# Six-Port Based Direction-Of-Arrival Detection in Radar System

**N. S. A. Arshad [1], L. Y. Chooi [2], S. Z. Ibrahim[3], M. S. Razalli [4]**

*School of Computer and Communication Engineering (SCCE)1234*

*University Malaysia Perlis (UniMAP)*

*Arau, Perlis, Malaysia.*

*anoorsuhaira@yahoo.com[1], jcly@live.com[2], sitizuraidah@unimap.edu.my[3], shahrazel@unimap.edu.my[4]*

*Abstract* **:**

*The phase measurement by using a wideband six-port correlator for Direction-of-Arrival (DOA) detection in radar system is presented. DOA detection is a fundamental procedure required by several monitoring and tracking. Phase-measurement DOA detection is commonly used in nowadays systems, but existing methods are based on traditional mixer architectures or expensive direct conversion devices which is high complexity and costly while compromising robustness. In this paper, an innovative measurement technique based on the six-port network principle is presented. The aim is to investigate a six-port correlator as a valid technology for direction finding and distance measurement. Its operation in reflection coefficient is tested with the six-port model as device under test (DUT) by vector network analyzer (VNA). Data measured is then compiled in MATLAB and followed by investigation through simulation in Agilent-ADS. The wideband characteristics of six-port model are analyzed and verified across frequency of 3-11GHz. Numerical effort such as BER method and addition of band pass filter can be applied in the future work to improve the project performance.*

***Keywords****-Six-Port Network, Direction-Of-Arrival, Phase Measurement, Passive Componen***.**

## I. INTRODUCTION

Direction-of-Arrival (DOA) measurement is a method for the determination of the direction of propagation of a radio-frequency wave incident with respect to an antenna array.[1] Countless security and defense systems require an accurate DOA detection for incoming electromagnetic waves as well as tracking system. A typical application is hostile radar detection for stealth aircrafts where the precise detection and measurement of the incoming signal direction can lead to a high-accuracy of the position where the radar is located. Other areas where DOA detection is important include industrial sensors for remote and non-invasive measurement of distances and positioning. DOA detection is also very important for modern wireless communication systems for orientation and electronic beam steering of smart-antennas [1].

In contrast with the conventional configuration that has a moderate bandwidth and large size, the proposed system feature wide operational bandwidth. The result expected in this paper is the implementation of a new approach for the Direction-of-Arrival measurement based on the wave phase measurement. This new approach is based on the use of a six-port component for the measuring of the phase shift. This offers the advantage that the oscillator is no-more needed and the signals are automatically down mixed from the six-port network. This is very important, because without oscillator the measurement system does not need to be thermal stabilized or also in particular situations where the detection system does not have to emit radiations. This measurements architecture then allows creating a robust, low-cost board able to measure the DOA angle with high accuracy. The proposed microwave system has been investigated within 3-11GHz.

## II. OPERATION OF SIX-PORT NETWORK IN RADAR SYSTEM

### A. *Classification of Radar*

Radar is an object detection system which uses radio waves to determine the range, altitude, direction, or speed of objects [2]. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. The radar dish or antenna transmits pulses of radio waves or microwaves which bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna which is usually located at the same site as the transmitter.

The information provided by radar includes the bearing and range of the object from the radar scanner. It is thus used in many different fields where the need for such positioning is crucial. The first use of radar was for military purposes: to locate air, ground and sea targets. This evolved in the civilian field into applications for aircraft, ships, and roads. Generally, radars are classified into primary radars and secondary radars as shown in Fig. 1 as one of basic classifications of radar.

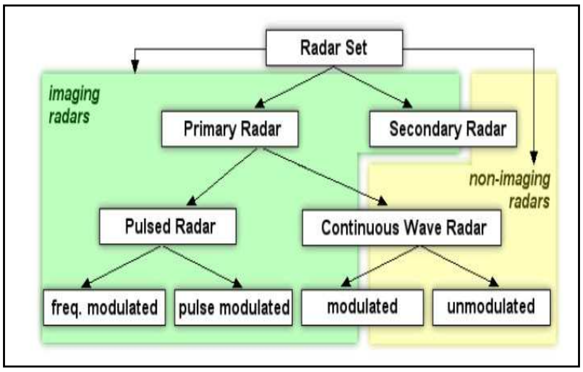


Fig. 1 Classification of radars[2].

### B. *Six-Port Based DOA Detection in Radar System*

Complete diagram of the six-port correlator DOA detection architecture that proposed to be implementing in radar system is shown in Fig. 2. The pink highlighted block represents the six-port correlator model. While blue highlighted block represent this project, the six-port based direction-of-arrival detection. The entire block diagram illustrated a simplified radar system. The two antennas is represent by RF-inputs for simulation with 5.8GHz as the operating frequency in ADS software. From the blue highlighted block, it shows the sub-components that perform the phase difference detection. The system is completely passive in the RF and extremely sensitive to phase variations. Angle detection can be calculated by applying from equation (1) and (2) The purpose of this project is accomplished to introduce the six-port network as a valid technology for direction finding and distance measurement tasks by satisfying the requirements imposed by different applications.

