Two Axis Direction Finding Antenna system using Sum – Difference Patterns in X Band

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Two Axis Direction Finding Antenna system using Sum – Difference Patterns in X Band

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Abstract - This work proposes the direction finding antenna system in two axis (θ_1, θ_2) in X band using sum ($\sum$) and difference (Δ) patterns of received signal. Direction finding system is constructed by implementing the microstrip patch antenna array and 180^0 hybrid rat race ring coupler which generates $\sum$ and Δ patterns of received RF signal. Initially, direction of arrival (DOA) is obtained in one axis, (θ_1), vertical direction, using the $\sum$ - Δ patterns of antenna array of two elements. Using the equations of $\sum$ and Δ of two input signals, radiation patterns at different θ values have been observed in simulation and compared with measured pattern values of constructed circuit. By taking the ratio of Δ to $\sum$ patterns, DOA has been estimated of designed circuit. Another circuit similar to first circuit, oriented at 90^0 (horizontal direction) has been implemented to estimate the DOA (θ_2) in other axis. By taking the 3D radiation patterns of each circuit in anechoic chamber, both circuits are measured for performance; and from 0 to ±40 degrees DOA has been observed with rms error of less than 5^0 in both axis. At 10 GHz operating frequency, experimental results, using material RT Duroid 5880, show that satisfactory performance can be achieved with proposed setup.

Key words: Direction of Arrival Systems, Microstrip Patch Antenna, Antenna Array and Rat Race Ring Coupler.

1. Introduction

The direction of arrival (DOA) or angle of arrival (AOA) estimation system having applications in radar, sonar, military, acoustic, communications and medical imaging, is an omnipresent task in array signal processing [1]. Recently developed a great number of radar and sensor systems require high efficiency, functionality and compactness [2]-[3]. One of the efficient methods of improving the quality of received signal is to find the DOA of the signal then targeting the reception only in the estimated direction which alternatively rejecting the interferer reception from other directions [4]. Hence the main objective of DOA system is to define a function which finds the angle of received signal. Many publications have studied the DOA system design and its characteristics which suggest different types of algorithms to estimate the direction of received signal, such as sensor array, Bartlett method, Capon method and MUSIC algorithm [1] & [4]. The techniques used in the literature are generally complex and require high signal processing computations.

The objective of this paper is to design a microstrip patch antenna array with 180^0 hybrid rat race ring coupler, to estimate the DOA of received signal in X band of frequency. Main motivation behind the antenna array and rat race coupler system is to find the direction of received signal in two axis using the sum ($\sum$) and difference (Δ) patterns at 10 GHz operating frequency. As part of the array section, microstrip patch antenna is designed as receiving element of the RF signal. Further, rat race coupler is designed and optimized at the central frequency in order to obtain accurate sum and difference of two received signals.

System design includes two antenna arrays placed in two directions (vertical and horizontal) each array consists of two microstrip patch antennas operating at 10 GHz frequency, rat race ring coupler providing the sum and difference of two received RF signals; and feeding network. The paper further is organized as follow: section 2 describes the working principle of the proposed DOA system, simulation and measured results are presented in section 3 and finally in section 4, paper is concluded.

2. System design and working principle

It is known that there exist one to one relationship between direction of a signal and the associated received steering vector [5]. It is therefore possible to estimate the direction of received signal by inverting this relationship. So in this work, a novel antenna system is proposed which includes microstrip patch antenna array, rat race ring coupler and feeding network. Block diagram of proposed DOA system and corresponding array configuration for both axis (θ_1 and θ_2), are shown in Fig.1 and Fig. 2, respectively.

Received signals by antenna array elements are fed to two input ports of 4-ports 180^0 hybrid rat race ring coupler which generates the sum ($\sum$) and difference (Δ) patterns at two output ports. As known from antenna array theory, coupler produces $\sum$ and Δ of applied input signals according to the following equations, respectively.

$$\sum = 1 + e^{-jkd\sin\theta} \qquad (1)$$

$$\Delta = 1 - e^{-jkd\sin\theta} \qquad (2)$$

Using above $\sum$ and Δ equations, direction of arrival is derived by taking the ratio Δ to $\sum$. After performing some mathematical iteration, DOA can be derived as given in following equation (3) [2].

$$\theta = \sin^{-1}\left(\frac{\lambda}{\pi d}\tan^{-1}\frac{\Delta}{\sum}\right) \qquad (3)$$

where λ is free space wavelength, d is spacing between two antenna elements, Δ and $\sum$ are the subtracted and summed amplitudes of RF signals received by antenna array of two elements.

