A Planar Monopulse Comparator Network Design from Port-Transformation Rat-Race Coupler

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***Abstract*—In this paper, a planar monopulse feeding network is designed using port-transformation rat-race couplers. The proposed port-transformation coupler is designed to symmetrically allocate the sum/delta ports with input ports, where a zero-phase delay crossover is designed to transform the unsymmetrical ports in the conventional rat-race coupler. This novel rat-race coupler resolves the issues in monopulse feeding network design e.g., multilayer, and expensive fabrication. To verify the theory, a planar monopulse comparator network operating at 2GHz is designed, simulated, and tested. A good agreement has been achieved between measurement and simulation results.**

Keywords—Monopulse comparator network, novel coupler, microwave circuits, symmetrical planar structure.

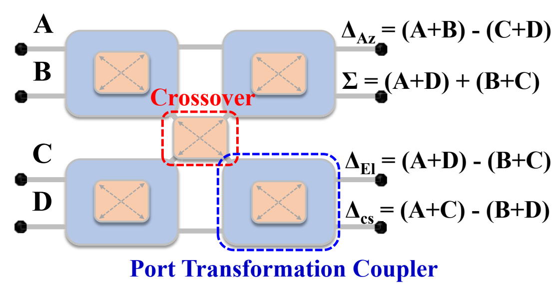

Fig. 1 Schematic of proposed symmetric uni-planar monopulse comparator network.

I. Introduction

Monopulse phased array systems are widely applied in high accuracy measurement such as tracking radar, wireless communications [1]-[3], gesture sensing, and even weather observation. As the vital components of monopulse array, the comparator network can preprocess the received signal in its pristine analog waveform from antenna elements to locate the target under detection. To achieve analog operations such as addition and subtraction, the comparator network requires four identical 180° couplers. In the previous works, either four rat-race couplers [4] or four 90° coupler plus 90° phase shifters [5] are implemented to realize unsymmetrical comparators, from which the additional delay lines often result in limited operating bandwidth, and amplitude imbalance. The symmetrical comparators were proposed to resolve the issues in unsymmetrical topology, but they require complicated structure and expensive fabrication process. For example, in [6], it proposes a symmetrical port 180° coupler by combining in-phase power splitter and Marchand balun, while the air bridge is applied to connect the couplers. In [7] - [8], multi-layer microstrip and substrate integrated waveguide (SIW) are used to design the comparator network. The same direction of output ports 180° planar hybrid coupler is proposed in [9] by utilizing multi-section transmission between two off-the-shelf couplers, and a fully symmetric planar monopulse is designed using cascaded hybrid couplers to achieve narrow bandwidth [10] - [11]. In summary, all the above are trying to resolve the layout difficulty of 180° coupler in the planar comparator network, where the sum (Σ) and delta (Δ) ports of rat-race coupler is crossed by input and isolated ports.

To overcome the challenges in conventional monopulse comparator network as unsymmetric topology, amplitude imbalance, etc., a novel planar symmetric comparator network is proposed in this paper as shown in Fig.1, where it is composed of four novel port-transformation 180° couplers and a zero-phase delay microwave crossover. To verify the design theory, the proposed comparator network is simulated and measured.

II. Design Theory of Novel Comparator Network

A. Novel Port-transformation 180° Coupler

As shown in Fig. 1, the proposed monopulse comparator network consists of four novel port-transformation 180° couplers and a zero-phase delay crossover, and the coordinate information along azimuth and elevation plane can be obtained