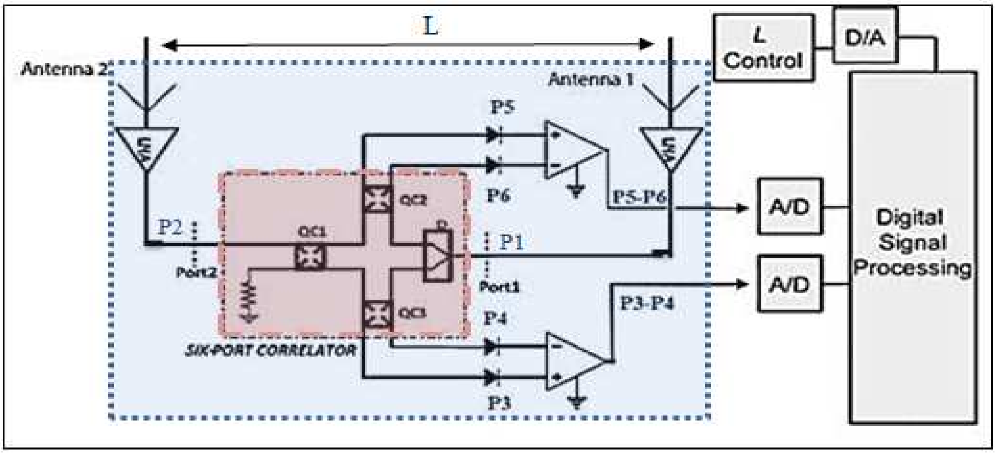


Fig. 2 Layout of six-port based DOA detection in radar system [3]

*C. Six-Port Based Phase Measurement*

The six-port based phase measurement concept is illustrated in Fig. 3. The two antennas needed for the DOA estimation are connected to the two input ports of the six-port receiver [4]. The phase fronts of the incident wave are highlighted in red. The two received signals interfere with each other in the six-port network generates four phase-shifted superposition at the six-port outputs. They are subsequently down-converted to baseband by power detectors. For this configuration, no reference source such as an LO is needed. The system is completely passive in the RF and extremely sensitive to phase variations, being based on the six-port correlator principle. Since the received signals are combined together to down-mix themselves to baseband without the need of a reference LO, the phase difference results only from a different incident angle of the detected wave on the reference plane and cannot be caused by phase noise of a reference LO. This implies a very high angular resolution.

The relationship between the incident angle, $\alpha$ and the detected DOA angle from the baseband signals B3, B4, B5 and B6 of the six-port receiver, through the phase difference $\Delta\phi$ is therefore given by

$$\alpha = \sin^{-1}\left[\tan^{-1}\left[\frac{B_3 - B_4}{B_5 - B_6}\right]\frac{\lambda}{2\pi.L}\right] \quad (1)$$

Where $\lambda$ is the wavelength of the signal and $L$ is the distance between the two receiving antennas. The detected phase $\Delta\phi$ is

$$\Delta\phi = \tan^{-1}\frac{B_3 - B_4}{B_5 - B_6} \quad (2)$$

The DOA range is limited to a half plane, which is from -90 to +90 deg. This range is given due to the limits of the arc-sine function that is defined only between -90 to +90 deg. Nevertheless, this is not a limitation for the addressed applications.

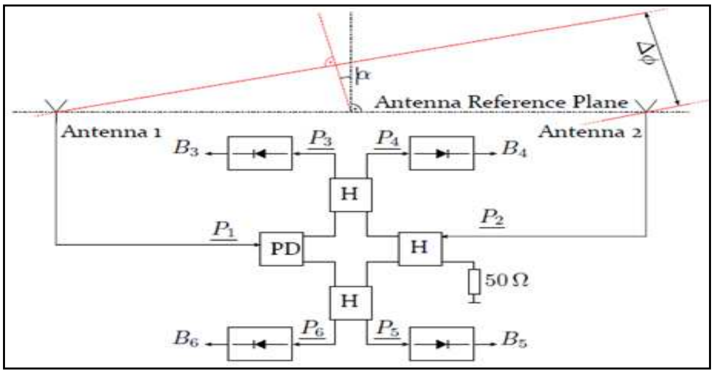


Fig. 3 Six-port based Direction-Of-Arrival Detection

## III. METHODOLOGY

This section collects and presents the experimental work and the methods, techniques and tool for the development of the six-port based DOA detection. Literature review presents the theoretical part for the six port network principle and its implementation. Firstly, the prototype six-port network is measured using VNA for its S-parameter performance. Measured data is then compiled using MATLAB code. The complied data is then imported into Agilent-ADS to simulate the six-port network with data item simulation tools. Types of the component choose, configuration and specification is added to validate the electromagnetic performance of the six-port correlator for DOA detection.

