Compact and Broadband 4 × 4 SIW Butler Matrix With Phase and Magnitude Error Reduction

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***Abstract*—A novel two-layer 4 × 4 Butler matrix by feeding substrate integrated waveguide is designed and realized. The proposed Butler matrix has broadband operation frequency range of over 8.5 to 10.6 GHz with excellent phase and amplitude performance. The proposed design in this letter prevents the loss of amplitude and phase shifts in Butler matrix and decreases amplitude imbalance to less than 0.6 dB. This is achieved by reducing the size of Butler matrix and avoiding the use of a line length which causes a phase shift.**

***Index Terms*—Beamforming feed network, Butler matrix, microwave component, substrate integrated waveguide.**

I. Introduction

DUE to the advantages of phased array antenna overcoming multi-path fading and co-channel interference problems are playing a key role in communication systems. One of the most important sections in a phased array design is designing the beam forming network (BFN). Basically, A BFN provides the necessary amplitudes and phases to the radiating elements to produce the desired beams [1]. Thus, different solutions to provide BFN have been proposed, such as Blass matrix, Nolen matrix, Rotman lens and Butler matrix [2]. The Butler matrix has been examined in this article due to its theoretically loss-free structure and employing the minimum number of components [2]. Although Butler matrix has less loss-free feature than the cases cited, by using a lower loss radiation transmission line, the problems in array antennas which result in deficiencies like lower gain, degradation in sidelobe level and cross polarization [3] can be overcome. Through incorporating waveguide-like propagation modes and printed technology techniques Substrate integrated waveguide (SIW) technology certifies that the radiation loss is kept at an insignificant level. This property allows the SIW structure to be used with quality which is a consequential property in utilizing SIW in the design of beam steering networks. So far, many papers offered the use of SIW technology in Butler matrix feed network [2], [4]–[6] and [8]. In most cases presented so far we see that improved size and bandwidth of Butler has been taken into consideration. One of the important approaches to design a Butler matrix feed Network is employing the broadband phase shifter with low loss magnitude.

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TABLE I
Comparison of the Proposed Feed Network Structure and Measured Charactersistics With Similar Articls

Ref.	Size (λ) (Width × Length)	B.W. (%)	Phase error(deg.)	Mag. Error(dB)
[2]	3λ × 3λ	24% (11-14GHz)	±10	±0.6
[4]	3.6λ × 5.4λ	6.7% (58-62GHz)	±24	±1.26
[5]	8.1λ ×7.3λ	11% (72-80GHz)	±7	±0.75
[6]	2.86λ × 2.86λ	11.3% (25-28GHz)	±15	±0.75
[8]	4.1λ × 2.2λ	16.6% (22-26GHz)	±10	±7.6
proposed	1.7λ × 1λ	22% (8.5-10.6GHz)	±5	±0.6

In most SIW Butler matrix, it has been reported [4]–[6] and [8] that the length of feed line as phase shifter have been used. In [2], a two layer butler matrix was suggested which, was used of slot between two layer instead of line length in order to provide phase shifting. In this work, a compact and broadband 4 × 4 two layer SIW Butler matrix employing broadband phase shifter and 90° coupler is presented. In the proposed Butler matrix, using width line instead of length line along with a decreased size of the Butler Matrix (55×34 mm^2), the error of phase ($\leq \pm 5°$) and magnitude ($\leq \pm 0.6$ dB) of proposed network in comparison with same article (as shown in Table I) declined. In fact, in this letter the approach of design by combining some microwave component which have been reported in recent paper with good results (as shown in follow section) and compact size is the most important innovation of it.

II. Dimension and Result of Couplers

In order to attain a broadband Butler matrix feed network, the use of broadband components is inevitable. Two broadband SIW couplers are shown in Fig. 1 and Fig. 2. In Fig. 1(a), the structure of short slot coupler is indicated. The short-slot coupler can be realized by juxtaposing two SIWs and removing the part of the common SIW wall. In this way, an empty region (coupling region) is generated, which causes the production of TE_{20} mode. The output magnitude and phase can be controlled by changing the dimension of the coupling region. The width of the coupling region must be reduced to prevent the undesired TE_{30} mode from propagating [5]. The simulated magnitude and phase response of the short slot coupler is presented in Fig. 1(b),

