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Design and realization of a compact substrate integrated coaxial line butler matrix for beamforming applications

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Abstract

This article presents the modeling and realization of a compact substrate integrated coaxial line (SICL) based butler matrix operating at 5 GHz for beam-forming applications. The proposed 4×4 butler matrix is developed using SICL-based hybrid coupler, crossover, and phase shifter. A compact 90° coupler comprising of center tapped unequal stubs is designed to enhance the size reduction as well as to extend the out of band rejection. Wideband SICL-based crossover operating from DC to 10 GHz is conceived for the proposed butler matrix using a plated through hole as transition. The SICL crossover features very high measured isolation of 65 dB owing to the reduction in coupling between the two signal paths within a lateral footprint of only 0.034 λ_g^2. A meandered SICL-based line is used in order to provide the necessary 45° and 0° phase shift to realize the butler matrix. The fully shielded and self-packaged compact 4×4 SICL-based butler matrix is fabricated and experimentally validated to operate at 5 GHz.

Introduction

Widespread utilization of wireless services at a low cost is driving the demand for high bandwidth to support a variety of user-applications with better coverage. Modern phased array antenna systems are increasingly used as they facilitate highly directional transmission [1] to reduce path loss and improve the signal to noise ratio as high frequency carriers are used to maximize throughput. Phased array antennas reduce interference and save power making those very resourceful in urban environments with high user equipment density. Passive networks such as the butler matrix are integral to develop phased array systems in order to provide the necessary progressive phase shift between the antenna elements to tilt the beam in the desired direction. Butler matrix is widely used in design of adaptive antenna for Wi-Fi system enhancement [2], improve diversity in MIMO systems [3] by enhancing received signal strength using beams from different antennas [4]. Beamforming network such as the butler matrix is fundamental in building multi-beam phased array antenna [5] for wide scanning angle in satellite communication. Also phase shifting networks for antennas provide crucial spherical coverage for excellent spatial coverage to boost the input power density for harvesting of ambient RF energy [6]. Telecommunication companies have demonstrated multiplexing techniques [7] using butler matrix to achieve over 100 Gbit/s wireless transmission. The extensive usage of butler matrix in phased array antennas motivates to explore novel techniques to achieve compact form factor with enhanced functionalities. Researchers have developed non-planar 3D printed W-band butler matrix [8] and a high-power butler matrix using mechanical milling for RADAR application [9]. However, for hand-held equipment, it is imperative to have planar and low-weight solution for beamforming networks. Microstrip technology aids in design of planar microwave/millimeter-wave butler matrix for beam scanning [10–12] using hybrids, crossover and phase shifter with simple layout. Although microstrip-based hybrids and crossover enjoy planar form-factor, they are usually built using quarter-wavelength transmission line which occupy a large lateral area, suffer from higher order harmonics and have poor shielding due to their semi-open structure. Substrate integrated waveguide (SIW) [13, 14] technology serves as an attractive candidate to overcome the problem of semi-open microstrip technology and have lower insertion loss. Moreover, SIW maintains the planar configuration as it utilizes the traditional PCB fabrication technique to synthesize waveguides in thin dielectric substrates. Researchers have extensively studied and developed SIW-based beamforming networks [15] for a variety of wireless applications. In [16, 17], multilayer configurations of SIW have been explored to reduce the lateral area and provide comparable performance. Although novel technologies such as integrated passive device [18] and SiGe-based fabrication [19] have shown to build compact butler matrices in a compact size, they often come at the expense of increased manufacturing cost. An interesting solution to this problem is adopting TEM-based transmission line that provides similar signal integrity as SIW but in smaller footprint with low cost and ease of integration with other planar technologies. Recently, substrate integrated coaxial line (SICL) has gained interest due to its non-dispersive unimodal TEM-propagation [20] for design of high performance microwave circuits. A lot of progress is made in SICL-based circuits with demonstration of bandpass filter [21], balun [22], coupler [23], oscillator [24] and antennas [25] for wireless applications. A broadband beam scanning antenna array using butler matrix [26] has been demonstrated based on SICL technology for Q-band application. But the proposed system occupies a large footprint due to utilization of traditional coupler and crossover conceived using back to back connected coupler.

