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Optically Transparent Compact 4×4 Butler Matrix for Wi-Fi Applications

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Abstract—In this paper, an optically transparent (OT) compact 4×4 Butler matrix (BM) operating at 2.4 GHz for Wi-Fi applications is proposed. The device has structured grids refined in quadrilateral cell shapes. The dimensions of cells are chosen based on a simple formula which guarantees a minimum required transparency level in conjunction with a limited rounds of optimizations. A theoretical optical transparency value of 76.2% has been obtained without affecting the excellent electrical performance of the BM. Moreover, complimentary square split ring resonators (CS-SRRs) are patterned in the ground plane of each transparent transmission line in the BM. This loading technique provides a relative size reduction of 16.6% compared to a conventional structure. Simulated and measured results of the proposed design agree well with conventional BM's results. The proposed technique and its related features can be expanded to other microwave devices.

1. INTRODUCTION

Butler matrices (BM) are essential parts in several wireless communication systems because of their ability to support multiple antennas communications [1]. In the last decade, several compact Butler matrices based on different miniaturization techniques have been proposed [2–6]. For example, a compact adaptive BM that provided continuous beam steering using controllable phase shifters was proposed in [2]. These phase shifters were able to fill the angular sectors between two adjacent beams. In [3], compact unit cells with lumped elements were deployed into crossovers and directional couplers to obtain a compact 4×4 BM which provided arbitrary power division ratios. However, most of these miniaturization techniques change the shape of conventional structure. Recently, a simple and effective split ring resonator (SRR)-based loading technique has been applied to miniaturize the physical size of conventional MW circuits [7]. At frequencies below their resonant frequencies, SRRs have a series inductive loading effect, which can be exploited to shorten transmission lines' physical lengths, i.e., the lines become relatively slow wave transmission mediums, having increased electrical lengths without increasing their physical lengths. Consequently, a physical size reduction can be achieved without affecting the electrical response of these lines. A quantitative performance study of this phenomenon has been introduced in [8].

Transparent transmission lines (TLs) have been proposed to decrease the possible disagreeable visual effect of conventional transmission lines [9]. Most of these structures are deployed into visible antenna designs to hide them from individual's eyes, and therefore, overcome visual beauty degradation when installing such devices [9]. Other RF front-end devices attached to such antennas can be designed in transparent layouts in order to have fully optically transparent systems. The electrical performance of transparent transmission lines and circuits have been described in several works [9–12]. It was shown

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that if the spacing between grid meshes was small compared to the guided wavelength, then, the meshed TL could be considered as a solid line [9].

This paper proposes a 4×4 transparent and compact Butler matrix to allow beamforming and channel capacity improvement in Wi-Fi links operating in the 2.4 GHz band. This circuit can be attached to different multiple transparent antennas to create radio beams in specific prescribed directions.

2. TRANSPARENT COMPONENTS FOR THE PROPOSED BUTLER MATRIX

In general, the higher transparent value of a meshed transmission line is, the higher its sheet resistance value is [13]. Therefore, a compromise between the visual properties of a meshed TL and its electrical performance is necessary [10]. From a practical point of view, a minimum acceptable transparent value of 70% is required for a human eye to consider a layer as transparent. The theoretical transparent value (T%) depends on the theoretical pitch of the mesh (p) and the theoretical strip width (s) according to the formula: $\mathrm{T}(\%) = (p - s)^2/p^2$ [12].

Figure 1 shows the layout of a meshed quarter-wavelength-microstrip TL loaded by a complimentary square SRR inclusion in its ground plane and its corresponding scattering parameters. The insertion loss of the line is less than 0.2 dB at the operating frequency (2.4 GHz), and a nonlinear phase shift response ($< S_{21}$) has been obtained, which explains the miniaturization feature of this line. The resonant frequencies (f_r) of the SRR inclusions must be higher enough ($f_r > 1.5 f_o$) than the device's operating frequency (f_o) [8]. This condition guarantees a proper inductive loading effect, and hence, a good miniaturization level with an acceptable radiation loss value, and almost a preserved passband bandwidth [7]. Meshed complimentary square-SRRs are patterned in the ground planes of each subcomponent in the BM. Their resonant frequency equals 4 GHz which allows an acceptable compactness factor ($> 15\%$) without a significant negative impact on the electrical performance of the device. The dimensions of the square SRR, which define the resonant frequency value can be calculated using the formulas introduced in [14] or using built-in optimization tools. A slight shift to the right of less than 0.2 GHz has be noticed in the resonant frequencies of the SRR-based meshed transmission lines, compared to solid SRR-based TLs, due to the inductive effect of meshes on C-SRRs. This shift can be adjusted with a few rounds of optimizations.

