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Research Article

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Planar Single and Dual Band Switched Beam Systems on Silicon at C/X-Band

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ABSTRACT

Microstrip realization of beam forming network integrated with dual-band antenna array on silicon substrate is presented. Design and implementation of broad band topologies of hybrid and phase shifter are discussed and further integrated to realize wideband 4× 4 Butler matrix. Proposed wideband Butler matrix is used to realize single-band and dual band antenna architectures on silicon substrate. Design aspects, detailed simulation and measured results of both are detailed.

Key words: Butler matrix, microstrip, patch antenna, switched beam system

INTRODUCTION

Multi beam forming networks are employed in modern communication technology such as satellite communications, radar systems, point-to-point communication links and imaging to accomplish electronic scanning of antennas by creating variety of radiation pattern. Multipath fading and interferences commonly encountered in above communication systems can be mitigated by employing scanning array concept [1]. The additional feature of such assembly is to reconfigure real-time according to time-varying requirements. Such requirements can be easily met by feeding networks consisting of dividers, hybrids and phase shifters to provide desired amplitude and phase [2]. Compared to continuous scanning applications which employs phased array antenna consisting of lot many elements, 1-D scanning can be achieved by utilizing the concept of switched-beam wherein simple phase distribution of beam forming network can create independent beams directed towards the desired directions.

Most commonly beam forming networks are the Butler matrix, the Blass matrix and the Rotman lens. Compared to lens type beam former i.e Rotman lens and Blass matrix, circuit type beam former employing Butler matrix is simpler to design and having minimum loss of input power [3]. It has additional features such as easier implementation, orthogonal beam generation, high directivity, less number of components, low cost etc. Further, it can form multiple fixed overlapping beams which will cover designated angular area providing wide coverage. Apart from beam forming it is also used in antenna feed applications, multiport power amplifiers, adaptive smart antenna systems for direction finding purposes Several reported structures such as reflective assembly using circulators [4], multi layer topologies [5,6] not only generate fabrication complexities but also poses measurement complexities and integration problems compared to planar implementation. Other reported topologies [7, 8] need tight fabrication tolerances to achieve the desired specifications.

Switched beam system integrates Butler matrix with antennas to form multiple fixed overlapping beams which are obtained with the phase increment provided by the Butler matrix [9]. Present day requirements for communications systems demand dual band operation for enhancing the integration level [10]. Reported topologies [11, 12] are basically having narrow band operations and could not operate at dual frequencies. At microwave frequencies, it is difficult to design a circuit with comparable performances at two uncorrelated frequencies without incorporating diplexer which in turn increases the size and complexity of the system. Various other approaches such as incorporation of broadband system [13] or dual-band elements are implemented by researchers covering large area. Dual band topology for Butler matrix as proposed by Collado et al [10] increases the size by half wavelength at the desired frequency and needs tight fabrication tolerances. This article details realization of single and dual band assemblies by utilizing wideband Butler matrix. Dual band operations in the same size are achieved by incorporating slotted patch antenna operating at two frequencies.

This article presents the design and development of two topologies working at single and dual frequencies. Single frequency approach operating at 7.3 GHz with inset feed antenna and dual-band operated switched beam system working at 7.0/8.1GHz are detailed and both are implemented on high resistivity silicon substrate. Design of individual circuits like hybrids, phase shifters, cross coupler, patch antennas are detailed and further integrated to realize broadband Butler matrix. Complete switched beam assemblies are realized after incorporating patch antennas at desired frequencies. Design details of the realized assemblies along with the experimental results are detailed in this article.

BUTLER MATRIX

A Butler matrix is a $2^n \times 2^n$ multi-beam forming network with 2^n input, 2^n output, constituting of directional couplers [$2^{n-1} \log_2 2^n$], cross over and phase-shifters [$(n-1)\ 2^n /2$] for providing linear phase distribution. Directional couplers can be either 90^0 or 180^0, which are selected based on the requirement of orthogonal or broadside coverage. Orthogonal coverage is achieved by incorporating matrix of 90^0 hybrids due to its symmetrical configuration. Present designs are based on 4×4 Butler matrix (n=2) as higher order (n>2) need several crossovers to isolate the signal [14]. Thus proposed Butler matrix consist of 4 inputs, 4 outputs, 4 hybrids (in 2 columns), and a cross over to isolate the cross-lines in the planar layout along with two phase shifters as shown in Fig.1.