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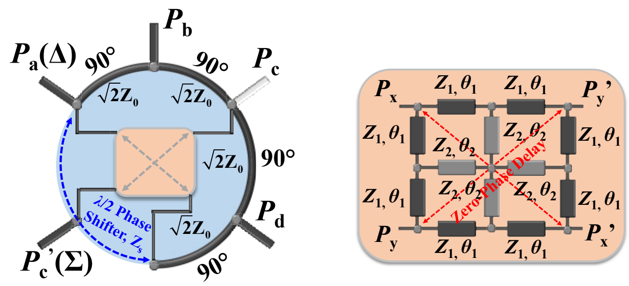
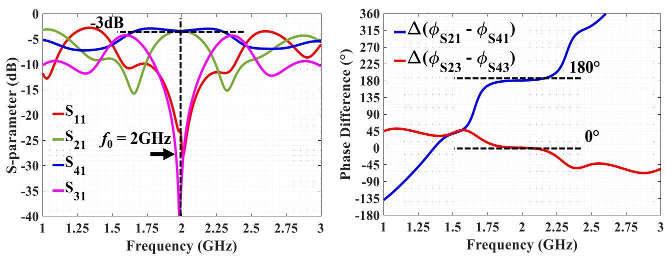


(a) (b)

Fig. 2 Proposed novel 180° coupler: (a) schematic diagram (b) zero-phase delay microwave crossover.



(a) (b)

Fig. 3 Simulation results of the proposed novel 180° coupler: (a) magnitude response (b) phase difference based upon input on sum and delta ports.

after the antenna received signal passing through the network. Here, the port-transformation 180° coupler relocates the sum and delta ports are on one side such that they do not cross by its input and isolated ports. The schematic diagram of proposed novel 180° is shown in Fig. 2 (a), where a crossover is inserted in conventional rat-race coupler to transfer the port position. The design theory of this coupler is derived from our previous work in [12]. To be specific, the modified coupler is divided into four identical quarter-wavelength transmission lines with the characteristic impedance $\sqrt{2}Z_0$ and a half-wavelength phase shifter with impedance Z_s (the blue dash line in Fig. 2 (a)). The ABCD-matrix through even-odd mode analysis is derived as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \begin{bmatrix} 1 & 0 \\ j/\sqrt{2}Z_0 & 1 \end{bmatrix} \begin{bmatrix} 0 & j/\sqrt{2}Z_0 \\ j/\sqrt{2}Z_0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j/\sqrt{2}Z_0 & 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} 1 & 0 \\ -j/\sqrt{2}Z_0 & 1 \end{bmatrix} \begin{bmatrix} 0 & j/\sqrt{2}Z_0 \\ j/\sqrt{2}Z_0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j/\sqrt{2}Z_0 & 1 \end{bmatrix} \quad (2)$$

From the analysis, it is found that the Z_s of the phase shifter can be arbitrarily defined, and it would not change the feature of the coupler. With this finding, the microwave crossover with port impedance of 50 Ω can physically move the port P_c to its new location P_c', which can separate the sum and delta input ports (P_a & P_c') from the output ports (P_b & P_d).

B. Zero-Phase Delay Microwave Crossover

To implement the design concept of proposed novel coupler, a zero-phase delay microstrip line crossover is added to reconstruct the conventional 180° rat-race coupler. Fig. 2 (b) shows the schematic of the crossover which includes outer branch lines and inner crossed lines. The characteristic impedance and electrical length of transmission lines are denoted as (Z_1, θ_1) and (Z_2, θ_2). According to the even-odd mode analysis [13], the following equations are derived to achieve crossover function ($S_{xx} = S_{xy'} = S_{xy} = 0$, $S_{xx'} = S_{yy'} = 1$):

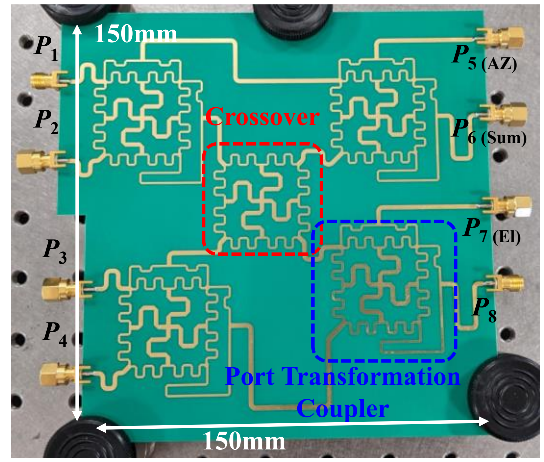
$$\theta_2 = 90° \quad (3)$$

$$(\tan\theta_1)^2 + 2\cdot[1 - (\tan\theta_1)^2]\cdot(Z_0/Z_3)^2 = 0 \quad (4)$$