### *A. Measurement of Prototype Six-port Network Using VNA*

VNA is a precision measuring tool that tests the electrical performance of high frequency components, in the radio frequency (RF), microwave, and millimeter-wave frequency bands. VNA can also characterize active devices such as transistors and amplifiers using S-parameters. High-frequency devices can have one or two or more ports. S-parameters are an extremely accurate representation of the linear behavior of the component under test, describing how it behaves and how it interacts with other devices when cascaded. It is specifically designed to measure the forward and reverse reflection and transmission responses of RF components. S-parameters have both a magnitude and a phase component, and they characterize the linear performance of the DUT.

The measurements are performed using the network analyzer, Agilent-EB326B with SMA connector connected with the six-port DUT from Fig. 4. This is the most commonly used and most complete calibration involving two ports. Measurement have to repeat to get all 36 S-parameters, this is because the VNA available only can perform to measure two ports at one time getting only four S-parameter values i.e. S11, S12, S21and S22. To overcome this, MATLAB is then use to compiled the saved s2p measured data file from VNA to produce full 36 S-parameter in one s6p file.

Fig. 4 VNA Measurement Setup

*B. Construction of the Six-Port DOA Network*

Construction of the six-port network for DOA detection application is focused in this part. Fig. 5 shows the structure of the six-port based DOA detector. The DOA detector consists of four components e.g. passive six-port network, two low noise amplifiers, four RF power detectors and an operational amplifier.

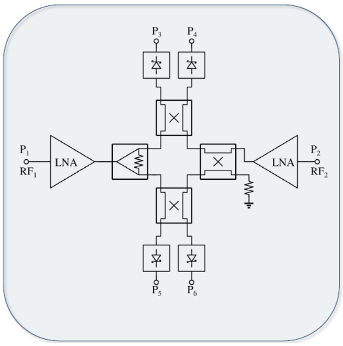


Fig. 5 The Six-Port Network

*1) Passive Six-Port Network*

The six-port network model consists of three quadrature hybrid coupler and one Wilkinson power divider. The reflection coefficient, transmission coefficient and isolation data measurements are performed using vector network analyzer (VNA) as illustrated in Fig. 6. The six-port network is simulated and experimentally tested across the frequency band from 3–11 GHz. Measured data is then compiled in MATLAB for the simulation file used in Agilent-ADS. MATLAB codes used for the data compilation is attached as appendix as reference. Besides that, the specification of passive six-port network can be seen in the Table I.

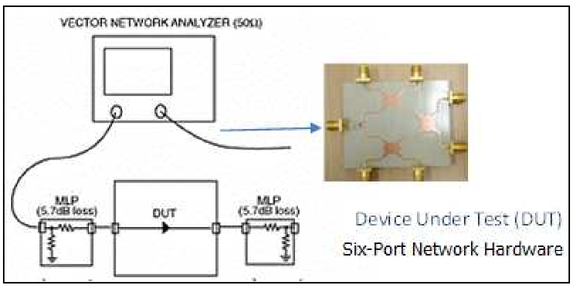

Fig. 6. S-parameter measurement of six-port using VNA.

TABLE I. DESIGN SPECIFICATION OF PASSIVE SIX-PORT NETWORK

| Design Specification | S-Parameter | Value |
|---|---|---|
| Transmission Coefficients | S31 = S41 = S51 = S61 | -7 ± 2 dB |
| | S32 = S42 = S52 = S62 | |
| Phase Differences, $\theta$ | S31 – S41 | +90° |
| | S32 – S42 | |
| | S51 – S61 | -90° |
| | S52 – S62 | |