This work explores the design of a compact 4×4 butler matrix in SICL technology. A branch line coupler with open stubs is devised in a compact size for enhanced rejection in the out of band region. The measurement results of wideband SICL-based crossover conceived for the proposed butler matrix indicates high isolation in a compact footprint. SICL-based crossover proposed in this work uses a plated through hole as transition with a square ground patch between the overlapping region of two paths. The required progressive phase shift between the input and output ports of butler matrix is achieved by a meandered SICL line to work as phase shifter. The TEM mode-based butler matrix in SICL technology is suitable for mass production using low cost PCB fabrication and has small footprint in a self-packaged and self-shielded form-factor.

Modeling of proposed SICL-based butler matrix

A substrate integrated coaxial line is realized by sandwiching a metallic conducting strip between two dielectric substrates covered with metal surfaces forming the top and bottom ground plane. The outer conductor of this planar coaxial line is created by using the plated through vias along the inner conductor connecting the top and bottom ground plane as shown in Fig. 1. The diameter of the plated via and pitch of vias are chosen such that wave-leakage from this planar shielded structure is minimized. Also the distance between via rows play an important role in determining the single-mode TEM-mode bandwidth of SICL [20]. In this work, the design methodology and development of SICL-based coupler, crossover, and phase shifter are discussed to realize a butler matrix for beamforming applications.

Design of compact SICL-based branch line coupler with harmonic suppression

A SICL-based branch line coupler depicted in Fig. 2 is constructed using a set of two transmission lines of characteristic impedance

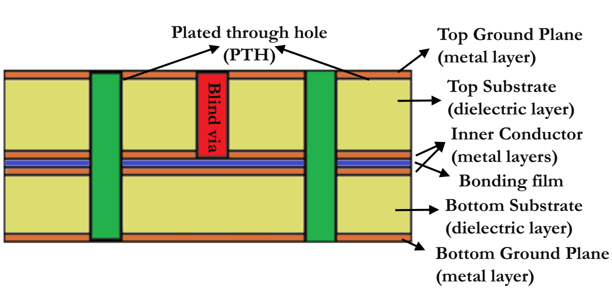

Figure 1. Multi-layer stack up of an SICL structure.

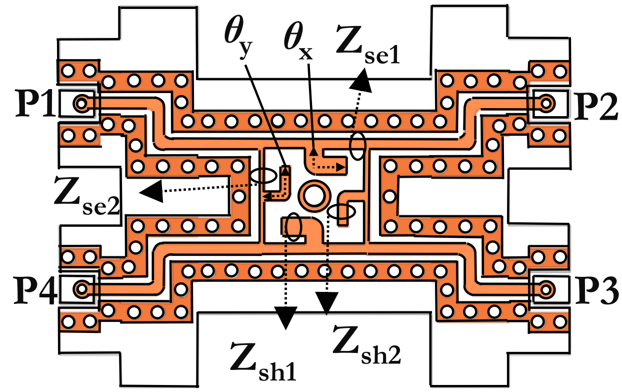

Figure 2. Layout of compact SICL-based branch line coupler with unequal length stubs.

Z_{se1} and Z_{se2} with the same electrical θ_a. Two open circuited stubs with unequal electrical length θ_x and θ_y are center tapped on the series transmission line with characteristic impedance Z_{se1} and Z_{se1} respectively as shown in Fig. 2. The electrical length of open stubs is selected such that they become quarter-wave length long in the out of band region to provide wide suppression to any spurious wave propagation. The characteristic impedance $Z_{se1,se2}$, $Z_{sh1,sh2}$ are related to the electrical length of the series and shunt branches of proposed coupler (θ_a, θ_x, θ_y) as derived in 1a–1d.

$$Z_{se1} = \frac{Z_o}{\sqrt{2}} \cot\left(\theta_a/2\right), \tag{1a}$$

$$Z_{se2} = Z_o \cot\left(\theta_a/2\right), \tag{1b}$$

$$Z_{sh1} = \frac{Z_o}{\sqrt{2}\cot\left(\theta_x\right)\left(1-\tan^2\left(\theta_a/2\right)\right)}, \tag{1c}$$

$$Z_{sh2} = \frac{Z_o}{\cot\left(\theta_y\right)\left(1-\tan^2\left(\theta_a/2\right)\right)}. \tag{1d}$$

The proposed SICL coupler is designed as discussed in detail in [23] to achieve a wide out of band suppression up to $4f_o$ with equal power division at 5 GHz.