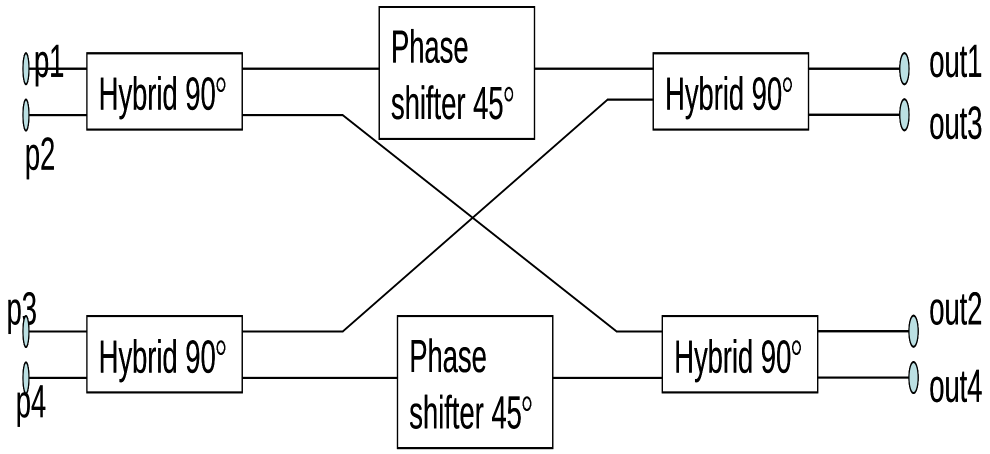

Fig. 1 Radiation Pattern of a 4 × 4 Butler matrix with 90^0 hybrid junctions

Each input of the Butler matrix produces a different set of four orthogonal phases; each set is used as an input for the four element antenna to create beams in different directions. Considering linear phase distribution and feeding the p^{th} input port, the main beam at the output is tilted by the angle as given below [3]

$$\theta_p = \sin^{-1}\left(\frac{N+1-2p}{2.N}\frac{\lambda}{d}\right) \qquad p=1,2,\ldots\ldots N \tag{1}$$

where λ is the free space wavelength, d is the distance between adjacent radiating elements , n is an integer (n=2 for present case) and $N=2^n$ is the order of the matrix. Feeding at port 1 (p=1), the main beam is tilted at an angle of θp= 48.59° and the resulting phase distributions at the output ports namely out1, out3, out2, out4 are -45°,-90°,-135° and -180° respectively. In terms of progressive phase shifts it comes out to be 0,-45°,-90° and -135°.

Switching between the four Butler inputs change the direction of the antenna array beam. For each input port, the network will produce signals with progressive phase shifts at the output ports with equal power. Feeding a 4-element antenna array using a 4×4 Butler matrix, 4 orthogonal beams can be generated and ideally each beam should have a gain of the whole array.

DESIGN METHODOLOGY

Butler matrix consists of quadrature hybrids, cross-over and phase-shifters which provide adequate phase shifts for switching applications. Mitering is incorporated in the circuits to have low losses.

Hybrid Coupler (3-dB)

As shown in Fig.1, the Butler matrix consists of the quadrature hybrids to create phase shift with equal amplitude. Butler matrix using conventional hybrids can operate within a very narrow bandwidth. As phase and amplitude are the most critical parameters of matrix so any fabrication errors could shift the desired frequency band and consequently shift the overall response of the conventional narrow band Butler matrix. Conventional 3-dB hybrid gives equal coupling at just the desired frequency. To obtain wide-band performance, incorporation of compensating network [15] at the output ports consisting of quadrature transformer in series and shunted by half-wavelength open stub is carried out as shown in Fig. 2. Manish and Kishk [9] proposed four port matching to realize broad bandwidth. Compared to four port compensation, proposed hybrid is provided with compensation at two adjacent ports to achieve wider bandwidth, without compromising symmetry of the structure. The width of the branch lines are chosen as 0.29 mm and 0.50 mm corresponding to the 50 Ω and 35 Ω impedances. The stub length is chosen to be around 180° for broad band operations.

This proposed methodology reduces the undesired coupling in the overall assembly along with maintaining the compactness and broad banding of the structure. Method of Moment (MOM) simulation is carried out utilizing commercial available software (Momentum), resulting in bandwidth enhancement of more than 25% at around 7.7 GHz as shown in Fig 3 to cover the frequency span from 7.0-8.1 GHz.

Cross-coupler is realized by the juxtaposition of two hybrids and optimized in electro-magnetic software (ADS). The widths of the outer vertical lines are 0.29 mm and inner section is having 0.15 mm. Simulated performance covering desired frequency band from 7-9 GHz is shown in Fig.4.