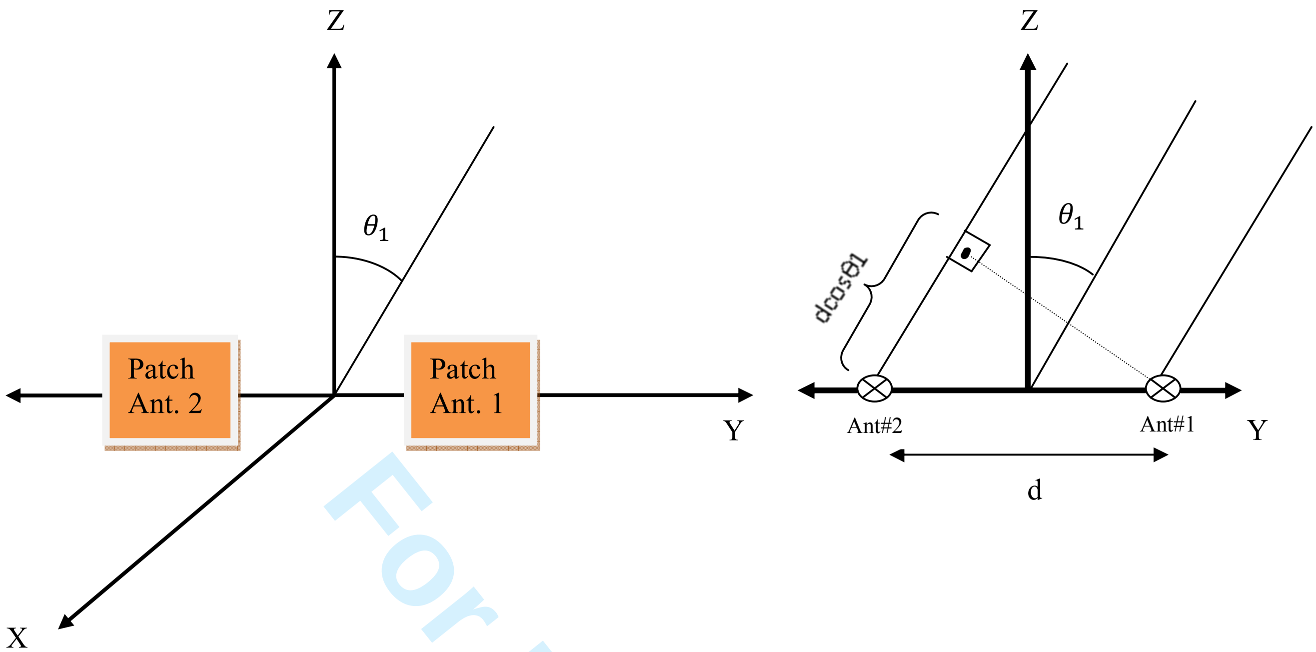

Fig. 1 Block diagram of DOA system and array configuration for θ_1

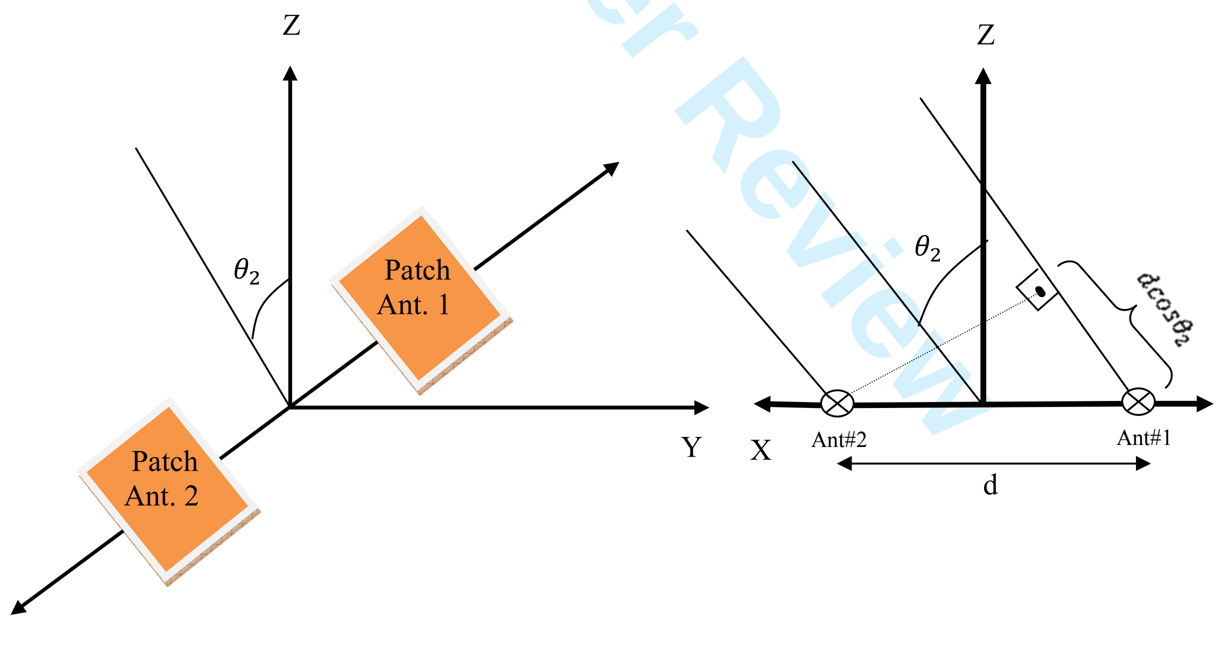

Fig. 2 Block diagram of DOA system and array configuration for θ_2

When rf signal is received by two antenna elements of an array, these two signals are applied to the two input ports of coupler which generates sum ($\sum_1$) and difference (Δ_1) at two output ports. By exploiting the sum and difference patterns of coupler, direction of arrival of received signal is estimated in one axis (θ_1) using the DOA function as shown in equation (3). For the sack of clear understanding, let's call this part of design as circuit 1 (in vertical direction). Similarly, another same part of design is constructed which is at 90^0 of first circuit and let's call it as circuit 2 (in horizontal direction) which also provides sum ($\sum_2$) and difference (Δ_2) patterns of two received signals. Again, by applying DOA function on obtained patterns as done in circuit 1, DOA (θ_2) in other axis is obtained. Each part of the system is designed and tested on ADS momentum software separately and optimized to the expected range of results; and then desired circuits are fabricated on RT Duroid 5880 substrate for experimental results. Substrate properties are shown in table 1.

Table 1: RT Duroid 5880 substrate properties

Substrate permittivity ε_r	2.2
Substrate thickness h	1.575 mm
Substrate tangent loss	0.0004
Copper conductivity	5.8 e^7 s/m
Copper thickness t	17 μm

Initially microstrip patch antenna was designed at 10 GHz central frequency and patch input impedance was matched with 50 Ω Transmission line using quarter wave transformer method. This designed patch antenna was analyzed carefully which in result provided better S-parameters, gain, directivity and radiation pattern. Microstrip patch antenna design procedure is well defined in [6] - [7]. After getting good design of patch antenna, array of two antenna elements was implemented while keeping 0.6λ distance (d) in between two elements. Detailed study about patch antenna arrays is explained in [8] - [10]. Elements spacing is trade-off between grating lobe and mutual coupling. Spacing greater than one λ produce grating lobes, while less than half λ create mutual coupling effects [11]. Later, in order to obtain the $\sum$ and Δ patterns of two received signals, 180^0 hybrid rat race ring coupler was designed separately at

10 GHz and optimized for the desired outputs. Basic design and working principle of ring coupler is given in [12] - [14].

3. System design implementation

Having simple structure, array of two patch antenna elements and ring coupler, system design is straight forward and able to provide the direction of arrival in two axis (θ_1, θ_2) of received signal using sum and difference patterns. The design implementation of the system to estimate θ_1 and θ_2 is explained in below two sub-sections, separately.

a) Estimating DOA for θ_1

As shown in Fig. 3, patch array is integrated with coupler and desired DOA system circuit has been formed in ADS software's layout tool. Received signal by array elements, are fed as two input signals to the 4 ports 180^0 hybrid rat race ring coupler. Coupler by performing its operation according to equations (1 and 2), generates sum and difference patterns of applied input signals at two output ports, called $\sum$ and Δ ports. After designing the setup, simulations were run and first of all, S-parameters of $\sum$ and Δ ports have been analyzed and are given in Fig. 4 where reflection loss of sum port is about -30 dB at 10.02 GHz and -27 dB at 10 GHz for difference port. While obtained gain of the array is 9.47dBi and directivity 10.99 dBi. Further, by exploiting $\sum$ and Δ pattern equations and values of θ from 0 to ± 40 degrees, absolute amplitude and phase values have been calculated for $\sum$ and Δ ports. As shown in Fig. 5, in ADS far field simulation, using these calculated values, $\sum$ and Δ ports were excited and beam was observed to be moved between 0 & ± 40 degrees as values of θ vary between 0 & ± 40 degrees. Although the array will be used for receiving, we have checked it in transmitting mode in ADS simulator. We have calculated the received signals and applied these as transmitting sources to see the beam steer. For example, when we put value of θ as $+15^0$ in

$\sum$ - Δ equations and excited $\sum$ and Δ ports then in simulated results of far filed patterns, maximum gain was obtained at $+15^0$.