*2) Low-Noise Amplifiers (LNA)*

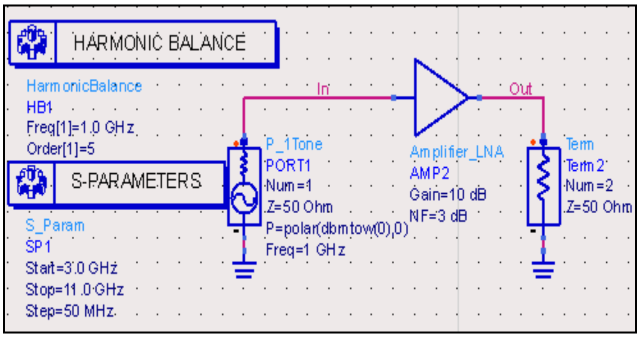


Fig. 7 Schematic of LNA simulation

*3) RF Power Detector*

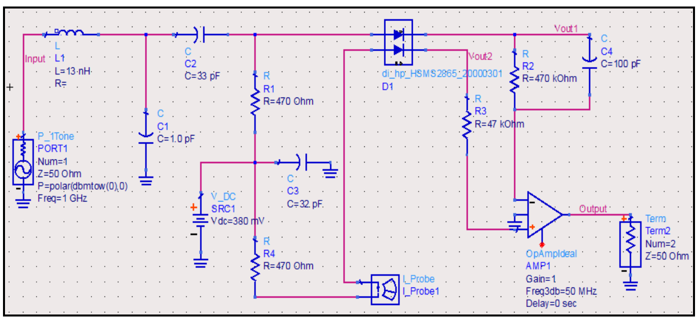


Fig. 8 Schematic of RF Power Detector simulation

*4) Operational Amplifier (Op-Amp)*

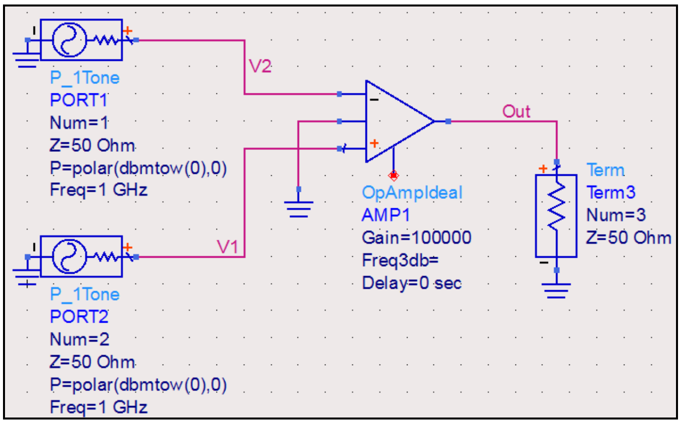


Fig. 9 Schematic of ideal op-amp in Agilent-ADS

*5) Six-Port Based Phase Measurement*

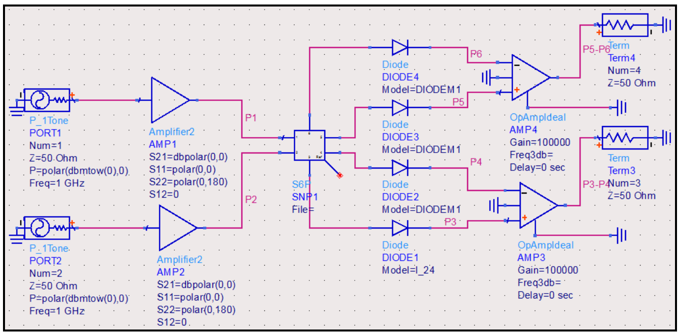


Fig. 10 Schematic of six-port DOA detection simulation in Agilent-ADS

## IV. RESULTS AND DISCUSSION

In this section, theoretical concepts and software simulation results are presented in support for the affirmations made. This part discusses illustrated effort put in designing and testing sub-components, to be used as a way for phase measurement from the high frequency power coupled by the detection output. The goal of the whole work is to provide a proof for the six-port DOA detection concept in radar.

### *A. Passive Six-Port Network*

The six-port network model consists of three quadrature hybrid coupler and one Wilkinson power divider. The reflection coefficient, transmission coefficient and isolation data measurements are performed using vector network analyzer (VNA) as illustrated in Fig. 6. The six-port network is simulated and experimentally tested across the frequency band from 3–11 GHz. Measured data is then compiled in MATLAB by using certain codes are used for data compilation.

