Performance Analysis of 180° HRR Coupler Used for Direction Finding with an Antenna Array

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Abstract—This paper presents a performance analysis of a 180^0 hybrid rat race (HRR) coupler, widely used in radio frequency (RF)/wireless communication systems to couple the power in the desired way. The 180^0 HRR ring coupler consists of 4 ports, two for the input signals and two for the output signals. In this work, the couplers have been designed and simulated at central frequencies (f_0) of 2.4 and 10 GHz using different types of substrates. Furthermore, the coupler has been analyzed in the context of direction finding, where we combine the designed 180^0 HRR coupler with a simple two antenna elements array and we have fabricated the circuit in order to validate the performance of the coupler by estimating the direction of arrival (DoA) using the difference (Δ) and sum ($\sum$) ports. The measured scattering parameters and DoAs are in good agreement to the simulated results. The experimental results show that the DoA can be estimated in the range 0 to ±50 degrees with errors less than 5^0.

Keywords—Couplers, radio frequency (RF) signals, antenna array, wireless communications.

1 Introduction

The ring coupler or 180^0 HRR coupler, consisting of four ports, is a type of coupler mainly used in RF/microwave devices. The couplers and power dividers are fundamental and important passive circuits in wireless front ends to couple the RF signals. Couplers can be incorporated with the balanced mixers, balanced power amplifiers; antenna feed networks, measurement systems, and so on; for power coupling and equal or unequal power division in a desired way [1]. The rat race coupler design produces a device with low voltage standing wave ratio (VSWR), excellent phase and amplitude balance, high output isolation and matched output impedances [2], [3]. It has a significant advantage of being realized in planar technologies such as microstrip and striplines using various techniques, such as the slow-wave artificial transmission lines [4-5], folded microstrips [6-7], left-handed transmission lines [8], and lumped-elements [2]. Moreover, it is easy to realize as compared to the magic tee (magic-T) coupler design and is a lossless, matched and reciprocal 4-port device, containing scattering matrix of the anti-symmetric form [9], [10]. An interesting usage of this coupler can be noted if we apply the two input signals at two ports, we can obtain the difference (Δ) and sum ($\sum$) of these inputs at two other output ports.

There are three common circuit configurations of 180^0 hybrid couplers such as rat race coupler, waveguide hybrid junction, also known as magic-T, and tapered coupled-line hybrid [11]. However, the most widely used among them is the HRR coupler. The magic-T coupler is used under certain specific conditions i.e., applications that work with high voltage powers. Additionally, due to its nonplanar configuration which is opposite toward the miniaturization of microwave/RF circuits, its applications are limited. While, for tapered coupled-line, although it contains a planar structure, the method needed to solve the coupling effect of the coupled line makes the design complicated. Moreover, this design also requires a large area. Thus, both of the couplers, magic-T and tapered coupled-line, are less popular as compared to the HRR coupler. The planar and simplified structure of the HRR coupler shows its importance to be integrated with the microwave circuits easily and current fabrication processes. Because this coupler can be designed in the frequency range from RF to microwave and even also in millimeter wave, its progress goes in parallel to some extent with the advancement of microwave passive components. Therefore, it is important to analyze the performance of the HRR coupler at various operation of frequencies and dielectric substrate materials in order to know all geometric design parameters, functionality, comprehensive S-parameters analysis for both reflection loss and phase differences, integration with microwave circuits e.g., patch antenna array, and fabricated results.

The objective of this paper is to analyze the performance of a 180^0 HRR coupler through electromagnetic (EM) field simulation at different frequencies of operation and dielectric substrates. Furthermore, one important application of this type of coupler can take place in the domain of direction finding antenna arrays. The coupler can be integrated with the microstrip patch antenna array consisting of two antenna elements in order to take the Δ and $\sum$ of the received signal to estimate the angle of arrival (AoA) of the received signal. Such an AoA estimation approach has the advantage of being realized in the RF domain which avoids the use of conventional and complex approaches that operate in base band and that require down-conversion hardware chains and digital signal processing. The performance is analyzed both via simulation and via experimental measurements using a fabricated coupler. Different geometries and substrate materials have been considered in two relevant application bands, i.e., 2.4 and 10 GHz. The former used by WLAN systems and the second by UWB and radar systems built for localization purposes.

The paper is organized as follows. In Section 2, we describe the 180^0 HRR coupler's design and working principle, where we do an analysis of the ports division property. Particularly, we describe the geometric structure of the coupler in the electrical length (lambda) domain. The simulated coupler designs and observed results at various frequencies and substrates are presented in Section 3. Moreover, in this Section, we also discuss how the coupler can be integrated with the microstrip patch antennas array in order to obtain the Δ and $\sum$ patterns from the two received signal samples. The Δ and $\sum$ equations are also provided. They can be exploited further to find the direction of the received signal. Finally, we conclude the paper in Section 4 by highlighting the key results of the paper.