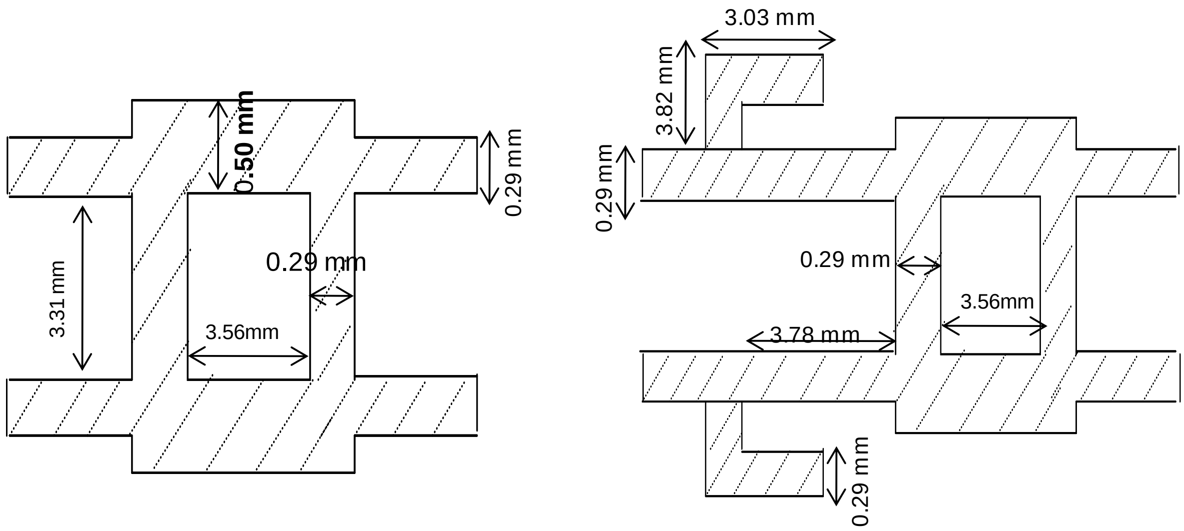

Fig. 2 Branch-line coupler (a) standard topology (b) compensated topology

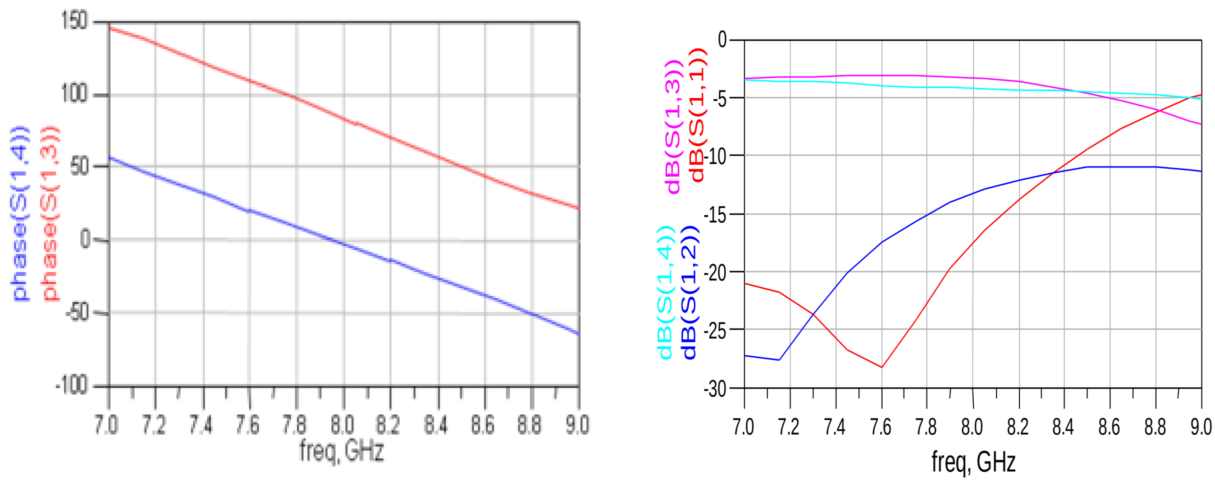

Fig. 3 Simulated result of compensated topology

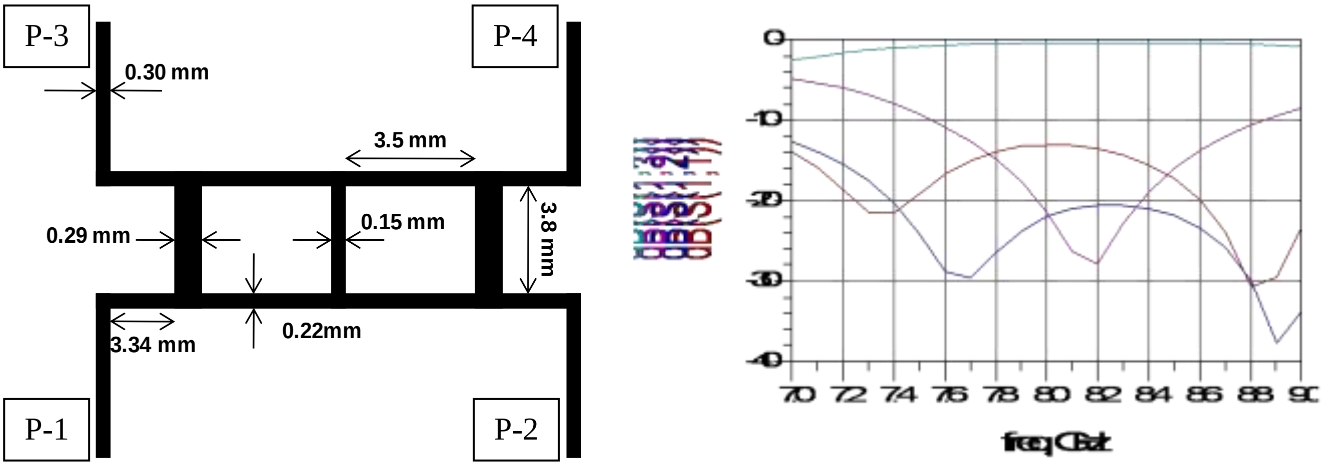

Fig. 4 Cross coupler schematic and simulated performance

Simulated response of the cross coupler indicate coupling loss |S14| < -0.2 dB, return loss and isolation better than 15 dB in the limited frequency range of 7.8-8.4 GHz. Parameters optimization is carried out in the integrated circuit to achieve the desired specifications covering single and dual frequency operations by shifting the frequency response. By employing compensation technique much wider response can be achieved at the expense of undesired coupling and enhanced size.

