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Design of Low-Cost RF Detector for Electric Field Determination in Antenna Radiation Pattern Measurement

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ABSTRACT

Antenna pattern measurement is a requirement for antenna characteristics determination. However, such sophisticated set-up measurement demands skilled authority. This project employed a low-cost RF detector (MAX4003) to capture the E-field and consequently assist in acquiring data for antenna radiation pattern. By fabricating a 3.0V circuit with MAX4003 and connecting to an Arduino, this compact module creates a basic interface between the antenna under test and user's measurement PC. The results show the measured voltage from the RF detector is in good agreement with the manufacturer's datasheet for 1.8GHz and 2.1GHz operating frequencies. The input power is also directly proportional to the output power. The project was further tested by conducting a full 360° antenna radiation pattern measurement. The results established a satisfying comparison to theoretical radiation pattern. Overall, the system benefits to individual such as students and researchers to replicate the same method in order to have a compact and attainable antenna measurement system.

1. Introduction

Over the past years, many special analytical methods have been developed to ease the calculation of antenna's properties, such as the geometrical theory of diffraction (GTD), Moment Method, Finite-Difference Time-Domain and Finite Element as stated by Balanis [1]. However, because of antenna's complex structural configuration and excitation method, it cannot be investigated analytically. This is where antenna measurement is carried out in order to validate the theoretical data of an antenna and obtain actual measurements.

One of the basic instruments required in antenna testing is the spectrum analyser. In the antenna test set-up, the source antenna is placed at the transmitting system while the Antenna under Test

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(AUT) is placed at the receiving system with the spectrum analyser connected to it. The spectrum analyser is to measure RF signal captured by the antenna over a defined band of frequencies received [2]. This is especially important for antenna radiation pattern measurement since spectrum analyser can provide a detailed analysis of signal power at each frequency level. How it works is by signals passing through a filter that allows only specific range of frequencies and the resulting signal is then passed through an amplifier and displayed on the screen [3]. The display on the screen consists of amplitude on the vertical axis against the function of frequency on the horizontal axis. The overall shape of the resulting plot is the spectral density of the signal. Provided that the AUT is rotated on a turn table, each peak of the signal level corresponding with each azimuth angle will form the radiation pattern of the antenna.

The spectrum analyser however is a costly instrument. Therefore, this paper will discuss alternative solution for the measurement set-up for antenna radiation pattern. The development of a 3.0V circuit with RF detector is presented. The RF detector will be able to convert the Electric (E) field captured by the receiving antenna to DC signals. Subsequently, the compact module is included in a system to process the E-field and plot the radiation pattern of an antenna. This method will give benefits to students and researchers to have a compact and attainable antenna measurement system.

1.1 Radiation Pattern

A radiation pattern expresses the way the antenna distributes or receives its electromagnetic waves from different direction [4]. It describes how much power the antenna is transmitting or collect in a function of angles. The basic pattern-measurement technique that most people are familiar with uses a single-axis rotational pattern. This technique involves an AUT placed on a rotational positioner and rotated about the azimuth to generate a two-dimensional polar pattern [5]. This measurement is commonly done for the two principal axes of the antenna to determine parameters such as antenna beam width in both the E and H planes. For linearly polarized antenna, the E-field determines the polarization of the radio waves. For example, in vertically polarized antenna, the E-field coincides with the vertical plane, while for horizontally polarized antenna, the E-field coincides with the horizontal plane. Since the magnetic field or H-field lies at the right angle to the E-field, a vertically polarized antenna means the H-field coincides with the horizontal plane while in horizontally polarized antenna, the H-field coincides with the vertical plane. Antenna radiation pattern measurement is a method of capturing the receiving power at each point during rotation from the source antenna, therefore few instruments are required in order to achieve this standard including the costly spectrum analyser.

1.2 Antenna Pattern Measurement System

Various techniques have been proposed in order to minimize the cost and increase the accessibility to antenna radiation pattern measurement. This can go as far back as in 2011, where Temme, VanderLaan and Zajac [6] contested in IEEE AP-S Student Design Challenge with "Radiation Patterns on a Budget" paper submission. Bill of Material (BOM) was also disclosed by Brown, Goora and Rouse [7], to prove an economical antenna measurement system under $1300. Authors from Rehman *et al.,* [8], Hamzah *et al.,* [9] and Wagih and Moody [10] proposed a low cost and portable antenna pattern measurement system, however microwave instruments such as the spectrum analyser and vector network analyser were maintained in their proposed method. Costs were minimized from their antenna rotating system which make use of an open-source microcontroller and GUI software. A screen-less version of spectrum analyser was applied by Dewandaru, Zulkifli and Rahardjo [11]. The authors employed a USB-SA44B 4.4GHz Signal Hound spectrum analyser which allowed a compact system set-up for large interleaved linear array antennas. A journal article from 2011 by Picco and Martin [12] titled "An Automated Antenna Measurement System Utilizing Wi-Fi Hardware" inspired author Hearn *et al.,* [13], to build an antenna measurement system using the GNU Radio software library by Linux. It is an open-source software platform for communication and signal processing that is well-suited for student-initiated code development. The GNU Radio Companion takes the antenna measurements, which processes the raw data from the radio and performs functions in software that typically are performed with hardware.

