

ANALYSIS AND DESIGN OF A LOW-PROFILE PRINTED ANTENNA FOR  
THROUGH-THE-WALL RADAR APPLICATIONS

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**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

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## **ABSTRACT**

### **ANALYSIS AND DESIGN OF A LOW-PROFILE PRINTED ANTENNA FOR THROUGH-THE-WALL RADAR APPLICATIONS**

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This thesis investigates low-profile printed antennas used as ultra-wideband (UWB) radar antennas in through-the-wall and ground-penetrating radars, and low-profile antenna to be used in TWR applications is analyzed, designed, and fabricated. Through the-wall-radars are used to look inside and behind the walls and receive information about the scene beyond the walls. UWB antennas are generally preferred by their wide operating frequency ranges and high pulse fidelity features. A four-element E-Patch antenna array is fabricated and tested, and results are compared with full-wave simulation results. Simulation results are obtained by using a full-wave electromagnetic (EM) simulation software ANSYS HFSS® program. Low-profile printed E-patch antennas with stand-alone, and array configurations result from different wall materials and different distance parameters are designed by using HFSS software. In addition, a bistatic radar set up with a corner reflector as a target object is simulated using HFSS software. Using a fabricated four-element E-Patch antenna array as a receiver and transmitter sensor, a prototype through-the-wall radar setup is installed. Monostatic radar results are taken with handheld VNA to compare measurement results with the simulated results.

Keywords: Through-the-wall Radar (TWR), Ultra-wide Band (UWB) Antennas, E-Patch Antenna, Wall Mediums, Monostatic Radar Application.



## ÖZ

### **DUVAR ARKASI RADAR UYGULAMALARI İÇİN PORTATİF BASILI BİR ANTENİN ANALİZİ VE TASARIMI**

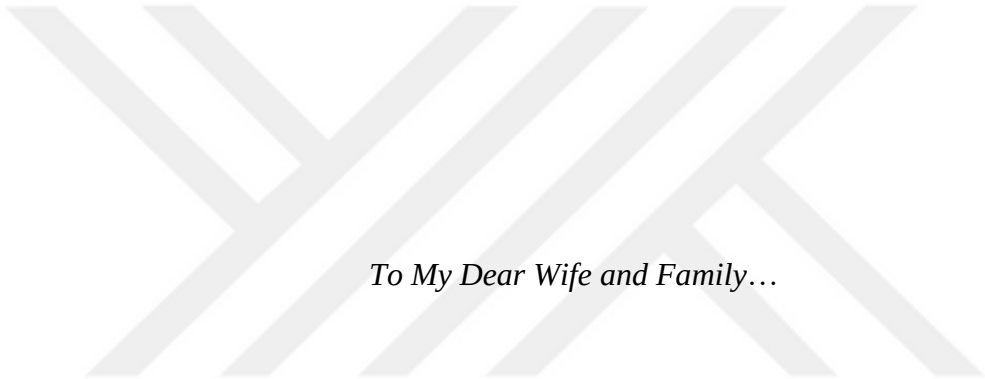
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Bu tezde, duvar arkası ve yere nüfus eden radarlar gibi ultra geniş bant (UGB) radar sistemlerinde kullanılan düşük profilli baskılı antenler analiz edilmiş, tasarlanmış ve üretilmiştir. Duvar arkası radarlar (DAR), duvarların arkasını görebilmek ve duvarların ötesinde gerçekleşen sahne hakkında bilgi almak için kullanılmaktadır. UGB antenleri genellikle geniş çalışma frekans aralıkları ve yüksek darbe doğruluğu özellikleri ile bu uygulamalar için tercih edilmektedir. Üretilen dört elemanlı E-Şekilli anten dizisi test edilmiş ve sonuçları tam dalga simülasyon sonuçlarıyla karşılaştırılmıştır. Simülasyon sonuçları, tam dalga elektromanyetik (EM) simülasyon yazılımı ANSYS HFSS® programı ile elde edilmiştir. Bağımsız ve dizi konfigürasyonunda kullanılan düşük profilli E-Şekilli anten dizisi, HFSS yazılımı ile farklı duvar malzemeleri ve farklı mesafe parametreleri ile simüle edilmiştir. Ayrıca hedef nesne olarak kullanılan köşe reflektörü ile bistatik radar uygulaması HFSS yazılımının yardımıyla simüle edilmiştir. Alıcı ve iletilen sensörü olarak üretilmiş E-Şekilli anten dizisi ile prototip bir duvar arkası radar test ortamı kurulmuştur. Sonuçlar taşınabilir network analizör ile alınmış ve simülasyon sonuçlarının doğrulanması için kullanılmıştır.

Anahtar Kelimeler: Duvar Arkası Radar (DAR), Ultra Geniş Bant (UGB) Antenler, E-Şekli Anten, Duvar Ortamları, Monostatic Radar Uygulamaları.





*To My Dear Wife and Family...*

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## **LIST OF ABBREVIATIONS**

### **ABBREVIATIONS**

TWR: Through-the-Wall Radar

EM: Electromagnetics

ADC: Analog-to-Digital Converter

DAC: Digital-to-Analog Converter

FPGA: Field-Programmable Gate Array

GPR: Ground Penetrating Radar

UWB: Ultra-Wide Band

GHz: Gigahertz

MHz: Megahertz

COTS: Commercial Off-the-Shelf

PW: Pulse Width

FCC: Federal Communications Commission of United States of America

CW: Continuous Wave

RCS: Radar Cross Section

PEC: Perfect Electrical Conductor

METU EEE: Middle East Technical University – Electrical and Electronics  
Engineering Department

## LIST OF SYMBOLS

### SYMBOLS

$P_t$ : Transmitted Pulse Peak Power

$G_t$ : Transmitter Antenna Gain

$G_r$ : Receiver Antenna Gain

$\lambda$ : Pulse Carrier Wavelength

$\sigma$ : Radar Cross Section of the Target Object

$k$ : Boltzmann's Constant ( $1.38 \times 10^{-23}$  W/Hz)

$T$ : Standard Temperature (290 K)

$F$ : Receiver Noises Figure

$B$ : Receiver Equivalent Bandwidth

$S/N$ : Needed Signal-to-Noise Ratio on the Receiver to demodulate the received pulse signal.

$\tau$ : Transmitted Pulse Width

$c$ : Speed of Light in Vacuum

$\epsilon_r$ : Dielectric Constant (Complex Permittivity)

$\tan(\delta)$ : Loss Tangent

## **CHAPTER 1**

### **INTRODUCTION**

Through-the-wall radar concept (TWR) has gained popularity over the last few years for many reasons. Some of those are for sensing and imaging moving and stationary targets through visually opaque obstacles such as walls. Examples of the application areas of TWR could be listed below:

- Law Enforcement search-and-rescue operations,
- Determining the locations of people inside a building or obscured by smoke and debris,
- Determining metal obstacles on wall mediums on construction sites.

Since the TWR system at first is still a radar, radar topology will be explained briefly. Then, the ultra-wideband concept, which is the core of a TWR system, will be summarized.

#### **1.1 Radar**

Since the TWR system at first is still a radar, radar topology will be explained briefly. Then, the ultra-wideband concept, which is the core of a TWR system, will be summarized.

Radar is an acronym for Radio Detection and Ranging. RADAR refers to electronic equipment that detects the presence of objects by using scattered electromagnetic energy. Electromagnetic signals have the constant velocity of light on air so, a radar system finds the difference in time between transmitted and received signals after

that range between the object and the radar system is calculated. An example of a radar block diagram that shows basic transmitter and receiver components can be seen in Figure 1-1.

The effective range of radar could be calculated using the radar equation given in Eq. 1.1 [7]. In the equation,  $R_{eff}$  defines the effective range of the radar with different radar parameters like transmitted power ( $P_t$ ), transmitter and receiver antenna gain values ( $G_t$ ,  $G_r$ ), radar cross-section value of the targeted object ( $\sigma$ ), receiver thermal noise parameters ( $kT_{FB}$ ) and, the receiver signal-to-noise ratio for a system to demodulate transmitted signal ( $S/N$ ). It depends on many parameters that may be adjusted depending on applications. Some of the parameters are not determined by radar designers, such as radar cross-section or thermal noise value; however, radar designer is free to choose transmitted peak power or antenna gain parameters; however, general conditions or applications limit the designer's freedom.

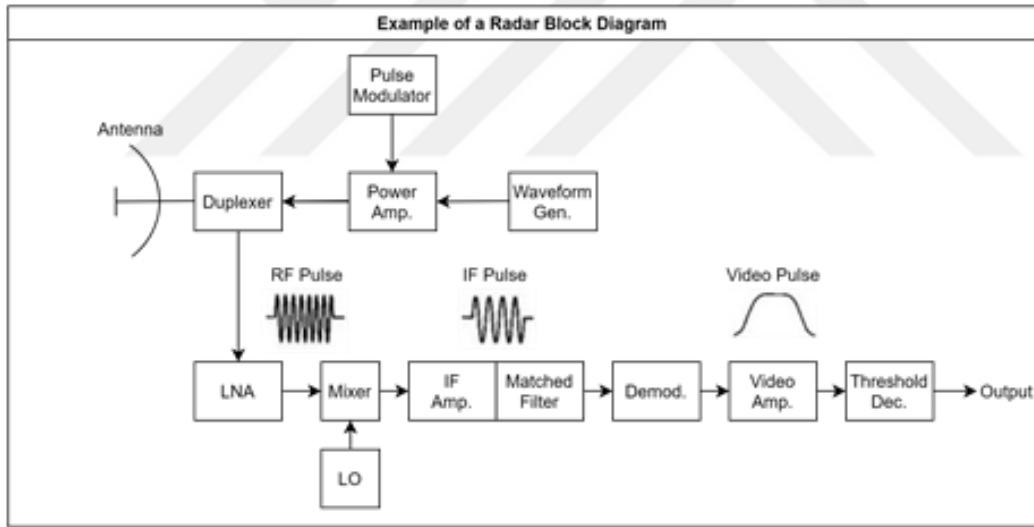


Figure 1-1 Example of a Radar Block Diagram [22].

$$R_{eff} = \left[ \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 k T_{FB} S/N} \right]^{1/4} \quad (1.1)$$

Conventional airborne or surface-based radars can be defined as the first UWB systems that have been used since the 1950s. Radars generally use short-time pulses

as the transmitted signals and then received signals are processed as reflected signals from an object known as echo. Conventional communication systems use continuous-wave signals as the carrier of their modulated information signals, so their bandwidth on the frequency spectrum is narrow-band. Therefore, communication systems are known as narrow-band systems. Time-domain signals cover a bandwidth in the frequency spectrum with the value of the formula given in Eq. 1.2. Generally, conventional radars have pulse width values of microseconds, so their bandwidth would be around the megahertz range. Therefore they could be defined as wideband systems compared to communication systems. In TWR systems, transmitted PW could be around even a hundred picoseconds, so the required instantaneous bandwidth value should be around 10 GHz for the antennas and microwave components used in the system. This subject will be examined deeply later. The bandwidth and pulse duration relationship is given in Eq (1.2).

$$B_{3dB} = \frac{1}{\tau} \quad (1.2)$$

where  $\tau$  represents the transmitted pulse width value and  $B_{3dB}$  3 dB bandwidth of the transmitted signal.

Radars detect objects by a resolution cell idea. The resolution cell contains the resolution capacity of radars on two dimensions: cross-range and down-range. While the cross-range of resolution cell is defined by the 3dB beamwidth of the radar antenna, and the down-range is defined by the transmitted pulse width of the radar. Radars divide their effective range, azimuth, and elevation coverage to cells to discriminate objects within them. If more than one target lies in a resolution cell, radar takes these targets as one echo and cannot discriminate these targets as discrete ones. So, it is crucial that radar designers, while keeping down transmitted pulse peak power as not detected by other sensors, must shrink transmitted pulse width to get a small resolution cell. It is crucial for tracking radars that they generally try to track more targets than a surveillance radar. A radar resolution cell is shown in Figure 1-2

and down-range and cross-range resolution cell formulas are given in Equations 1.3 and 1.4 [10], respectively

$$\Delta R \text{ (range resolution)} = \frac{c}{2B} \quad (1.3)$$

$$\theta_{az,el} \text{ (angular resolution)} = \theta_{3dB} \text{ of antenna radiation pattern } az,el \quad (1.4)$$

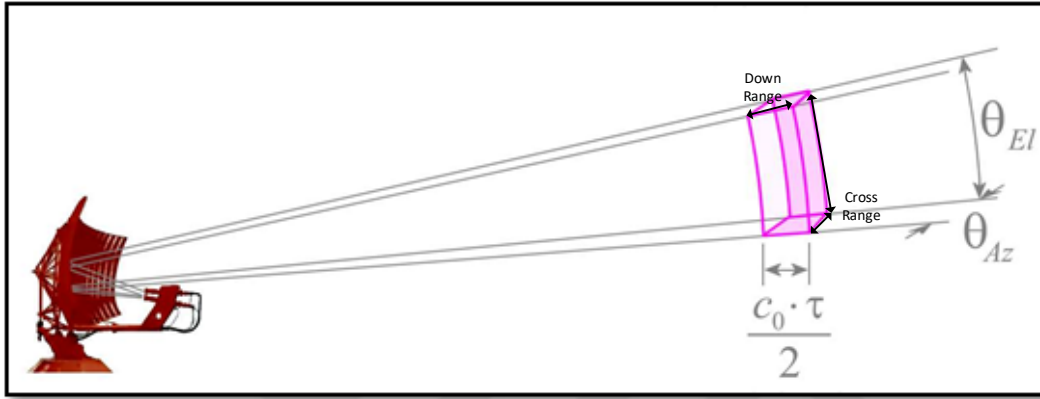


Figure 1-2 An example of a radar resolution cell.

It is essential to understand the radar resolution cell idea because, in TWR systems, physical dimensions that we need to sense are not as big as an aircraft that can be a target to conventional surface-based tracking radars so, down-range resolution cell of a TWR should be around cm's to detect objects like a chair or a human inside a room. It forces TWR to have transmitted pulse widths of nanoseconds contrary to microseconds found in a tracking radar.

Sensors used on this radar system should also have a wideband operating frequency range to transmit and receive short-pulse signals without distorting the original shape and widening pulse width. Also, microwave components used at the front ends of the transmitter and receiver circuits need substantial instantaneous bandwidth to carry out short-pulse-based signals. UWB antennas are the most attractive candidates for this task. Lots of different UWB antennas are used and investigated on the TWR

systems. Wideband low-profile printed patch antennas with a bandwidth of 30%-70% are among the most used UWB radar systems [1].

The first practical microstrip patch antennas were invented by Bob Munson in 1972 [2]-[3] and became popular starting in the 1970s. However, earlier research about microstrip antennas started with G. Dechamps and W. Sichak around the 1950s [4]. After the microstrip patch antenna concept was unveiled, many researchers intensely studied and designed a microstrip patch antenna for various applications.

Microstrip antennas consist of a thin metallic patch placed a small fraction of a wavelength above a ground plane [5]. The microstrip patch is designed, so its pattern maximum is normal to the patch (broadside radiator). This is accomplished by adequately choosing the mode (field configuration) of excitation beneath the patch. The strip (patch) and the ground plane are separated by a dielectric sheet (referred to as the substrate) or even air. The radiating patch may be square, rectangular, dipole, circular, elliptical, triangular, or any other shape. Linear and circular polarization can be achieved with either single elements or arrays of microstrip antennas.

Microstrip antennas are used in different applications such as satellite and mobile communications, radar systems, and biomedical systems. They are usually low profile, lightweight (can even be “conformal”), low cost, and easy to use in an array to increase directivity. However, most microstrip antennas suffer from narrow bandwidth, lower gain, and power handling capacity as compared to traditional antennas [6]. Due to the advantages of microstrip antennas, researchers have handled these limitations with different techniques throughout history. To use a microstrip antenna in a UWB radar system as a transmitting and receiving sensor, operating bandwidth needed to increase from 3%-5% to 30%-70%. So later, it will be discussed how to increase the operating bandwidth with some changes on the original patch diagram. Also, microstrip-type antennas are widely used in an array configuration to gain from array factor phenomena to eliminate the lower gain problem.

This thesis aims to study low-profile printed antennas for TWR applications that need broad bandwidth characteristics to transmit and receive short-pulse signals. Namely, E-Patch with stand-alone and array configurations are designed and simulated with wall materials to see the effect of the different wall materials on the antenna performance. After the printed antenna is analyzed and designed, it is fabricated and used as a receiver and transmitter antenna with a prototype TWR system set with COTS (Commercial of the shelf) equipment in a real-world experiment.

## **1.2 Ultra-wide Band (UWB) Concept**

TWR systems are also called ultra-wideband systems due to the usage of short transient pulses. UWB is defined as any radio technology having a spectrum that occupies a bandwidth greater than  $\frac{1}{4}$  the center frequency or bandwidth of greater than 500 MHz [8]. A simple example of an ultra-wideband transmission would be an RF (Radio Frequency) transmission with a bandwidth of at least 250 MHz having a center frequency of 1 GHz or a transmission with a bandwidth of greater than 500 MHz having a center frequency of 6 GHz. It differs from narrowband technologies, where the bandwidth is typically 10% or less of the center frequency. An example of a specification using narrowband technology is 802.11b WLAN, where the bandwidth is 22MHz with a center frequency in the range of 2.4GHz.

Advantages of UWB pulses are listed below [9]:

- Extremely low transmission energy (less than 1mW),
- Very high bandwidth within short range (200Mbps within 10m),
- Extremely difficult to intercept,
  - Short pulse excitation generates wideband spectra – low energy densities. As seen in Figure 1-3,
  - Low energy density also minimizes interference to other services.
- Multipath immunity,

- Radar
  - Inherent high precision – sub-centimeter ranging,
  - Wideband excitation for detection of complex, low RCS targets,
  - Geolocation/Positioning,
  - Sub-centimeter resolution using pulse leading edge detection,
  - Passes through building blocks, walls, etc. (LOS not required).
- Low Cost
  - Nearly “all-digital” architecture,
  - Ideal for micro miniaturization into a chipset.
- Frequency diversity with minimal hardware modifications.

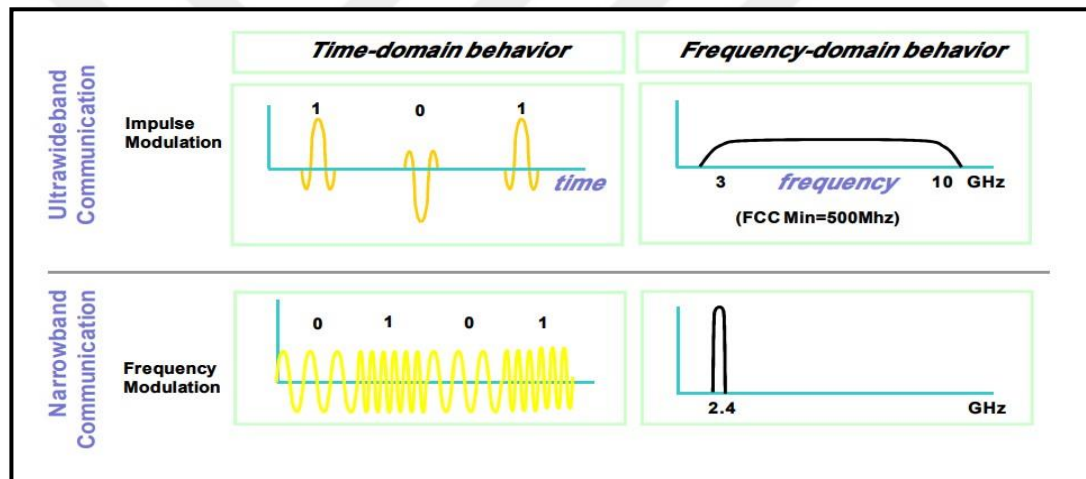


Figure 1-3 UWB and NBW Communication on signal bandwidth.

All the advantages of UWB signals are applied to TWR systems due to usage of short-duration transient pulses to have high range resolution, to prevent multipath signals from the wall and objects inside the room. However, TWR systems have short range compared to conventional radars as they generally have low transmitted power. The use of low transmitted power is committed since FCC of USA ruled permits of UWB signals as -41 dBm/MHz, which can be seen in Figure 1-4.

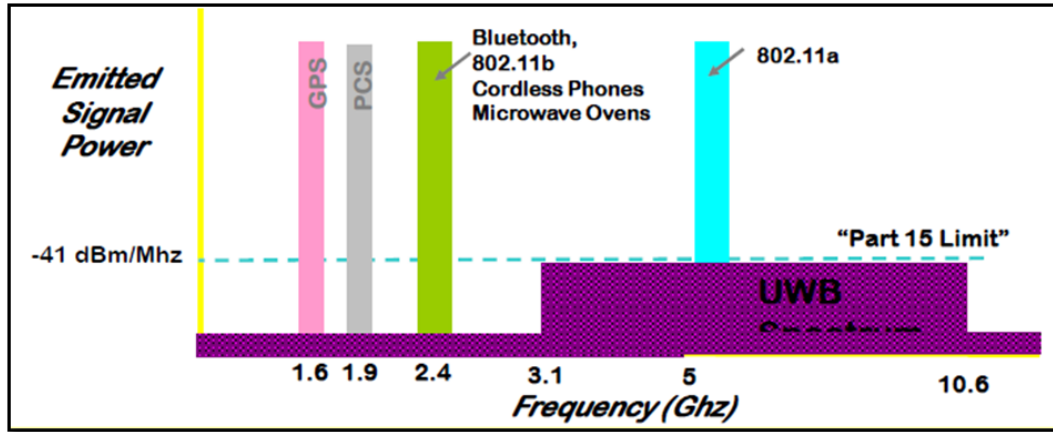


Figure 1-4 Permitted UWB Spectrum by FCC on USA.

Low transmitted power for UWB signals is forced not to damage narrowband communication on similar transmitted frequencies. In addition, UWB radar is superior to the conventional narrowband radar for TWR applications due to its robustness to multipath reflection, high range resolution characteristics, and excellent performance in severe clutter environments. To understand resolution characteristics of a TWR system:

- A high-resolution TWR system is desired to have antenna elements that operates over a wide frequency band or radiate short-duration transient pulses for better range resolution and image quality ( $\Delta R = \frac{c\tau}{2}$ ).
- The cross-range resolution is determined by the antenna aperture size ( $\Delta R_{cross} = \theta_{3dB(radian)} \times R \cong \left(\frac{\lambda}{D}\right) \times R$ ). That means that either a large radar array with fixed stationary elements or SAR with one or more moving elements are necessary for that kind of application.

### 1.3 Through-the-Wall Radar (TWR) Concept

Through-the-Wall Radar is still a radar at its core, having the same working principles as detecting an object's presence by sending out electromagnetic signals

(i.e., radio waves). The signal is generated by the radar and then reflected by an object. Part of the reflected signal then travels to a receiver that detects the reflected signal. The receiver is typically (although not necessarily) the same device as the transmission source. The reflected signal then indicates the presence of an object; the strength of the reflected signal may indicate the proximity and how reflective the object is (i.e., size, material composition (RCS)). With advanced signal formation (e.g., pulses) and signal processing methodologies, other target qualities can be deduced, qualities such as the range to the target and whether the target is stationary or moving [11].

The main difference between a conventional radar and a through-the-wall radar is the medium where the radio wave propagates. While conventional radar systems use free space as the medium that waves propagate, in TWR systems, waves have to sense objects beyond the walls. To sense an object on the other side of a wall, the transmitted TWR signal must be able to penetrate through the wall, reflect off an object, travel back through the wall, and finally reach back to the receiver. How easily the TWR detects an object depends on the amount of signal returned to the receiver. This, in turn, depends on how much signal the object reflects and how well the signal passes through barriers (e.g., walls) between the object and the TWR device. Loss of signal due to barriers is known as attenuation, and the amount of attenuation depends on the properties of the barrier material and its thickness. Figure 1-5 shows the attenuation properties of several typical building materials at different frequencies. In Figure 1-5, it can be seen that lower frequencies tend to penetrate barriers better than higher frequencies. However, the composition of building materials may vary significantly from manufacturer to manufacturer. Using a wide range of frequencies for the signal will help “probe” the frequency spectrum so that the device uses the best tradeoff of penetration to detection/localization. This can be accomplished by either changing the frequency of the signal (i.e., using a “frequency sweep”) or by using a wideband signal that inherently contains a wide range of frequencies.

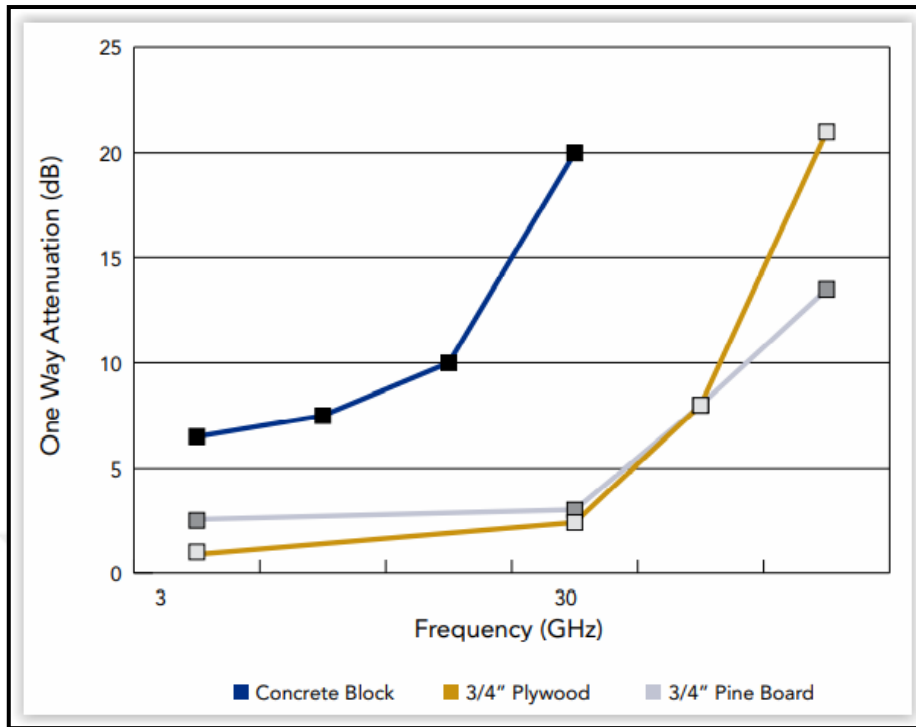


Figure 1-5 Attenuation properties of common building materials on wide frequency ranges.

After showing that wall attenuation increases at higher frequencies, we will mainly concentrate on working at lower frequencies 1-3 GHz. However, it should be known that microwave components and antennas are larger than those used at higher frequencies at these frequencies. The wall parameters such as dielectric constant ( $\epsilon_r$ ) and loss tangent ( $\delta$ ) are essential to model the wall and simulate for TWR applications. We may sort different type of walls from the most lossy to the least lossy as Concrete > Cinderblock > Brick > Plywood type of walls. Figure 1-6 shows the measured  $\epsilon_r$  and  $\tan(\delta)$  of several types of walls in dry conditions. These walls include 1.3 cm plywood, 8.89 cm brick, 13 cm solid concrete, and 25 cm hollow-core concrete (cinder block). These are also the values that we used in our antenna and wall simulations that are shown later.

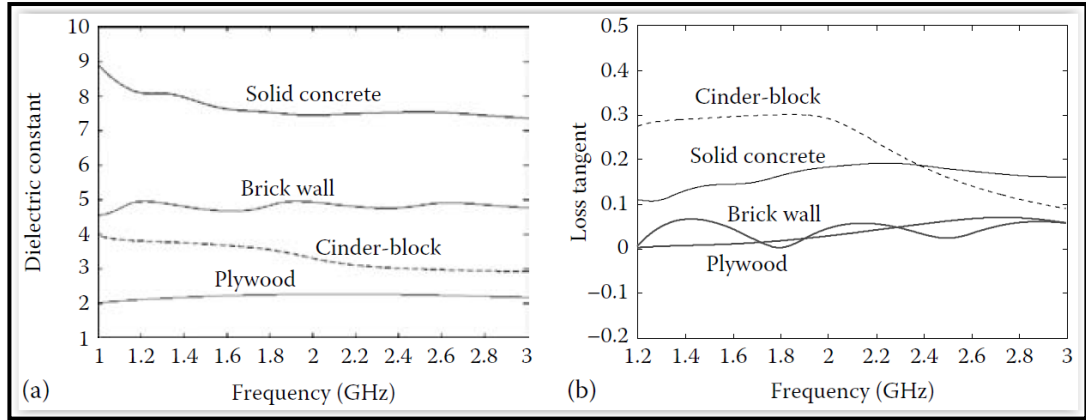


Figure 1-6 Measured permittivity of various walls. (a) Dielectric constant ( $\epsilon_r$ ) and (b) loss tangent ( $\delta$ ).

Since the cinder blocks form a heterogeneous wall with many air-wall interfaces, multiple reverberations and Bragg effects are present. Therefore, strictly speaking, the cinder block wall is an anisotropic medium. The measured parameters shown in Figure 1-6 for a cinder-block wall represent effective values for  $\epsilon_r$  and  $\tan(\delta)$  for normal incidence, assuming a homogeneous lossy dielectric slab equivalent model of the wall. The complex permittivity of concrete and cinder-block walls under different wetness conditions was also measured. It was found that  $\tan(\delta)$  vary significantly within the 1-3 GHz band [12].

TWR systems have other challenges that need to be addressed by designers besides the wall effect. Some of the challenges of the TWR systems that different authors propose are listed below as [16]:

- Characterizations of walls, particularly the exterior, include attenuation loss, permittivity, periodicities, hidden pipes, etc.
- Adverse wall affects the elements' input impedance and gain when the array operates near an exterior wall.
- High wall losses at the microwave frequencies. Multi-reflection situations occur in TWR applications.

- Development of efficient forward scattering electromagnetic models.
- Utilization of inverse scattering techniques suitable for wall and multiple room building geometries.
- Exploration of the roles of polarization in image enhancement as well as wall characterization, such as detection of pipes and rods.
- Design of low-profile antenna arrays with the required bandwidth and polarization diversity.

In this thesis, we focused on designing low-profile printed antennas to be used in TWR systems.

First commercially available TWR systems are introduced to understand where the trend goes for these complex and unique systems. There are two different TWR system concepts as CW-based and pulse-based systems. In CW-based systems, CW instruments send out radio waves without breaks or pulses in the signal emission. These devices can be configured to take advantage of Doppler effects to detect tiny movements. However, they cannot provide accurate range data because the continuous nature of the signal does not allow for accurate timing between the transmission and reception of the signal.

In a typical CW system, the signal's frequency is precisely controlled and essentially consists of a single frequency. When the transmitted signal reflects off a moving target, the frequency of the reflected signal will be slightly shifted from that of the transmitted signal. An audio analog of this effect can be heard as a car pass: the sound produced by the car is higher in tone as the car approaches and lowers after the car passes. Similarly, for CW radar, if the target is moving toward the transceiver, the frequency will be shifted slightly higher; if the target is moving away from the transceiver, the frequency will be shifted slightly lower. Also, the faster a target is moving, the more the frequency shifts. Even slight movements can be detected by this method.

In pulse-based systems, due to the nature of using pulse, contrary to CW systems, the range of the object can be determined if the timing between transmitted and received signal is measured. Also, due to use of short-pulse signals make higher range resolution compared to CW signal-based systems. Pulse-based systems are also classified into two main categories as frequency sweep-based and short-pulse (nanoseconds) based. At frequency sweep-based systems, intra-pulse modulation is applied, such as linear frequency modulation. The required bandwidth is taken as receiving all information on one frequency sweep then processing it by a matched filter.

In short-pulse systems, using a tiny pulse in time already contains that required bandwidth, and it is enough to take that pulse to find echo signal; however, required instantaneous bandwidth can be massive and not practical with available microwave equipment then frequency sweep on pulse could be mandatory.

Two different commercially available TWR systems which are Rex-Plus (STI) based on CW signals and, Xaver 400 based on short-pulse (UWB) signals are presented here.

Rex-Plus (STI) Rex-Plus, by Safety Technology International, Inc. (STI), is a consumer device designed to be placed inside a residence and detect motion outside. The device demonstrates what can be achieved with essential components. It costs around \$100 and is comparatively low-tech. When placed on one side of a wall, the device uses radio waves to detect motion on the other side. The device puts out a continuous signal at 2.4 GHz and will alarm once reflected energy is received. The alarming frequency and volume increase as the target gets closer. Therefore, as someone walks toward a wall, the signal reflects off the individual and back to the receiver. Once the signal reaches a certain threshold, the alarm is turned on. The reflected signal strength increases as the individual get closer to the wall, triggering higher alarm rates and volume. A device such as this may help monitor a low traffic area. However, the time required to set a reliable threshold level, the necessity for 120V AC, and the potential for false alarms (both positive and negative) make it

unsuitable for most applications that law enforcement or first responders require. Note that although the Rex-Plus was the only device of its class identified by the FCC of USA – namely a commercial TWR device marketed to civilian non-law enforcement – because the assessment’s focus is on security, defense, and law enforcement technologies, others in this class may exist [13].

The Xavier 400 (FCC ID: A42X400F) is made by Camero-Tech and distributed in North America by Mistral Security. Compared to the Xavier 100, the Xavier 400 is a larger two-handed device that provides additional information, such as approximate direction (azimuth) and tracking, for user interpretation. The Xavier 400 can detect living and static objects within a maximum range of 20 meters with a field of view of 120 degrees. The Xavier 400 operates in three modes (Tracker, Expert, and High Penetration) and has three maximum detection ranges (4 meters, 8 meters, and 20 meters). Because it can detect static objects, the Xavier 400 can provide information about room dimensions and significant infrastructure elements. Image quality in cluttered environments is improved using image reconstruction algorithms. An optional internal wireless video transmitter is available for remote display. Camero-Tech states that the Xavier 400 has been widely deployed with leading military and law enforcement users worldwide. The device is available from the U.S. distributor, Mistral Security, at a price of approximately \$47,500 [14]-[15].

### **1.3.1 Research Areas in TWR Systems**

After introducing general TWR concepts and challenges of the systems, some research areas have to be studied in this section. Some of the important ones are given below [20].

- Detectability of Human Being

Even the TWR systems can pinpoint objects inside a room; sensing a human is an entirely different topology. State-of-art TWR systems use micro-Doppler phenomena for finding humans beyond the walls or buried under rubble after a

building has collapsed or an earthquake. However, sensing micro-Doppler signals need high-resolution sensitive radars and well train-set data for machines to learn micro-Doppler signatures of a heart rate or breathing of a human. That is not easy because every human being has a different signature of these behaviors, so more different human micro-Doppler signature data, even for children of different ages, are needed to solve the decision process's ambiguities. More study is needed in this area.

- Wall Modeling

TWR systems operate on mediums as walls so, different wall models should be investigated, and more wall material parameters are required to be extracted. These parameters are then used to extract information about objects beyond the walls. However, it should be known that not all wall materials are homogeneous and have constant values in a wide operating frequency band. Even wetness or humidity of the medium changes the important wall parameters so, more research should be done to have more information on wall modeling. Nowadays, researchers work on information extraction algorithms that do not need wall parameters to be solved, but this is still a new topic and needs more steps to work on complex scenarios.

- Target Differentiation

TWR is used to detect human beings inside buildings. However, state-of-art systems could not differentiate humans. For example, in a hostage rescue operation, it is essential to differentiate a hostage from the targets so, new topologies are needed to differentiate different human beings in challenging situations.

After discussing research gaps and challenges of the TWR systems, UWB antennas used at these systems will be investigated. The primary goal of this thesis is to propose light, low-cost UWB antennas to be used in portable TWR systems.

### 1.3.2 UWB Antennas on TWR Systems

UWB antennas that are used in these systems will be investigated. For desired TWR applications, a system:

- Should have a large aperture size ( $D$ ) over a wide frequency range to resolve cross-range, down-range resolutions.
- Sensitive to magnitude, phase, the polarization of the scattered signal. Preferably, dual-polarization capability at both transmission and reception of a scattered signal.
- Physically small, low-profile, and low cost.
- Easy to mount and match, good transmission and radiation performance.
- UWB antennas should have almost constant gain and a linear phase across the operating band for time-domain operations to minimize signal distortion.

From the above requirements for the desired TWR system, it is crucial to have UWB antennas as the receiving and transmitting sensors. Many portable or onboard TWR radar platforms require antenna features given below:

- Wideband antenna elements, which are low profile and lightweight,
- Have simple feed structures,
- Easy to integrate with other passive and active transceiver components.

To satisfy the features that are given above, many TWR systems use two types of UWB antenna elements as wideband microstrip-type antenna elements such as E-Patch antennas or more traditional antennas such as ridge horn or impulse radiating antennas. Now we will focus on these two different antenna configurations.

- Ridge Horn Antennas

A standard horn antenna with a rectangular waveguide feed does not cover the bandwidth required for many TWR applications. However, a ridge-loaded waveguide will cover the band, and its waveguide cutoff frequency is lowered, thus reducing the required size of the corresponding ridge flared (Vivaldi) horn antenna. A quad-ridge horn antenna for dual-polarization provides both polarizations. However, the required element spacing in an array environment does not allow for any significant flare to the antenna aperture, affecting matching and individual element directivity. In addition, horn antennas are, in general, heavy, bulky, and not well suited for portable or vehicular TWR applications. As a result, the ridge horn antenna is most suitable when used as a single receive element in the SAR operation.



Figure 1-7 An ETS Lindgren 3164-08 quad-ridged horn antenna (BW: 10 GHz) [32].

- Impulse Radiating Antenna

The IRA is a class of UWB antennas designed to radiate a short pulse in a narrow beam for high power pulse radiation and application in transient radar [17]. An example of its application in TWR is the impulse synthetic aperture radar (ImpSAR) developed by Eureka Aerospace, where high power pulses, with pulse widths on the

order of 100 picoseconds (BW:  $\sim 12$  GHz), are transmitted via ultra-broadband IRAs. An example IRA is shown in Figure 1-8.



Figure 1-8 IRA-3Q operates from 250 MHz to 18 GHz and has a time response of fewer than 100 picoseconds [18].

- Log-Periodic Antenna

The log-periodic dipole array (LPDA) is a series of dipole elements whose length, diameter, and spacing are scaled logarithmically, and adjacent elements are mechanically fed out of phase to achieve an end-fire pattern a near-continuous performance over an extensive frequency range. Two LPDA elements can be

combined at  $90^\circ$  to one another to produce a dual-polarized element. Due to its relatively large length, when designed for UWB operation, it may not be well suited for implementation as an element in large TWR receive arrays.

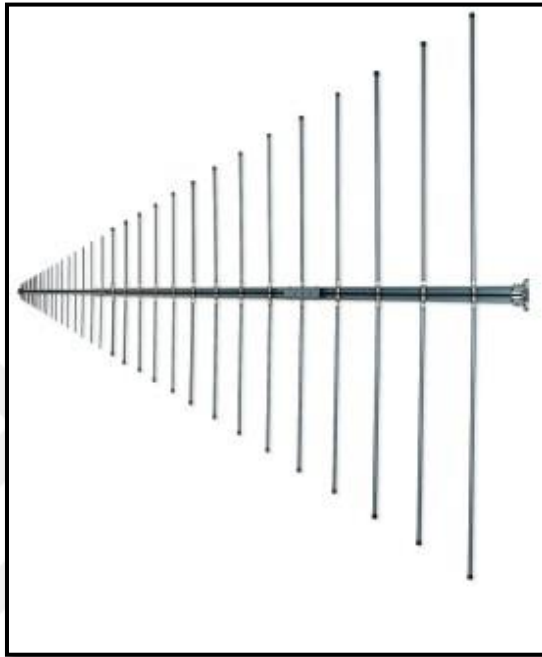


Figure 1-9 R&S HL033 Log-Periodic dipole array UWB antenna.

- Bowtie Antenna

The antenna works on the basic bandwidth enhancement principle that tapering off the diameter of a dipole antenna increases its bandwidth. The principal design is that two isosceles triangles are connected at the vertex by the feed point. The transient analysis of the standard bowtie dipole antenna shows that the radiation due to an input monocycle pulse does not perfectly reproduce the input pulse. There is an inherent time-dispersive response to standard antenna structure; this is not ideal for impulse radiating applications like TWR.

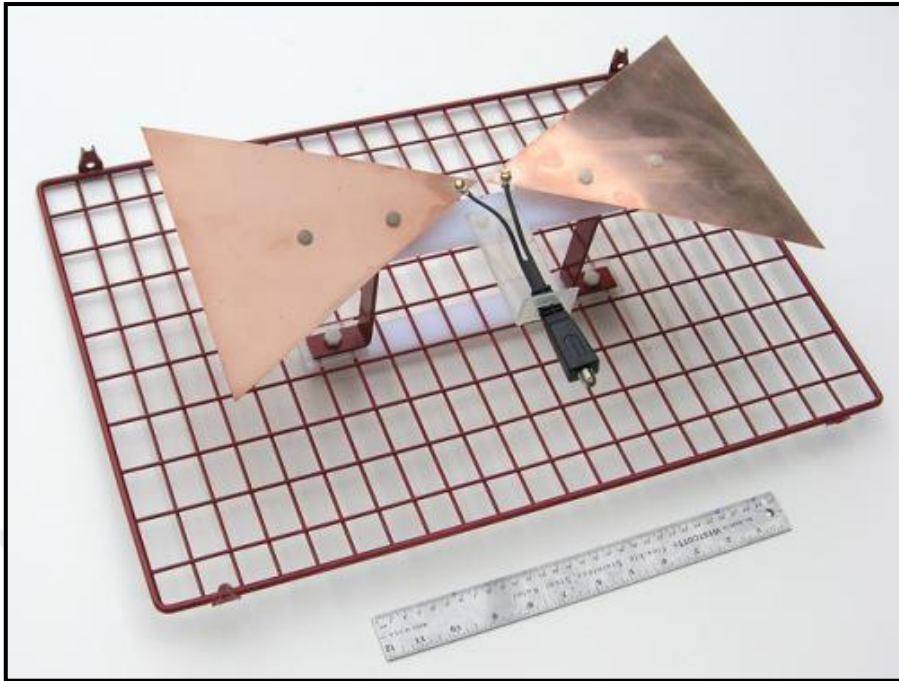


Figure 1-10 An example of a printed Bowtie Antenna [33].

- Printed Spiral Antenna

The printed spiral is a frequency-independent antenna. The frequency range of operation is determined by the inner and outer radii of the spiral. For this kind of antenna, the symmetry is maintained using a self-complementary structure, although some wideband structures have been demonstrated that do not follow this rule. One such permutation is a double-sided spiral dipole that utilizes a rectangular coupling patch and is capacitively coupled using a central circular disk region on the spiral [19]. This antenna can achieve a fractional bandwidth of 66% while maintaining a small footprint and a maximum gain of 4.1 dBi. However, the standard printed spiral antennas, which utilize asymmetrical design, exhibit dispersed (distorted) radiated waves at the falling edge due to the spiral's resonant nature. This dispersion, however, can be almost eliminated if a tapered resistive loading is applied with distributed loads along the arms of the spiral. That results in greater signal fidelity in both transmitted and received waveforms when a monocycle pulse is used in both directions.



Figure 1-11 Two-arm, tightly wrapped, the logarithmic spiral antenna [34].

- Volcano Smoke Antenna

The volcano smoke antenna (VSA), initially proposed by John Kraus, boasts UWB performance and exhibits radiation patterns similar to that of a broadband monopole antenna on a finite circular ground plane. The VSA also possesses cross-polarization patterns typically below -20 dB from that of the vertical-plane patterns. Although the VSA has no specific design equations available, it is generally accepted that the bulb's height should be  $\lambda/4$  (at the longest wavelength) above the highest point on the ground. In addition, it has been shown that, for a simplified version of the VSA, the input impedance is governed by the half cone angle,  $\psi$  [28]. It also nicely follows the monocycle input signal and is suitable for using TWR systems.

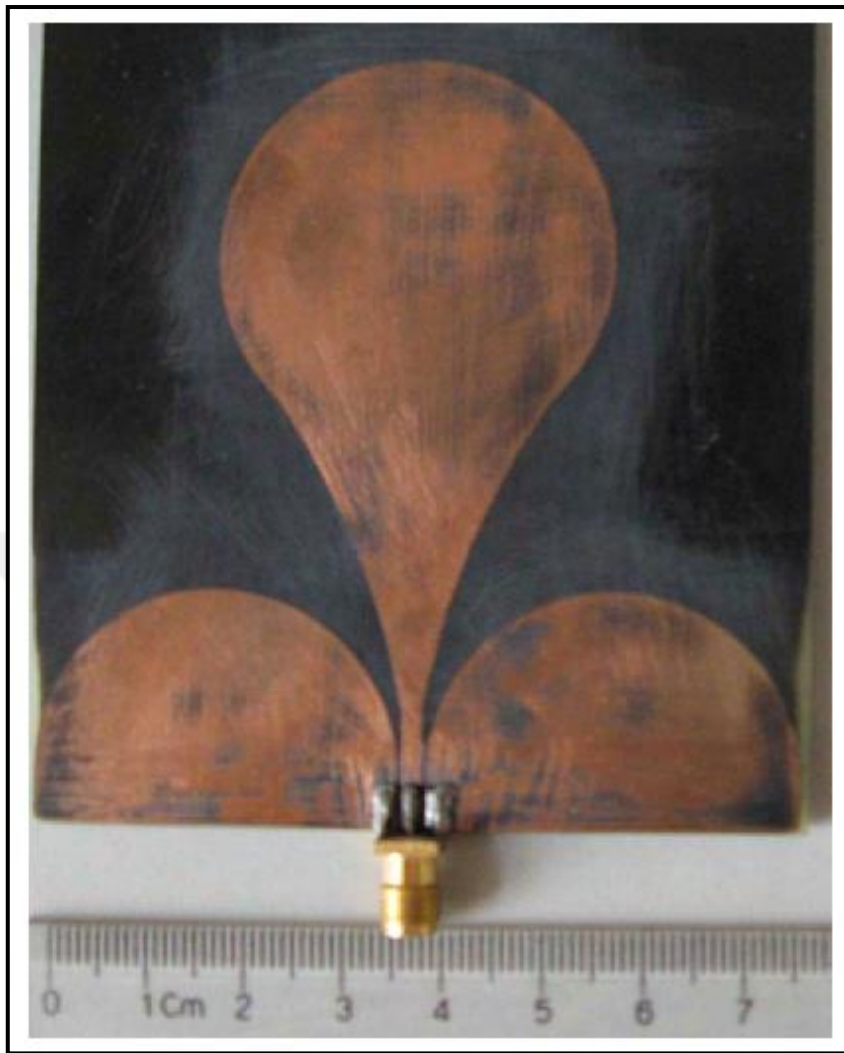


Figure 1-12 An example of VSA with  $S_{11} < 10$  from 1.5 GHz to 5 GHz [35].

- Wideband Microstrip Printed Antennas

Many portable or onboard TWR platforms require wideband antenna elements, low profile and lightweight, have simple feed structures and are easy to integrate with other passive and active transceiver components. While microstrip and other printed-type antennas satisfy many of these requirements, they suffer from relatively narrow bandwidth, typically about a few percent when used on an electrically thin substrate backed by a ground plane.

Basic methods for increasing the bandwidth of microstrip-type antennas are given below.

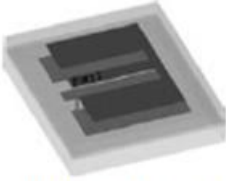
- Increasing the substrate thickness,
- The use of parasitic elements either in a multilayer geometry or in a planar gap-coupled elements configuration,
- Cutting slots to patch surface,
- The use of complementary structures,
- Adding reactive components to reduce VSWR,
- The use of multi-resonators to form a compact microstrip antenna,
- The use of “frequency-independent antenna” concepts to increase BW.

Examples of some wideband microstrip-type antennas are given below.

