A Fully Symmetrical Uni-Planar Microstrip Line Comparator Network for Monopulse Antenna

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***Abstract*— In this letter, a fully symmetrical uni-planar comparator network is proposed for monopulse antenna feeding. To break through the fundamental limitation of a conventional 180° coupler (crossing between input and output ports and amplitude imbalance), a novel symmetric ports coupler is designed by cascading two identical 90° couplers with two-phase delay lines, where the total phase delay of two lines is 180°. To realize in planar structure, a zero-phase delay planar crossover is designed to resolve signal crossing between two stage couplers in a comparator network. To verify our design concept, a prototype monopulse array operating at 5.7 GHz is designed, fabricated, and measured, and results are aligned well with simulation and theory.**

***Index Terms*— 180° coupler, antenna array, monopulse comparator network, symmetrical planar structure.**

I. Introduction

MONOPULSE antennas are well applied in radar, wireless communication, remote sensing, imaging, and autonomous driving applications to estimate the angular location and relative distance of a target in 3-D space. In monopulse array, the comparator feeding network will preprocess received signal in its 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, and it can be categorized into two major types symmetrical and unsymmetrical networks, where four rat-race couplers are applied in the symmetrical topology, and four 90° coupler plus four 90° phase shifters [1], [2], [3], [4], [5], [6] are designed in an unsymmetrical network. To realize in planar structure, the unsymmetrical comparator network is widely applied in a monopulse array. However, due to additional phase delay lines, the operating bandwidth is limited, and it causes an amplitude imbalance in the comparator network. The symmetrical comparators resolve the issues in unsymmetric topology, but it requires a complicated structure and an expensive fabrication process. For example, in [7], a combination of in-phase power divider and Marchand balun is proposed to realize a symmetrical port 180° coupler, and the airbridge is applied to connect the couplers. In [8], [9], and [10], a multilayer microstrip structure is designed to integrate antenna array with the conventional comparator network. In [11], substrate integrated waveguide (SIW) is applied to realize the monopulse antenna. A compact magic-tee with a waveguide to coaxial transition has been proposed in [12]. Furthermore, in [13], a unique 3-D micromachining process—Polystrata technique is applied to design 3-D comparator network with integrated cavity-backed patch antennas and diode detectors. In [14], the entire monopulse antenna array is designed in 2-D conical form. In summary, all the above methods 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. The same direction of output ports 180° planar hybrid coupler is proposed in [15] utilizing multisections transmission between two off-the-shelf couplers. Beyond the coupler, a fully symmetrical planar lumped element comparator network is proposed in [16]. However, the parasitic effect from lumped elements causes significant performance degradation, especially at high frequencies.

To overcome the challenges in conventional monopulse comparator network (crossing between inputs & output, unsymmetric, and amplitude imbalance, etc.), a novel planar symmetric comparator network is proposed in this letter, where it consists of a novel 180° coupler and zero-phase delay crossover. To validate the design concept, the proposed comparator is simulated and measured, and the corresponding radiation pattern is characterized as well.

II. Design Theory of Comparator Network

A. Novel 180° Coupler With Symmetrical Ports Allocation

As in Fig. 1, the proposed fully symmetrical planar comparator is composed of novel symmetric 180° couplers and a zero-phase delay crossover. Here, the novel 180° hybrid coupler relocates all the ports so that the sum and delta ports are on one side and do not cross by input and isolated ports. The schematic of the proposed novel 180° coupler is shown in Fig. 2, where two 3 dB 90° couplers ($Z_1 = Z_0$, $Z_2 = Z_0/\sqrt{2}$, and $\theta_1 = 90°$) are cascaded by two different phase delay lines.

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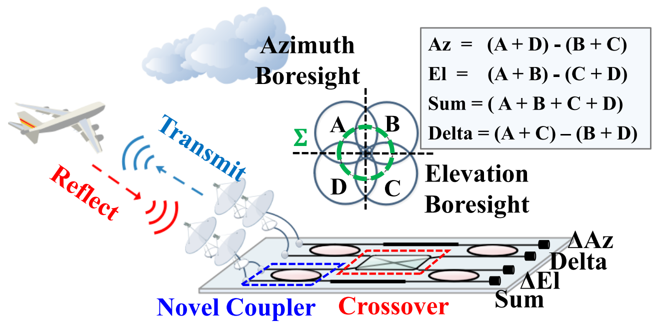

Fig. 1. Proposed novel uni-planar monopulse comparator network.