Similarly, instead of using the spectrum analyser, antenna measurement system by Gupta *et al.*, [14] uses a Software-Defined Radio (SDR) to transmit and receive signals in time domain. The frequency of operation, operational bandwidth and the real part of the input impedance are computed from the reflection coefficient or S11 measurement. The set-up consists of a two-port SDR to transmit the signal with unit power and a dual-directional coupler (DDC) to observe the transmitted and reflected power. Figure 1 exhibits the measurement test set-up to acquire the signal power computed by reflection coefficient, with ports denoted by P.

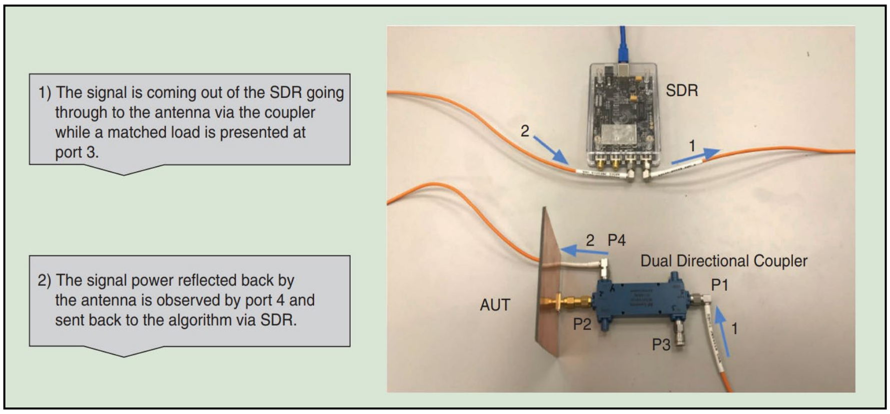

Fig. 1. Reflection coefficient measurement test set-up (Gupta *et al.*, [14])

The normalized 2D radiation pattern captured by this method was then compared to radiation pattern observed by a Vector Network Analyzer (VNA). The results between the two methods are identical, except for very low power, where the conventional setup using VNA is much more sensitive.

Another alternative approach that measures the antenna's radiation pattern was proposed by Rea *et al.*, [15]. The authors proposed a method of using Universal Software Radio Peripheral (USRP), a tuneable RF transceiver with a high-speed analogue-to-digital converter and digital-to-analogue converter for streaming baseband I and Q signals to a host PC over 1 Gigabit Ethernet. Both transmitting and receiving antenna is connected to one USRP each. A PC was then connected to the receiving antenna to gather the information from Arduino and USRP in the form of the number of steps that can be translated into angular position and the signal-to-noise ratio (SNR). The SNR values gathered per iteration in the execution of the application program result in a very big array from which the radiation pattern is obtained. Here, instead of a spectrum analyser, we can observe the authors applied the SNR principle to obtain the antenna measurement by utilizing USRP. However, because the principle of the system is based on SNR, the set-up is suitable for inside semi-anechoic chambers or in a clear field, due to the sensitivity of data captured that may cause inaccurate measurement.

Most of the studies utilizes significant amount of signal processing to a general-purpose processor instead of being done in special-purpose hardware. Consequently, these methods do offer reducing the processing cost to conduct an antenna pattern measurement, however, in the expense of measurement accuracy. In 2013, Taygur *et al.,* [16], proposed an FPGA-based antenna pattern measurement system. The aim was for educational purpose where students can do antenna measurement without the sophisticated equipment. The system consists of an embedded hardware in the FPGA that are connected to a logarithmic RF detector board, an RF source and a DC motor-rotary encoder. However, the complication of FPGA is subjugated by simpler and more flexible microcontrollers like Arduino as the interface between the antenna and the users' PC. The same method was conducted by Kiraz, Hatık and Günel [17], where they benefitted from their stand-alone web browser-based control panel that allows multi-user view of the measurement results.