- Stacked Coupled Patches,
- U-slotted patch,
- E-shaped patch,
- Proximity-fed microstrip log-periodic array (MLPA),
- Microstrip Spiral Antenna and Slot Spiral Antenna.

Note that, notwithstanding their bandwidth limitation, microstrip-based antennas are attractive for many applications since they provide a nearly unidirectional coverage due to the presence of their ground plane. An example list of UWB microstrip type antennas is listed in Table 1-1.

Table 1-1 Wideband Microstrip Antenna Elements for TWR.

| Antenna                                                                                                                              | Thickness<br>( $\lambda_0$ ) | Footprint<br>( $\lambda_0 \times \lambda_0$ ) | Bandwidth<br>(%) | Gain within the<br>Band |
|--------------------------------------------------------------------------------------------------------------------------------------|------------------------------|-----------------------------------------------|------------------|-------------------------|
| <br>Stacked patch                                   | 0.093                        | 0.35x0.37                                     | 27               | > 7.3 dBi               |
| <br>U-patch                                         | 0.096                        | 0.39x0.44                                     | 30               | > 6.1 dBi               |
| <br>E-shaped patch                                 | 0.083                        | 0.36x0.43                                     | 31               | > 6.58 dBi              |
| <br>Dual-stacked E-patch                          | 0.12                         | 0.38x0.41                                     | 40               | > 7.0 dBi               |
| <br>MFMS patch<br>multi-feed multi-<br>slot patch | 0.096                        | 0.41x0.50                                     | 51               | > 4.9 dBi               |
| <br>DFDA patch<br>dual-feed dual-<br>arm patch    | 0.099                        | 0.24x0.31                                     | 70               | > 2.0 dBi               |

In this thesis, wideband E-Patch antenna is investigated to use in TWR systems. Other proposed antennas that are given in the table above are not easy to fabricate and feed in an array configuration. Also, gain values for a single element are not so high that we decided not to go forward on those options. After all, engineering means a trade-off in all directions, and we do not want to risk antenna fabrication and test processes with complex single wideband elements.

#### **1.4 Organization of the Thesis**

The thesis consists of seven chapters.

The aim of the thesis is given in the Introduction Chapter, together with the definition and basics of TWR systems and UWB antennas used on it, and the associated literature review.

Proposed low-profile printed UWB antenna, namely E-Patch, is detailed in Chapter 2 with its theory, design, and simulation results. Also, wideband low-profile printed E-Patch antenna results are given with its single element and four-element array configurations with the help of ANSYS HFSS [21].

In chapter 3, to observe the wall effect of wideband low-profile E-Patch antenna with a single element and array configurations, simulations are carried out for detuning the input impedance and free space radiation patterns.

Using information gained on different wall effects on the E-Patch antenna, a bistatic radar case is simulated in ANSYS HFSS with two E-Patch antennas as transmitter and receiver sensors. As the target, a metal corner reflector is employed with a wall medium to see RCS results. Results are given in Chapter 4.

The proposed wideband low-profile printed E-Patch antenna array is manufactured and measured in an anechoic chamber. The results are given in Chapter 5.

After verifying the fabricated antenna results with simulation results, a monostatic radar setup is constructed to test the four-element E-Patch antenna array as a receiving and transmitting sensor in a prototype TWR system created with COTS equipments. Results of the test are given in Chapter 6.

Finally, the thesis is concluded with a summary of fundamental achievements and the critical results in Chapter 7, the Conclusions Chapter.

## CHAPTER 2

### LOW-PROFILE PRINTED WIDEBAND ANTENNA ELEMENTS

In this chapter, as a wideband printed antenna element, namely E-Patch antennas, are analyzed and designed with the help of the full-wave EM simulator ANSYS HFSS. As mentioned in Chapter 1, printed antenna elements favor the TWR designers by low-profile, low-cost, and easy to integrate into arrays. However, their narrow bandwidth is insufficient to transmit and receive short-pulse signals around nanoseconds to have a small range resolution to detect objects in a room. However, it has been shown that with some design techniques bandwidth of the printed antennas can be increased with additional resonance circuits. Resonance is created by adding some slots to the original patch antenna or adding another patch layer resulting double patch antenna design [23].

On the other hand, these methods typically enlarge the antenna size in the antenna plane or the antenna height [24]. Also, substrate permittivity and thickness play a critical role in stored energy beneath the patch and result in additional loss and efficiency parameters. It is known that the bandwidth of the patch antennas is roughly proportional to the substrate thickness and inversely proportional to permittivity [42].

$$BW = f_r \left( 3.77 * \frac{(\epsilon_r - 1) * W * h}{\epsilon_r^2 * L * \lambda} \right) \quad (1.5)$$

In this case, some researchers used air with its unit permittivity as a substrate with relatively thick formation, contrary to the conventional substrate-based antennas, together with slots opened on the patch. [25]-[26].

Commonly used examples of slotted printed patch antenna is probe-fed E-shaped patch antennas. Slots and patches resonate differently in these antennas but

neighboring frequencies, making the antenna work as a wideband antenna. However, the complicated part is parametrically optimizing these two different resonance frequencies and at the same time with having good gain and beamwidth characteristics.

Its principle of operation at lower resonant frequency is determined by the slots, at the higher resonant frequency is determined by original patch itself. A wideband E-Patch rectangular antenna is shown in Figure 2-1.

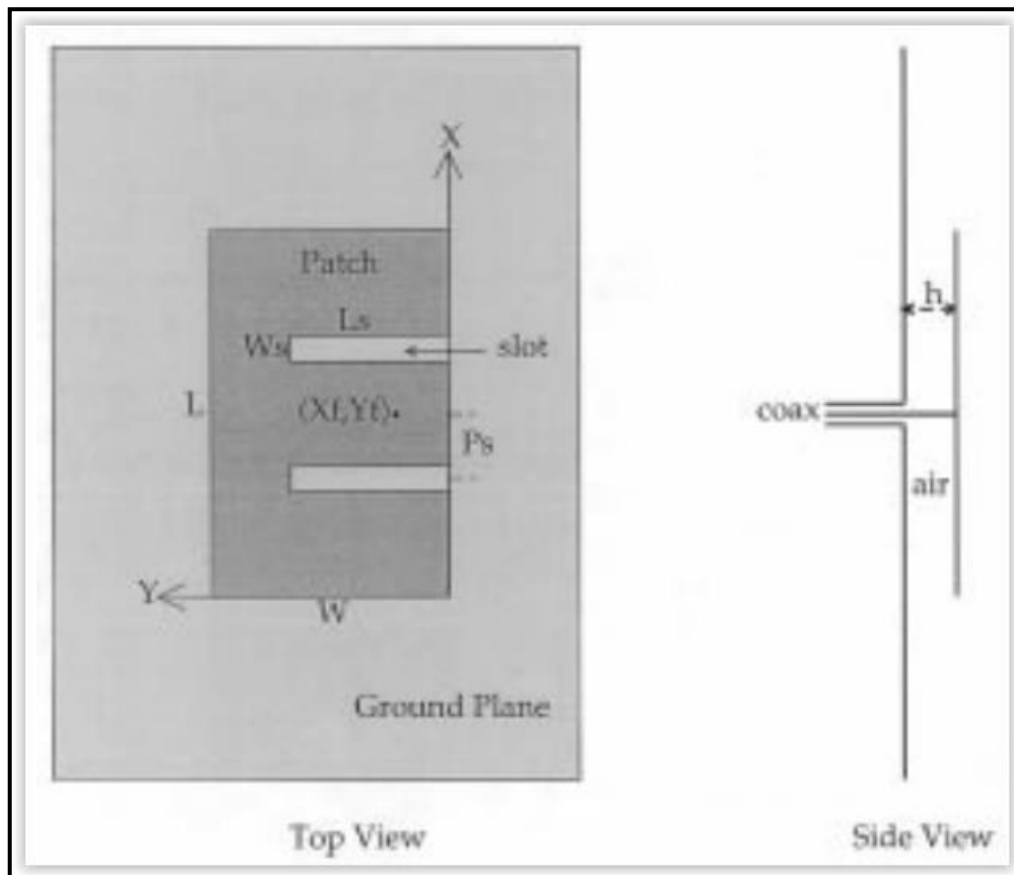


Figure 2-1 Geometry of a wideband E-shaped patch antenna consisting of two parallel slots in the patch.

Figure 2-2 demonstrates the basic idea of the wideband mechanism of an E-shaped patch antenna. The ordinary microstrip patch antenna can be modeled as a simple  $LC$  resonant circuit [Figure 2-2(a)]. Currents flow from the feeding point to the top and

bottom edges of the ordinary patch. These current path lengths determine  $L$  and  $C$  values, and the resonant feature changes when two slots are incorporated into the patch, as shown in Figure 2-2(b). In the central part of the patch, the current flow is like a standard patch. It represents the initial frequency. However, at the edge part of the patch, the current must flow around the slots, and the length of the current path is increased. This effect can be modeled as an additional series inductance  $\Delta L_s$ . So, the equivalent circuit of the edge part resonates at a lower frequency. Therefore, the antenna changes from a single  $LC$  resonant circuit to a dual resonant circuit. These two different resonance points together form a wideband antenna.

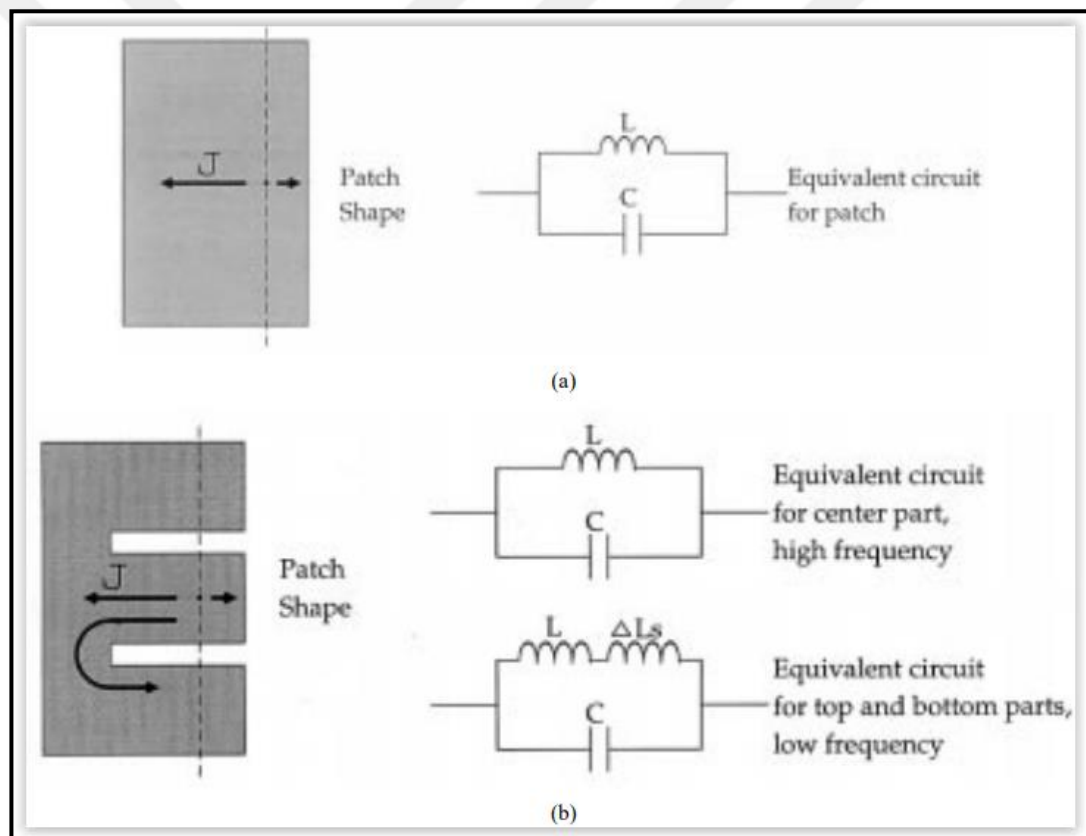


Figure 2-2 Dual resonance: the wideband mechanism of E-shaped patch antennas. (a) The ordinary microstrip patch antenna. (b) The E-shaped patch antenna.

The main idea behind the slotted patches is that; when a thick substrate is used, it causes large probe inductance, which cannot be compensated by changing the feed location of the antenna. By incorporating a slot, capacitive reactance is created, compensating the large probe inductive reactance, and wideband characteristic is achieved. E-patch antennas need thick air substrates to have wideband characteristics. However, they are still thinner than double layer or multilayer antenna configurations, making them attractive for low-profile, low-cost applications such as TWR. Also, more accessible to manufacture than dual feed or dual-layer wideband elements, especially in an array configuration.

### **2.1.1 Optimal Value Analysis of E-Patch Antenna**

In this section, an optimum value analysis is done to find the optimum antenna parameters for our intended case given in below. E-Patch antenna used on a TWR system, our objectives being of the:

- Having an operating bandwidth as broad as possible in 1-3 GHz range on that frequency, attenuation from the wall medium is smaller than higher frequencies, as shown earlier. Target is to have around ~600 MHz at the center frequency to transmit and receive two ns short-pulse signals without distorting the signal shape. It is achievable with the E-patch antennas given in Table 1-1.
- Have a unidirectional radiation pattern with a high front-to-back ratio.
- Have at least 3dB beamwidth value of 50 degrees to radiate all room with a single element.
- Have a gain similar to the values given in Table 1-1 for E patch antennas around 7 dBi.
- Have at least gain flatness value of 3 dB across the operating bandwidth of the antenna not to distort the short-pulse shape.
- Have low-profile, low-cost, and suitable to place in an array configuration.

For the E-patch antenna design, initially an ordinary patch without slots can be designed with transmission line model formulas given in [42] with intended resonance frequency. After that two identical slots are placed symmetrically with respect to feed center point of the patch. These two slot dimension and position parameters should parametrically be resulted with simulation programs to find optimum values to have wideband behaviour.

The initial design of the wideband rectangular E-Patch antenna for to use in dual-band GSM operations, the design parameters of are used. However, for our need for wideband behavior and other requirements given above to work in a TWR system, the antenna and slot size and length parameters are changed with a given range of values from Table 2-2 to Table 2-6 to find the required input return loss characteristics as given in above as having more than 600 MHz operating bandwidth to radiate small pulse signal needed for our TWR requirements.

The simulations are carried out by a well-known ANSYS HFSS full-wave 3D EM solver. In HFSS, an E-Patch antenna is drawn with given parameters shown in Figure 2-3 and Figure 2-4. Initial antenna dimensions and substrate parameters that are designed for dual-band GSM operations are given in Table 2-1.

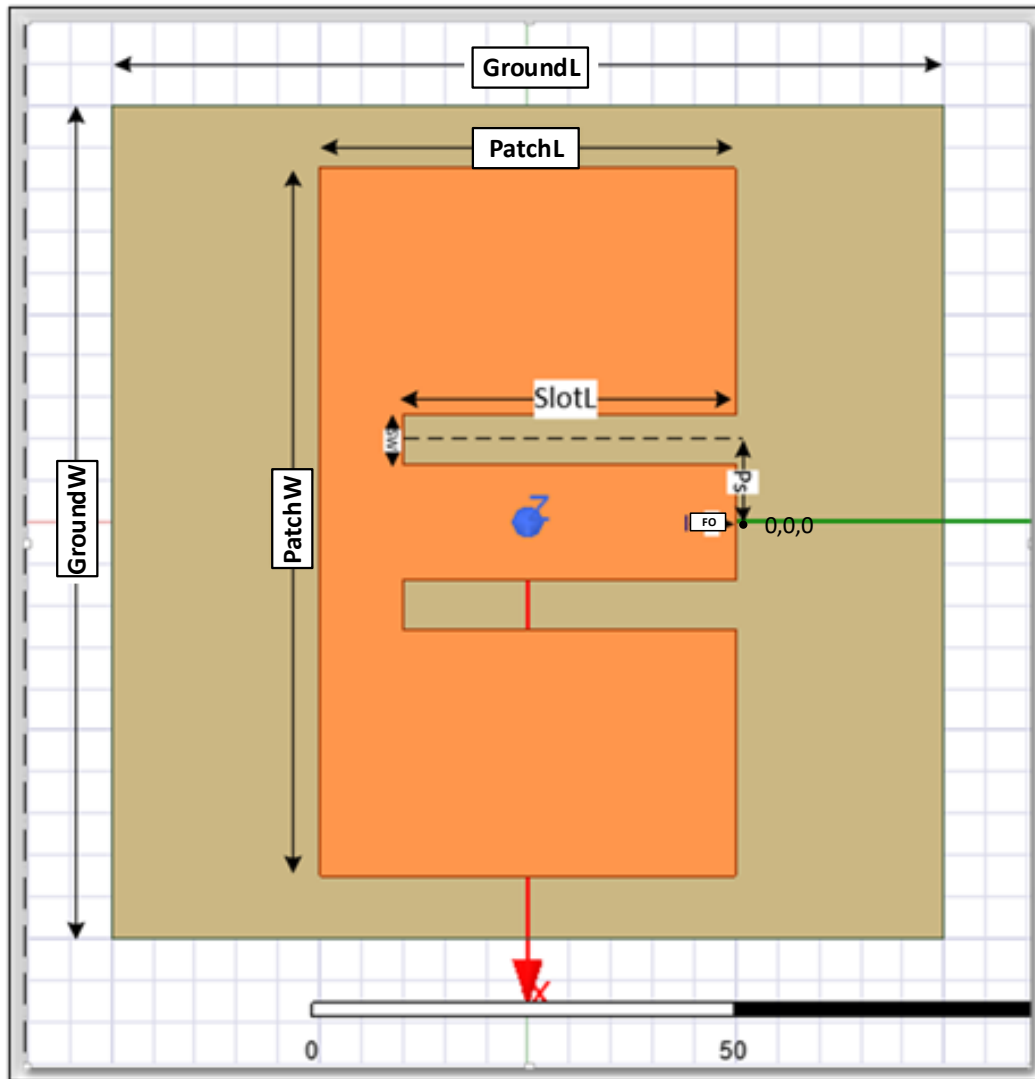


Figure 2-3 Wideband E-Patch antenna dimensions on the x-y plane

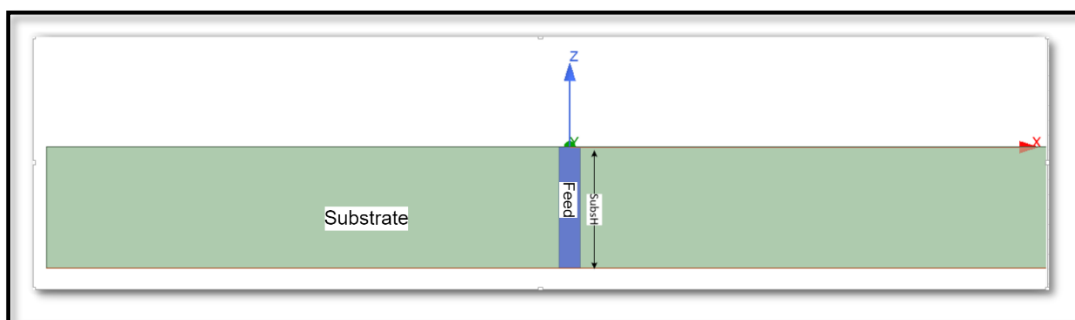


Figure 2-4 Wideband E-Patch antenna dimensions on the x-z plane

Table 2-1 Initial design parameters of wideband E-Patch Antenna.

| Parameter                                    | Initial Value | Electrical Length |
|----------------------------------------------|---------------|-------------------|
| Ground Width @ X axis, GroundW               | 210 mm        | $1.61 \lambda$    |
| Ground Length @ Y axis, GroundL              | 140 mm        | $1.07 \lambda$    |
| Patch Width @ X axis, PatchW                 | 70 mm         | $0.53 \lambda$    |
| Patch Length @ Y axis, PatchL                | 50 mm         | $0.39 \lambda$    |
| Substrate Height @ Z axis, SubsH             | 15 mm         | $0.11 \lambda$    |
| Slot Width @ X axis, SlotW (SW)              | 6 mm          | $0.05 \lambda$    |
| Slot Length @ Y axis, SlotL                  | 40 mm         | $0.3 \lambda$     |
| Slot Center Offset from (0,0,0) @ X axis, Ps | 10 mm         | $0.08 \lambda$    |
| Feed Offset from (0,0,0) @ Y axis, FO        | 6 mm          | $0.05 \lambda$    |
| Dielectric Constant (air), $\epsilon_r$      | 1             | -                 |

In the optimal value simulations, one of the variables in Table 2-1 are changed each time while keeping the others at their initial value. E-Patch antenna differs from conventional patch antennas by using air with unity relative permittivity ( $\epsilon_r$ ) as a substrate between ground and patch; patch height from the ground is the same as substrate height (SubsH). The antenna is excited by a normalized feed having a characteristic impedance of  $50 \Omega$ . After all, that makes sense; if fabricated, a  $50 \Omega$  coaxial connector is used on the feed part.

Antenna dimensions used in optimal value simulations are given in Table 2-2 to Table 2-6. Table 2-2 is applied to see the effect of ground width and length

parameters on  $S_{11}$ , Table 2-3 focuses on  $S_{11}$  in more detail values found in Figure 2-6. In

Table 2-5, the substrate height parameter is swept on two different value gaps while the first one has coarse values, the other one focuses height value on detail. It is also the same for SubsL and SubsW parameters. For slot and patch parameter simulations, found ground parameters in the Figure 2-6 are replaced with initial values.

Table 2-2 Wideband E-patch parametric simulation-1 dimensions

| <b>Swept Parameters</b>         | <b>From:</b> | <b>To:</b> | <b>Steps:</b> |
|---------------------------------|--------------|------------|---------------|
| Ground Width @ X axis, GroundW  | 100 mm       | 320 mm     | 30 mm         |
| Ground Length @ Y axis, GroundL | 70 mm        | 210 mm     | 30 mm         |
| <b>Others remain constant</b>   |              |            |               |

Table 2-3 Wideband E-patch parametric simulation-2 dimensions

| <b>Swept Parameters</b>         | <b>From:</b> | <b>To:</b> | <b>Steps:</b> |
|---------------------------------|--------------|------------|---------------|
| Ground Width @ X axis, GroundW  | 190 mm       | 210 mm     | 5 mm          |
| Ground Length @ Y axis, GroundL | 130 mm       | 150 mm     | 5 mm          |
| <b>Others remain constant</b>   |              |            |               |

Table 2-4 Wideband E-patch parametric simulation-3 dimensions

| <b>Swept Parameters</b>                                    | <b>From:</b> | <b>To:</b> | <b>Steps:</b> |
|------------------------------------------------------------|--------------|------------|---------------|
| Slot Length @ Y axis, SlotL                                | 10 mm        | 50 mm      | 5 mm          |
| Slot Width @ X axis, SlotW                                 | 1 mm         | 12 mm      | 1 mm          |
| <b>Others remain constant except GroundL &amp; GroundW</b> |              |            |               |

Table 2-5 Wideband E-patch parametric simulation-4 dimensions

| <b>Swept Parameters</b>                                    | <b>From:</b> | <b>To:</b> | <b>Steps:</b> |
|------------------------------------------------------------|--------------|------------|---------------|
| Substrate (Patch) Height @ Z axis, SubsH                   | 7.5 mm       | 22.5 mm    | 1 mm          |
| Substrate (Patch) Height @ Z axis, SubsH                   | 10.5 mm      | 11.5 mm    | 1 mm          |
| <b>Others remain constant except GroundL &amp; GroundW</b> |              |            |               |

Table 2-6 Wideband E-patch parametric simulation-5 dimensions

| <b>Swept Parameters</b>                                    | <b>From:</b> | <b>To:</b> | <b>Steps:</b> |
|------------------------------------------------------------|--------------|------------|---------------|
| Patch Width @ X axis, PatchW                               | 35 mm        | 105 mm     | 10 mm         |
| Patch Length @ Y axis, PatchL                              | 40 mm        | 80 mm      | 10 mm         |
| <b>Others remain constant except GroundL &amp; GroundW</b> |              |            |               |

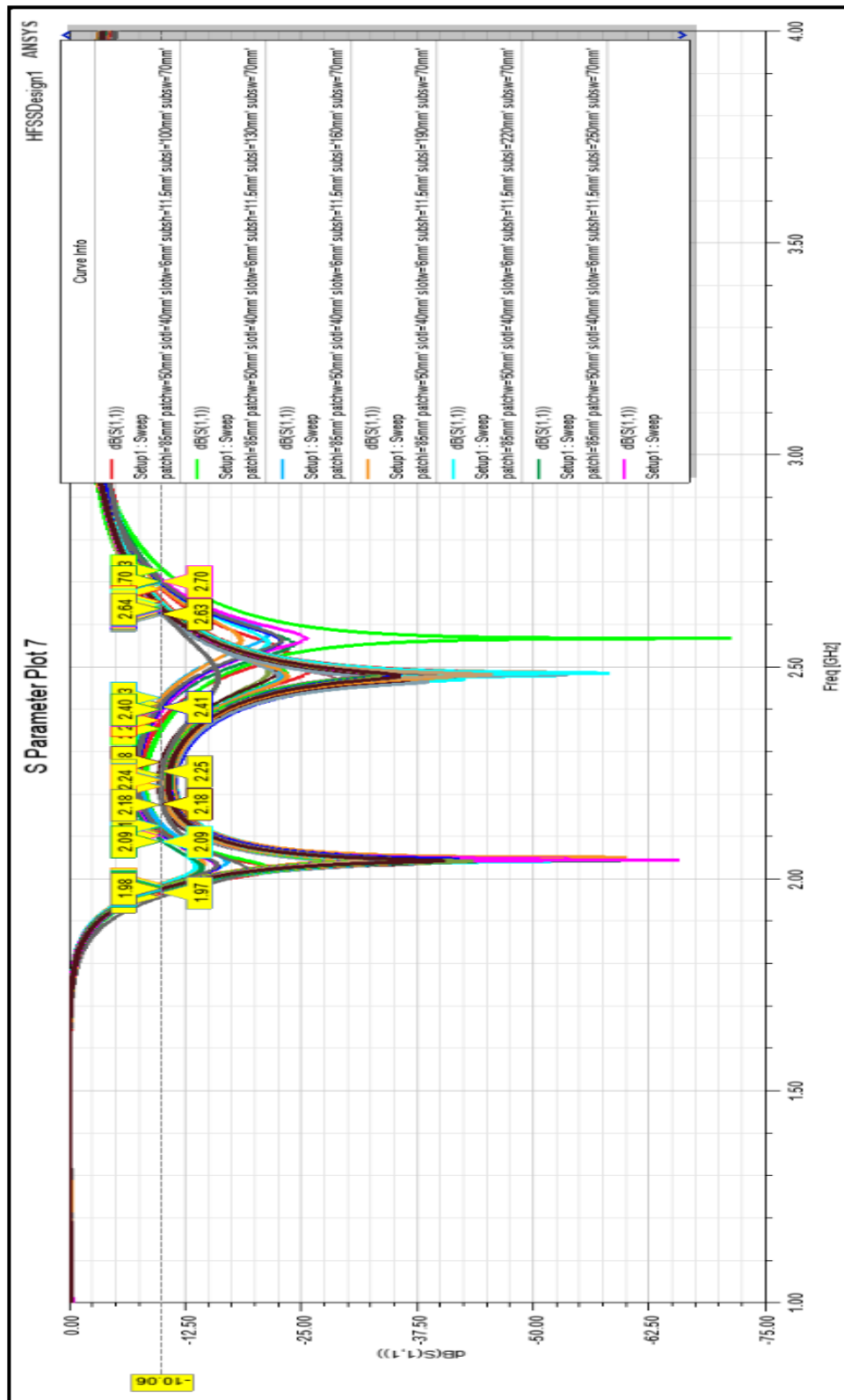


Figure 2-5 S<sub>11</sub> of the wideband E-Patch antenna for coarse GroundL and GroundW dimensions

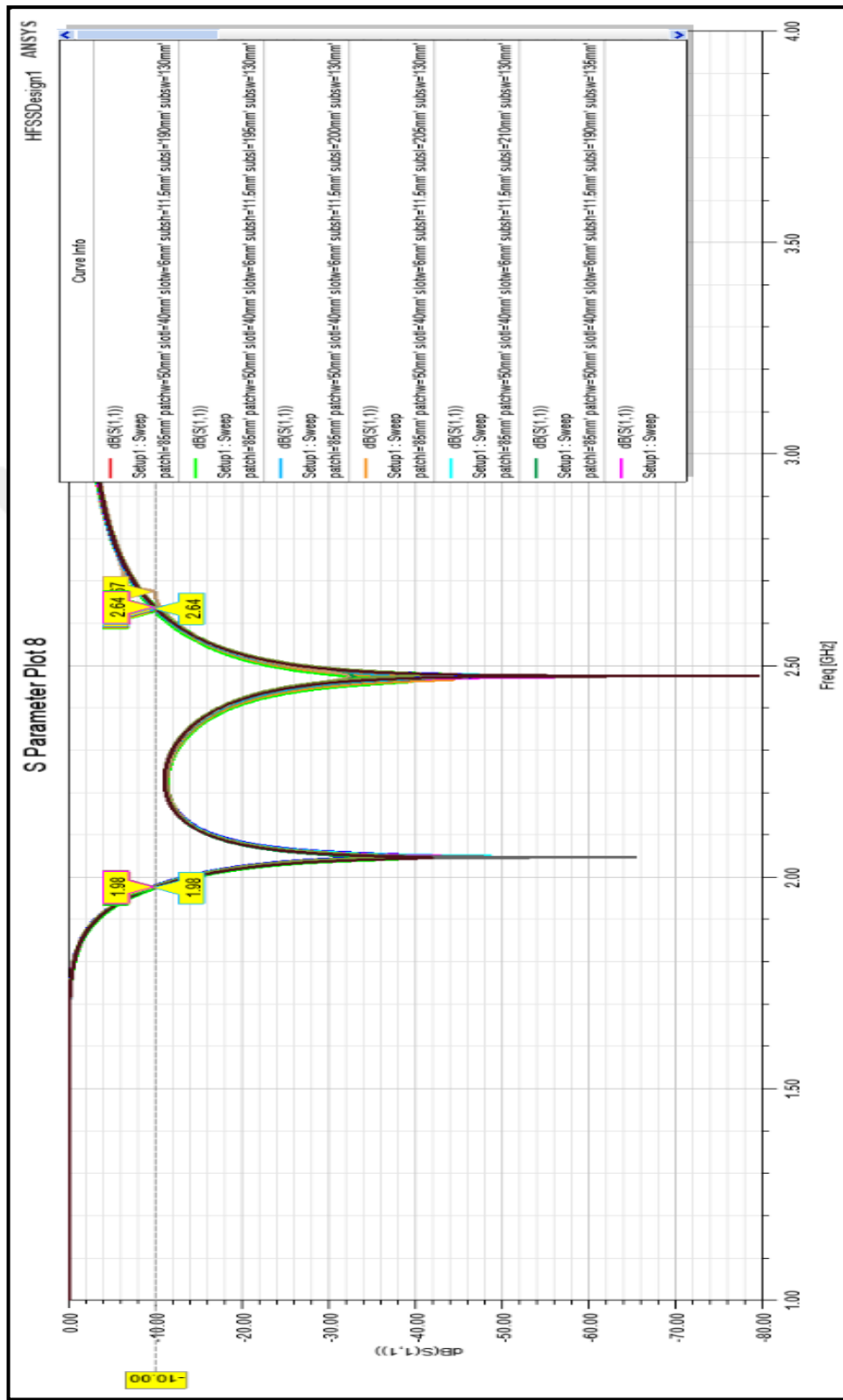


Figure 2-6 S<sub>11</sub> of the wideband E-Patch antenna for detailed GroundL and GroundW dimensions

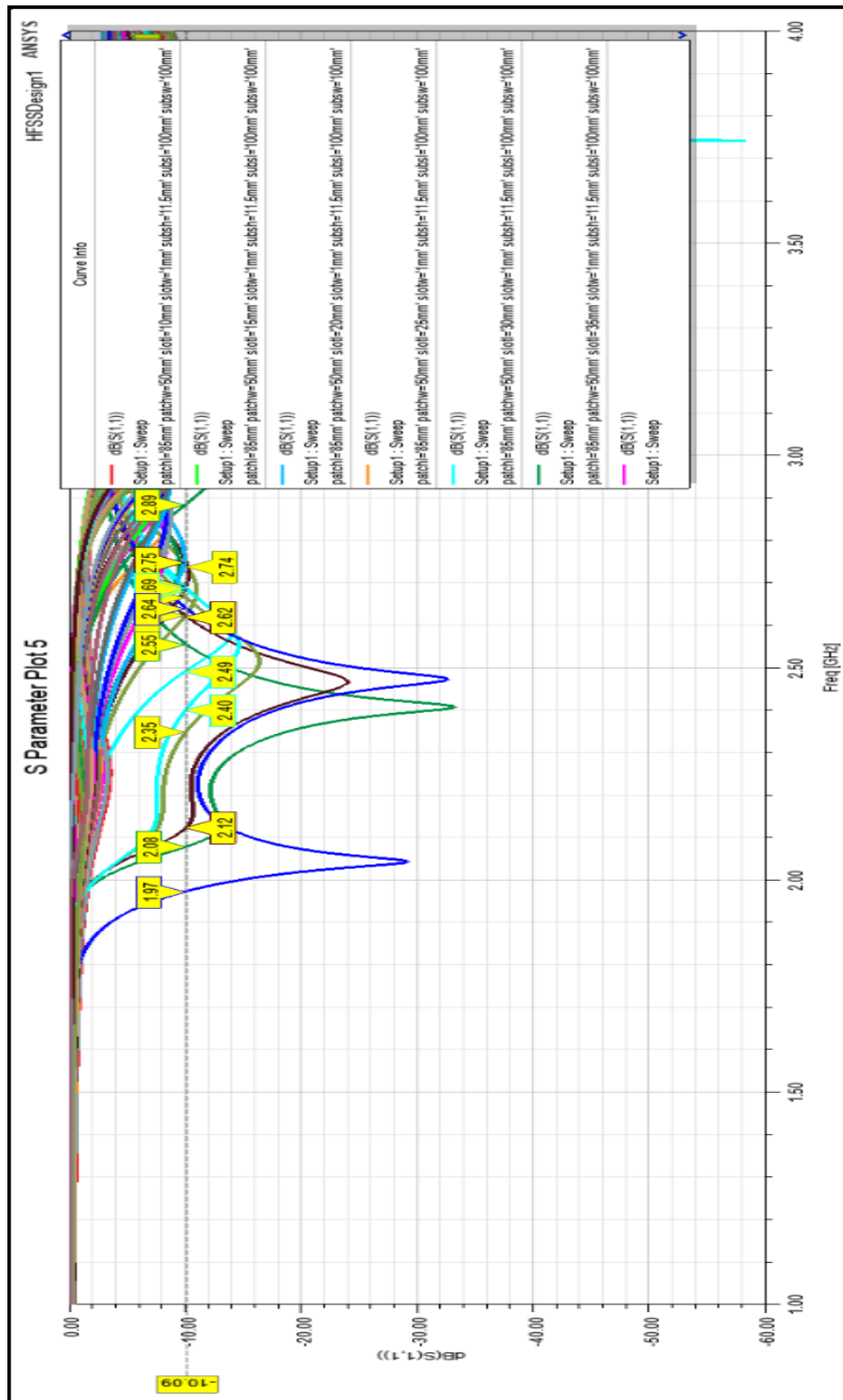


Figure 2-7  $S_{11}$  of the wideband E-Patch antenna for SlotL and SlotW dimensions

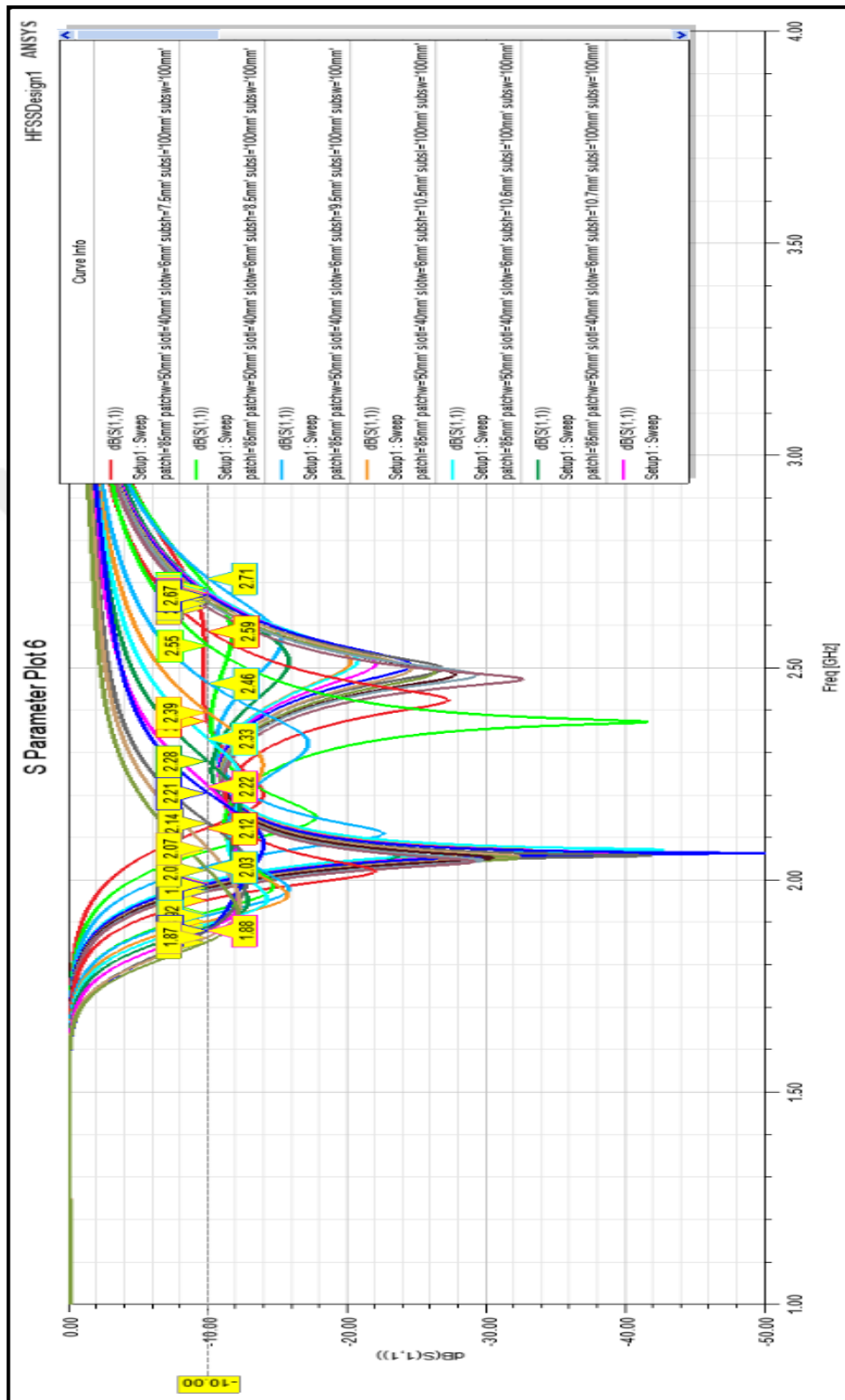


Figure 2-8  $S_{11}$  of the wideband E-Patch antenna for SubsH dimensions

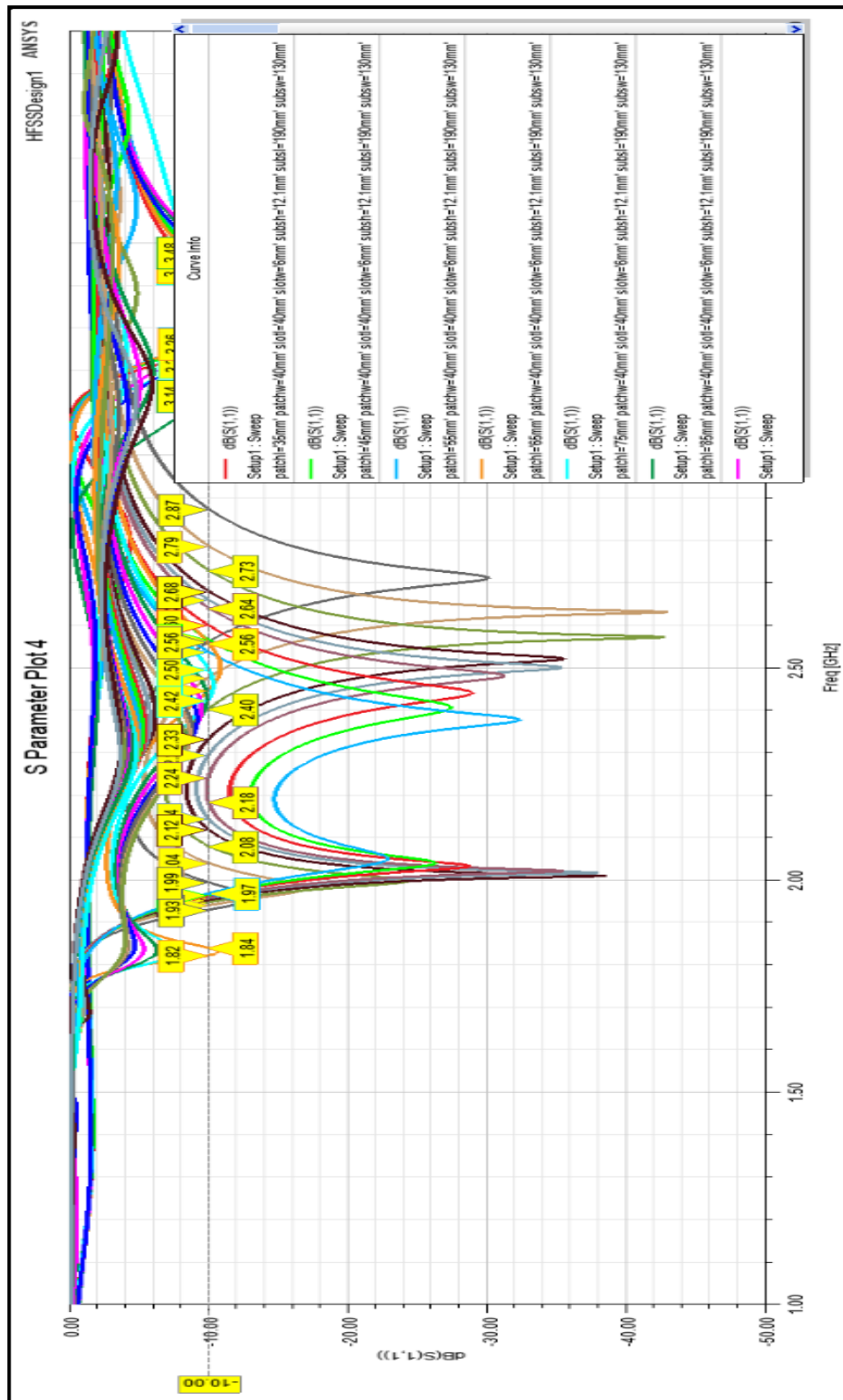


Figure 2-9  $S_{11}$  of the wideband E-Patch antenna for PatchL and PatchW dimensions

After having the required operating bandwidth (~600 MHz) at the 1-3 GHz operating frequency range with some patch, ground and slot dimensions obtained in E-Patch optimum value simulations, parametric analysis of the E-Patch antenna in detail is resulted in the next section.

### 2.1.2 Parametric Analysis of E-Patch Antenna

There are two distinct resonance points in the E-patch antenna: high frequencies from the middle part of the patch and low frequencies from the slot mechanism. Due to these special responses for the slotted type patch antennas, it is critical to optimize slot and patch dimensions to set two resonance frequencies to have wideband behavior. In the section 2.1.1, optimum dimension values that give aimed antenna objectives given in 2.1.1 for slot and patch parameters are found to have a wideband E-patch antenna. In this section, a detailed parametric study are investigated to see effect of the dimensions in the resonance characteristics of the antenna. Patch antenna dimensions are parametrically changed and input return loss values are resulted. For other dimensions are kept at their values are given in the section 2.2.

#### 2.1.2.1 Ground Dimensions Parametric Study

In this study, five different ground length and width parameters are varied given in Table 2-7 and Table 2-8, and resulted  $S_{11}$  responses are given in Figure 2-10 and Figure 2-11.

Table 2-7 Ground Width Parametric Study Values

| Swept Parameter                | Values         | Electrical Length |
|--------------------------------|----------------|-------------------|
| Ground Width @ X axis, GroundW | 80 mm          | 0,61 $\lambda$    |
|                                | 100 mm (Final) | 0,77 $\lambda$    |
|                                | 120 mm         | 0,92 $\lambda$    |
|                                | 210 mm         | 1,62 $\lambda$    |

| Table 2-7 Cont'd               |        |                |
|--------------------------------|--------|----------------|
| Ground Width @ X axis, GroundW | 320 mm | 2,46 $\lambda$ |
| Others Remain Constant         |        |                |

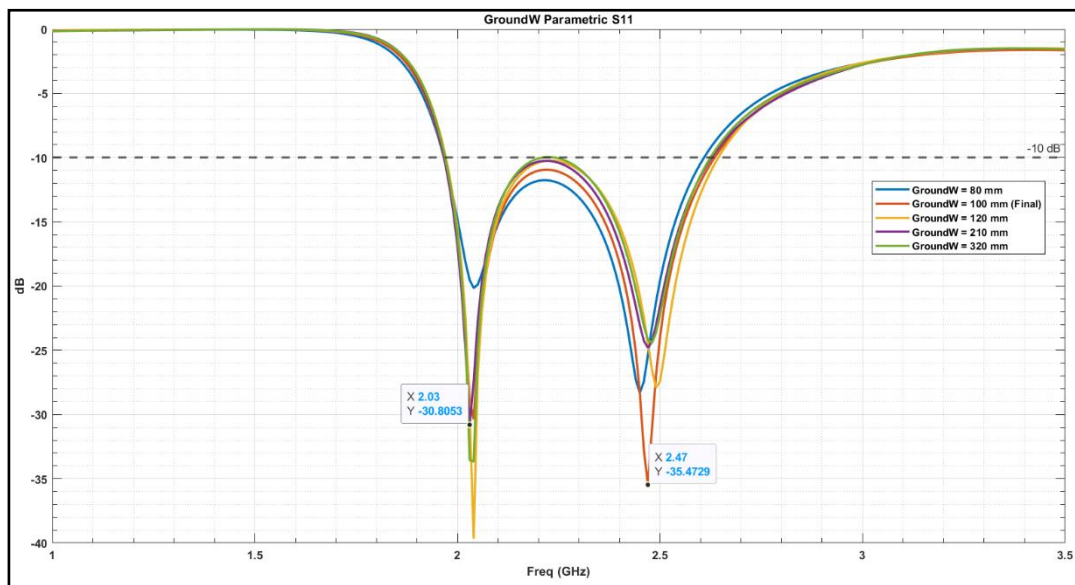


Figure 2-10 GroundW Parametric Study  $S_{11}$  Simulation (Blue: 80 mm, Orange: 100 mm (Final), Yellow: 120 mm, Purple: 210 mm, Green: 320 mm).

