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A Novel Direction of Arrival Estimation Planar Monopulse Receiver

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***Abstract*— In this paper, a monopulse receiver is proposed to estimate the arrival of angle. The entire system is composed of a 4 - element planar monopulse array and a down conversion link. The array is composed of planar comparator network including novel coupler and zero-phase delay crossover. The down conversion link is composed of filter, low noise amplifier, mixer, and PLL. To verify the design concept, a prototype planar monopulse array operating at 5.7 GHz is designed and fabricated, and Keysight microwave kits is configured as down conversion to receive the signals from array. The system level measurement results are aligned well with simulation and theory, and the angular information of remote target is estimated from the two-channel signal.**

Keywords—*Monopulse antenna array*, direction of arrival estimation, *microwave circuits*.

I. Introduction

With emerging new wireless technology, beamforming array technique is widely applied in wireless communication, remote sensing, and autonomous driving etc. Monopulse array is one of beamforming array [1] - [3] which is very often applied to estimate angular location, relative distance of a remote target, vital sign detection, and gesture recognition. To be specific, the received signal from 2D antenna array in monopulse array will be processed through comparator network in electromagnetic waveform domain to extract the location and velocity of moving object. Here, the comparator network is passive microwave network composed by four identical 180° couplers. To the best of our knowledge, the previous monopulse receivers [4] - [9] are designed from nonplanar comparator (i.e., rat-race coupler-based network) or unsymmetrical comparator (90° coupler + 90° phase delay), which results complex fabrication, high power loss, and low integration etc.

In this paper, a new type of monopulse receiver is proposed and verified as a solution to overcome the drawback in conventional designs. The proposed receiver utilizes a planar symmetric comparator network, consisting of four innovative 180° couplers and a zero-phase delay crossover. The Keysight U3851A microwave kits is applied as down-convertor for difference and sum signals obtained from the monopulse array. The direction of arrival (DoA) is then calculated from the resulting analog signals.

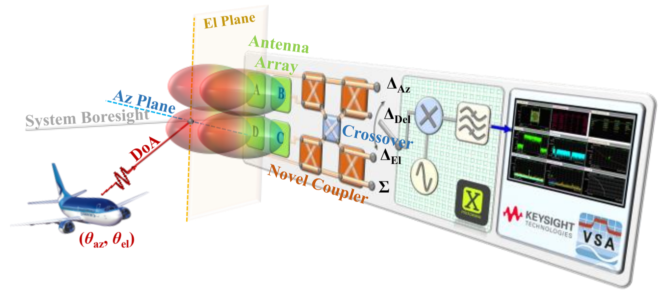

Fig. 1 Scenario description of the proposed fully planar monopulse receiver with symmetrical comparator network.

II. Design Theory of Novel Monopulse Receiver

As shown in Fig. 1, the proposed monopulse array includes a 4 - element 2D antenna array and the novel planar symmetric comparator network. The novel fully symmetric 180° couplers and a zero- phase delay microwave crossover is integrated to realize novel comparator network. The output ports of comparator network are denoted as sum (Σ) and difference (Δ_{Az}, Δ_{El}, and Δ_{Del}), which perform operations as:

$$\Delta_{Az} = (A + D) - (B + C) \tag{1}$$

$$\Delta_{El} = (A + B) - (C + D) \tag{2}$$

$$\Delta_{Del} = (A + C) - (B + D) \tag{3}$$

$$\Sigma = (A + B + C + D) \tag{4}$$

A. Estimation of Direction of Arrival (DoA)

Amplitude or phase comparison is typical method to estimate the angular information of arrival signal. In this monopulse receiver, the phase comparison method is applied due to planar antenna structure providing identical boresight direction. For example, as shown in Fig. 2, a two-element linear array separated with d can determine the angle of arrival from

$$r_{s,A(B)} = r_s \mp \frac{d}{2} \cdot \sin\theta_s \tag{5}$$

Where θ_s is direction of arrival (DoA) of the target from the reference boresight direction, and r_s is target distance from array center. The echo signal received at two antennas (A & B) can be expressed as

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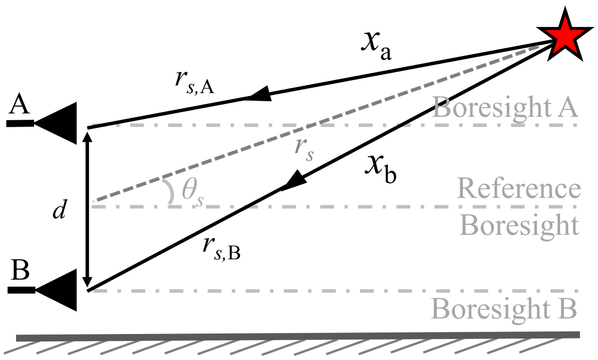


Fig. 2 Schematic diagram of DoA estimation with monopulse comparison.