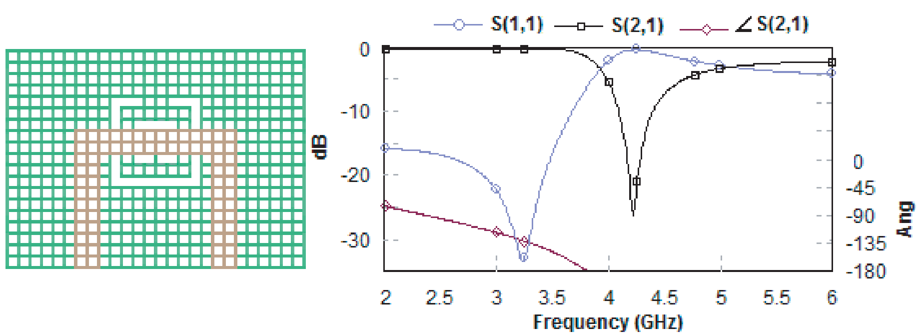

Figure 1. Layout and simulated response of a meshed CS-SRR loaded transmission line.

Figure 2(a) shows the layout and simulated response of the proposed hybrid branch line coupler. The coupling levels around the operating frequency is close to the theoretical values with an error of less than 0.3 dB. Satisfactory values of isolation and return loss values are obtained (> 20 dB). A quadrature phase difference between the output ports with an error of less than 2^0 at 2.4 GHz is achieved with linear phase variation across the whole bandwidth (~ 0.35 GHz). The amplitude imbalance value between the output ports is less than 0.15 dB, and return loss/isolation values are more than 20 dB within the passbands. Figure 2(b) displays the layout and response of the new crossover. Excellent performance has been demonstrated, which includes low insertion loss at the diagonal port of less than 0.4 dB, input-ports return losses greater than 20 dB, and a minimum port isolation of 20 dB.

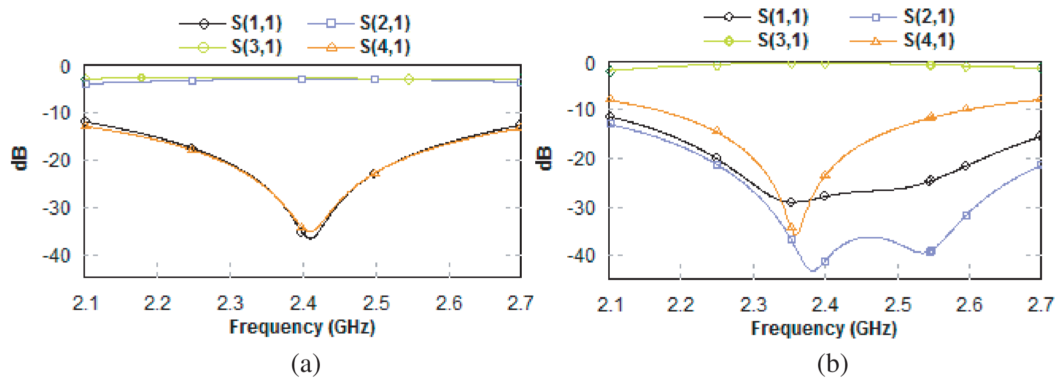

Figure 2. Simulated s-parameters of: (a) HBLC; (b) crossover used in the BM.

3. COMPACT TRANSPARENT BUTLER MATRIX

The above structures have been brought into a conventional 4×4 Butler matrix as shown in Figure 3. A plastic substrate having a height of 1.6 mm and relative permittivity of 3 has been used for the design. The mesh's size was adjusted to satisfy two conditions. Firstly, the transparent value should be ranged between 70% and 80%. Secondly, the width and length of all strips in the Butler matrix should fit an integer multiple number of meshes. Thirdly, the width of each meshed transmission line in the BM equals the width of its equivalent conventional line, and hence, they will have approximately the same characteristic impedance value. According to these conditions, the dimensions of each mesh in the BM equals 2.05 mm $\times$ 2.05 mm, and the mesh strip's width equals 0.26 mm. Therefore, the theoretical transparency value equals 76.2%.