Table 2-8 Ground Length Parametric Study Values

| Swept Parameter                 | Values         | Electrical Length |
|---------------------------------|----------------|-------------------|
| Ground Length @ Y axis, GroundL | 80 mm          | 0,61 $\lambda$    |
|                                 | 100 mm (Final) | 0,77 $\lambda$    |
|                                 | 120 mm         | 0,92 $\lambda$    |
|                                 | 160 mm         | 1,23 $\lambda$    |
|                                 | 210 mm         | 1,62 $\lambda$    |
| Others Remain Constant          |                |                   |

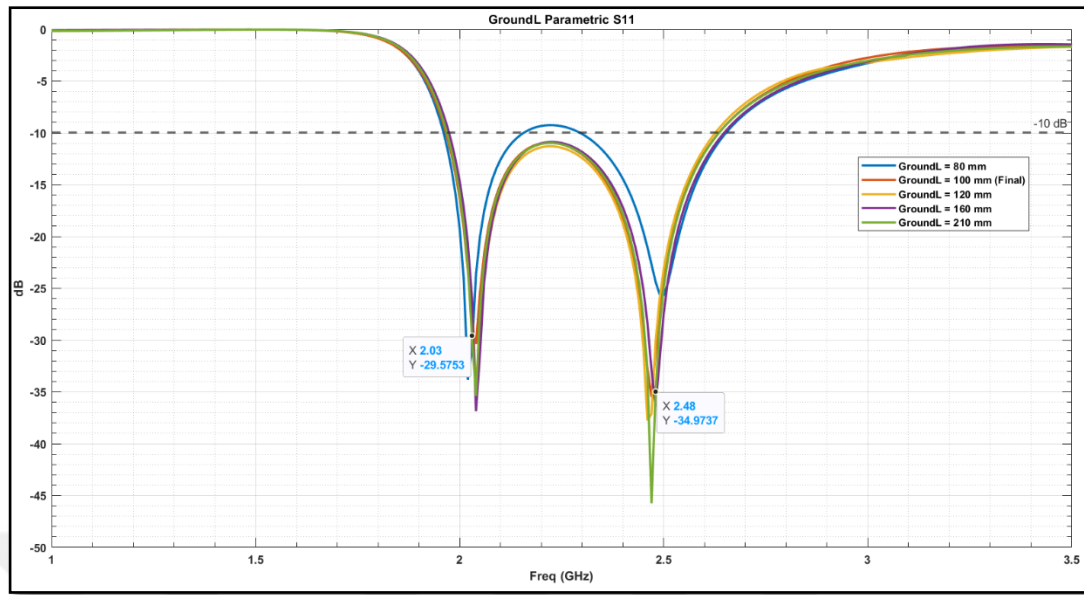


Figure 2-11 GroundL Parametric Study  $S_{11}$  Simulation (Blue: 80 mm, Orange: 100 mm (Final), Yellow: 120 mm, Purple: 160 mm, Green: 210 mm).

As seen from Figure 2-10 and Figure 2-11, ground parameters do not affect the wideband behavior of the antenna more than the slot and feed parameters. Choosing as small as possible is important to have reasonable array dimensions for E-patch antennas.

#### 2.1.2.2 Patch Dimensions Parametric Study

In this study, four different patch width and five different patch length parameters are varied given in Table 2-9 and Table 2-10, and resulted  $S_{11}$  responses are given in Figure 2-12 and Figure 2-13.

Table 2-9 Patch Width Parametric Study Values

| Swept Parameter              | Values | Electrical Length |
|------------------------------|--------|-------------------|
| Patch Width @ X axis, PatchW | 35 mm  | $0.27 \lambda$    |

| Table 2-9 Cont'd             |               |                |
|------------------------------|---------------|----------------|
| Patch Width @ X axis, PatchW | 60 mm         | 0,46 $\lambda$ |
|                              | 85 mm (Final) | 0,65 $\lambda$ |
|                              | 90 mm         | 0,69 $\lambda$ |
| Others Remain Constant       |               |                |

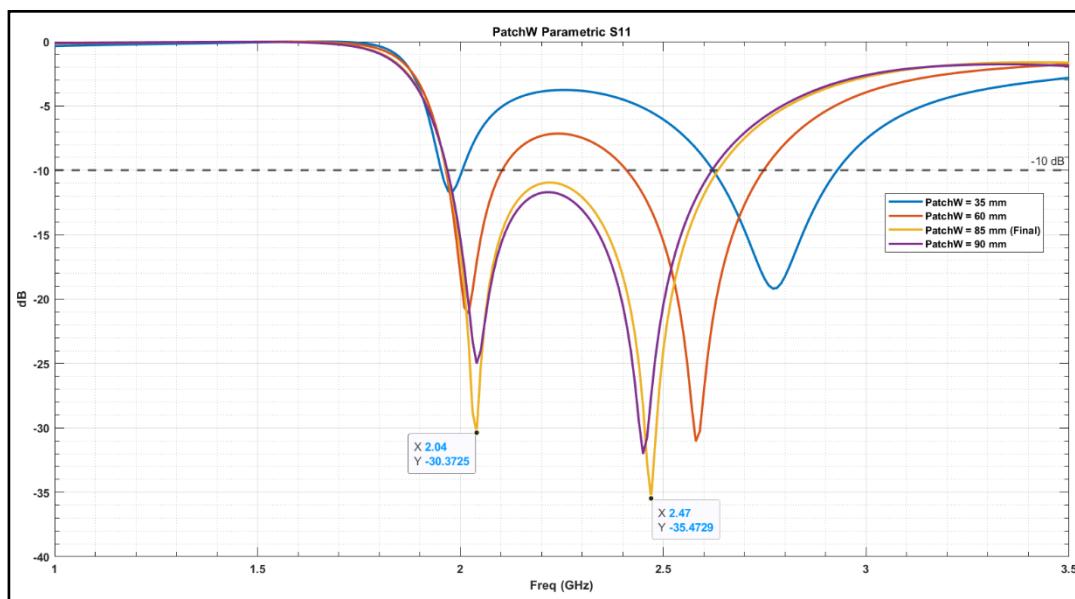


Figure 2-12 PatchW Parametric Study  $S_{11}$  Simulation (Blue: 35 mm, Orange: 60 mm, Yellow: 85 mm (Final), Purple: 90 mm).

As seen from the Figure 2-12, when the patch width at x axis is getting larger, higher resonance frequency response is getting smaller. However, smaller resonance frequency response does not change substantially. This is expected since, smaller resonance frequency are resulted from the added slots to the patch antenna but, higher resonance frequency is a result of the middle of the patch and therefore overall patch dimensions are effecting higher resonance frequency response more. When the patch width is increasing, current path to the edges of the antenna is also increasing and that creates additional inductance to the original modelled inductance value

( $+\Delta L$ ). Therefore, increased inductance value are decreasing the higher resonance frequency as expected and seen in Figure 2-12. Also, it is important to choose a optimum value to have overall wideband behaviour for the patch antenna as seen from the first value of the PatchW does not have the intended  $S_{11}$  response. It is also expected to have at least  $\lambda/2$  value for the patch width and length dimension values to antenna resonate. Therefore, initial patch width and length parameters can be chosen as  $\lambda/2$ .

$$f_{res} = \frac{1}{2\pi\sqrt{(L+\Delta L)C}} \quad (1.6)$$

Table 2-10 Patch Length Parametric Study Values

| Swept Parameter               | Values        | Electrical Length |
|-------------------------------|---------------|-------------------|
| Patch Length @ Y axis, PatchL | 45 mm         | 0,35 $\lambda$    |
|                               | 47 mm         | 0,36 $\lambda$    |
|                               | 50 mm (Final) | 0,38 $\lambda$    |
|                               | 52 mm         | 0,4 $\lambda$     |
|                               | 54 mm         | 0,41 $\lambda$    |
| Others Remain Constant        |               |                   |

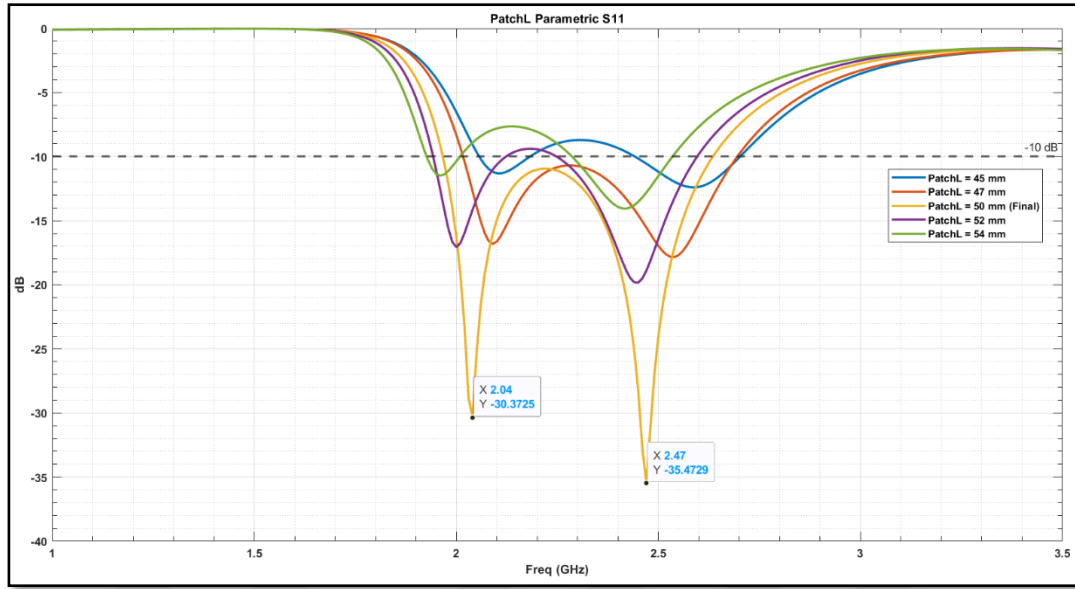


Figure 2-13 PatchL Parametric Study S<sub>11</sub> Simulation (Blue: 45 mm, Orange: 47 mm, Yellow: 50 mm (Final), Purple: 52 mm, Green: 54 mm).

As seen from the Figure 2-13, it is essential to optimize patch parameters to have wideband behaviour for our E-patch antenna. For the patch length parameter, the same mechanism applies to width as overall patch dimensions are getting larger, current patch is also increasing. Therefore, the higher resonance frequency effected more than the smaller resonance frequency. Also seen that until losing the wideband behaviour of the antenna, higher resonance frequency is getting smaller when the patch length increases. It is also known that cutted slots or slits on patch surface decreases the resonance frequency of the antenna [40]. Therefore seen in Figure 2-13 for PatchL value of 50 mm for an ordinary patch without slots or slits should be around 3 GHz ( $\lambda/2$ ) but due to slots, higher resonance frequency value decreased to 2.47 GHz. For cutted slot and slit type patch antennas, the patch dimensions should be smaller than the  $\lambda/2$  values for initial values. After that, parametric study is needed to adjust dimensions.

### 2.1.2.3 Slot Dimensions Parametric Study

In this study, five different slot length and width parameters are varied given in Table 2-11 and Table 2-12, and resulted  $S_{11}$  responses are given in Figure 2-14 and Figure 2-15.

Table 2-11 Slot Length Parametric Study Values

| Swept Parameter             | Values        | Electrical Length |
|-----------------------------|---------------|-------------------|
| Slot Length @ Y axis, SlotL | 36 mm         | 0,28 $\lambda$    |
|                             | 38 mm         | 0,29 $\lambda$    |
|                             | 40 mm (Final) | 0,31 $\lambda$    |
|                             | 42 mm         | 0,32 $\lambda$    |
|                             | 44 mm         | 0,34 $\lambda$    |
| Others Remain Constant      |               |                   |

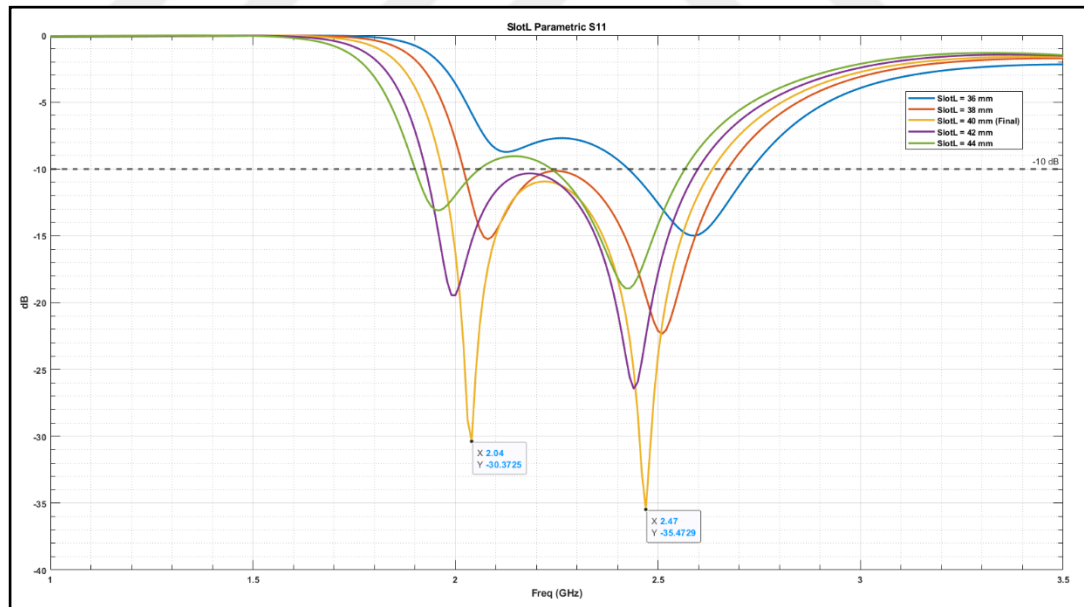


Figure 2-14 SlotL Parametric Study  $S_{11}$  Simulation (Blue: 36 mm, Orange: 38 mm, Yellow: 40 mm (Final), Purple: 42 mm, Green: 44 mm)

In the E-patch antenna, added slots increase the current path and add additional inductance. Larger inductance values create another resonant frequency lower than the frequency of the original patch due to the additional inductance effect. In Figure 2-14, it is also observed that slots play an essential role in controlling the wideband characteristics of the E-Patch antenna that is also compatible with the theory stated in [27]. It is observed that when the slot length is small, there is only one resonant frequency, and no wideband behavior occurs. However, the enlargement of the slot creates another resonant point on the antenna. Also, it is observed that when the slot length increases, lower resonance frequency decreases.

Table 2-12 Slot Width Parametric Study Values

| Swept Parameter               | Values       | Electrical Length |
|-------------------------------|--------------|-------------------|
| Slot Width @ X axis, SlotW    | 1 mm         | 0,008 $\lambda$   |
|                               | 4 mm         | 0,03 $\lambda$    |
|                               | 6 mm (Final) | 0,05 $\lambda$    |
|                               | 8 mm         | 0,06 $\lambda$    |
|                               | 12 mm        | 0,09 $\lambda$    |
| <b>Others Remain Constant</b> |              |                   |

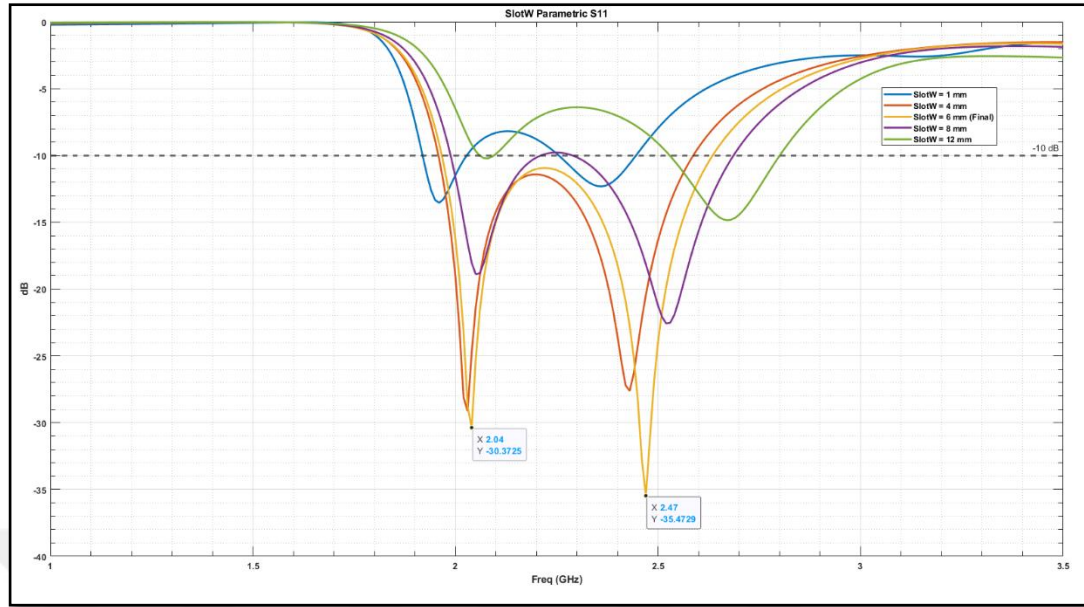


Figure 2-15 SlotW Parametric Study  $S_{11}$  Simulation (Blue: 1 mm, Orange: 4 mm, Yellow: 6 mm (Final), Purple: 8 mm, Green: 12 mm).

As seen that slot width is also effecting wideband behaviour of the E-patch antenna as the length. When slot width parameters is small, wideband behaviour is lost and antenna is not operated as intended. Difference to the slot length parameter, width parameter are affected more the higher resonance frequency value than the lower resonance frequency. It is also expected that slot width controls middle area of the patch that results higher resonance frequency response. When the slot width is getting larger, less current is concentrated on the middle of the patch.

#### 2.1.2.4 Substrate Height Parametric Study

In this study, seven different substrate height parameter as the air distance between the ground and patch of the antenna are varied given in Table 2-13, and resulted  $S_{11}$  responses are given in Figure 2-16.

Table 2-13 Substrate Height Parametric Study Values

| Swept Parameter                  | Values          | Electrical Length |
|----------------------------------|-----------------|-------------------|
| Substrate Height @ Z axis, SubsH | 7.5 mm          | 0,058 $\lambda$   |
|                                  | 9.5 mm          | 0,073 $\lambda$   |
|                                  | 10.5 mm         | 0,08 $\lambda$    |
|                                  | 11.5 mm (Final) | 0,089 $\lambda$   |
|                                  | 12.5 mm         | 0,097 $\lambda$   |
|                                  | 13.5 mm         | 0,10 $\lambda$    |
|                                  | 17.5 mm         | 0,13 $\lambda$    |
| Others Remain Constant           |                 |                   |

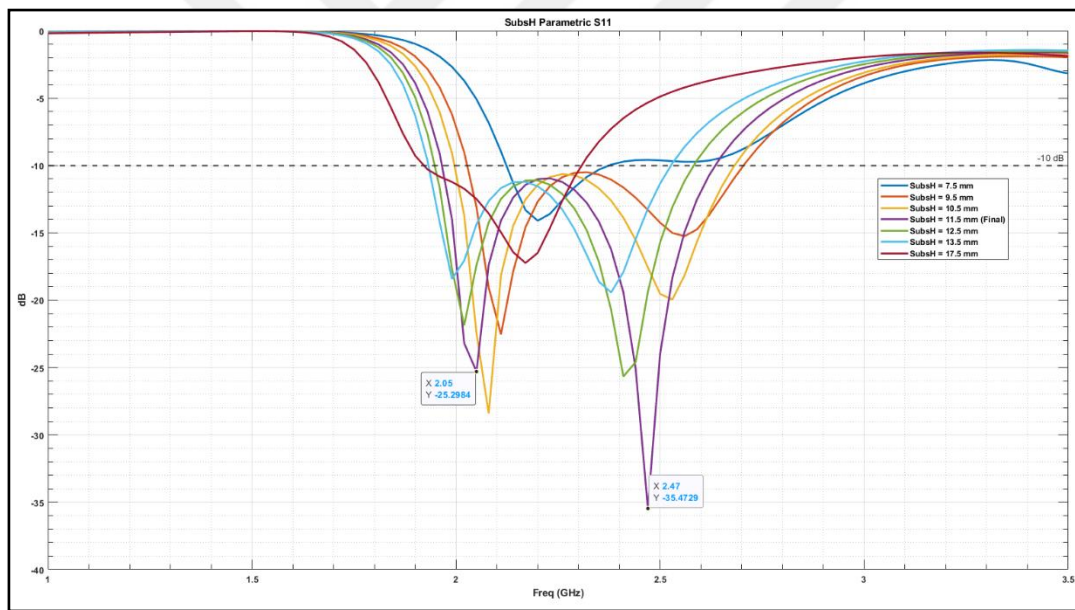


Figure 2-16 SubsH Parametric Study  $S_{11}$  Simulation (Blue: 7.5 mm, Orange: 9.5 mm, Yellow: 10.5 mm, Purple: 11.5 mm (Final), Green: 12.5 mm, Turquoise: 13.5, Brown: 17.5 mm).

Another critical parameter for the antenna to optimize the required bandwidth is the substrate height parameter. It can be seen from Figure 2-16 that when substrate height increases, lower and higher resonant frequencies decrease. The effect of the substrate height parameter can be figured out from ordinary patch antenna TEM mode analysis [38]. The effective dielectric constant of a microstrip line given as;

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\left( (\epsilon_r - 1) * \left[ 1 + \frac{12 * h}{W} \right]^{-1/2} \right)}{2} \quad (1.7)$$

In this design, the use of air as a substrate (with  $\epsilon_r = 1$ ) causes the  $\epsilon_{eff}$  values to equal 1. The  $\epsilon_{eff}$  value remains between 1 (the dielectric constant of air) and the dielectric constant of the substrate,  $\epsilon_r$ , because the electromagnetic fields that are excited by the microstrip reside partially in the air and partially in the substrate. However, to improve the electromagnetic (EM) fields in the air, which account for radiation, the patch width (W) must be increased. Radiation of electromagnetic fields can be improved by decreasing  $\epsilon_r$  or increasing the thickness of the substrate (h). It should be noted that selecting antenna dimensions requires a compromise between ‘W’ and ‘h’, as they are limited by input impedance and unwanted surface waves, respectively. Moreover, it is important to consider the design requirements of microstrip transmission lines or circuits as they are often feed or integrated with microstrip patches.

Calculation of effective length as [39];

$$L_{eff} = \frac{c}{2 * f_{res} * \sqrt{\epsilon_{eff}}} \quad (1.8)$$

Calculation of length extension;

$$\Delta L = 0.412 * h \left[ \frac{\epsilon_{eff} + 0.3}{\epsilon_{eff} - 0.258} * \frac{\left(\frac{W}{h}\right) + 0.264}{\left(\frac{W}{h}\right) + 0.8} \right] \quad (1.9)$$

Calculation of actual length of patch;

$$L = L_{eff} - 2\Delta L \quad (1.10)$$

In our parametric study substrate height parameter  $h$  increases,  $\Delta L$  parameter from Eq. 1.9 also increases so, to have same physical length  $L$  from Eq. 1.10,  $L_{eff}$  parameter also should increase. Therefore, resonance frequency value should decrease from Eq. 1.8. It means that for the same patch length and width value, due to the fringing effect of the patch antenna, substrate height changes the both resonance frequencies. However, when substrate height parameter  $h$  decreases,  $\Delta L$  parameter also decreases from Eq. 1.9. so, to have same physical length  $L$  from Eq. 1.10.,  $L_{eff}$  parameter also should decrease. Therefore, resonance frequency value should increase from Eq. 1.8. That response explains our parametric substrate height results as when  $h$  parameter increases, both resonance frequencies decreases and vice versa.

However, increasing height intensely means losing the E-Patch's wideband behavior, so designers should carefully optimize it to aim for dual-tone or wideband requirements.

#### 2.1.2.5 Feed Offset Parametric Study

In this study, five different feed offset distance value parameter from origin (0,0,0) point seen from the Figure 2-3 are varied given in Table 2-14, and resulted  $S_{11}$  responses are given in Figure 2-17.

Table 2-14 Feed Offset Parametric Study Values

| Swept Parameter          | Values       | Electrical Length |
|--------------------------|--------------|-------------------|
| Feed Offset @ Y axis, FO | 2 mm         | 0,001 $\lambda$   |
|                          | 4 mm         | 0,03 $\lambda$    |
|                          | 6 mm (Final) | 0,05 $\lambda$    |
|                          | 8 mm         | 0,06 $\lambda$    |
|                          | 10 mm        | 0,08 $\lambda$    |
| Others Remain Constant   |              |                   |

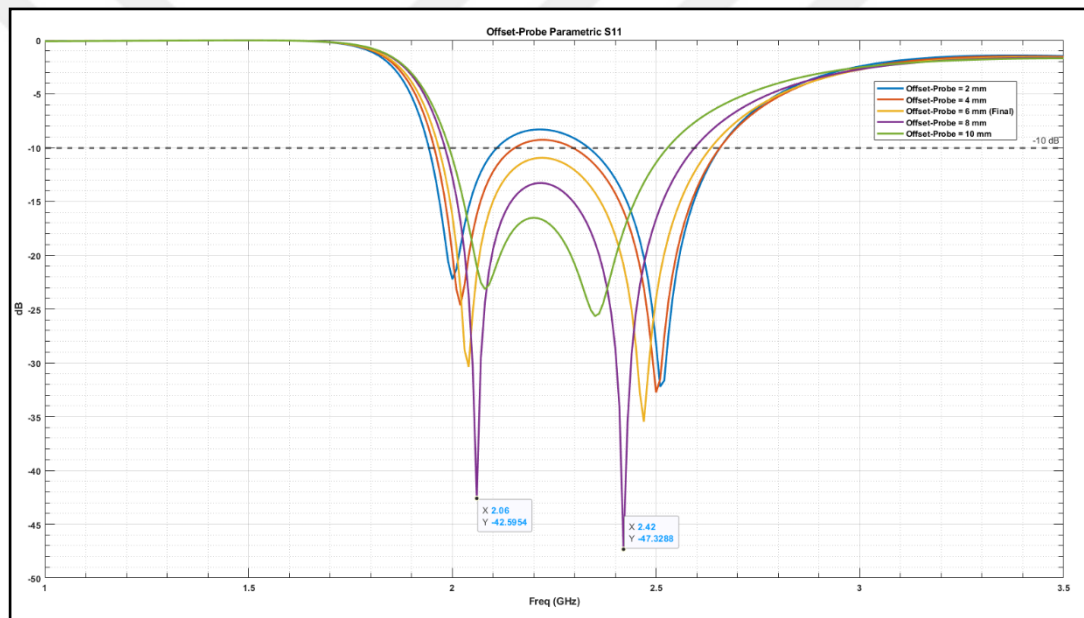


Figure 2-17 Feed Offset (FO) Parametric Study  $S_{11}$  Simulation (Blue: 2 mm, Orange: 4 mm, Yellow: 6 mm (Final), Purple: 8 mm, Green: 10 mm).

As seen from Figure 2-17, feed offset value affects wideband behaviour of the E-patch antenna. However, besides slot and patch dimensions, its effect are minor. Still, it is important to optimize the feed value to have intended input return loss.

### 2.1.2.6 Slot Center Offset Parametric Study

In this study, five different slot center offset distance value ( $P_s$ ) parameter from origin (0,0,0) point seen from the Figure 2-3 are varied given in Table 2-15, and resulted  $S_{11}$  responses are given in Figure 2-18.

Table 2-15 Slot Center Offset Parametric Study Values

| Swept Parameter                    | Values        | Electrical Length |
|------------------------------------|---------------|-------------------|
| Slot Center Offset @ X axis, $P_s$ | 5 mm          | 0,038 $\lambda$   |
|                                    | 8 mm          | 0,061 $\lambda$   |
|                                    | 10 mm (Final) | 0,077 $\lambda$   |
|                                    | 12 mm         | 0,092 $\lambda$   |
|                                    | 15 mm         | 0,11 $\lambda$    |
| Others Remain Constant             |               |                   |

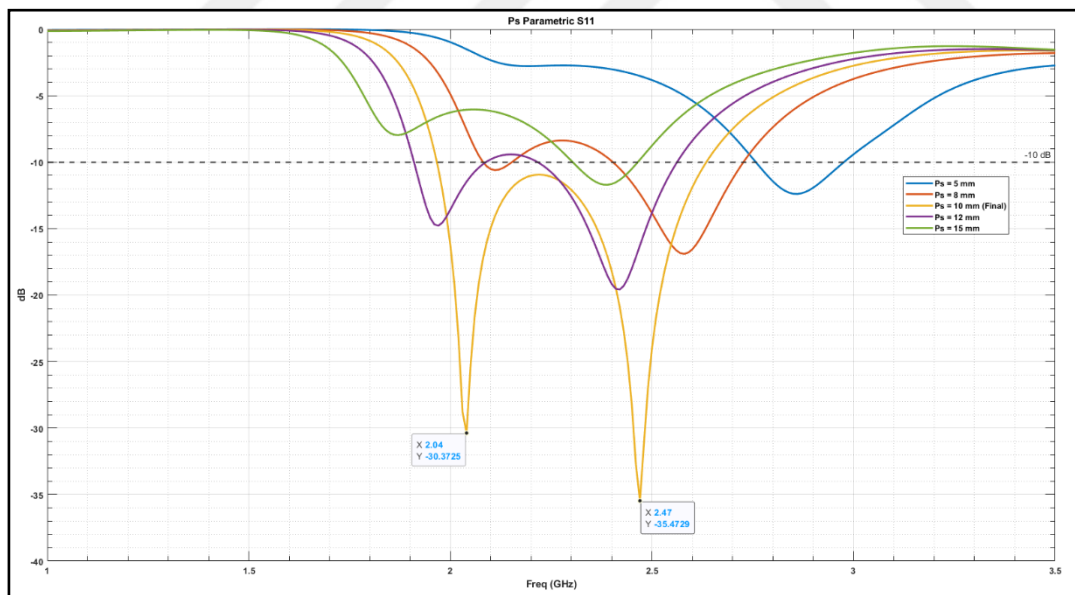


Figure 2-18 Slot Center Offset ( $P_s$ ) Parametric Study  $S_{11}$  Simulation (Blue: 5 mm, Orange: 8 mm, Yellow: 10 mm (Final), Purple: 12 mm, Green: 15 mm).

As seen in Figure 2-18, it is not only important of the value of slot dimension parameters, also placement of that slots on the patch antenna is critical to have wideband behaviour. A difficult and detailed parametric simulation of the slot center offset (Ps) parameter is needed to have intended bandwidth characteristics of the antenna. Even a small offset value from the optimum value completely changes the wideband behavior of the antenna. So, it is also critical in manufacturing process of the antenna that even a small error results different antenna behaviour. It is seen that when the slot centers are coming closer the edges of the antenna both lower and higher resonance frequencies are decreasing. That result shows that E-patch antenna has very distinct and complicated radiation mechanisms and the designer carefully should optime slot and patch parameters to have required results.

## 2.2 Final Design Values of the Wideband E-Patch Antenna

The optimal value and parametric study in the previous section provided valuable information about the design parameters of the E-Patch antenna. The dimensions that produce the required bandwidth are also applied with a single element and then array configurations. Only single element results are represented later; in section 2.2.1, four array configurations will be studied.

Antenna dimensions that met the required objectives are listed in Table 2-16. simulated E-Patch antenna results of  $S_{11}$ , 2D, and 3D radiation patterns, gain flatness, and axial ratio plots are shown from Figure 2-19 to Figure 2-25. Also, a summary of the simulated E-patch antenna specifications is given in Table 2-17.

Table 2-16 Final design parameters of the wideband E-Patch Antenna.

| Parameter                       | Final Value | Electrical Length |
|---------------------------------|-------------|-------------------|
| Ground Width @ X axis, GroundW  | 100 mm      | $0.76 \lambda$    |
| Ground Length @ Y axis, GroundL | 100 mm      | $0.76 \lambda$    |
| Patch Width @ X axis, PatchW    | 85 mm       | $0.65 \lambda$    |

| <b>Table 2-16 Cont'd</b>                     |         |                |
|----------------------------------------------|---------|----------------|
| Patch Length @ Y axis, PatchL                | 50 mm   | $0.38 \lambda$ |
| Substrate (Patch) Height @ Z axis, SubsH     | 11.5 mm | $0.08 \lambda$ |
| Slot Width @ X axis, SlotW (SW)              | 6 mm    | $0.05 \lambda$ |
| Slot Length @ Y axis, SlotL                  | 40 mm   | $0.31 \lambda$ |
| Slot Center Offset from (0,0,0) @ X axis, Ps | 10 mm   | $0.08 \lambda$ |
| Feed Offset from (0,0,0) @ Y axis, O         | 6 mm    | $0.05 \lambda$ |
| Dielectric Constant (air), $\epsilon_r$      | 1       | -              |

As it can be seen in the Figure 2-19 - Figure 2-25, the E-patch antenna meets all requirements listed before, such as operating bandwidth, large unidirectional beamwidth, high front-to-back ratio, good gain, and suitable for array configuration with its low-profile, low-cost, and gain flatness requirements. The E-Patch antenna has two distinct resonant frequencies: the patch itself, the other due to slot structure. Optimizing these two resonances gives us a broadband behavior that is requested to have. As is seen below, Antenna has around 670 MHz (29%) operating bandwidth in the center frequency of 2.31 GHz. These specs are needed to work with a short-pulse system. Far-field peak realized gain value results as 8.72 dBi. It is suitable with the values given in Table 1-1. Far-field azimuthal and elevational 3dB beamwidth values are enough for our system to radiate every corner of the room behind the wall. It is essential to receive an echo signal of different objects. Gain flatness is also critical not to distort the short-pulse signal, and the proposed E-patch meets this requirement given in Figure 2-24. It has linear polarization as expected due to the position of the feed, and it is demonstrated with the axial ratio value given in Figure 2-25.

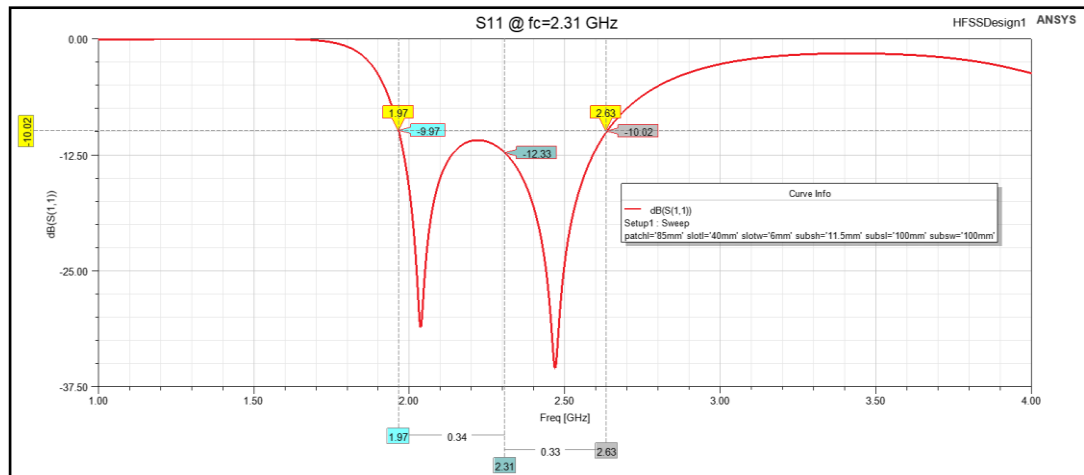


Figure 2-19  $S_{11}$  of the wideband E-Patch antenna

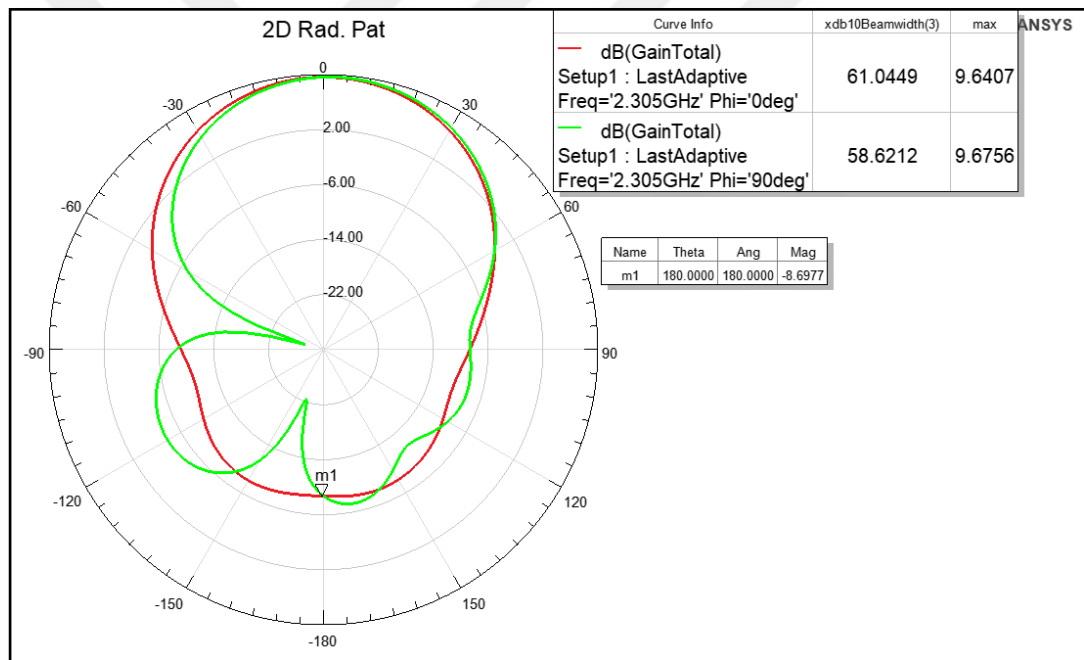


Figure 2-20 Far-field 2D radiation pattern of the wideband E-Patch antenna @  $f_c = 2.31$  GHz (Red:  $\theta = 0$  representing azimuthal (x-z axes) axes; Green:  $\theta = 90$  representing elevational (y-z axes) axes; m1: back lobe gain value)

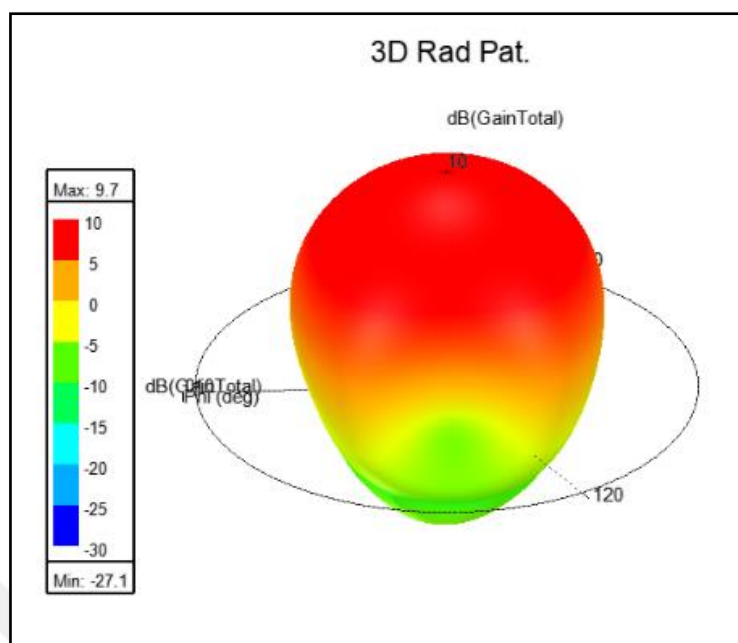


Figure 2-21 Far-field 3D polar plot of the wideband E-Patch antenna @  $f_c=2.31$  GHz (Max. Gain is seen as 9.7 dBi)

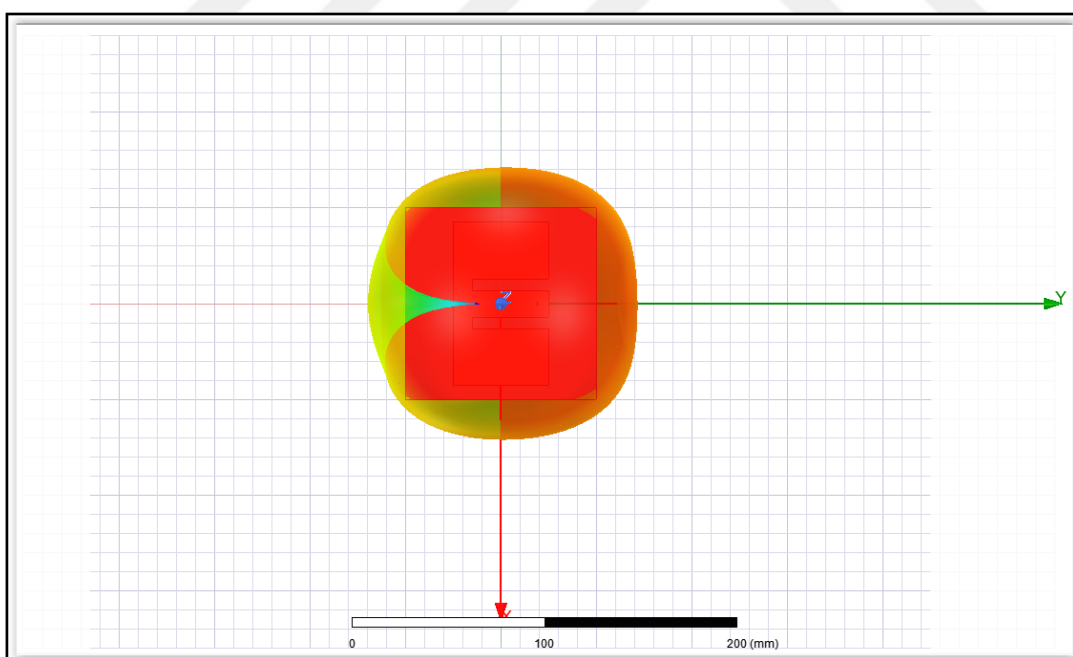


Figure 2-22 Far-field 3D radiation pattern on the E-Patch antenna on top view.

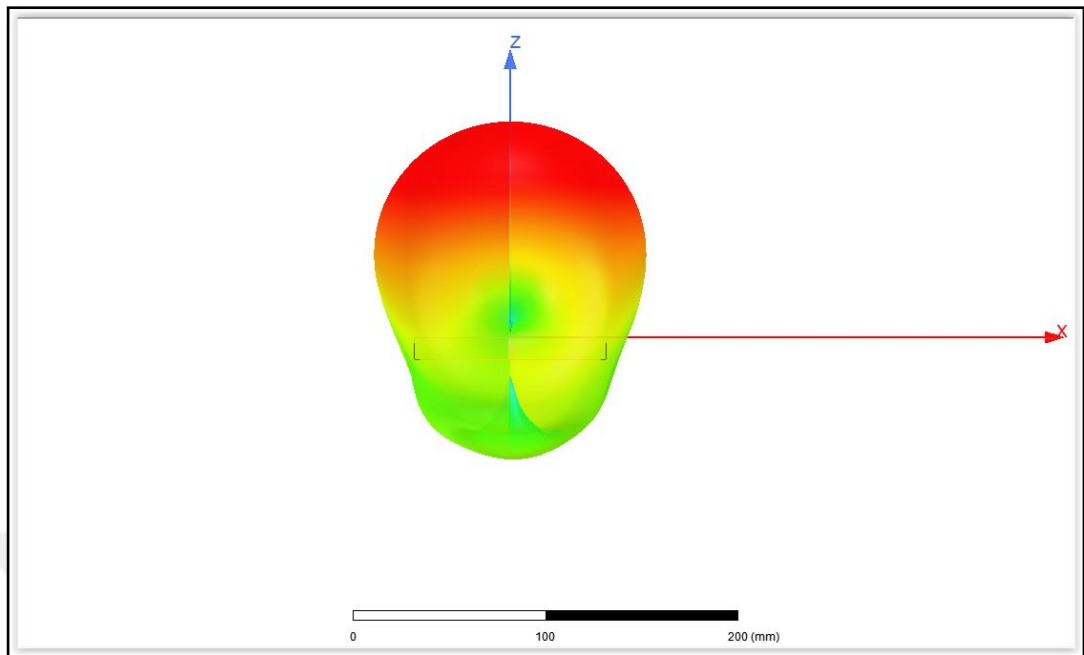


Figure 2-23 Far-field 3D radiation pattern on the wideband E-Patch antenna on the side view.

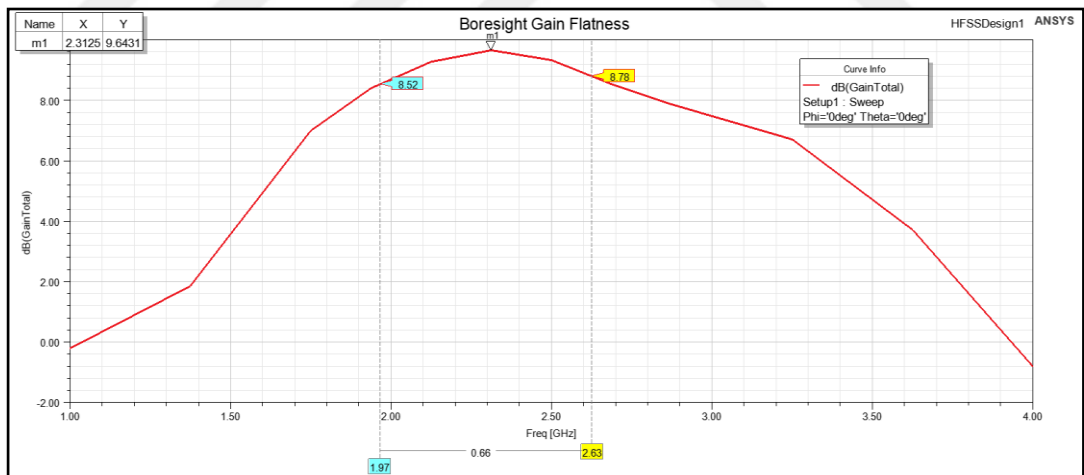


Figure 2-24 Boresight gain flatness of the wideband E-Patch antenna.

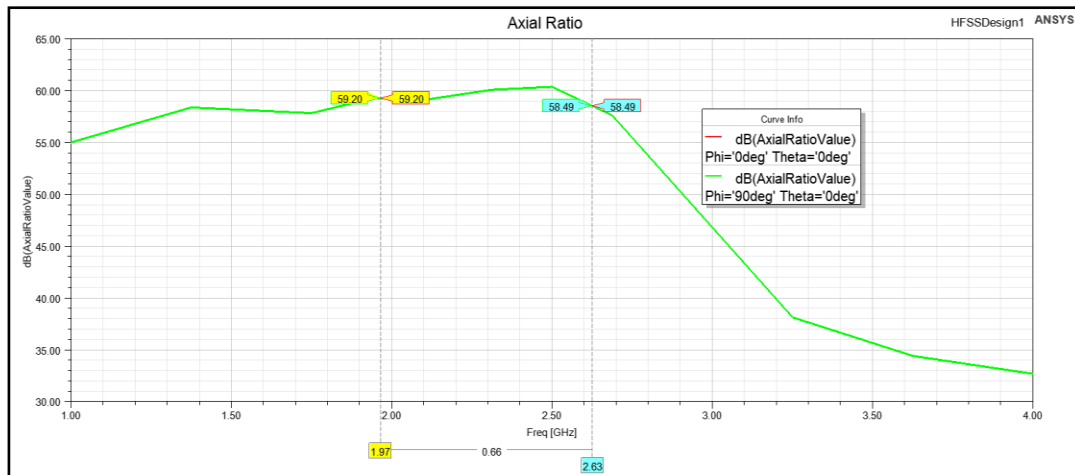


Figure 2-25 Axial ratio of the wideband E-Patch antenna.

Table 2-17 Summary of the results of wideband E-Patch antenna.

| Simulated Specs                      | Value           |
|--------------------------------------|-----------------|
| Frequency Range ( $S_{11} < -10$ dB) | 1.97 – 2.63 GHz |
| Operating Bandwidth                  | 670 MHz (29%)   |
| Far-Field Peak Directivity @ $f_c$   | 8.95 dBi        |
| Far-Field Peak Gain @ $f_c$          | 9.28 dBi        |
| Far-Field Peak Realized Gain @ $f_c$ | 8.72 dBi        |
| Axial Ratio ( $> 3$ dB = Linear)     | 59 dB           |
| Radiation Pattern                    | Hemispherical   |
| Azimuthal $3_{db}$ Beamwidth         | $61^\circ$      |
| Elevational $3_{db}$ Beamwidth       | $59^\circ$      |
| Front to Back Ratio                  | 18.3 dB         |

E-Patch radiation theory states that most currents concentrate under the patch, and more areas are needed for low frequency. In other words, the ground plane is determined by the low frequency. To prove this statement, surface current distribution on the ground is given in two resonance frequencies given in Figure 2-26

and Figure 2-27. The figures show that more current is distributed on the ground at a lower resonance frequency than the higher frequency.