2 Design and working principle

The layout design of 180^0 HRR coupler is shown in Figure 1. It consists of two input ports namely port 3 and port 4 where we apply the two received signals as input; and two output ports, namely difference (Δ)-port (port 1) and sum (∑)-port (port 2). From these two output ports, the difference and the sum of the two applied input signals is obtained. Thus, this type of coupler can be used to obtain the ∑ and Δ patterns of two input fed signals, as well as can be used as equal power divider if we input a signal on port 1. The ports at the top half ring are spaced from each other by $\lambda/4$ distance while the ports at the bottom half ring are separated by 3λ/4, where λ is the wavelength at central frequency f_o. Thus, the 180^0 HRR coupler designed in this work consists of a 3λ/4 large section and three λ/4 small sections of microstrips. Furthermore, the ring has a characteristic impedance of a factor $\sqrt{2}$ compared to the port impedance, for example, for 50 Ω, it is $\sqrt{2}$*50=70.7 Ω. It has a circumference equal to 1.5λ or 6 times λ/4. So the radius of the ring can be obtained by using well known expressions, S=2πr; where *S* is the circumference and *r* is radius.

For an ideal 3dB rat race coupler, the full S-parameter (scattering) matrix is given by

$$S = \frac{-j}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -1 & 0 & 1 & 0 \end{pmatrix} \tag{1}$$

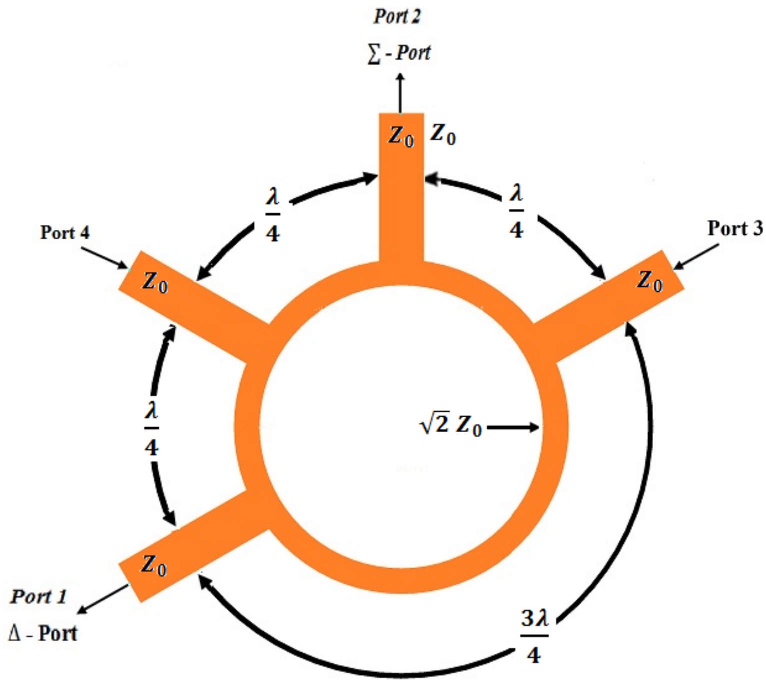


Fig. 1. Overview of 180^0 HRR coupler layout design.

The working principle of the rate race coupler is straight forward to be explained. When we excite the two input ports, herein labeled with ports 3 and 4, with any desired two RF signals, then at port 2 ($\sum$ - port), both signals from the two input ports arrive with same phase but opposite in direction, due to same length distances ($\frac{\lambda}{4}$ - $\frac{\lambda}{4} = 0^0$ phase difference), and combined to give the sum ($\sum$) of the applied signals. While on other hand, at port 1 (Δ - port), both signals from the input ports arrive with opposite phase i.e., 180^0, due to different length distances ($\frac{3\lambda}{4}$ - $\frac{\lambda}{4} = \frac{\lambda}{2} = 180^0$ phase difference), and combined to give the difference (Δ) of the applied signals.

The coupler ring consists of six sections. The electrical length of each section equals 90^0 (λ/4) [10, 12-15]. Thus, the effective electrical length (E_Eff) of the ring is $6\times90^0 = 540^0$ at characteristic impedence of $\sqrt{2}\, Z_0$. Therefore, by using the expression in (2) as mentioned earlier, we can calculate the radius (*r*) of the ring and hence all desired widths of the coupler, as:

$$r = \frac{\text{Observed length at } \sqrt{2}\, Z_0 \text{ and } E_{Eff}=540^0}{2\pi} \tag{2}$$

For a clear and detailed design point of view, in this paper, different types of dielectric materials have been used with their specific parameter values. Table 1 shows the substrates names and their properties that have been considered in this work. Here, $\boldsymbol{\varepsilon_r}$, *t* and TanD represent the dielectric constant, thickness in millimeter (mm) and tangent loss of the of substrate, respectively.

Table 1. Properties of considered substrates

Substrate	ε_r	t (mm)	TanD
RT Duroid 5880	2.2	1.575	0.0004
FR4	4.6	1.6	0.02

3 Simulation Results, Experimental Results and Discussions

In this section, we discuss the results obtained from the coupler designs and comparing the simulated Δ and $\sum$ patterns results with the ones obtained with the designed real coupler circuit. All the simulations at different central frequencies and substrates have been accomplished in an EM field simulator. Initially, at any particular substrate and operational frequency, we calculate the required lengths, widths and radius of the ring coupler. Then the coupler's layout is designed to realize the actual structure of the coupler. Furthermore, this layout structure is simulated to validate the desired performance results.

