A Switched Beam Antenna Array with Butler Matrix Network using Substrate Integrated Waveguide Technology for 60 GHz Radio

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Abstract **—** A switched beam antenna array based on substrate integrated waveguide (SIW) technology is designed and simulated for 60 GHz communications. The antenna array is fed by 4x4 planar butler matrix network in order to achieve the switched beam characteristic. Each of the components is designed and verified through simulations in electromagnetic field simulation tools, CST MWS and HFSS. The components are integrated later to form the switched beam antenna array. The return losses and isolations are better than 10 dB from 57 GHz to 64 GHz for all of the input ports. The peak gain for the switched beam antenna array is 18 dBi at 60 GHz.

Index Terms **—** Beamforming, butler matrix, electro-magnetic simulation, millimeter wave, slot antenna, substrate integrated waveguide, switched beam antenna.

I. INTRODUCTION

These days the availability of high bandwidth at 60 GHz band is a highly attractive option for high speed wireless communications allowing transfer of uncompressed data, voice and video at the speed of gigabit per second [1]. At millimeter wave frequency band the losses in the planar microstrip circuit is high. Therefore this requires more efficient technology like the substrate integrated waveguide (SIW) to be used, which provides advantages of the traditional rectangular waveguide such as low loss, high quality factor, complete shielding and capability of handling high power along with the combined advantage of planar circuit designs [2]. Analysis of SIW structures is presented and compared with HFSS simulation results in [3]. SIW structures have proved to be a good choice for the construction of millimeter wave beamforming networks and multi-beam antennas, which includes techniques like SIW based Butler matrix, Blass matrix, Rotman lens etc. As compared to Blass and Nolen matrix, the Butler matrix requires the least number of couplers [4]. Butler matrix has been widely used in radar, warfare and satellite applications. As the length of the crossover is small for 60 GHz it becomes difficult to design the phase shifter which fits that size using straight delay lines in the butler matrix. One option is to use a curved delay line. In this work, a new design approach is used in designing the switched beam antenna. Here, the SIW based 4x4 planar butler matrix consisting of curved phase shifters and constructed using circular vias is integrated with the SIW slot antenna array constructed using rectangular vias to form the switched beam antenna for 60 GHz communications. The switched beam antenna array structure is designed on a Rogers RT/Duroid 5880 substrate with a dielectric constant of 2.2, thickness of 0.254 mm and loss tangent of 0.0009 at 10 GHz. It is designed, simulated and verified utilizing the electromagnetic field simulation tools, CST MWS and HFSS.

II. DESIGN OF BUTLER MATRIX

Butler matrix is one of the most popular multiple beamforming network. The 4x4 butler matrix design has four input ports and four output ports. Exciting each input port provides a different output beam as the relative phases across the output ports change. The general block diagram of 4x4 butler matrix is shown in Fig. 1. The 4x4 butler matrix has four 3 dB 90° hybrid couplers, two crossovers and phase shifters.

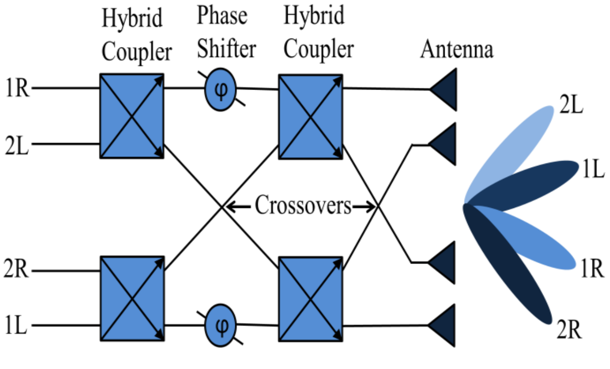

Fig. 1. Butler matrix block diagram with antenna array.

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A. 3 dB 90° hybrid coupler and crossover

The diagram of the 3 dB hybrid coupler is shown in Fig. 2 where, Lc = 2.862 mm and Wc= 4.745 mm. The SIW designs are based on equations in [2] with diameter of vias as 0.2 mm and pitch as 0.35 mm. Figure 3 shows the magnitude and phase of the coupler. From Fig. 3 it is observed that the return loss and isolation are better than 10 dB from 57 GHz to 64 GHz. Also, S21 and S31 are almost equal in magnitude. Further, from Fig. 3 it is also observed that S21 and S31 have phase difference of almost 90° throughout the entire 60 GHz band. The simulation results from both HFSS and CST are observed to be similar. The schematic of crossover is also shown in Fig. 2 where, Lc = 6.012 mm and Wc = 4.745 mm. Figure 4 shows the magnitude and phase of the crossover. From Fig. 4 it is observed that S11, S21 and S41 are below -10 dB. Both HFSS and CST simulation results are observed to be similar.