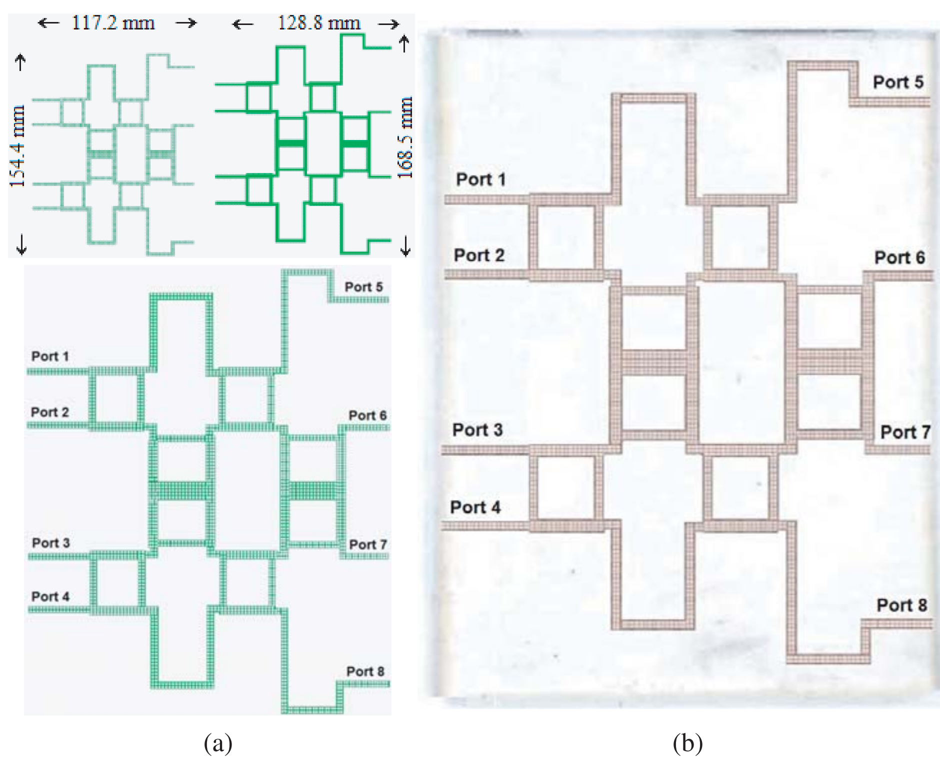

Figure 3. Proposed Butler matrix operating at 2.4 GHz. (a) Layout of the proposed BM with a size comparison to a conventional BM in the upper left corner; (b) Photograph of the top layer of the proposed BM.

In the new BM, an imbalance response of less than 2 dB between the input and output ports is noticed. This can be explained as: (i) the relatively high sheet resistance values for the meshed TLs which affect their characteristic impedance values (ii) different miniaturization levels that each subcomponent is experienced. Therefore, a limited number of optimizations were necessary to enhance the previous results. The optimization of layout includes the transmission lines at the input ports which explains their relatively extra lengths. It was shown that a narrowband response (as expected) is achieved with a fractional bandwidth in passband of 8% and a layout's dimensions of 154.4 mm $\times$ 117.2 mm. The phase and magnitude imbalance values that define the device's bandwidth are 4^0, and 0.5 dB, respectively.

For the sake of comparison, a conventional BM has been designed and simulated on the same