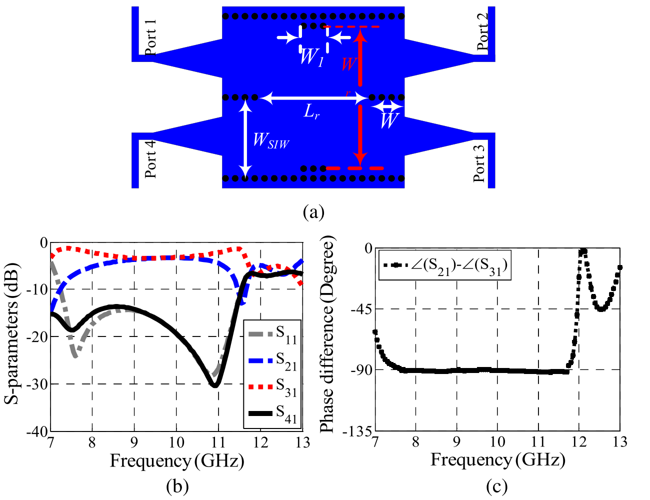

Fig. 1. Configuration and result of the short slot coupler. a) Configuration of proposed 90° coupler, b) Simulated S-parameters magnitude, and c) Simulated phase differences. $W_{SIW} = 12.5$, $W_r = 22$, $W = 5.5$, $W_1 = 4$, $L_r = 17$ (*all value in mm*).

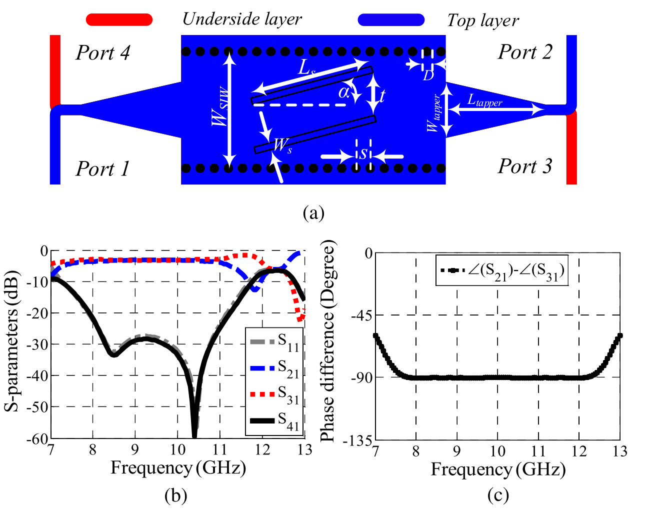

Fig. 2. Configuration and result of two layer coupler. a) Configuration of proposed two layer 90° coupler, b) Simulated S-parameters magnitude, and c) Simulated phase differences. ($W_{SIW} = 12.5$, $L_s = 13.2$, $W_s = 0.7$, $W_{tapper} = 6$, $L_{tapper} = 10.6$, $s = 1.5$, *and* $D = 1$ (*all value in mm*)) $\alpha = 15°$.

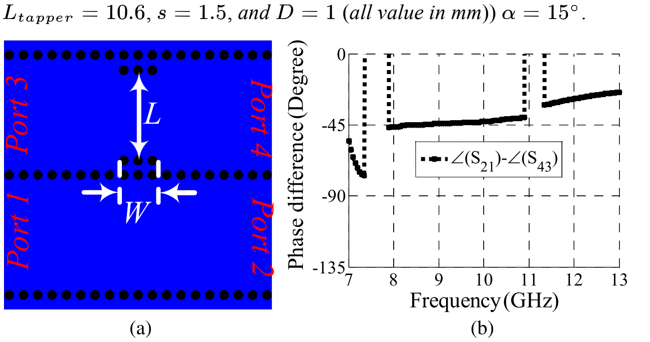

Fig. 3. Configuration and response of 45° phase shifter. a) Configuration of proposed phase shifter, and b) Simulated phase differences. ($W_1 = 5.5$ mm, $L = 9.4$ mm).

(c). As shown in Fig. 2(a), the two-layer SIW coupler includes two parallel waveguides coupled via two narrow oblique slots in the joint broad copper sheet. For further details of the proposed coupler, the reader is referred to [7]. The coupler has been optimized for a −3 dB coupling value with 90° phase difference between the coupled and direct ports. The simulated results show a peak-to-peak error for the coupling coefficient less than 0.5 dB over the 7.4–11 GHz frequency band, while isolation and reflection coefficients are below −15 dB with a relative phase difference which is almost constant at −90° [as shown in Fig. 2(b), (c)] [2].