A research paper by Moe, Phaebua and Lertwiriyaprapa [18] employed a low-cost RF transmitter using voltage control oscillate (VCO) and the receiver using RF power detector. The proposed low-cost RF measurement equipment was evaluated by 3 experts. Moreover, 3 groups of 3 students were given a chance to test the system. The results showed that the average score of students is 4.8 points (total of 5 points). As a result, it can be concluded that the proposed system can be used effectively and provide students with the knowledge and practical skills. Similarly, Leitao *et al.* [19], developed a complete setup that allowed the measurement of an antenna by using VCO at the transmitter side and RF detector at receiving side, without specific GUI for users. The aim was to entice more students into telecommunication subject with the simplicity in the set-up. This shows that, using alternative and cost-effective method for antenna measurement is feasible and acceptable for educational purpose.

In this paper, another alternative method to antenna radiation pattern is proposed by using a low-cost RF detector, MAX4003, which converts AC output voltage from antenna to DC signals. By fabricating a 3.0V circuit with MAX4003 and connecting to an Arduino, this compact module creates a basic interface between the AUT and user's measurement PC.

1.3 RF Detector, MAX4003

The MAX4003 low-cost, low-power logarithmic amplifier was designed to detect the power levels of RF power amplifiers (PAs) operating from 100 MHz to 2500 MHz. A typical dynamic range of 45 dB makes this logarithmic amplifier useful in a variety of wireless applications including TSSI for wireless terminal devices and other transmitter power measurements [20].

Technically, a signal from the receiver is passed to the detector and amplifier for signal conditioning so that the received signal is amplified and analysed by the microcontroller. Basically, in this stage, a RF logarithmic power detector together with its correlated RF passive components is used to detect and amplify the signal from the receiver. MAX4003 which is a low cost and low power logarithmic detector as well as amplifier is used for this purpose. The pin configuration of MAX4003 is shown in Figure 2 and pin description is shown in Table 1.

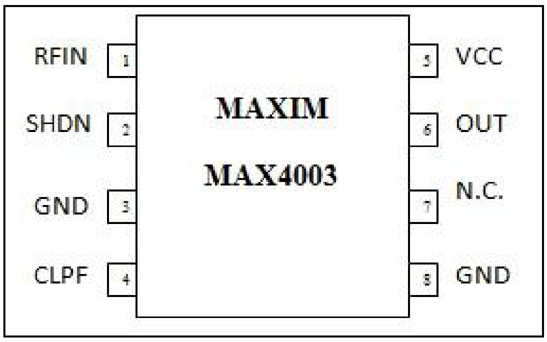

Fig. 2. MAX4003 pin configuration

Table 1
MAX4003 pin description

PIN	NAME	DESCRIPTION
1	RFIN	RF input
2	SHDN	Shutdown input. A logic LOW on SHDN shutdowns the entire IC
3, 5	GNDs	Ground. Connected to PC board ground plane
4	CLPF	Lowpass filter connection. Connect external capacitor between CLPF and GND to set the control-loop bandwidth
6	N.C.	No connection
7	OUT	Detector output
8	VCC	Supply voltage

2. Development of RF Detector Circuit

The functionality of the detector is to amplify the input signal and convert it from RF signal to DC signal as output and input for microcontroller circuit as shown in Figure 3.

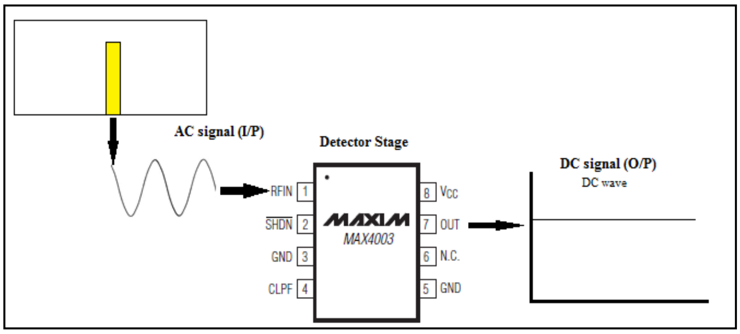

Fig. 3. Function of the RF detector

Figure 4 shows the recommended circuit for MAX4003 RF detector which is taken by the manufacturer data sheet. Since the RF detector input voltage is 3.0V, a 3.0V voltage divider circuit has been developed to help regulate higher input voltage. The circuit consists of 10nF capacitor, 100nF capacitor, resistor chip 49R9 and MAX4003 RF detector.

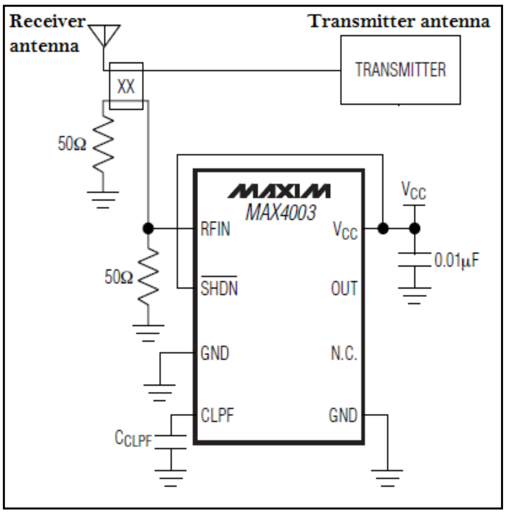

Fig. 4. MAX4003 typical application circuit

Figure 5 shows the designing of the circuit using CST Microwave Studio software. The dimension of the detector and other components were taken from the data sheet provided by supplier.