Phase Shifter

Desired phase shift (θ) in the Butler matrix is implemented using delay lines utilizing transmission line of length ℓ to introduce phase shift of $\theta = 360°\ell / \lambda$ which is applicable for narrow band of operations. Proposed Butler matrix is incorporated with Schiffman C-section to achieve wider band performance [16]. Output port of the input hybrids (Fig.1) consist of extra transmission line configured as Schiffman C-section to realize 45° phase shift. This is achieved by using a quarter wave coupled transmission line cascaded as a section of normal transmission line and adjusting the length until the phase shift slope is matched to that of the crossover, resulting in differential phase shift of 45°. The Schiffman C-section [5] along with reference line is optimized to serve as broadband phase shifter. The reference line length after meandering is taken as 315°as shown in Fig.5. Standard coupled section equations are used to find out dimensions and further optimized to provide bandwidth of more than 20% with phase error of less than 1°.

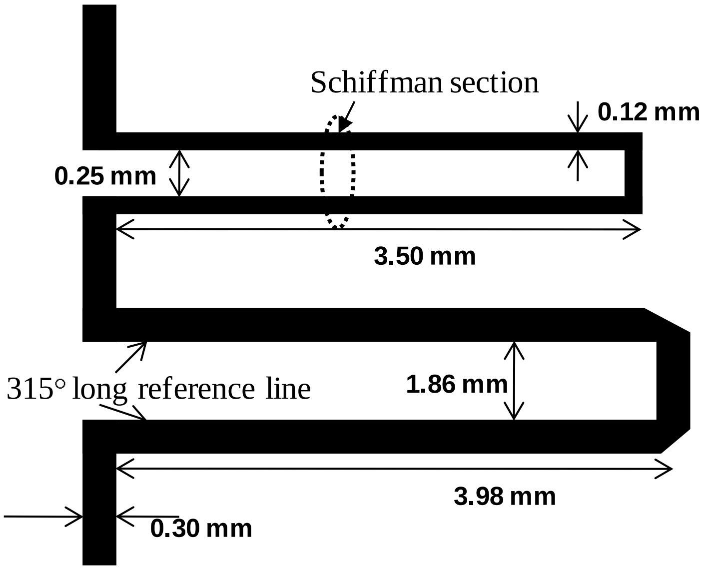

Fig.5 Implemented Schiffman C-section phase shifter

Patch Antenna -Inset feed and dual band

Radiating elements of switched beam assembly is realized by inset feed arrangement. Four such identical radiating elements are configured in an array with uniform excitation. The separation distance between adjacent element is chosen to be half-wavelength. Standard design equations (Eq. 2-4) are used to find out effective length and width of rectangular patch antenna for dominant TE_{10} mode [17]:

$$f_{r,10} = \frac{c}{2L\sqrt{\varepsilon_r}} \qquad W = \frac{c}{f}\frac{1}{\sqrt{2\varepsilon_r + 2}} \tag{2}$$

$$L = \frac{\lambda_{eff}}{2} - 2\Delta l \tag{3}$$

$$\Delta l = 0.412\frac{(\varepsilon_{eff} + 0.3)(W/h + 0.264)}{(\varepsilon_{eff} - 0.258)(W/h + 0.8)} \tag{4}$$

where λ_{eff} and $\in_{eff}$ is the effective wavelength and substrate permittivity respectively whereas W and h is width and height of the silicon substrate (ε_r=11.8, h=270um,tanδ=0.01). Feed position of inset feed is calculated as (Cartesian coordinate system):

$$R_{in}(y = y_0) = R_{in}(y = 0)\left\{\cos\left(\frac{\pi}{L}y_0\right)\right\}^2 \quad \text{(assuming feed in the y-direction)} \tag{5}$$

Feed position is optimized to achieve the desired input impedance and return loss performance of the patch as shown in Fig.6 which is shifted by 100 MHz and taken care in the integrated assembly.