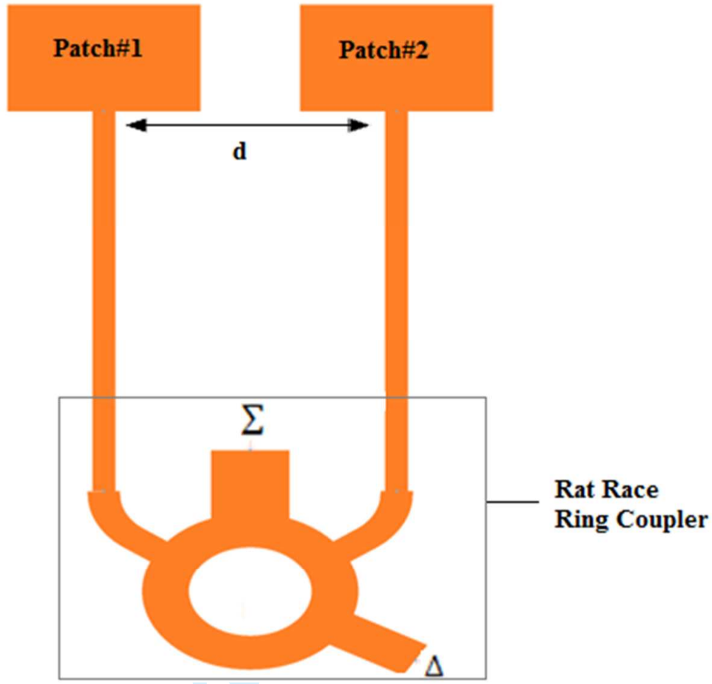

Fig. 3 ADS layout design of DOA circuit 1

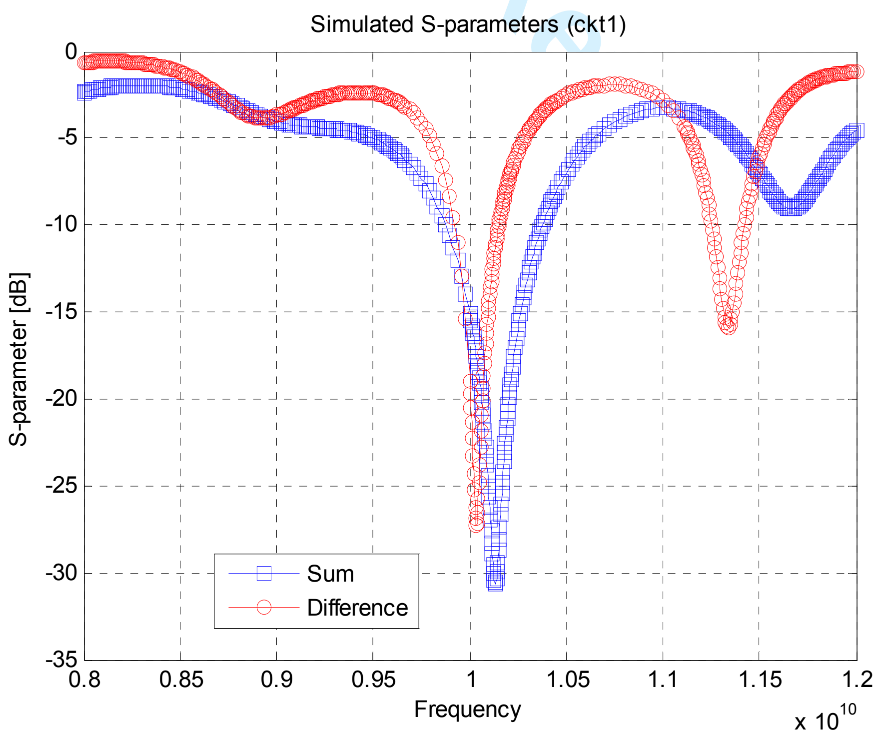

Fig. 4 Simulated S-parameters of circuit 1

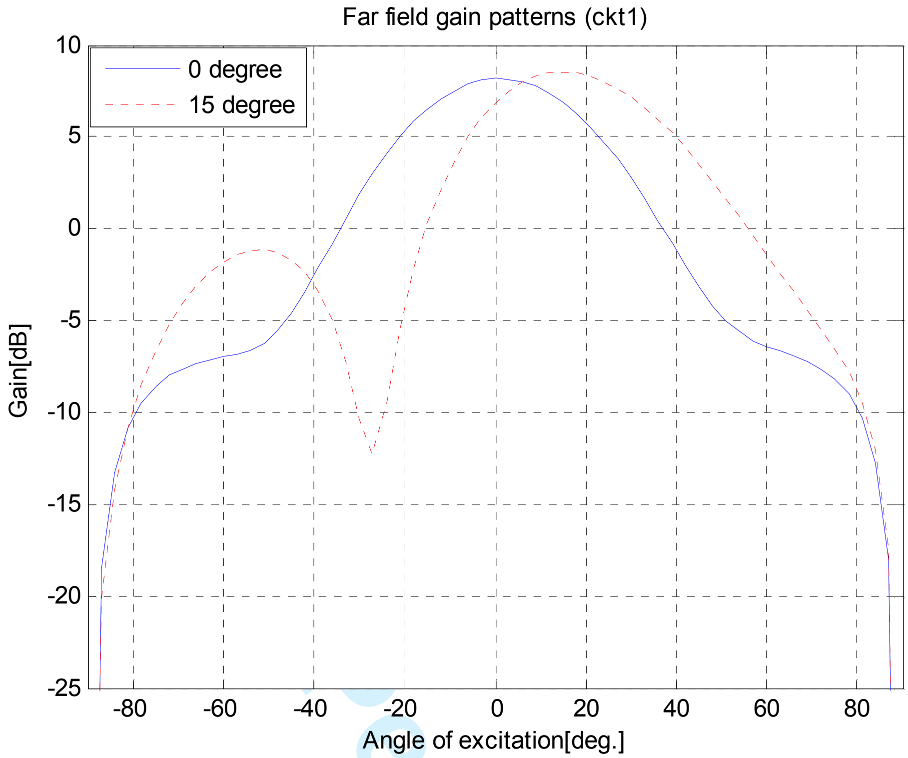

Fig. 5 Far field gain patterns, at excited angle of 0^0 and $+15^0$

Simulated ADS layout design has been fabricated for experimental results of the DOA for θ_1. From ADS layout, gerber file was exported in order to fabricate the design on selected RT Duroid 5880 material. This fabricated circuit is shown in Fig. 6 with SMA connectors soldered from back side. Later this circuit was tested in receiving mode in anechoic chamber of Sabanci University, SUNUM department for better experimental results. In this regard, a horn antenna was used as transmitting antenna and constructed circuit as receiving of 10 GHz signal from transmitting horn antenna. Further, using Agilent Network Analyzer (up-to 50 GHz), S-parameters were analyzed which later plotted by importing in Matlab and are shown in Fig. 7. Reflection loss about -21 dB at 9.95 GHz for sum port and 21 dB at 10.01 GHz for difference port, has been observed. Fig. 8 shows the measured sum-difference patterns of the implemented circuit. Having $\sum$ - Δ patterns of experimental setup, direction of arrival (θ_1) can be obtained. For this purpose a Matlab code has been written in which measured $\sum$ - Δ

patterns were imported and by putting in equation (3), DOA has been estimated as 0 to ±40 degrees. These estimated values of angle of arrival of received signal v.s actual transmitted signal angles are plotted in Matlab from 0 to 40 degrees and are shown in Fig. 9.