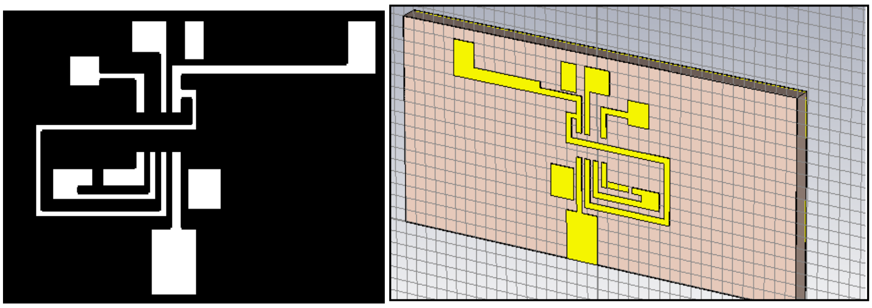

Fig. 5. Designing of detector and amplifier stage using CST software

The components of the circuit are mounted using Surface Mount Device (SMD) soldering machine. The fabricated circuit was first applied with solder paste on components pads and by using tweezers, the components are then placed at their correct position. Before proceeding with the soldering process, the solder machine is pre-heated up to 120°C. Once the pre-heat period is over, the circuit board is placed into the soldering machine. The soldering process is then started with heating process for 3 mins @ 200°C. The large, motorized drawer automatically opens for cooling of the PCB. The components positions were checked as soon as the drawer opened. There is a window of 10 seconds period to correct the components position manually while the solder paste is still hot. The connection of the circuit was tested using multimetre to make sure the circuit is functioning well.

The RF detector circuit is then attached with an SMA connector. This is so that it will be able to connect with an antenna for any measurement purposes. Because the SMA connector is use, the bottom layer of RF detector circuit became a ground surface and holes have been made to connect both layers of the RF detector circuit by using through-hole rivets as shown in Figure 6.

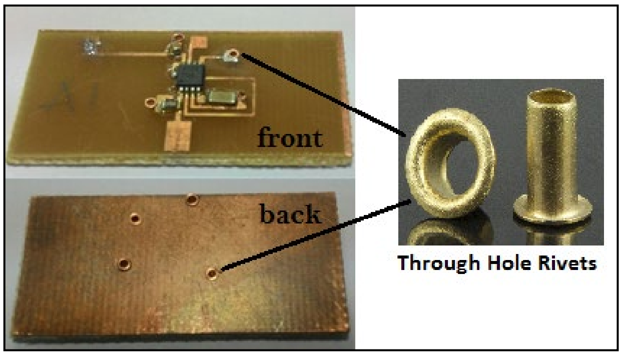

Fig. 6. Through-hole rivets to connect the front and the back of the circuit

3. Radiation Pattern Measurement

There are many pre-requisites prior to radiation pattern measurement test. As elaborated by Derat [21], when describing the behaviour of the EM field created by an antenna, three concentric spherical regions encompassing the radiating source need to be considered. The Fraunhofer region or otherwise known as far-field (FF) region is where the angular distribution is independent from the distance to the antenna. Therefore, in most cases, the FF region has been used in determining the antenna pattern. Additionally, to have the best result, is doing the measurement indoor in an anechoic chamber fully covered with absorbers to absorb miscellaneous electromagnetic waves and simulate the free space environment, as stated by Fróes *et al.,* [22].

In this project, the RF detector is tested to plot the radiation pattern in a semi anechoic chamber. The complete set up of the measurement consists of a signal generator connected to a 0.7-18 GHz high directive horn antenna at the transmitting side and a dipole antenna with operating frequency of 900 MHz connected to the RF detector circuit at the receiving side. The RF detector's pin 7 is connected to analogue pin, A0 of the Arduino which has the ability to measure DC voltage. The measurement captured will 'write' the plotting of the radiation pattern in a developed user interface. Figure 7 exhibits the set-up in the far field range of 3m and the stacking of RF detector circuit.