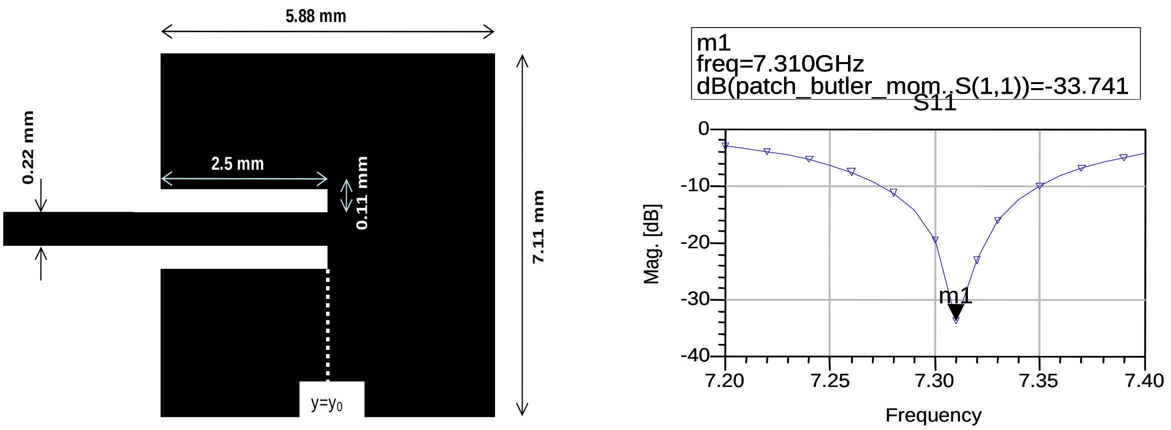

Fig. 6 Simulated performance of inset feed patch antenna

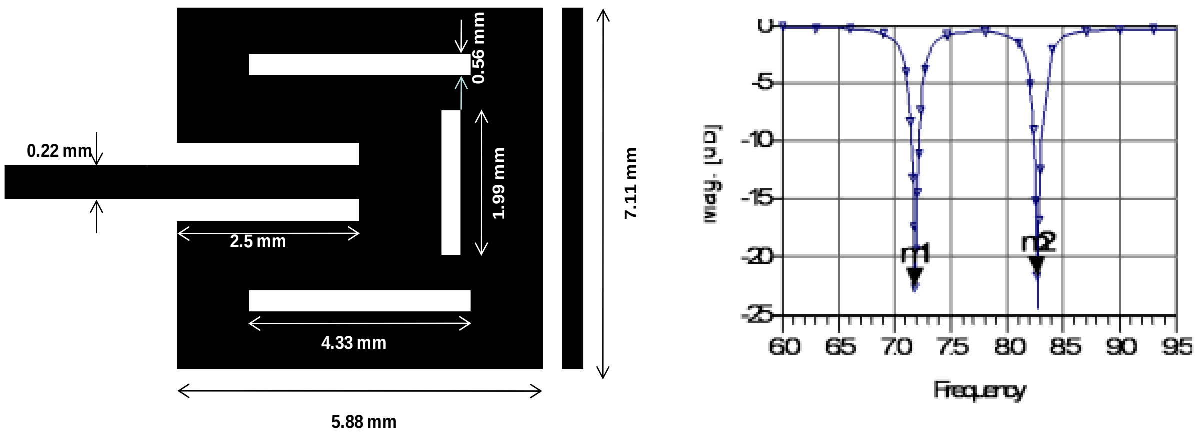

Fig.7: Schematic of dual frequency patch and its response

To achieve dual frequency performance, the same patch is modified by incorporating slots at the appropriate positions as shown in Fig.7. Locations, length and width of the slots are optimized to achieve the desired performances [18, 19]. The length of the finalized structure is 7.11 mm and width of 5.88 mm. Inset feed line width is kept around 2.5 mm and gap is kept 0.11 mm. Simulated response shows minimum return loss of 21 dB at 7.15 GHz and 8.25 GHz which is further optimized and shifted in the integrated topology due to change in the reference plane.