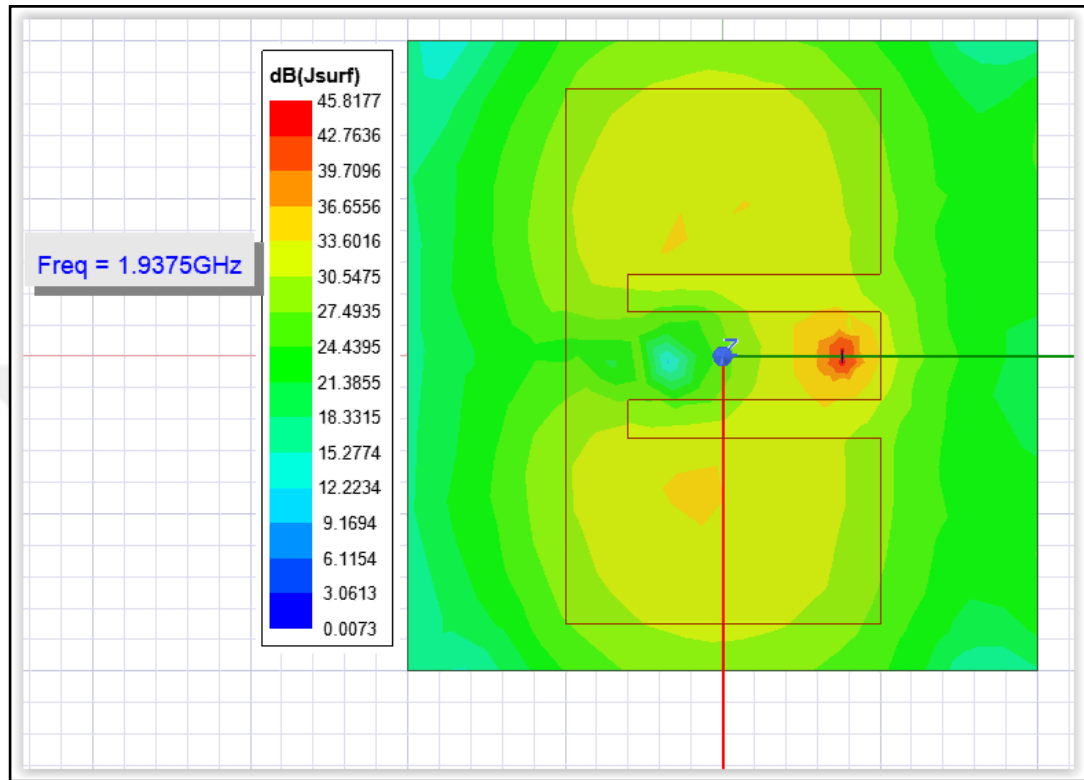


Figure 2-26 Surface current distribution of the E-Patch antenna on its ground at 1.9 GHz (lower resonance frequency).

In the E-Patch antenna it is observed that slots increase the length of the current path, and this path adds additional inductance to the patch. Therefore, the additional lower resonance frequency is created by the slots. The central part region of the patch radiates like a standard patch without any slots. At higher frequencies, the amplitudes of the currents around the slots are almost same as those at the left and right edges of the patch. The effect of the slots in this case is not significant. The patch operates like an ordinary patch without any slots. Therefore, the high resonant frequency is mainly determined by patch width (W) and length (L), less affected by the slots. While at low frequency, the amplitudes of the current around the slots are greater

than those at high frequency. The slots congregate the currents, and this effect can be modeled as an inductance. Due to this additional inductance effect, it resonates at a low frequency. Thus, this lower resonant frequency is mainly characterized by the slots. Figure 2-28 and Figure 2-29 prove that theory as it is seen that currents at lower resonance frequency are distributed more in the outer part of the slot E. In higher resonance frequency, currents are concentrated inside of slot E.

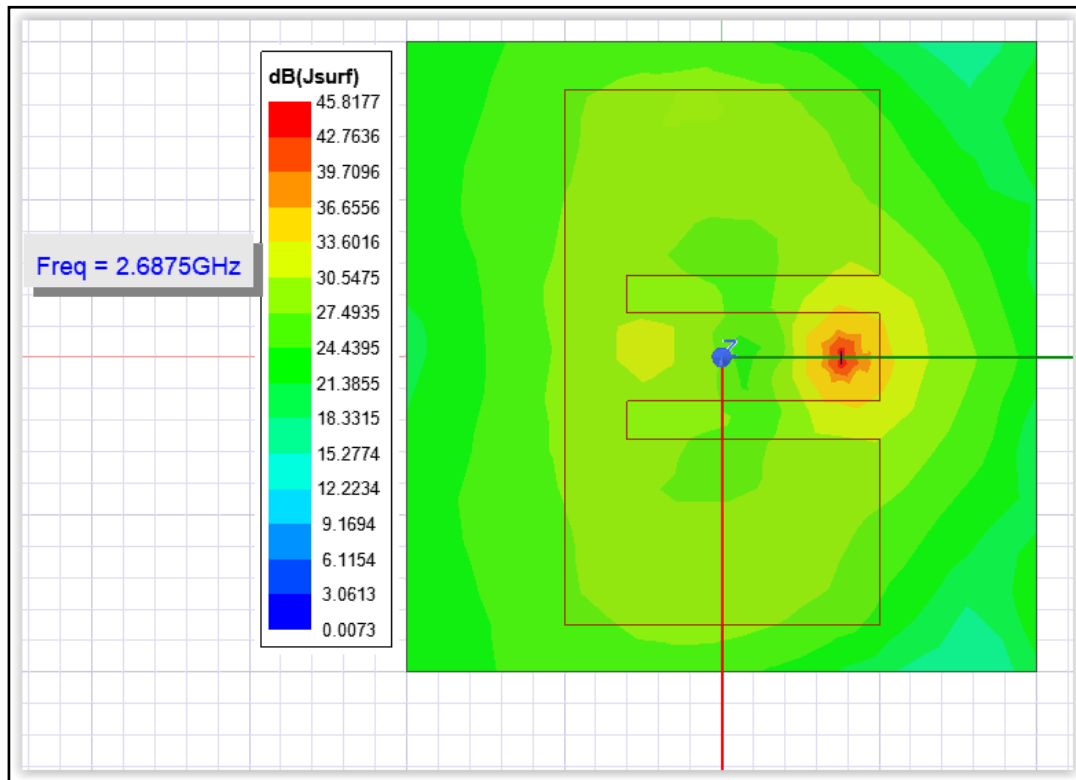


Figure 2-27 Surface current distribution of the E-Patch antenna on its ground at 2.6 GHz (higher resonance frequency).

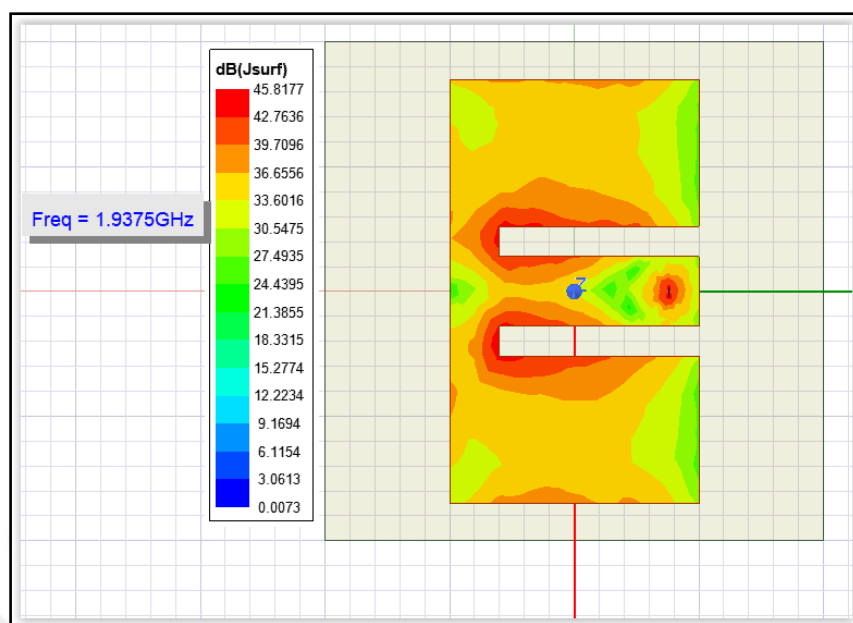


Figure 2-28 Surface current distribution of the E-Patch antenna on its patch at 1.9 GHz (lower resonance frequency).

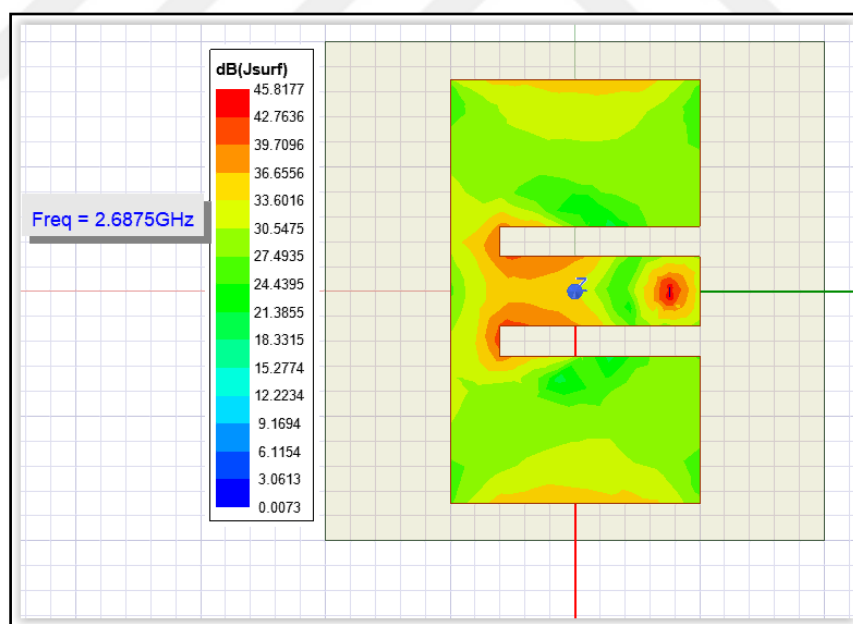


Figure 2-29 Surface current distribution of the E-Patch antenna on its patch at 2.6 GHz (higher resonance frequency).

### 2.2.1 Four-Element E-Patch Antenna Array Design

An array configuration with four identical elements is designed to gain more than a stand-alone configuration. The geometry of the array is given in Figure 2-30. A parametric study is carried out to find optimum element spacing between the elements. Results of that simulations are given from Figure 2-31 to Figure 2-36.

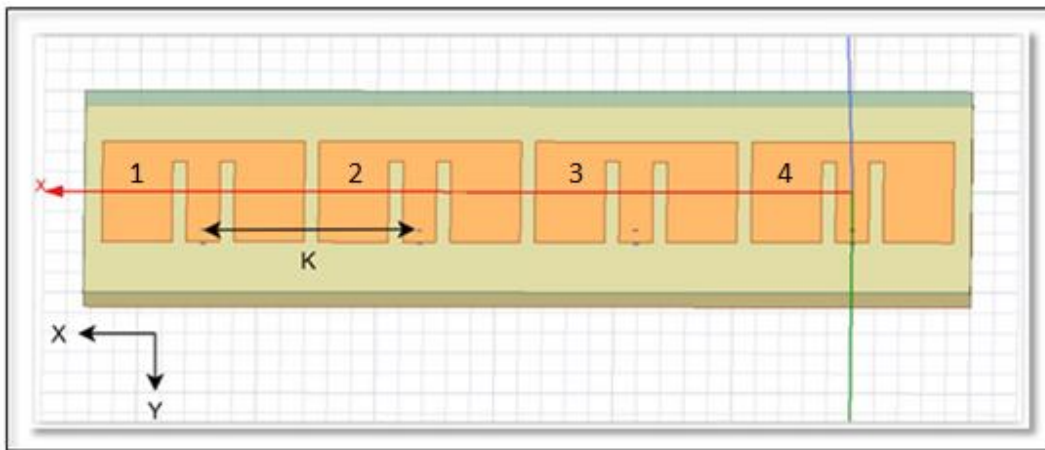


Figure 2-30 Geometry of four-element wideband E-Patch antenna (k represents element spacing in terms of wavelength,  $k=0.5\lambda$  in this geometry for showing purposes only, first element in the -x direction is denoted 11 in the S parameter result and the others denoted as 22, 33 and 44).

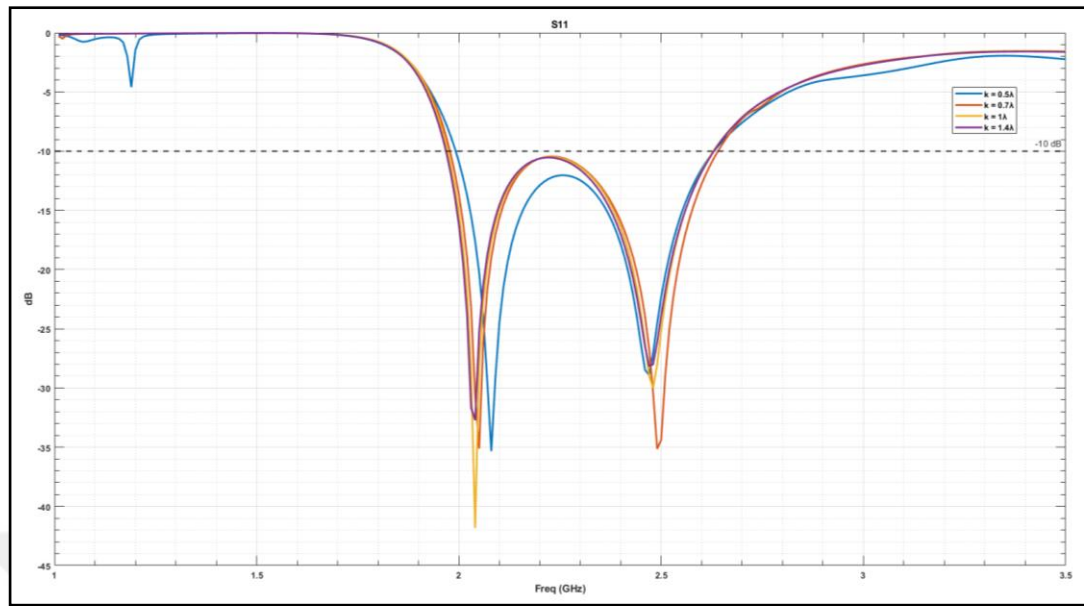


Figure 2-31  $S_{11}$  of the wideband four-element E-Patch antenna array (**Blue (k):  $0.5 \lambda$** , **Orange (k):  $0.7 \lambda$** , **Yellow (k):  $1 \lambda$** , **Purple (k):  $1.4 \lambda$** ).

As shown in Figure 2-32, when element spacing between the array elements increases,  $S_{13}$  values become better; this is expected because when elements are getting far, mutual coupling between elements also decreases.

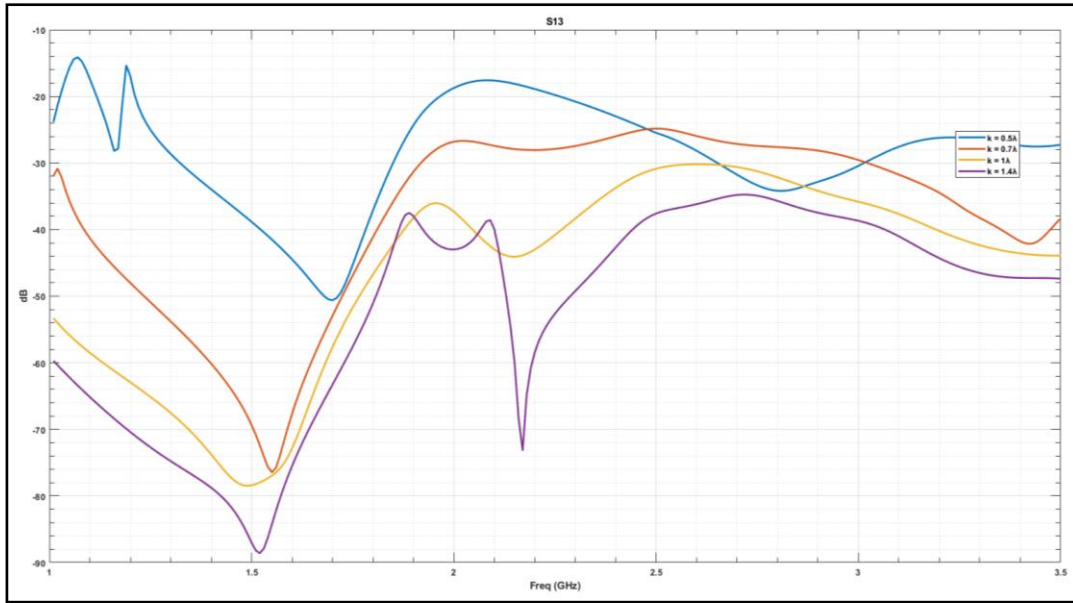


Figure 2-32  $S_{13}$  of the wideband four-element E-Patch antenna array (Blue ( $k$ ):  $0.5\lambda$ , Orange ( $k$ ):  $0.7\lambda$ , Yellow ( $k$ ):  $1\lambda$ , Purple ( $k$ ):  $1.4\lambda$ ).

Figure 2-33 is also appropriate because that when array elements are placed farther, 3 dB beamwidth and gain increase, but sidelobes occur, and sidelobes level increases. It can be verified with the far-field 2D azimuthal radiation pattern. Nothing is changed for the elevational radiation pattern give in Figure 2-34, and this is expected since no array elements are added on the y-axis. Far-field 3D radiation patterns for  $k = 0.5\lambda$  and  $1.4\lambda$  can be seen in Figure 2-35-Figure 2-36.

As discussed earlier, when element spacing increases, sidelobes start to appear. It is a trade-off that the radar designer should decide. If the sidelobe levels are critical for the system antenna, some techniques should be applied to decrease sidelobes. It is essential to state that if an array configuration is used on a TWR system as a transmitting or receiving sensor, main lobe beamforming by changing phase shift should be applied to radiate all objects inside the room. If the target room is small, main lobe beamwidth of the array antenna could be enough, but beamforming must be used for larger rooms, increasing the system's complexity. Also, with a stand-alone antenna configuration with large mainlobe beamwidth, the radar system can

only measure range due to the large resolution on the cross-range. An antenna array configuration with beamforming mechanism is needed to measure target location and range simultaneously on TWR systems.

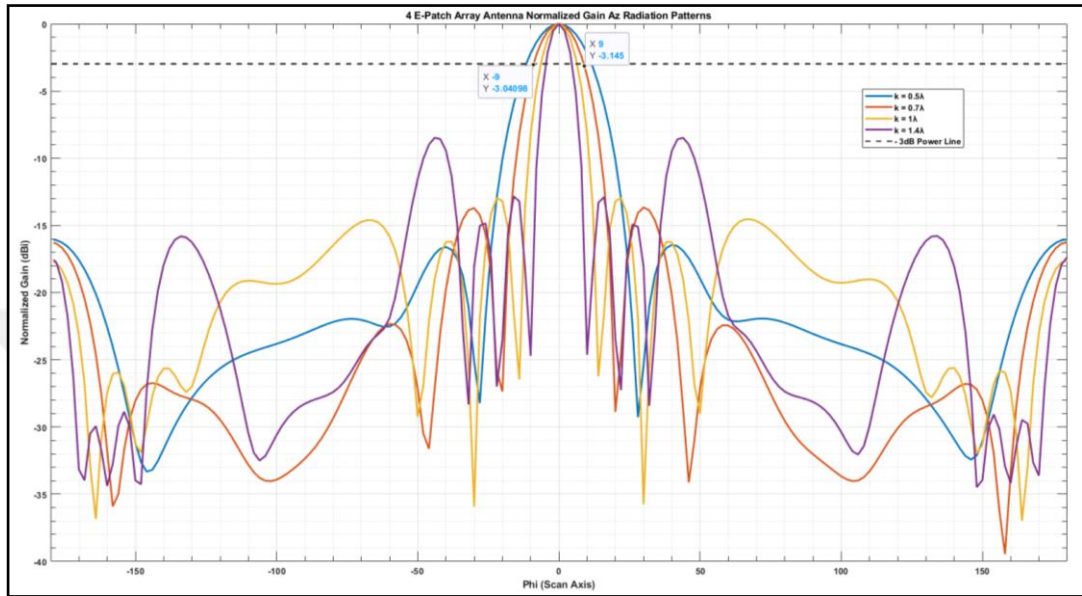


Figure 2-33 Azimuthal 2D radiation pattern of the wideband four-element E-Patch antenna array @  $f_c=2.31$  GHz (@  $\theta=0$  representing azimuthal (x-z axes) axes) (Blue (k):  $0.5\lambda$ , Orange (k):  $0.7\lambda$ , Yellow (k):  $1\lambda$ , Purple (k):  $1.4\lambda$ ).

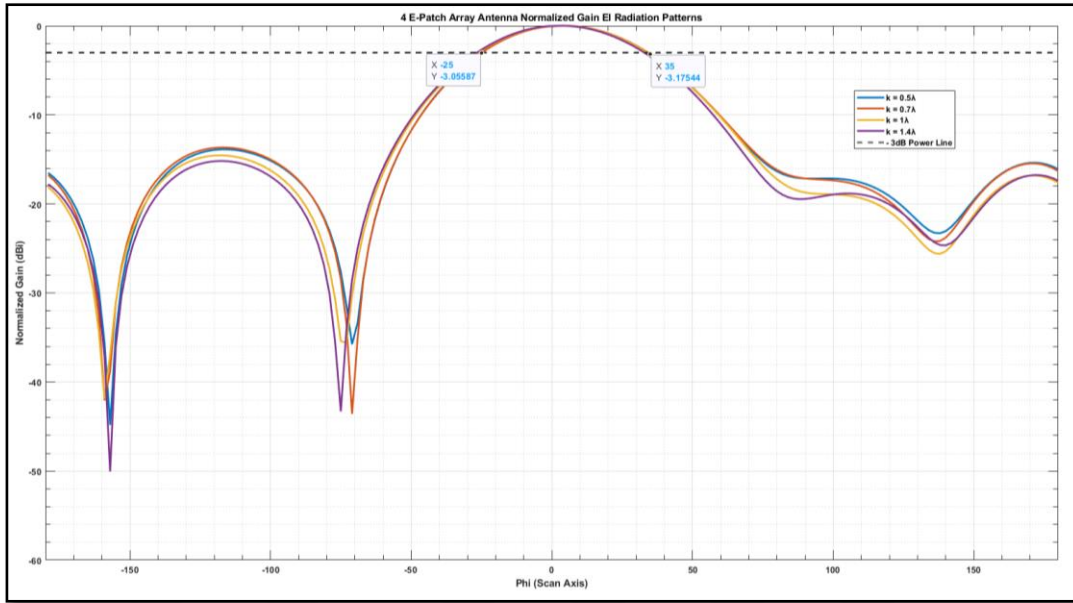


Figure 2-34 Elevation 2D radiation pattern of the wideband four-element E-Patch antenna array @  $f_c=2.31$  GHz (@  $\theta=90$  representing elevational (y-z axes) axes) (Blue (k):  $0.5\lambda$ , Orange (k):  $0.7\lambda$ , Yellow (k):  $1\lambda$ , Purple (k):  $1.4\lambda$ ).

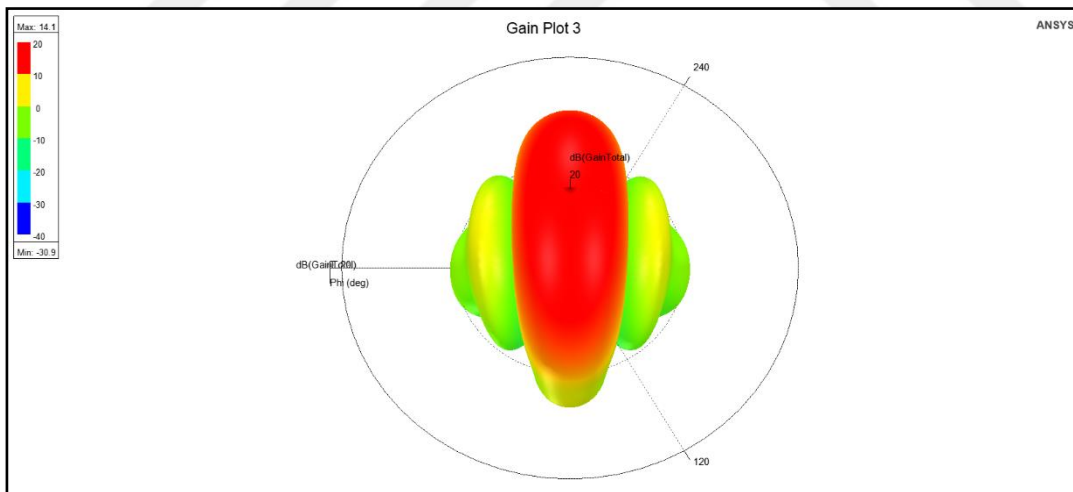


Figure 2-35 Far-field 3D polar plot of the wideband four-element E-Patch antenna array when  $k=0.5\lambda$  @  $f_c=2.31$  GHz (Max. Gain is seen as 14.1 dBi)

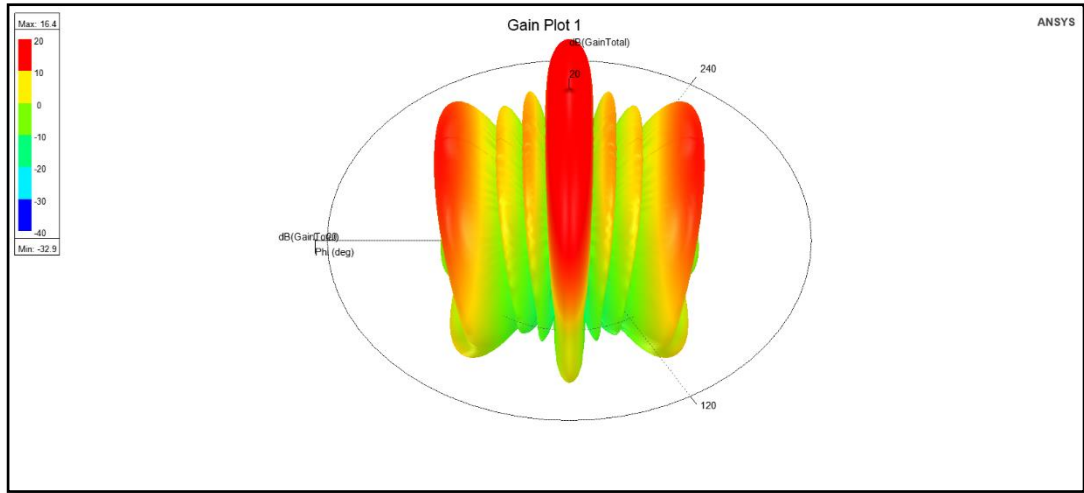


Figure 2-36 Far-field 3D polar plot of the wideband four-element E-Patch antenna array when  $k=1.5\lambda$  @  $f_c=2.31$  GHz (Max. Gain is seen as 16.4 dBi)

Table 2-18 Summary of the results of four-element E-Patch antenna array with element spacing value as  $k=0.7\lambda$

| Simulated Specs                       | Value           |
|---------------------------------------|-----------------|
| Frequency Range ( $S_{11} < -10$ dB)  | 1.97 – 2.63 GHz |
| Operating Bandwidth                   | 670 MHz (29%)   |
| Far-Field Peak Gain @ $f_c$           | 15 dBi          |
| First Sidelobe Level (FSL)            | ~ -14 dB        |
| Axial Ratio (> 3 dB = Linear)         | 50 dB           |
| Radiation Pattern                     | Sinc            |
| Azimuthal $3_{\text{dB}}$ Beamwidth   | $18^\circ$      |
| Elevational $3_{\text{dB}}$ Beamwidth | $58^\circ$      |
| Front to Back Ratio                   | ~ 16 dB         |

## 2.3 Conclusion

In chapter 2, a low-profile wideband printed antenna element is analyzed and designed. Optimal value and parametric E-patch antenna simulations are carried out to see the antenna design parameters' effect and find a design rule to work with TWR systems. In E-patch antenna design, it is learned that two slots and overall patch create two different resonance characteristics, so to have a wideband behavior, designer should optimize antenna slots parameters to close resonance frequencies to each other.

Then, E-patch antennas are designed with the parameters that are found on optimal value simulations. Results and radiation theory of the antenna are investigated in given figures and tables. E- patch antenna is also realized on array configuration with four elements. The array antennas are simulated and compared with stand-alone configuration. In the end, the E-patch antenna with its free-space results seems appropriate to use on a TWR system. In Chapter 3, the antenna with different wall mediums is simulated to see the effect of walls on the antenna.

## CHAPTER 3

### ANTENNA PLACED BEHIND WITH THE WALLS - SIMULATION RESULTS

In this chapter, after the wideband E-patch antenna with a single element and array configurations is designed and analyzed. The simulations are carried out for the most commonly used wall materials to see their effect on the antenna return loss or radiation patterns. It is essential because these antennas will be used on a TWR system that operates very close to the target room walls. Researchers reported that the room's temperature makes the antenna operate different from the free-space conditions with heterogeneous characteristics and different permittivity and loss values that change due to moisture. Researchers reported that the wall medium has heterogeneous characteristics and different permittivity and loss values. [29]-[30]. Three different wall materials with dielectric constant and loss tangent values taken from Figure 1-6 are created and simulated on an HFSS EM solver to test the concept. The complexity of the materials and the electrically large sizes make simulation times longer than expected. Used wall materials with their electrical parameters and sizes on simulations are given in Table 3-1.

Table 3-1 Electrical parameters and sizes of the walls used in the simulations.

| Wall Material  | Size<br>(L × W × H in cm)<br>(X × Y × Z axis) | $\epsilon_r$ | $\tan(\delta)$ |
|----------------|-----------------------------------------------|--------------|----------------|
| Plywood Wall-1 | 100 × 100 × 1.3                               | 2            | 0.05           |
| Plywood Wall-2 | 100 × 100 × 1.3                               | 2            | 0.2            |
| Brick Wall     | 100 × 100 × 8.89                              | 5            | 0.1            |
| Solid Concrete | 100 × 100 × 13                                | 8            | 0.2            |

### 3.1 Single-Element E-Patch Antenna Behind a Wall Simulation Results

E-Patch antenna designed and finalized in chapter 2 is simulated with different wall materials given in Table 3-2. To analyze the effect of distance from antenna to wall material, a wall offset variable is used in the simulations. Plywood, brick, and concrete wall results are shown one by one in this section.

#### 3.1.1 Plywood Wall Simulation Results

The simulated geometry of the plywood wall and antenna is given in Figure 3-1. Wall is placed in front of the antenna centered in the middle of the geometry. The antenna return loss and radiation patterns are shown from Figure 3-2 to Figure 3-6.

Table 3-2 Wall offset variable to see the effect of wall distance on the antenna.

| Swept Parameter      | From: | To:    | Steps: |
|----------------------|-------|--------|--------|
| Wall-Offset @ Z axis | 10 cm | 100 cm | 10 cm  |

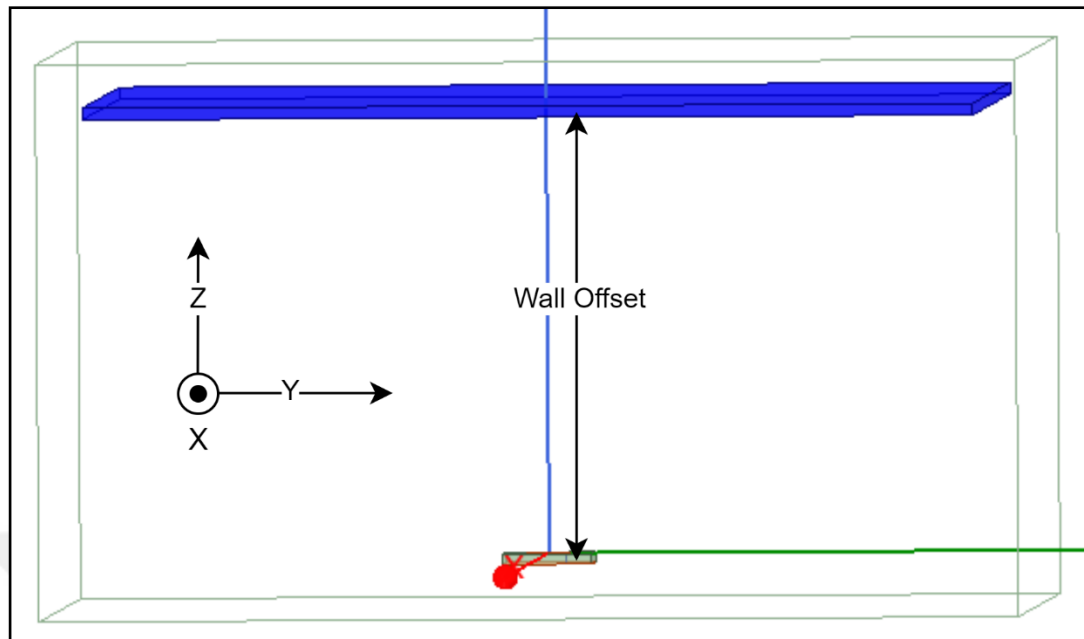


Figure 3-1 Geometry of plywood wall-1 and antenna with wall offset variable (In this figure, wall offset is 100 cm).

As seen from Figure 3-2, antenna input return loss is affected by the wall in front of it, but this effect is limited for a wall offset value larger than 10 cm. If the wall is too close to the antenna, detuning of the antenna  $S_{11}$  starts but in other distances antenna operates like it is in free-space conditions.

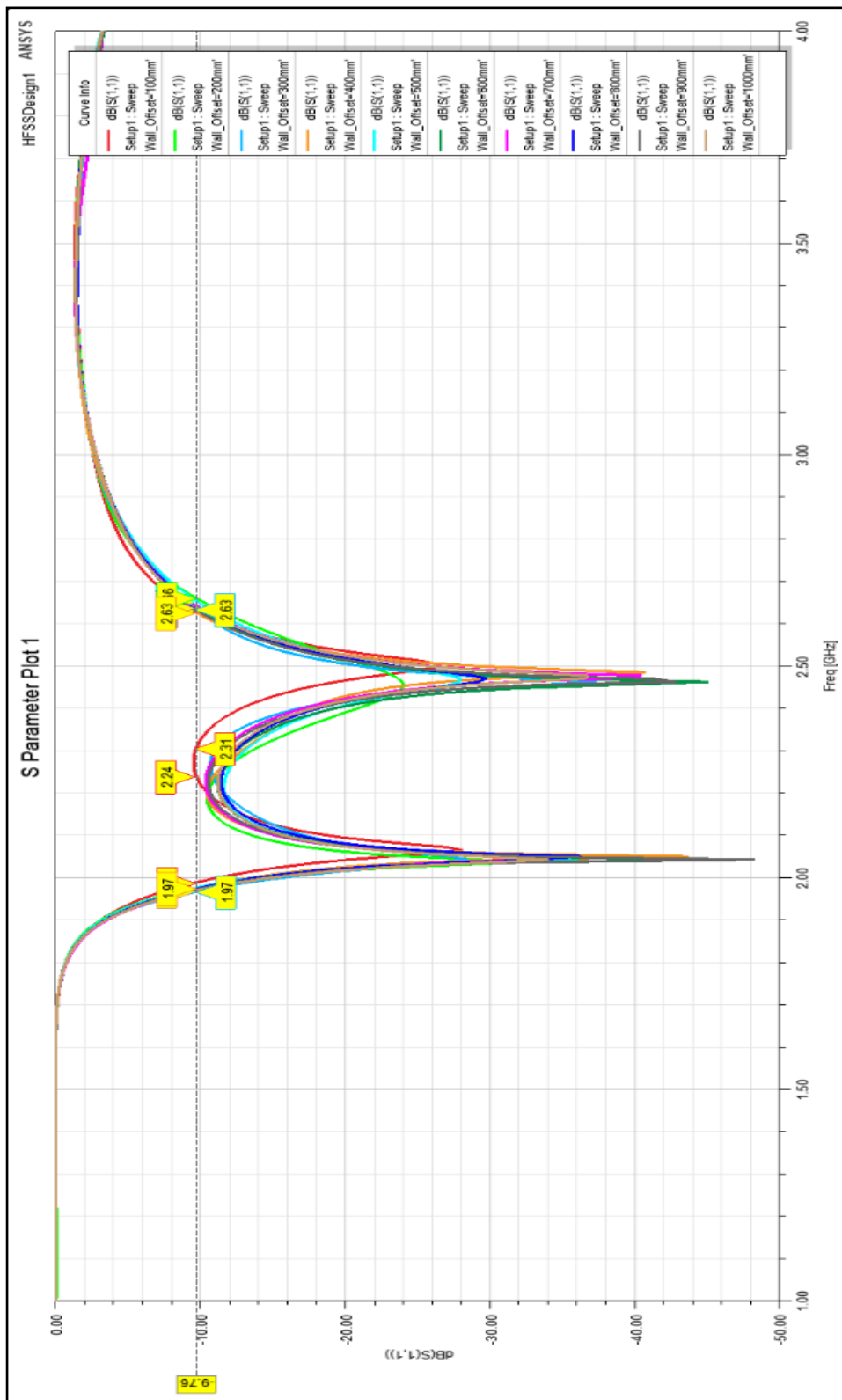


Figure 3-2  $S_{11}$  of the wideband E-Patch antenna with plywood wall-1 added.

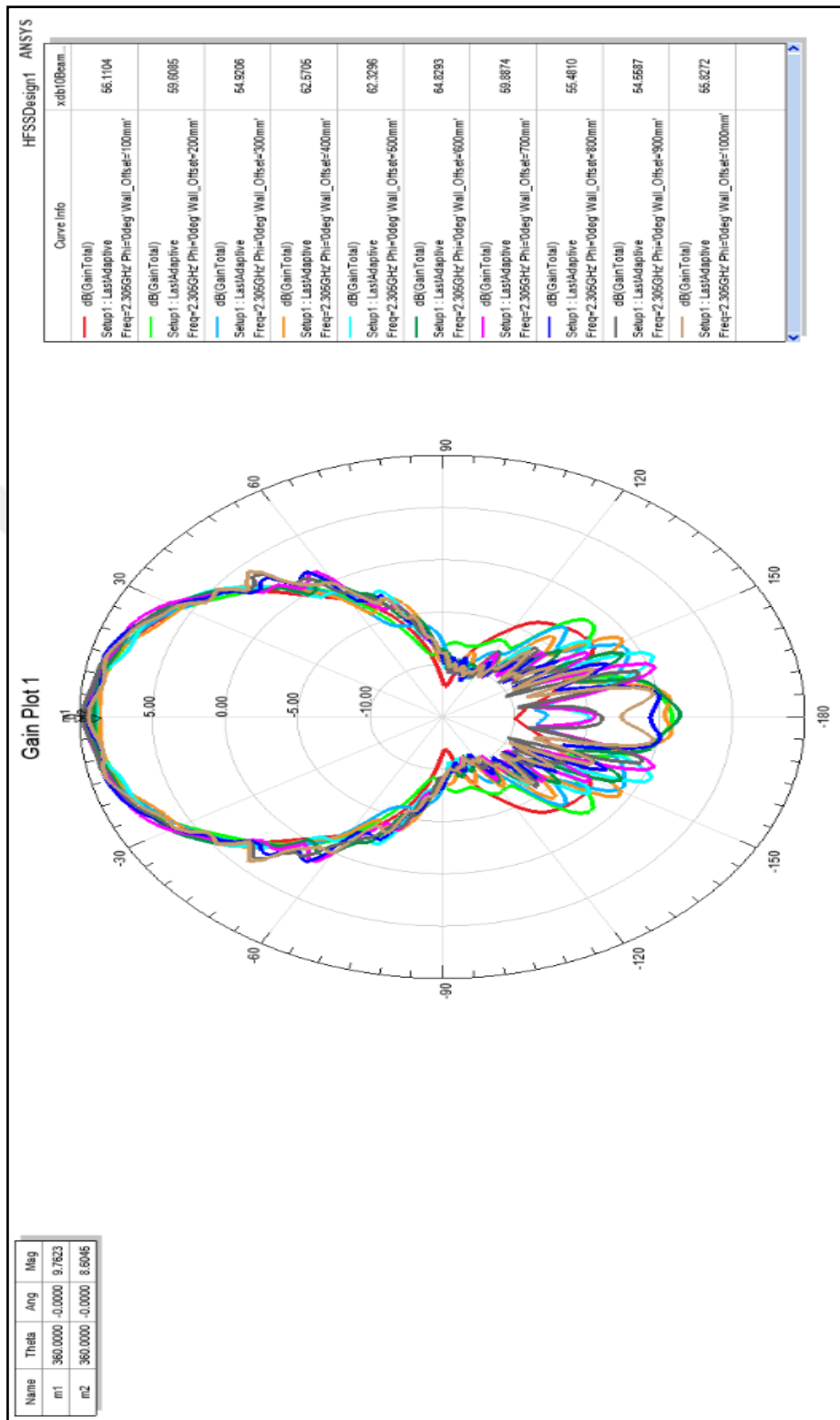


Figure 3-3 Far-field 2D azimuthal (x-z plane) radiation pattern of the wideband E-Patch antenna with plywood wall-1 added @  $f_c = 2.31$  GHz.

In Figure 2-20, it is observed that 2D radiation pattern in free space, plywood wall is not critically affecting the azimuthal radiation pattern of the antenna. Only for the wall-offset value of 10 cm, boresight gain is reduced from 9.6 dBi to 8.6 dBi, and also, the back lobe of the antenna is changed substantially due to the multipath effect of the wall.

In Figure 3-3, it is the same case with the azimuthal radiation pattern that plywood wall did not affect the pattern shape and boresight gain values considerably. In Figure 3-5 and Figure 3-6, the far-field 3D radiation pattern of the antenna with wall materials can also be seen.



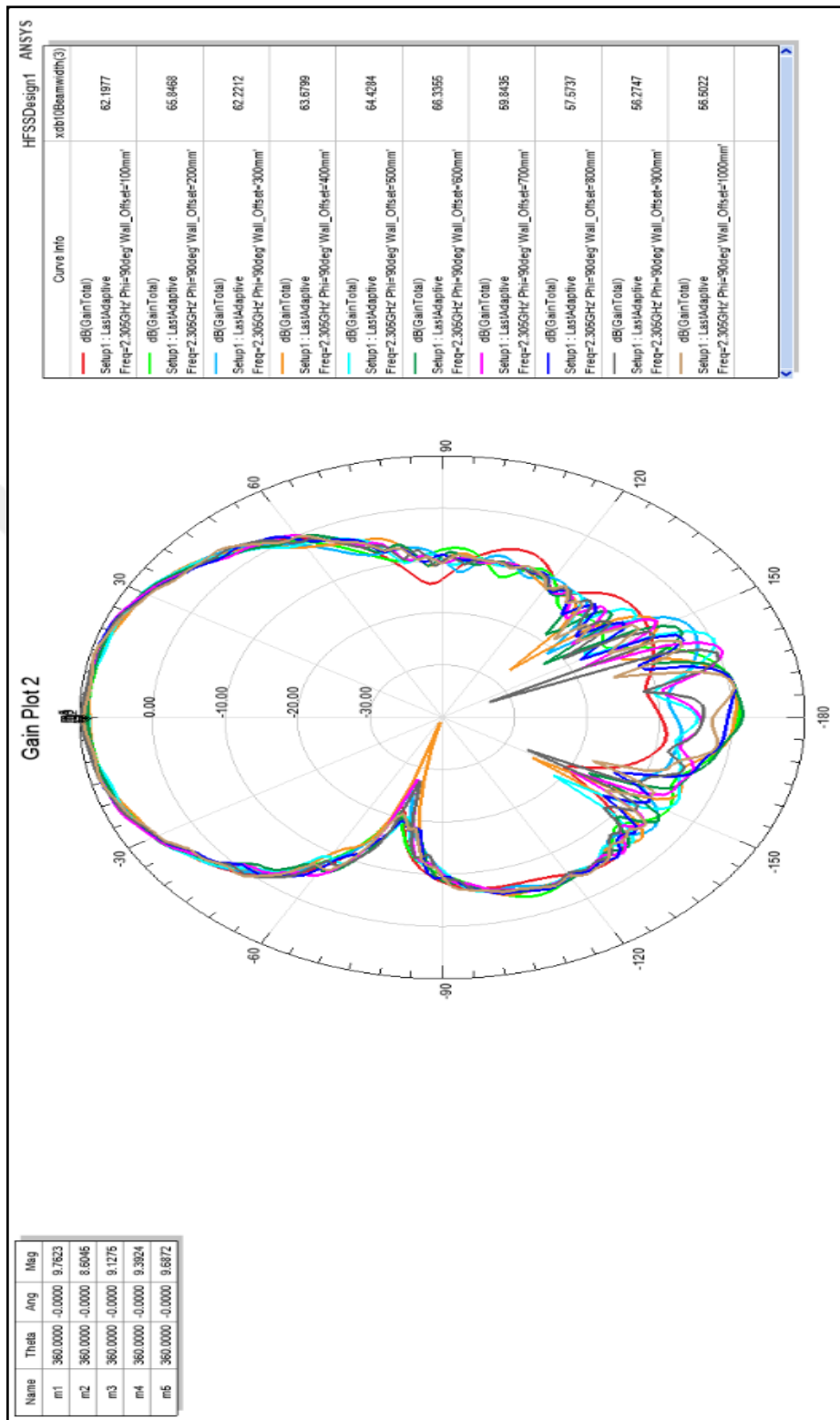


Figure 3-4 Far-field 2D elevational (y-z axes) radiation pattern of the wideband E-Patch antenna with plywood wall-1 added @  $f_c=2.31$  GHz.

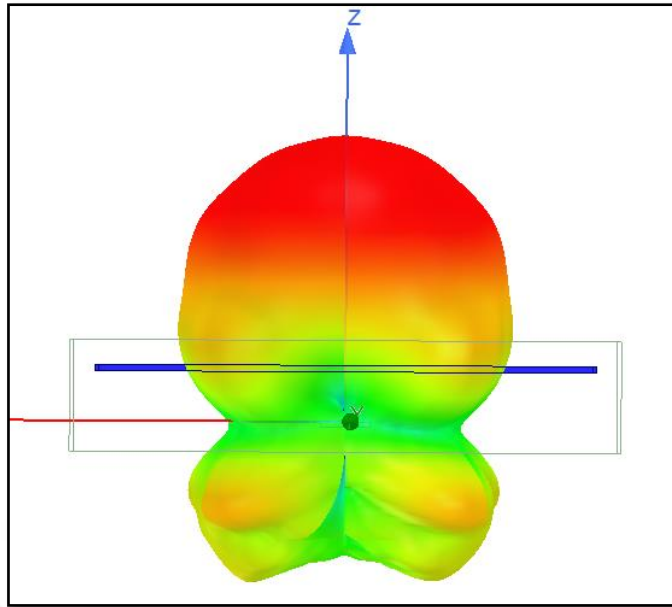


Figure 3-5 Far-field 3D polar plot of the wideband E-Patch antenna with plywood wall-1 added when wall-offset=10 cm @  $f_c=2.31$  GHz.

