Miniaturized Butler Matrix and Tunable Phase Shifters for 5G and Beyond

MULTIPLE-in–multiple-out (MIMO) technique is one of the critical techniques for 5G and beyond. For supporting the beamforming configurations of 5G and beyond massive phased arrays are usually required, which has led to the extensive investigation on phased arrays. A phased array involves the manipulation of the progressive phase difference between individual antenna elements to obtain array patterns radiating in the desired direction for high-data-rate requirements, while beamsteering is to extend the spatial coverages.

The phase manipulation can be achieved with either the use of phase shifters or through beamforming networks, such as Butler matrices. The beamforming systems are strongly dependent on the operating frequencies. With some modifications to the hybrid couplers in Butler matrices, a relatively flat phase difference response between the output ports can be achieved across a wide bandwidth and the integration of phase shifters with Butler matrices achieves the continuous beamsteering [item 1) in the Appendix].

Normally, Butlers have been realized using either by hollow waveguides that perform well up to terahertz frequencies but have the disadvantage of having a relatively large physical size or by planar structures such as microstrip lines with a relatively small form factor but have a tendency to suffer from significant radiation loss at higher frequencies. It is desirable to compromise between the small form factor and the lower losses.

The article published in this issue [item 1) in the Appendix] by Der *et al.* proposed the application of ridged half-mode substrate integrated waveguide (RHMSIW) for the implementation of Butler matrices, and through the transverse resonance technique, it can be shown that half-mode substrate integrated waveguides (HMSIWs) can be further miniaturized by the introduction of a capacitive ridge. The result is a miniaturization of up to 70% or more in comparison to full-mode substrate integrated waveguide (SIW). The channel width of an SIW and HMSIW is approximately $\lambda/2$ and $\lambda/4$, respectively, whereas RHMSIW can achieve less than $\lambda/6$ with less radiation loss in comparison to HMSIW.

The total effective area that the proposed Butler matrix design occupies, excluding the coaxial interconnects and microstrip transitions, is $11.43\lambda^2$. The proposed Butler matrix yields an average insertion loss of 2.2 dB and has a maximum phase error of $\pm 22^\circ$ over a 5% bandwidth centered at 3.51 GHz.

Since early publish in IEEE Xplore, the article [item 1) in the Appendix] has drawn much attention and got the highest numbers of "**Full Text Views**" in IEEE Xplore among all the articles presented in this issue. The article [item 1) in the Appendix] demonstrates that the performance can be improved further and can even be scaled up for operation at the 5G millimeter wavebands. RHMSIW technology has been shown to be a promising solution for implementing miniaturized beamforming devices at sub-6-GHz 5G bands and shows potential for expansion into the millimeter-wave domain.

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Appendix
Related Work

1) E. T. Der, T. R. Jones, and M. Daneshmand, "Miniaturized 4 × 4 butler matrix and tunable phase shifter using ridged half-mode substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 8, pp. 3379-3388, Aug. 2020.

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