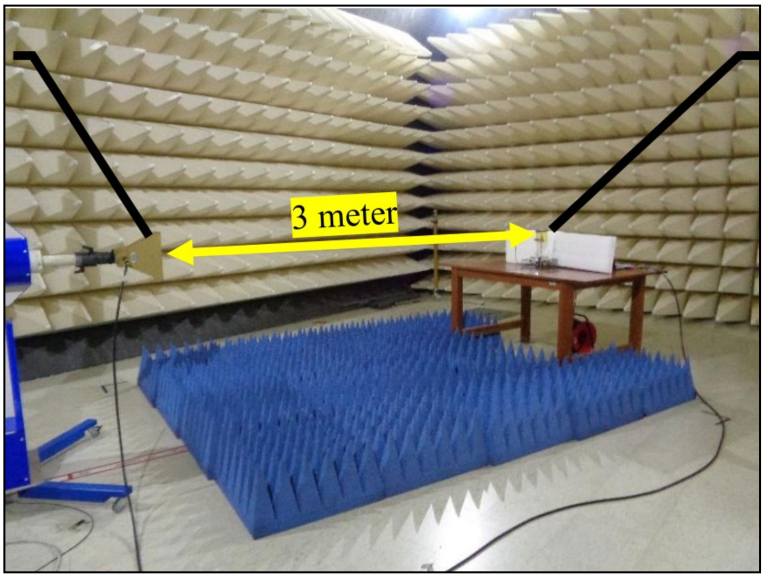

Fig. 7. Radiation pattern measurement test in far field distance

Arduino connected below the dipole antenna shown in Figure 8. Meanwhile, Figure 9 shows the connection of the voltage divider circuit to the Arduino by a PCB designed as an adapter to the analogue pins.

Fig. 8. Set-up of dipole antenna, RF detector and Arduino

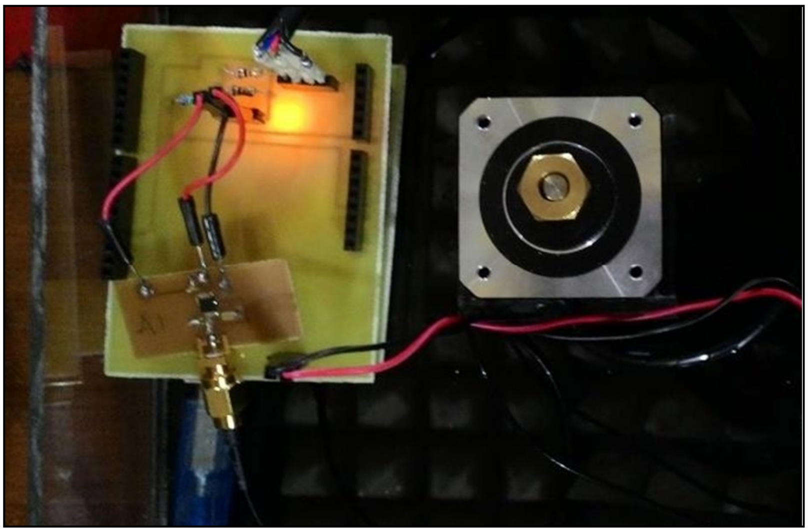

Fig. 9. A PCB designed as an adapter connecting the 3.0V voltage divider circuit to the pins of Arduino

4. Results and Analysis

The results of MAX4003 functionality and E-field determination in antenna measurement will be discussed in this section.

4.1 RF Detector Functionality

MAX4003 RF detector was tested to determine its functionality. Input signal from a signal generator is connected to the RF detector circuit and the output voltage is observed at pin 7 by multimetre. Frequencies were tested at 1.8 GHz and 2.1 GHz. Meanwhile, the input power is set from -50 dBm to 5 dBm. Table 2 shows the result of output voltage versus input power according to their operating frequencies at 1.8 GHz and 2.1 GHz.

Table 2
Output voltage obtained

Input power (dBm)	Freq. (GHz)	
	1.8	2.1
	Vout (V)	
-50	0.4	0.38
-45	0.45	0.4
-40	0.57	0.45
-35	0.7	0.56
-30	0.84	0.71
-25	0.99	0.86
-20	1.14	1.02
-15	1.28	1.16
-10	1.42	1.31
-5	1.56	1.45
0	1.66	1.59
5	1.7	1.66

The results show the measured voltage is in good agreement with the manufacturer's datasheet as shown in Figure 10 and Figure 11 for 1.8GHz and 2.1GHz respectively. The input power is also directly proportional to output power.