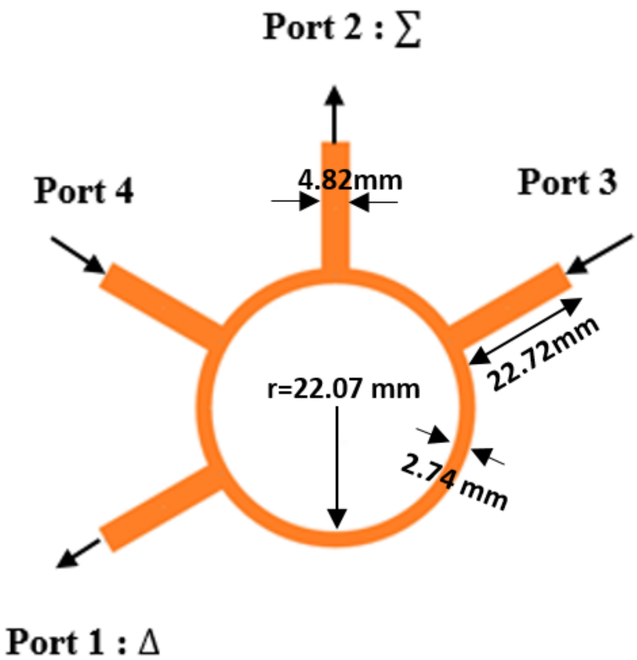
The frequencies of operation considered in this work are 2.4 and 10 GHz, because such frequencies are frequently used in wide range of RF devices and DoA estimation applications. Specifically, radar communication for direction finding is also carried out in X-band (8-12 GHz) frequency range [16]. Moreover, we integrate the coupler with a patch antenna array consisting of two antenna elements in order to find the direction of the received signals from the Δ and $\sum$ patterns. This direction finding microwave circuit has been designed and fabricated for 10 GHz frequency with Duroid substrate, and is described after coupler's design simulations in order to show the simulated coupler's performance practically. The designed couplers and their performance results are reported in the following subsections.

3.1 180^0 HRR Coupler Design

3.1.1 At f_0 = 2.4 GHz

Substrate parameters such as ε_r and t are relevant in microstrip designs because they determine the characteristic impedance z_0. In this part, we design the couplers by considering the substrates RT Duroid 5880 and FR4 at f_0 = 2.4 GHz. Initially, 180^0 HRR couplers have been designed and analyzed using an electromagnetic field simulator. The layout designs of the couplers are provided in Figure 2 (a) and (b). In this way, we run the simulation and verified the S-parameters results first. The reflection loss coefficient curves of each port (S11, S22, S33, S44) for both substrates couplers are given in Figure 3 (a). A good matching of each port has been observed with reflection coefficient of approximately -26.68 dB for the Duroid based coupler while of -22.77 dB for the FR4 based coupler. The isolations between Δ and $\sum$ output ports and between the two input ports are shown in Figure 3 (b). They are approximately equal to -52.11 dB and -33.61 dB for the Duroid and FR4 based couplers, respectively. Even though the size of the Duroid substrate based coupler is slightly greater than the FR4 substrate based coupler, the S-parameters results of the Duroid coupler are better than the FR4 coupler as shown in Figure 3. One of the possible reasons for the differences in S-parameters between the two substrate couplers might be due to each material's properties for instance the tangent loss of the FR4 substrate (TanD=0.02) is greater than the Duroid substrate (TanD=0.0004).

For both substrates couplers, Figure 4(a) shows the observed phase difference equal to 180^0 at the Δ-port between the two input signals of frequency 2.4 GHz. On the other end, Figure 4(b) shows the observed phase difference equal to 0^0 at the $\sum$-port between the two input signals of the same frequency 2.4 GHz. Note that, by taking the difference between two indicated points at 2.4 GHz, as shown in Figure 4 (a) and (b), we can visualize the desired phase difference of 180^0 (i.e., in Duroid, $107.7 - (-71.88) \approx 179.58^0$) for the Δ-port and 0^0 (i.e., in Duroid, $107.5 - 107.2 \approx 0.3^0$) for the $\sum$-port. It can be noted that the phase differences of both substrates based couplers are approximately similar to each other with marginal differences of upto 2^0. These marginal differences might be due to the mismatching between the coupler's ring and the 50-ohm transmission (Tx) line sections in the FR4 substrate coupler which can be overcome by some adjustments in the widths and/or positions of the 50-ohm Tx-lines.



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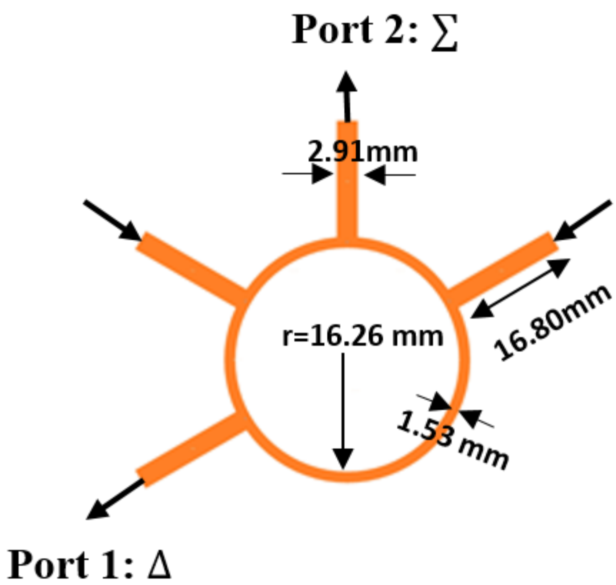

