]. Quarter wavelength transformers are then applied in order to match the 100 Ω Z_o to 50 Ω 1.85 mm connectors and antenna arrays. Consequently, we set the width of the pair of the quarter wavelength Z_o MLs to 0.1 mm, and their lengths to 0.8 mm, while for the other pair of $Z_o/\sqrt{2}$ MLs, we set their widths to 0.22 mm and their lengths to 0.82 mm.

A Cross-over is composed of two 90° hybrid couplers in series. The bends connecting the outputs of the couplers and the inputs of cross-overs must be carefully designed at such high frequency in order to reduce radiation loss and to match it to Z_o.

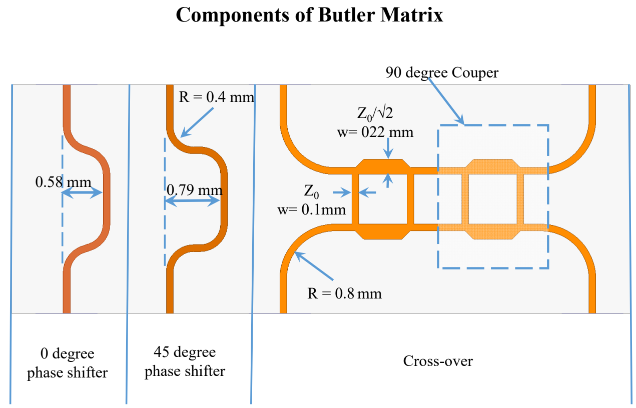

Fig. 2. Critical Dimensions of Butler Matrix Components

B. Phase Shifter

Two pair of phase shifters are required in a 4×4 Butler Matrix Network. One pair has two 45° shifters, and the other pair has 0° phase shifters in reference to a cross-over. The curved bends of phase shifters also needs to be well designed to avoid impedance mismatch.

Figure 2 shows the critical dimensions of 90° couplers, phase shifters, and cross-overs.

C. Performance

Because of the symmetry of the structures, it is sufficient to validate the performance by considering only the input signal from Port 1 and Port 2. Figure 3 shows phase increments generated by the Butler Matrix. We can see from the plots that while using Port 1 as input, the phase difference between adjacent ports was $-45°$. Using Port 2 as input resulted in $+135°$ phase difference. For Port 3 and Port 4, the phase difference was $-135°$, and $+45°$ respectively. The simulated maximum phase increment unbalance is $\pm 8°$ within the 1GHz BW.

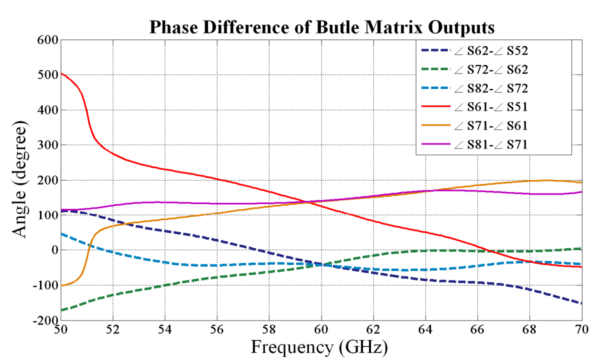

Fig. 3. Simulated BM phase increments v.s frequency. Maximum phase unbalance is less than $\pm 7°$

Figure 4 shows that the maximum output magnitude unbalance was less than ± 1.2 dB. Further the overall insertion Loss of the matrix is less than -4 dB. Figure 5 also demonstrates great return loss and isolation at all ports.