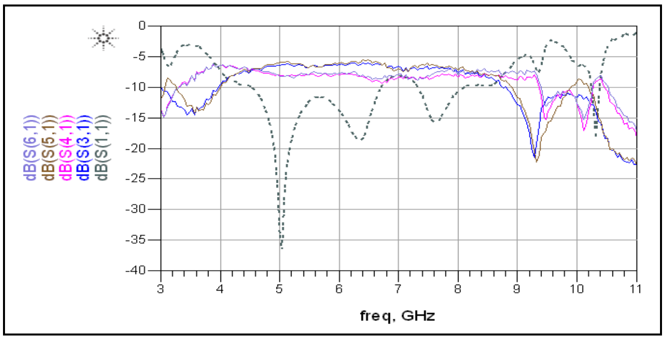


Fig. 11  Simulated S-parameters referring to input Port 1

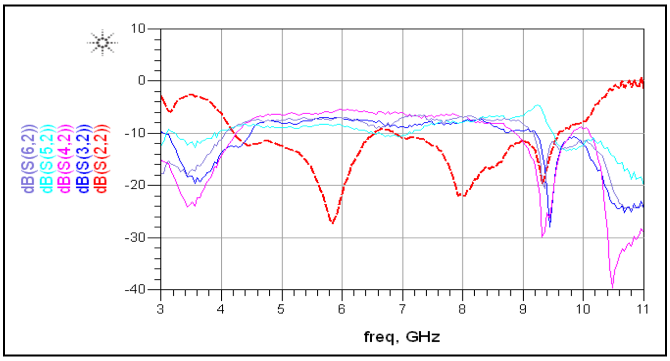


Fig. 12  Simulated S-paramters referring to input Port 2

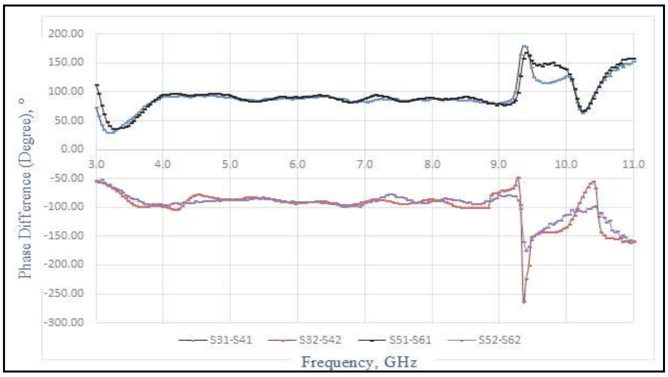


Fig. 13 Phase difference referring to Port 1 and Port 2

Fig. 11 and 12 shows the simulated S-parameter performance of the six-port network model. According to both figure, the return losses from Ports 1 and 2 are greater than 12 dB and 13 dB, respectively, across the band from 3–11GHz. The transmission coefficients from Port 1 to Ports 3, 4, 5 and 6 are -7 dB ±2 dB over the frequency range 4.5–10.5 GHz. Also, the transmission coefficients from Port 2 to Ports 3, 4, 5 and 6 are -7 dB ±2 dB over the frequency range of 4.5 to 10.5 GHz. Fig. 13 show the phase results which close to the required specification ±90° in the band from 4–10 GHz. .

For the ideal case, the phase differences should be integer multiples of 90°. Theoretically, the phase difference should be 90° when referring to Port 1 and -90° when referring to Port 2 as the input port. Both configurations show an almost constant phase shift for both the simulated and measured results over the intended frequency band of 4.5–9 GHz. The phase shifts are close to the specific required values.

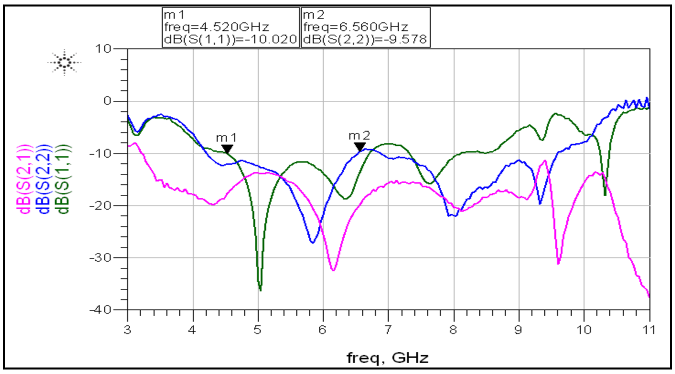


Fig. 14 Simulated reflection coefficient of input Port 1 and Port 2 and isolation between input Port 1 and Port 2.

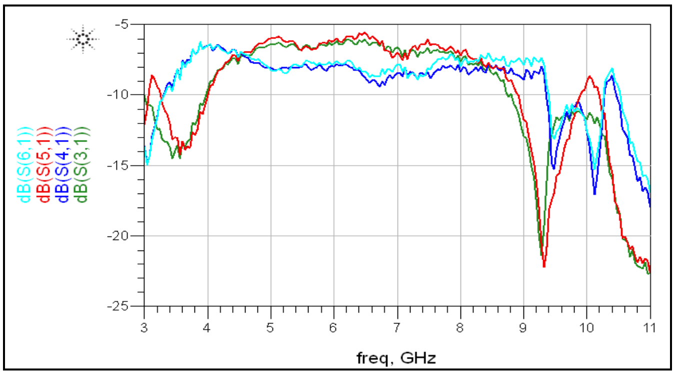


Fig. 15 Simulated transmission coefficient of output Ports 3, 4, 5 and 6 referring to input Port 1.