Modeling of a compact SICL-based crossover with very high isolation

The 3D stack up and layer-wise view of the proposed SICL crossover is shown in Fig. 3. The proposed SICL-based crossover comprises of two transmission paths. The path 1 comprises of two 50 Ω SICL lines which are connected through a GCPW line. The SICL conductor in the middle layer and GCPW line co-located in the top ground of SICL line is connected using a vertical plated through hole as transition. In order to avoid shorting path 1 with the bottom ground plane, a slot with diameter D_{out} is created a shown in Fig. 3. Similarly path 2 consists of two 50 Ω SICL lines that are connected through a GCPW line located on the bottom ground plane of SICL line as shown in Fig. 3. The advantage of using a through via instead of blind via is it reduces the fabrication complexity. It is crucial the complete transmission path is 50 Ω in order to minimize any reflections at the SICL-GCPW junction and GCPW-SICL junction. The diameter of the plated through

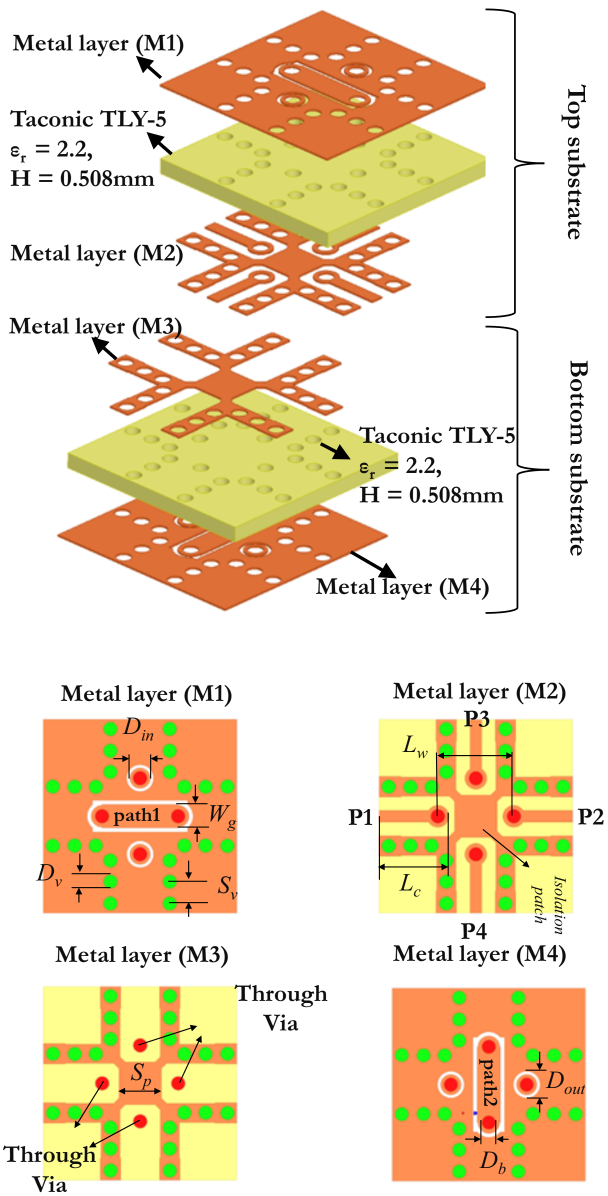

Figure 3. Stack up of the proposed compact SICL-based crossover and individual metal layer with dimensions: $D_b = 1$ mm, $D_{in} = 1.5$ mm, $D_{out} = 1.98$ mm, $D_v = 1$ mm, $L_c = 4.5$ mm, $L_w = 5.58$ mm, $S_p = 3.1$ mm, $S_v = 1.55$ mm.