Fig. 6 Fabricated DOA circuit 1

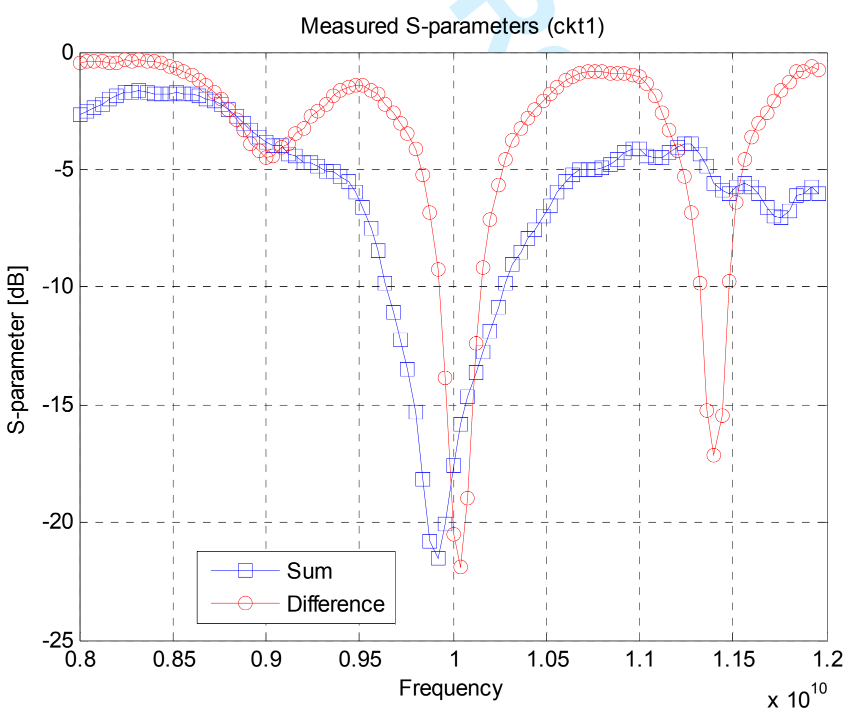

Fig. 7 Measured S-parameters of circuit 1

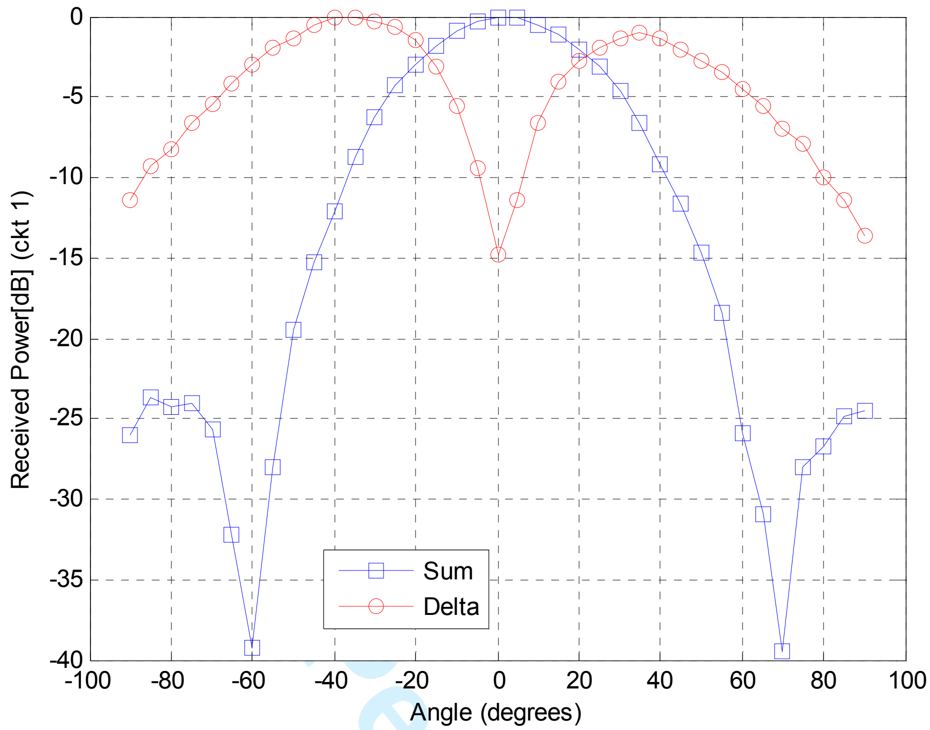

Fig. 8 Measured radiation patterns of $\sum$ and Δ ports

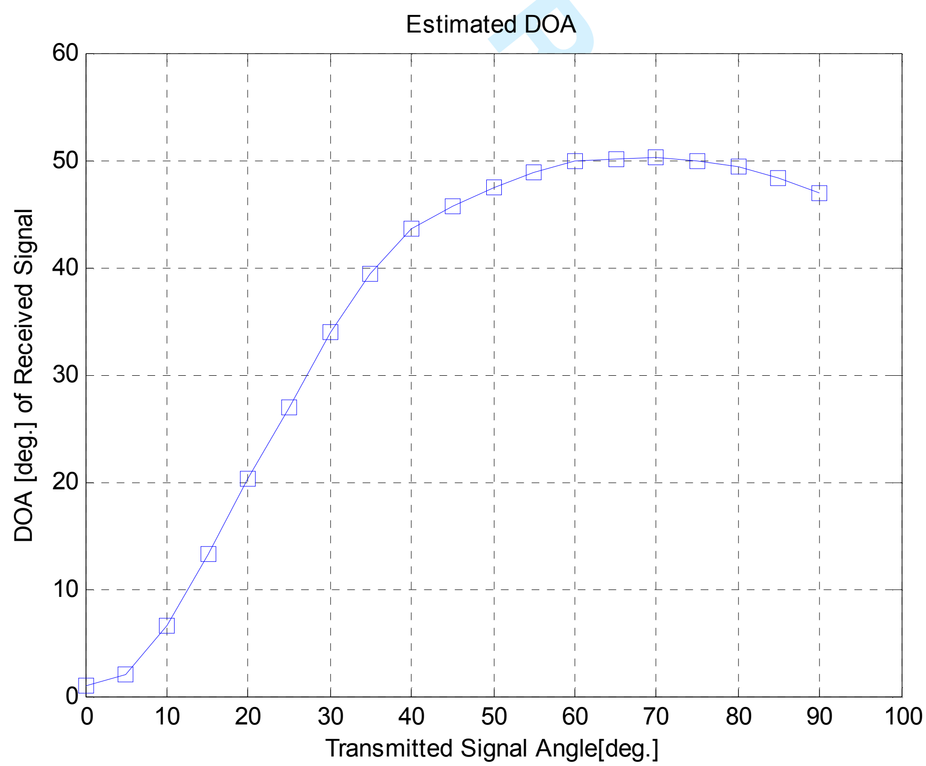

Fig. 9 Measured Direction of Arrival (θ_1)

Same circuit has been utilized to obtain the 3D radiation pattern from theta2 = -90 to +90. Using 3D radiation patterns of sum and difference ports in Matlab, DOA has been observed same from 0 to ±40 degrees. Also rms error has been calculated for the performance measurement of estimated DOA. As shown in Fig. 10, for DOA up-to 40^0, rms error is less than 5 degrees. In order to check the performance of this circuit above 40^0, rms error has been calculated by finding DOA as -60^0 to $+60^0$ and -80^0 to $+80^0$. This performance is shown in Fig. 11 which indicates that beyond 40^0, system is not capable of providing acceptable results.

