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COMPACT PLANAR MICROSTRIP CROSSOVER FOR BEAMFORMING NETWORKS

B. Henin* **and A. Abbosh**

School of ITEE, The University of Queensland, QLD 4072, Australia

Abstract—The design of a fully planar microstrip crossover for beamforming networks is presented. The design starts by using a conventional half-wavelength square patch and two sets of orthogonal feeding lines. Rectangular and circular slots are introduced on the square patch in order to reduce the required area of the patch by 82%. The proposed crossover is fabricated and tested for performance confirmation. The measured data shows less than 1 dB insertion loss, more than 13 dB isolation, and around 0.1 ns deviation in the group delay across 12% fractional bandwidth. The proposed crossover is suitable for planar Butler matrix which is a key component in beamforming networks.

1. INTRODUCTION

Crossing transmission lines is a common problem in most modern beamforming networks. Butler matrix is the key component of those beamforming networks that are widely applied in smart antennas [1, 2]. It is a passive microwave network consisting of N input and N output ports. Depending on which of the N inputs are accessed, the network can generate a set of N orthogonal beams to feed an array of N antennas. The Butler matrix contains one or more crossover circuits. The poor isolation and high return loss caused by an improperly designed crossover dramatically reduce the performance of the Butler matrix, and eventually, the whole system using it.

An ideal four-port crossover provides 0 dB insertion loss to the diagonal ports and perfect high level of isolation to the adjacent ports. The traditional way used in beamforming networks to isolate the signals on the intersection is to use a three-dimensional structure, e.g., bond wires, air bridges or multi-layer structures [3–7]. The use of

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* Corresponding author: Bassem Henin (b.henin@uq.edu.au).

those non-planar structures increases the fabrication complexity and cost significantly.

In the literature, a few fully planar structures are proposed, such as the conventional approach of cascading hybrid and symmetric four-port junctions [2, 8–12]. The cascaded structures utilized in [2, 8] result in a large size, whereas the use of very thin lines [9] limits the power handling capability, which is crucial factor in the beamforming networks of microwave transmitters. The structures presented in [10–12] uses slotted grounds and thus they are not perfectly compatible with uniplanar microstrip circuits.

We propose a new planar four-port crossover in this letter. The main features of the proposed device are the full planar structure without any slots in the ground, the compact size, and the high power handling capability that enables its use with transmitting beamforming networks. The starting point of the design is a conventional square microstrip patch with two pairs of orthogonal microstrip feeding lines [13]. Following the procedure explained in [14–17] for different types of couplers, the size of the patch can be reduced by etching slots in the patch or in the ground plane. The proposed crossover in this paper uses two perpendicular rectangular slots and four arc-shaped slots on the patch to reduce the size. The added slots enable a huge 82% reduction in the size as proved by simulations and measurements.

2. THEORY

According to the cavity theory [13], a microstrip square patch as depicted in Fig. 1 can be represented as a dielectric loaded cavity. If the thickness of the substrate is very small compared with the wavelength, the fringing fields along the edges of the patch are very small. In this case, the only field in the cavity is the transverse magnetic (TM) field configuration. Following the analysis presented in [13], it is possible to show that the two fundamental modes of the structure are TM100 and TM010. They have the following resonant frequency

$$f_r = \frac{c}{2l\sqrt{\varepsilon_r}} \tag{1}$$

ε_r: Dielectric constant of the substrate, c: Speed of light in free-space, and l: Length of the patch.

The field distributions for the mode TM100 are [13]

$$H_y = A_3 \sin(\pi x/l); H_x = 0 \tag{2}$$

While or the mode TM010, they are [10]

$$H_x = A_2 \sin(\pi y/l);\ H_y = 0 \tag{3}$$

A_i: Amplitude of the fields.

The above results indicate that the two fundamental modes have orthogonal magnetic fields. According to the Poynting vector theory [18], the signal flows in the x-direction for the TM100 mode and in the y-direction for the TM010 mode. Thus, each face-to-face pair of ports can be properly aligned to couple one of those modes. In this case, the isolation is high between the two pairs of ports while a low insertion loss is maintained between the face-to-face ports.

The initial dimensions of the square patch depicted in Fig. 1 and its four feeding lines are calculated using (1) and microstrip design equations assuming the resonant frequency= 2.4 GHz, and 50 Ω for the characteristic impedance of the four ports. Using Rogers RT6010LM (thickness 0.64 mm and $\varepsilon_r = 10.2$) as the substrate, the dimensions are: $W = 30$ mm, $L = 20$ mm and $W_f = 0.67$ mm. The simulated performance of the designed crossover is depicted in Fig. 2. It is to be noted that due to symmetry $S_{11} = S_{22} = S_{33} = S_{44}$, $S_{13} = S_{24}$, and $S_{12} = S_{34}$.