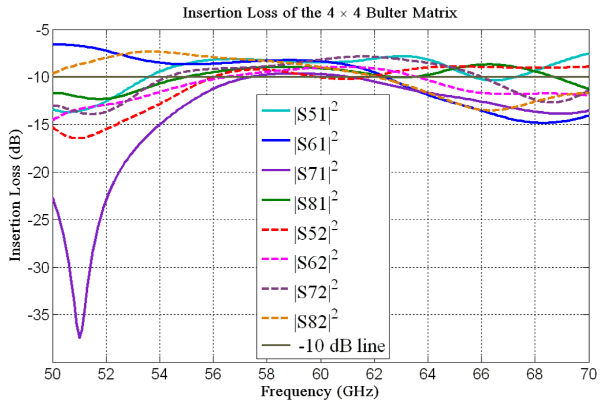

Fig. 4. Simulated maximum output magnitude unbalance is less than ±1.2 dB

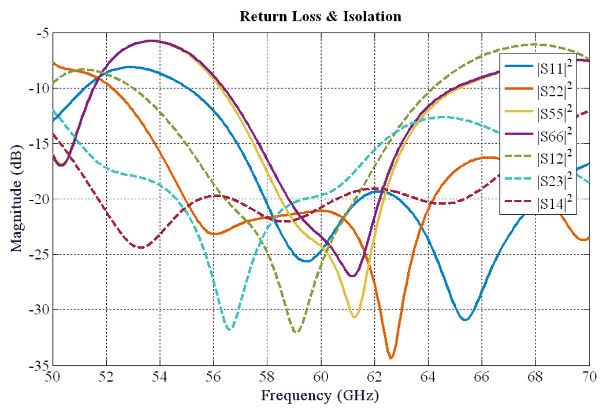

Fig. 5. Simulated return loss and port isolation of Butler Matrix

III. SERIES MICROSTRIP ANTENNA ARRAY

Series-fed microstrip antennas are commonly used due to its neat feed line compared with complex parallel-fed networks. One design is fed from the center of the array [8], with another one using different termination element for 50 Ω matching [4]. The center-fed design needed to consider 180° phase difference for two parts of the array; while the patch elements of the latter design can't be tapered to compress side lobes. Our work takes advantage of the loss of a transmission line, using edge-fed half-wavelength patches and half-wavelength MLs, to implement 50 Ω match. After connecting the first element to the other 9 half-wavelength patches and 9 half-wavelength MLs, the whole structure stays resonant at 60 GHz, but the resonant impedance reduces from 300 Ω, with only one element, to 50 Ω with 10 elements as the return loss plot shows in Figure 7. Then, the widths of each patch are tapered using Chebyshev polynomials for equal sidelobe level in magnitude. The tapering ratio is 1: 0.91 : 0.74 : 0.54 : 0.38 from the center patch to edge to ensure that the side-lobe level is 20 dB lower than the main beam in E plane. We used 1.3 mm for the length of patch elements, 0.1 mm shorter than half-wavelength due to the fringing fields near the edge of each patch, we also used approximately half-wavelength (1.45 mm) long, 0.3 mm wide MLs to connect patches together. The distance between adjacent patch elements is 2.75 mm, which is about 0.55 wavelength in the air. The figure6 shows the dimensions of a single row antenna array. The 1×10 series-fed microstrip antenna array can achieve 14.7 dBi gain with 87% radiation efficiency, as demonstrated in Figure 8.

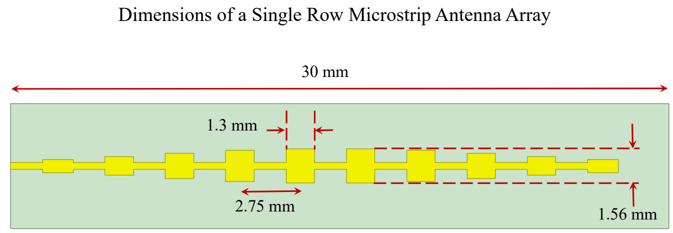

Fig. 6. A 1×10 series-fed microstrip antenna array is composed of tapered half-wavelength patches and half-wavelength ML that connect the patches

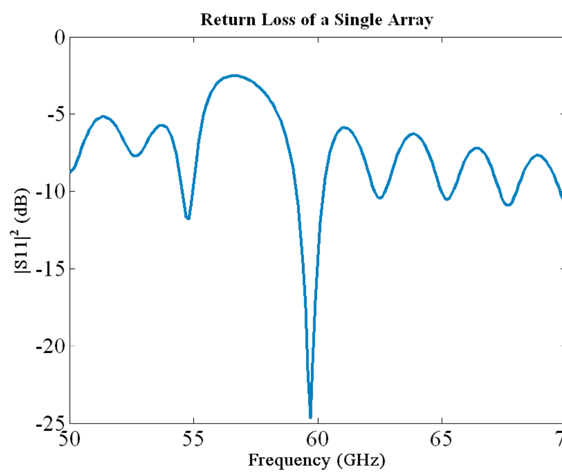

Fig. 7. Return Loss of a Single 1×10 patch array shows the -10dB BW of the antenna array is 1GHz