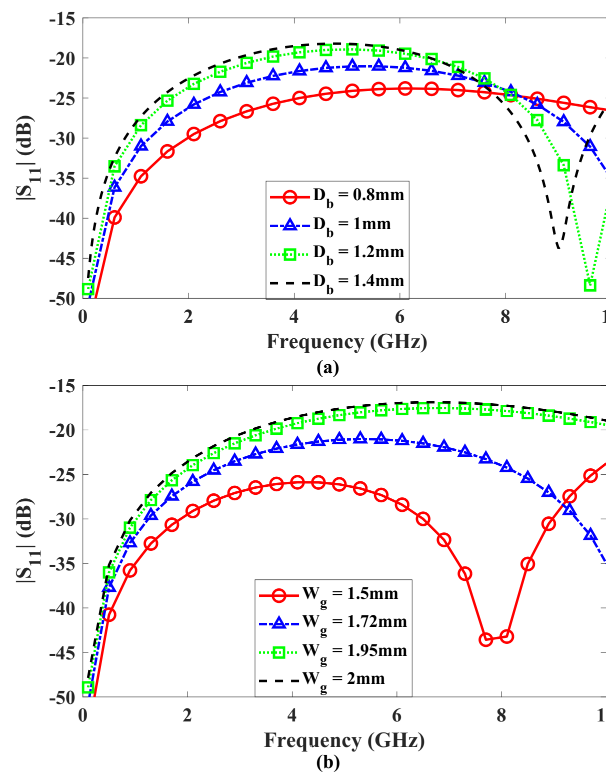

Figure 4. Analysis of proposed crossover to study the effect of change in (a) diameter of through hole (D_b) and (b) width of GCPW line located on top/bottom ground plane of SICL.

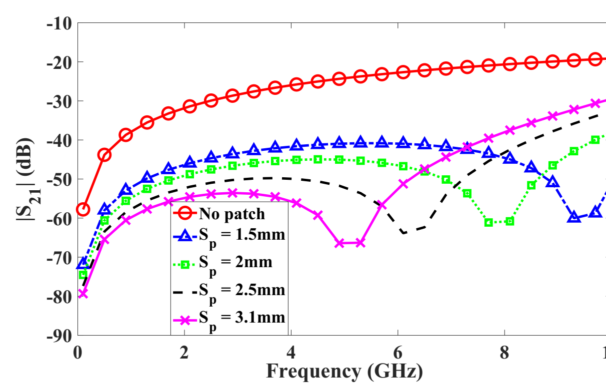

Figure 5. Variation in isolation of proposed crossover with change in side length of square patch (S_p).

hole used to connect the SICL inner conductor with the GCPW line is carefully selected in order to ensure minimal discontinuity at junction as shown in Fig. 4(a). Also the GCPW line width in the top and bottom ground plane is chosen after studying the effect of overlap between path 1 and path 2 as shown in Fig. 4(b). The isolation between the two paths is an important parameter in design of a crossover. In the proposed crossover the isolation is a function of separation between the two paths which is decided by the height of substrate, dielectric constant of the substrate and area of overlap between the two paths. The main cause for degradation of isolation is coupling between the two paths through the overlap region formed by the GCPW line in the top and bottom ground plane. In order to enhance the isolation between the two paths, a square patch of side length S_p that is connected to the ground plane is introduced. The effect of the square ground patch separating the overlapping regions of path 1 and path 2 is studied in Fig. 5 through full-wave simulation. The isolation between the two paths of the proposed crossover is enhanced from 24 dB (no isolating square patch) to 72 dB when the a square patch of side length 3.1 mm is chosen.

Design of self-packaged and self-shielded compact butler matrix in SICL technology

Branch line coupler, crossover, and phase shifter form the building blocks of a butler matrix. However, one of the major shortcomings of the traditional butler matrix is the utilization of microwave networks that consist of quarter-wavelength transmission lines.