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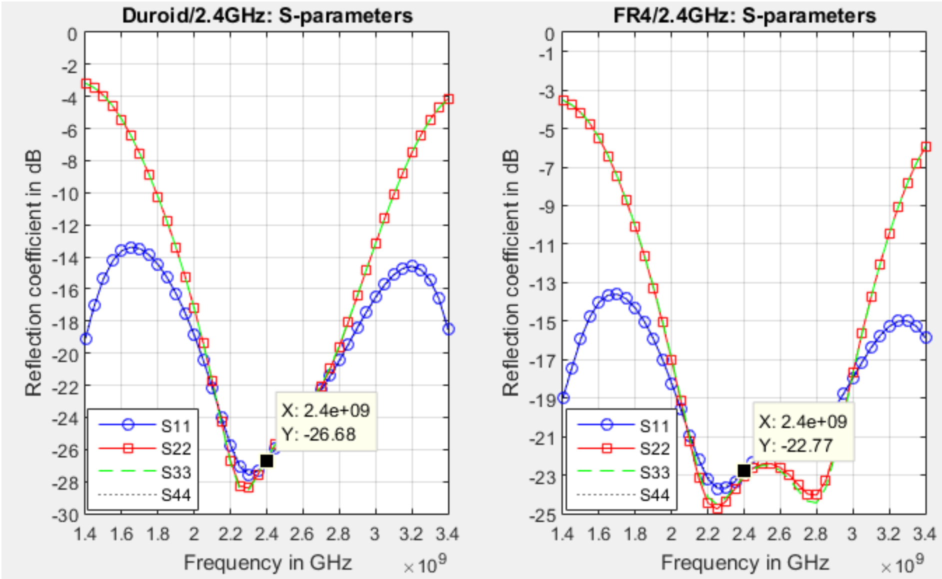
Fig. 2. Layout design of 180^0 HRR coupler at 2.4 GHz using substrate **a)** Duroid, and **b)** FR4



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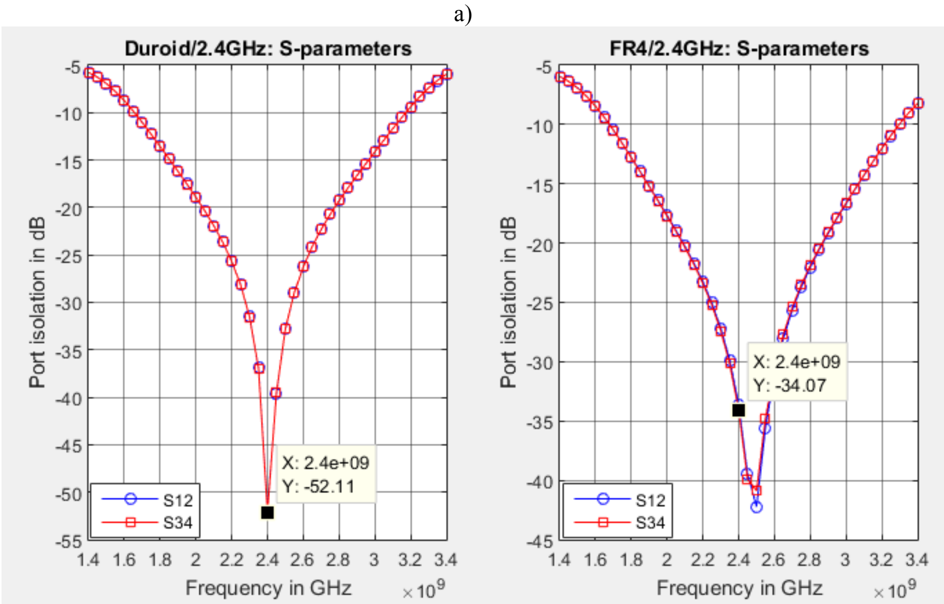

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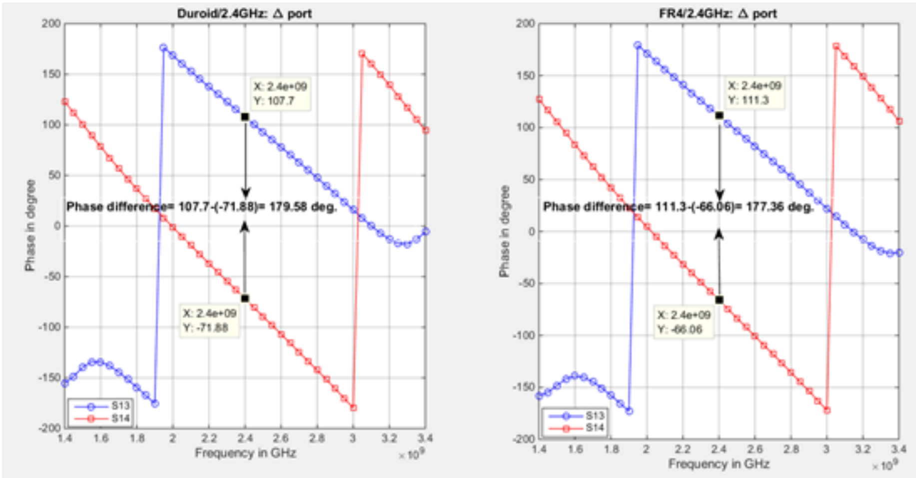
Fig. 3. Simulated S-parameters for Duroid and FR4 substrates based couplers: a) reflection loss of each port, and b) port isolations.