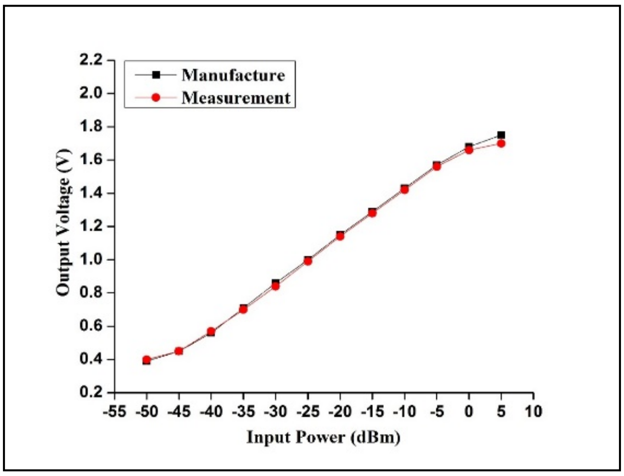

Fig. 10. Output voltage versus input power for 1.8GHz

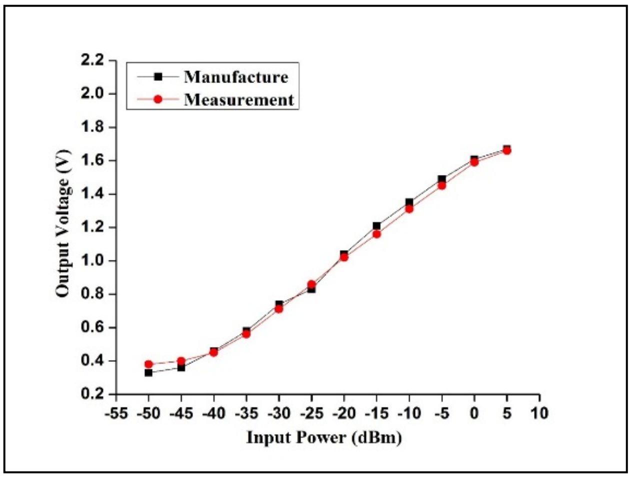

Fig. 11. Output voltage versus input power for 2.1GHz

4.2 E- Field Measurement and Radiation Pattern

The measurement set-up was conducted in semi-anechoic chamber to ensure that the power transmitted is direct to the AUT and the resulting output voltage is sensitive enough to be read by the RF detector. The transmitted signal is supplied by a signal generator with input power set at 0 dBm and frequency at 900 MHz. This is in-line with the RF detector input power and operating frequency range. Meanwhile in the receiving side, a patch dipole antenna as the AUT was connected to the RF detector and to the Arduino Pin to measure the output voltage. A graphical user interface (GUI) is built as a standalone to control the system's movement via Arduino and plot the radiation pattern from the DC voltage measured at pin A0 as stated in section 3.

Figure 12 shows the resulting radiation pattern of the dipole antenna after completing 360° rotation.

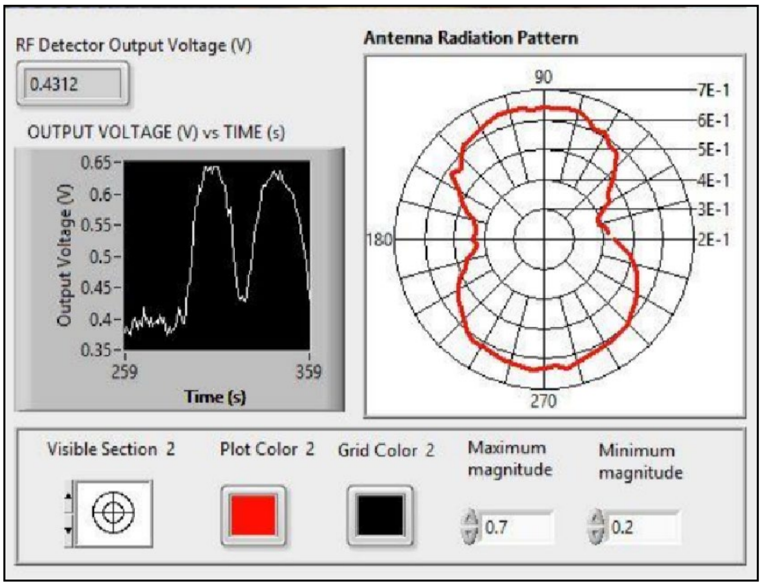

Fig. 12. Plotted radiation pattern

The output DC voltage from the RF detector at each point of azimuth is collected in Table 3. It is observed that that the RF detector was able to capture the transmitted signal.

The radiation pattern observed has the lowest voltage of 0.392V at rotation of 15° and the highest voltage of 0.642V at 90° rotation. This is relatively similar to the expected radiation pattern in Figure 5, whereby at 0° and 180°, the power is at its minimum, while at 90°, the power received is maximum. The radiation pattern of a ½ λ dipole antenna is a classic '8'shape, referred from Antenna Theory and Analysis by Balanis [23], as shown in Figure 13.