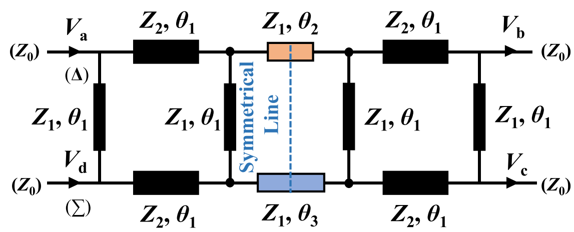

Fig. 2. Proposed 180° coupler with symmetrical port allocation (Z_1 = 50 Ω, Z_2 = 35.35 Ω, θ_1 = 90°, θ_2 = 45°, and θ_3 = 135°).

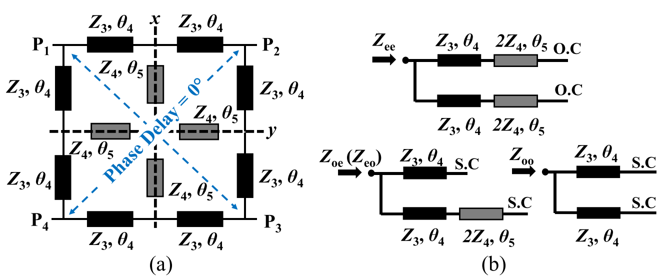

Fig. 3. Zero-phase delay microstrip line crossover. (a) Schematic (Z_3 = 57 Ω, Z_4 = 50 Ω, θ_4 = 90°, and θ_5 = 90°). (b) Reduced networks with equivalent input impedances under different excitations (i.e., even–even, even–odd, odd–even, and odd–odd).

To determine the electrical length of θ_2 and θ_3, the wave with normalized $V_a = 1$ is applied at input port a, and the signal at through port b and coupled port c are calculated as

$$V_b = \frac{1}{2} \cdot \left[-e^{-j\theta_2} + e^{-j\theta_3}\right] \tag{1}$$

$$V_c = \frac{1}{2} \cdot \left[e^{-j\left(\frac{3\pi}{2}+\theta_2\right)} + e^{-j\left(\frac{3\pi}{2}+\theta_3\right)}\right]. \tag{2}$$

To achieve equal power dividing ratio and 180°/0° phase difference between two output ports, the following two equations must satisfy:

$$\left|\frac{V_b}{V_c}\right| = 1 \tag{3}$$

$$\angle\left(\frac{V_b}{V_c}\right) = 180°/0°. \tag{4}$$

From (3) and (4), it can derive $\theta_2 = 45°$ and $\theta_3 = 135°$. The proposed 180° coupler is a symmetric network (in vertical), and the outputs ports (sum and delta) are always on the opposite of input and isolation ports, which is totally different from the conventional rat-race coupler.

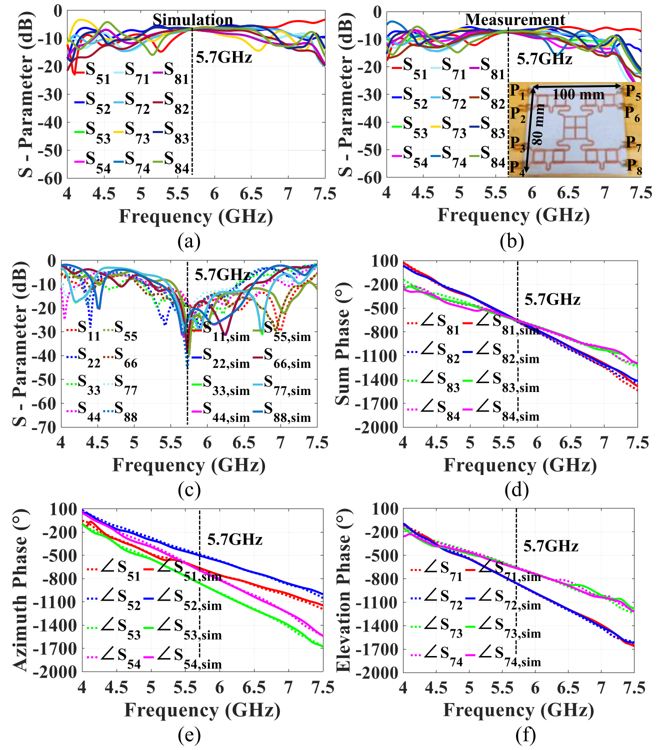

Fig. 4. Simulation and measurement results of proposed monopulse comparator network. (a) and (b) Insertion loss. (c) Return loss. (d)–(f) Phase difference of sum, azimuth, and elevation ports.