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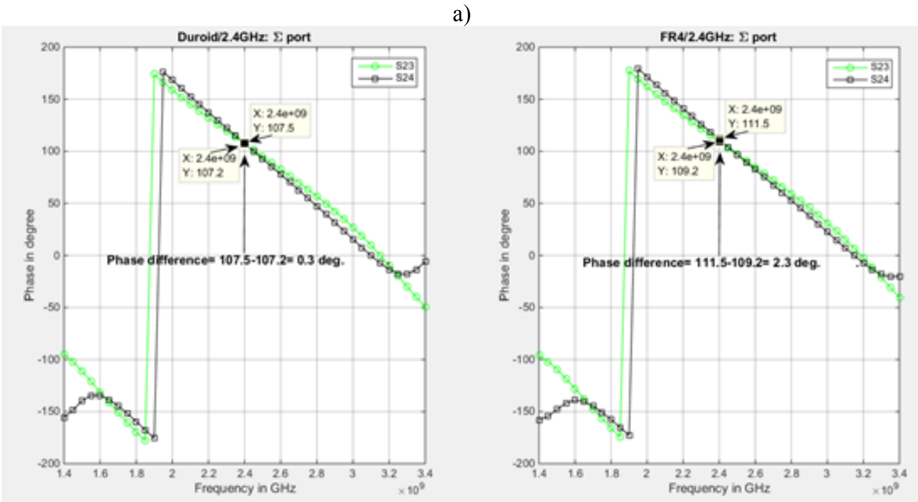


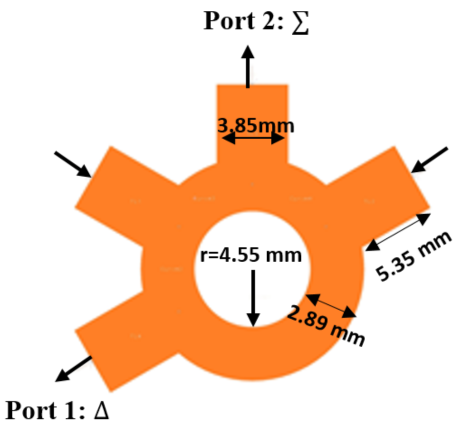
b)

Fig. 4. Obtained phase differences at f_0 = 2.4 GHz for Duroid and FR4 substrates based couplers, **a)** 180^0 phase difference at Δ-port, and b**)** 0^0 phase difference at ∑-port.

3.1.2 At f_0 = 10 GHz

We now consider the resonant frequency of 10 GHz, and design two couplers with Duroid and FR4 substrates. Layout designs of both substrate couplers are reported in Figure 5 (a) and (b), respectively. From the simulation results, first the S-parameters were analyzed. Figure 6 (a) shows the obtained reflection loss coefficient curves of both couplers ports which exhibit good matching with reflection loss of -44.85 dB and -35.46 dB for Duroid and FR4 based couplers, respectively. Moreover, the port isolations (between Δ and ∑ ports and between two input ports), as shown in Figure 6 (b), are approximately -64 dB and -38.96 dB for Duroid and FR4 couplers, respectively. Here, the results for the S-parameters with the Duroid substrate based coupler are improved as compared to the FR4 substrate based coupler due to the low tangent loss coefficient (TanD) of the Duroid material.

Furthermore, Figure 7(a) shows the observed phase difference of 180^0 between two input fed signals at frequency 10 GHz at Δ-port. While, Figure 7(b) shows two input signals (port 3 and 4) arriving in phase with phase difference of approximately 0^0 at the $\sum$-port. It can be noted from Figure 7 that the Duroid based coupler's performance is better in providing the desired phase differences as compared to the FR4 based coupler. The performance differences between two couplers might be due to the mismatching between the coupler's ring and 50-ohm Tx-line sections which can be overcome by some adjustments in the layout designs.



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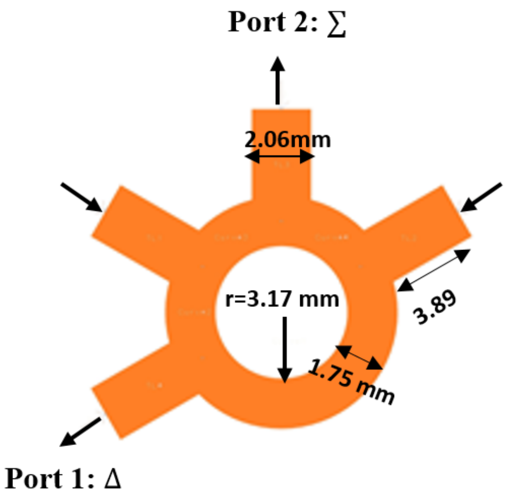
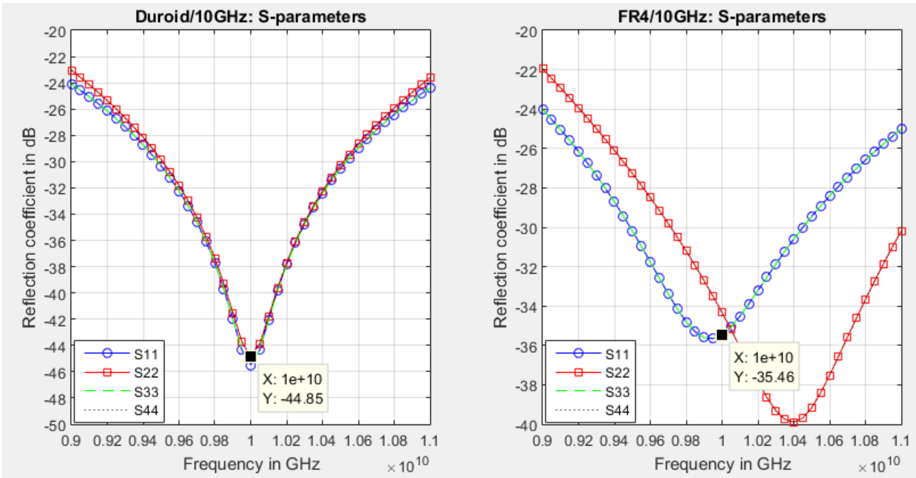


b)