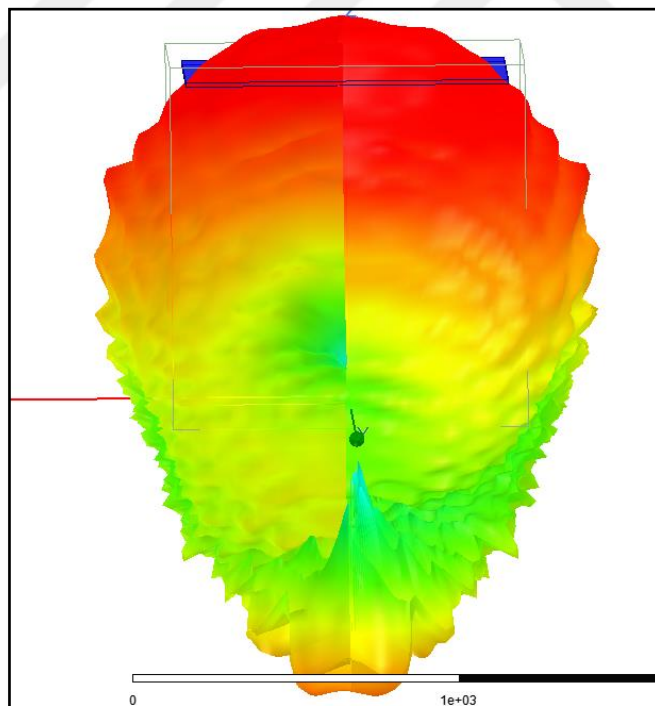


Figure 3-6 Far-field 3D polar plot of the wideband E-Patch antenna with plywood wall-1 added when wall-offset=100 cm @  $f_c=2.31$  GHz.

### 3.1.2 Brick Wall Simulation Results

The simulated geometry of the brick wall and the antenna is given in Figure 3-7. Results of the antenna return loss and radiation patterns are shown from Figure 3-8 to Figure 3-12.

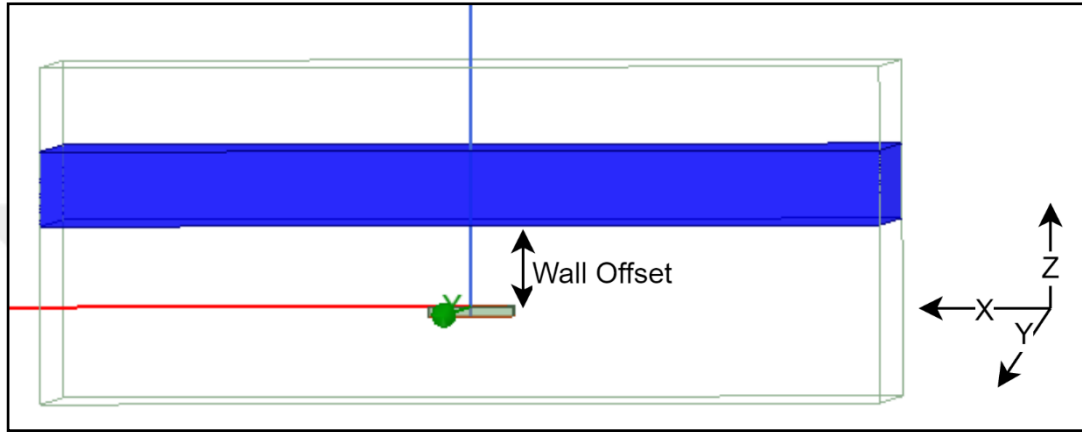


Figure 3-7 Geometry of brick wall and antenna (In this figure, wall offset is 10cm).

In Figure 3-8, it is seen that brick wall affected free-space input return loss more than plywood wall, especially for wall offset value 10 cm. In that distance,  $S_{11}$  values of the resonance frequencies increased, and broadband characteristics suffered. For other wall distances, even  $S_{11}$  is affected; they are still below -10 dB. Effect of the brick wall is stronger than plywood wall that is expected due to more significant dielectric constant value ( $\epsilon_r$ ), makes the brick wall more reflective than the plywood wall, and detuning input matching of the antenna. However, the wall is separated from the antenna; this reflection effect decreases, and return loss would not change more than free-space values.

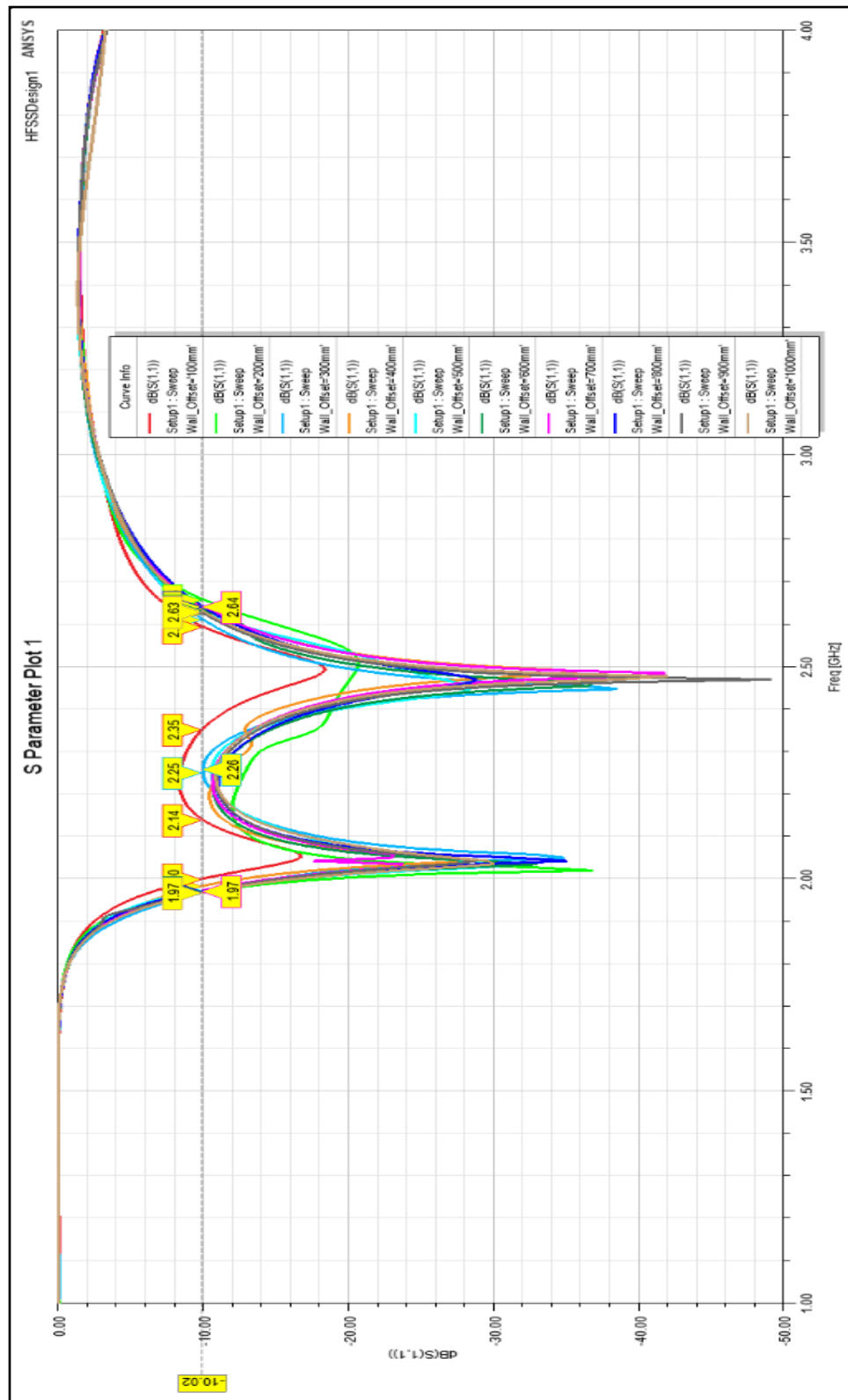


Figure 3-8  $S_{11}$  of the wideband E-Patch antenna with brick wall added.

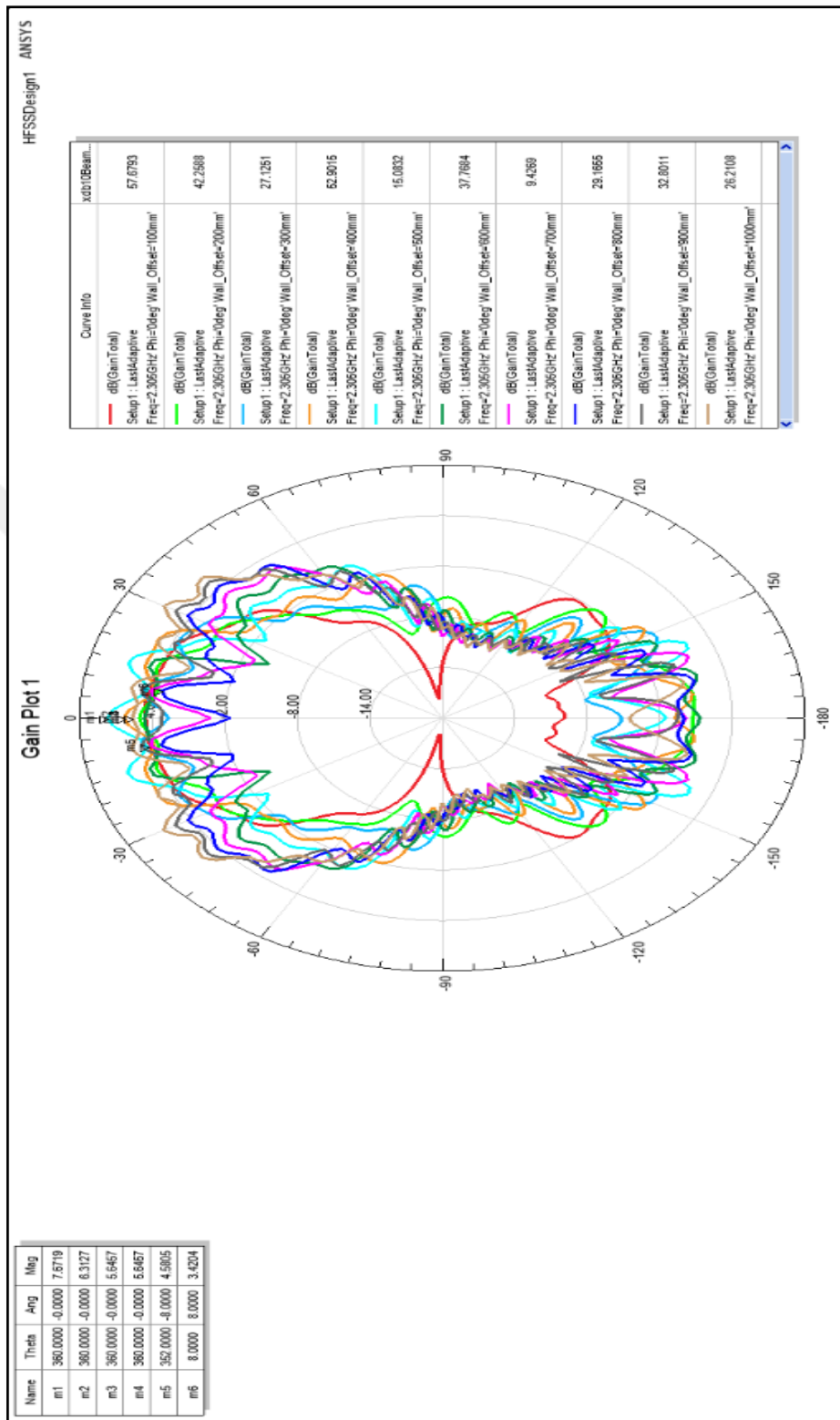


Figure 3-9 Far-field 2D azimuthal (x-z plane) radiation pattern of the wideband E-Patch antenna with brick wall added @  $f_c=2.31$  GHz.

Another observation that the 2D azimuthal radiation pattern is affected massively by the brick wall with a larger dielectric constant ( $\epsilon_r$ ) and loss tangent ( $\delta$ ) values than the plywood counterpart. In Figure 2-20, even hemispherical pattern shape is protected, due to occurrence of sidelobes, 3dB beamwidth values are decreased from  $60^\circ$  to  $9^\circ$  for some distance values. Boresight gain values are also decreased from 9.6 dBi to 3.4 dBi for a wall distance value of 80 cm. It is also expected since with larger loss tangent values than plywood and air; the brick wall starts to attenuate propagated wave as theory stated. Some transmitted wave power is lost on the brick wall and reflected less to the antenna feed. Antenna back lobe values are also different than free-space results.

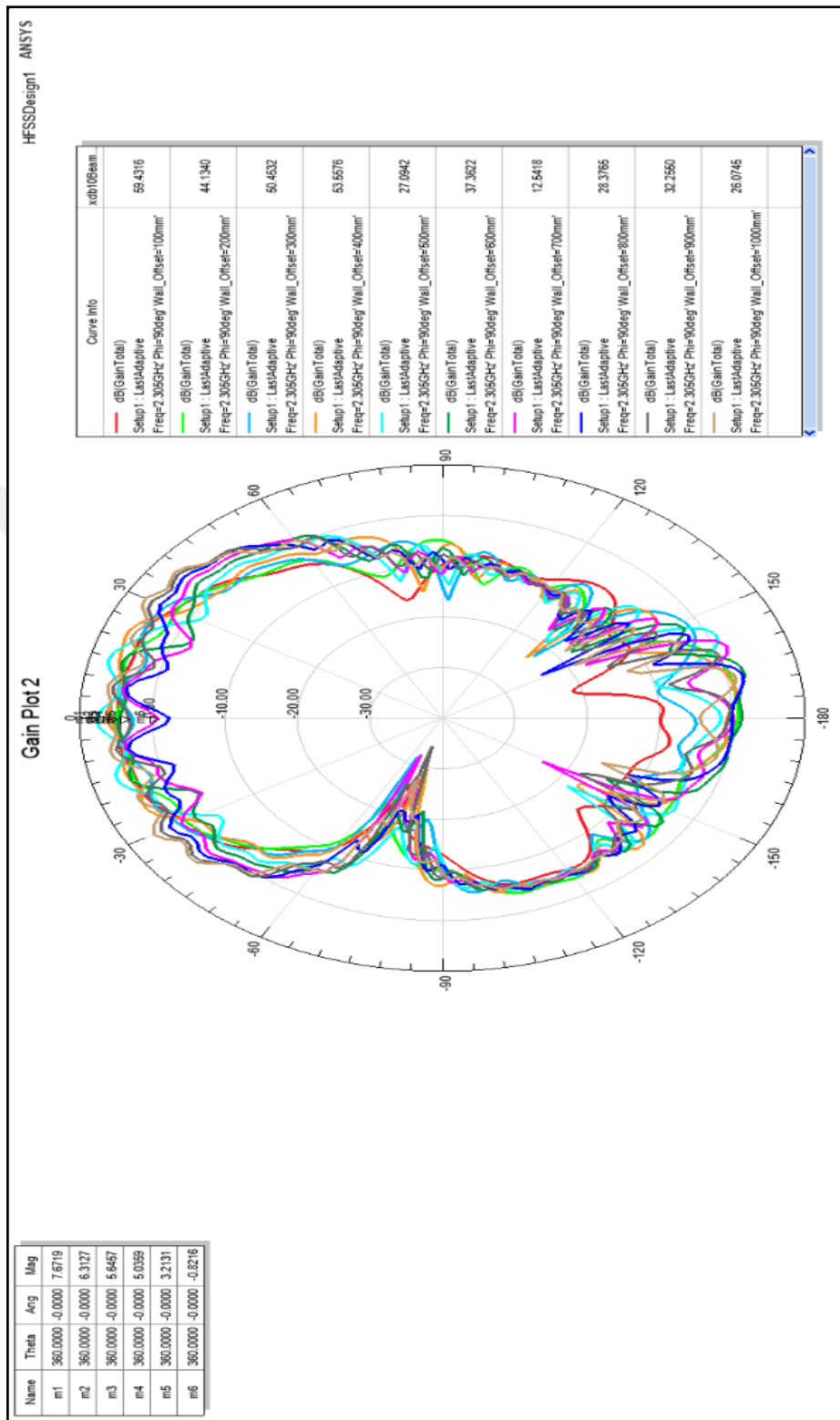


Figure 3-10 Far-field 2D elevational (y-z plane) radiation pattern of the wideband E-Patch antenna with brick wall added @  $f_c=2.31$  GHz.

As expected from the azimuthal radiation pattern results, elevational ones seen from Figure 3-10 are also considerably affected hugely by the brick wall medium. It is not a surprise due to the larger dielectric constant ( $\epsilon_r$ ) and loss of tangent ( $\delta$ ) values of the brick wall.

From Figure 3-11 and Figure 3-12, the far-field 3D radiation pattern of the antenna with brick wall material with 10 cm and 100 cm distances can also be seen. Compared to the plywood wall results, more sidelobes occur, and the far-field radiation pattern is more affected in brick wall setups. As seen from Figure 3-12, because of high reflective wall barrier, multiple reflections create ripples on the radiation pattern of the antenna.

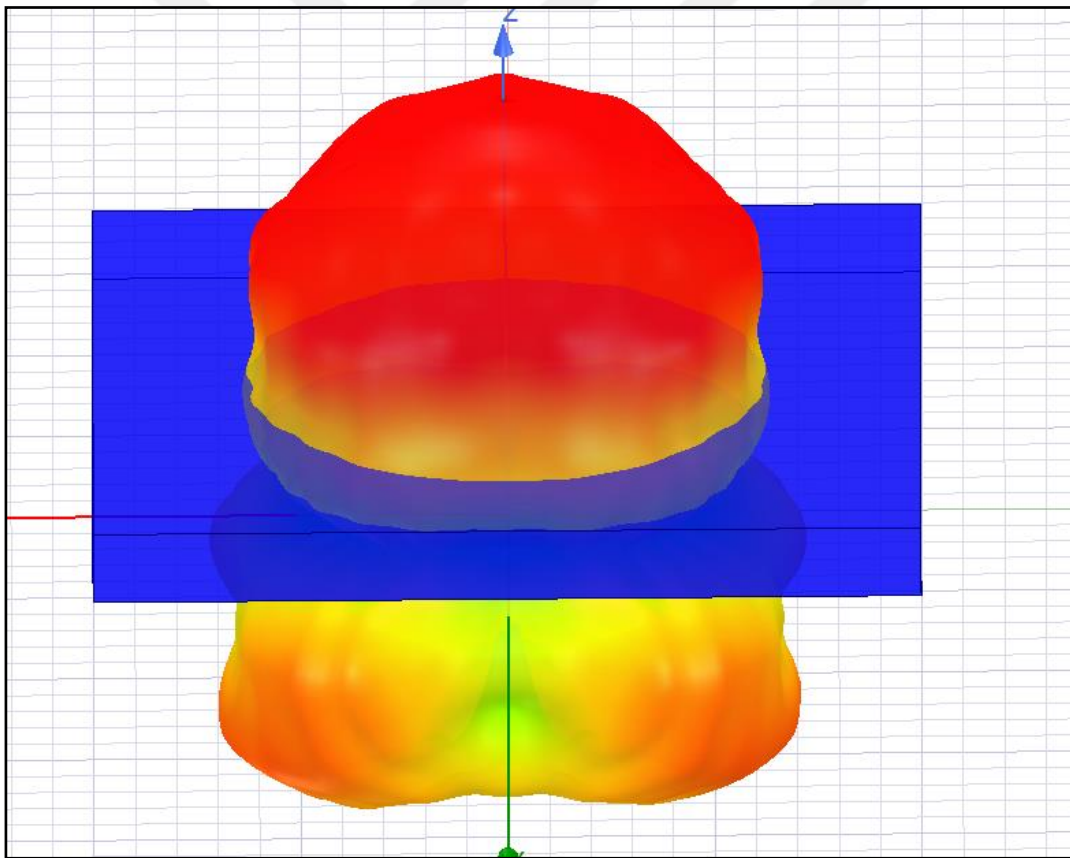


Figure 3-11 Far-field 3D polar plot of the wideband E-Patch antenna with brick wall added when wall-offset=10 cm @  $f_c=2.31$  GHz.

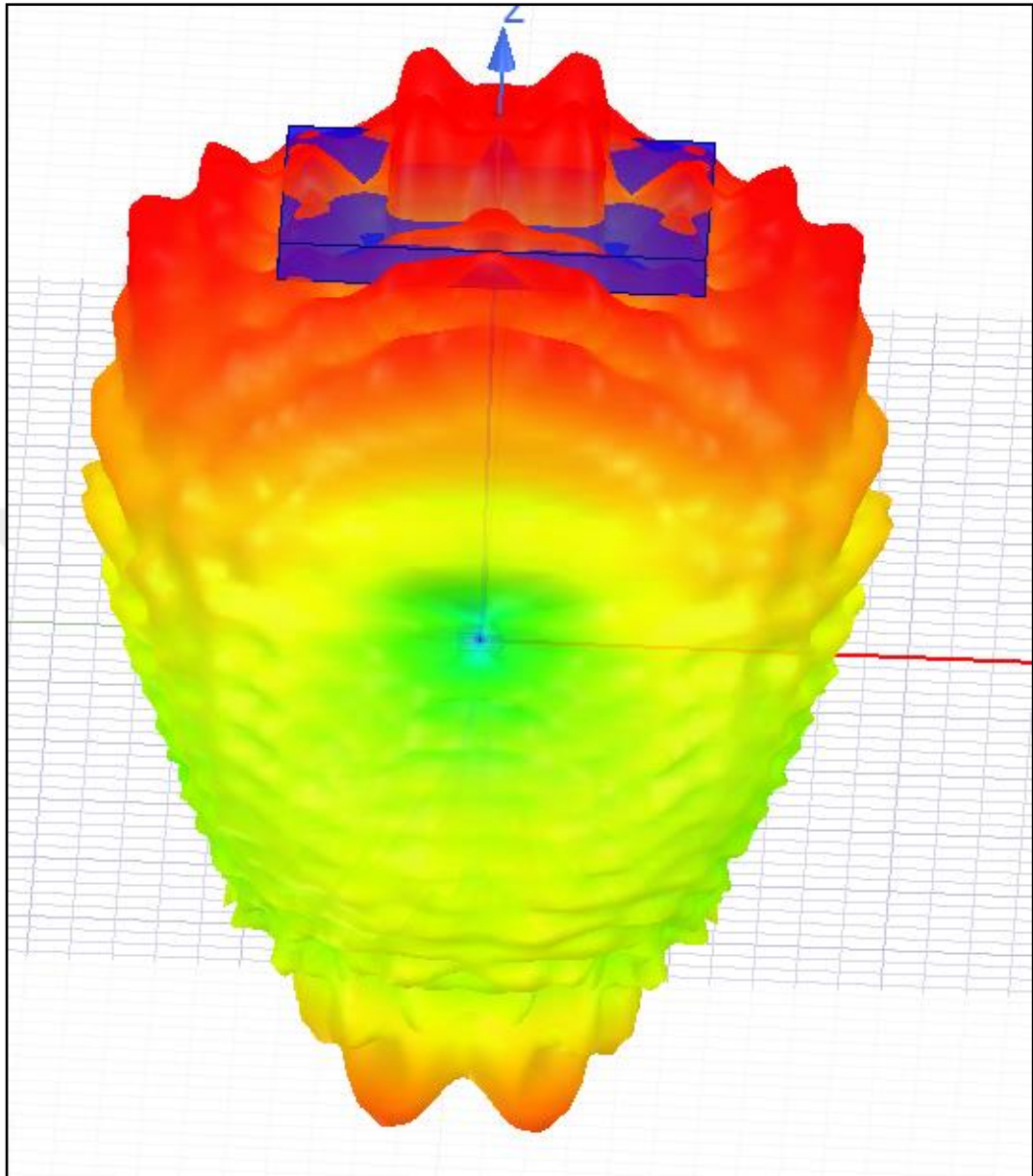


Figure 3-12 Far-field 3D polar plot of the wideband E-Patch antenna with brick wall added when wall-offset=100 cm @  $f_c=2.31$  GHz.

### 3.1.3 Concrete Wall Simulation Results

The simulated geometry of the concrete wall and antenna is given in Figure 3-13. The antenna return loss and radiation patterns are shown from Figure 3-14 to Figure 3-18.

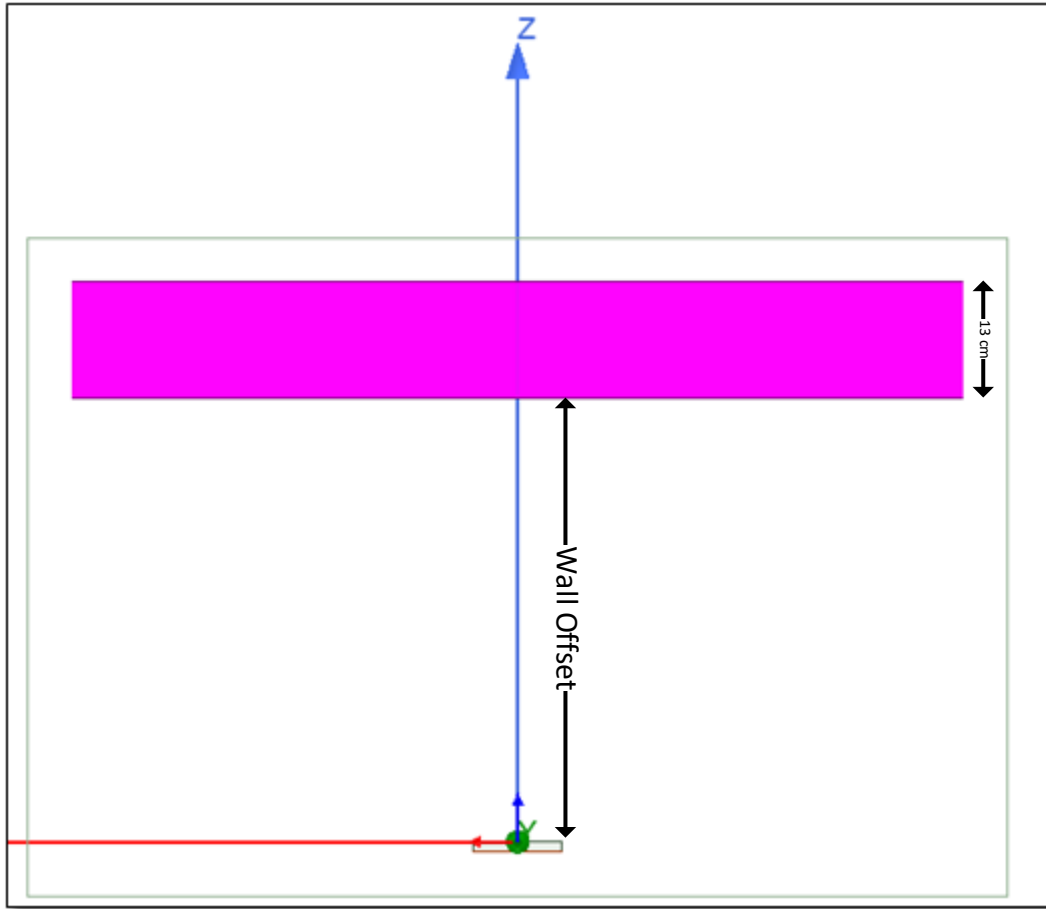


Figure 3-13 Geometry of concrete wall and antenna (The figure wall offset is 100 cm).

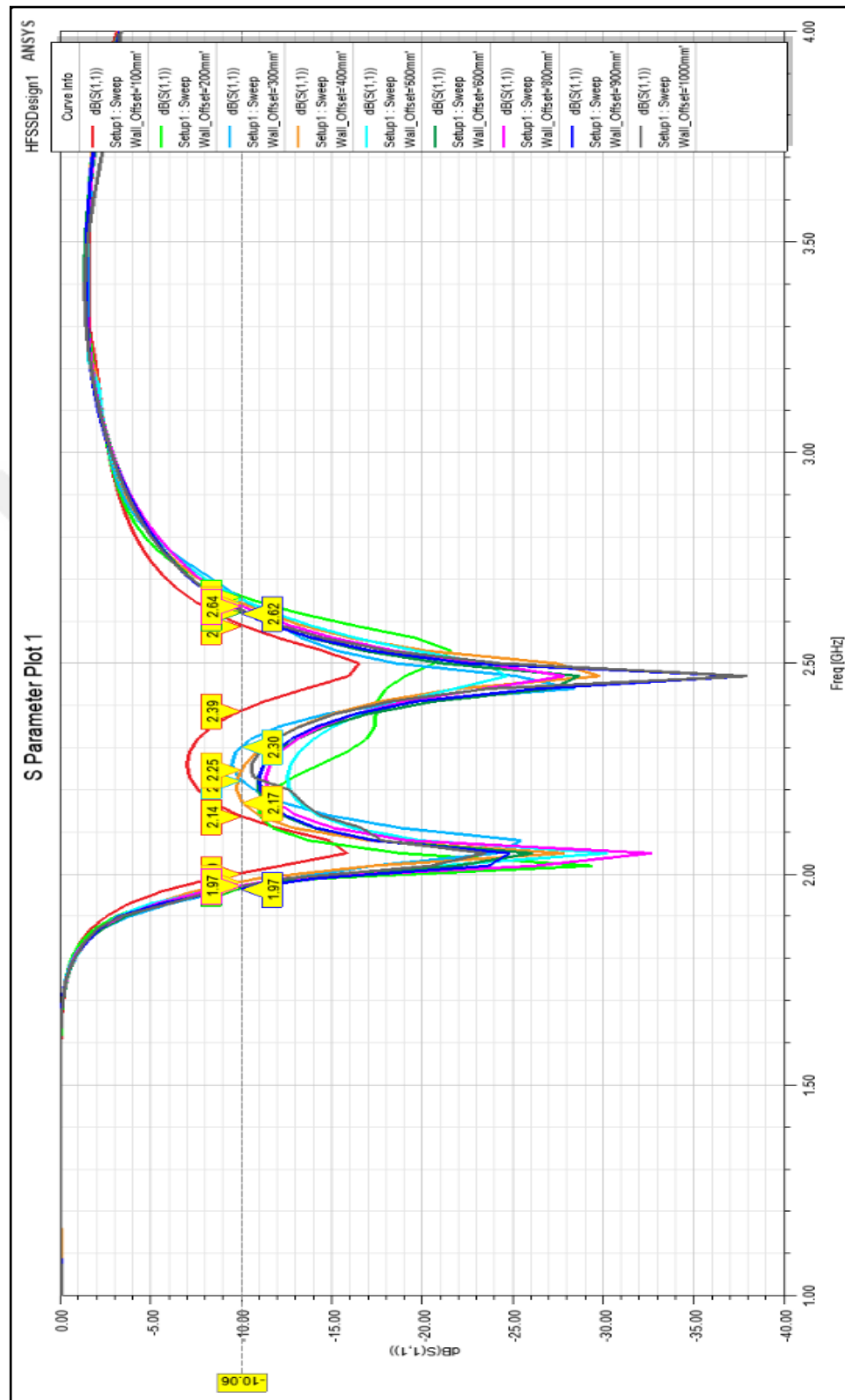


Figure 3-14  $S_{11}$  of the wideband E-Patch antenna with concrete wall added.

As seen in Figure 3-14, concrete wall affected antenna input return loss, especially for 10 cm wall distance more than plywood and brick walls as expected with the larger dielectric constant value ( $\epsilon_r$ ). When the dielectric constant value increases, the wall's reflectivity also increases and detunes more antenna input return value. It is a phenomenon that TWR designers should care about if the system is working too close to the wall; antenna characteristics could change so, the designed wideband antenna should be tested with different wall materials and with different air conditions to guarantee the operation of the antenna.



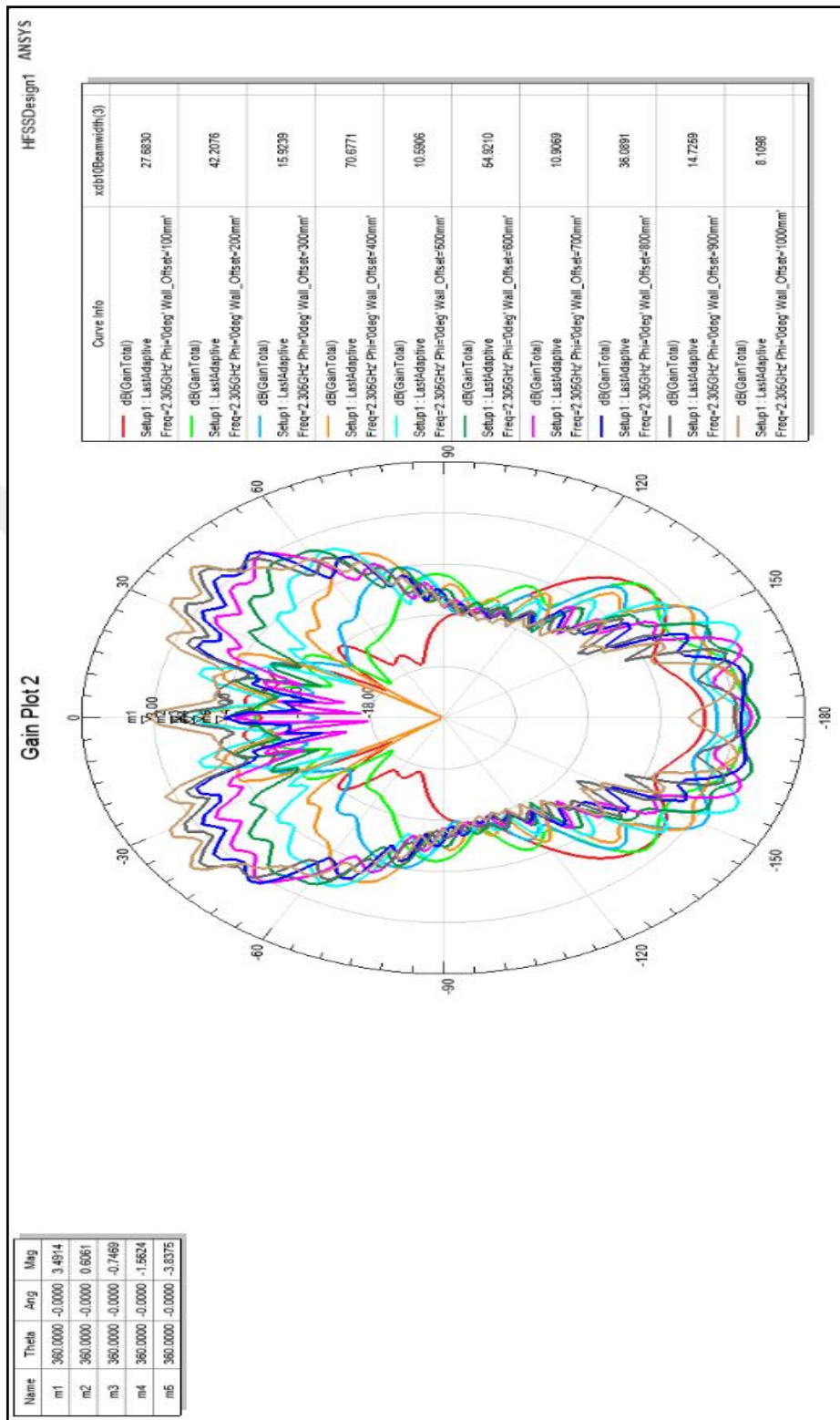


Figure 3-15 Far-field 2D azimuthal (x-z plane) radiation pattern of the wideband E-Patch antenna with concrete wall added @  $f_c=2.31$  GHz.

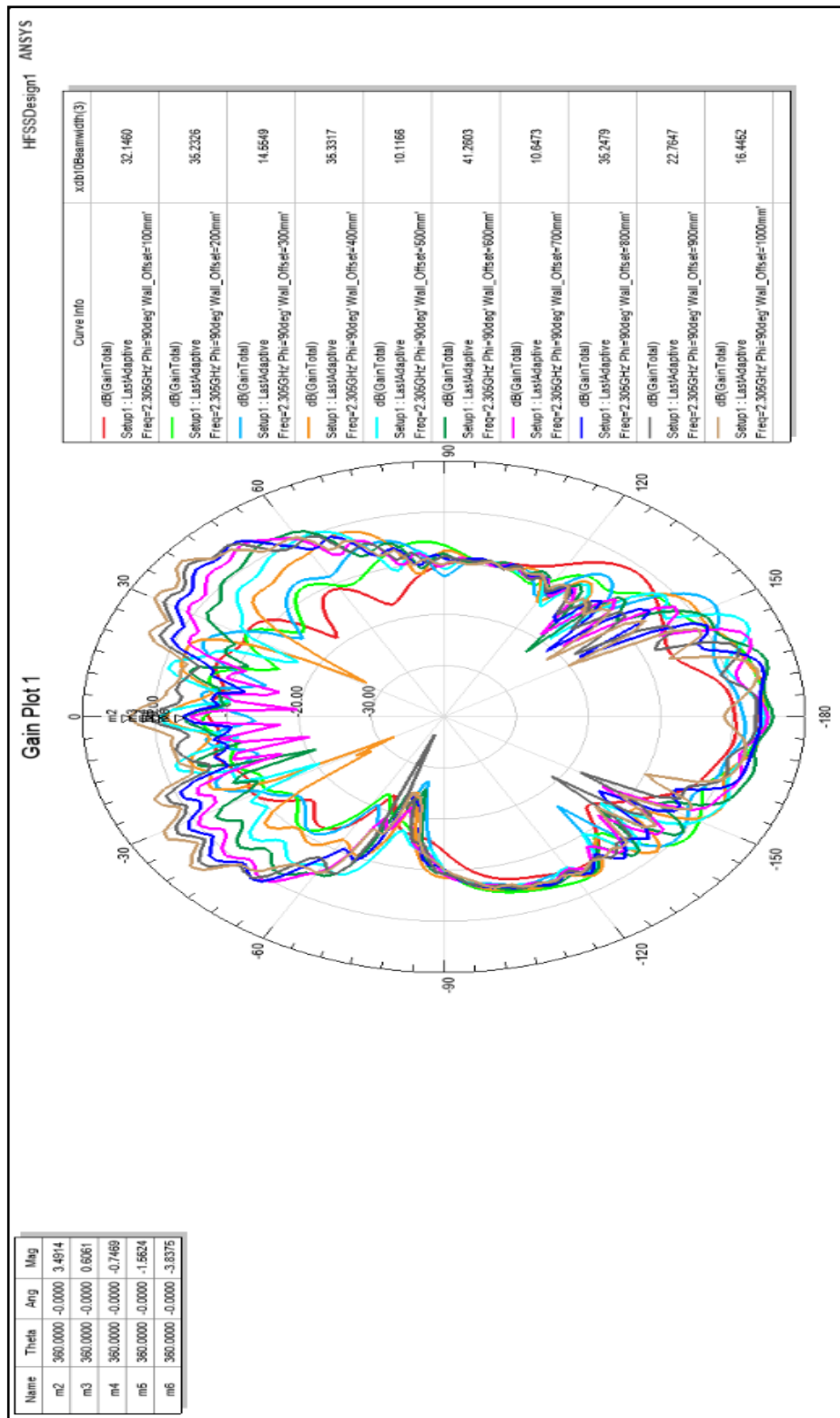


Figure 3-16 Far-field 2D elevational (y-z plane) radiation pattern of the wideband E-Patch antenna with concrete wall added @  $f_c=2.31$  GHz.

The concrete wall results are very different from free-space radiation patterns as it can be seen in Figure 2-20. The hemispherical radiation pattern that the free-space antenna has is spoiled with creating bigger sidelobes than the main lobe. Later gain values were decreased from 9.6 dBi to 0 dBi and even -3 dBi for a wall distance of 10 cm. It is also observed that boresight gain values increase when the antenna gets farther than the concrete wall but nowhere near the free-space result. It should be noted that with concrete wall setup antenna is detuned more than the other two wall materials. At a wall distance of 10 cm, the antenna is not operating as it should be in free space, so the TWR designer should ensure that different antenna topologies are applied in concrete wall mediums. 3D antenna radiation patterns with the concrete wall for wall offset values 10 cm and 100 cm are given in Figure 3-17 and Figure 3-18. As seen in the Figure 3-17 and 3-18, massive reflectivity happens, and propagated waves are mainly reflected when the concrete wall is too close to the antenna. That is also decreasing antenna  $S_{11}$  as we expected. For wall offset value 100 cm, reflection is less than the first case, but gain still less than free-space gain, and 3dB beamwidths are destroyed with formed sidelobes. The results are consistent with the TWR theory that concrete and brick wall materials with large dielectric constants create huge reflectivity and detune the antenna parameters. That theory is verified with the given simulation results.

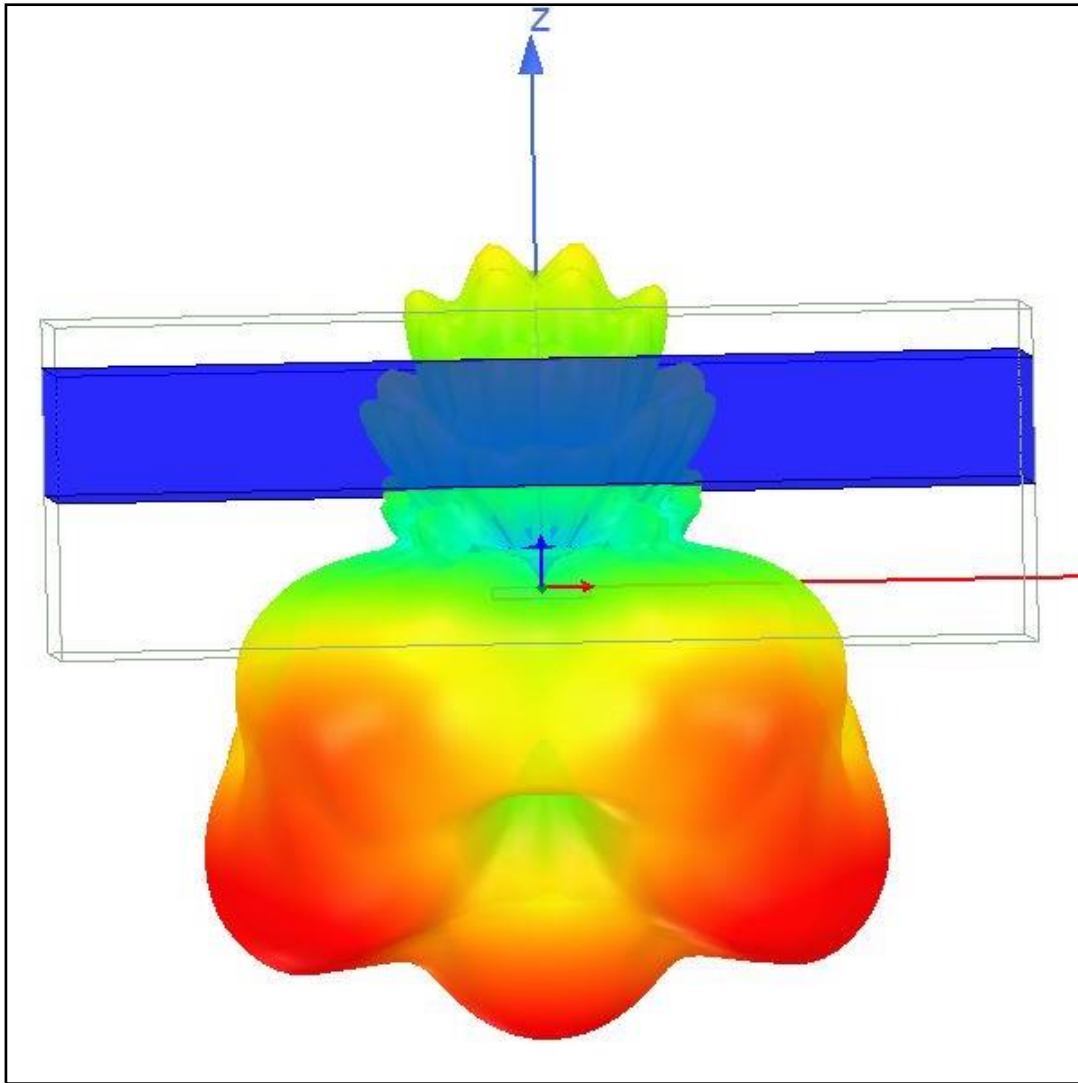


Figure 3-17 Far-field 3D polar plot of the wideband E-Patch antenna with concrete wall added when wall-offset=10 cm @  $f_c=2.31$  GHz.

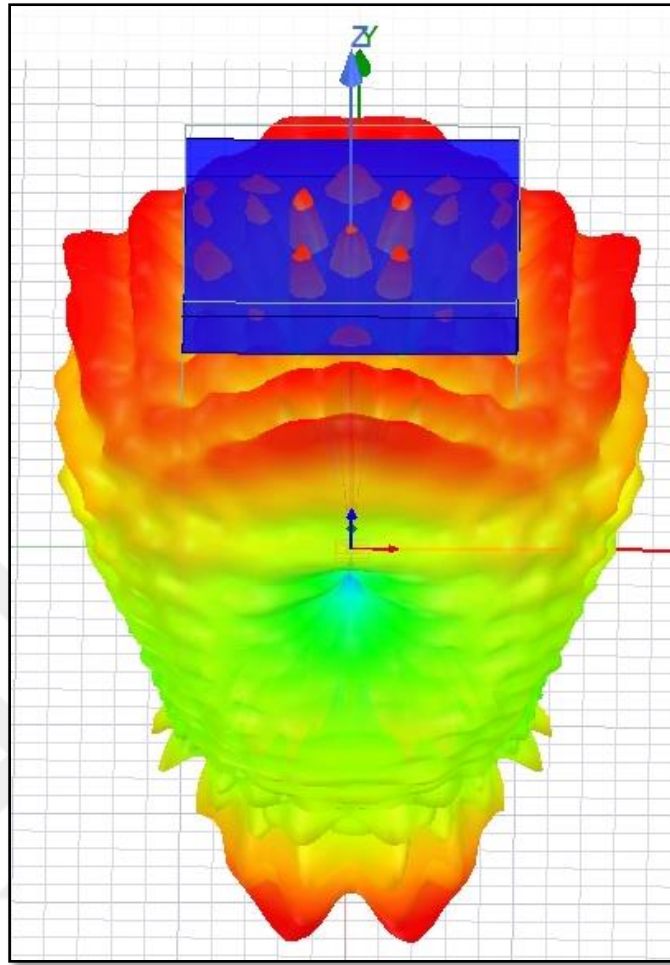


Figure 3-18 Far-field 3D polar plot of the wideband E-Patch antenna with concrete wall added when wall-offset=100 cm @  $f_c=2.31$  GHz

### 3.2 Four-Element E-Patch Antenna Array Behind a Wall Simulation Results

After simulation of single-element E-patch antenna with different walls was completed, it is observed that the radiation pattern is spoiled with sidelobes reducing boresight gain values, especially for brick and concrete type wall materials. The four-element E-Patch antenna array discussed in chapter 2 is simulated only with plywood and concrete wall materials to eliminate this effect. In comparison, the four-element array is simulated with plywood wall-2 and solid concrete wall. Their electrical parameters are given in Table 3-1. For four-element array antenna simulations,

plywood wall-2 is used instead of plywood wall-1. The only difference between the two wall types is that wall-2 has a more extensive loss than wall-1 due to a larger loss tangent value.

A four-element E-Patch antenna array with element spacing value  $k=1\lambda$  that is designed and finalized in section 2.2.1 is simulated with concrete and plywood wall-2 materials with their electrical parameters given in Table 3-1. To analyze the effect of the wall distance on the antenna, a wall offset variable is used on the simulations. However, for four-element antenna array results, the wall offset parameter is only 10 cm, 50 cm, and 100 cm to decrease simulation times.

### 3.2.1 Plywood Wall Simulation Results

Simulated geometry of plywood wall-2 and four-element antenna array is given in Figure 3-19. The antenna return loss and radiation patterns are shown from Figure 3-20 to Figure 3-24.