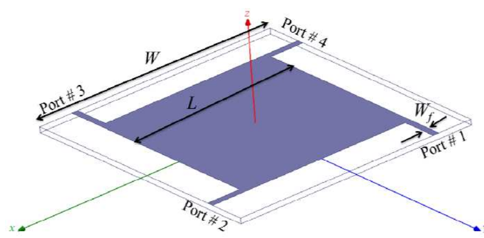


Figure 1. Square microstrip patch crossover.

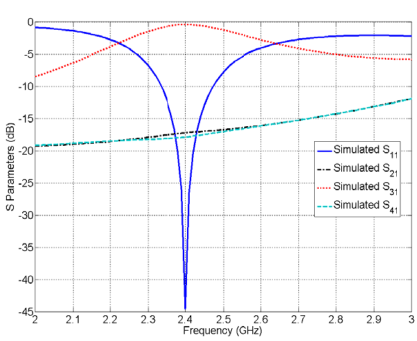


Figure 2. Simulated S parameters of the square patch crossover.

Figure 2 shows an insertion loss less than 1 dB, return loss more than 10 dB, and isolation of 15 dB over 8% fractional bandwidth. The main drawback in the design that prohibits its use in compact Butler matrices is the large size of the utilized structure. Thus, the next step of the design, which is the contribution of the current work, is the miniaturization of the size so that the crossover can be utilized in the applications that have limited space for the intersections.

3. MINIATURIZED CROSSOVER

In order to reduce the required length of the utilized patch from half wavelength, as needed in the previous design, to quarter wavelength or shorter, two perpendicular rectangular slots of length l_1 and width w_1 are introduced inside the square patch. The modified crossover #1 is shown in Fig. 3.

The dimensions of the square patch are $W = 30\,\text{mm}$, $L = 20\,\text{mm}$ and $W_f = 0.6\,\text{mm}$) as in the initial patch design. Fig. 4 shows the simulated results for the reflection coefficient at port 1 for different lengths l_1 of the slots with constant slot width $w_1 = 1\,\text{mm}$. It is clear from the figure that the resonant frequency shifts to lower values as the length of the rectangular slots increases. The resonant frequency when using a short rectangular slots of length $l_1 = 5\,\text{mm}$ is 2.35 GHz, while it is around 1.3 GHz for $l_1 = 25\,\text{mm}$. This result gives a clear indication that the size of the crossover can be reduced significantly by using those slots if the resonant frequency is kept constant at 2.4 GHz.

To give a physical insight into the effect of the utilized slots, the following explanation is given. Incorporating those slots on the patch forces the current to detour around the slots, and therefore increases the effective inductance of the signal path and slows down the wave propagation. This phenomenon lowers the resonant frequencies of the patch. Increasing the length of the slots increases the inductance of

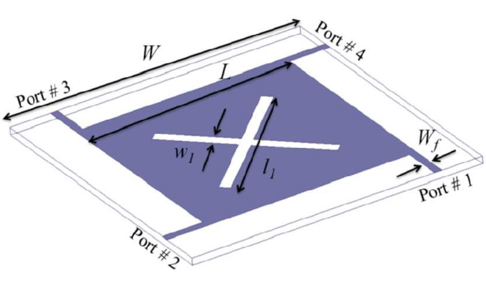


Figure 3. Modified crossover #1 using two perpendicular slots.

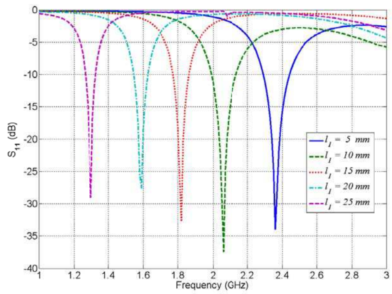


Figure 4. Reflection coefficient at port 1 of the modified patch crossover for different slot lengths.

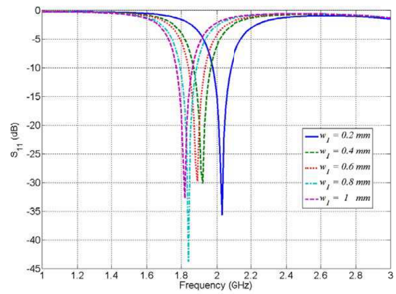


Figure 5. Reflection coefficient at port 1 of the modified patch crossover for different slot widths.

the signal and then reduces the resonant frequencies. Thus, the length of the slots is the key parameter in the amount of reduction in the size.

