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A High Purity Fused Silica (HPFS) Glass Substrate based 77 GHz 4 × 4 Butler Matrix for Automotive Radars

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Abstract

- The design of a 77 GHz 4 × 4 Butler matrix on a High Purity Fused Silica (HPFS) glass substrate for automotive radar applications has been presented.
- The design and 3D Finite Element Method (FEM) simulation of the 4 × 4 Butler matrix beamformer has been conducted using an industry-standard CAD tool Advanced Design System (ADS) from Keysight™ Technologies.
- The 4 × 4 Butler matrix having a footprint area of 9.5 mm × 8.3 mm with 0.8-micrometer copper cladding thickness has been designed using a 0.2 mm thick HPFS glass as the microstrip dielectric substrate.
- The simulated insertion loss is –8 ± 2 dB.
- The return loss and isolation of the input ports are both below –20 dB respectively.
- This 4 × 4 Butler matrix can generate beam patterns at an elevation angle of –42°, –15°, 0°, 15°, and 42° when a corresponding port is excited.
- The maximum and minimum isotropic main lobe gain achieved are 20.322 dB and 16.763 dB, respectively.
- These characteristics make the designed Butler matrix suitable for automotive radar applications, such as Adaptive Cruise Control (ACC), Collision Mitigation (CM), blind-spot detection, vehicle tracking, and pre-crash warning system.

Butler Matrix Beamformer: Operation and Advantages

- The Butler Matrix is a passive network which is employed in beamforming and scanning networks for linear and circular antenna arrays.
- It has N input ports (beam ports) and N output ports, where $N = 2^n$ and n is a positive non-zero integer.
- It has $\frac{N}{2}\log_2 N$ 90° hybrid couplers, where $N = 2^n$.
- Reciprocal and passive networks.
- Compact design.
- The schematic of the Butler Matrix is identical with the programming structure for the Fast Fourier Transform.
- Equal distribution of power at the output ports.
- Equal phase difference between the adjacent output ports.

4 × 4 Butler Matrix Beamformer Architecture

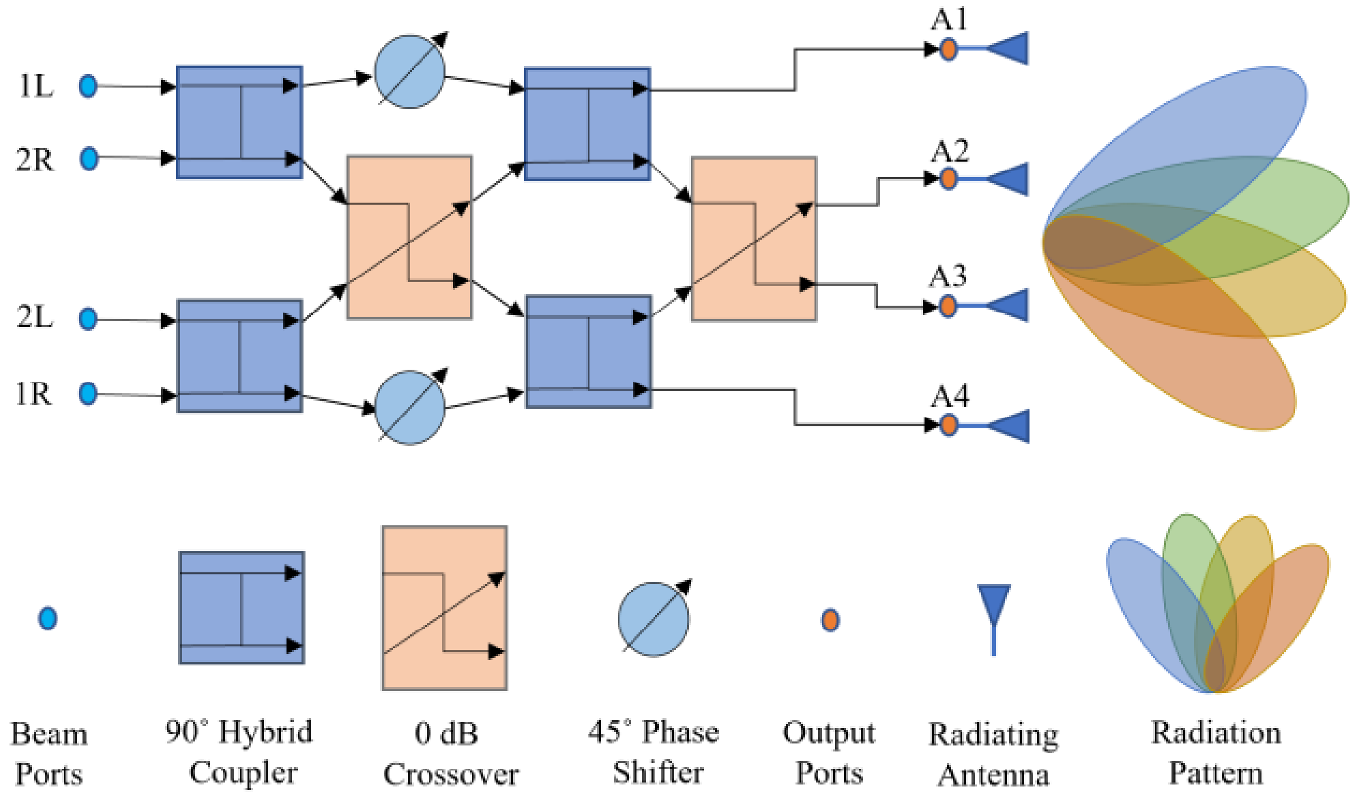

Figure 1. Block diagram of 4 × 4 Butler Matrix Beamformer

- It has four input ports and four output ports.
- It consists of building blocks –
  - Four 90° hybrid couplers
  - Two 0 dB crossovers
  - Two 45° phase shifters

Phase Distribution in a 4 × 4 Butler Matrix

Table 1. Phase distribution in 4 × 4 Butler Matrix.