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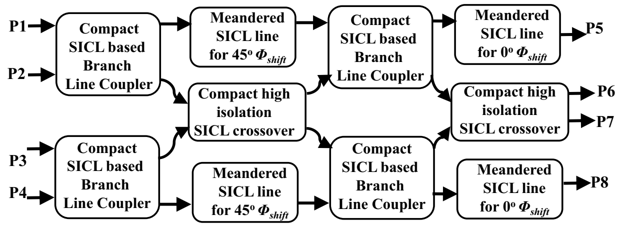

Figure 6. Schematic diagram of the proposed compact SICL-based butler matrix.

Table 1. Phase shift between input and output ports of butler matrix

Input port	Output port				Phase difference between ports
	P5	P6	P7	P8	
P1	−45°	−90°	−135°	−180°	−45°
P2	−135°	0°	−225°	−90°	135°
P3	−90°	−225°	0°	−135°	−135°
P4	−180°	−135°	−90°	−45°	45°

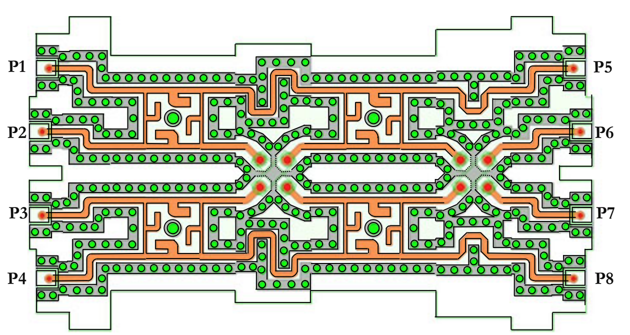

Figure 7. Geometrical layout of the SICL-based butler matrix.

At low frequency, they occupy large lateral and increase the overall size and weight of the system. In this work, an interesting solution is proposed to address this problem by utilizing compact microwave networks developed in SICL technology. The proposed 4×4 butler is conceived using an compact SICL hybrid coupler, compact SICL crossover with very high isolation to minimize inter-channel interference and a meandered SICL line as phase shifter. SICL-based coupler, crossover, and phase shifter are integrated to form the proposed butler matrix as per the schematic shown in Fig. 6. It consists of four hybrid couplers, two crossovers and four phase shifters. The phase difference between the input and output ports of the butler matrix is shown in Table 1. In order to verify the performance of the proposed butler matrix, at each input and output ports of the butler matrix an SICL to GCPW transition is designed to facilitate the mounting of an SMA connector. The layout of the proposed compact SICL-based butler matrix after integration of the coupler, crossover, and phase shifter is shown in Fig. 7.

Experimental validation and discussion

In this work, all the proposed designs have been fabricated using two layers of Taconic TLY-5 ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$) substrate. One of the major advantages of SICL is its low-cost fabrication and the prototypes developed in this work are built using micro-milling technique in LPKF protomat E33 machine. In order to maintain

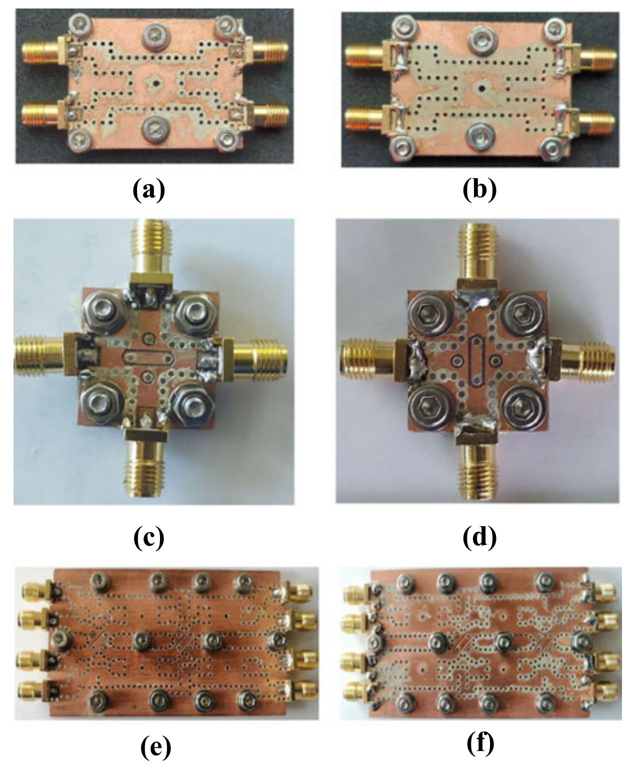

Figure 8. Photograph of the fabricated SICL-based components: (a) top view of branch line coupler, (b) bottom view of branch line coupler, (c) top view of crossover, (d) bottom view of crossover, (e) top view of butler matrix, (f) bottom view of butler matrix.