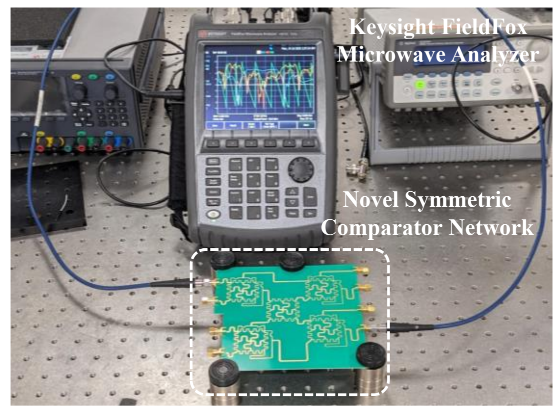
$$\frac{2\cdot\sqrt{2\cdot(\tan\theta_1)^4 - 2\cdot(\tan\theta_1)^2}}{(\tan\theta_1)^3 - 3\cdot\tan\theta_1} = 0 \quad (5)$$

From equations (3) - (5), it is observed that multiple solutions exist to satisfy the condition of crossover. To achieve zero-phase delay from inputs to outputs (from P_x to P_x', and from P_y to P_y'), the design parameters for inner and outer transmission lines are selected as $Z_1 = 57\Omega$, $Z_2 = 50\Omega$, $\theta_1 = \theta_2 = 90°$. The importance of zero-phase delay design is that it can remove the frequency sensitive phase compensation transmission lines to improve the loss and bandwidth of proposed comparator network.

The EM simulation results of the proposed coupler are given in Fig. 3. By correlating to the coupler in Fig. 2 (a), it is observed that the insertion loss is better than 3.2dB at operating frequency of 2GHz, and the return loss and isolation are better than 24dB. In Fig. 2 (b), the phase difference between output ports based on sum and delta input are 180° and 0°, respectively. From this port-transformation coupler, a planar monopulse comparator



(a)



(b)

Fig. 4 Proposed novel symmetric uni-planar monopulse comparator network: (a) fabrication circuit (b) measurement setup.