	Beam Ports			
Output ports	1L	2R	2L	1R
A1	–45	–135	–90	–180
A2	–90	0/360	–225/135	–135
A3	–135	–225/135	0/360	–90
A4	–180	–90	–135	–45
Phase difference (Δϕ)	45	–135	135	–45
Beam angle (θ)	–14.47	48.6	–48.6	14.47

* All values are in degrees

- When beam ports 1L, 2R, 2L and 1R are excited individually, the phase of signals output ports A1, A2, A3 and A4 are received as per given in table 1.
- The equations to find Δϕ and θ are given as follows –

$$\Delta\phi = \pm \frac{2q-1}{N} \times 180^\circ$$

Where, Δϕ is phase difference, q=1,2..p+1. p=2, N=4 for 4×4 Butler matrix.

$$\sin\theta = \frac{\lambda}{180^\circ} \times \Delta\phi$$

Where, θ is elevation angle.

Microstrip Line Theory

- Low cost.
- Low weight and volume.
- Complete circuit on a substrate.
- Suitable for insertion of MIC (Microwave Integrated Circuits).

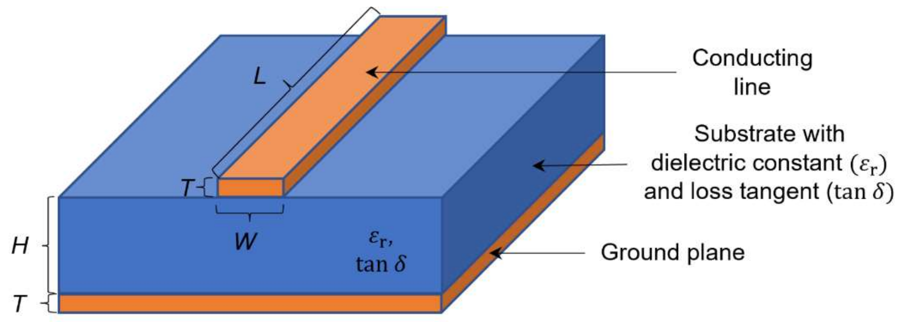

Fig 2. Microstrip line geometry.

1. $$\frac{W}{H} \approx \begin{cases} \dfrac{8e^A}{e^{2A}-2} & \dfrac{W}{H} \le 2 \\ \dfrac{2}{\pi}\left\{B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right]\right\} & \dfrac{W}{H} > 2 \end{cases}$$

2. $$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left[0.23 + \frac{0.11}{\varepsilon_r}\right];$$
$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}};$$

3. $$\varepsilon_{eff} = \begin{cases} \dfrac{\varepsilon_r + 1}{2} + \dfrac{\varepsilon_r - 1}{2}\left[\left(1 + 12\dfrac{H}{W}\right)^{-\frac{1}{2}} + 0.04\left(1 - \dfrac{W}{H}\right)^2\right] & \dfrac{W}{H} \le 1 \\ \dfrac{\varepsilon_r + 1}{2} + \dfrac{\varepsilon_r - 1}{2}\left[\left(1 + 12\dfrac{H}{W}\right)^{-\frac{1}{2}}\right] & \dfrac{W}{H} \ge 1 \end{cases}$$

4. $$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}};$$

5. $$\frac{t}{H} \le 0.005$$

HPFS Glass Substrate Advantages and Specifications

HPFS glass substrate possess the following advantages which makes it suitable for its use in 77 GHz frequency radar applications -

- ✓ Stable dielectric constant and loss tangent for wide range of frequencies.
- ✓ Superior dimensional stability and high reliability.
- ✓ High electrical insulation.
- ✓ Low coefficient of thermal expansion.
- ✓ Low thickness.
- ✓ Low surface roughness.
- ✓ In this research, HPFS glass substrate from Corning™ has been used.

Table 2. Specifications of HPFS glass substrate.

Property	Value
Density	2.2 g/cm^3
Young's modulus	73 GPa
Thermal conductivity	1.38 W/m.K
Coefficient of linear expansion	0.57×10^{-6}/°C
Dielectric constant (ε_r)	3.82
Dissipation factor (tan δ)	0.0005
Thickness of substrate (H)	0.2 mm
Roughness	≤ 10 Å

Design and Performance of a 90˚ Hybrid Coupler

- The 90˚ hybrid coupler is a four-port directional coupler which is used to divide the input power equally at respective output ports and provide 90˚ phase difference across the output ports.

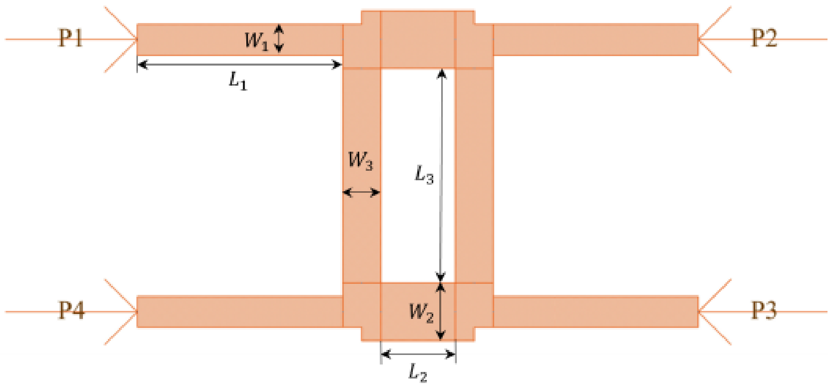

Fig 3. Layout of microstrip 90˚ hybrid coupler.