the necessary alignment between the bottom and top substrate layers along with metallic screws, standard epoxy glue has been used. Furthermore, all the via holes in the proposed SICL devices are metalized using LPKF ProConduct paste to provide lateral shielding. Also the outer conductor of the SICL formed by plated though holes and ground planes create a self-packaged structure making it an attractive candidate for deployment in densely integrated systems with good electromagnetic compatibility. The photograph of the final fabricated prototype of the proposed compact SICL coupler, crossover, and the integrated butler matrix is shown in Fig. 8. The fabricated prototype is experimentally validated by measuring the S-parameters up to 20 GHz using Keysight E5080B vector network analyzer (VNA). The full-wave simulated S-parameters generated using Ansys high-frequency structural simulator are compared with the S-parameters recorded using VNA. In Fig. 9, the branch line coupler measured results indicate return loss and isolation better than 15 dB at 5 GHz with harmonic suppression up to 20 GHz. Furthermore, the SICL coupler demonstrates low measured amplitude imbalance of ± 0.5 dB and phase imbalance less than $\pm 3^{\circ}$ in the frequency range covering 4.6–5.3 GHz with a footprint of 11.6 mm × 11.6 mm, or equivalently an area of 0.078 λ_g^2 [23].

The measured and full-wave simulated S-parameters of the proposed SICL-based crossover are shown in Fig. 10. The proposed crossover demonstrates return loss better than 10 dB across DC to 10 GHz with return loss better than 21 dB at 5 GHz. The role of central square patch in substantially enhancing the isolation is justified in the proposed crossover with measured isolation greater than 56 dB between port 1 and port 3, and 65 dB between port 3 and port 2 at 5 GHz. The proposed compact SICL-based crossover

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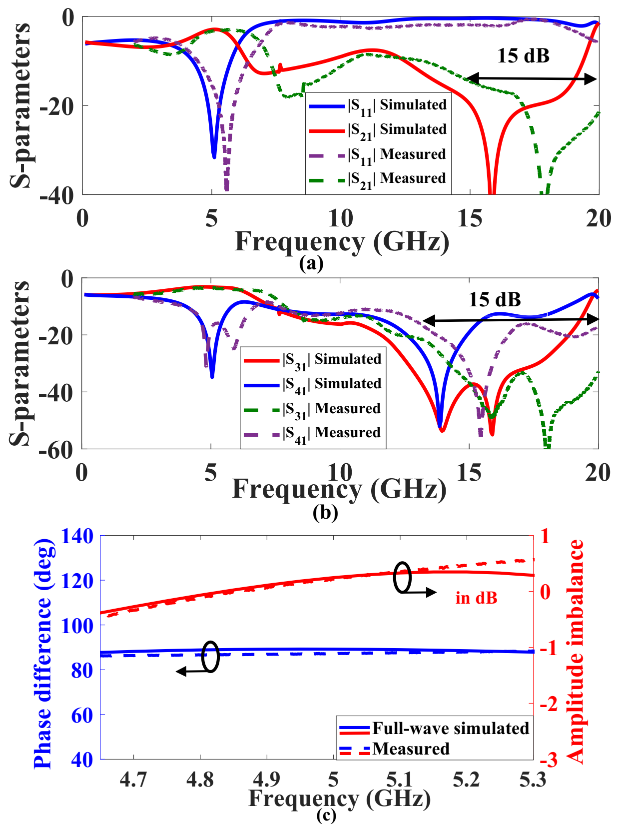

Figure 9. Full-wave simulated and experimentally measured results of the proposed SICL-based compact branch line coupler with broad out of band rejection. (a) & (b) S-parameters, (c) phase difference and amplitude imbalance.