Table 3-3 Wall offset variable for four-element antenna array simulations.

| Swept Parameter      | 1.    | 2.    | 3.     |
|----------------------|-------|-------|--------|
| Wall-Offset @ Z axis | 10 cm | 50 cm | 100 cm |

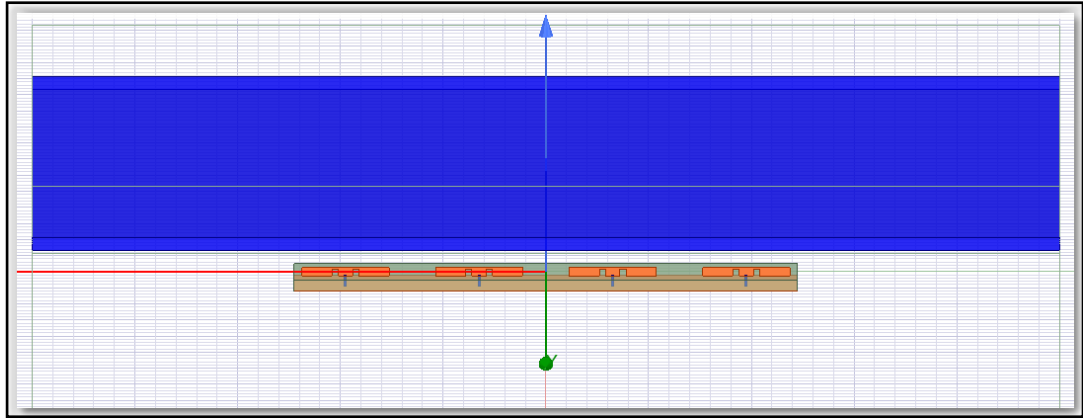


Figure 3-19 Geometry of plywood wall-2 and four-element antenna array (In this figure, wall offset is 10 cm, and antenna element spacing is  $1\lambda$ ).

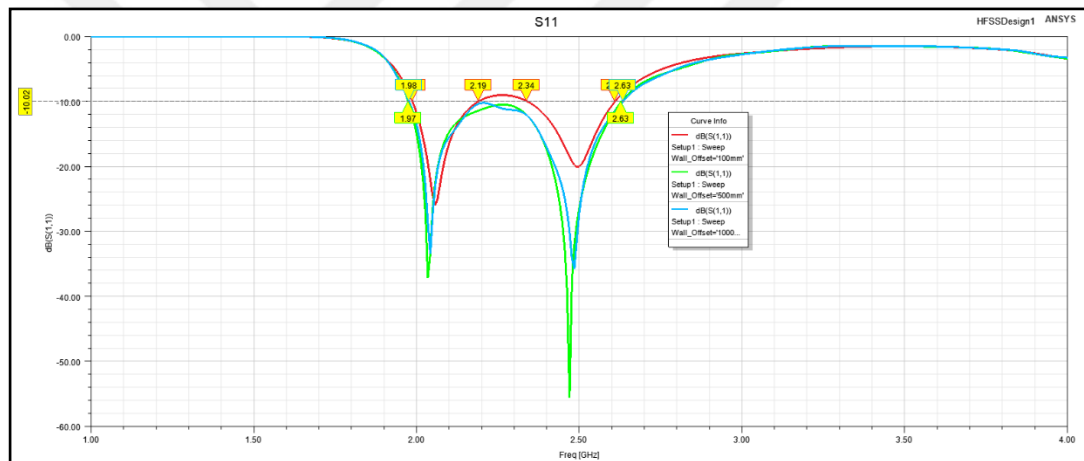


Figure 3-20  $S_{11}$  of the wideband four-element E-Patch antenna array with plywood wall-2 added.

As expected, the  $S_{11}$  results of the four-element array are no different from the single E-patch antenna result given in Figure 3-2. For a wall offset value for 10 cm,  $S_{11}$  is slightly out of the -10 dB for a small portion of the bandwidth.

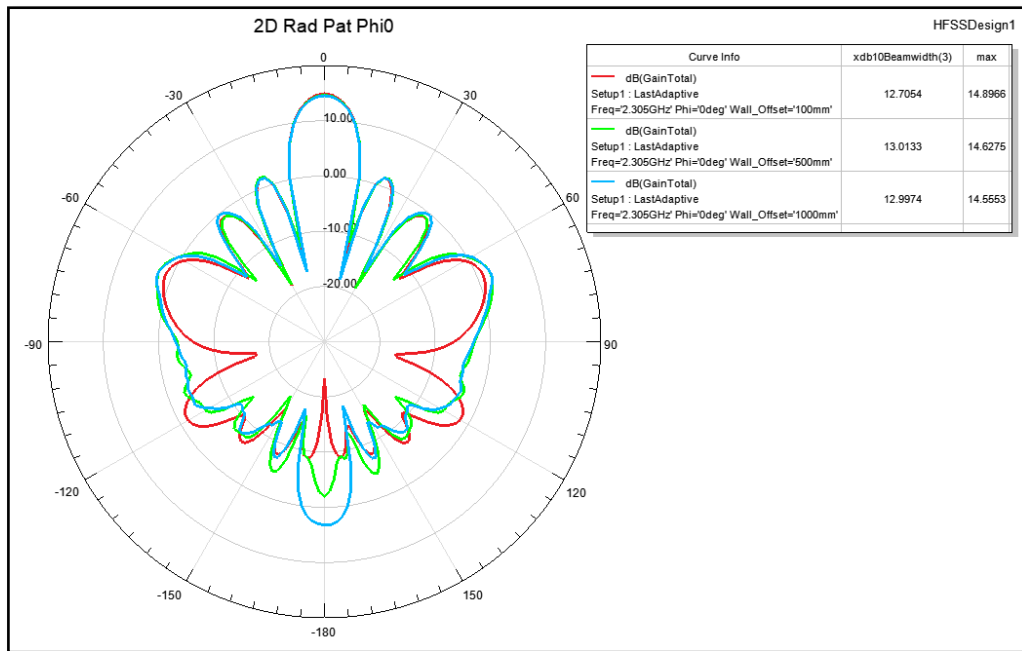


Figure 3-21 Far-field 2D azimuthal (x-z plane) radiation pattern of the wideband four-element E-Patch antenna array with plywood wall-2 added @  $f_c=2.31$  GHz.

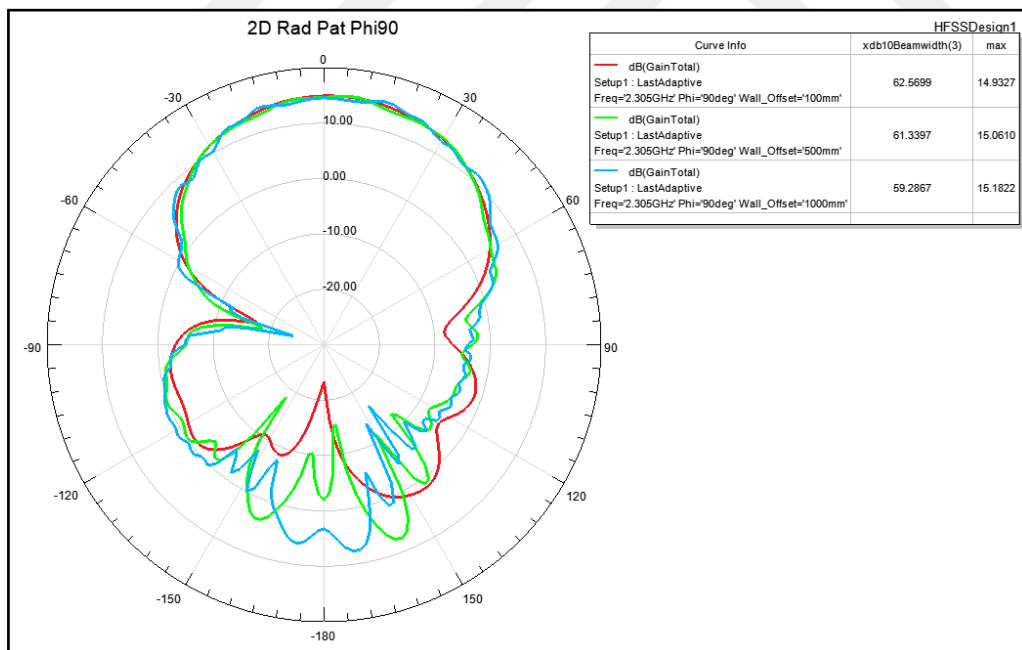


Figure 3-22 Far-field 2D elevational (y-z plane) radiation pattern of the wideband four-element E-Patch antenna array with plywood wall-2 added @  $f_c=2.31$  GHz.

As expected, plywood wall medium does not significantly affect the antenna radiation pattern, as seen in Figure 3-21 and Figure 3-22. Only boresight gain value is decreased 1 dB compared to free-space value as seen in Figure 2-33. It is an expected result since wall material attenuates propagated wave with proportional to its loss tangent value. Also, the results of the 3D radiation pattern with plywood wall-2 added are given in Figure 3-23 and Figure 3-24.

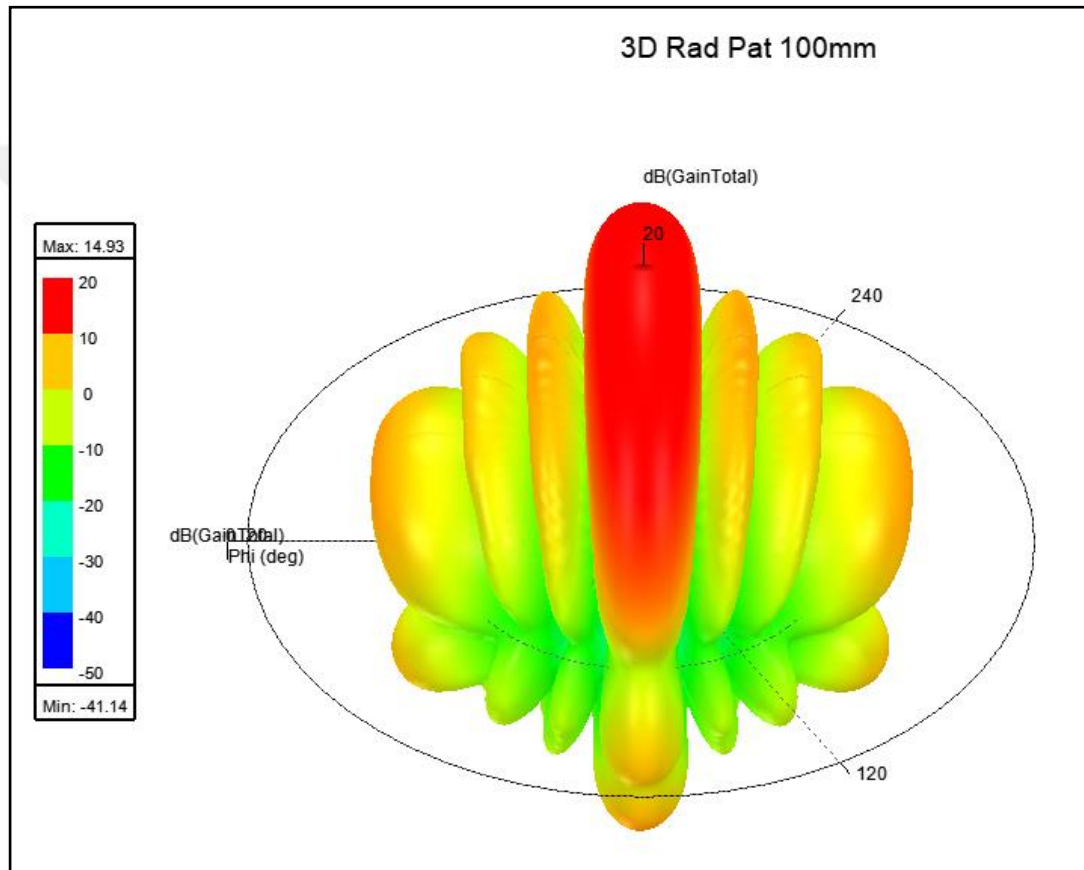


Figure 3-23 Far-field 3D polar plot of the wideband four-element E-Patch antenna array with plywood wall-2 added when wall-offset=10 cm @  $f_c=2.31$  GHz.

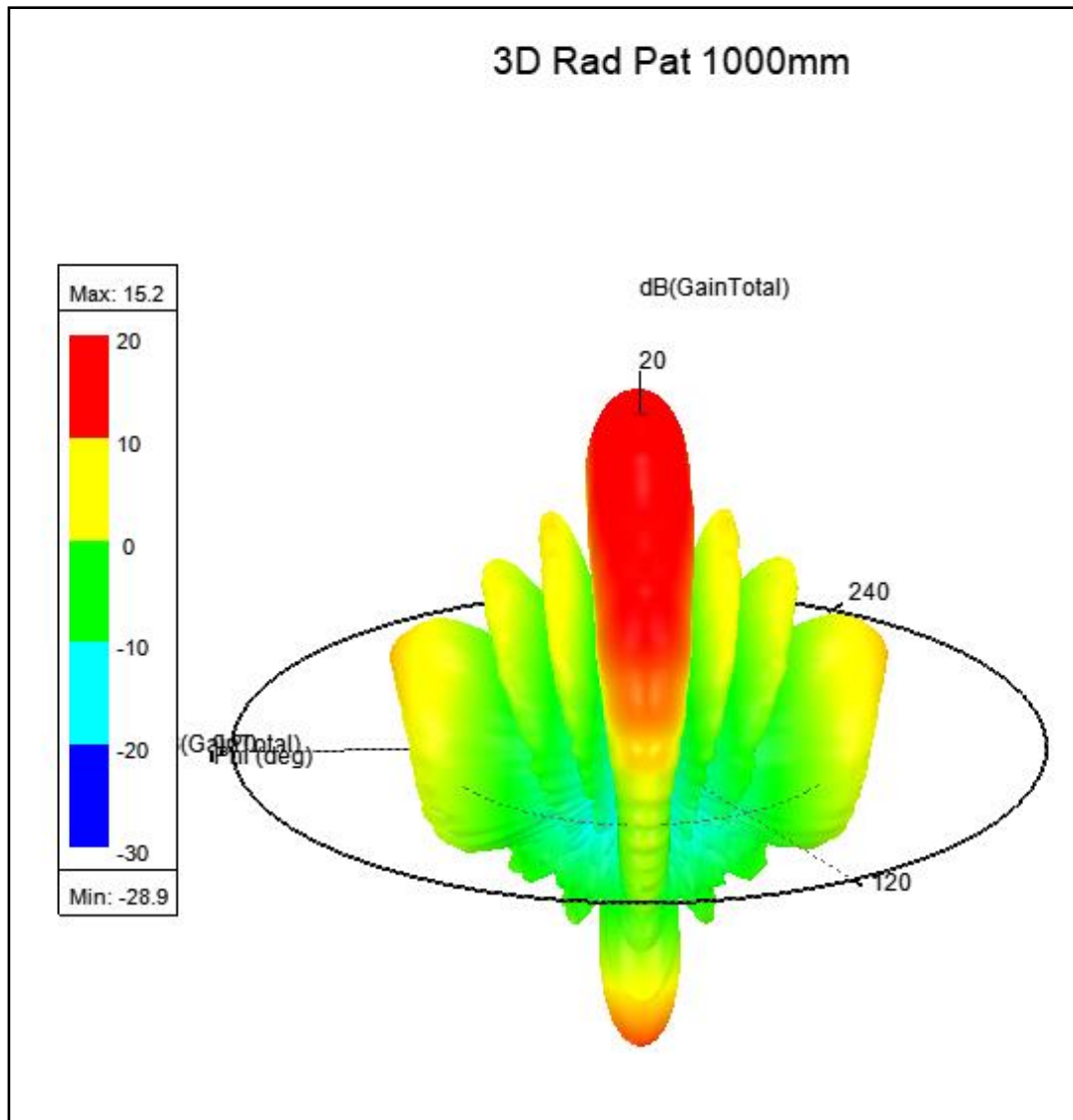


Figure 3-24 Far-field 3D polar plot of the wideband four-element E-Patch antenna array with plywood wall-2 added when wall-offset=100 cm @  $f_c=2.31$  GHz.

### 3.2.2 Concrete Wall Simulation Results

The simulated geometry of the concrete wall and antenna is given in Figure 3-25. The antenna return loss and radiation patterns are shown from Figure 3-26 to Figure 3-30.

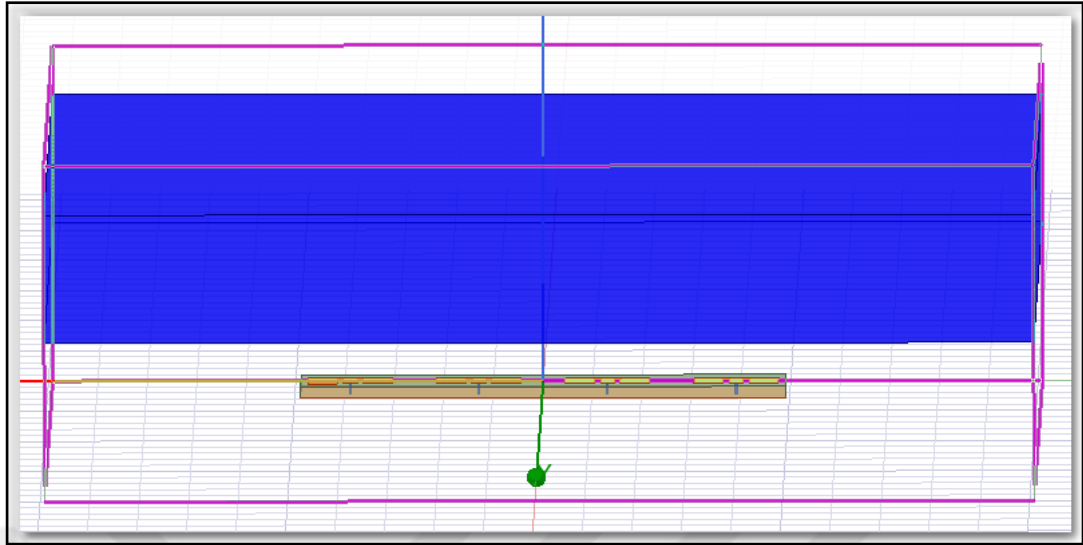


Figure 3-25 Geometry of concrete wall and four-element antenna array (In this figure, wall offset is 10 cm, and antenna element spacing is  $1\lambda$ ).

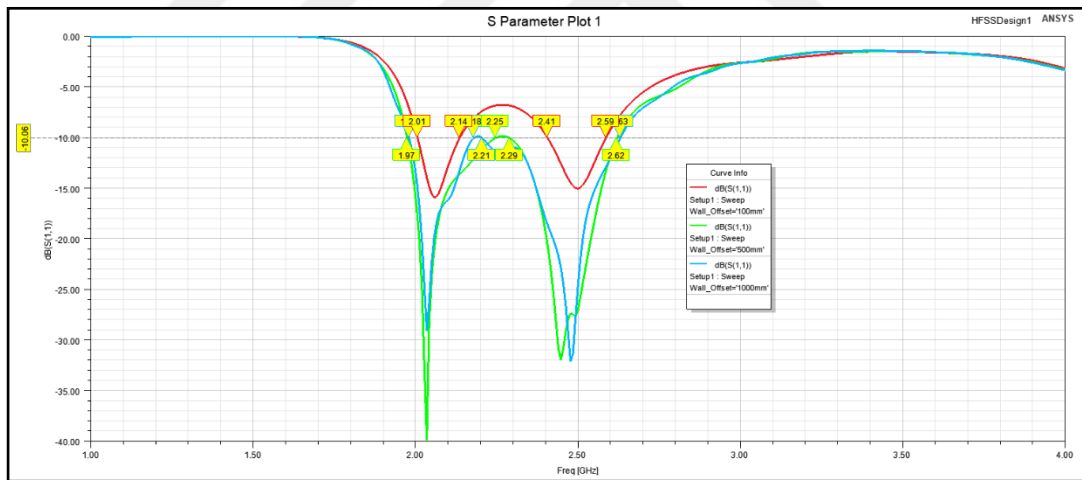


Figure 3-26  $S_{11}$  of the wideband four-element E-Patch antenna array with concrete wall added.

Compared to the single-element case, the  $S_{11}$  characteristic of the antenna array is not changed. Still, for a wall offset value of 10 cm,  $S_{11}$  is out of the band and does not have broadband characteristics contrary to the free-space results. It is expected

since the concrete wall has a high dielectric constant value that acts like a reflecting surface and detuning the antenna reflection coefficient value. For other wall offset values,  $S_{11}$  values are on edge but have a broadband frequency range.

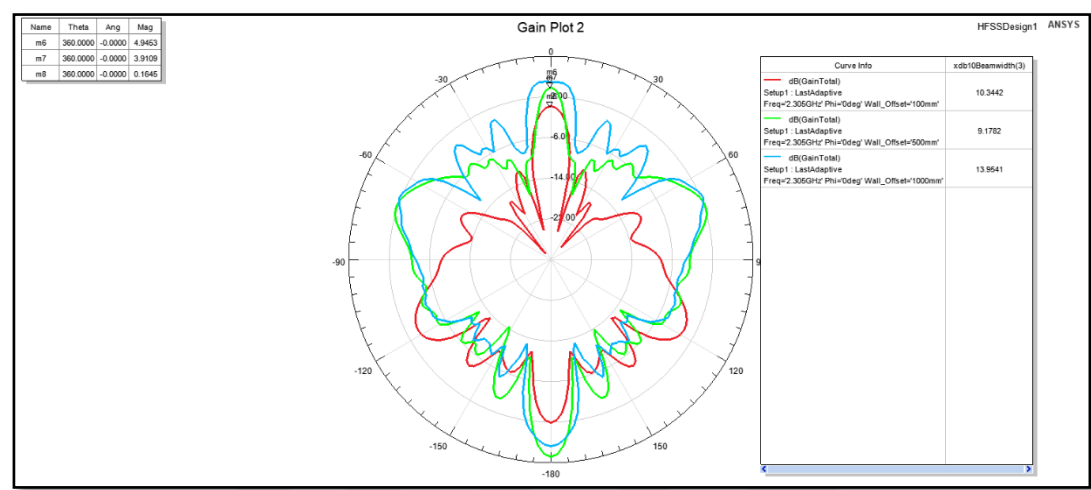


Figure 3-27 Far-field 2D azimuthal (x-z plane) radiation pattern of the wideband four-element E-Patch antenna array with concrete wall added @  $f_c=2.31$  GHz.

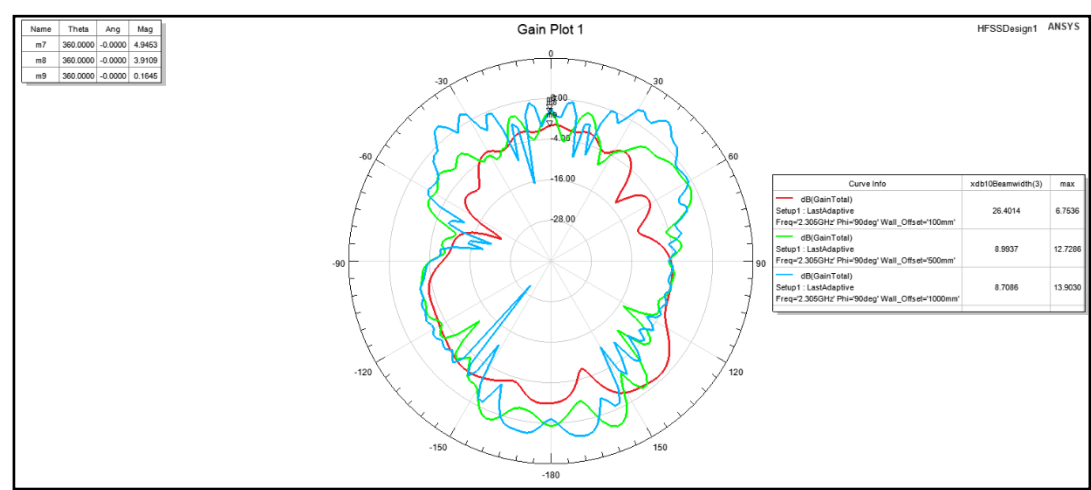


Figure 3-28 Far-field 2D elevational (y-z plane) radiation pattern of the wideband four-element E-Patch antenna array with concrete wall added @  $f_c=2.31$  GHz.

As discussed in previous section 2.2.1, array configuration significantly impacts the gain and azimuthal radiation pattern results compared to single-element results as seen in Figure 3-15. Firstly, the antenna's main lobe still has a similar characteristic to the free-space one and is not poorly distorted compared to the single-element result. Also, in an array configuration, sidelobe levels are smaller than the main lobe; in a single-element case, antenna sidelobes have similar gain levels to the main lobe with concrete wall added. Then, the main lobe gain of the radiation pattern is distorted less than the single-element case, with a wall offset value of 10 cm. The main lobe gain of the array antenna is increased by 3 dB compared to the single-element gain value. However, even with the four-element array configuration, back lobe levels are almost identical with the main lobe values but are still better than the single-element case. In the end, antenna array configuration is needed for concrete walls with a high dielectric constant value to improve antenna radiation pattern shape and gain values. Also, results of the four-element E-Patch antenna array 3D radiation pattern with concrete wall added are given in Figure 3-29 and Figure 3-30. As seen from 3D radiation pattern values, reflection increases when the array is closer to the wall, and back lobe values are more than a farther case. If the antenna array has to work with concrete wall materials, it should not be so close to the wall that distorts the array's radiation pattern.

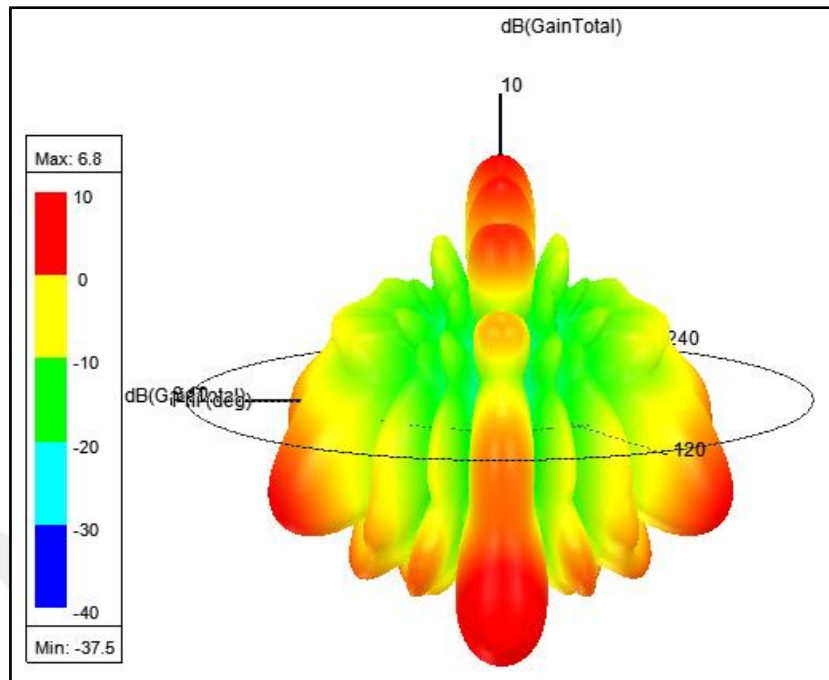


Figure 3-29 Far-field 3D polar plot of the wideband four-element E-Patch antenna array with concrete wall added when wall-offset=10 cm @  $f_c=2.31$  GHz.

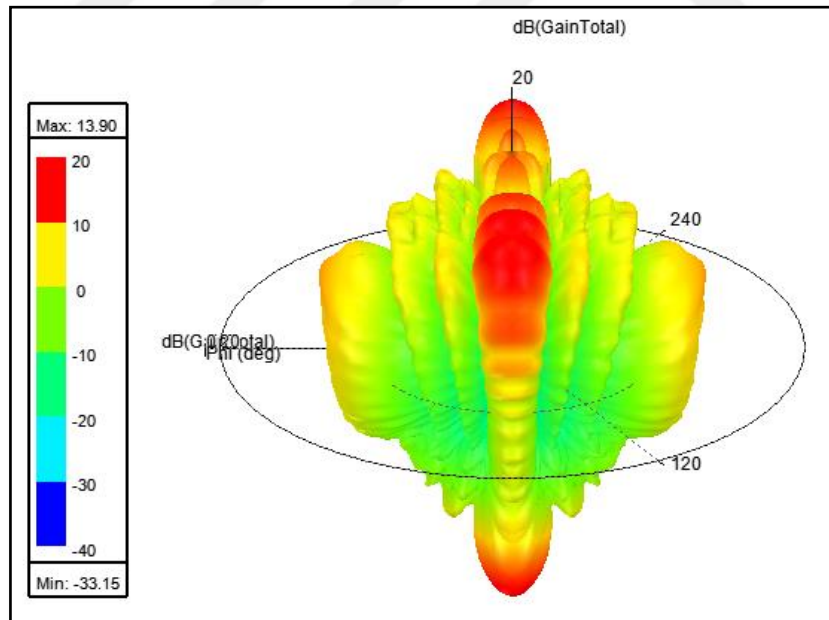


Figure 3-30 Far-field 3D polar plot of the wideband four-element E-Patch antenna array with concrete wall added when wall-offset=100 cm @  $f_c=2.31$  GHz.

### 3.3 Conclusions

After the E-Patch antenna elements and array configurations are analyzed and designed in Chapter 2, antennas are simulated by using different commonly used wall materials to see their effect on antenna operating parameters. TWR systems generally operate close to the wall of the target room, and this wall offset distance is crucial for antenna input return loss and radiation pattern shapes. This chapter shows that the concrete and brick walls with high dielectric constants create reflectivity, change the antenna's input reflection coefficient, and distort and attenuate antenna radiation pattern and gain values. However, this effect is more significant for single-element E-Patch antenna than array configurations. Array antennas with their more directional radiation patterns are less affected and attenuated with their higher gain. For plywood wall type materials, it is seen that walls do not distort radiation pattern shape and  $S_{11}$  characteristics than the other two types of wall materials. With its loss tangent value, the wave is attenuated, and gain values are decreased compared to free-space ones. The TWR designer should apply array configurations for the antenna to operate correctly to work with concrete-type solid walls. Also, single-element printed antennas with large hemispherical radiation patterns could not locate target locations in angular directions. A 2D TWR system with measurements of range and location needs a directional pattern with small beamwidth to have angular information. This also needs a beamforming mechanism to rotate the pattern to cover all intended room regions without blindspot. That also increases the complexity of the TWR system and is a trade-off for the design process.



## CHAPTER 4

### BISTATIC RADAR SIMULATION

In this chapter, after single and four-element E-Patch antenna arrays are simulated with the most used different type wall materials to investigate their effect on antenna operating parameters and radiation patterns, a simple bistatic radar setup to simulate on ANSYS HFSS is developed. In this setup, while two identical single-element wideband E-Patch antennas that are resulted in section 2.2 are used as transmitting and receiving sensors, for the wall medium, the same plywood wall-1 with electrical parameters and size given in Table 3-1 is used. A metal corner reflector with parameters given in Figure 4-1 is drawn and used as the target object. In theory, the RCS of a metal corner reflector is given in equation 4.1. From the equation, with our corner reflector length dimension of 50 cm, the  $RCS_{max}$  of our target object comes around 13 dBsm at the center frequency of 2.31 GHz.

Two antenna and plywood wall-1 without corner reflector are simulated to create a reference for  $S_{11}$  and  $S_{21}$  values. Then, the corner reflector added results are simulated and compared with the first case to see how the antenna responds to the target object and works as transmitting and receiving sensors. The radar cross-section of a corner reflector is given in equation 4.1 where  $\sigma_{max}$  Represents maximum radar cross-section value, and L is a diagonal distance of the reflector.

$$\sigma_{max} = \frac{4\pi L^4}{3\lambda^2} \quad (4.1)$$

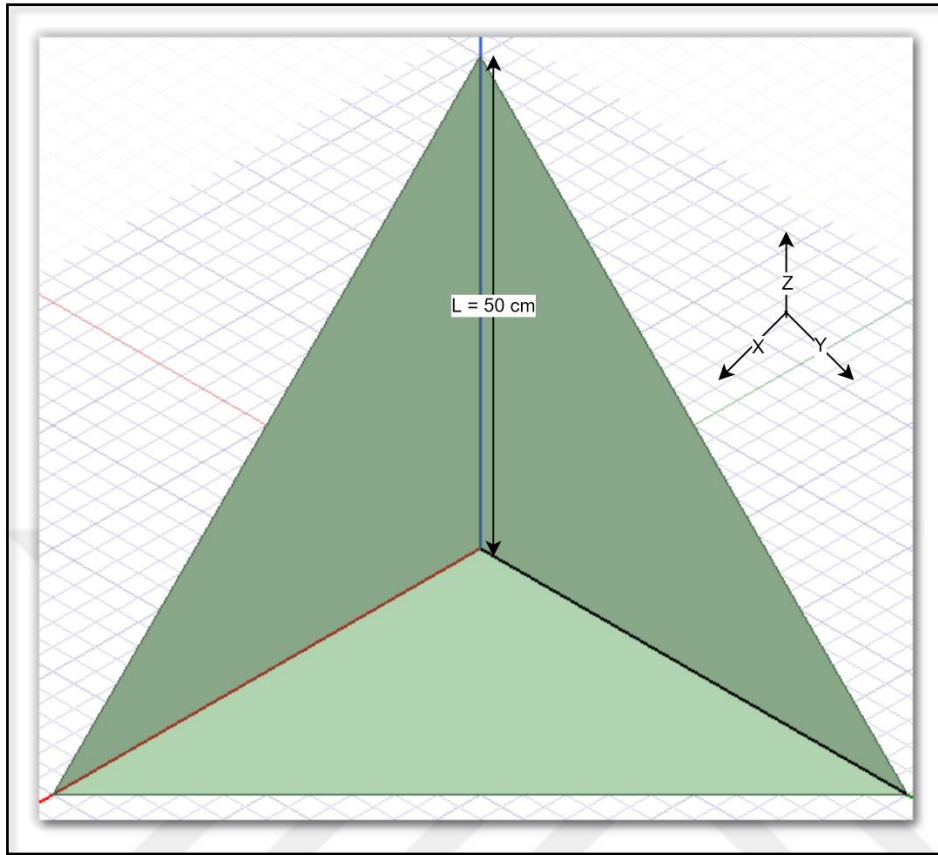


Figure 4-1 Metal corner reflector as the target object in bistatic radar setup.

#### 4.1 Results of Bistatic Radar Setup without Corner Reflector

In the first part, bistatic radar setup without metal corner reflector as the target object is installed on HFSS given in Figure 4-2. The identical single-element wideband E-patch antennas that result in section 2.2 are used as transmitting and receiving sensors. The distances of the radar setup are given in Table 4-1, with swept parameter wall offset values given in Table 4-2.

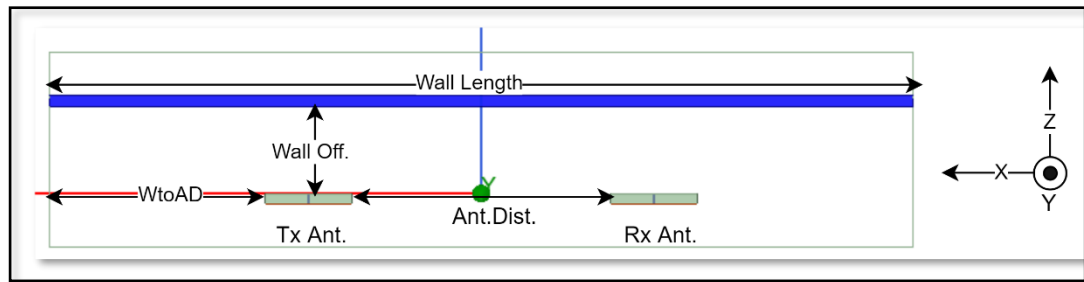


Figure 4-2 Geometry of bistatic radar with plywood wall-1 without corner reflector in x-z axis.

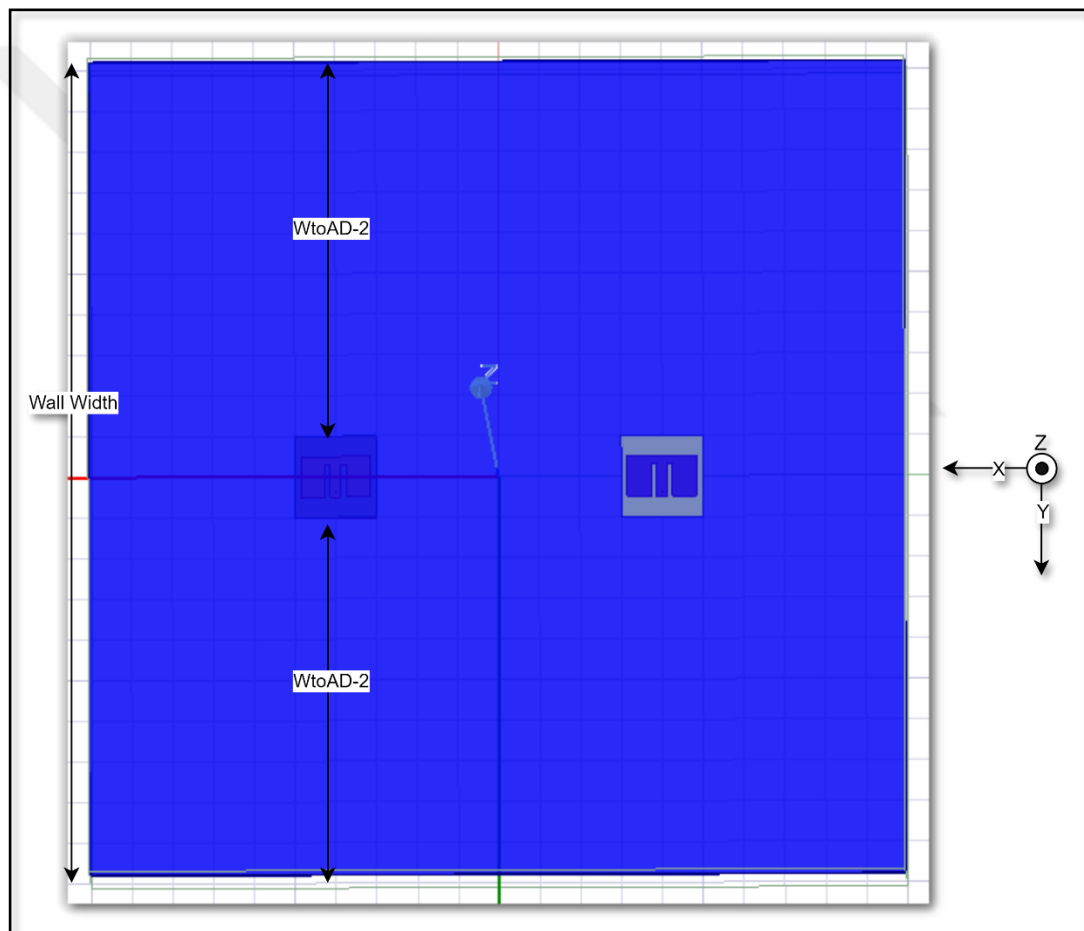


Figure 4-3 Geometry of bistatic radar with plywood wall-1 without corner reflector in x-y axis.

Table 4-1 Bistatic radar setup distances are given in Figure 4-2 and Figure 4-3.

| Distance Parameter                         | Value           |
|--------------------------------------------|-----------------|
| Wall Length @ X-axis                       | 100 cm          |
| Wall Width @ Y axis                        | 100 cm          |
| Wall Height @ Z-axis                       | 1.3 cm          |
| Wall Offset @ Z axis, Wall Off.            | Sweep Parameter |
| Wall to Antenna Distance @ X axis, WtoAD   | 25 cm           |
| Wall to Antenna Distance @ Y axis, WtoAD-2 | 45 cm           |
| Antenna Distance @ X axis, Ant.Dist.       | 30 cm           |

Table 4-2 Wall offset variable to see the effect of wall distance on the antenna.

| Swept Parameter      | From: | To:    | Steps: |
|----------------------|-------|--------|--------|
| Wall Offset @ Z axis | 10 cm | 100 cm | 10 cm  |

After geometry and setup are established,  $S_{11}$  and  $S_{21}$  values are resulted given in Figure 4-4 and Figure 4-5.

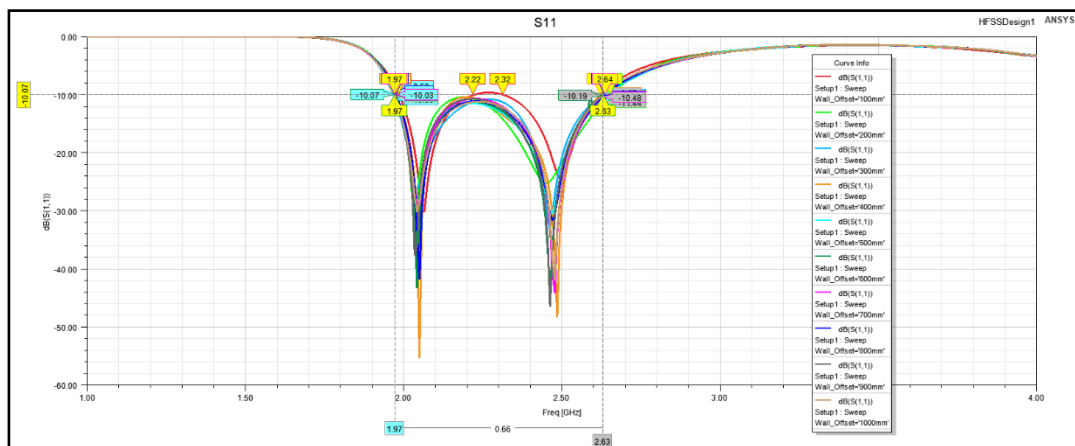


Figure 4-4  $S_{11}$  of the bistatic radar setup with plywood wall-1 without corner reflector.

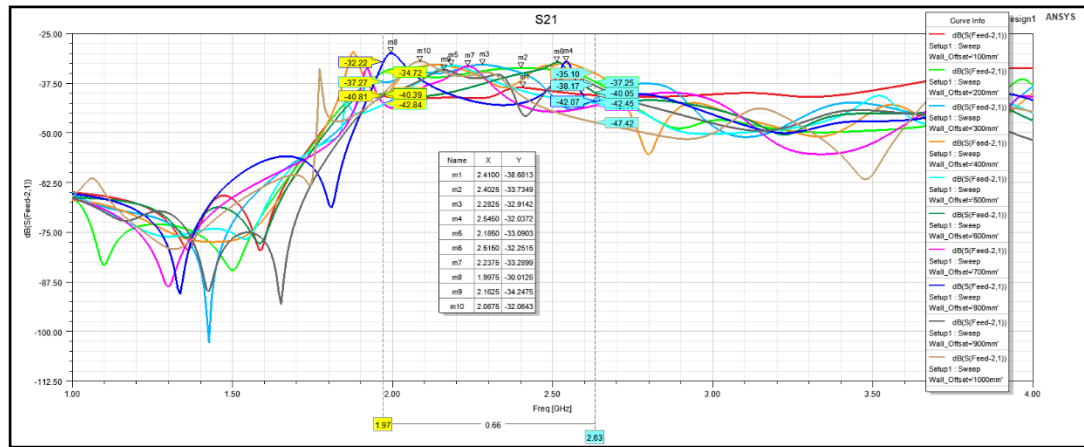


Figure 4-5  $S_{21}$  of the bistatic radar setup with plywood wall-1 without corner reflector.

As seen in Figure 4-4 and Figure 4-5,  $S_{11}$  bistatic radar setup with plywood wall-1 added is not different from the single-element antenna with plywood wall results given in Figure 3-2. It is expected that since the geometry is the almost identical only difference is two antennas placement, the first antenna is placed with an offset 30 cm in x-axis compared to section 3.1 configuration. The  $S_{21}$  is resulted in getting a reference for a case with a target object radar setup. This setup is called bistatic because transmitting and receiving happen with two identical antennas instead of one on monostatic radar setups.

#### 4.2 Results of Bistatic Radar Setup with Corner Reflector

After getting the results of a bistatic radar setup with a plywood wall without a target object, the second case with a corner reflector which has a very high RCS is simulated in this section in Figure 4-6. Dimension of the corner reflector is given in Figure 4-1. A wall offset variable is used in the simulations to analyze the effect of wall distance on the antenna. However, for bistatic radar with target object results,

the wall offset parameter is only 10 cm, 50 cm, and 100 cm to decrease simulation times.

Table 4-3 Bistatic radar setup distance given in Figure 4-6.

| Distance Parameter                      | Value   |
|-----------------------------------------|---------|
| Target Object to Wall Distance @ Z-axis | 48.7 cm |

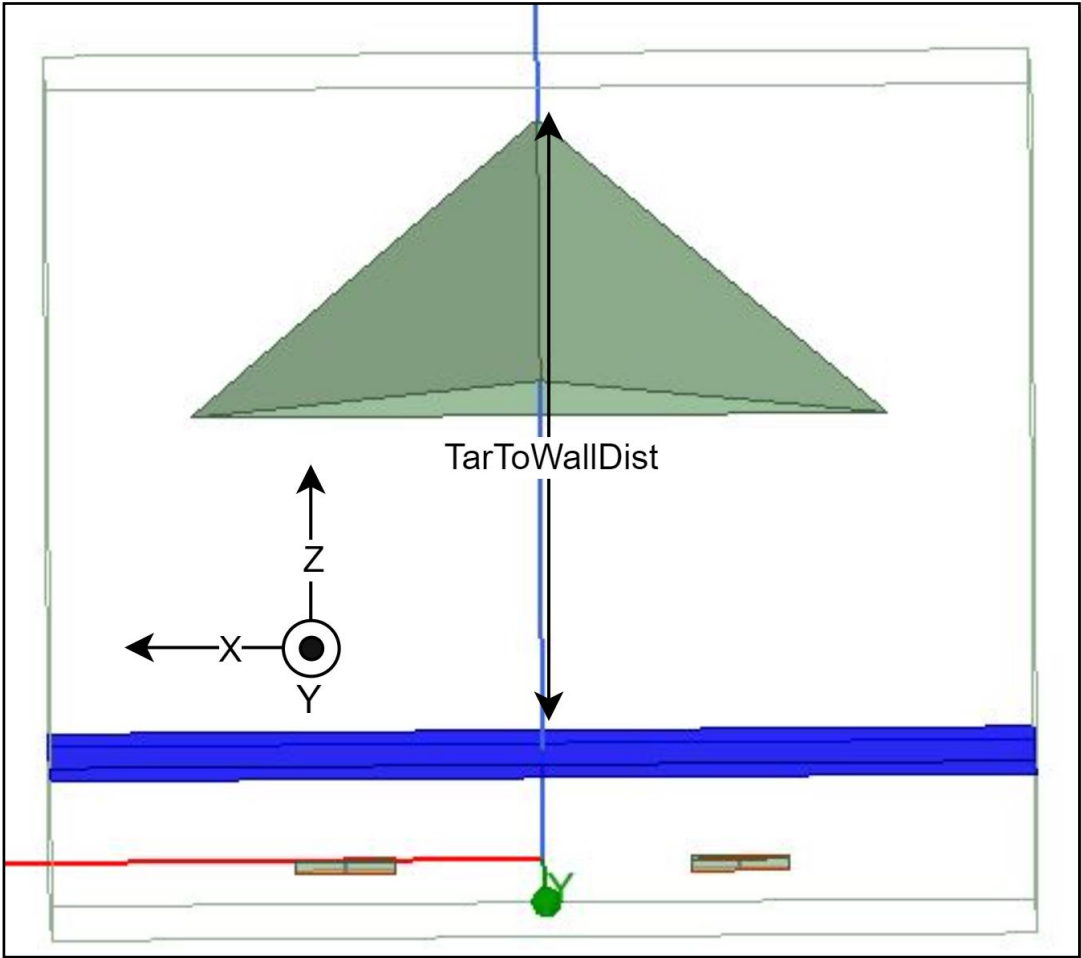


Figure 4-6 Geometry of bistatic radar with plywood wall-1 with corner reflector in x-z axis.