B. Zero-Phase Delay Crossover

With the novel coupler, a zero-phase delay microstrip line crossover is designed to interconnect two-stage couplers in the proposed planar symmetrical comparator network. Fig. 3 shows a schematic of the proposed crossover. It includes outer branch lines and inner crossed lines, where the characteristic impedance and electrical length of transmission lines are denoted as (Z_3, θ_4) and (Z_4, θ_5). The crossover is symmetric both in x- and y-planes, and the even-odd mode analysis method is applied to determine the transmission lines. Therefore, the input impedances of a simplified network are denoted as Z_{ee}, Z_{eo}, Z_{oe}, and Z_{oo} and are shown in Fig. 3(b). The corresponding reflection coefficients based on different excitations can be expressed as

$$\Gamma_{ee,eo,oe,oo} = \frac{Z_{ee,eo,oe,oo} - Z_0}{Z_{ee,eo,oe,oo} + Z_0} \tag{5}$$

where Z_{ee}, Z_{eo}, Z_{oe}, and Z_{oo} can be derived from the theory in [17]. To achieve crossover function, it must satisfy $S_{55} = S_{65} = S_{85} = 0$, $S_{75} = S_{86} = 1$, which are developed in our previous work [18], [19], [20]. Thus, the following equations are obtained:

$$\theta_5 = 90° \tag{6}$$

$$(\tan\theta_4)^2 + 2 \cdot \left(1 - (\tan\theta_4)^2\right) \cdot \left(\frac{Z_0}{Z_3}\right)^2 = 0 \tag{7}$$

$$\frac{2 \cdot \sqrt{2 \cdot (\tan\theta_4)^4 - 2 \cdot (\tan\theta_4)^2}}{(\tan\theta_4)^3 - 3 \cdot \tan\theta_4} = 0. \tag{8}$$

From (7) and (8), it is observed that multiple solutions exist to satisfy the condition of crossover. To achieve zero-phase

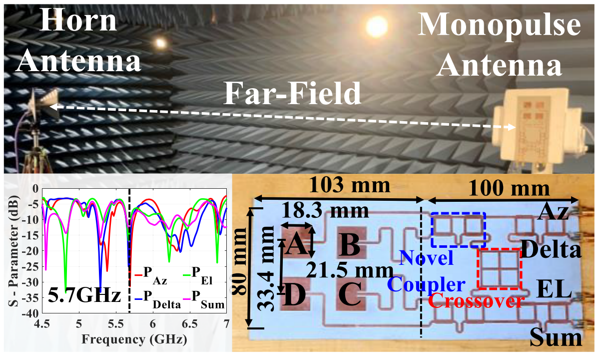

Fig. 5. Fabrication and measurement of proposed monopulse antenna.

delay from inputs to outputs (P_5 to P_7 or P_8 to P_6), the design parameters for inner and outer lines are selected as $Z_3 = 57\ \Omega$, $Z_4 = 50\ \Omega$, and $\theta_4 = \theta_5 = 90°$, which can remove the frequency sensitive phase compensation transmission lines between two stage couplers to improve the loss and bandwidth of proposed comparator network.

By integrating the proposed novel coupler and zero-phase delay crossover, the proposed comparator network is realized in a planar structure with symmetrical input/output ports, low amplitude, and phase imbalance.