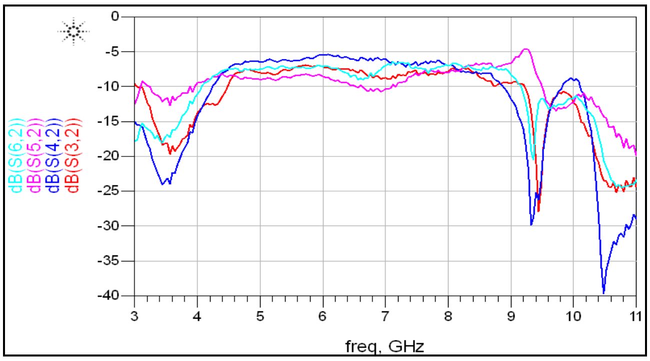


Fig. 16 Simulated transmission coefficent of output Ports 3, 4, 5 and 6 referring to input Port 2

According to Fig. 14, the simulated and measured return loss exceeds 10 dB at Port 1, and 12 dB at Port 2 across 4.5–6.5 GHz band. Fig. 15 shows the simulated isolation between Ports 1 and 2 is greater than 17 dB. The simulated and measured transmission coefficients are 7dB ± 2dB over 4.5–8.5 GHz. It can be stated that the simulated results are well performed, and the transmission coefficients are close to the theoretical value of 6 dB over the operating frequency band. Similar performances are obtained in Fig. 16 when Port 2 is designated as the input port. In an ideal case, these coefficients should have a magnitude of -6 dB.

*B. RF Power Detector*

Schottky diode, also known as hot carrier diode, is the most common used device for low drop voltage and for the quadratic relation between voltage and current. Based on the project research, Agilent's Schottky diode, HSMS-2865 is chosen as the RF power detector in this project due to its low cost, high volume and high frequency detector characteristic. Simulation tests were run to affirm it performance. Fig. 8 shows the simulation and parameter used and is it repeated with different RF input referring to Fig. 17

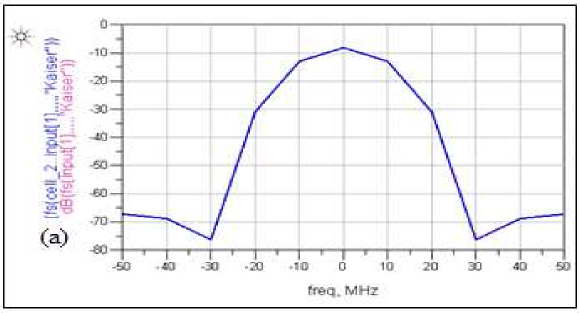


Fig. 17 Input RF power detector simulation result

The detector rectifies input RF signal, converting it to baseband at output by using the transfer function of a nonlinear device. The nonlinear voltage-current transfer function enables a power-to-current conversion that is needed for the power detection process. From Fig. 17 and 18, the diode rectifies the incident power (interpreted as the square of the RF signal voltage amplitude) into an output current signal of one polarity with amplitude proportional to the input power level.

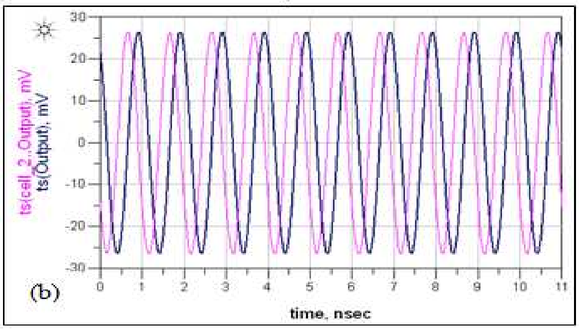


Fig. 18 Output RF power detector simulation result

*C. Low Noise Amplifier*

The received signal of the DOA detector is amplified by an LNA and a variable attenuator chain to guarantee that the amplitude of the input signal P2 comparable to the amplitude of the reference signal P1. Assuming a very low incoming signal power, a proper Low-Noise Amplifier (LNA) stage is required to guarantee an overall good dynamic range. In this project, LNA model from Agilent-ADS's RF library is chosen to be simulated and analyzed its performance. Fig. 7 shows the schematic of LNA simulation. Default parameter is set with frequency from 3-11GHz. The following figure demonstrated the simulation result had fulfilled the requirement.

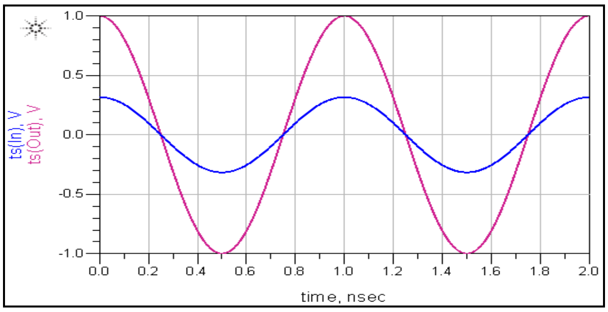


Fig. 19 LNA simulation result

*D. Operational Amplifier*

In six-port DOA detection, operational amplifier is needed as a differential amplifier or comparator to generate the phase difference at the output. The four outputs such as P3, P4, P5, and P6 from the RF diode detectors are connected to operational amplifier to observe performance the phase difference detection which resulting as P3-P4 and P5-P6. Ideal Op-Amp is used in the simulation software.