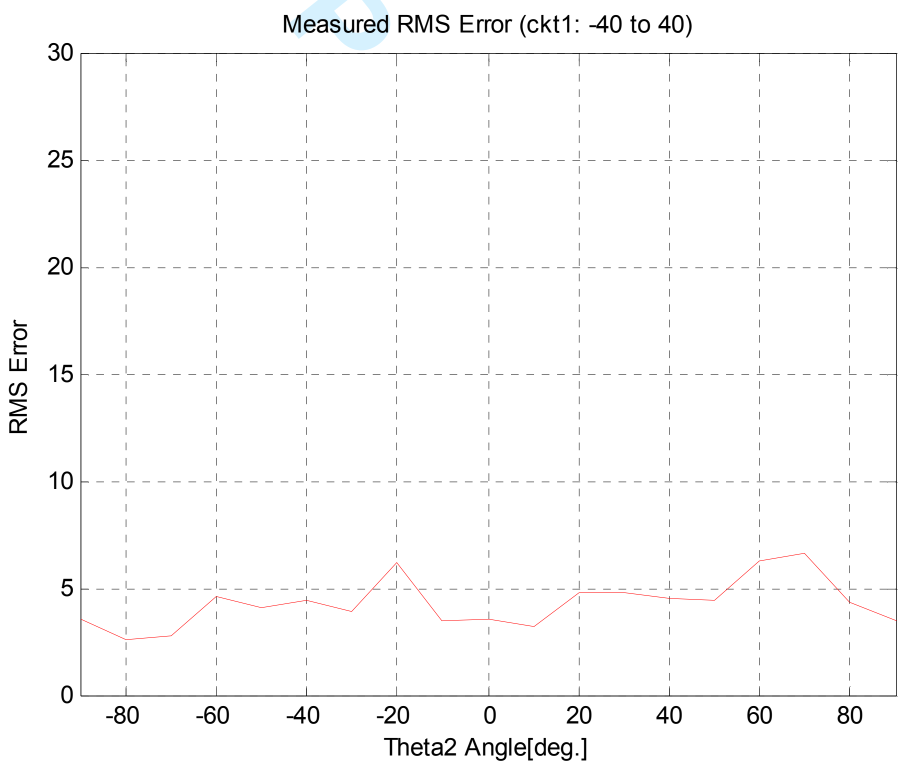

Fig. 10 Measured rms error of DOA for θ_1

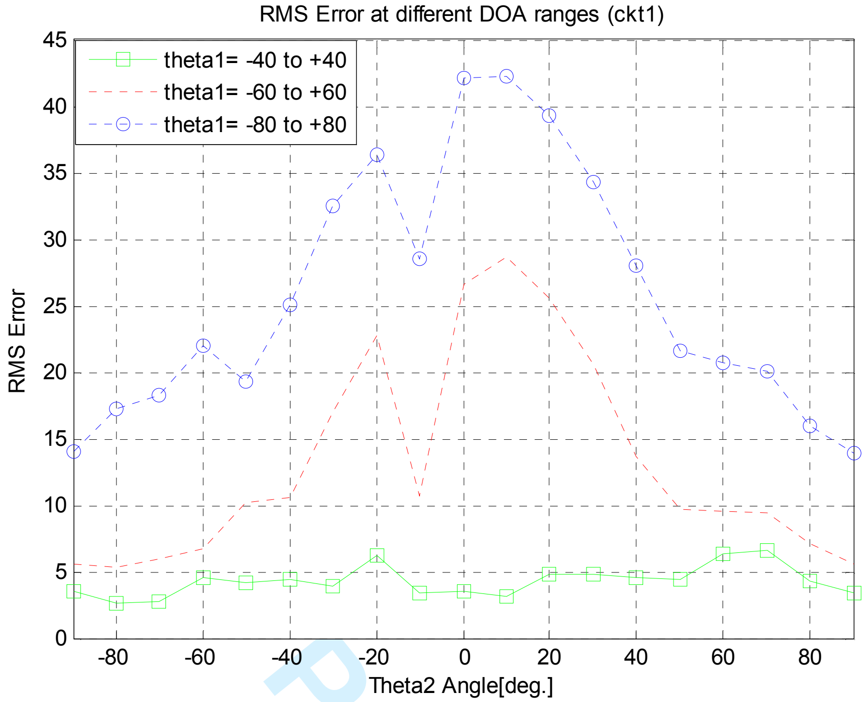

Fig. 11 Measured rms error at different DOA ranges of θ_1

b) Estimating DOA for θ_2

Similarly like previous circuit, another DOA system (circuit 2), which is at 90^0 (horizontal direction) than circuit 1, has been designed to obtain the DOA for θ_2. First, it is designed in ADS layout and simulated for desired results as did for circuit 1 and then fabricated for practical results. ADS layout design of this circuit 2 is shown in Fig. 12. Its simulated S-parameters are shown in Fig. 13 which indicates that sum port has reflection loss about -20 dB at 10 GHz and -25 dB at 9.9 GHz for difference port. Fig. 14 shows the far filed patterns of this circuit. In this circuit, gain obtained is 8.89 dBi and directivity 10.13 dBi. These simulated results again are in satisfactory range. Later this circuit has been fabricated on same substrate RT Duroid 5880. This fabricated circuit is given in Fig. 15 with SMA connectors soldered from back side. Circuit was then tested in anechoic chamber for practical results for θ_2. By using the Agilent Network Analyzer (up-to 50 GHz); S-parameters of sum and difference ports were measured and are shown in Fig. 16. Reflection loss about -15 dB at 10

GHz for sum port and -30 dB at 9.85 GHz for difference port, has been observed. Further, Fig. 17 shows the measured $\sum$ - Δ patterns. Having $\sum$ and Δ patterns of experimental setup, angle of arrival (θ_2) can be estimated as did for circuit 1, by putting pattern values in equation (3). Similarly as done for circuit 1, a Matlab code is written for this task and direction of arrival from 0 to ±40 degrees has been observed. These values of estimated DOA of received signal v.s actual transmitted signal angles are plotted in Matlab from 0 to 40 degrees and are shown in Fig. 18. For performance measurement of this circuit, 3D patterns were measured and as shown in Fig. 19, rms error for DOA (0^0 to $\pm 40^0$), has been estimated which is less than 5^0, equivalent to circuit 1. Also Fig. 20 indicates that circuit is not capable of providing acceptable DOA values beyond 40^0.