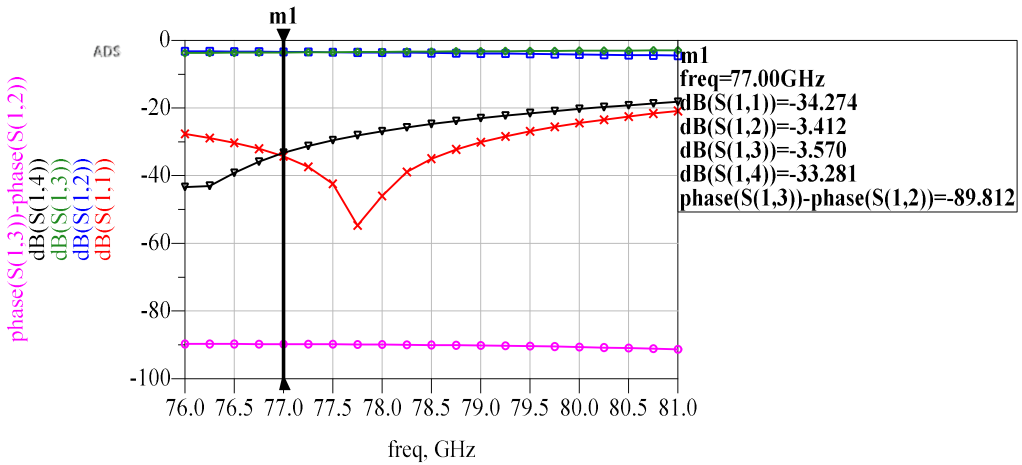

Fig 4. Performance of microstrip 90˚ hybrid coupler.

Table 3. 90˚ hybrid coupler dimensions.

Parameter	W_1	L_1	W_2	L_2	W_3	L_3
Values(mm)	0.118	0.779	0.145	0.816	0.22	0.28

Design and Performance of a Crossover

- A crossover is also a directional coupler used to spatially switch a signal in a planar geometry without any coupling.

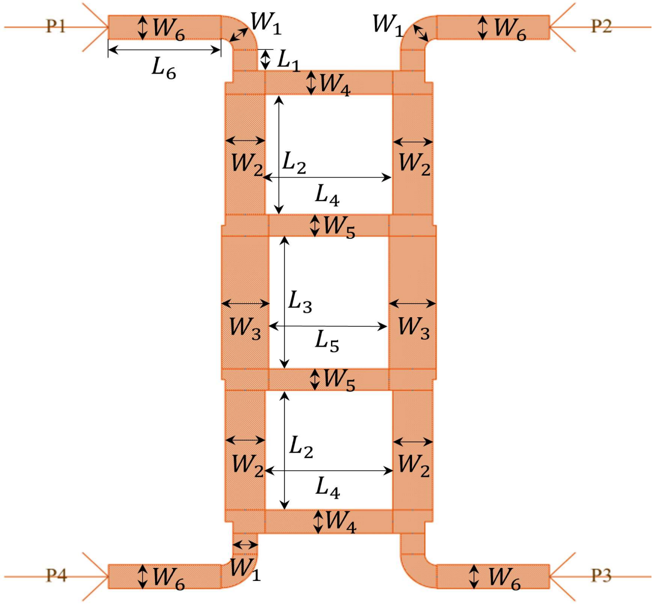

Fig 5. Layout of microstrip crossover.

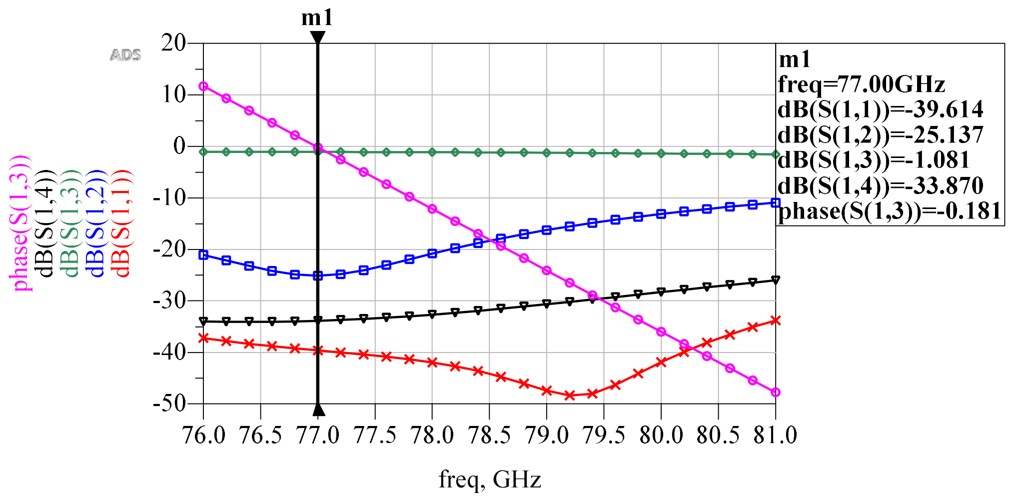

Fig 6. Simulation result of microstrip crossover in ADS

Table 4. Crossover dimensions.

Parameter	W_1	L_1	W_2	L_2	W_3	L_3	W_4	L_4	W_5	L_5	W_6	L_6
Values(mm)	0.116	0.107	0.192	0.618	0.226	0.686	0.12	0.616	0.11	0.582	0.122	0.547

Design and Performance of a 45° Phase Shifter in ADS

- The implemented phase shifter is a microstrip transmission line that is used to adjust the phases of the output signals of the various components in the Butler matrix.