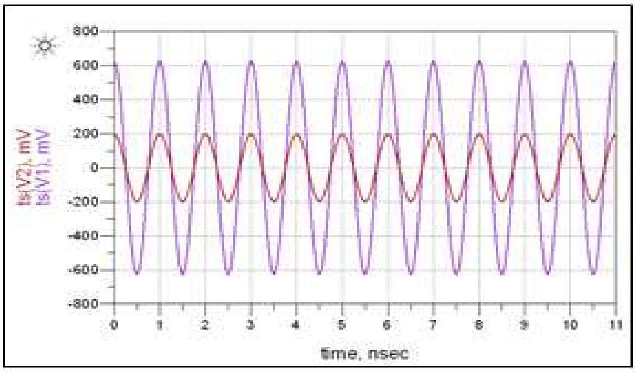


Fig. 20 Input simulation result $V_1$=0dBm and $V_2$=-10dBm

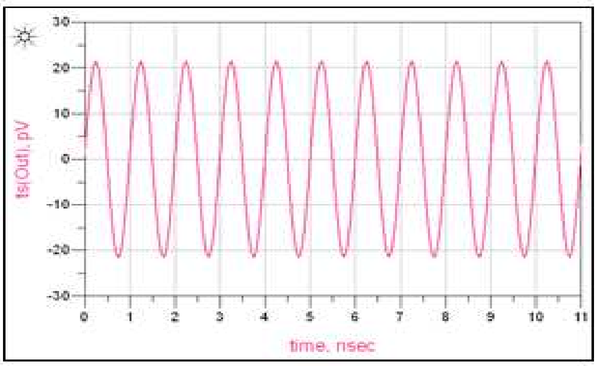


Fig. 21 Op-Amp simulation result

Simulation is repeated at -20dBm for V2 as the input signal to compare and analyze its simulated output waveform. V1 input remains the same at 0dBm for both simulations. The op-amp amplifies the difference in voltage between the two inputs, each input influences the output voltage in opposite ways. The result of their inputs and outputs in time domain signal is checked as Fig. 20, 21 and Fig. 22, 23. An op-amp with no feedback is already a differential amplifier, amplifying the voltage difference between the two inputs.

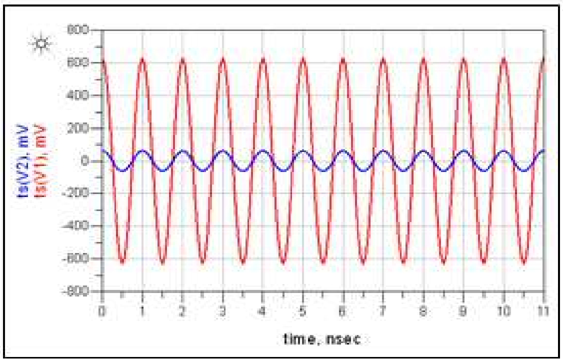


Fig. 22 Input Op-Amp simulation result V1=0 dBm and V2=-20 dBm

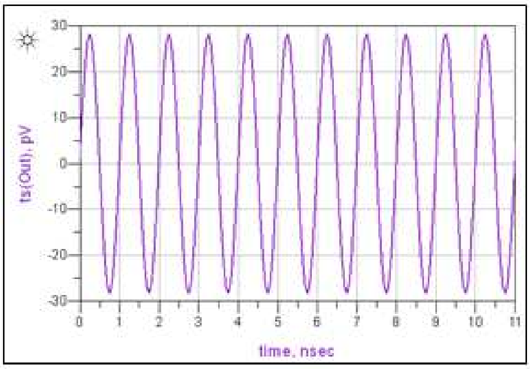


Fig 23 Output Op-Amp simulation result

An ideal differential amplifier only amplifies the potential difference between its two input connections, not the voltage between any one of those connections and ground. The output polarity of a differential amplifier, just like the signed indication of a digital voltmeter, depends on the relative polarities of the differential voltage between the two input connections.

*E. Six-Port Based Phase Measurement*

The RF design of the six-port correlator is such that only one of four possible modulation states is correctly identified at a time. This is one particular feature of the proposed six-port concept. Waveforms displayed in Fig. 24 indicate that each output voltage of the phase by six-port correlator, during a 360° phase shift between RF inputs. This means that have a minimum value for 0°, 90°, 180°, and 270° phase shift, respectively, between the 2 input signals.