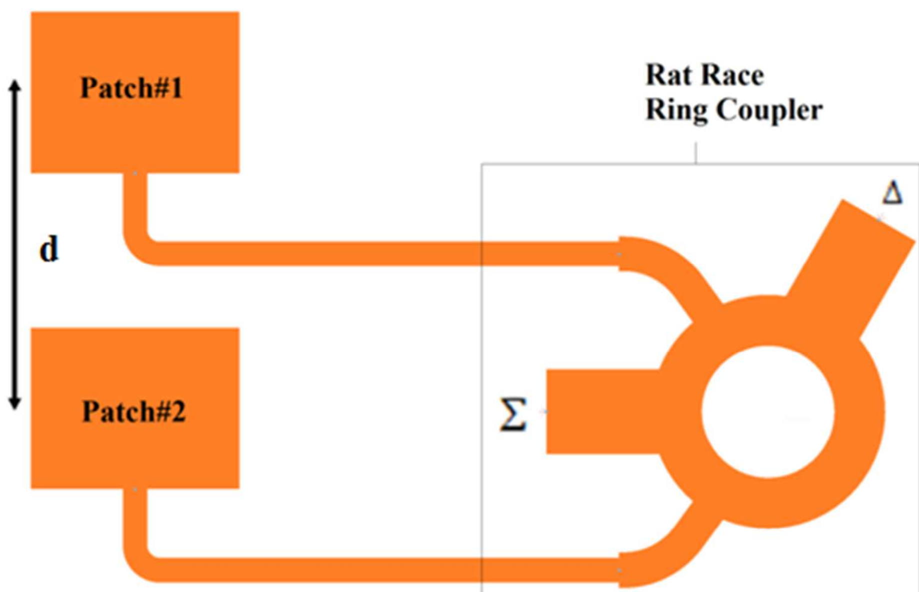

Fig. 12 ADS layout design of DOA circuit 2

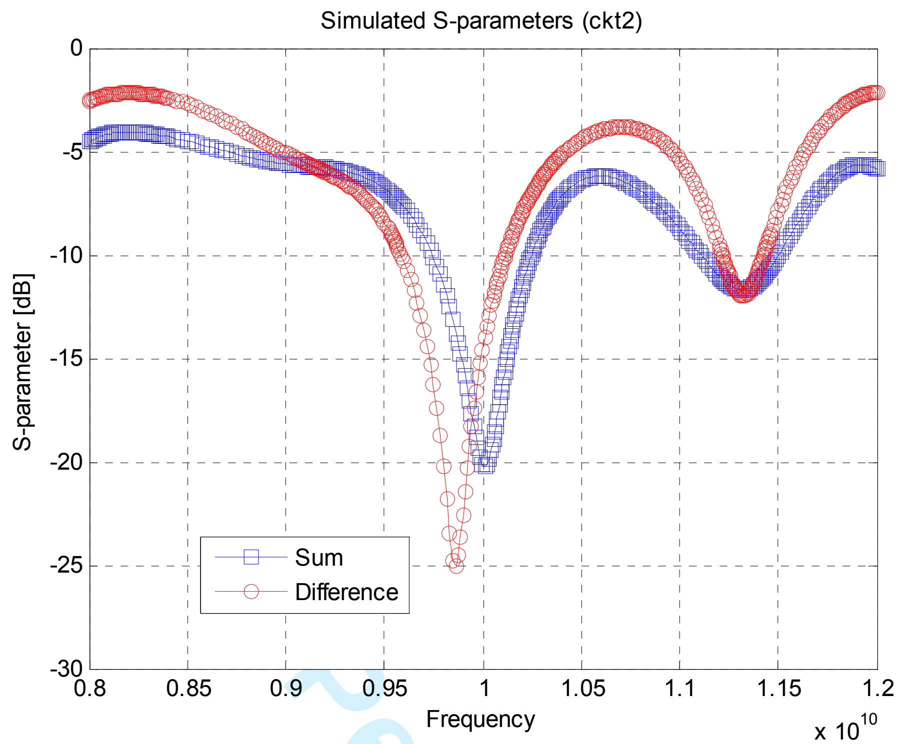

Fig.13 Simulated S-parameters of circuit 2

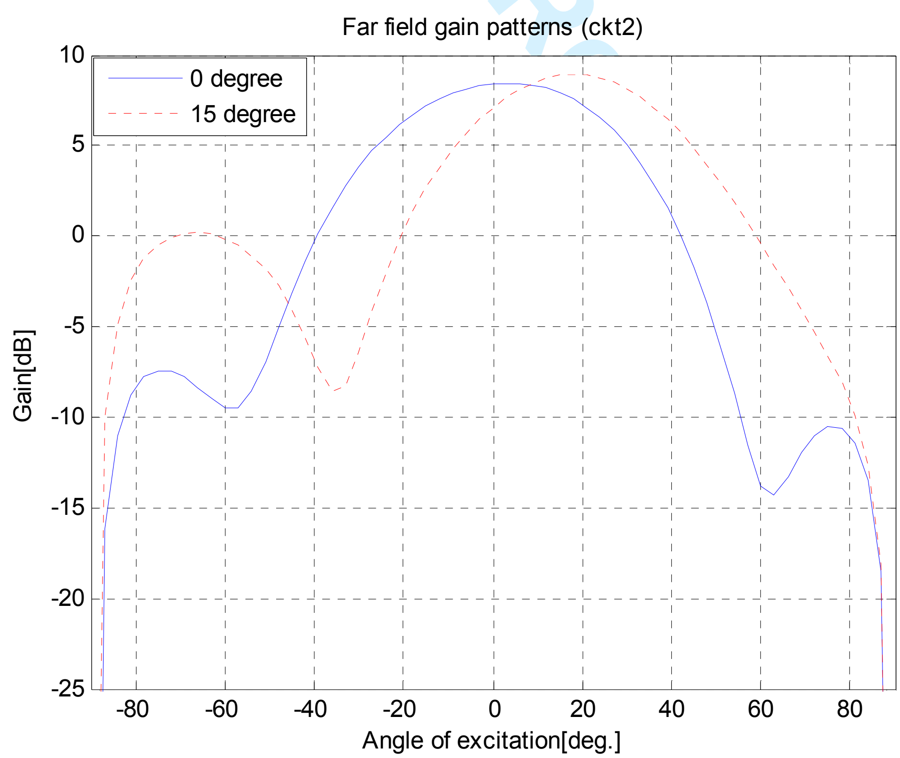

Fig.14 Far field gain patterns, at excited angle of 0^0 and $+15^0$

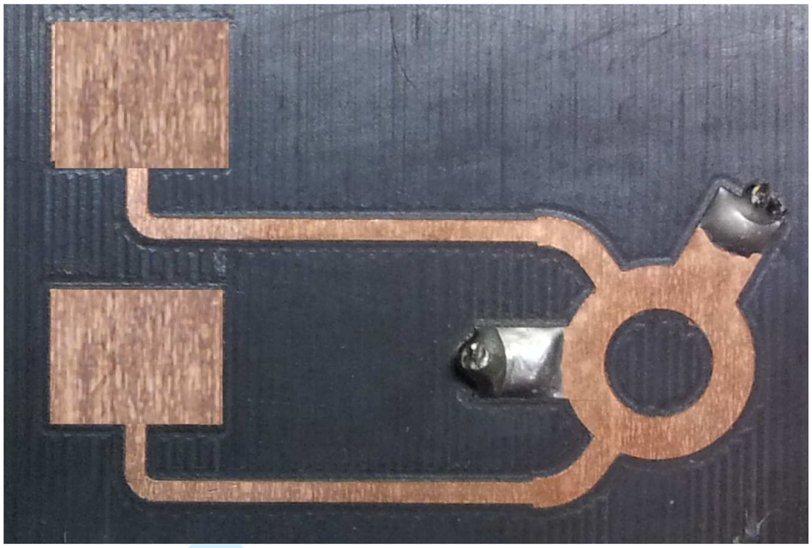