III. Simulation and Measurement Results

To validate the design theory, first, the proposed comparator network is designed and fabricated on Rogers 5880LZ substrate with thickness = 0.508 mm, ε_r = 2, and tanδ = 0.002, and the prototype is shown in Fig. 4. The operating frequency is 5.7 GHz. The simulated and measured results of the comparator network are shown in Fig. 4. In specific, the transmission achieves 6.8 ± 0.2 dB at 5.7 GHz, and the return losses are better than 15 dB as plotted in Fig. 4(a)–(c). The phase responses in Fig. 4(d)–(f) show the relative phase differences of 0° ± 2° for the sum port and 180° ± 1° for azimuth and elevation ports, respectively. With an amplitude imbalance of ±0.5 dB and phase imbalance of ±8°, the operating bandwidth of the proposed novel comparator network is about 8%. The bandwidth of the proposed comparator network can be future extended by designing wideband proposed coupler and zero-phase crossover.

To validate radiation characteristic, a monopulse array is designed by integrating 2 × 2 patch antennas and the proposed comparator network in a planar structure, and the prototype is shown in Fig. 5. The size of a patch antenna is 18.4 × 21.5 mm, and the distance between adjacent elements is about 33 mm. In Fig. 5, the return loss is around 15 dB for the monopulse array. Fig. 6(a) and (b) shows the sum patterns of monopulse array in azimuth and elevation plane, where the sidelobe level is better than 15 dB. The difference patterns of monopulse array are shown in Fig. 6(c) and (d), where the null depth is around 20 dB. The small difference between simulation and measurement in azimuth and elevation planes are mainly attributes from small variation from comparator and nonuniform antenna patterns caused from feeding lines between antenna elements.

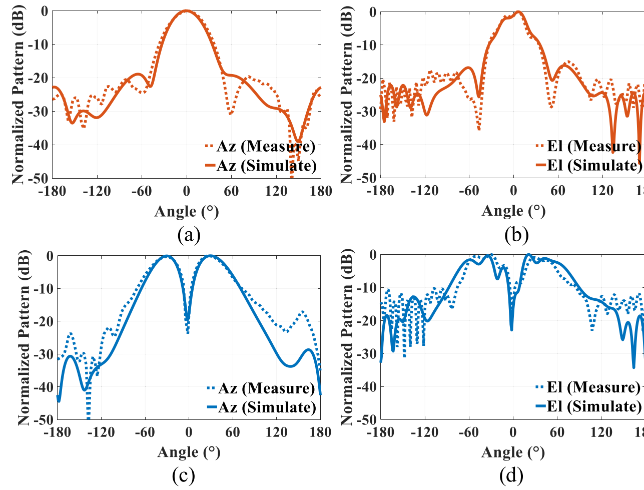

Fig. 6. Sum and difference pattern at 5.7 GHz. (a) and (b) Sum patterns in azimuth and elevation plane. (c) and (d) Difference patterns in azimuth and elevation plane.

TABLE I

Comparison of Planar Comparator

Reference	[1]	[3]	[11]	[14]	**This Work**
Process Type	SIW	Planar	SIW	2D Conical	Planar
Symmetry	No	No	No	No	Yes
Elements Type	Directional Coupler + TEM Line	Branch - Line Coupler	TEM Line	Rat-race Coupler	Symmetric Coupler + zero-phase crossover
Network Size (λ^2)	15 × 14	6.5 × 6	4 × 2	3 × 1.7	1.9 × 1.5
Amplitude Distribution	Uniform	Non-uniform	Uniform	Uniform	Uniform
Magnitude Imbalance	2.1 dB	0.84 dB	/	/	0.5 dB
Phase Imbalance	± 6.3°	± 2.5°	/	/	± 8°
Array Type (Qty)	Slot (16)	Patch (192)	Slot (16)	Conformal (4)	Patch (4)
Aperture (λ^2)	14 × 10	13 × 12	4 × 2	/	1.95 × 1.5
SLL	11 dB	17 dB	9 dB	15 dB	15 dB
ND	46 dB	30 dB	29 dB	25 dB	20 dB
BW (%)	7.4	5.6	100	22.2	8

In Table I, it shows the comparison of state-of-the-art monopulse array, and our proposed novel comparator network features planar, symmetric, and compact size. The radiation characteristic can be further improved by applying multiple antenna elements to replace single patch in monopulse array.

IV. Conclusion

In this letter, a novel symmetrical microstrip line monopulse comparator network in uni-planar layout is proposed and designed, where a novel symmetric 180° coupler and zero-phase delay crossover are proposed and applied in planar topology. To verify the design concept, a comparator network and monopulse array operating at 5.7 GHz is designed and fabricated. The measurement results align 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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