Figure 5 shows the simulated results for the reflection coefficient of port 1 for different slot widths w_1 with fixed slot length $l_1 = 15\,\text{mm}$. The figure shows that increasing the slot width shifts the resonant frequency of the designed crossover to lower values. It is clear from the results that the shift in the resonant frequency due to the increase in w_1 is small in comparison with the effect of l_1 as depicted in Fig. 4.

For the modified structure that includes a pair of crossed slots (Fig. 3), the dimensions W, L, l_1 and w_1 are optimized to make the resonant frequency constant at 2.4 GHz for a compact size. The values in (mm) of the optimized parameters are: $W = 20$, $L = 13.6$, $l_1 = 13$ and $w_1 = 0.5$. In this case the length of the square patch is reduced to $0.34\lambda g$ compared with $0.5\lambda g$ for the original design. This new length achieves more than 50% reduction in the overall area of the crossover.

It is clear from the previous results that increasing the length of the slots inside the patch enables size reduction. However, the length of the slots inside the patch is limited by the patch size. Thus, different types of meandered slots are investigated for a possible miniaturization. In one of the approaches, four arc-shaped slots of width w_1 and separation distance w_2 are added at the end of the rectangular slots as explained in the modification #2 depicted in Fig. 6. The dimensions of the slots are optimized for a smallest size while maintaining or even enhancing the bandwidth of the crossover. Fig. 7 shows the simulated results for the reflection coefficient of port 1 for different separation distances w_2. The other dimensions are: $W = 20\,\text{mm}$, $L = 13.6\,\text{mm}$, $l_1 = 12\,\text{mm}$ and $w_1 = 0.2\,\text{mm}$. Fig. 7 indicates that reducing the separation distance shifts the resonant frequency to lower values. This

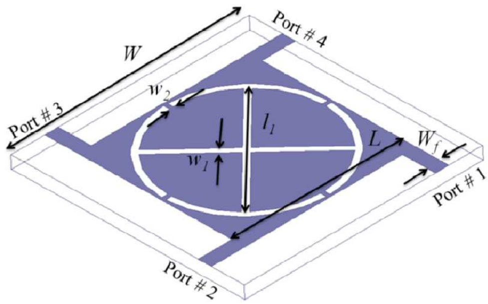


Figure 6. Modified crossover #2.

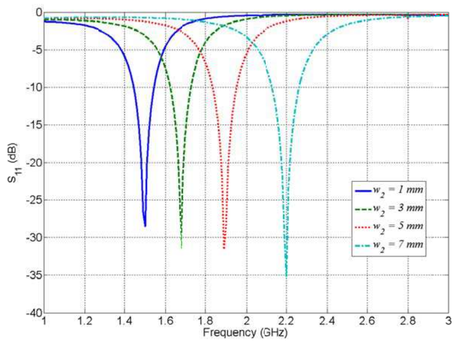


Figure 7. Reflection coefficient at port 1 of the modified patch crossover for different separation distances w_2.

effect can be explained by the fact that reducing w_2 means that longer slots are used and thus the resonant frequency shifts to lower values.

The crossover is optimized to work at 2.4 GHz using the same substrate of the initial design. The optimized dimensions are: $W = 13$ mm, $L = 8.6$ mm, $l_1 = 8.4$ mm, $w_1 = 0.2$ mm and $w_2 = 0.2$ mm. The size of the new design is only 18.5% of the initial design.

In order to increase the effective length of the slots, more circular slots can be added to the rectangular slots as shown in the modified crossover #3 in Fig. 8. For a resonant frequency at 2.4 GHz, the side length of the patch L can be reduced to 8 mm using seven sets of circular slots relative to 8.6 mm with only one set of circular slots. The reduction in size using those seven sets of circular slots is not significant compared with the modified structure #2. Moreover, it is not a preferred option to use so many slots in the patch as this approach may limit the power handling capability of the crossover if used in beamforming networks of high power transmitters.

Another possible technique to increase the effective length of the slots is to use meandered lines instead of straight lines as shown in Fig. 9. However, a parametric analysis indicates that modification #4 does not achieve significant size reduction as compared with the modified crossover #2. For the modification #4, the optimum length of the patch L can be reduced to 9.5 mm.