Fig. 15 Fabricated DOA circuit 2

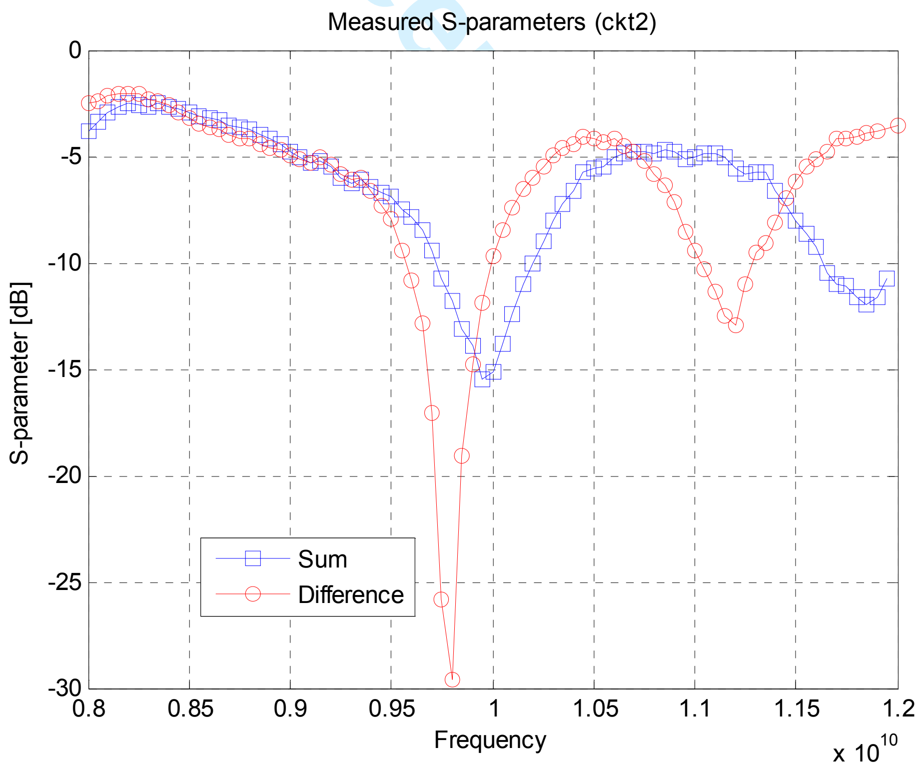

Fig.16 Measured S-parameters of circuit 2

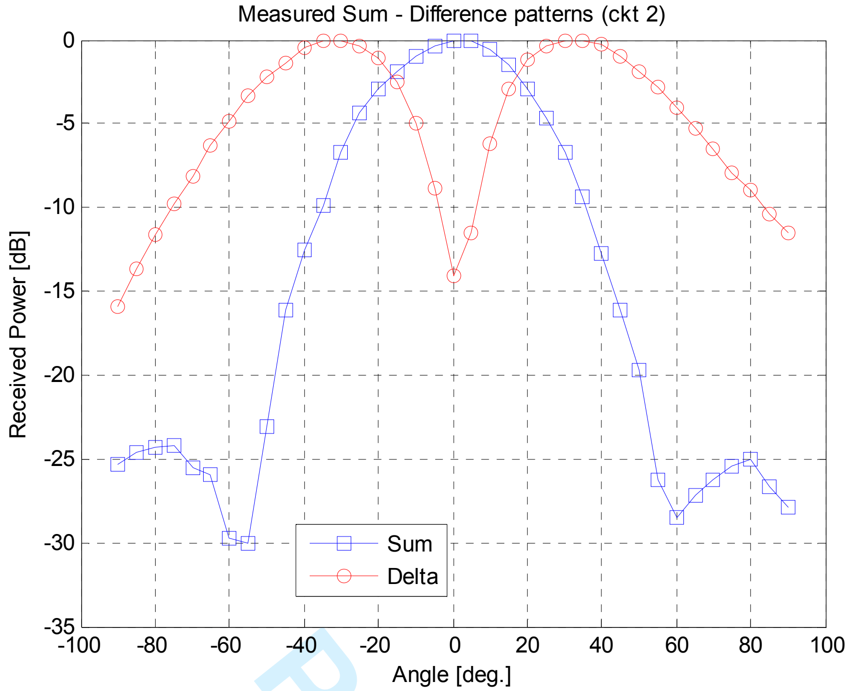

Fig. 17 Measured radiation patterns of ∑ and Δ ports

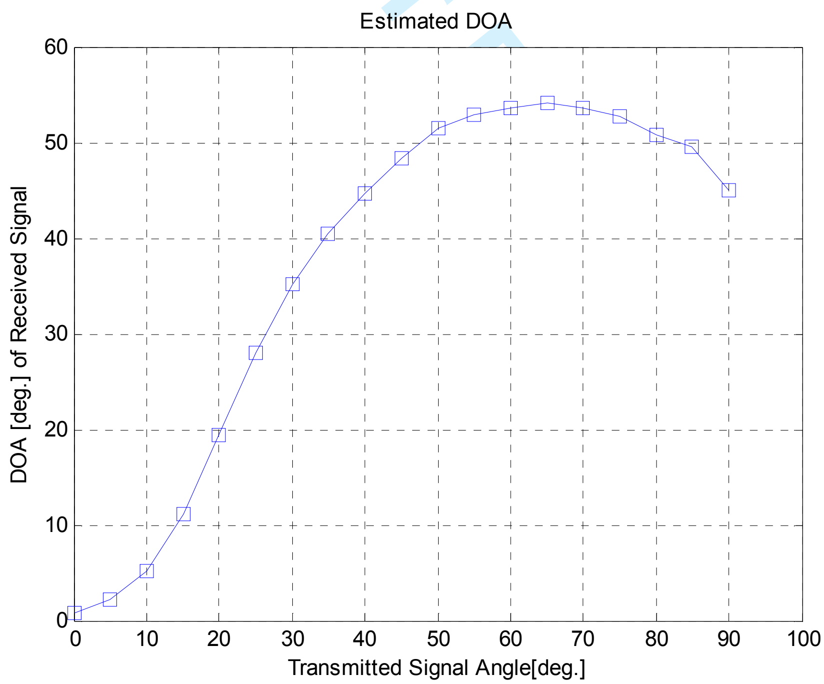

Fig. 18 Measured Direction of Arrival (θ_2)