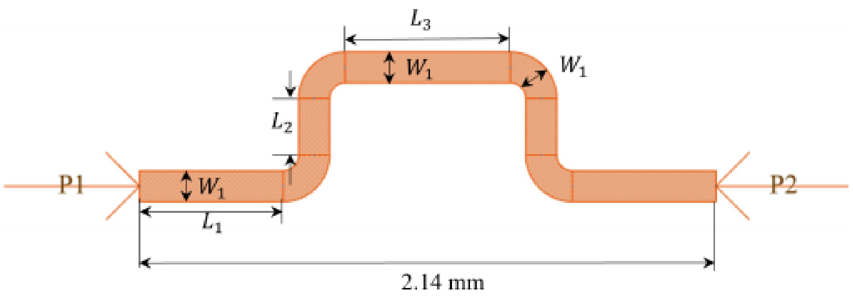

Fig 7. Layout of microstrip 45° phase shifter

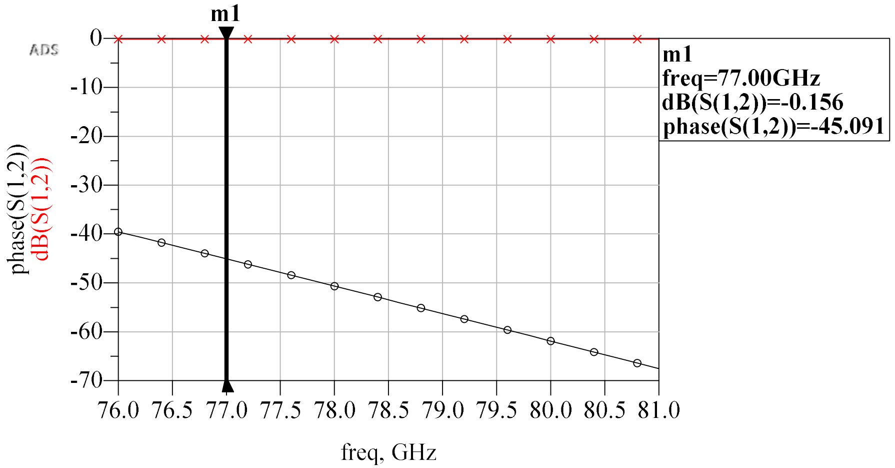

Fig 8. Simulation result of microstrip 45° phase shifter in ADS.

Table 5. 45° phase shifter dimensions.

Parameter	W_1	L_1	L_2	L_3
Values(mm)	0.118	0.532	0.136	0.616

Design of 4 × 4 Butler Matrix in ADS

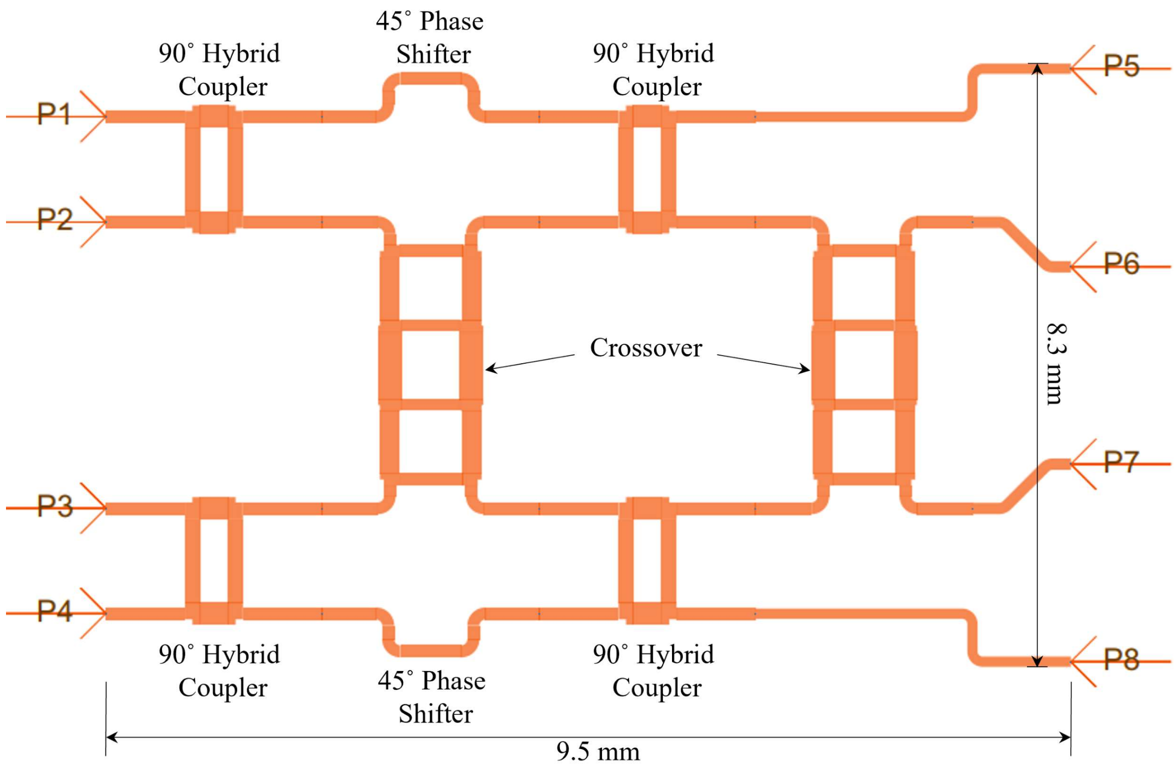

Fig 9. Layout of microstrip 4 × 4 Butler Matrix in ADS.

- After successfully optimizing the designs of 90° hybrid coupler, crossover, and 45° phase shifter, the components were then integrated as per the block diagram shown in Figure 1 to realize the complete 4 × 4 Butler matrix.
- The beam ports 1L, 2R, 2L, and 1R are the same as P1, P2, P3, and P4 respectively.
- The total footprint area of the completed 4 × 4 Butler matrix is 9.5 mm × 8.3 mm.