Based on the aforementioned discussions, the modified structure #2 is selected for the fabrication as shown in Fig. 10. Fig. 11 shows the simulated and measured results for the return loss, insertion loss and isolation of the reduced size crossover. The results show a very good agreement between the simulated and measured results. The crossover has less than 1 dB insertion loss and more than 13 dB isolation across 12% fractional bandwidth. The return loss is more than 20 dB at 2.4 GHz.

The deviation in the group delay and the phase performance for the proposed crossover are depicted in Fig. 12. The variation in the group delay is around 0.1 ns across the whole bandwidth and the phase shows a reasonably linear phase variation at the band of interest. This

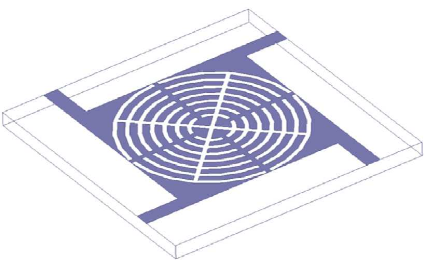


Figure 8. Modified crossover #3.

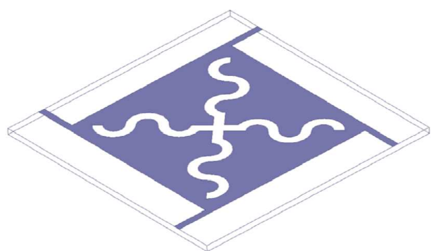


Figure 9. Modified crossover #4.

Figure 10. Fabricated prototype of the reduced size square patch crossover.

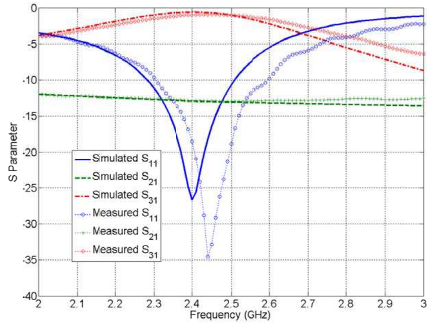
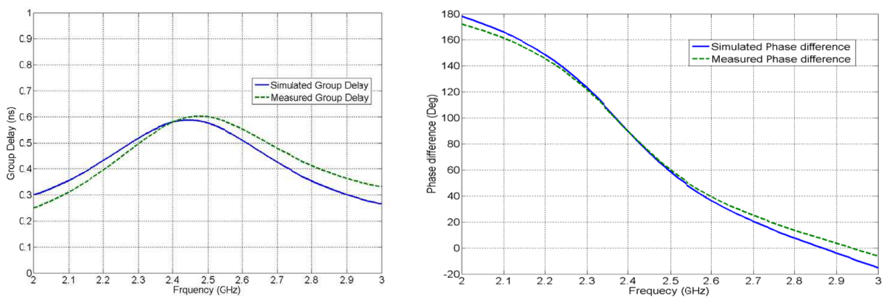


Figure 11. Simulated and measured S parameters of the reduced size square patch crossover.



(a) (b)

Figure 12. Reduced size square patch crossover (a) group delay and (b) transmission phase.

deviation in the group delay is an attractive very small value that guarantees a distortionless performance across its bandwidth.

In order to quantify the level of the radiation losses, the designed crossover is simulated while it is enclosed within a metallic shielding box. It is noticed that the insertion loss at the center frequency 2.4 GHz decreases from 0.7 dB without enclosure to 0.5 dB with the enclosure. This result means that the proposed structure has around 0.2 dB radiation loss, which is a very low value.

The proposed crossover does not use any slots in the ground plane. The signal transmission across the two crossing lines is achieved using a wide microstrip patch. The device has a flat group delay indicating a linear phase variation with a distortionless performance across its band of operation. Those features enable the use of the crossover in the beamforming networks of high power transmitters.

4. CONCLUSIONS

The design of a planar microstrip crossover has been presented. The proposed crossover utilizes a square microstrip patch with four perpendicular microstrip feeding line. To reduce the size, two perpendicular rectangular slots and four arc-shaped slots are introduced inside the patch. The simulated and measured results have shown less than 1 dB insertion loss, more than 10 dB return loss, more than 13 dB isolation and less than 0.1 ns deviation in the group delay across 12% bandwidth centered at 2.4 GHz. Furthermore, the crossover has a high power handling capability with a compact size of 8.6 mm $\times$ 8.6 mm. Those features are welcome in many applications especially for beamforming networks.

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