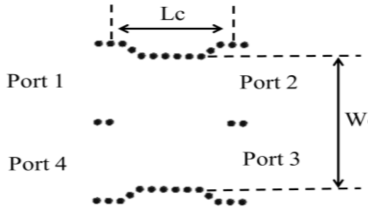


Fig. 2. Schematic of coupler and crossover.

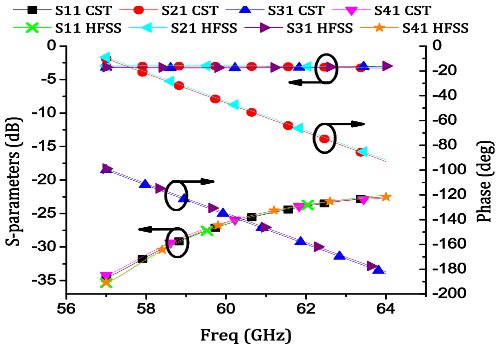


Fig. 3. S-parameters and phase of hybrid coupler.

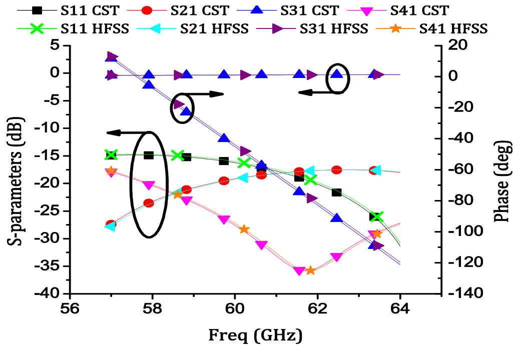
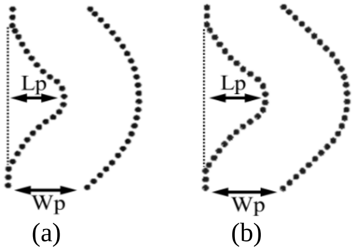


Fig. 4. S-parameters and phase of crossover.

B. Phase shifters

The phase shift is obtained in this design using curved transmission line as it is not possible to achieve the required phase shift of 0° and 45° using straight transmission line. Figure 5 (a) and Fig. 5 (b) show the 0° and 45° phase shifters respectively.



(a) (b)

Fig. 5. Phase shifters: (a) 0° and (b) 45°.

In Fig. 5, Lp = 2.019 mm and Wp = 2.81 mm for 0° phase shifter. For 45° phase shifter Lp = 2.281 mm and Wp = 2.835 mm. The magnitude and phase of the 0° and 45° phase shifter is shown in Fig. 6. From Fig. 6 it is observed that the return loss for both phase shifters is better than 10 dB for the entire 60 GHz band. Also, from Fig. 6 it is observed that the phase difference between the phase shifters is 45° at 60 GHz. The simulation results from HFSS and CST agree well with each other.

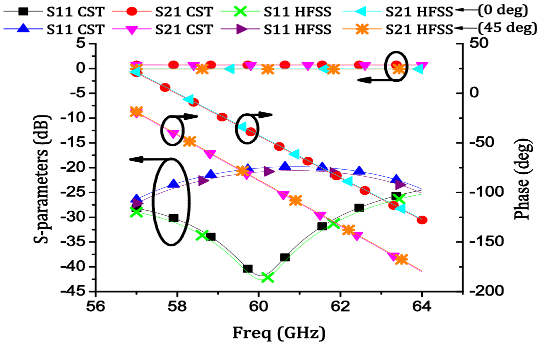


Fig. 6. Magnitude and phase of 0° and 45° phase shifters.