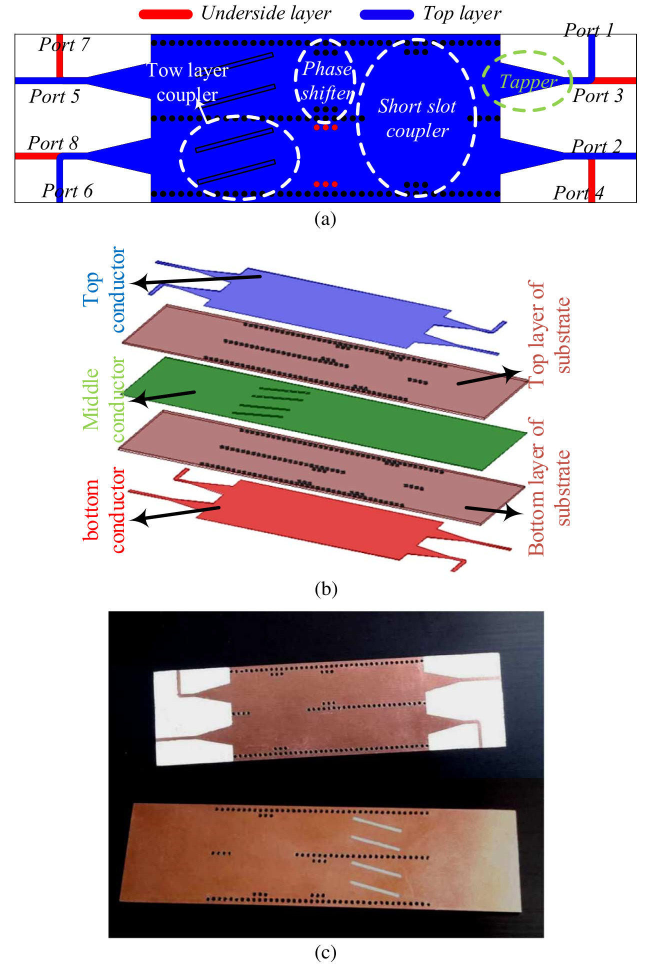

Fig. 4. Configuration of proposed two layer Butler matrix. a) Top view, b) Layered perspective view, and c) Prototype of configuration.

III. Phase Shifter

Phase shifters are a significant part of phased array feed networks, so a broadband phase shifter can develop those bandwidths. In [1]–[7], the length of the line has been exploited to make a phase shifter without changing the line width, a phase shifter with compact size and fixed length can be achieved by varying the propagation constant β of an SIW. It causes a change in the group velocity of the wave. The configuration and phase response of proposed 45° delay line is shown in Fig. 3. The proposed phase shifter structure has been implemented based on the [9]. As introduced in [9], the phase difference when width of line is changed, is calculated by (1):

$$\varphi(f) = \left\{ \sqrt{\left(\frac{2\sqrt{\varepsilon_r} f}{300}\right)^2 - \left(\frac{1}{\omega_{e2}}\right)^2} - \sqrt{\left(\frac{2\sqrt{\varepsilon_r} f}{300}\right)^2 - \left(\frac{1}{\omega_{e2}}\right)^2} \right\} \quad (1)$$