IV. ANTENNA SYSTEM PERFORMANCE

As a final step, four of the 1×10 antenna arrays were placed side by side with a distance of 2.67 mm, for the purpose of simplifying the design of connection MLs between Butler Matrix and antenna arrays. The outline dimensions were 47×13 mm as shown in figure 1 which is compact enough for potential cell phone integration. As shown in figure 10, after connecting the designed antenna to the Butler Matrix, the return loss of the antenna system is below -18 dB in the desired band; and the port isolation remains at a good value below -15 dB. The system BW is restricted by two factors: one was the phase increment of the Butler Matrix; the other was the 1 GHz BW of single row antenna arrays. The source editor tool provided by Ansys HFSS (High Frequency Structure

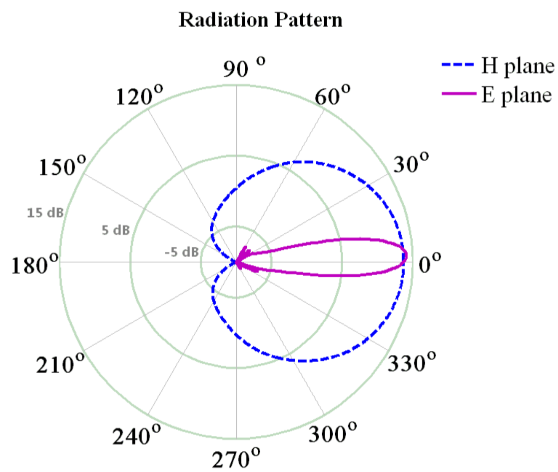

Fig. 8. Gain of a Single 1 × 10 patch array

Simulator) was used to calculate the radiation patterns for each port excitation as shown in figure 9. The plots showed that the 4dB BW of the two central patterns and 3dB BW of the side beams are all around 25°, therefore the antenna system has 100° coverage in H plane. The antenna system efficiency was calculated to be higher than 60% achieving 16.5 dBi system gain.

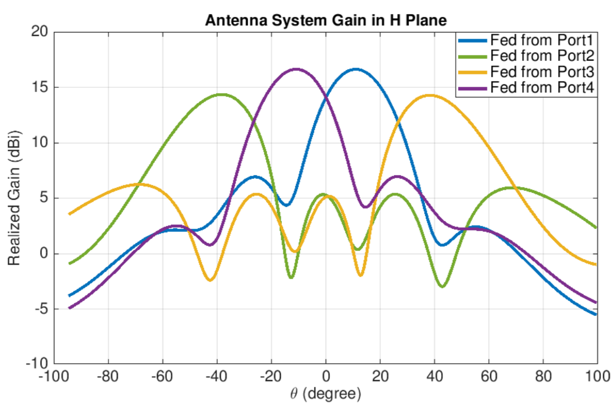

Fig. 9. Realized Gain of Antenna System

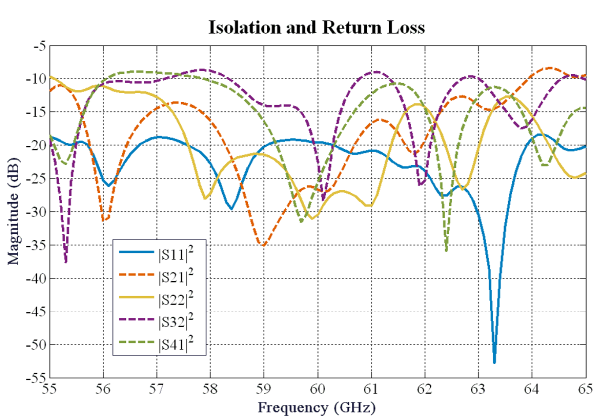

Fig. 10. Simulated port isolation and return loss of proposed antenna system

V. Conclusion

This paper presented the design of planar 60 GHz-antenna arrays consisting of series-fed microstrip patch rows. The patch rows were arranged in parallel and were connected with a 4 × 4 Butler Matrix network. A low-cost ML structure was built on RO4003C™ material. The design started with simulations of each critical components, such as 90° couplers, phase shifters, and single row antenna array. Then a study of the overall integrated system has been presented. Despite the fact that we used a substrate that is not ideal for mmWave antennas, this work still shows great performance in terms of phase/magnitude unbalance of BM and maximum 16.5dB realized system gain.

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