Table 4-4 Wall offset variable to see the effect of wall distance on the antenna.

| Swept Parameter      | 1.    | 2.    | 3.     |
|----------------------|-------|-------|--------|
| Wall Offset @ Z axis | 10 cm | 50 cm | 100 cm |

After geometry and setup are established, simulated results of  $S_{11}$  and  $S_{21}$  values are resulted given in Figure 4-7 and Figure 4-8.

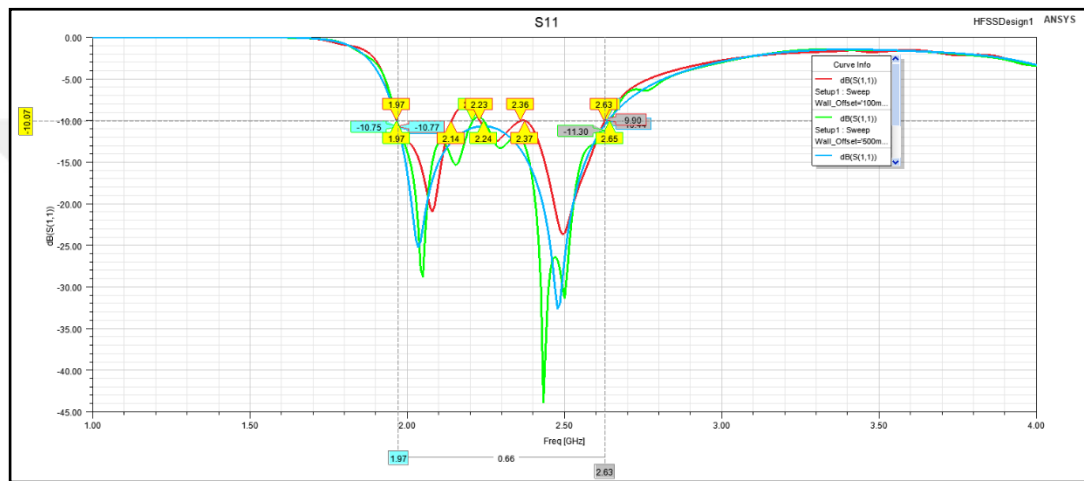


Figure 4-7  $S_{11}$  of the bistatic radar setup with plywood wall-1 with corner reflector as the target object.

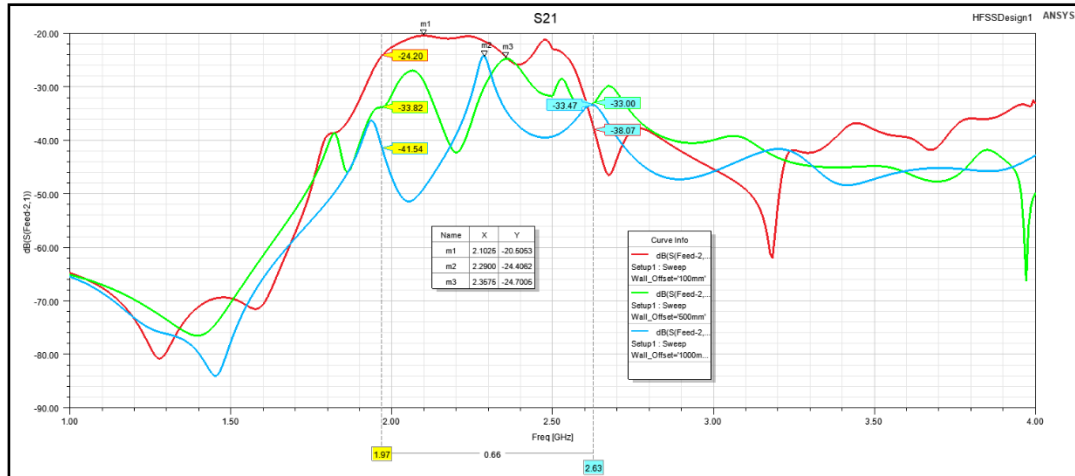


Figure 4-8  $S_{21}$  of the bistatic radar setup with plywood wall-1 with corner reflector as the target object.

Compared to the  $S_{11}$  result of bistatic radar without corner reflector given in Figure 4-4, due to a highly reflected corner reflector in front of the antenna, for a wall offset value of 10 cm,  $S_{11}$  is out of level of -10 dB for some frequencies. However, for other wall offset distances, it still has a broadband frequency response. Corner reflector as an object affects antenna input reflection similar to a concrete wall for smallest wall offset distances. That is expected since the corner reflector has substantial reflectivity with its PEC material and shape.

Compared to the  $S_{21}$  result of bistatic radar without corner reflector given in Figure 4-5, it is clear that the antenna senses corner reflector. For wall offset value of 10 cm,  $S_{21}$  is increased from -38 dB to -20 dB, for wall offset value of 50 cm,  $S_{21}$  is increased from -33 dB to -24 dB and, for a wall offset value of 100 cm,  $S_{21}$  is increased from -32 dB to -24 dB in some frequencies in the operating bandwidth of the antenna. It is already seen from the figure that in the bandwidth of the antenna, all  $S_{21}$  values increased from the band antenna not operating. Of course, HFSS results give only an indication that wideband E-patch antennas can work in a TWR setup;

an actual setup is set with comparable wall and target objects to prove this characteristic.

### **4.3 Conclusions**

Wideband E-Patch antennas are simulated in a bistatic radar setup with a corner reflector as a target object. From the results given above, it is seen that antennas are sensing objects with a wall material in the middle as attenuator and barrier. After proving that the proposed E-Patch antenna can be used as transmitting and receiving sensors in a TWR setup, antenna fabrication is done and results with real-world setup.



## CHAPTER 5

### REALIZATION OF WIDEBAND FOUR-ELEMENT E-PATCH ANTENNA AND MEASUREMENT RESULTS

After a low-profile wideband E-patch antenna is designed and analyzed with a state-of-the-art full-wave EM solver, an antenna with wall materials is simulated to observe the effect of the wall on antenna parameters such as input matching and radiation patterns. Later, a bistatic radar setup is simulated with a highly reflective target object to understand that the antenna can be used with a TWR system. In this chapter, the proposed low-profile four-element E-patch antenna array manufactured with limited capability is given in Figure 5-1 to Figure 5-3. Then, the antenna measurements carried out in the Anechoic chamber facility of METU EEE Department of the manufactured E-patch antenna array are presented given here. For the antenna array, due to the both manufacturing ease and trade-off between mainlobe and sidelobe levels,  $0.7\lambda$  array separation value is chosen.

Low-profile wideband four-element E-Patch antenna array that is designed in section 2.2 is manufactured with copper plates. Four E-shape patch and a ground plate with given dimensions given in Table 2-16 is cut by laser. In our design, the feed mechanism is designed as an 11.5 mm dipole between the patch and ground, as shown in Figure 2-4. For the excitation mechanism, four RF SMA connectors are modified to our intended height and soldered to our patches. Photos of the manufactured antenna array are given in Figure 5-1 to Figure 5-3. After manufacturing antenna array, a krytar 7020180 4-power divider [37] is installed to the excite patches with RF signal. Photos of the antenna array with power divider and RF cables can be seen in Figure 5-4 and Figure 5-5.

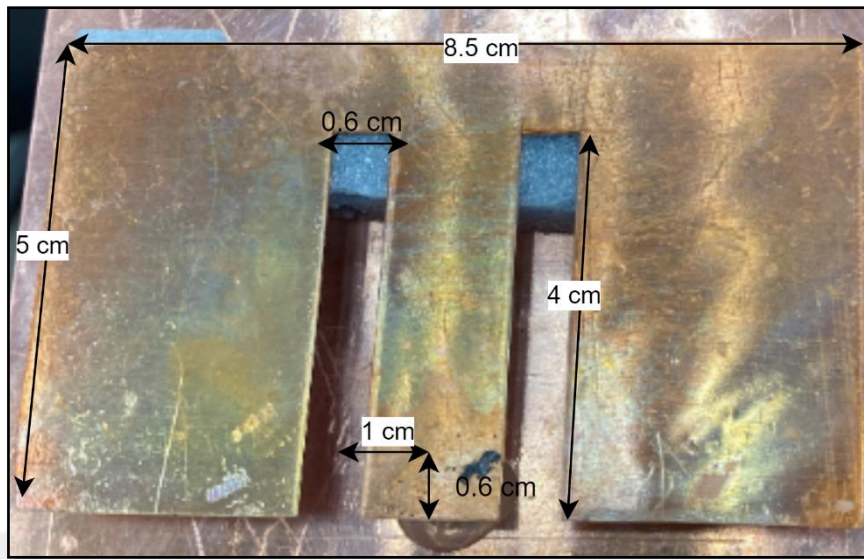


Figure 5-1 Manufactured low-profile single E-patch antenna photo-1.

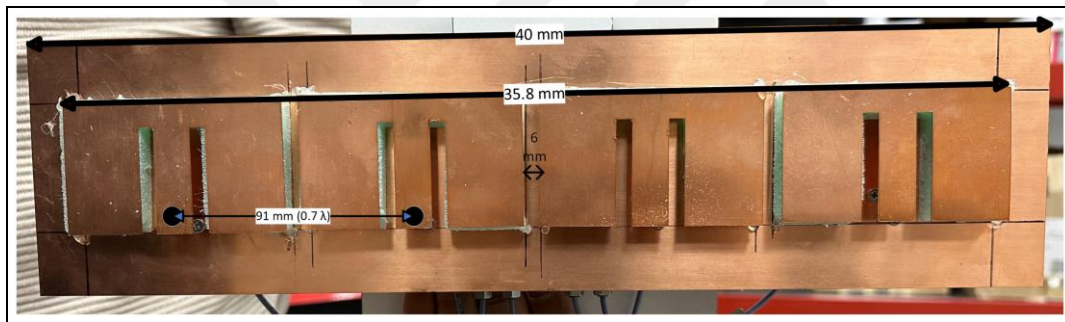


Figure 5-2 Manufactured low-profile four-element E-patch antenna array photo-2.



Figure 5-3 E-patch antenna array height photo.

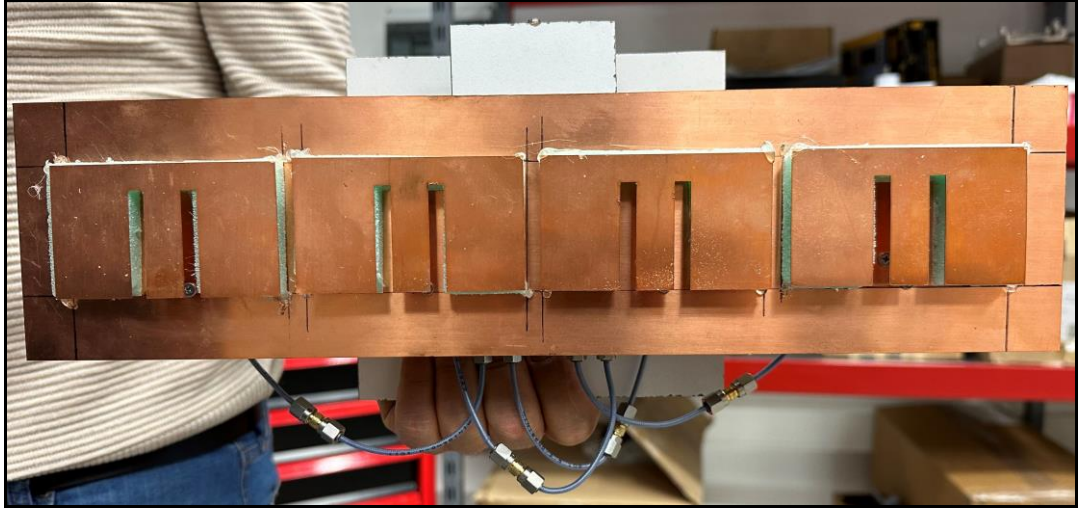


Figure 5-4 4-Elements E-Patch Antenna Array with Power Divider and RF Cables-  
Photo 1

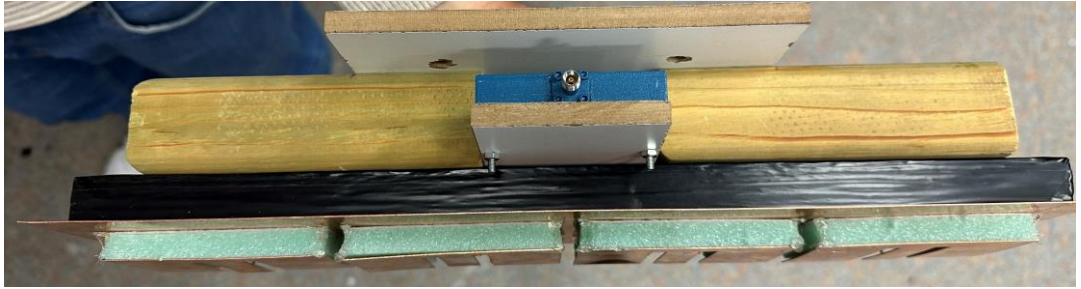


Figure 5-5 4-Elements E-Patch Antenna Array with Power Divider and RF Cables-  
Photo 2

### 5.1 Measurement Results of Manufactured E-Patch Antenna Array

After the four-element E-patch antenna array is manufactured, its design specifications are tested in the anechoic chamber of METU EEE with the help of Prof. Dr. Sencer Koç. Antenna input return loss values are realized with the network analyzer placed on the Tübitak İltaren RF laboratory. Measured S parameter results are given in 5.1.1.

### 5.1.1 S Parameter Measurements

Measured  $S_{11}$ ,  $S_{22}$ ,  $S_{33}$  and  $S_{44}$  values of the manufactured E-patch antenna are given in Figure 5-6 to Figure 5-9. Also  $S_{11}$  results of E-patch antenna array with four power divider are given in Figure 5-10. As seen in Figure 5-10, input return loss response of the E-patch antenna array with power divider is still coincident with the response of the without divider but some ripples on some frequencies are occurring due to the input return loss characteristics of the power divider.

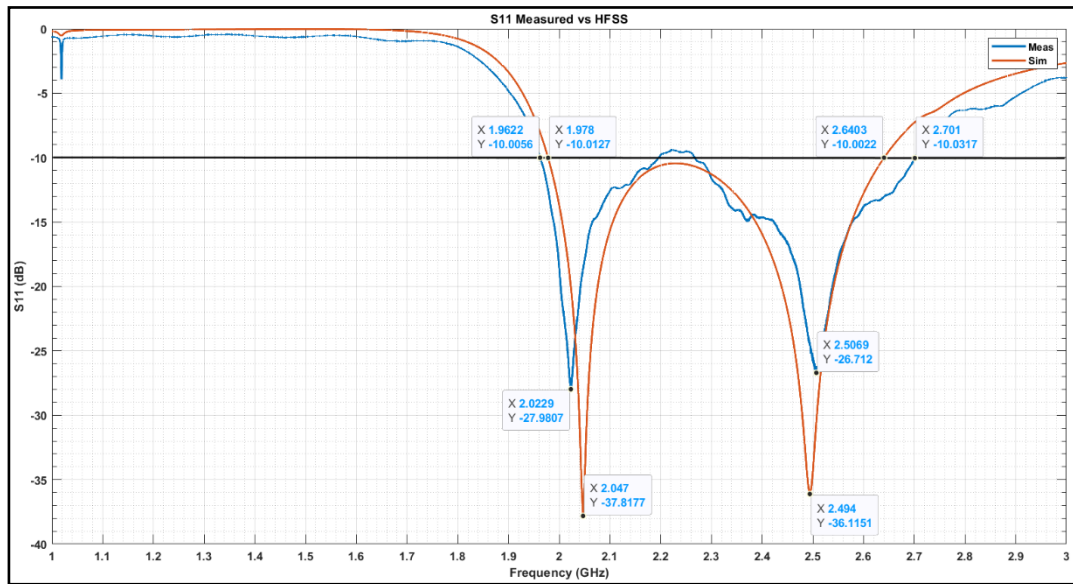


Figure 5-6 Measured  $S_{11}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

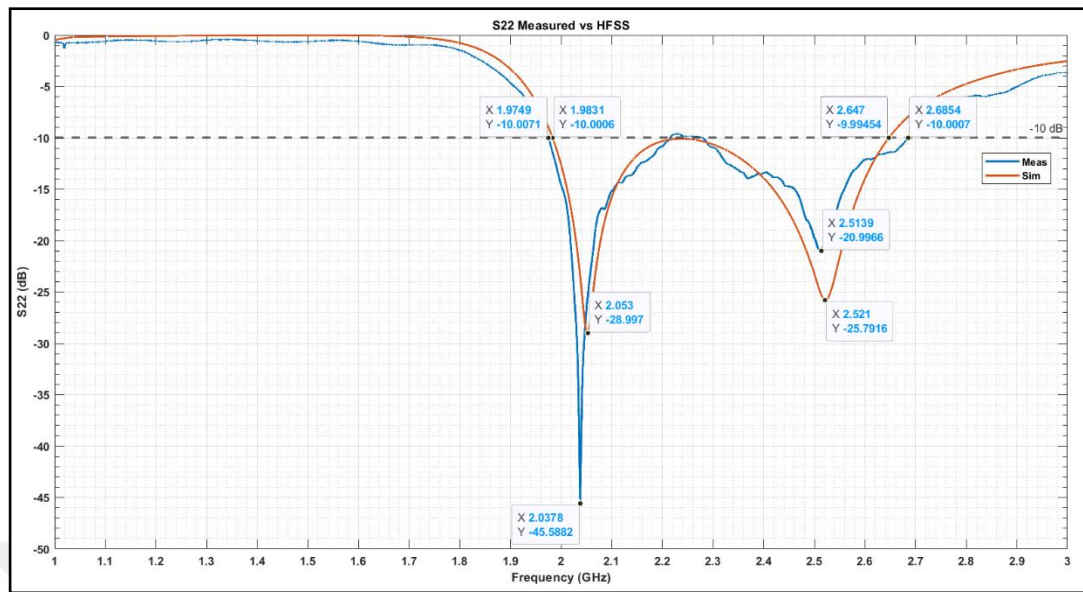


Figure 5-7 Measured  $S_{22}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

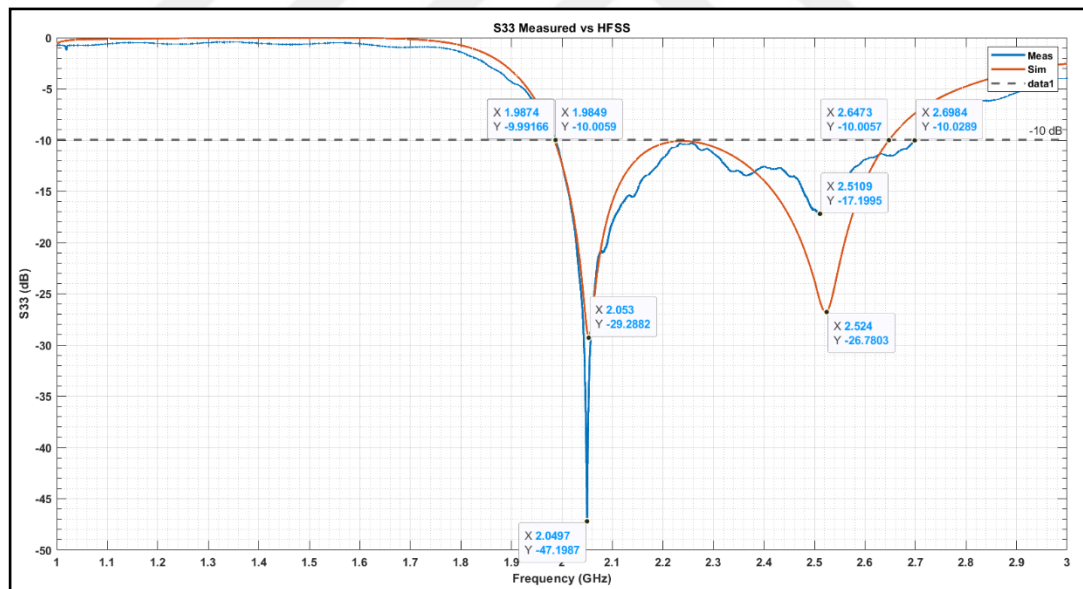


Figure 5-8 Measured  $S_{33}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

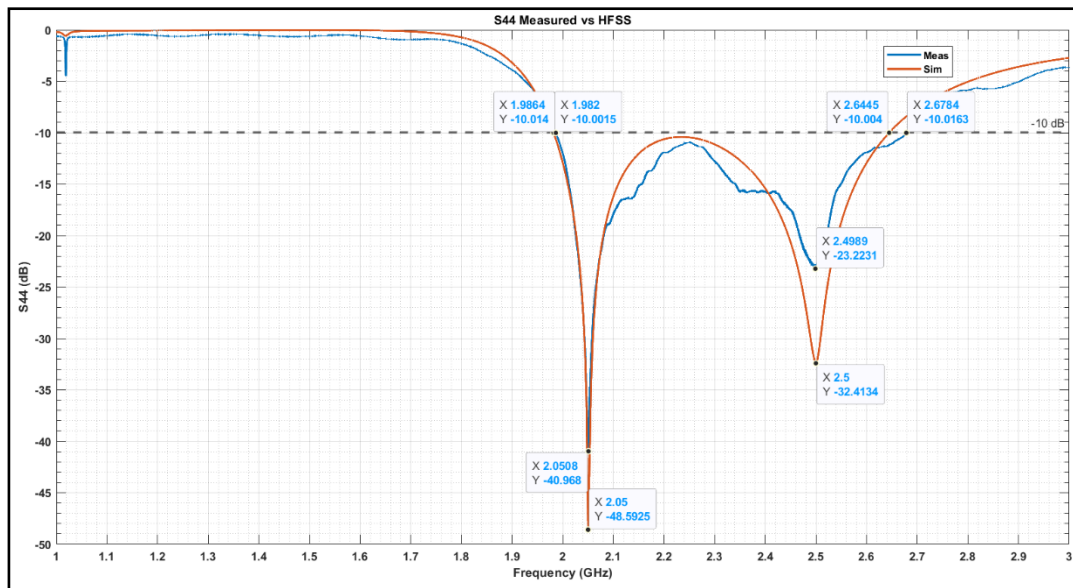


Figure 5-9 Measured  $S_{44}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

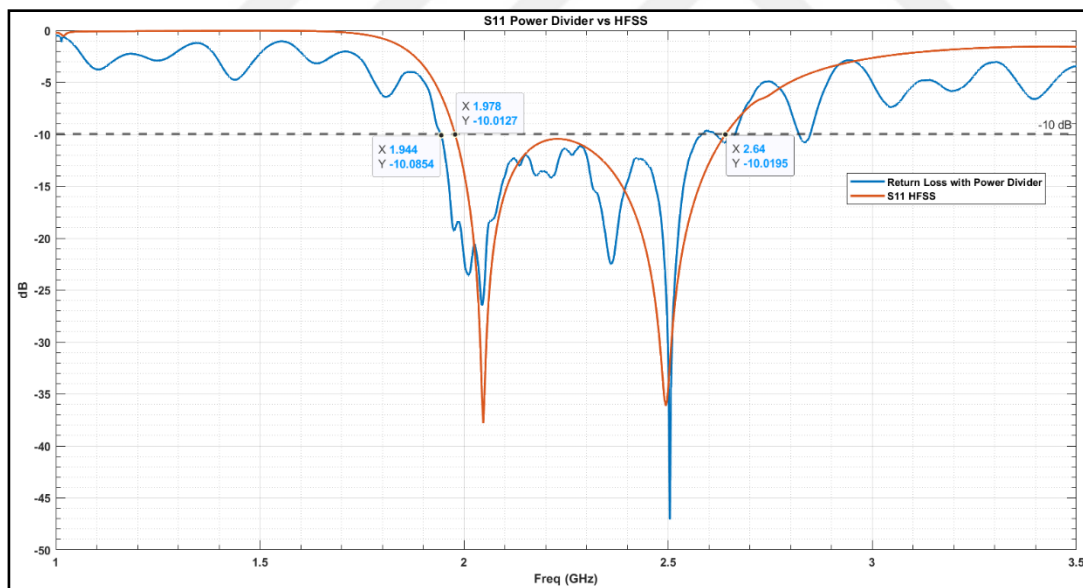


Figure 5-10 Measured  $S_{11}$  of the manufactured E-Patch antenna array with power divider vs HFSS Simulation.

As seen in Figure 5-6 to Figure 5-10, the manufactured antenna has two resonance frequencies at 2 and 2.5 GHz where HFSS simulations show the same response. The antenna has around 740 MHz bandwidth (for  $S_{11} < -10$  dB), 32%, and could be enough for short-pulse signals used on TWRs.

After seeing input return loss results, also mutual coupling results of the array elements are given in from Figure 5-11 to Figure 5-14. As seen from the figures, measurement results are aligned with the simulation results, and it shows that manufacturing process was successful and resulted as intended. It is also seen from Figure 5-14, when the distance between the array elements are getting far, mutual coupling effect is decreasing as expected.

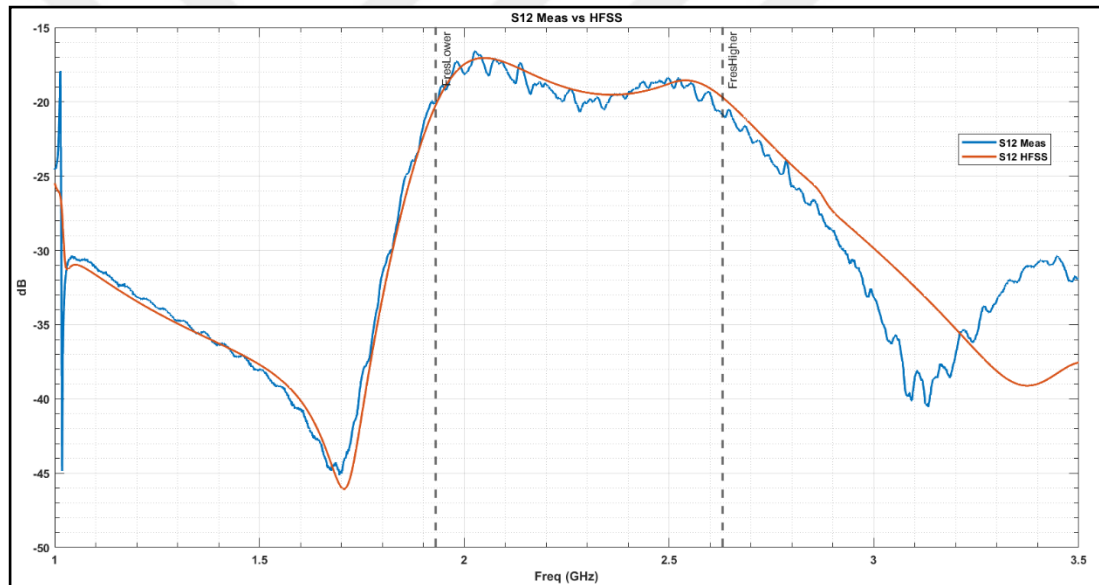


Figure 5-11 Measured  $S_{12}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

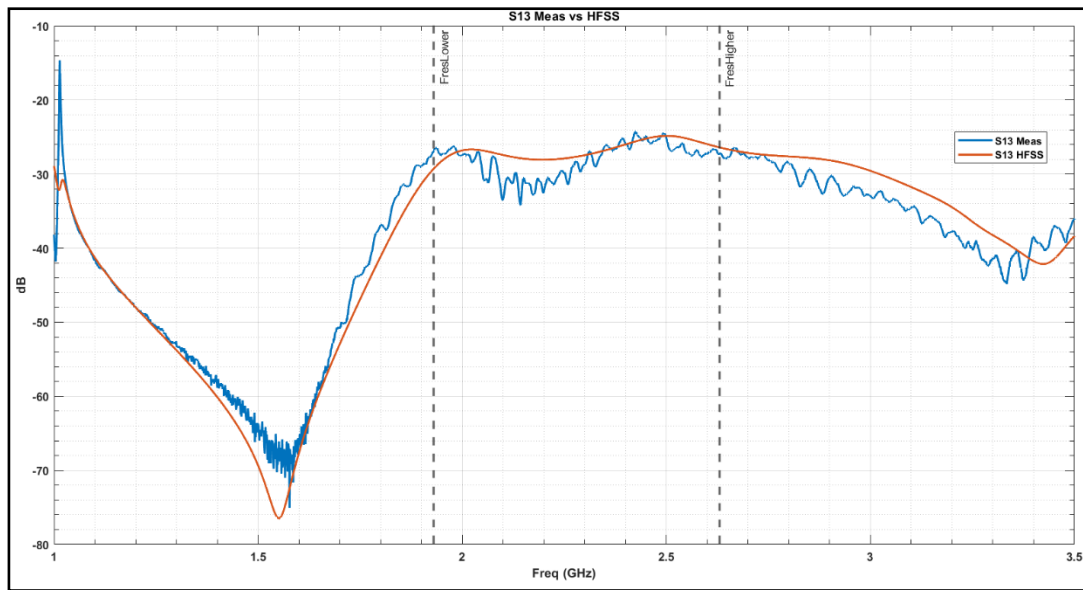


Figure 5-12 Measured  $S_{13}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

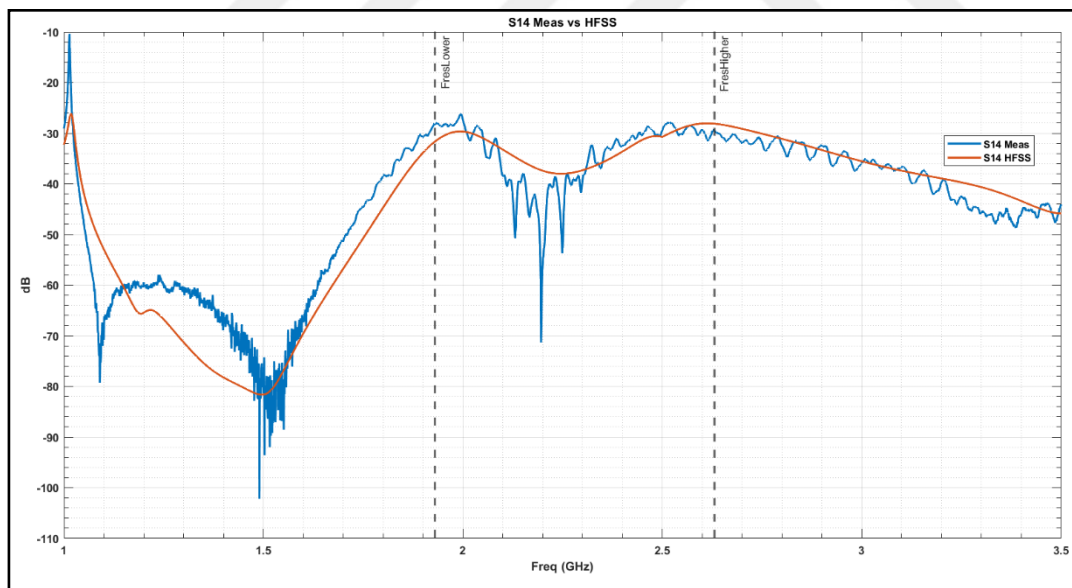


Figure 5-13 Measured  $S_{14}$  of the manufactured E-Patch antenna array vs HFSS Simulation.

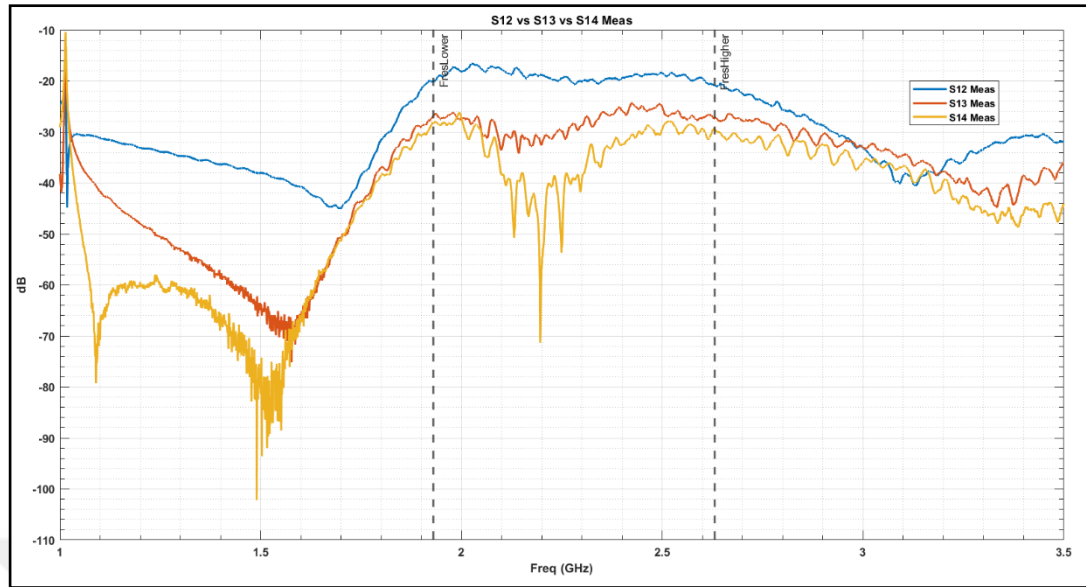


Figure 5-14 Measured  $S_{12}$  &  $S_{13}$  &  $S_{14}$  of the manufactured E-Patch antenna array.

### 5.1.2 Radiation Pattern Results

After clarifying input return loss and mutual coupling results, with the photos of anechoic chamber measurements given in Figure 5-15 and Figure 5-16, normalized 2D co-pol and cross-pol azimuthal and elevational radiation patterns have measured at the frequencies, 2, 2.3 and 2.7 GHz given in Figure 5-18 to Figure 5-25. For the measurements, azimuthal (H-plane) is defined as x-z axis like fingers of the antenna looking down, and for elevational (E-Plane) is defined as y-z axis like fingers of the antenna looking right.

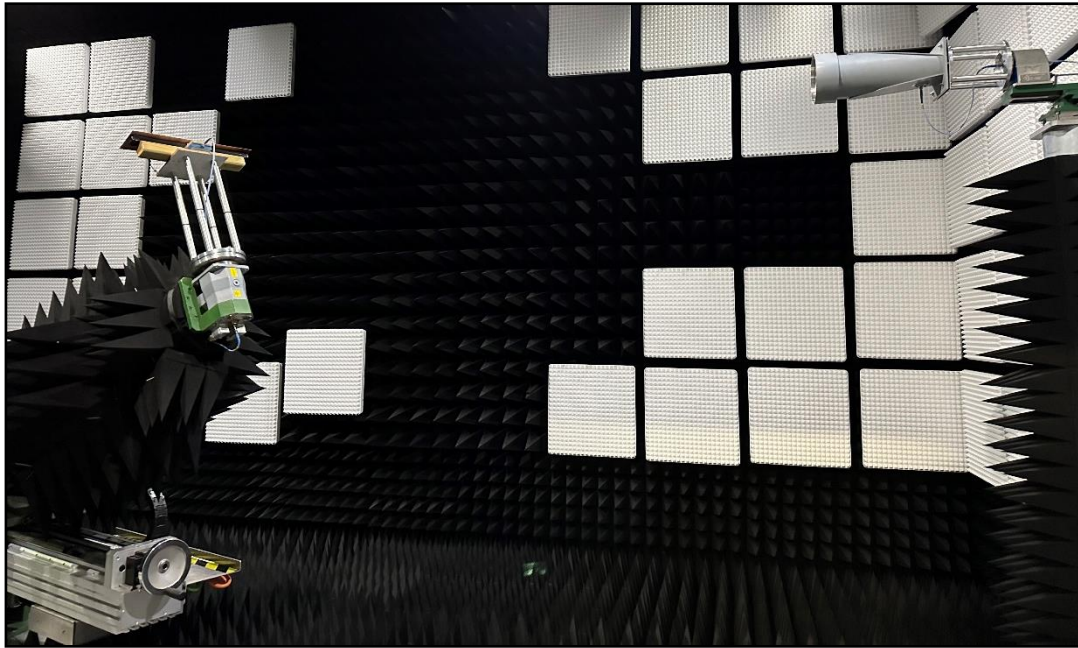


Figure 5-15 Photo-1 of manufactured E-Patch antenna array for radiation pattern measurements in METU EEE Anechoic Chamber.



Figure 5-16 Photo-2 of manufactured E-Patch antenna array for azimuthal (H-Plane) radiation pattern measurements in METU EEE Anechoic Chamber.

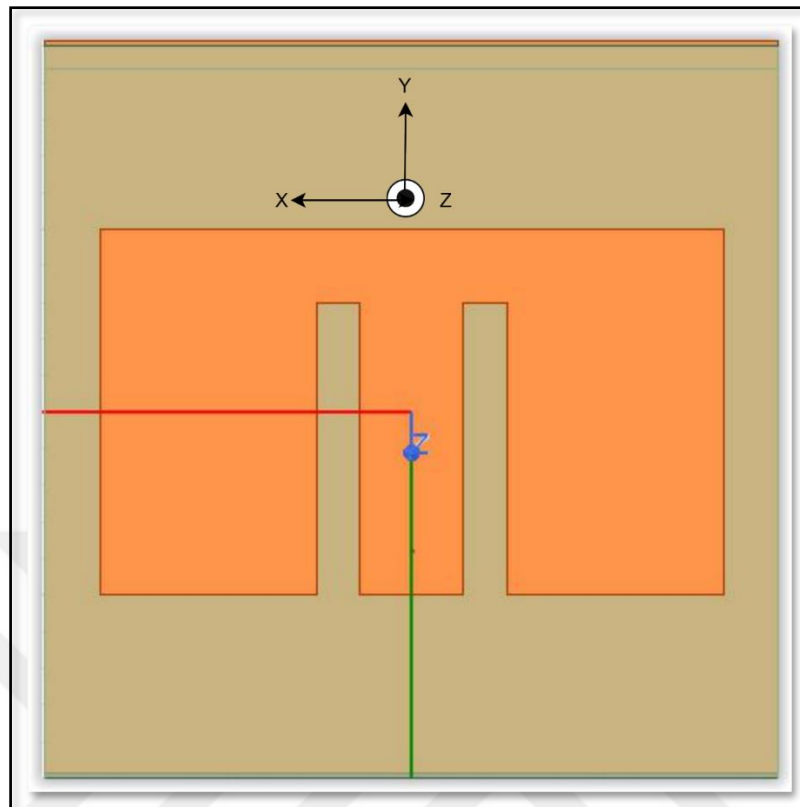


Figure 5-17 Azimuthal radiation pattern as x-z axis, elevational radiation pattern as y-z axis.

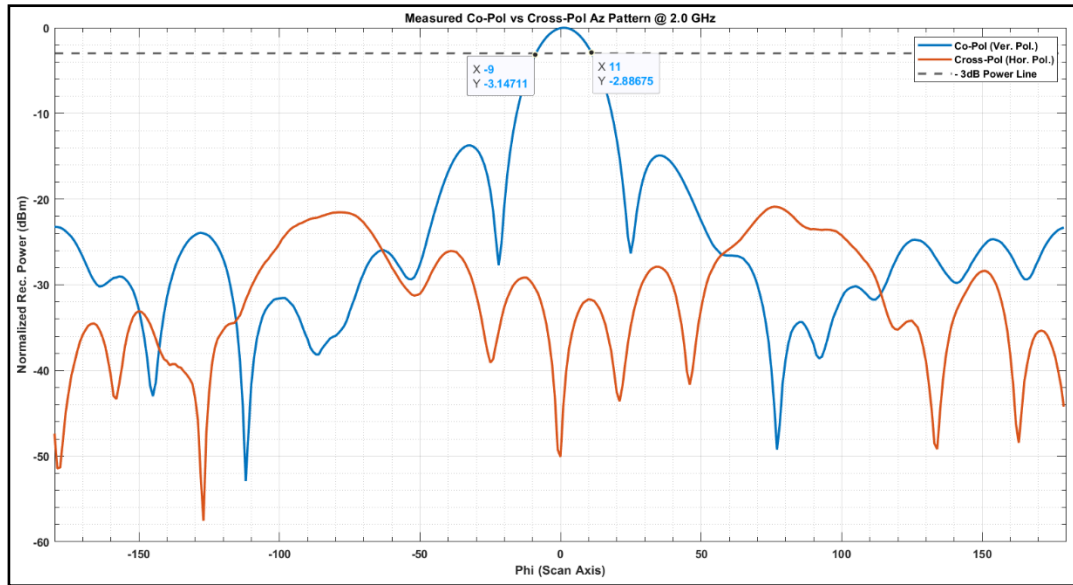


Figure 5-18 Normalized Co-Pol (V) and Cross-Pol (H) Az (H-Plane) Pattern @ 2.0 GHz

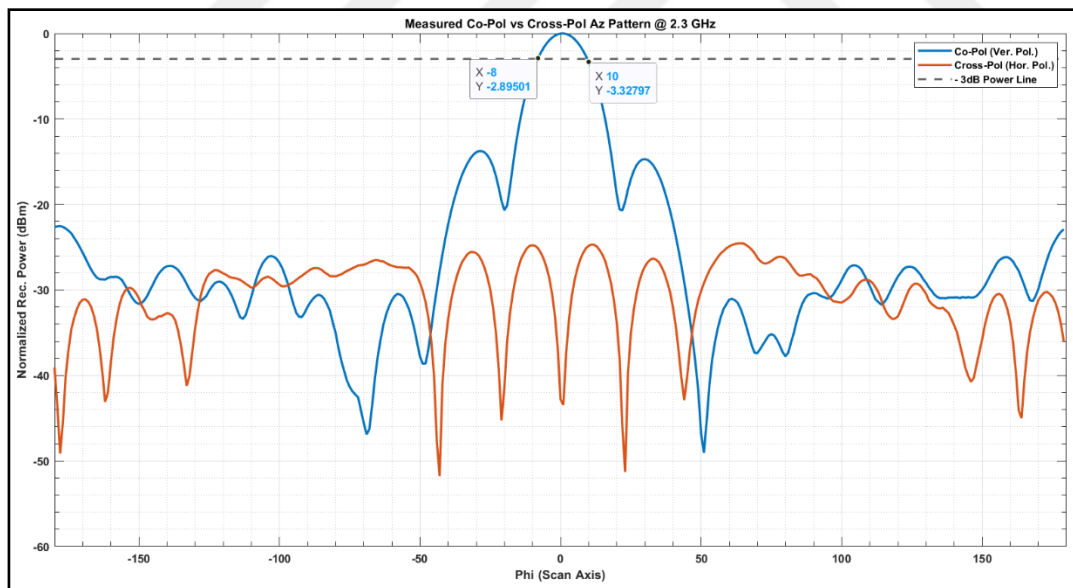


Figure 5-19 Normalized Co-Pol (V) and Cross-Pol (H) Az (H-Plane) Pattern @ 2.3 GHz

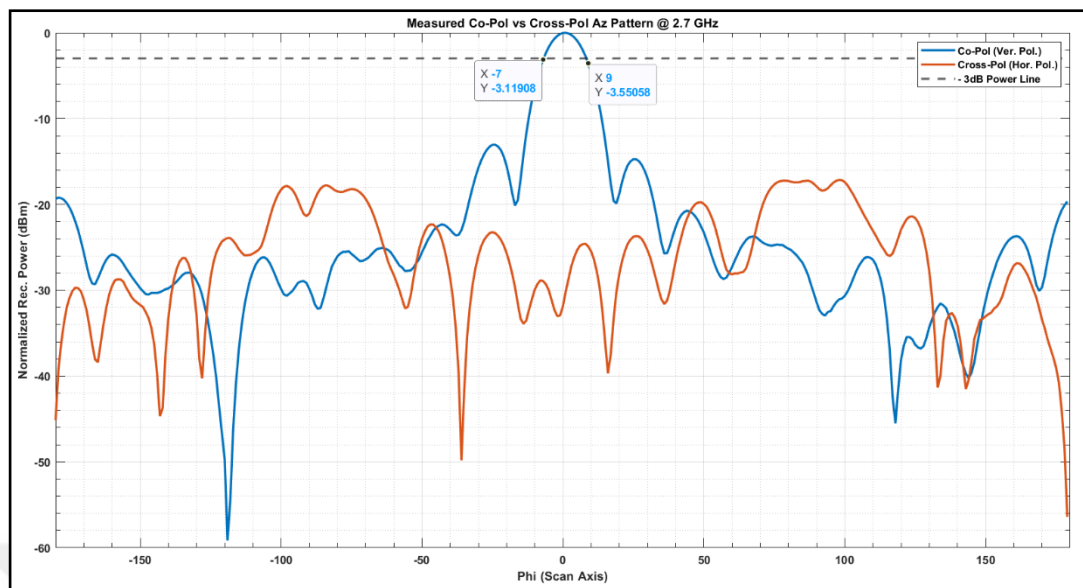


Figure 5-20 Normalized Co-Pol (V) and Cross-Pol (H) Az (H-Plane) Pattern @ 2.7 GHz

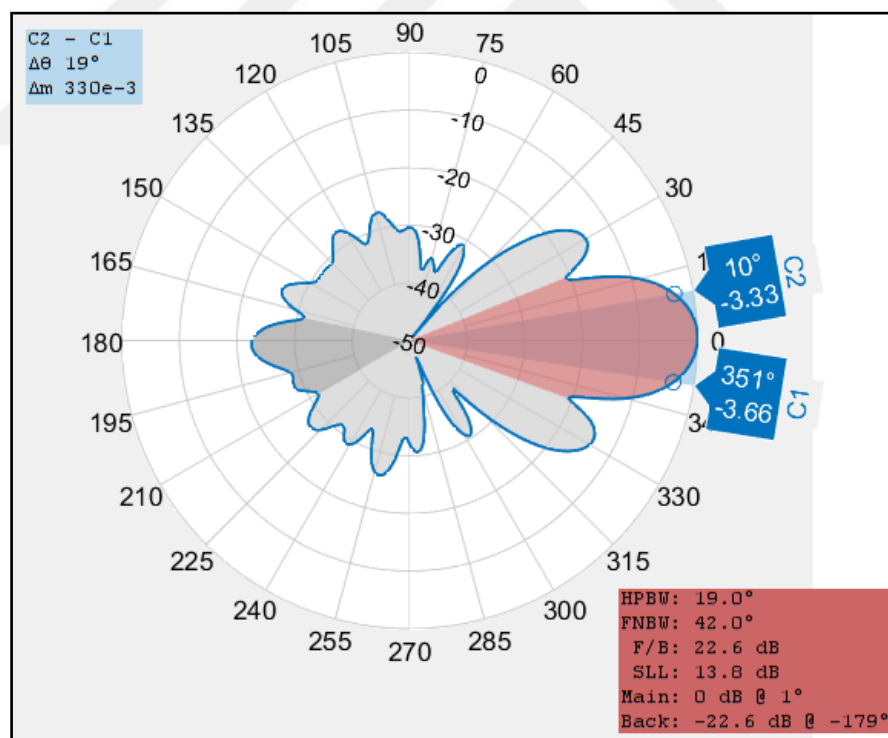


Figure 5-21 2D Co-Pol (V) Az (H-Plane) radiation pattern of manufactured E-Patch antenna array @ 2.3 GHz