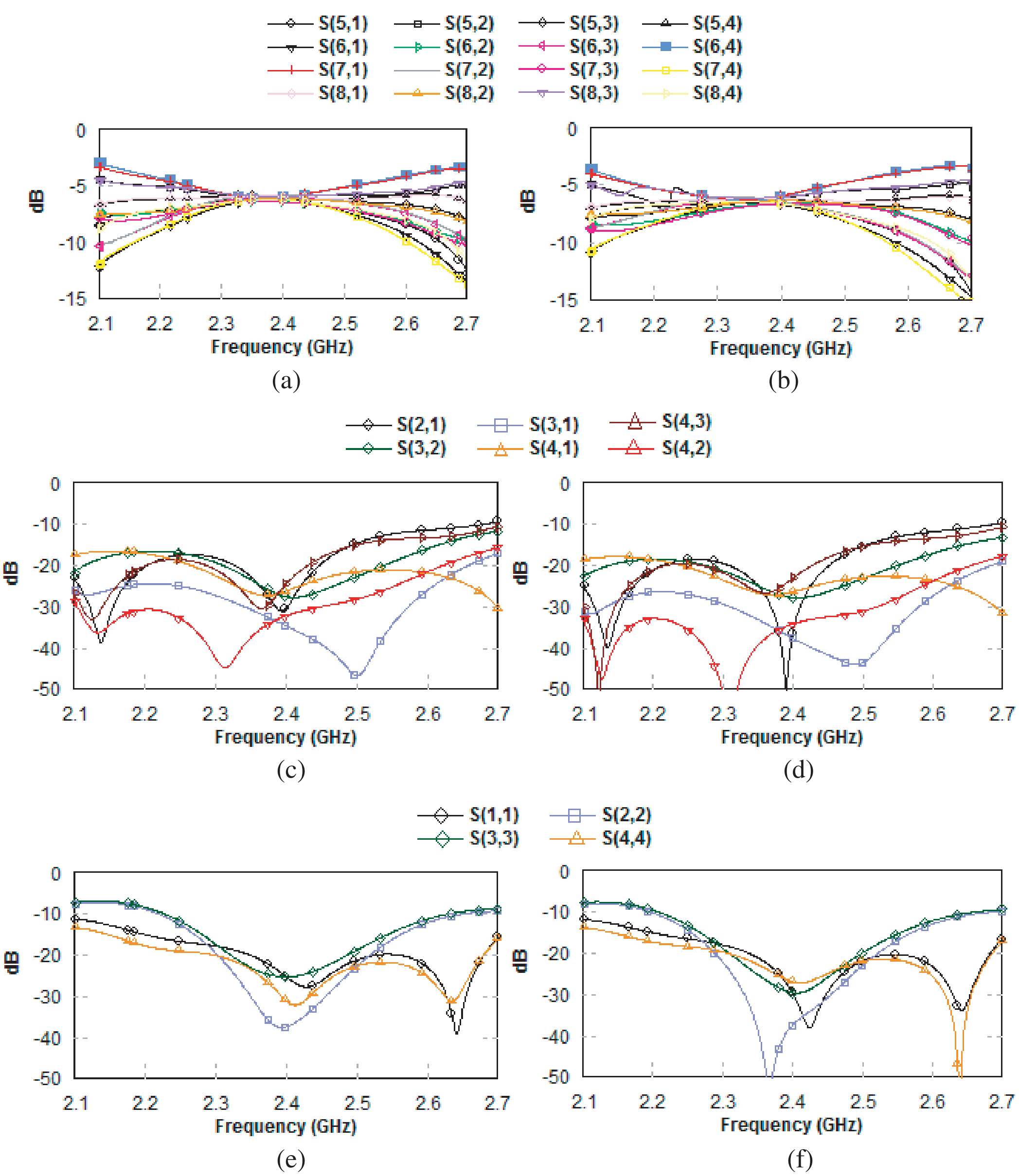

Figure 4. Scattering parameters of the meshed CS-SRR loaded BM. (a) Simulated coupling *s*-parameters; (b) Measured coupling *s*-parameters; (c) Simulated isolation values between input ports; (d) Measured isolation values between input ports; (e) Simulated reflect losses at the input ports; (f) Measured reflection losses at the input ports.

substrate at the same operating frequency. The dimensions of the conventional BM are: 168.5 mm × 128.8 mm. Therefore, a miniaturization factor in size of 16.6% has been achieved. The fractional bandwidth is slightly changed to be 10% based on the same aforementioned criteria. Thus, the design involves a trade-off between its compactness factor and transparency level on one hand, and the passband bandwidth and losses on the other hand.

Simulated and measured results for the device are shown in Figure 4. Very good couplings between input and output ports have been obtained. The differences among measured, simulated and theoretical s-parameters' amplitudes are less than 0.6 dB (All values < 6.7 dB). Moreover, excellent isolation values (> 20 dB) and return losses (> 16 dB) at the input ports are archived. Therefore, the proposed BM demonstrates a very good electrical performance.

Table 1 shows the simulated and measured input/output scattering (phase) characteristics of the BM at 2.4 GHz. Absolute errors of less than 3^0 between simulated and measured scattering parameters' phases have been achieved. Furthermore, Table 2 shows the input/output coupling characteristics for the BM. Simulated and measured values are in very good agreement and close to the theoretical results, which verifies our proposed BM.

Table 1. I/O scattering (phase) characteristics.

Port		5	6	7	8
1	Sim.	135.5	89.3	47.1	1.7
	Mea.	134.5	89.1	42.8	−2.1
2	Sim.	45.8	180.7	−46.7	91.1
	Mea.	43.6	−179.5	−44.5	90.4
3	Sim.	90.2	46.8	−181.2	44.2
	Mea.	89.3	−43.6	−177.1	46.3
4	Sim.	0.5	45.2	91.4	135.8
	Mea.	−0.6	43.3	88.8	133.9

Table 2. I/O coupling characteristics.

Port		5	6	7	8
1	Sim.	−6.47	−6.49	−6.11	−6.0
	Mea.	−6.61	−6.69	−6.04	−6.16
2	Sim.	−6.02	−6.31	−6.22	−6.17
	Mea.	−6.12	−6.59	−6.42	−6.35
3	Sim.	−6.14	−6.36	−6.38	−5.92
	Mea.	−6.31	−6.58	−6.65	−6.03
4	Sim.	−6.01	−6.04	−6.40	−6.44
	Mea.	−6.18	−6.02	−6.56	−6.64

4. CONCLUSION

An optical transparent and compact BM that operates at 2.4 GHz is proposed. Simulated and measured results of each part of the matrix showed excellent agreement with its conventional design's results, in terms of bandwidth, isolation levels, return losses and insertion losses. The meshes' sizes were chosen to satisfy an accepted transparent value of 76.2% and fit the characteristic impedances of the device's transmission lines. The compact size of the new circuit was achieved using a SRR-based loading technique, where a miniaturization factor of 16.6% compared to a conventional BM designed on a similar substrate was obtained.

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