Fig. 5. Layout design of 180^0 HRR coupler at 10 GHz using substrates **a)** RT Duroid, and **b)** FR4



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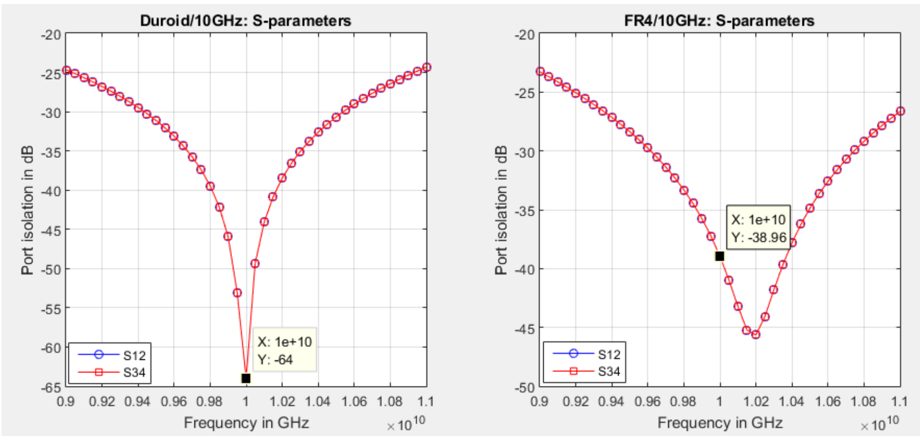

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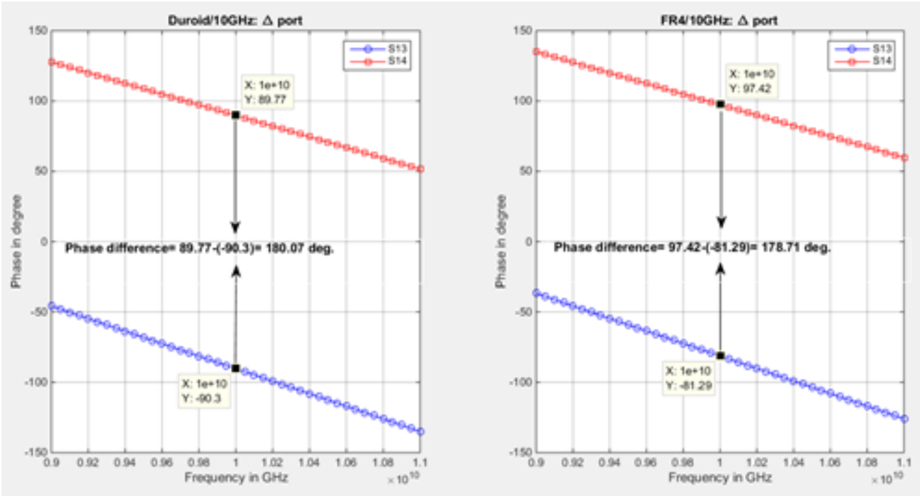
Fig. 6. Simulated S-parameters for Duroid and FR4 substrates based couplers: a) reflection loss of each port, and b) port isolations.



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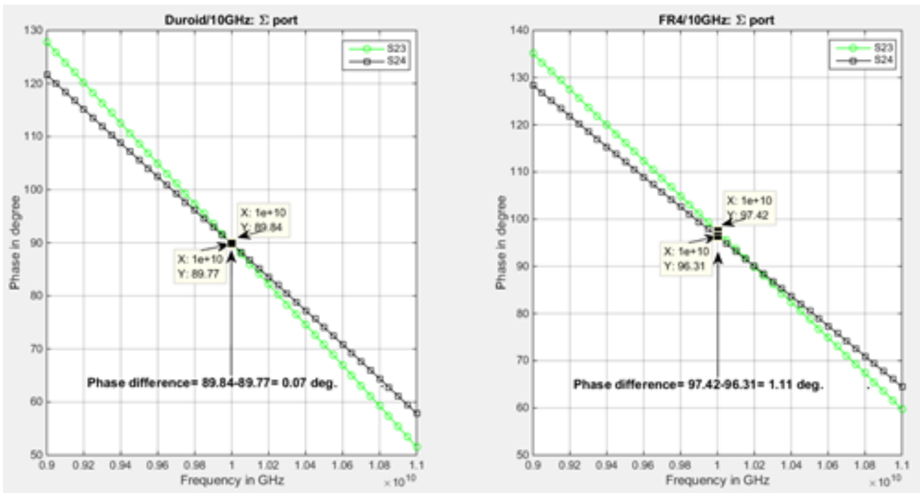

b)

Fig. 7. Obtained phase differences at f_0 = 10 GHz for Duroid and FR4 substrates based couplers, a) 180^0 phase difference at Δ-port, and b) 0^0 phase difference at ∑-port.