Performance of 4 × 4 Butler Matrix

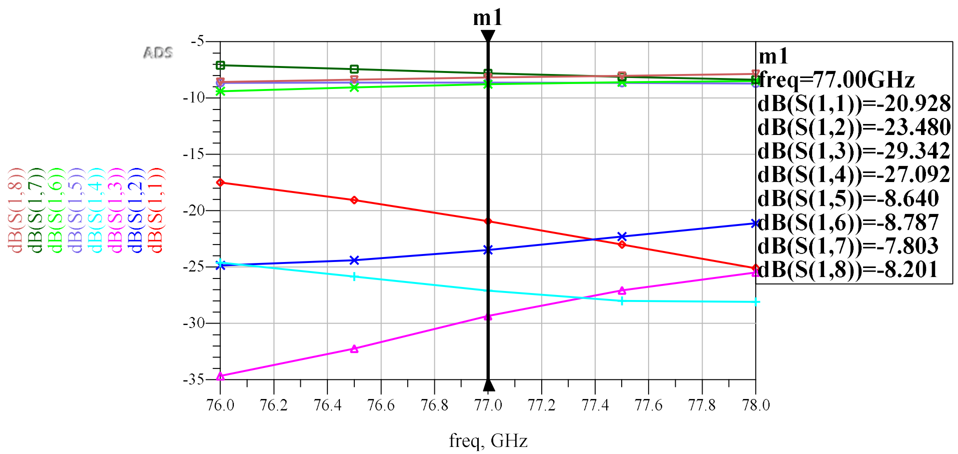

Fig 10. Simulation result of microstrip 4 × 4 Butler Matrix when Port 1 is excited.

- The insertion loss between port 1 or 4 and ports 5, 6, 7, and 8 are between –7.5 dB and –8.8 dB.
- The return losses at respective ports are below -20 dB.
- The isolation between adjacent ports is below -20 dB.

- The insertion loss between port 2 or 3 and ports 5, 6, 7, and 8 are between –7.4 dB and –10 dB.
- The return losses at respective ports are below -20 dB.
- The isolation between adjacent ports is below -20 dB.

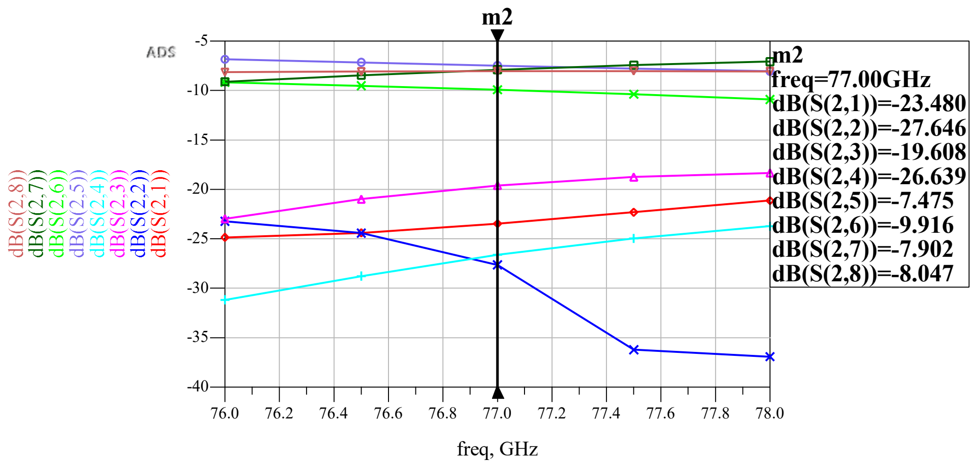

Fig 11. Simulation result of a microstrip 4 × 4 Butler Matrix when Port 2 is excited.