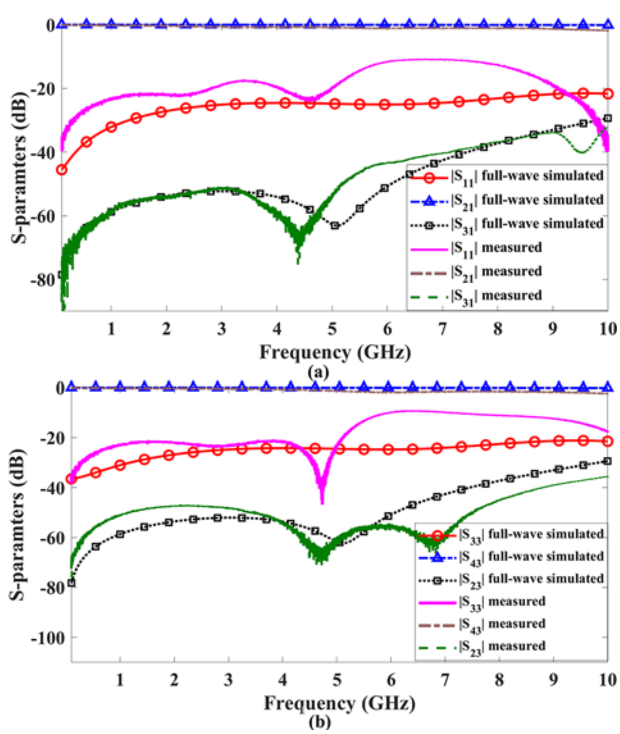

Figure 10. Measured and full-wave simulated S-parameters of the proposed compact SICL-based crossover: (a) Port 1 is excited and (b) Port 3 is excited.

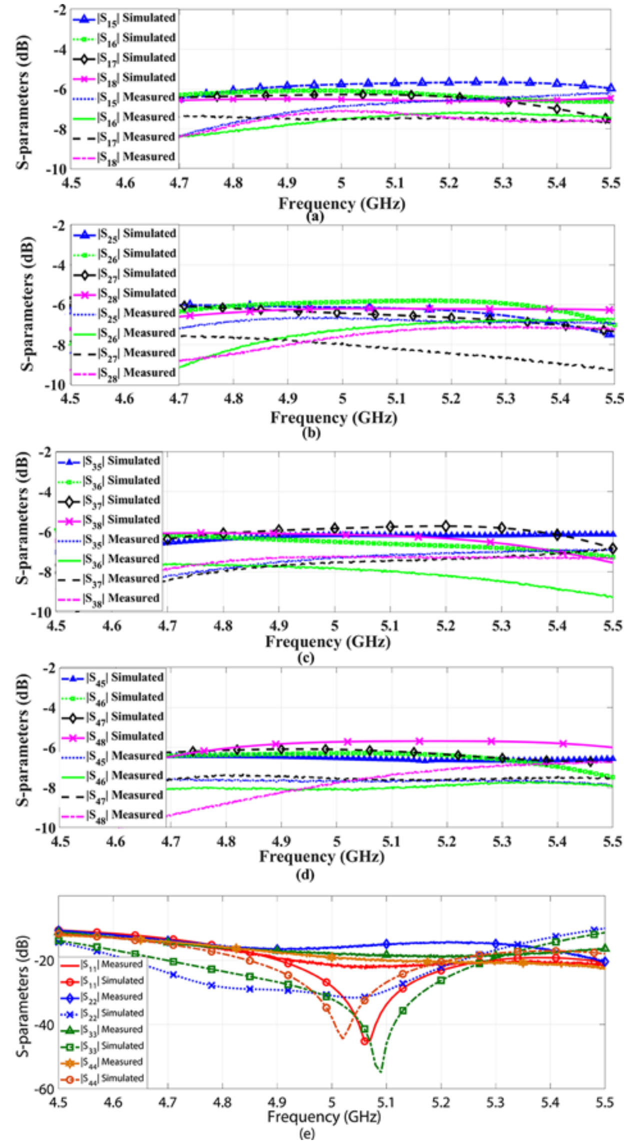

Figure 11. Comparison between full-wave simulated and measured transmission coefficients of SICL-based butler matrix when input: (a) Port 1, (b) Port 2, (c) Port 3, (d) Port 4 is excited and (e) reflection coefficients.