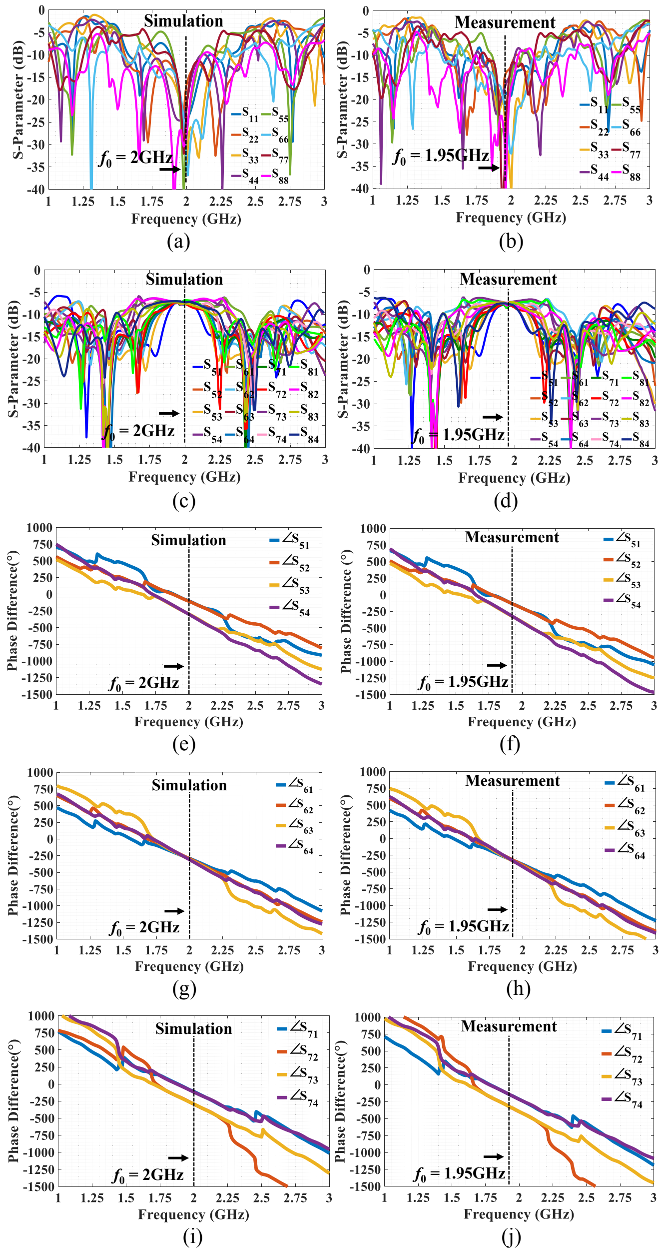


Fig. 5 Simulation and measurement results of proposed symmetric momopulse comparator network: (a) - (b) reflection (c) - (d) transmission (e) - (f) phase difference on azimuth port (Δ_{Az}) (g) - (h) phase difference on sum ($\sum$) port (i) - (j) phase difference on elevation port (Δ_{El}).

network is designed by integrating four of the proposed port transformation couplers and a zero - phase delay crossover, achieving symmetrical input/output ports, and low amplitude and phase imbalance.

III. Validation with Experimental Results

To verify the design theory, the proposed comparator network is designed and fabricated on Rogers 4350B substrate with thickness = 0.76mm, ε_r = 3.48, and tanδ = 0.004, as shown in Fig. 4 (a). The circuit size is 150mm × 150mm, and input & output ports are located on two sides, respectively. The experiment setup is shown in Fig. 4(b), where Keysight Fieldfox microwave analyzer is applied to measure scattering parameters.

TABLE I Comparison of Planar Comparator

Reference	[4]	[5]	[10]	**This Work**
Process	SIW	Planar	Planar	Planar
Symmetry	No	No	Yes	Yes
Elements	Directional Coupler + TEM Line	Branch - Line Coupler	Symmetric Coupler + Crossover	Rat-Race Coupler + Crossover
Size (λ^2)	15 × 14	6.5 × 6	1.9 × 1.5	1 × 1
Magnitude Imbalance	2.1 dB	0.84 dB	0.5dB	0.5 dB
Phase Imbalance	± 6.3°	± 2.5°	±8°	± 5°
BW (%)	7.4	5.6	8	14

The simulated and measured results of the comparator network are shown in Fig. 5. The transmission achieves 7.0 ± 0.5dB at 1.95GHz, and the return losses are better than 17dB as plotted in Fig. 5 (a) - (d). The phase responses in Fig. 5 (e) - (j) show the relative phase difference, where 0° ± 5° and 180° ± 5° are measured at azimuth and elevation ports, respectively. The operating bandwidth of the proposed novel comparator network is about 14% based on amplitude imbalance of ± 0.5dB and phase imbalance of ± 10°. The minor frequency shift between simulation and measurement results are from the fabrication tolerance. In Table I, it shows the comparison of state-of-the-art monopulse comparator network, and the proposed novel comparator network features planar, symmetric, and low amplitude & phase imbalance.

IV. Conclusion

In this paper, a novel symmetrical planar microstrip line monopulse comparator network is proposed and designed, where a novel port-transformation symmetric 180° coupler is proposed by reconstructing rat-race coupler with a zero-phase delay crossover. To verify the design theory a comparator network is fabricated and tested. The measurement results align well with the simulation results so that the proposed comparator network can be applied in low cost and highly integrated monopulse tracking radar and other wireless communication systems.

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