DESIGN A V-BAND 4×4 BUTLER MATRIX FOR SWITCHED BEAM-FORMING OPERATION
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ABSTRACT: A compact V-band 4x4 Butler matrix, using 0.35 µm SiGe bipolar process, is proposed in this work. This design exhibits an average insertion loss of 3 dB with amplitude variation less than 1.5 dB and an average phase imbalance of less than 10 degrees from 55 GHz to 65 GHz. The chip area is only 0.5x0.9 mm² including all pads. The SiGe Butler matrix is an excellent candidate for MIMO systems and applied in high data-rate communications.

KEY WORDS: Butler matrix, beam-forming, SiGe

INTRODUCTION: The millimetre-wave band, especially the unlicensed spectrum at the 60 GHz carrier frequency, provides the ability to support high-rate wireless communication application. Compared with microwave band communication, the amount of available bandwidth at 60 GHz is plentiful [1] (frequencies of 57–64 GHz are available in North America and Korea, 59–66 GHz in Europe and Japan). However, 60 GHz systems exhibit several challenges that have made them difficult to deploy for general use. A major one in the implementation is high path loss, which implies a need for high-gain beam-forming antennas.

To be commercially viable, a number of electronically scanning antennas have been proposed to improve the system signal-to-noise ratio and enhance the communication quality, including switched beam arrays [2-4]. It employs switched-beam antenna with the Butler matrix network and have multiple input/output ports, each corresponding to a different beam direction. By judging power levels of detected EM waves, the main beam of the radiation pattern of the antenna can point to the optimal direction, and then build up the communication link.

As shown in Fig. 1 [5], when different input ports are excited, the Butler matrix is treated as a beam forming network to provide four output signals with equal power levels and the progressive phases of +45, -45, +135 and -135, respectively. Hence, one can switch the
direction of the radiation main beam by exciting the designated input port. In this letter, a compact 60-GHz 4x4 Butler matrix, using 0.35 µm SiGe bipolar process, is proposed. This design exhibits an average insertion loss of 3 dB with amplitude variation less than 1.5 dB and an average phase imbalance of less than 10 degrees from 55 GHz to 65 GHz. The chip area is only 0.5x0.9 mm$^2$ including all pads.

**COUPLER DESIGN:** Usually the 3-dB 90 degrees coupler is generally designed with branch-line coupler, based on quarter-wavelength transmission line or lumped component. However, such a design suffers either large chip size or high process tolerance/parasitic effect on component fabrication at high frequency. For example, $1/4\lambda$ length equals 0.5 mm at 60 GHz with the Si process used here. As a consequence, a transformer coupler is used to solve this problem [5]. It is implemented with a pair of mutual-coupling transmission line in broadside coupling configuration using the SiGe multi-metal layer structure. Figure 2 shows a layout example, where the first winding starting from Port 1 is placed on the thicker Metal-4 layer (2.8 µm thickness) and then is routed down on the Metal-3 (1.5 µm thickness) to Port-3. At the same time, the second winding starting from Port-2 is placed on the Metal-3 layer and then is raised up on Metal-4 to port-4. These windings are completely overlapped and the ground plane beneath the stacked windings is taken away to acquire a high coupling value. Thus only 250 um winding length is needed, which is approximately equal to $1/10\lambda$.

![Transformer Coupler](image)

Fig. 2 Transformer Coupler

Fig. 3 shows the EM simulated results of the proposed transformer coupler. The insertion loss is 3.5 ± 0.5 dB and the output phase difference is 90° ± 0.5° in 55-65 GHz. The return loss and isolation are greater than -23 dB. These results demonstrate the excellent quadrature coupling performance.
**MEASUREMENTS:** The S-parameters of the proposed butler matrix was measured with excitation at port-1, output at port-3 and all the other input ports pending and output ports terminated with 50 ohm. The measured insertion loss and phase shift are shown in Fig. 5. Ideally, the signal incident from one of input ports is distributed to all the four output ports with equal amplitude, resulting in a theoretical 6-dB insertion loss. However, due to the conduction and substrate losses, fabrication and simulation tolerance, an extra insertion loss of 3 dB is measured and the amplitude imbalance is around 1.5 dB at 60 GHz. The ideal relative phase between adjacent output ports is -45°, -135°, +135° and +45° respectively. The measured phase error is about 8° at 60 GHz. We think this imbalance error mainly come from the interfering from the pending ports and the insertion loss of the crossover.

When the measured amplitude and phase characteristics of the proposed Butler matrix are substituted into a linear 1×4 phase array with 1/2λ antenna spacing for array factor calculation [6], the results are shown in Fig. 4, which give around 10GHz bandwidth from 55-65GHz.
CONCLUSION: A 60 GHz 4-way Butler matrix in 0.35μm SiGe technology is presented in this work. A miniature passive Butler matrix with 0.5x0.9 mm² chip area is obtained and demonstrates the broadband potential from 55 to 65 GHz.

REFERENCE