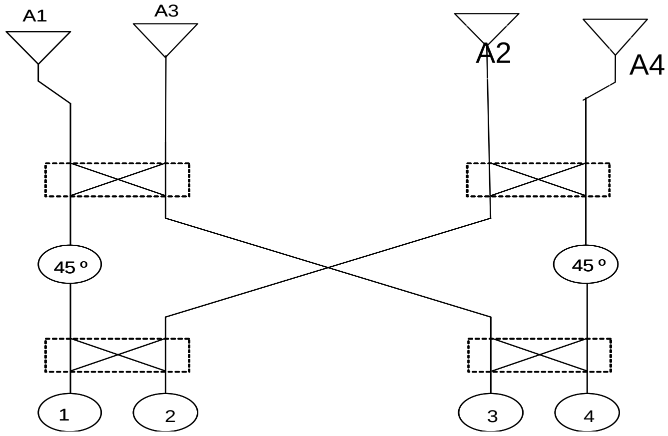

Fig.8 Schematic of switched beam assembly

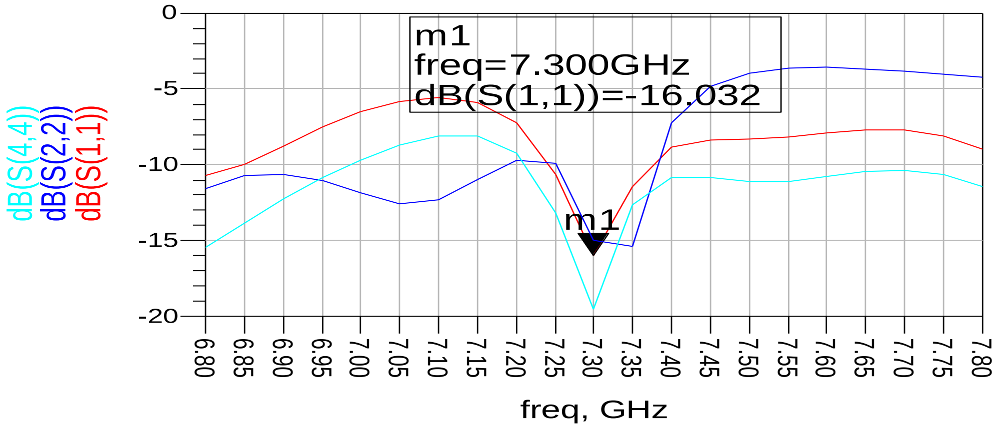

Fig. 9 Simulated response of single frequency assembly

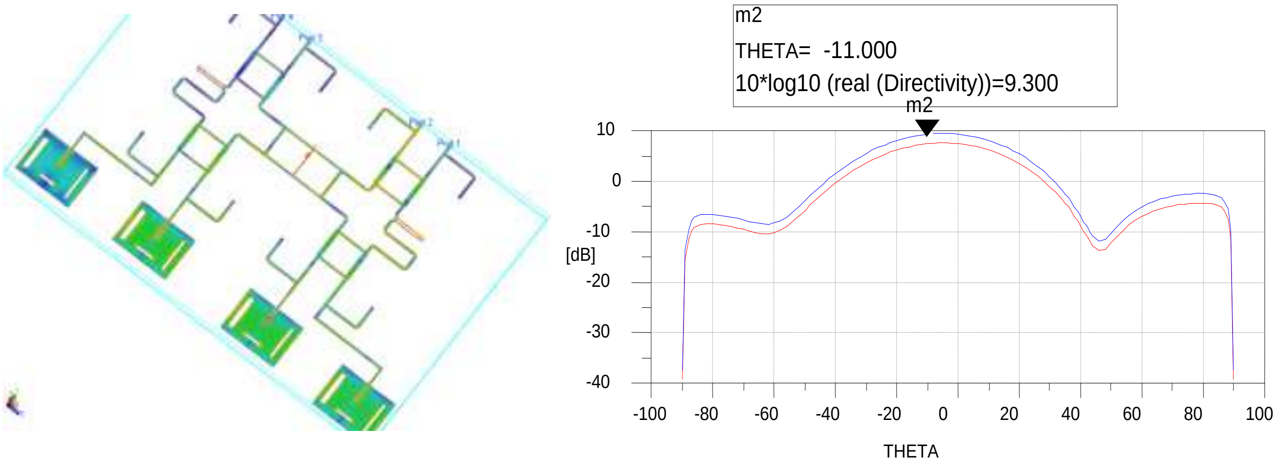

Fig.10 Simulated current and directivity/gain plot [13]

Four identical radiating elements are connected [20] with the Butler matrix output (Fig.8) and overall single band assembly is simulated and further optimized to compensate the interconnection losses. The simulated input return loss plot of the overall single band assembly shows minimum return loss of around 15.0dB at 7.3 GHz.

Second assembly incorporating dual-band antenna topology and integrated with broadband Butler matrix which is optimized at 7.0 GHz and 8.1 GHz. Simulated input return loss plot of this topology shows min return loss of 10 dB with directivity of 9.3 dB as shown in Fig.10.

FABRICATION ASPECTS

Butler matrix along with patch antennas is fabricated on the high resistivity silicon substrate (> 8 k ohm-cm) having permittivity (εr) of 11.8 and $\tan\delta \sim 0.01$. Standard high resistivity silicon of 675 um is subjected to wet etching techniques to realize 270± 20 um thickness. After subjecting to standard thin film substrate cleaning cycles, high resistivity silicon substrates ($50 \times 50 \times 0.25$ mm) are sputtered with thin layer of TiW (200 - 300Å) followed by 8000Å of gold film on both sides of substrates. This combination of seed layers is electroplated with gold to the required thickness of $4.5\mu \pm 3\%$ and circuits are patterned using standard optical lithography and subtractive etching process. The patterned substrate has been attached to test zig using silver based conductive epoxy RF connectors are soldered as shown in the Fig. 11.

Fig.11 Single band assembly and dual band assembly on silicon [10]

RESULTS

Butler matrix is realized on Alumina substrate first and measured performance is shown in Fig.12. Insertion loss characteristics clearly demonstrate wide band response covering 6.2 GHz to 7.3 GHz with total insertion loss variation within 0.6 dB. Measured return losses at all the ports are better than 15dB and isolation achieved is better than 20 dB which is as per the simulated values.