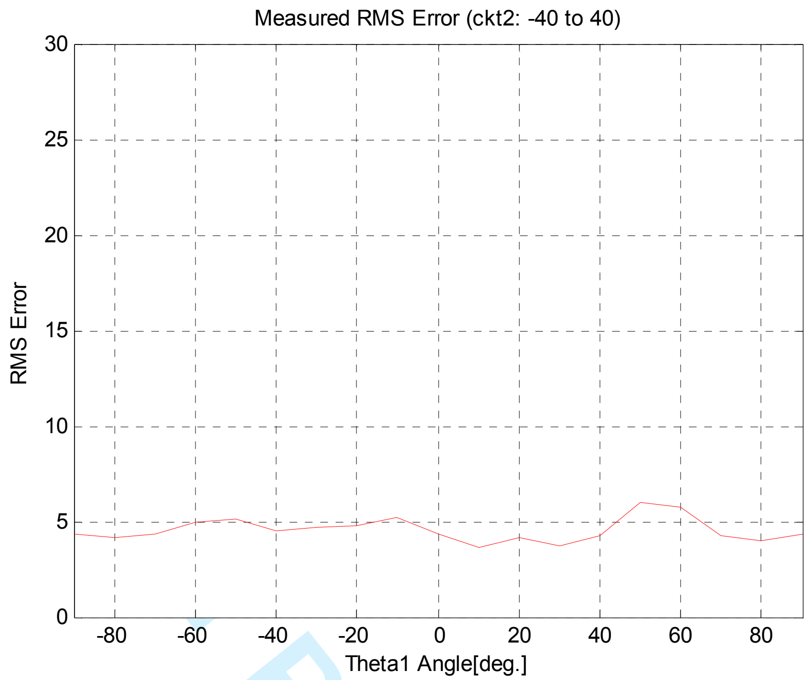

Fig. 19 Measured rms error of DOA for θ_2

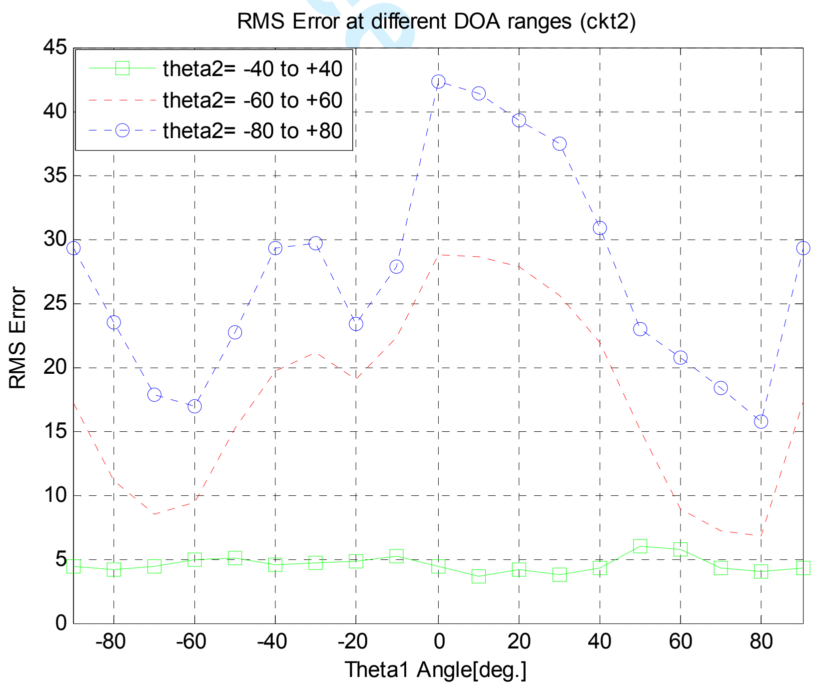

Fig. 20 Measured rms error at different DOA ranges of θ_2

Estimated DOAs 0 to ±40 degrees in two axis (θ_1, θ_2), are together plotted and shown in Fig. 21 along with implemented system design circuits.

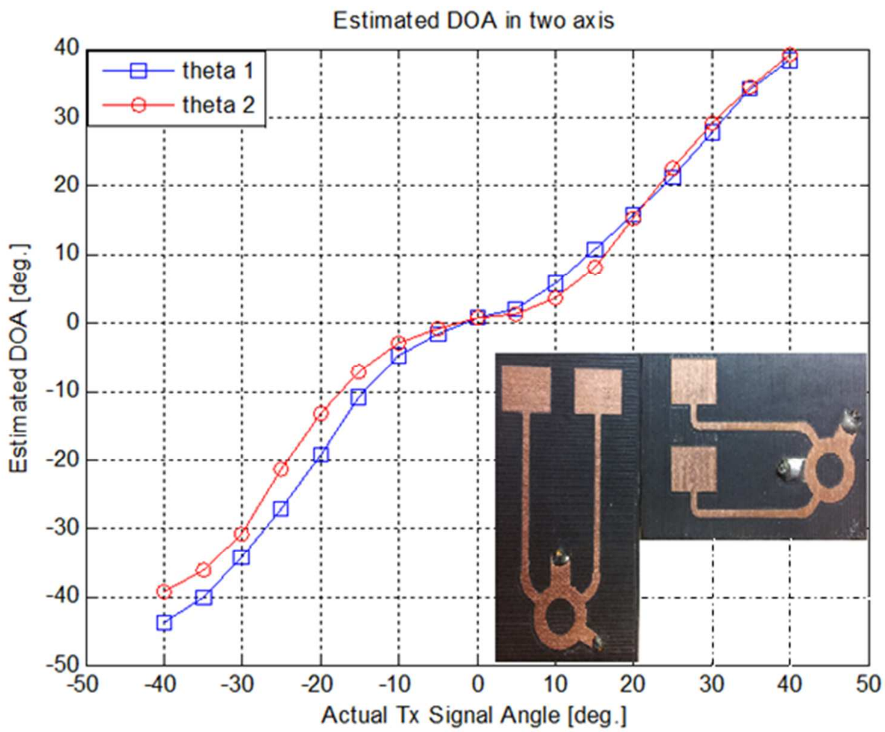

Fig. 21 Measured DOA in two axis (θ_1, θ_2) along with antenna system design

4. Conclusions

In this paper, a simple two axis direction finding antenna system has been implemented to estimate the DOA of received signal at 10 GHz frequency using $\sum$ and Δ patterns. Proposed system consists of microstrip patch antenna array of two elements spaced 0.6 λ and 180^0 hybrid rat race coupler which generates $\sum$ and Δ patterns of two received signals. Antenna array and coupler were integrated and $\sum$ - Δ patterns obtained, in vertical and horizontal directions, by constructing two separate same design circuits, one for finding DOA for θ_1 and other circuit finding DOA for θ_2. By putting $\sum$ - Δ patterns in equation (3), angle of arrival has been estimated. This task first has been simulated in ADS layout and optimized for expected results. Later simulated designs of both circuits were fabricated on RT Duroid 5880 substrate. Each circuit's 3D, ∑ - Δ patterns were taken as measured data. Experimentally obtained data was imported in Matlab for analysis of DOA. Measured S-parameters and far field ∑ - Δ patterns are very close to simulated results. From ∑ - Δ patterns of each circuit, DOA has been estimated for both axis. Both circuits are able to find direction of received signal from 0 to ±40 degrees in their respective axis. For performance measurement, rms error also has been calculated which is less than 5 degrees in both circuits. However, it increases more as we go above the 40 degrees which suggests that designed DOA system works well for 0 to ±40 degrees. By looking at all simulated and measured results, proposed system design of DOA works in satisfactory range which in result fulfills the purpose of this paper.

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