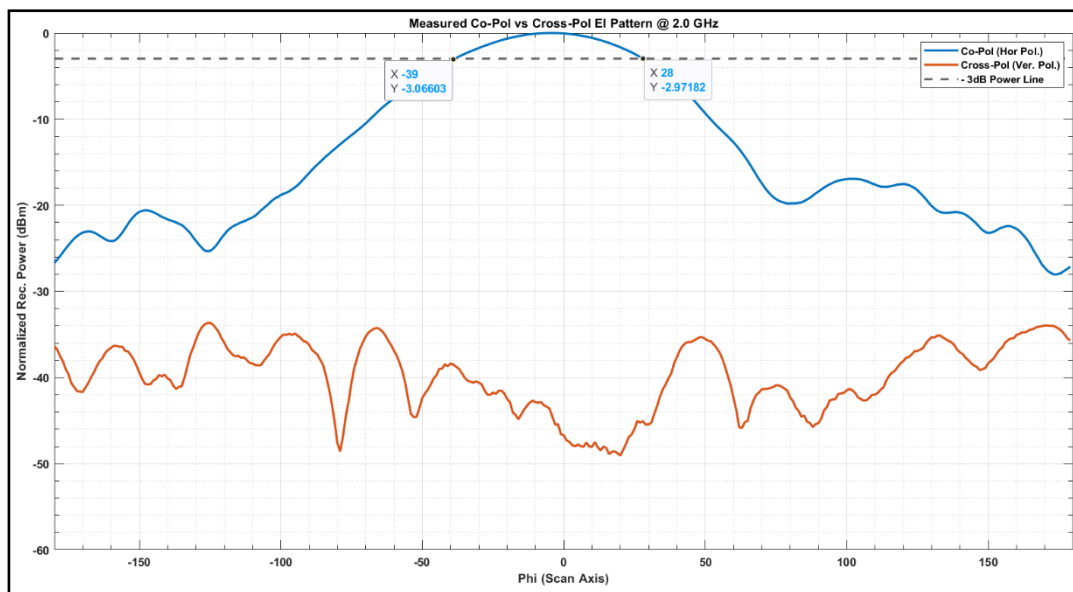


Figure 5-22 Normalized Co-Pol (H) and Cross-Pol (V) El (E-Plane) Pattern @ 2.0 GHz

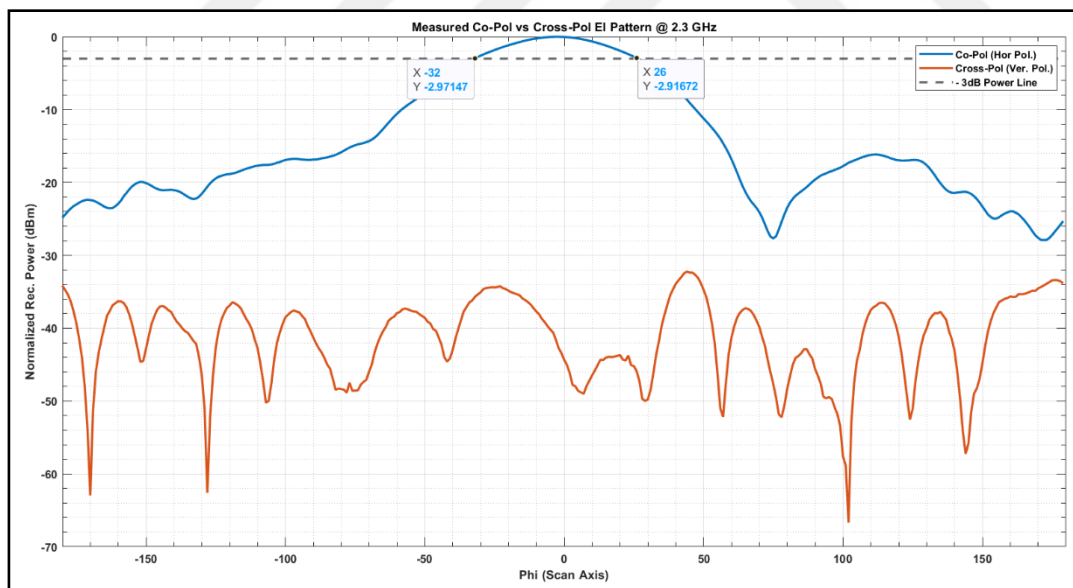
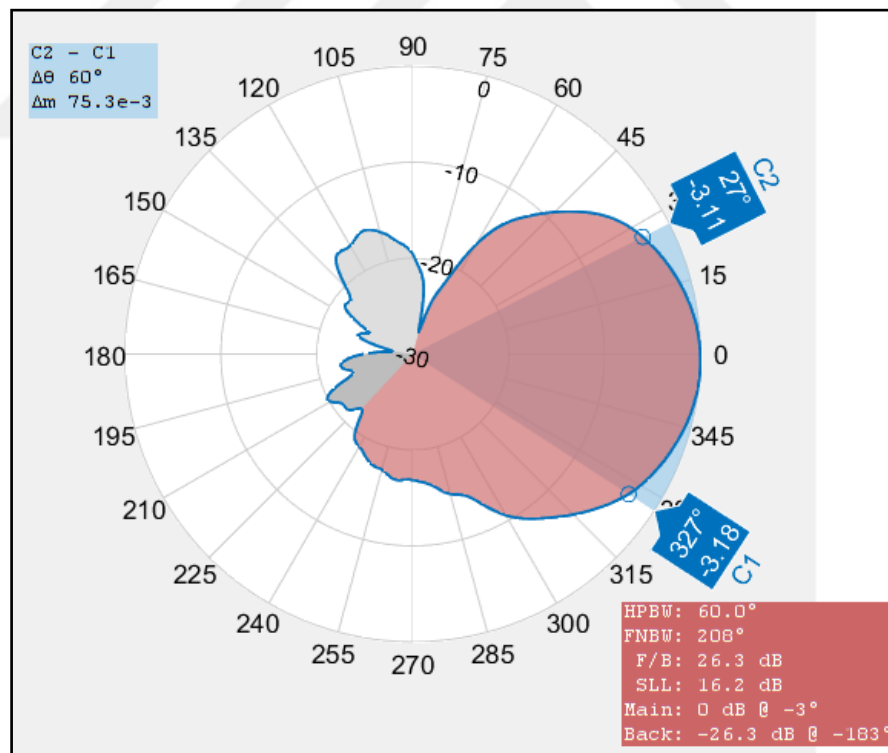
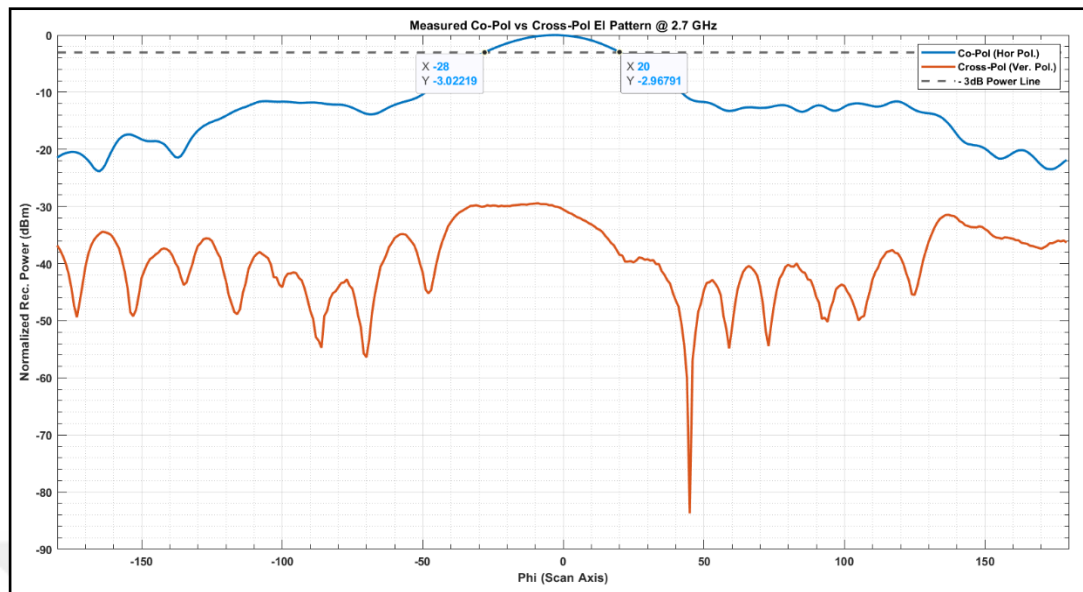


Figure 5-23 Normalized Co-Pol (H) and Cross-Pol (V) El (E-Plane) Pattern @ 2.3 GHz



Compared to the simulation results of four-element E-Patch antenna array radiation patterns given in Figure 2-33 and Figure 2-34, sinc shape, 3 dB beamwidth, and back lobe values of the manufactured antenna are aligned with simulation results.

The boresight gain value of the manufactured antenna from 2 GHz to 2.6 GHz is measured with the two antenna method for details which are given in the. Briefly, to explain the method, the first system under test (SUT) antenna (in our case, E-Patch array) is measured with a standard antenna whose gain values in different frequencies are known. Then the standard gain antenna is measured with a reference antenna whose gain is not critical and not be used. After that, two measured received power equations have subtracted each other, and only the standard antenna with SUT antenna gain values remain. With the knowledge of standard antenna gain and received power levels found with the network analyzer, SUT antenna boresight gain could be measured. The gain expression is given in Equation 5.1.

$$\begin{aligned}
 (G_A)_{dB} + (G_B)_{dB} &= 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 10 \log_{10} \left( \frac{P_{rb}}{P_{ta}} \right) \\
 (G_A)_{dB} + (G_c)_{dB} &= 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 10 \log_{10} \left( \frac{P_{rc}}{P_{ta}} \right) \\
 (G_B)_{dB} - (G_c)_{dB} &= (P_{rb})_{db} - (P_{rc})_{db} \\
 P_{r_{test}} - P_{r_{st}} &= G_{test} - G_{st}
 \end{aligned} \tag{5.1}$$

Our measurements received and transmitted powers with standard antenna as ASYSOL Asyprob-1726 standard horn gain values at 2 and 2.7 GHz given in Table 5-1.

Table 5-1 Measured received transmitted powers and reference antenna gain values.

| Parameter                                    | Value      |
|----------------------------------------------|------------|
| Standard Horn Gain Value @ 2 GHz, $G_{st}$   | 15.9 dBi   |
| Standard Horn Gain Value @ 2.3 GHz, $G_{st}$ | 17.1 dBi   |
| Standard Horn Gain Value @ 2.6 GHz, $G_{st}$ | 17.9 dBi   |
| Received Power-test @ 2 GHz, $P_{rtest}$     | -45.34 dBm |
| Received Power-st @ 2 GHz, $P_{rst}$         | -40.75 dBm |
| Received Power-test @ 2.3 GHz, $P_{rtest}$   | -46.63 dBm |
| Received Power-st @ 2.3 GHz, $P_{rst}$       | -42 dBm    |
| Received Power-test @ 2.6 GHz, $P_{rtest}$   | -47.85 dBm |
| Received Power-st @ 2.6 GHz, $P_{rst}$       | -42.69 dBm |

Using the values given above, manufactured E-Patch antenna boresight gain values are measured in equation 5.2. Due to the lost coupled by SP4T and RF cables, 3 dB variation is put to gain calculation.

$$\begin{aligned}
 -45.34 \text{ dBm} + 40.75 \text{ dBm} &= G_{test} - 15.9 \text{ dBi} + 3 \text{ dB} \\
 G_{test}(@ 2 \text{ GHz}) &= 14.36 \text{ dBi}
 \end{aligned}
 \tag{5.2}$$

Using this formula for other 2 frequency values given in Table 5-2 is found.

Table 5-2 Resulted E-Patch Antenna Array Gain Values

| Parameter                                      | Value     |
|------------------------------------------------|-----------|
| E-Patch Array Gain Value @ 2 GHz, $G_{test}$   | 14.36 dBi |
| E-Patch Array Gain Value @ 2.3 GHz, $G_{test}$ | 15.55 dBi |
| E-Patch Array Gain Value @ 2.6 GHz, $G_{test}$ | 15.75 dBi |

After finding boresight gain values of E-Patch antenna array, this gain values are applied to other received powers and normalized to zero. Firstly, simulated by HFSS normalized gain pattern of the four-element E-Patch antenna array at center

frequency of operation can be seen in Figure 5-26. After taking values of this pattern and fitted together with the measured normalized gain pattern of the manufactured antenna array at center frequency at 2.3 GHz can be seen in Figure 5-27. As seen, simulated and measurement result of manufactured antenna is very similar to each other. It shows that manufacturing process have high quality standarts and current paths on the patches are aligned with the simulations.

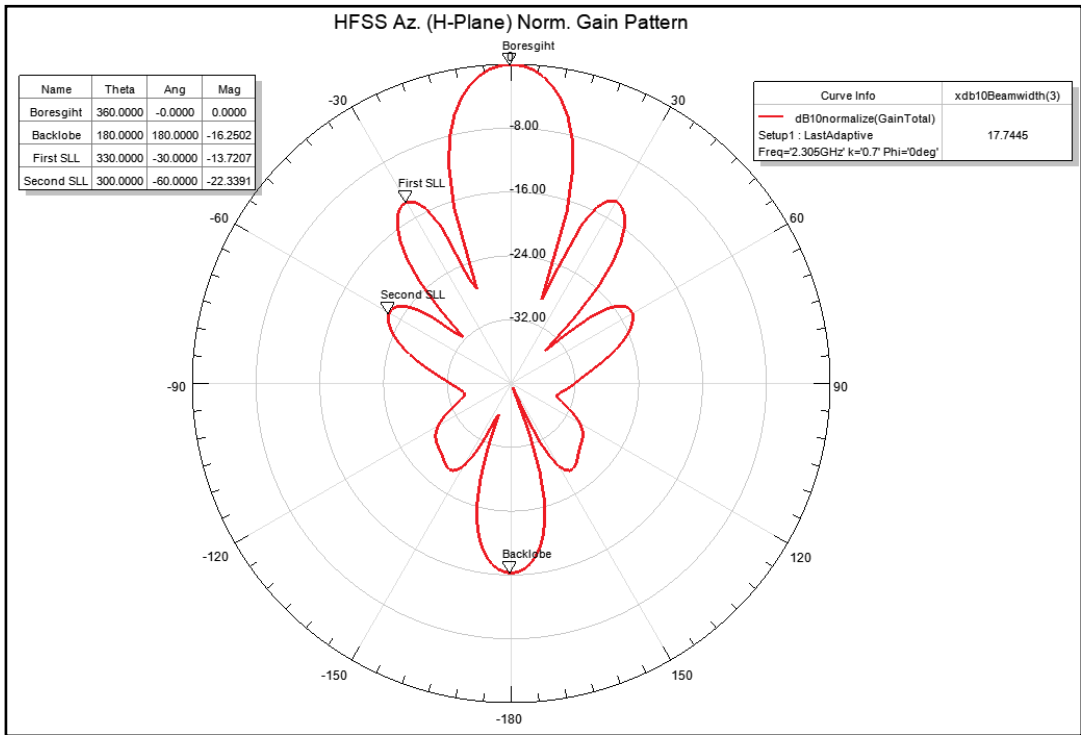


Figure 5-26 Simulated Result of Az. (H-Plane) Co-Pol (V) 4-Elements E-patch Antenna Array with  $k=0.7 \lambda$  Normalized Gain Pattern @ 2.3 GHz

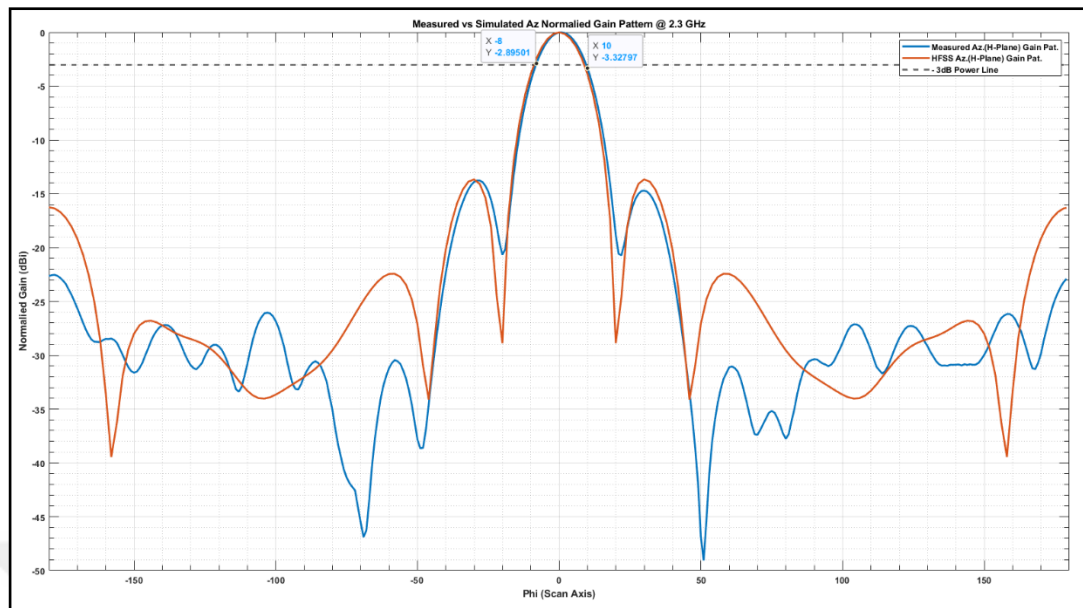


Figure 5-27 Measured vs Simulated Az. (H-Plane) Normalized Radiation Pattern @ 2.3 GHz

It is comparable with the gain values that are found in Figure 2-33 (~15 dBi @2.3 GHz). Summary of the measurement results of manufactured E-Patch antenna array versus to designed antenna array with simulated in HFSS is given in Table 5-3.

Table 5-3 Summary of the results of manufactured and designed E-patch array antennas.

| Antenna Specs                        | Designed Values      | Manufactured Values      |
|--------------------------------------|----------------------|--------------------------|
| Frequency Range ( $S_{11} < -10$ dB) | 1.97 – 2.63 GHz      | 1.96 – 2.70 GHz (<-9 dB) |
| Operating Bandwidth                  | 670 MHz (29%)        | 740 MHz (32%)            |
| Far-Field Peak Realized Gain @ $f_c$ | 15.09 dBi @ 2.31 GHz | 15.55 dBi @ 2.3 GHz      |
| Axial Ratio (> 3 dB = Linear)        | 59 dB                | -                        |
| Radiation Pattern                    | Sinc                 | Sinc                     |
| Azimuthal $3_{dB}$ Beamwidth         | 17.74°               | ~19°                     |

| <b>Table 5-3 (cont'd)</b>             |          |         |
|---------------------------------------|----------|---------|
| Elevational 3 <sub>db</sub> Beamwidth | 57.87°   | 60°     |
| Front to Back Ratio                   | 16.25 dB | 22.4 dB |

## 5.2 Conclusions

Designed and simulated four-element E-patch antenna array is fabricated by using copper plates via using laser cutting. The fabricated antenna array is measured in an anechoic chamber and with a network analyzer of the METU EEE department. The results are compared with the designed antenna array simulation results. The final fabricated antenna array has a broadband characteristic in the higher resonance frequency, radiation patterns, and gain values are suitable for TWR applications. To demonstrate that a prototype TWR setup is established with COTS equipment in Chapter 6.

## CHAPTER 6

### TWR TEST RESULTS

In this chapter, after making sure that fabricated antenna array with its broadband operating characteristics, sinc radiation pattern, good boresight gain, and high front-back ratio value, a prototype through-the-wall radar setup is established with COTS equipment and E-patch antenna as receiving and transmitting sensor. As the target object, a handmade corner reflector is used with different distances to the wall. Measurements are done with a plywood barrier representing the wall between sensors and target.

TWR setup is installed in a monostatic radar case with same Tx and Rx equipment as handheld VNA and array antenna. The radar setup is placed in an open area without massive metal objects that could be prominent, creating multipath effects and distorting our measurements tests. In our measurements, the only radial range can be found due to not having phase shifting diagram that angular discrimination cannot be realized. To obtain target location in a room, an E-Patch antenna array with smaller azimuth beamwidth is needed with beamforming mechanisms.

The geometry of the TWR setup with plywood barrier representing the wall of the room is given in Figure 6-1. Photos of the experimental TWR setup with E-Patch antenna array, the target object, and plywood barrier are given in Figure 6-2 and Figure 6-3.

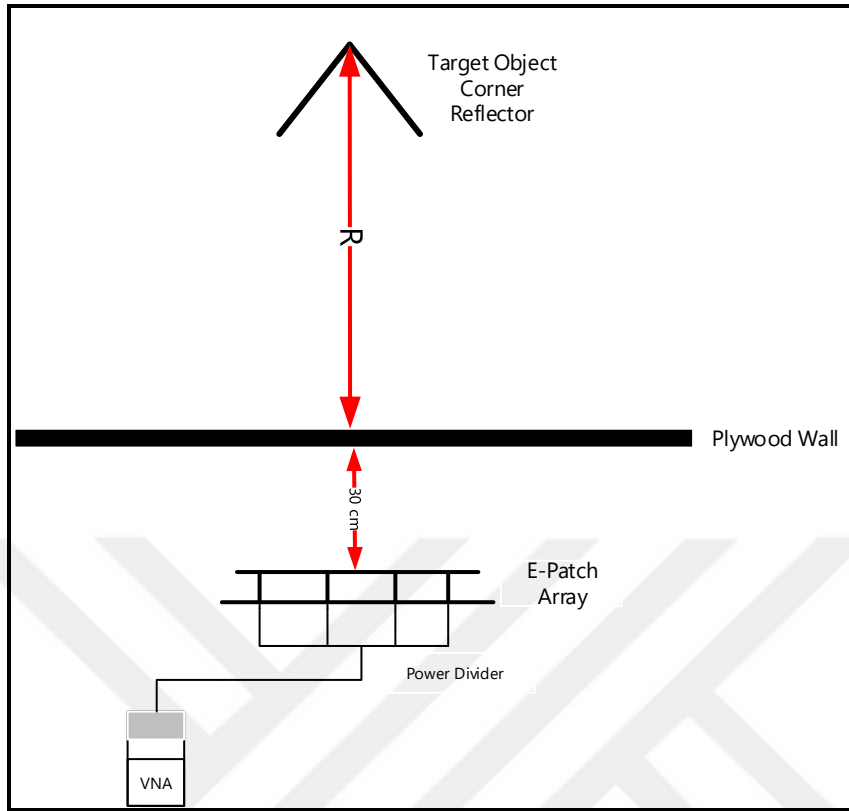


Figure 6-1 Geometry of prototype TWR setup placed in an open-area with plywood barrier as the wall.

The COTS equipment used in the TWR setup as transmitter and receiver is handheld VNA as FieldFox N9915A with time-domain transformation mode. Time-domain operations option applies inverse fast Fourier transform to reflection measurements of the device under test such as  $S_{11}$  and shows time characteristics of the system with picoseconds resolution. With the help of time-domain transformation, our E-patch antenna array is used in the range measurements test setup. In this setup, a metal corner reflector is used as a target object, and its range to the antenna is measured with a network analyzer. To not measure the distance of the RF cables from the measurement port to the power divider, VNA is mechanically calibrated and reference point is taken as the tip of the RF cable. Network analyzer calculates range value given in the screen as related to time by the speed of light and relative velocity;

in space,  $V_{rel} = 1$  ( $3 \times 10^8$  m/s); for distance to response in reflection measurement, multiply by 1/2.

$$Distance = 3 \times 10^8 \text{ m/s} \times V_{rel} \times Time \quad (6.8)$$



Figure 6-2 Photo-1 of experimental TWR setup with E-Patch antenna array with a corner reflector as the target object.



Figure 6-3 Photo-2 of experimental TWR setup with E-patch antenna array.

Details of measurement options, values and modes used on VNA are given in Table 6-1.

Table 6-1 Details of VNA Parameters.

| COTS Equipment        | Item Name             |
|-----------------------|-----------------------|
| NA Mode               | Time-Domain mode [36] |
| Start Freq.           | 2 GHz                 |
| Stop Freq.            | 2.8 GHz               |
| IF BW                 | 1 kHz                 |
| Output Power          | 3 dBm                 |
| # of Points           | 201                   |
| Max. Measurable Range | 125 ns (~18 m)        |

With its sizes as 30 cm (Length), the maximum RCS of the corner fefflector with  $f_c = 2.3 \text{ GHz}$  in theory [31] would be as below:

$$\sigma_{max} = \frac{15.59L^4}{\lambda^2} = 7,43 \text{ m}^2 = 8,7 \text{ dBsm} \quad (6.1)$$

After explaining the test setup, used COTS equipment as VNA, range measurements with experimental TWR with plywood barrier as a wall have resulted in the next section.

## 6.1 Range Measurements with Network Analyzer

After understanding the TWR setup with VNA, three different target object distanctes are set and measured. Firstly, target is put to around 170 cm off to plywood barrier as seen in Figure 6-4. In all of the range measurements, antenna array is

placed to the plywood barrier as 30 cm to not have distortion effect on the antenna input return loss and radiation patterns.

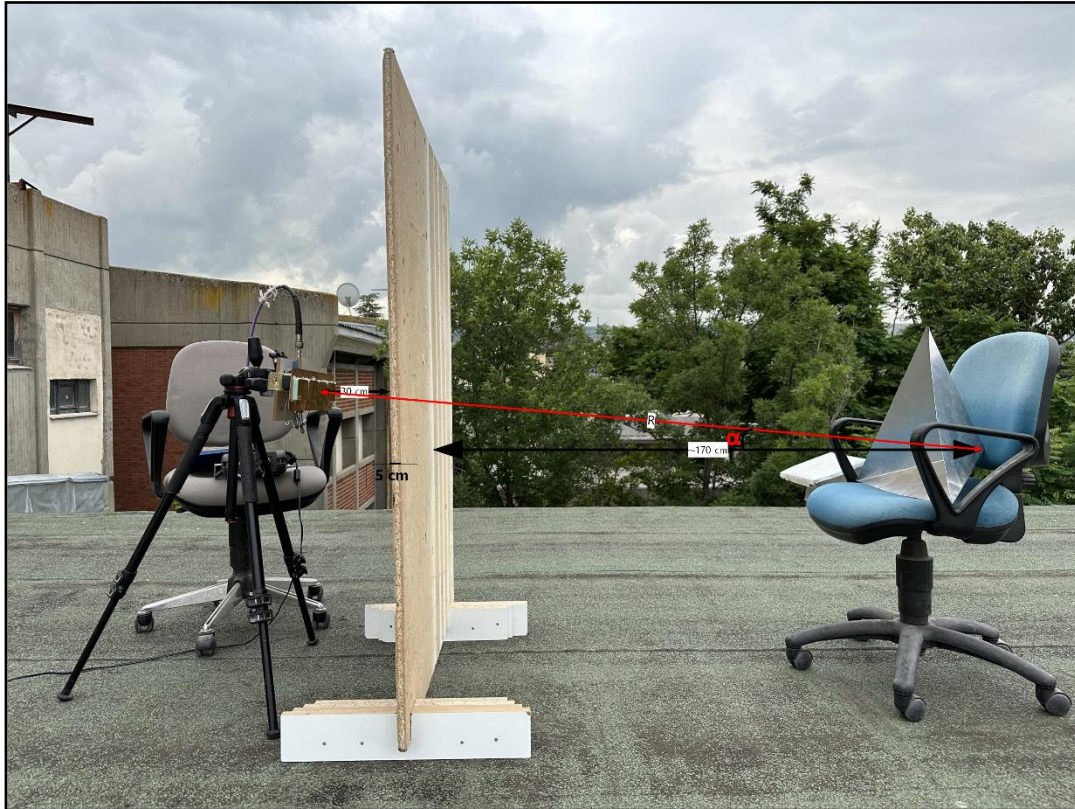


Figure 6-4 TWR Setup-1, target is placed to the plywood as distance of 170 cm.

The measurement result of the first distance value with VNA can be seen in Figure 6-5. As it is seen, first signal with marker 2 represents large reflection scattered from the plywood wall as distance is found around 98 cm's. It is expected since VNA measures time delay value after tip of the RF cable, however power divider and small RF cables that are used to excite SMA ports of the array lengthens the distance to the wall and target object. This delay value measured with a test setup using signal generator and oscilloscope seen in Figure 6-6 and delay value approximately found in Figure 6-7. RF power divider, RF cables and I-point creates some delay and this delay value contributes to the range value. From the first graph and delay values, it seems that RF equipments create around 70 cm range difference. This value should

be accounted for other range measurements. Also in the Figure 6-4, it can be seen that VNA measures the radial distance to the corner reflector mapped as red line in the figure. There is a elevation error due to not having a tripod on the target object, so that creates also a range error as angle difference between radial range and measured range. These two errors should also take account for other two range measurement setups. Second signal with marker 1 represents large reflection scattered from the corner reflector and measures the distance to the antenna. Value is found as  $274 \text{ cm} - 70 \text{ cm}$  (App. Delay value due to RF divider+RF Cables) =  $204 \text{ cm}$ . It is aligned with measured range as  $170 \text{ cm} + 5 \text{ cm} + 30 \text{ cm} = 205 \text{ cm}$ .

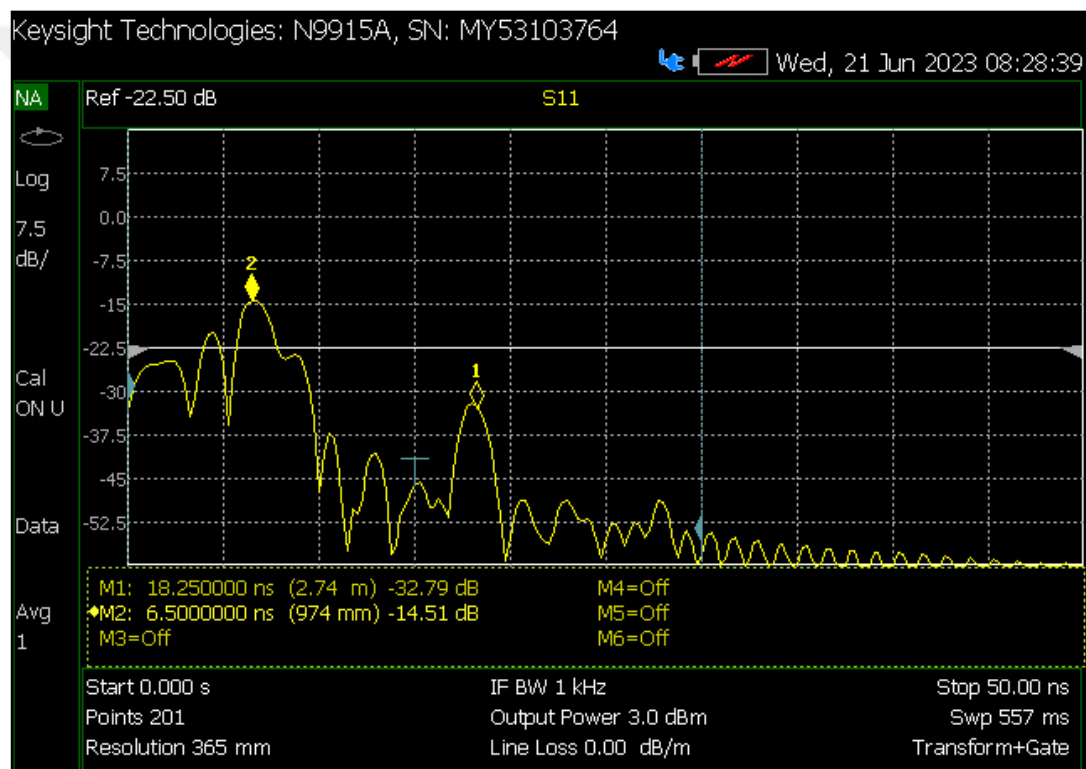


Figure 6-5 TWR Setup-1, Result of the radial range measurement on the VNA screen.

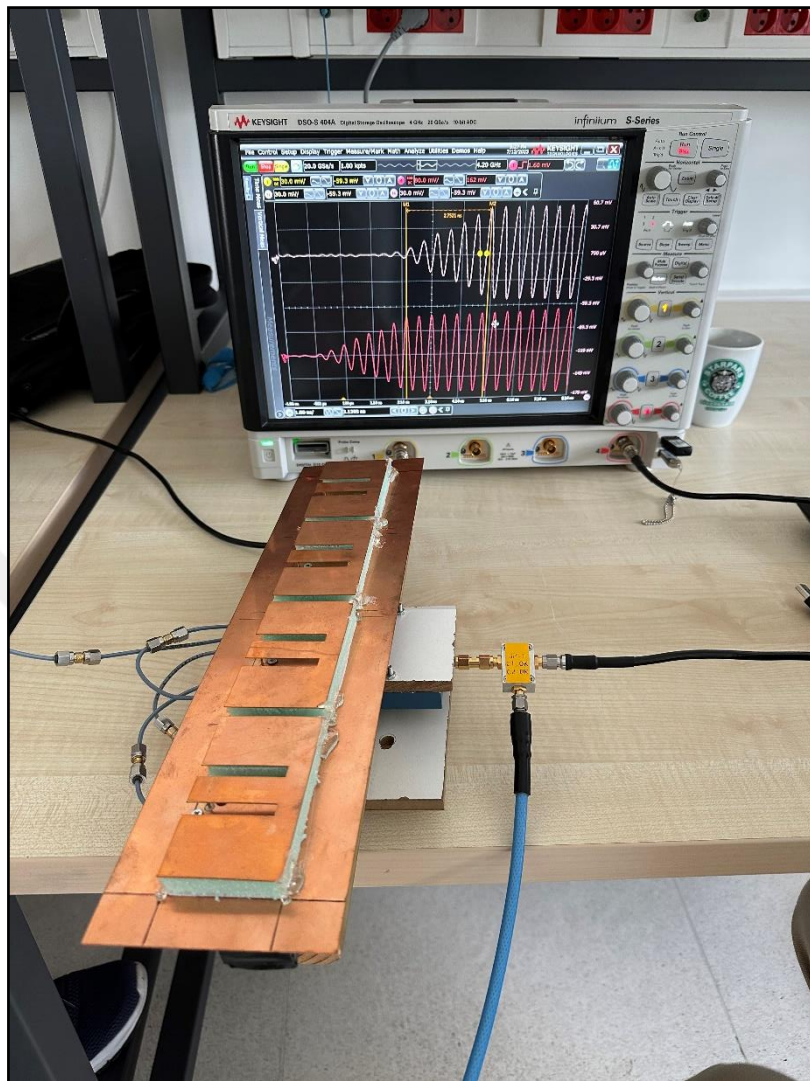


Figure 6-6 4-Divider+RF Cables Delay Measurement Setup

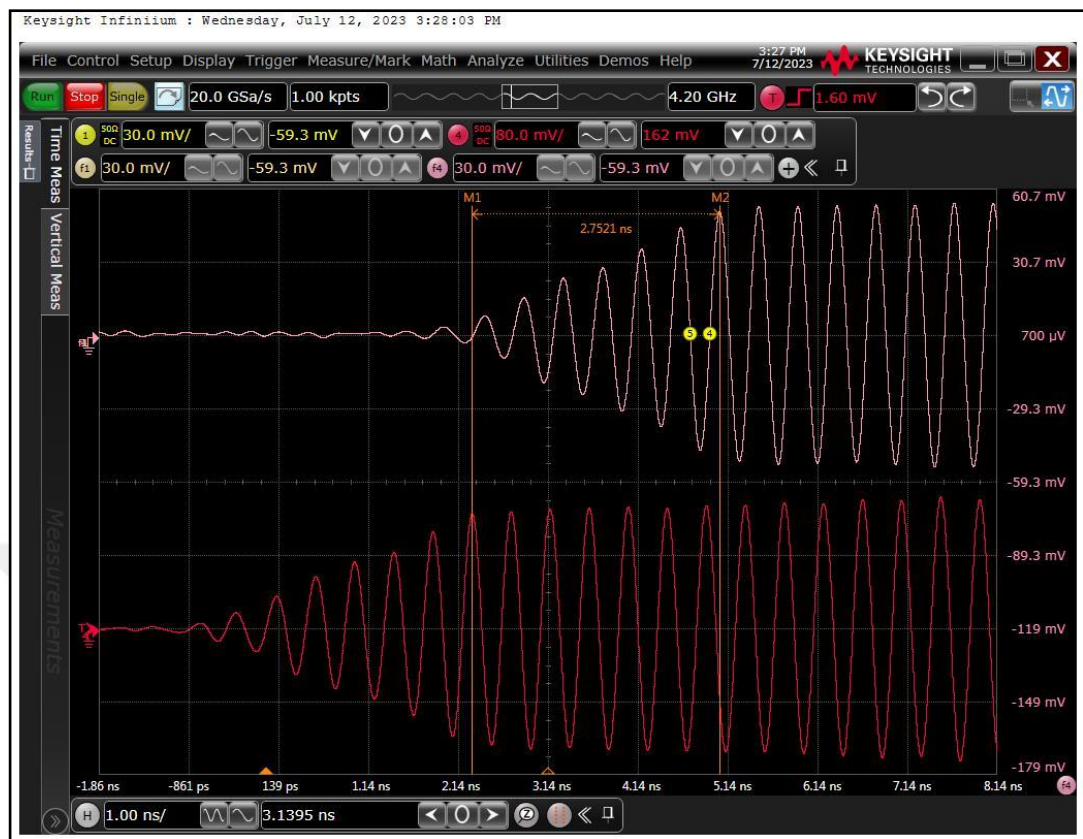


Figure 6-7 4-Divider+RF Cables+I Point Delay Measurement



Figure 6-8 TWR Setup-2, target is placed to the plywood as distance of around 225 cm.

The measurement setup-2 can be seen in Figure 6-8. As seen from the figure, distance between target and plywood barrier around 225 cm. The VNA measurement result is in Figure 6-9. Marker 2 still represents distance to plywood barrier and still has same value as in first setup. Marker 1 shows the distance between antenna array and target object. As seen from the Figure 6-9, radial range is measured as 345 cm and if range delay value is accounted as  $345 - 70 \text{ cm}$  (App. Delay value due to RF divider+RF Cables) = 275 cm. This value is very close to the sum of horizontal distance between target object, antenna and barrier as  $225 \text{ cm} + 5 \text{ cm} + 30 \text{ cm} = 260 \text{ cm}$ . Due to difference between radial range and horizontal distance some range error should be accounted.

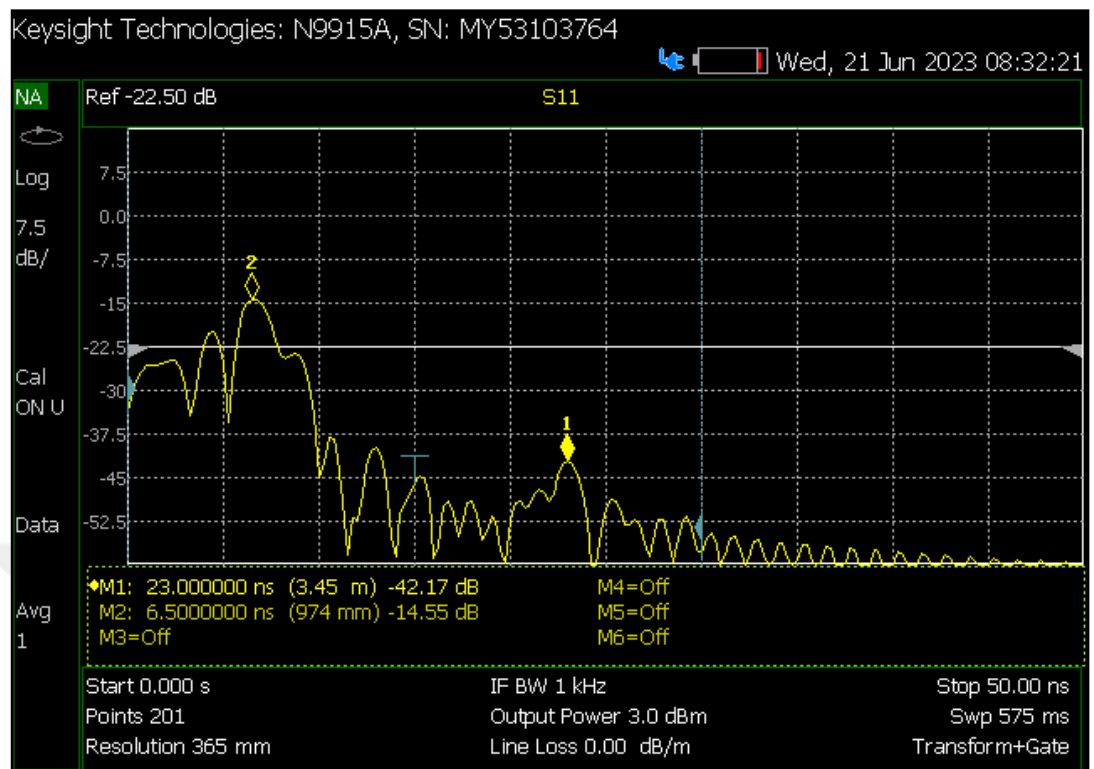


Figure 6-9 TWR Setup-2, Result of the radial range measurement on the VNA screen.



Figure 6-10 TWR Setup-3, target is placed to the plywood as distance of around 245 cm.

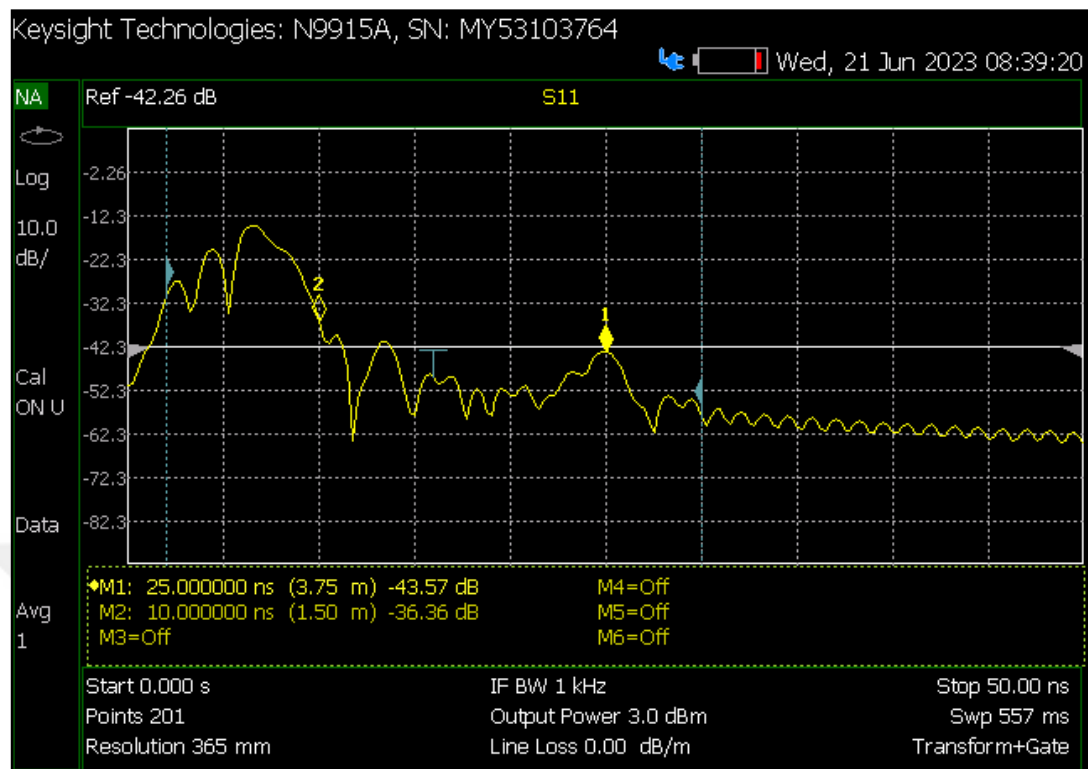


Figure 6-11 TWR Setup-3, Result of the radial range measurement on the VNA screen.

The measurement setup-3 can be seen in Figure 6-10. As seen from the figure, distance between target and plywood barrier around 245 cm. The VNA measurement result is in Figure 6-11. Marker 2 still represents distance to plywood barrier and still has same value as in first setup. Marker 1 shows the distance between antenna array and target object. As seen from the Figure 6-11, radial range is measured as 375 cm and if range delay value is accounted as  $375 - 70 \text{ cm}$  (App. Delay value due to RF divider+RF Cables) = 305 cm. This value is very close to the sum of horizontal distance between target object, antenna and barrier as  $245 \text{ cm} + 5 \text{ cm} + 30 \text{ cm} = 280 \text{ cm}$ . Due to difference between radial range and horizontal distance some range error should be accounted.

From the Figure 6-5, Figure 6-9 and Figure 6-11, it is also observed that the power of the echo signal decreases with larger range values. It is again proven that our E-Patch wideband antenna array can be operated as a transmitting and receiving sensor in a through-the-wall radar system that requires low-profile, wide bandwidth, high front-to-back ratio, suitable gain antennas.

## **6.2 Conclusions**

In this chapter, the designed and manufactured E-Patch antenna array is shown to operate as a receiving and transmitting sensor of an experimental TWR system. A test setup is established with COTS equipment and a target object to measure radial range with a VNA. The target object is placed at different distances to the antenna with a plywood barrier representing the wall of a room. In the end, it is seen that some range measurements are done and proved that the E-patch antenna array could operate in a TWR system with its broadband characteristics, good gain, large beamwidth, and high front-to-back ratio. Test measurements could be improved with more professional test setups and environments.

## CHAPTER 7

### CONCLUSIONS

The purpose of this thesis was to propose low-profile wideband printed antennas for through-the-wall radar applications. TWR systems differentiate from conventional radars due to different working environments, transmitted pulse characteristics, ultra-wideband frequency coverage, and more minor transmitted power levels.

In Chapter 1, radar, ultra-wideband, and through-the-wall radar concepts are briefly explained to give an insight into the systems and sensors used on those applications. Challenges and research gaps of the TWR systems are also mentioned. Also, UWB antennas used on the TWR systems are presented to understand the required antenna parameters for our applications.

In chapter 2, proposed low-profile printed wideband E-shaped patch antenna is parametrically studied. The theoretical features of the radiation and the effects of the antenna parameters are analyzed to get the required antenna for TWR applications. In Section 2, the E-patch antenna was chosen due to more straightforward construction and better simulation results. All of the simulations have resulted in a full-wave EM solver HFSS program. Then, chosen E-patch antenna is analyzed and designed with single-element and array configurations.

In Chapter 3, E-patch single-element and antenna arrays are simulated with primarily used wall materials to investigate the effect of wall medium on antenna working mechanism and specifications. It affects the antenna input matching and radiation patterns mainly for wall mediums with high dielectric constants like brick and concrete type walls. To overcome this problem, antenna arrays with smaller beamwidth and higher boresight gain are needed to operate for concrete and brick

wall materials. However, an antenna array with smaller beamwidth needs a beamforming mechanism to radiate all room with intended objects, which increases system complexity and cost.

In Chapter 4, after proving that wall mediums affect the antenna operating parameters, a bistatic radar with two E-patch antennas as transmitting and receiving sensors is simulated with and without a target object as a corner reflector. In the first case, radar with only a plywood wall is simulated to reference the target object. Later the same scenario is applied with a corner reflector behind the wall. The RCS of the target is realized with E-patch antennas, and it is proven that E-patch antennas are suitable for TWR applications.

In Chapter 5, the designed low-profile wideband E-Patch antenna array is manufactured with limited capabilities manually. Then simulation results of the antenna array are compared with measurement results obtained in the anechoic chamber facility of METU EEE.

An experimental TWR system with COTS equipment is established with a manufactured E-Patch antenna as receiving and transmitting sensor in Chapter 6. This setup proves that a manufactured E-patch antenna array with broadband characteristics, good gain, and large front-to-back ratio values are suitable for TWR applications. TWR system is used to measure the different radial ranges to a target object with and without plywood barrier as representing the wall of a target room. It is seen that the manufactured E-patch antenna array is successful in receiving short-pulse signals that are used in UWB systems.

## **7.1 Future Work**

In the future, designed E-patch antenna arrays with beamforming mechanisms are planned to design, and test with TWR applications. Also, other wideband antenna elements will be simulated and compared with the manufactured E-patch antenna.



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