3.2 Direction Finding Antenna Array Using the 180^0 HRR Coupler

As mentioned earlier, we now combine a two antenna elements array with the designed 180^0 HRRC in order to estimate the direction of arrival (DoA) of the received signal at operational frequency of f_o=10 GHz using the RT Duriod 5880 substrate (ε_r=2.2 and t=1.575). The designed and fabricated circuit is shown in Figure 8.

Initially, in simulation, a simple microstrip patch antenna array, consisting of two antenna elements, was designed at operational frequency of 10 GHz. Moreover, by using the quarter wave transformer (QWT) matching technique, the patch input impedance was matched with 50 Ω transmission line. The patch antenna designed in this work was analyzed carefully so to obtain good S-parameters (e.g., return loss), gain, directivity and radiation patterns. The design procedure of QWT microstrip patch antenna can be found in [9]. Herein, we highlight the design parameters of the microstrip QWT patch antenna array in Figure 8 for 10 GHz frequency. The design parameters of the 10 GHz-Duroid substrate based 180^0 HRRC coupler are the same as mentioned earlier. In this way, we integrated the designed 180^0 HRRC with the antenna array and simulated the whole optimized circuit which later was fabricated, as shown in Figure 8, to obtain the difference (Δ_p) and sum ($\sum_p$) patterns. The Δ_p and $\sum_p$ patterns of the two input (signals) antenna elements at Δ and ∑ ports can be mathematically defined as

$$\Delta_p = 1 - e^{-jkd\sin\theta} \tag{3}$$

$$\sum\nolimits_p = 1 + e^{-jkd\sin\theta} \tag{4}$$

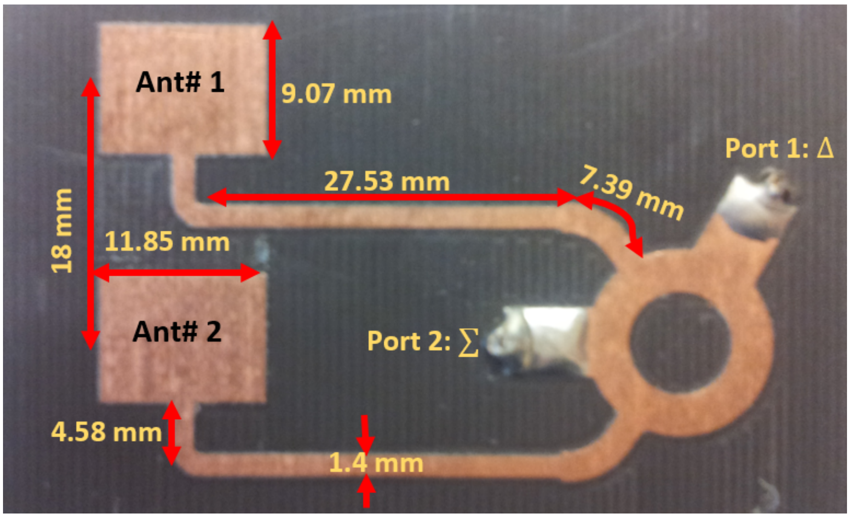

Fig. 8. Designed circuit for DoA estimation using 180^0 HRR coupler.

where $k=2\pi/\lambda$ is a wave number, d is the space between two antenna elements which is assumed 0.6λ in this work, and θ represents the DoA or angle of arrival (AoA) of the RF signal impinging on the array. By taking the ratio of Δ_p in (3) to $\sum_p$ in (4), we can estimate the DoA, as

$$\theta = \sin^{-1}\left(\frac{\lambda}{\pi d}\tan^{-1}\frac{\Delta p}{\Sigma p}\right) \tag{5}$$

Using the designed circuit, first, Δ_p and $\sum_p$ patterns were measured assuming an impinging signal with DoA from 0^0 to $\pm 90^0$ with angular step of 5^0 and then these patterns were used into expression (5). Consequently, the designed circuit was able to estimate the DoA of the received signal from 0^0 to $\pm 50^0$ with error of less than 5^0 which shows the practical angular resolution/coverage of the designed array along with the rat race coupler.

The measured reflection coefficient curve (S11 for Δ-port and S22 for $\sum$-port) and the radiation patterns of Δ and $\sum$ ports are shown in Figure 9 and Figure 10, respectively. Furthermore, the measured DoAs in degrees at various angles are provided in Figure 11. In order to validate the measured DoAs results, we have simulated the expressions in (3, 4 and 5) using Matlab by forming the received signal model in [12] with signal to noise ratio (SNR) = 10dB. The measured AoAs are in good agreement to the simulated results.