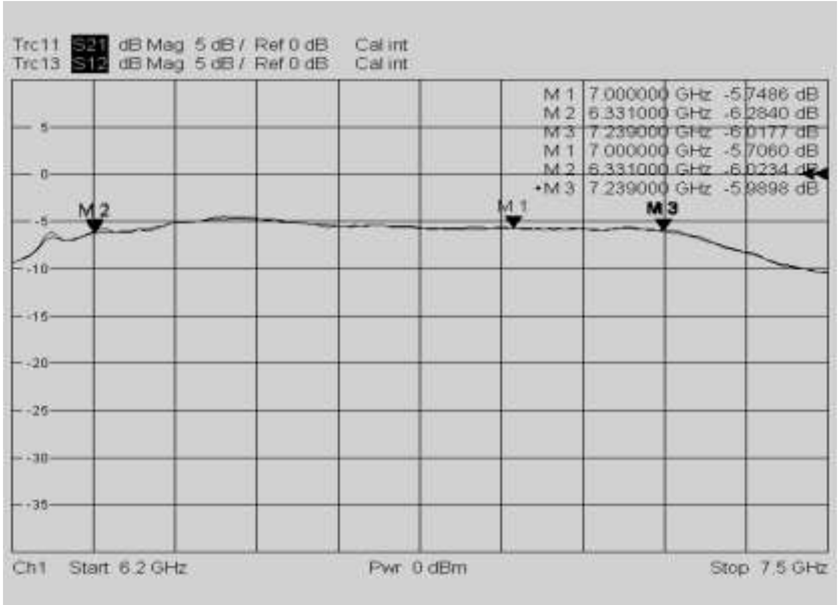

Fig.12 Measured insertion loss of Butler matrix [11]

Phases at various ports are measured and progressive phases at 7 GHz are tabulated as below:

$$\begin{bmatrix}1\\2\\3\\4\end{bmatrix}=\begin{bmatrix}+159^{0} & -110^{\circ} & -68.0^{\circ} & -30^{\circ}\\ -53.0^{0} & +28.0^{\circ} & +116^{\circ} & -99^{\circ}\\ -99.0^{0} & +116^{\circ} & +27.0^{\circ} & -53^{\circ}\\ -46.0^{0} & -77.4^{\circ} & -116^{\circ} & +179^{\circ}\end{bmatrix}\begin{bmatrix}5\\6\\7\\8\end{bmatrix} \qquad \begin{bmatrix}1\\2\\3\\4\end{bmatrix}=\begin{bmatrix}0^{0} & -269^{\circ} & -227^{\circ} & -189^{\circ}\\ 0^{0} & +81^{\circ} & +169^{\circ} & -46^{\circ}\\ 0^{0} & +216^{\circ} & +127^{\circ} & +45^{\circ}\\ 0^{0} & -32^{\circ} & -70^{\circ} & +225^{\circ}\end{bmatrix}\begin{bmatrix}5\\6\\7\\8\end{bmatrix}$$

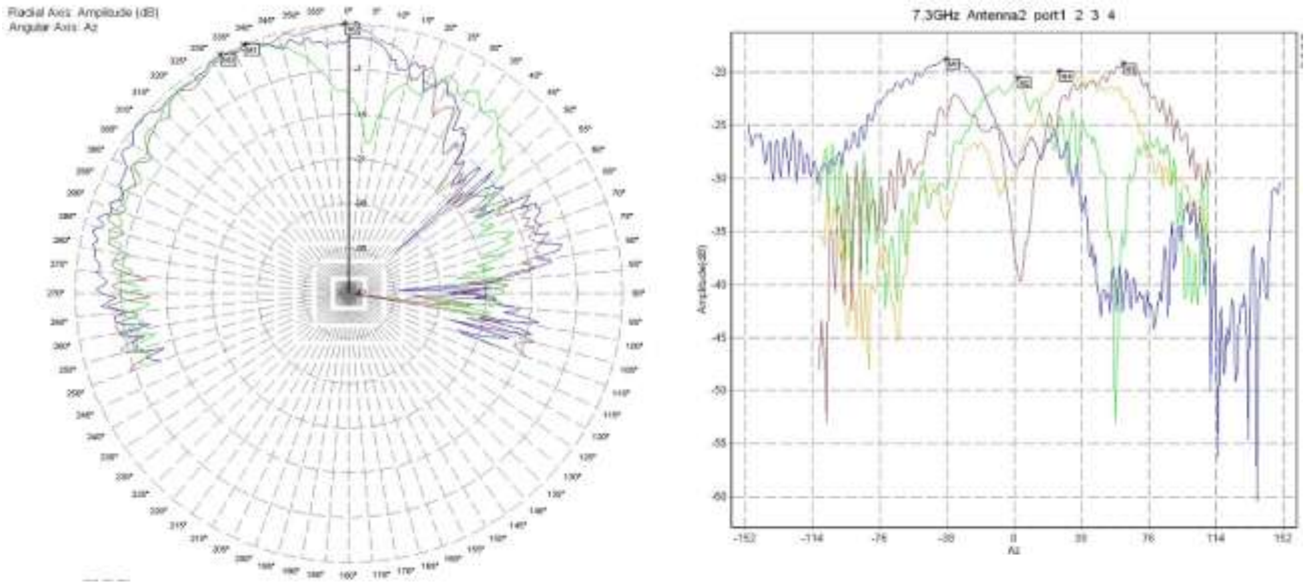

Fig.13: Polar and 2-D plot of single band assembly [12]