C. Butler matrix

The butler matrix is designed by integrating the components designed above. The performance of the butler matrix is verified through simulation in CST MWS and HFSS. Fig. 7 shows the designed butler matrix. Figure 8 shows the magnitude at the ports of the butler matrix when port 1 is excited, and Fig. 9 shows the relative phases at the output ports when port 1 is excited. Similarly, Fig. 10 shows the magnitude at the ports when port 2 is excited and Fig. 11 shows the relative phases at the output ports when port 2 is excited.

From Fig. 8 it is observed that when port 1 is excited, the return loss is better than 10 dB for the entire band from 57 GHz to 64 GHz. The magnitudes of output at port 5, 6, 7 and 8 are also observed to be in acceptable range. Further, from Fig. 9 it is observed that the relative phase differences between the output ports are around -45°, -90° and -135° for ports 6, 7 and 8 with respect to port 5 when port 1 is excited.

From Fig. 10 it is observed that when port 2 is excited, the return loss is better than 13 dB for the entire band from 57 GHz to 64 GHz. Further, it is observed that the magnitudes of output at port 5, 6, 7 and 8 are also within the acceptable range. Similarly, from Fig. 11 it is observed that the phase differences between the output ports are around 135°, -90° and 45° for ports 6, 7 and 8 with respect to port 5. Also, the simulation results of CST MWS and HFSS are observed to be similar.

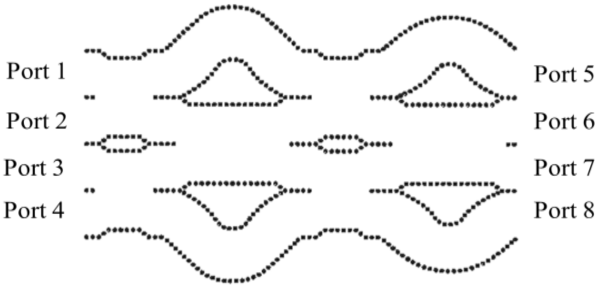


Fig. 7. SIW butler matrix structure.

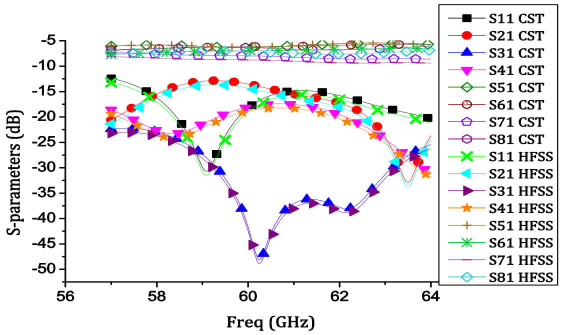


Fig. 8. S-parameters of butler-matrix when port 1 is excited.

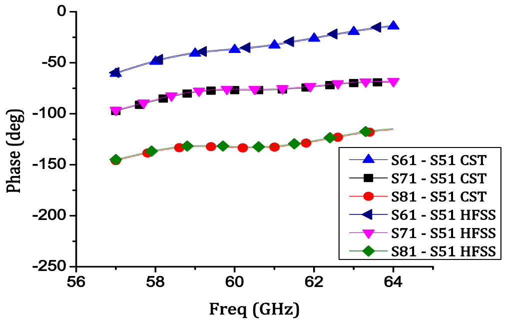


Fig. 9. Butler matrix output phase with port 1 excited.

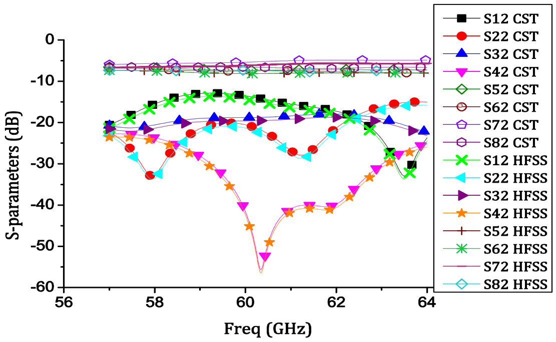


Fig. 10. Butler matrix S-parameters with port 2 excited.