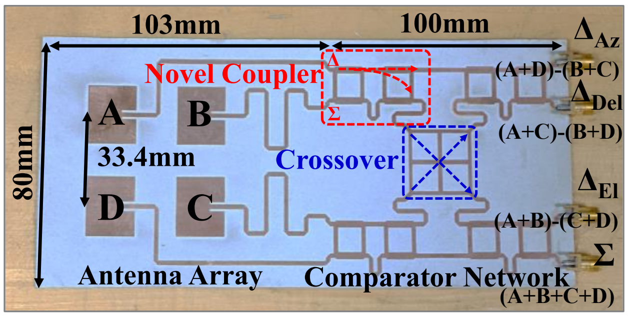


Fig. 3 Fabricated fully planar symmetric monopulse array, including 2 × 2 antenna array and novel comparator network.

$$x_{a(b)} = e^{-j\frac{2\pi}{\lambda}\cdot(2r_s \mp \frac{d}{2}\sin\theta_s)} \tag{6}$$

and the difference and sum of signals received by A and B can be derived as

$$\begin{aligned}\Delta &= x_a - x_b \\ &= -2j\cdot e^{-j\frac{4\pi r_s}{\lambda}}\cdot\sin(-\frac{\pi}{d}\sin\theta_s)\end{aligned} \tag{7}$$

$$\begin{aligned}\Sigma &= x_a + x_b \\ &= 2j\cdot e^{-j\frac{4\pi r_s}{\lambda}}\cdot\cos(\frac{\pi}{d}\sin\theta_s)\end{aligned} \tag{8}$$

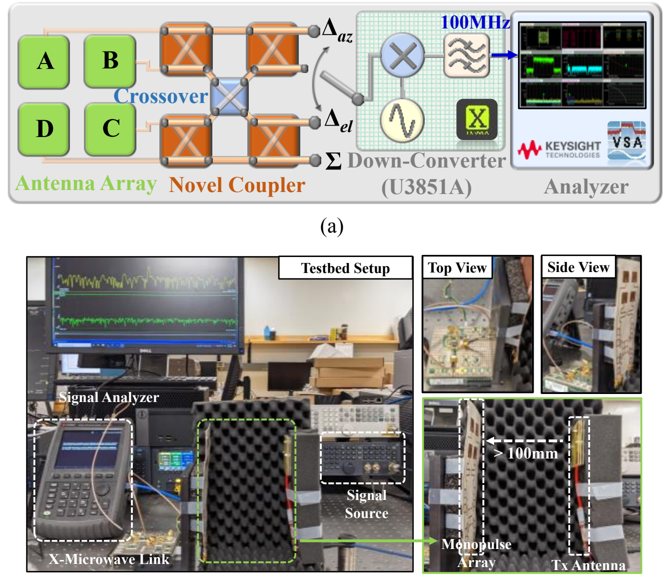
The angular information of arrival signal can be calculated based on the ratio (γ) of difference to sum signals, which yields

$$\gamma = \frac{\Delta}{\Sigma} = j\cdot\tan(-\frac{\pi d}{\lambda}\cdot\sin\theta_s) \tag{9}$$

Similarly, the angles in two dimensions are evaluated from equations (5) - (9) by placing 2D antenna array in quadrant.

B. *Design of Fully Planar Symmetrical Comparison Network*

Fig. 3 shows our novel monopulse comparator network. The entire circuit consists of four novel 180° couplers [10] and a zero-delay crossover. To be more specific, the proposed coupler is a symmetric network (in vertical), where two 3-dB 90° couplers are cascaded by two different phase delay lines. Therefore, the outputs ports (Σ and Δ) of the novel coupler are on the opposite of the input and isolation ports, which is totally different from the conventional rat-race coupler. In addition, a microstrip line crossover [11] is applied to interconnect two stages of couplers. Based upon the characteristic of zero-phase delay, it 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 proposed novel coupler, zero-phase delay crossover, and 2D antenna array, the monopulse array is realized in planar structure with symmetrical input / output ports, low amplitude, and phase imbalance.