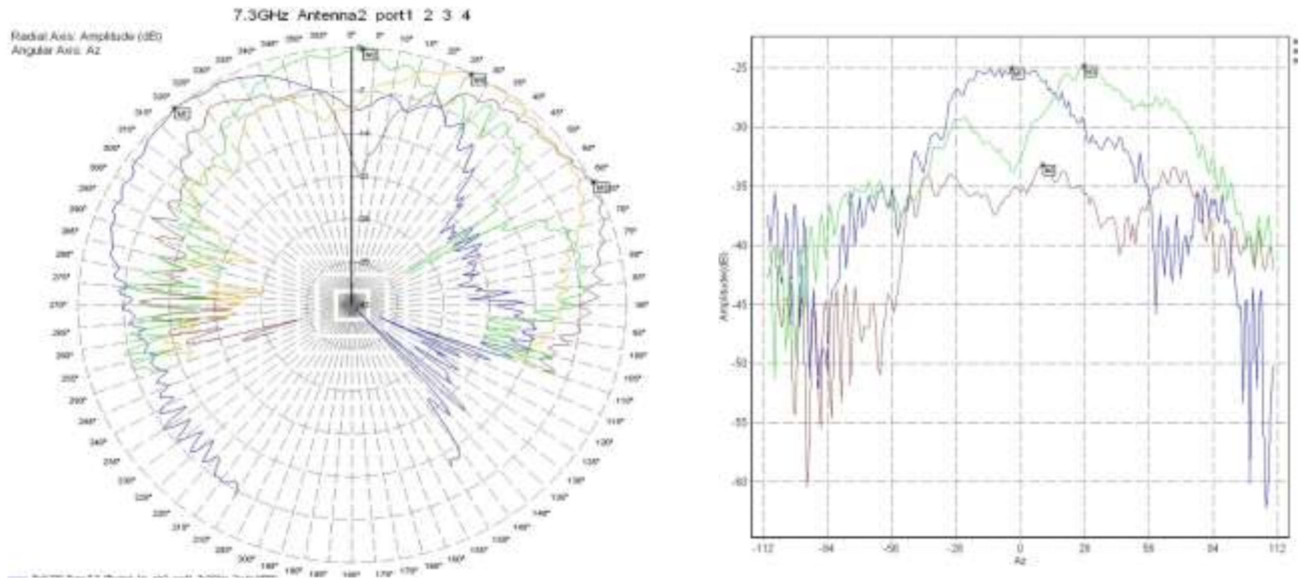

Fig. 14: Measured polar and 2-D plot at dual frequencies for single port excitation [14]

Considering the port 1 excitation, progressive phase shift of 0,-227°,-269° and -189° are measured which can be written as 0,43°,91° and 181°. Variation with respect to theoretical values as mentioned in Sec-II is attributed to the fabrication tolerances.

The overall size of the Butler matrix is 32.5mm × 32 mm. Radiation pattern measurement of realized single band assembly is carried out at 7.3 GHz and measured results are shown in Fig.13. Radiation plots at 7.3 GHz show four patterns at different locations according to input port excitation. Butler assembly is further integrated with dual band assembly and optimized to cover dual frequencies i.e 7.0 and 8.1 GHz respectively. Measured radiation patterns as shown in Fig.14 demonstrate dual band operations. Measured results are tabulated below:

Table -1 Comparison of Performances for Single and Dual Band Assembly

	Ports	Frequency (GHz)	Gain (dBi)	Return Losses (dB)
Single Band Antenna	P1	7.3	8.8	17.0
	P2	7.3	7.1	16.6
Dual Band Antenna	P1	7.0 8.1	9.0 8.1	15.76 18.2
	P2	7.0 8.1	6.9 6.46	13.5 11.5

Variation in losses at different port excitation is due to undesired coupling associated with mounting of the assembly and slight mismatch of the connector. Same pattern is repeated for other two ports due to symmetrical structure.

Table - 2 Phase Peaks Comparison of Single and Dual Band System

	Single Patch	Dual Patch	
Frequency / Excitation	7.3 GHz	7.0 GHz	8.1 GHz
Port 1	320°	332.16°	337.5°
Port 2	2.32°	27.04°	356.2°
Port3	61.6°	313.7°	5.61°
Port4	34.8°	57.5°	353°

Port to port isolation is better than 25 dB but side lobe levels are higher due to mutual coupling between radiating elements. Half power beam width of the measured radiation pattern is coming around 38°.Gain is also lower than simulation due to extra losses associated with silicon substrate. Overall sizes of both switched beam assemblies are 41 mm × 54 mm.

CONCLUSION

Compact and broadband 4 × 4 Butler matrix is realized on silicon substrate. Novel hybrid with adjacent port compensation is being implemented. The wide band Butler matrix is fabricated together with the antenna array to form beam forming systems working at dual frequency within same dimensions as of single band assembly. Single band switched beam assembly provides gain of 8.8 dBi whereas dual band provides typically around 8 dBi. Good isolation, return losses and radiation characteristics of the antenna arrays validate the adopted approach. The silicon substrate has added advantage of micromachining which can provide overall higher efficiency. Slight mismatch between simulated and measured performance can be easily overcome by depositing oxide layer over high resistivity silicon using CMOS technique. This is first reported switched beam topology on silicon having additional feature of small size and light weight. Microstrip implementation provides ease of implementation of the proposed topology. This assembly will pave way for low cost complex dual band RF-CMOS architecture fully implementable on silicon substrate with standard fabrication techniques.

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