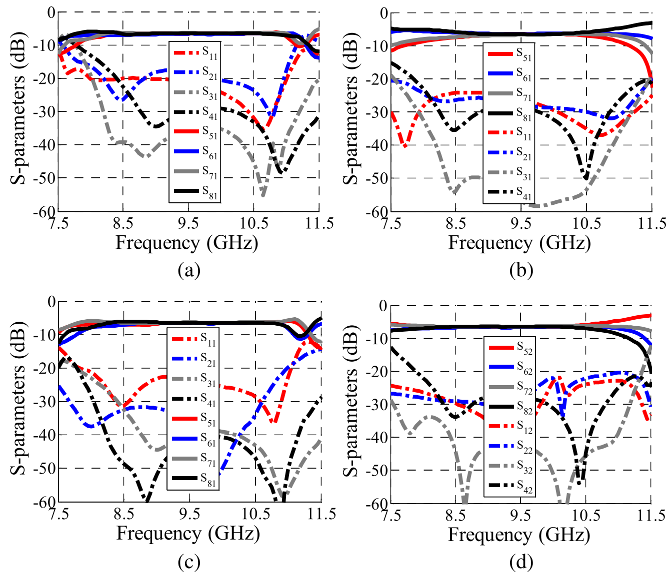

Fig. 5. Simulated and Measured S-magnitudes of the proposed Butler matrix. a) Simulated magnitude for port 1, b) Measured magnitude for port 1, c) Simulated magnitude for port 2, and d) Measured magnitude for port 2.

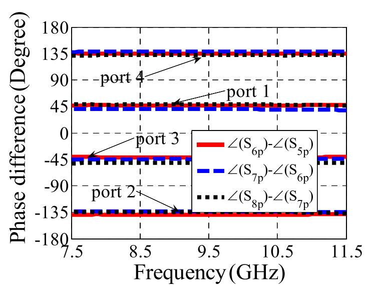

Fig. 6. Differential phase for all four ports. Here, p is the input port number.

which

$\varphi(f)$ phase shift [phase ($S_{21} - S_{43}$)] of this phase shifter;

ω_{e1}, ω_{e2} two different equivalent widths ω_{e1} and ω_{e2} ($\omega_{e1} < \omega_{e2}$);

ε_r material's relative permittivity.

IV. Butler Matrix Result and Discussion

In Fig. 4 the configuration of proposed two layer Butler matrix is demonstrated. Formation of the proposed 4 × 4 SIW Butler matrix was designed and constructed on Rogers 4003 with the dielectric substrate thickness of $h = 20$ mil (0.508 mm) and relative permittivity of $\varepsilon_r = 3.55$. As indicated in Fig. 4, the Butler structure is constructed from two type of coupler illustrated in Fig. 1, Fig. 2 and the phase shift of Fig. 3. By stimulating port1 in 4 × 4 Butler matrix, after crossing the microstrip line and taper transformer (EH mode) the signal is applied to the SIW structure (TE_{10} mode). The input signal with generated TE_{20} mode in coupling region is coupled with the other side with 90° phase shifting. Then, it passes through the broadband 45° phase shifter and enters the output coupler (Fig. 2). In output coupler, the input signal shifted with 45° is observed in port 5 and after coupling from slots to underside layer (TM mode), a signal with 135° phase is obtained. In the other side, after leaving the short slot coupler and passing any phase shifter the output signal arrives to the two layer coupler. After crossing in to ports 6 and 8, the signal is obtained as 90 and 180° phase shift, respectively. Eventually, the signal is divided to equal amplitude($= -6$ dB) and obtained as 45, 90, 135, and 180° phase shifted at 5–8 output ports, respectively. This method can be generalized to the other ports. The phase and magnitude S-parameters of the proposed Butler Matrix were measured using the Agilent 8722ES vector network analyzer.

Measurement method is similar to the procedure set forth in [2]–[8]. In Fig. 5(b), (d) the measured S-parameters of the proposed 4 × 4 compact feed network for the input ports 1 and 2 are presented. As indicated in Fig. 5(b), (d), the measured −6 dB bandwidth for port 1 is over 8.5 to 10.6 GHz where Si, 1 (i =1, 2, 3 and 4) is less than −20 dB and the measured −6 dB bandwidth for port 2 is from 7.7 to 10.6 GHz. As displayed in Fig. 5(a), (b), the amplitude imbalance is less than 0.6 dB. The phase difference between the two different outputs is plotted in Fig. 6. As indicated in Fig. 6, optimized phase dispersions of two different output ports are less than 5° over the frequency range of 8.6–10.6 GHz. The proposed matrix has better phase and amplitude performance while maintaining a more compact size than in [6].

V. Conclusion

A broadband 4 × 4 SIW Butler matrix with compact size has been presented. The proposed Butler matrix consists of two 90° couplers and a broadband phase shifter that allows us to obtain a broadband operated frequency range. The −3 dB bandwidth of proposed Butler matrix is about 22% with a peak-to-peak error which is less than 0.6 dB over the 8.5–10.6 GHz frequency band and the phase error is less than 5°.

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