Design of 4 × 4 Butler Matrix with microstrip antenna array of four elements

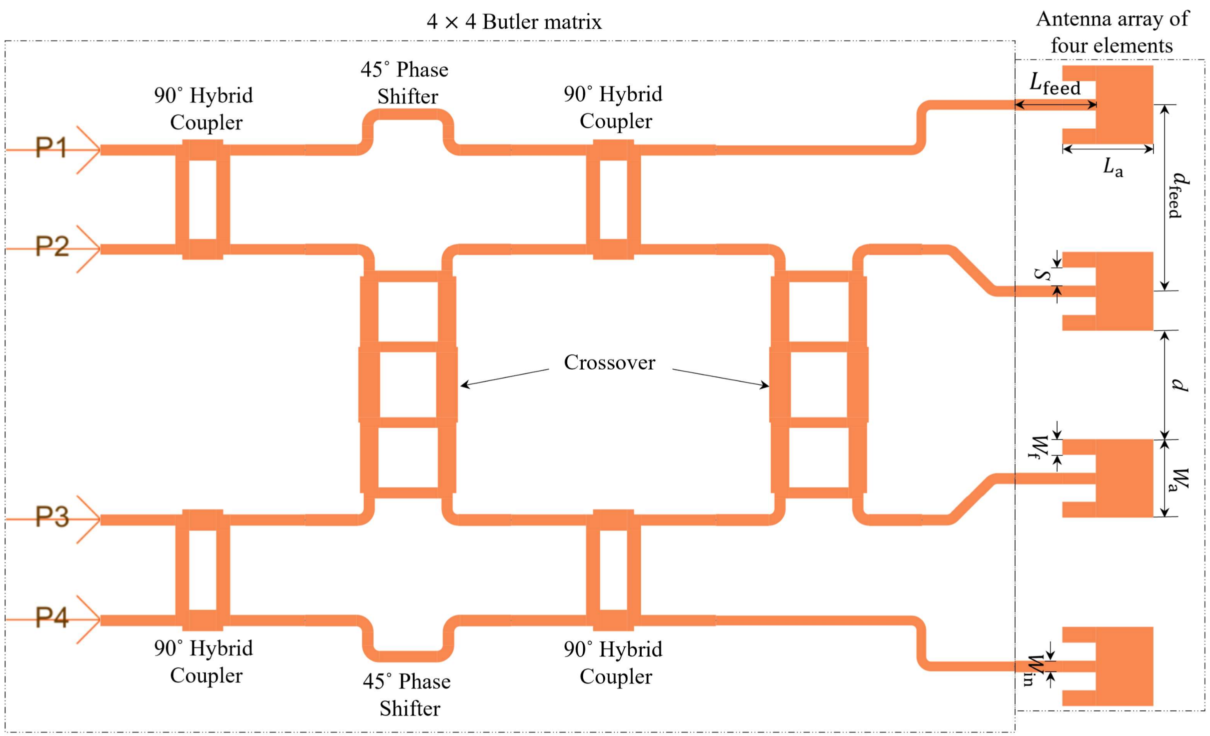

Fig 12. Layout of microstrip 4 × 4 Butler Matrix with microstrip antenna array of four elements in ADS.

Table 5. Microstrip inset fed antenna dimensions.

Parameter	d_{feed}	d	L_{feed}	L_a
Values(mm)	1.945	1.126	0.843	0.945
Parameter	**S**	**W_a**	**W_f**	**W_{in}**
Values(mm)	0.187	0.819	0.163	0.118

Beamforming by designed 4 × 4 Butler Matrix

- When input ports 1, 2, 3, and 4 are excited individually, the beam patterns are observed at θ = –15˚, 42˚, –42˚,and 15˚ respectively for azimuth angle (φ) = 90˚
- The beam angle phase error is ±7˚ from the expected beam angle phase.

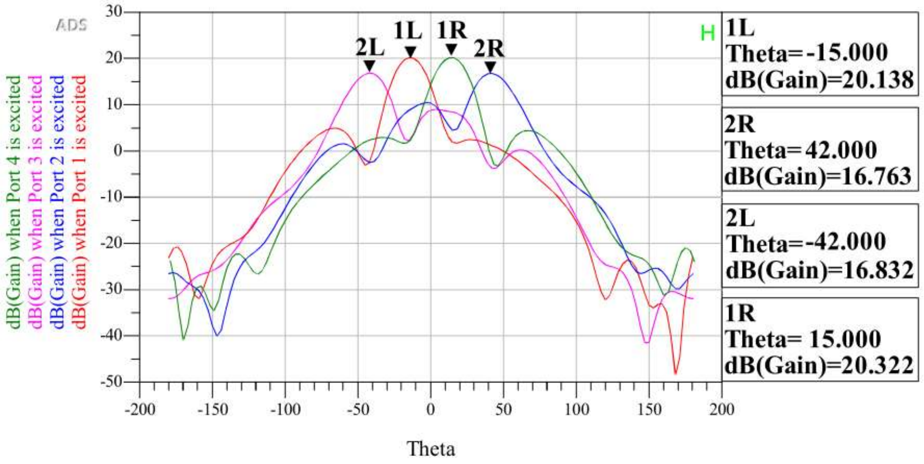

Fig 13. Rectangular plot of beamforming by the designed 4 × 4 Butler Matrix.

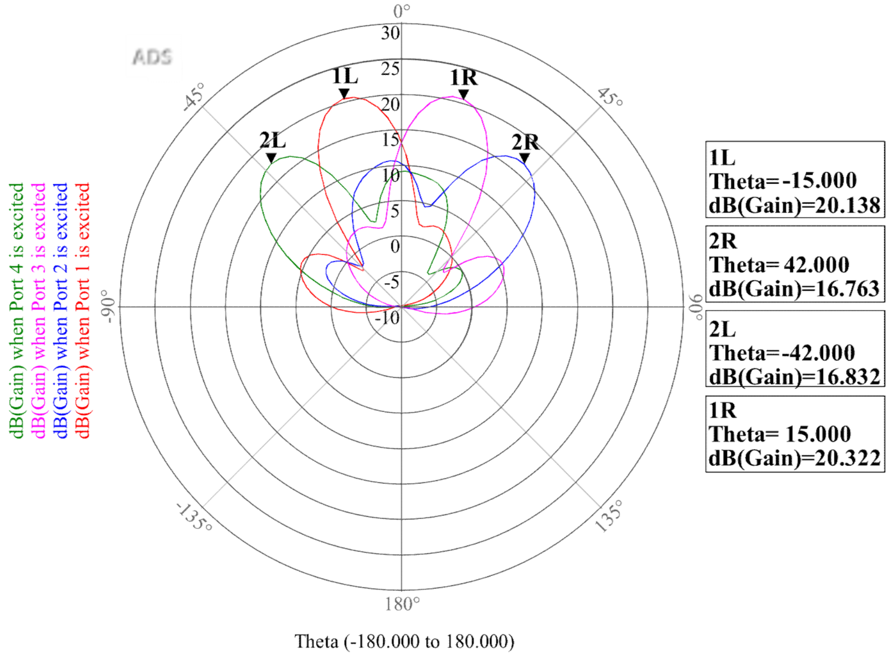

Fig 14. Polar plot of beamforming by the designed 4 × 4 Butler Matrix.

Beamforming by designed 4 × 4 Butler Matrix

- When all input ports 1, 2, 3, and 4 are excited together, the beam pattern is observed at $\theta = 0^{\circ}$ respectively for azimuth angle $(\varphi) = 90^{\circ}$
- The respective gain of the main lobe is 17.357 dB. The difference between main lobe level and side lobe levels is significantly more than 11 dB.