(a)

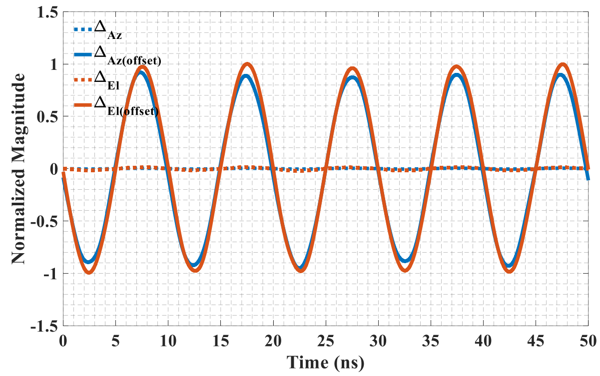
(b)

Fig. 4 Proposed fully planar symmetric monopulse receiver: (a) Schematic diagram (b) Measurement setup.

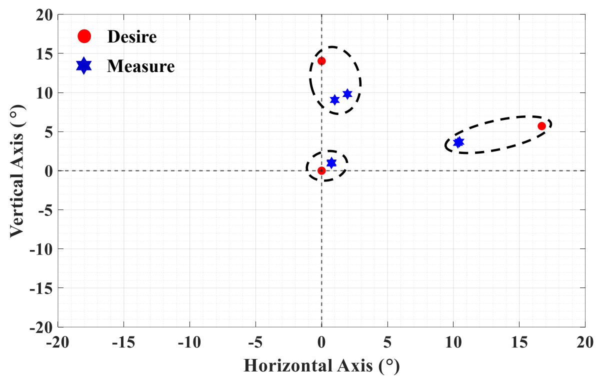
III. Experimental Results and Analysis

To validate the design theory, a monopulse array with 2 × 2 patch antennas is prototyped in planar structure as shown in Fig. 3. The operating frequency is 5.7GHz, and Rogers 5880LZ (thickness = 0.508 mm, $\varepsilon_r = 2$, $\tan\delta = 0.002$) is applied for fabrication. The individual patch antenna achieves size of 18.4 × 21.5 mm and the distance of adjacent element is 33.4 mm. To estimate DoA, the monopulse receiver is realized by integrating proposed monopulse array with Keysight U3851A down-converter, and the receiver system prototype is shown in Fig. 4. To be specific, as in Fig. 4 (a), the received RF signals from Δ_{Az}, Δ_{El}, and Σ are down converted into 100MHz baseband signals, then being captured, and analyzed through vector signal analyzer (VSA). The measurement testbed setup is shown in Fig. 4 (b), where a 5.7GHz standard antenna connecting on the signal source is put in far-field distance (>100mm) to behaves as the remote target.

The measurement results are displayed in Fig. 5, where both difference signals and DoA are evaluated. Specifically, Fig. 5 (a) shows the measured results for difference signals with/without angular offset. From equations (1) - (2), the difference signals can be clearly detected only if there is phase offset between arrival signals captured in two quadrants along either azimuth or



(a)



(b)

Fig. 5 Measurement results of monopulse receiver: (a) Difference signals (Δ_{Az} & Δ_{El}) demonstrating the azimuth and elevation phase shifts (b) Estimation of direction of arrival (DoA) with different desired locations.

TABLE I COMPARISON OF MONOPULSE RECEIVER

Reference	[4]	[5]	[7]	**This Work**
Process Type	Planar	Waveguide	Planar	Planar
Symmetry	No	No	No	Yes
Elements Type	Branch-Line Coupler	Branch-Line Coupler	Rat-race Coupler	Symmetric Coupler + zero-phase crossover
Network Size (λ^2)	2.4 × 4	13.5 × 15	1.7 × 1.8	1.9 × 1.5
Elements Number	N.A.	1	2 × 2	2 × 2

elevation direction, which reveals the angular deviations from the reference boresight. The estimation of direction of arrival is shown in Fig. 5 (b). Compared to the original locations at boresight in vertical axis and 2nd quadrant, all measured results can clearly locate the target. It is noted that the physical location and measured locations start deviate when the target moving away from antenna center position. This can be improved by designing large array for each antenna. In Table I, it presents the side-by-side comparison of the other monopulse receiver designs with our newly introduced design that is characterized by a planar, symmetric, and space-saving configuration.

IV. Conclusion

In this paper, a novel monopulse receiver with fully planar symmetric comparator network has been proposed and designed, where a novel symmetric 180° coupler and zero-phase delay crossover are applied to realize in planar topology. To verify the design concept, a monopulse array operating at 5.7 GHz is designed and fabricated. A monopulse receiver is then designed by integrating U3851A and monpulse array, and the DoA is evaluated. The measurement results align well with the theory, such that proposed monopulse receiver can be applied in low cost and highly integrated monopulse tracking radar and other wireless communication systems.

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