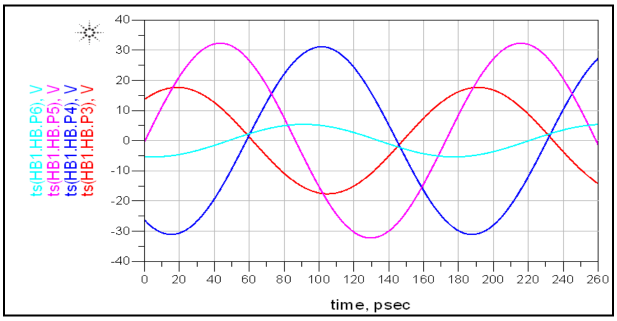


Fig. 24 Output voltage waveforms of the detectors: P1, P2, P3 and P4.

### *F. Six-Port Based DOA Detection in Radar System*

The simulated output waveforms, as plotted in Fig. 25, confirm the operating principle of the six-port correlator that proposed as DOA detection. By creating four interferences of the two input signals with quadrature phase shifts between each other, two differential signal pairs in baseband are created illustrated in Fig. 10. This makes the six-port correlator more robust against non-idealities due to the benefit of a differential signal representation.

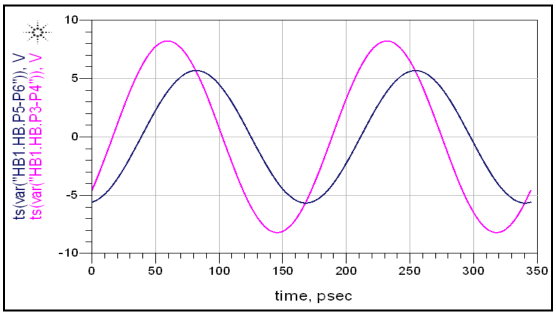


Fig. 25 Output voltage waveforms from the two op-amp: P3-P4 and P5-P6

The relationship between the baseband signals P3 to P6 as well as of *P3-P4 and P5-P6* and with the phase shift $\Delta\phi$ between the two input signals P1 and P2 is represented. A sample time scale from 0 to 350 ps is hereby represented and it has been chosen for representative purposes only. From this plot with referring to Fig. 24, it can be noticed that the *P3-P4* and *P5-P6* are differential pairs.

## V. CONCLUSION

Six-port network was chosen for this project for direction of arrival detection because of its advantages as low power consumption, low manufacturing cost, simplicity and good performance in high frequency and wideband application. The prototype six-port circuit was modeled in Agilent-ADS and the design was modified to enhance the operation performance. Simulation and measurement of subcomponents such as RF input signal, six-port correlator, RF power detector, operational amplifier and low noise amplifier in one single housing are carried out. Simulation results of each passive microwave components have been validated with measurements showing the design performance. An overall evaluation of the six-port direction-of-arrival detection demonstrates a high precision in its phase different measurement.

There several suggestions to produce better six-port DOA detection and the recommendations for improvement in future. Analysis calculation through the six port network to determine the phase different of the direction of arrival, which is a challenging task putting high requirements on accuracy, robustness, usability, and costs. Increase in the frequency range over which the junction and correlator to meet the optimum performance specifications is suggested. Besides that, other possible optimization methods and error functions for the calibration of the six-port correlator can be apply to improve the measured parameter accuracy. BER method can also add in to reduce the result error. Computational device to generate the result in digital form from the phase difference detection and programming device can be added to speed up the detection and increase the result accuracy. Other than that, band-pass filter can be added at the input to filter the receiving signals.

ACKNOWLEDGMENT

The author would like to thank the Ministry of Higher Education of Malaysia (MOHE) for the financial support for this research work in the form of a research grant RAGS-9018-00057.

## REFERENCES

[1] A. Koelpin, G. Vinci, B. Laemmle, D. Kissinger, and R. Weigel, "The Six-Port in Modern Society," *IEEE Microwave Magazine,* vol. 11(7), Dec. 2010, pp. 35-43.

[2] G. Vinci, A. Keplin, R. Weigel, “Employing six-port technology for phase-measurement-based calibration of automotive radar”, *Asia Pacific Microwave Conference*, Singapore, Dec. 2009.

[3] F. Harabi, I. Sfar, A. Gharsallah, “A direction of arrival estimation system using five-ports reflect meter”, *in: 5th Intern.Conf, SETIT*, Tunisia, 2009.

[4] I. Sfar, L. Osman, A. Gharsallah, “A five-port reflect meter for communication receiver applications”, *in: 8th Intern. Multi-Conference on SSD*, Tunisia, 2011.