Table 3
Output voltage by 5°

Degree of rotator (°)	Output voltage (V)	Degree of rotator (°)	Output voltage (V)
5	0.416	185	0.426
10	0.412	190	0.436
15	0.392	195	0.465
20	0.392	200	0.480
25	0.416	205	0.510
30	0.451	210	0.529
35	0.461	215	0.549
40	0.500	220	0.564
45	0.534	225	0.578
50	0.578	230	0.598
55	0.583	235	0.612
60	0.612	240	0.612
65	0.603	245	0.617
70	0.627	250	0.622
75	0.642	255	0.627
80	0.642	260	0.632
85	0.637	265	0.637
90	0.642	270	0.632
95	0.632	275	0.622
100	0.642	280	0.637
105	0.642	285	0.627
110	0.632	290	0.617
115	0.632	295	0.612
120	0.627	300	0.608
125	0.617	305	0.608
130	0.612	310	0.603
135	0.593	315	0.598
140	0.564	320	0.583
145	0.578	325	0.573
150	0.524	330	0.559
155	0.505	335	0.544
160	0.475	340	0.529
165	0.441	345	0.514
170	0.431	350	0.490
175	0.431	355	0.461
180	0.436	360	0.431

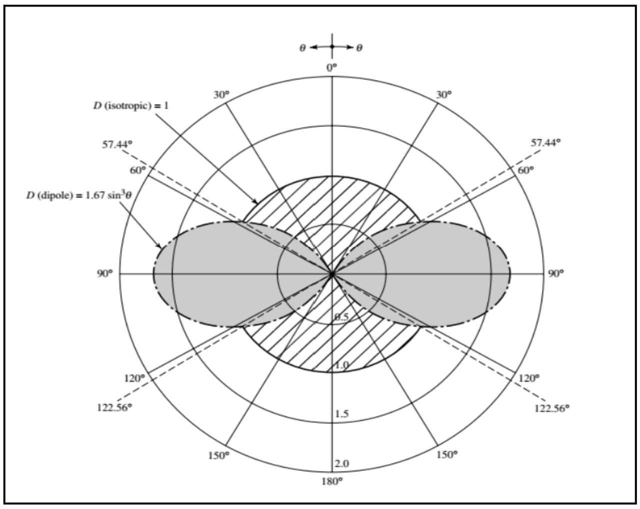

Fig. 13. Two-dimensional directivity of ½ λ dipole [23]

5. Conclusions

The aim of this project is to fabricate a RF detector (MAX4003) and its 3.0V voltage divider circuit with operating frequency from 100 MHz to 2.5 GHz. The module along with an Arduino or any microcontroller is an advantage to provide a low-cost measurement system for antenna radiation pattern. The accuracy of the RF detector and capability to capture E-field was analysed. In conclusion, the RF detector is functioning well and is able present itself as an alternative to expensive equipment in antenna measurement. The development of this project is beneficial to users in terms of reducing the measurement set-up cost.

More upgrades can be made in future works such as adding amplifier at receiver part of measurement to amplify the power received from the transmitter, so that the output voltage can be more precise. In this project, from the datasheet of RF detector, the power limitation is between -45 dBm to 0 dBm. However, the power received from the measurement is much lower which is about -80 dBm which RF detector cannot detect due to the power limitation itself. So, amplifier could be added to amplify the power received.