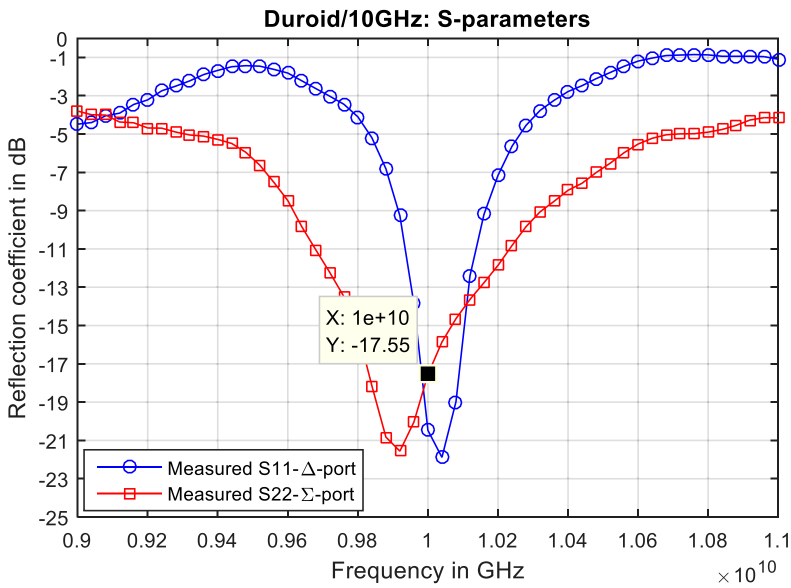

Fig. 9. Measured reflection loss of Δ and $\sum$ ports.

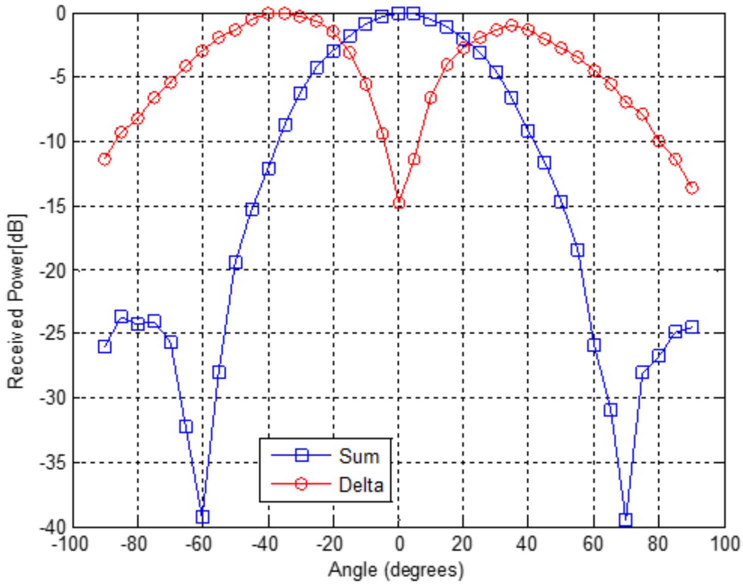

Fig. 10. Measured radiation patterns of Δ and ∑ ports.

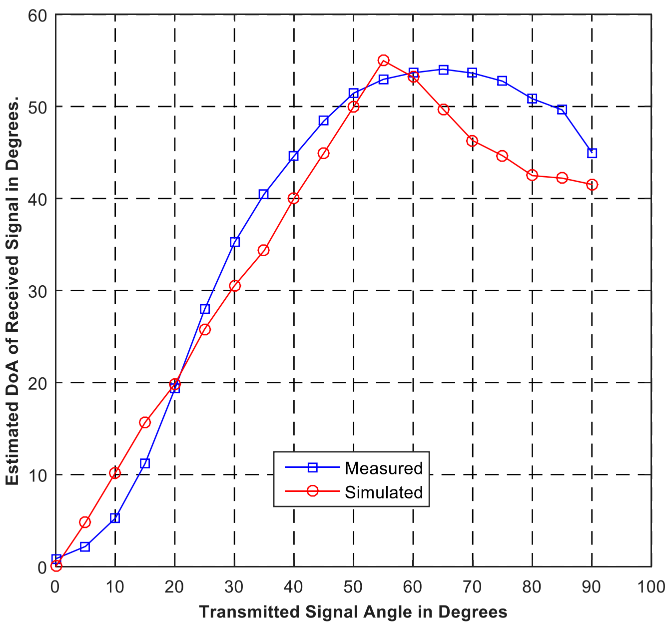

Fig. 11. Measured and simulated DoAs (θ).

4 Conclusion

Couplers for power combining and dividing are widely used in RF/microwave communication system devices. In this paper, 180^0 HRR couplers have been designed and analyzed in view of their application in DoA estimation systems. Different central frequencies (2.4 GHz and 10 GHz) and substrates (RT Duroid and FR4) have been considered. At various frequencies of operation and dielectric substrates, we have obtained the S-parameters via EM field simulation for the designed 180^0 HRR couplers. The reflection loss, port isolations, and delta and sum port phase differences assume good values. However, the couplers designed using the RT Duroid 5880 substrate provides better results as compared to the FR4 substrate based couplers.

Furthermore, a circuit was designed and fabricated to measure the DoA of the received signal from the Δ and $\sum$ patterns at 10 GHz, by combining the Duroid substrate based coupler with a simple patch antenna array. The designed circuit provided the DoA estimates in the range 0 to ±50 degrees with errors less than 5^0. The obtained results validated the performance of the designed coupler for the use in DoA estimation. Overall, the results are promising and offer stimulus to further investigations and applications of DoA estimation with those that deploy a massive number of antennas as for instance it was proposed in [11] although resorting to completely digital signal processing algorithms. The idea is then to combine electromagnetic lens antennas that are able to focus the impinging signal energy in a small subset of antenna elements, with 180^0 HRR couplers. This enables direction finding with high resolution and using an analog solution that operates directly at RF and that greatly simplifies hardware complexity.

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