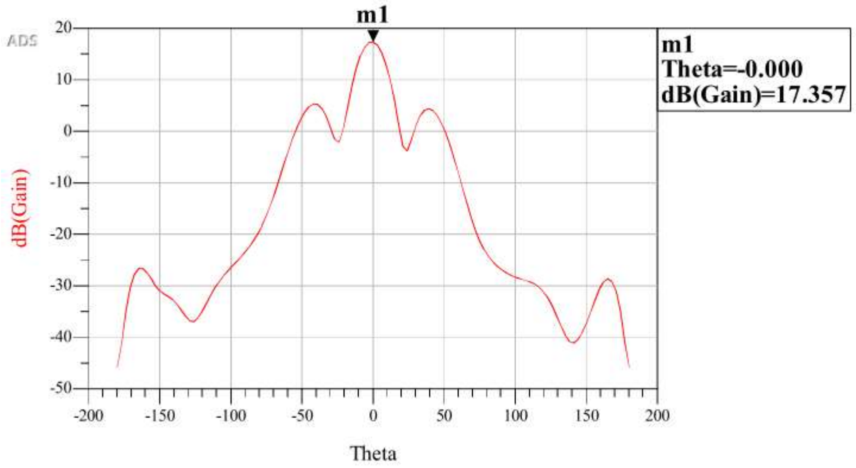

Fig 15. Rectangular plot of beamforming by the designed 4 × 4 Butler Matrix.

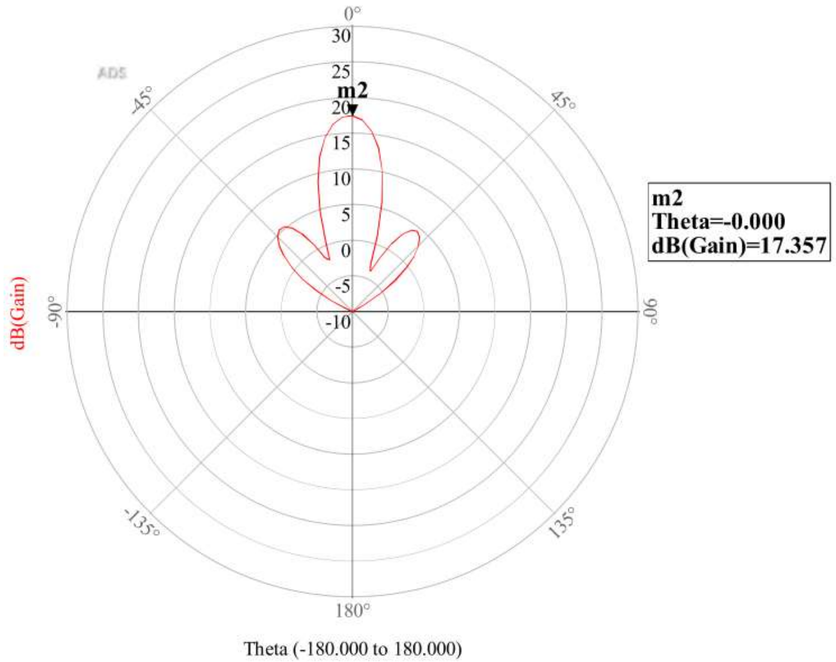

Fig 16. Polar plot of beamforming by the designed 4 × 4 Butler Matrix.

3D Beamforming by designed 4 × 4 Butler Matrix

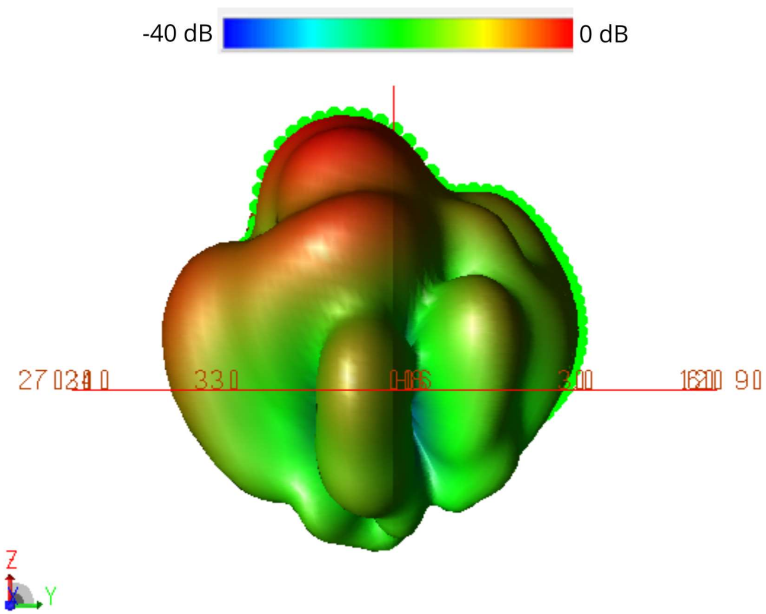

Fig 17. 3D beamforming when Port 1 is excited.