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References

[1] Balanis, Constantine A. *Antenna theory: analysis and design*. John wiley & sons, 2016.
[2] Awati, Rahul. “Spectrum Analyzer.” *TechTarget*, (2021).
[3] Keysight. "How Does a Spectrum Analyzer Work," *Keysight*.
[4] Chryssomallis, Michael and Christos Christodoulou. "Antenna radiation patterns." *Wiley Encyclopedia of Electrical and Electronics Engineering* (1999): 1-18. https://doi.org/10.1002/047134608X.W1204.pub2
[5] Foegelle, Michael D. "Antenna pattern measurement: concepts and techniques." *Compliance Engineering* 19, no. 3 (2002): 22-33.
[6] Temme andrew, Donald VanderLaan and Stephen Zajac. "Radiation patterns on a budget: IEEE AP-S Student Design Challenge 2011." *IEEE Antennas and Propagation Magazine* 53, no. 5 (2011): 166-175. https://doi.org/10.1109/MAP.2011.6138459
[7] Brown, Brandon C., Frédéric G. Goora and Chris D. Rouse. "The design of an economical antenna-gain and radiation-pattern measurement system." *IEEE Antennas and Propagation Magazine* 53, no. 4 (2011): 188-200. https://doi.org/10.1109/MAP.2011.6097321
[8] Rehman, A., T. Rasul, M. F. Shafique, B. Ijaz, K. S. Alimgeer, M. Saeed Khan, Raed M. Shubair and N. Khaddaj Mallat. "Development of a cost effective antenna radiation pattern measurement setup." In *2016 16th Mediterranean Microwave Symposium (MMS)*, pp. 1-4. IEEE, 2016. https://doi.org/10.1109/MMS.2016.7803823
[9] Hamzah, Nazurah, Syarfa Zahirah Sapuan, Ahmed M. Sayegh and Mohd Zarar M. Jenu. "A portable measurement system for antenna's radiation pattern." In *2017 IEEE Asia Pacific Microwave Conference (APMC)*, pp. 547-550. IEEE, 2017. https://doi.org/10.1109/APMC.2017.8251503
[10] Wagih, Mahmoud and Thomas Moody. "Open-Source Low-Cost Antenna Measurement Setup for Rapid Echoic Measurements." In *2021 IEEE Conference on Antenna Measurements & Applications (CAMA)*, pp. 98-101. IEEE, 2021. https://doi.org/10.1109/CAMA49227.2021.9703629
[11] Dewandaru, Bambang, Fitri Yuli Zulkifli and Eko Tjipto Rahardjo. "A simple radiation pattern measurement for large array antennas." In *2019 IEEE Conference on Antenna Measurements & Applications (CAMA)*, pp. 325-328. IEEE, 2019. https://doi.org/10.1109/CAMA47423.2019.8959685
[12] Picco, Vittorio and Keith Martin. "An automated antenna measurement system utilizing Wi-Fi hardware." *IEEE Antennas and Propagation Magazine* 53, no. 6 (2011): 173-184. https://doi.org/10.1109/MAP.2011.6157745
[13] Hearn, Christian W., Dustin S. Birch, Daniel Newton and Shelby L. Chatlin. "Open-source antenna pattern measurement system." In *2020 Antenna Measurement Techniques Association Symposium (AMTA)*, pp. 1-6. IEEE, 2020.

[14] Gupta, Arjun, John Argyres, Ralph Lyndon Gesner, Delaney Rose Heileman, Daniel Madison Feaster, Christos G. Christodoulou and Firas Ayoub. "Diy antenna studio: A cost-effective tool for antenna analysis [education corner]." *IEEE Antennas and Propagation Magazine* 63, no. 2 (2021): 83-88. https://doi.org/10.1109/MAP.2021.3057310

[15] Rea, Félix Moncayo, Nelson Tovar, Maricela Freire Barba and Juan C. Aviles. "Approximate antenna radiation pattern determination using a low cost measuring system at 2.4 GHz." In *2018 IEEE 10th Latin-American Conference on Communications (LATINCOM)*, pp. 1-5. IEEE, 2018. https://doi.org/10.1109/LATINCOM.2018.8613212

[16] Taygur, Mehmet Mert, Semih Baş, Erkut Yumrukaya, Emre Alp Miran and Serkan Günel. "Low-cost FPGA based antenna pattern measurement system." In *2013 International Conference on Applied Electronics*, pp. 1-4. IEEE, 2013.

[17] Kiraz, Efe, Furkan Aslan Hatık and Serkan Günel. "Standalone Antenna Measurement System." In *2022 International Conference on Applied Electronics (AE)*, pp. 1-5. IEEE, 2022. https://doi.org/10.1109/AE54730.2022.9920022

[18] Moe, May Sandar, Kittisak Phaebua and Titipong Lertwiriyaprapa. "Development of Low-cost Radio Frequency (RF) Laboratory for Microwave Filter and Antenna Course." In *2020 59th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, pp. 657-662. IEEE, 2020. https://doi.org/10.23919/SICE48898.2020.9240326

[19] Leitao, Lucas, Manuel Neves, Francisco Pinto, Guilherme Maniezo, Tania Ferreira, Joao Nuno Matos and Armando Rocha. "2019 ieee ap-s student design contest-team knowantenna [education corner]." *IEEE Antennas and Propagation Magazine* 62, no. 5 (2020): 120-125. https://doi.org/10.1109/MAP.2020.3012895

[20] Maxim. "100Mhz to 2500MHz, 4dB RF Detector in a UCSP." *Datasheet4u,* (2014). https://datasheetspdf.com/pdf/498110/Maxim/MAX4003/1

[21] Derat, Benoît. "5G antenna characterization in the far-field: How close can far-field be?." In *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, pp. 959-962. IEEE, 2018. https://doi.org/10.1109/ISEMC.2018.8393926

[22] Fróes, Saulo M., Pablo Corral, Marcela S. Novo, Miguel Aljaro and Antônio C. de C. Lima. "Antenna radiation pattern measurement in a nonanechoic chamber." *IEEE Antennas and Wireless Propagation Letters* 18, no. 2 (2019): 383-386. https://doi.org/10.1109/LAWP.2019.2891972

[23] Balanis, Constantine A. *Antenna Theory: Analysis and Design*. John Wiley & Sons, 2015.