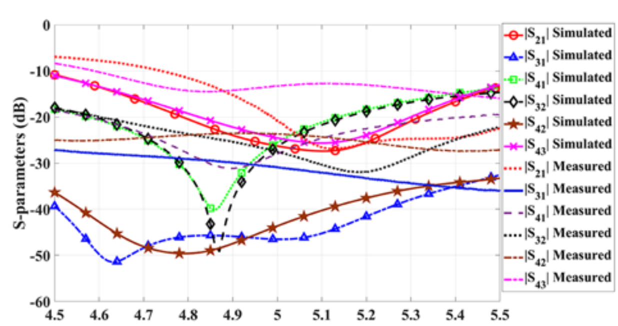

Figure 12. Full-wave simulated and measured isolation between input ports (Port 1–Port 4) of the proposed SICL-based butler matrix.

exhibits an insertion loss of 0.84 dB in path 1 and 1.2 dB in path 2. The core part of the crossover without the additional feeding SICL lines and GCPW transition occupies 7.5 mm × 7.5 mm, covering

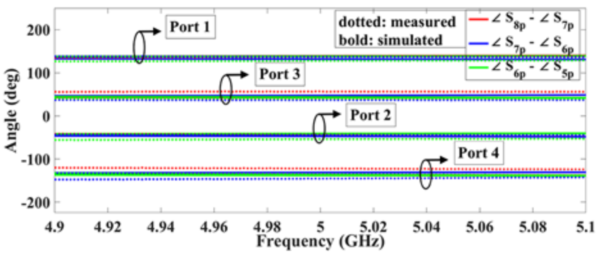

Figure 13. Comparison between full-wave simulated and measured phase difference between input and output ports of the proposed SICL butler matrix.

an area of of 0.034 λ_g^2, where λ_g is the guided wavelength at 5 GHz. The proposed SICL offers very high isolation and is highly compact compared to the other substrate integrated circuit (SIC) counterparts. The photograph of the fabricated SICL butler matrix is shown in Fig. 8. Comparison between the full-wave simulated and measured reflection and transmission coefficients of the SICL-based butler matrix when input ports, Port 1, Port 2, Port 3, and Port 4 are excited is shown in Fig 11. The proposed butler matrix demonstrates a measured return loss better than 16 dB at 5 GHz. Furthermore, measured insertion loss less than 1.78 dB when port 1, port 2, and port 3 are excited and 2 dB when port 4 is excited has been recorded at 5 GHz. The isolation between input ports is measured better than 16 dB between port 1 to port 2 and port 3 to port 4 as shown in Fig. 12. Whereas, the measured isolation is better than 40 dB between port 1 to port 3 and port 2 to port 4 owing to the high isolation offered by the proposed SICL crossover. The measured and full-wave simulated phase shift between the input and output ports in Fig. 13 shows a phase imbalance of $\sim$8.78° at 5 GHz. The deviation between measured and simulated results can be attributed due to the fabrication tolerance and air gaps created during bonding the multi-layered SICL structure.

Conclusion

In this work, design and analysis of a compact 4 × 4 butler matrix is reported. The butler matrix operating at 5 GHz utilizes a coupler modeled using open stub that is center tapped to each arm of the coupler in order to generate transmission zeros in the out of band region and reduce the overall footprint to 0.078 λ_g^2. A novel wideband SICL-based crossover to maintain high isolation between overlapping paths in the butler matrix is conceived with insertion loss less than 0.84 and 1.2 dB in path 1 and path 2, respectively. Moreover, the SICL crossover exhibits an measured isolation greater than 56 and 65 dB between the adjacent ports. Finally, a 45° and 0° phase shifter is realized using a meandered SICL-based transmission line for the proposed 4 × 4 butler matrix to provide required progressive phase shifts between the output ports. The integrated compact butler matrix shows a measured return loss better than 16 dB and insertion loss less than 2 dB at 5 GHz. SICL makes an worthy candidate due to its compact size and low cost fabrication for a variety of practical applications.

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Competing interests. None declared.

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