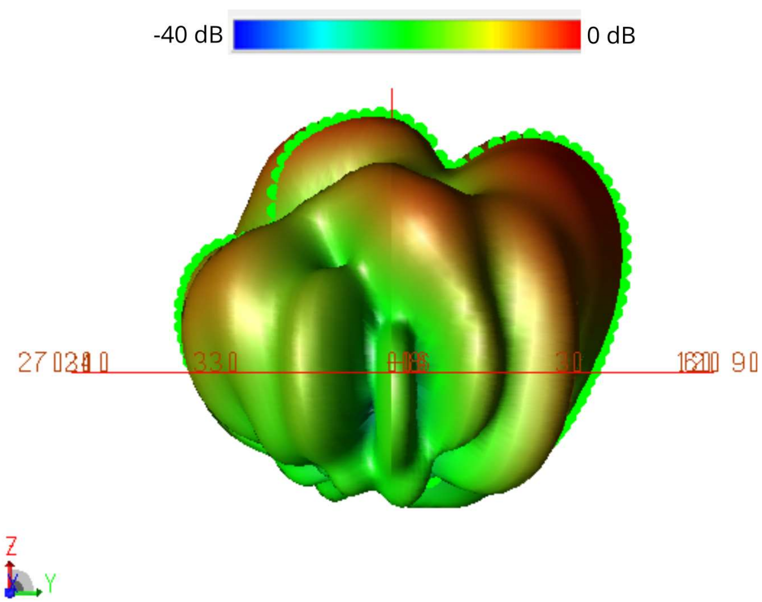

Fig 18. 3D beamforming when Port 2 is excited.

3D Beamforming by designed 4 × 4 Butler Matrix

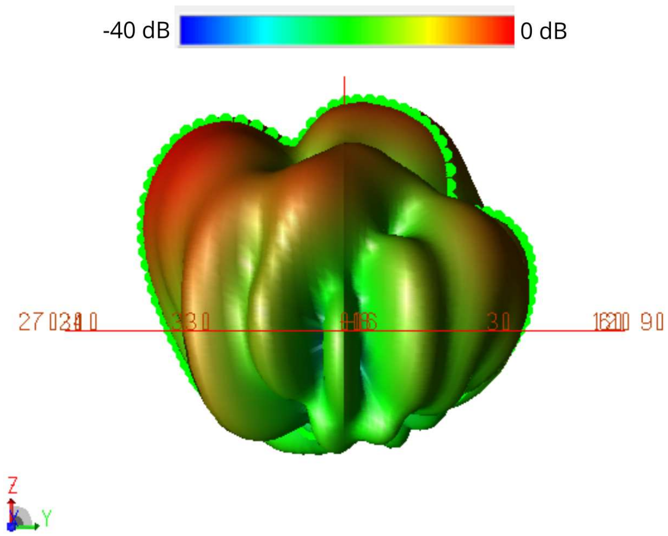

Fig 19. 3D beamforming when
Port 3 is excited.

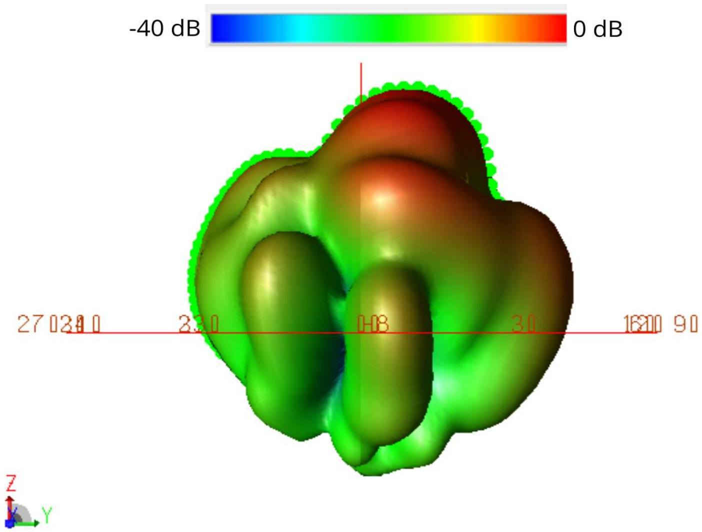

Fig 20. 3D beamforming when
Port 4 is excited.

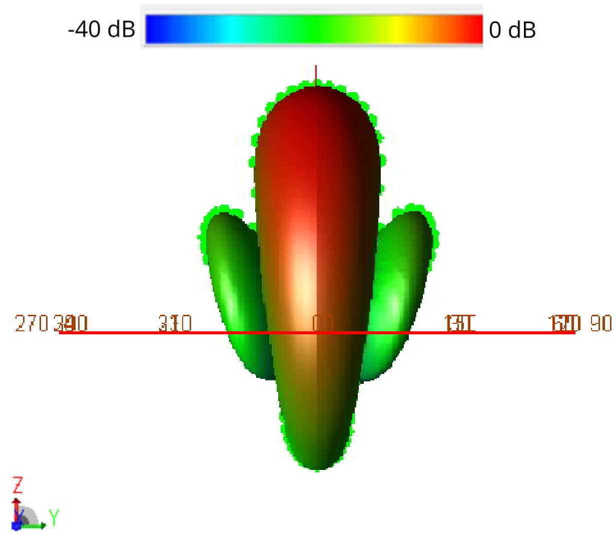

Fig 21. 3D beamforming when
all ports are excited.

Conclusion

- The designed 77 GHz microstrip 4 × 4 Butler matrix on a 0.2 mm thick HPFS glass substrate has the potential to provide superior performance at a lower cost, smaller size, and thickness to realize compact radars to improve road safety and driving comfort for vehicles with advanced driver-assistance system (ADAS) and autonomous vehicles.
- It was observed that the glass substrate from Corning™ has superior loss characteristics to minimize insertion loss at high frequencies.
- However, optimization of the phase characteristics and insertion losses in a 3D FEM simulation environment requires more than 500 GB of memory.
- The time taken by ADS solvers to run one simulation is computationally extensive. Further optimization is necessary to improve the insertion loss and the phase error.
- Initial investigation shows that the device can be fabricated using a standard microfabrication technique, such as the lift-off process available in any standard microfabrication facility.
- The device will be fabricated and tested once the optimization process is completed.

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