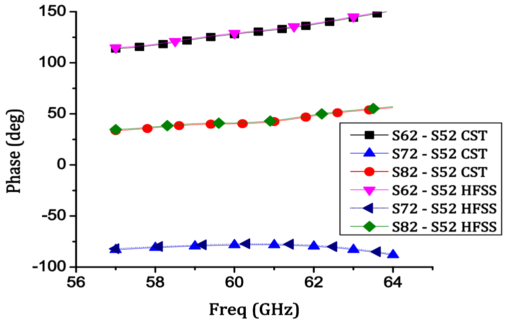


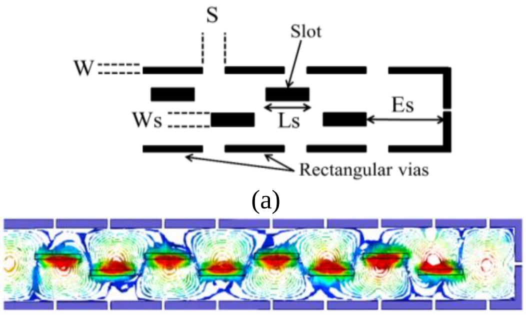
Fig. 11. Butler matrix output phase with port 2 excited.

III. SWITCHED BEAM SLOT ANTENNA

The waveguide longitude slot antennas are popular for beam steering applications. The diagram of slot antenna is shown in Fig. 12 (a) and Fig. 12 (b) shows the E-field in it. In Fig. 12 (a), S = 0.15 mm, W= 0.3 mm, Ws = 0.198 mm, Ls = 1.789 mm, Es = 2.1 mm and slots displacement from the center is 0.17 mm. The antenna is designed as per the design equations mentioned in [5] using SIW technology with rectangular shaped vias which act as the side wall of the waveguide.

The theoretical values are used in the design of the antenna slots and further the design is optimized through CST MWS and verified through HFSS simulations. Figure 13 shows the radiation pattern of the single antenna. The E-plane and H-plane radiation patterns are shown in the figure. It is observed that the gain is 13 dBi. Figure 14 shows the design of the complete switched beam slot antenna array.

The radiation pattern of the switched beam antenna array is shown in Fig. 15. The gain is observed to be 17 dBi when port 2 or port 3 is excited. However, the gain is observed to be 18 dBi when port 1 or port 4 is excited. Further, it is observed that the main beam is directed towards +15° and -15° when port 1 and port 4 is excited respectively. It shifts to -39° and +39° when port 2 and port 3 is excited respectively. It is observed that the simulation results from CST MWS and HFSS agree well with each other.



(a)

(b)

Fig. 12. Slot antenna: (a) schematic and (b) E-field distribution.

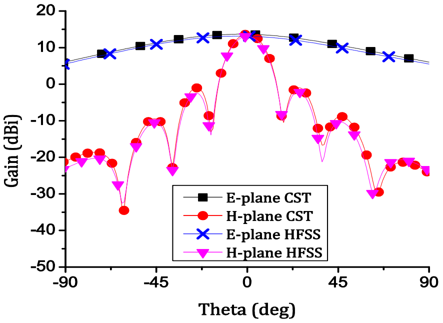


Fig. 13. Radiation pattern of slot antenna.

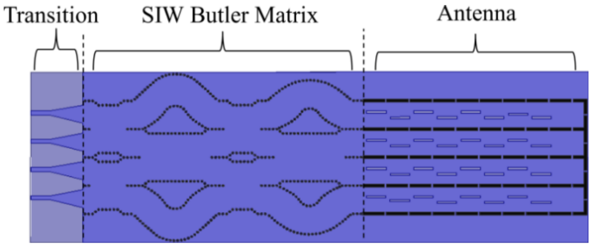


Fig. 14. Switched beam slot antenna array.

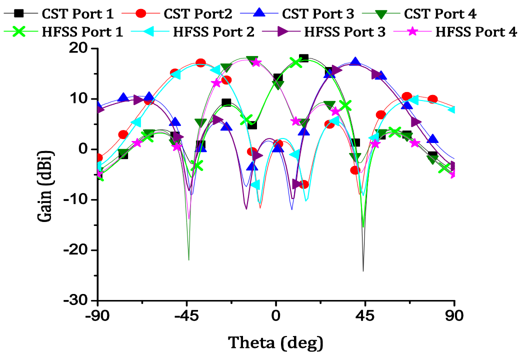


Fig. 15. Radiation patterns when different ports are excited.

IV. CONCLUSION

In this communication, a planar 60 GHz switched beam antenna array has been designed and simulated. The designed switched beam antenna demonstrates a good performance as a candidate for beam steering and for systems on substrate applications.

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