T.C.
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE
DEPARTMENT OF COMPUTER ENGINEERING

OPTIMIZATION OF PATCH ANTENNAS FOR NEXT GENERATION MOBILE COMMUNICATION SYSTEMS

Prepared by
ALI IHSAN NAJI AL-HUSSEIN

Supervisor
Asst. Prof. Dr. Bilal BABAYİĞİT

M. Sc. Thesis

July 2017
KAYSERİ

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"Optimization of Patch Antennas for Next Generation Mobile Communication Systems" named Erciyes University Graduate Thesis has been prepared accordance with Erciyes University Graduate Thesis Proposal and Thesis Writing Guidelines.

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ALI IHSAN NAJI AL-HUSSEIN

Kayseri, July 2017

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Erciyes University, Graduate School of Natural and Applied Sciences
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ABSTRACT

Mobile communication has been an important part of our social, academic and business activities. Especially, with the proliferation of smart phones and other mobile data devices like netbooks, tablets, laptops, mobile data traffic shows an unprecedented growth. Ultra wideband and millimeter waveband are two candidate technologies for next generation mobile communication systems. However, electronic components, such as antennas, already exist in ultra wideband and millimeter wave communication systems are too big in size and consume too much power to be applicable in mobile communication. Nowadays, lots of researchers have started and much of engineering efforts have been invested in developing antennas for such technologies.

Recently, Bow-tie and Quasi-Yagi antennas has gained popularity due to their attractive features such as low power spectral density, high speed data rate, high gain, low power consumption, and low cost. Because of these attractive features, these antennas are promising for next generation mobile communication systems.

In this thesis, a Quasi-Yagi antenna and two types of Bow-tie antennas are investigated, designed and simulated for next generation mobile communication systems. Quasi-Yagi antenna with an array of two elements is designed for ultra wideband applications. Of two types of Bow-tie antennas, a coplanar waveguide fed Bow-tie antenna is designed for both ultrawide band and millimeter waveband (X-band, Ku-band, and K-band) and a slotted Bow-tie antenna is designed at Ka-band for 5G applications.

The proposed designs are analyzed and optimized on five different substrate materials (FR4, Neltec, Nelco, Arlon, Rogers). Simulation results show that the proposed antennas have high radiation efficiencies, low reflection coefficients, and satisfactory gains. The proposed antennas can be a suitable candidate for ultrawide band and millimeter waveband applications.

Keywords: Bow-tie antenna, Quasi-Yagi antenna, Ultra wideband, Millimeter waveband, 5G applications

GELECEK NESİL MOBİLE HABERLEŞME SİSTEMLERİ İÇİN YAMA ANTEN OPTİMİZASYONU

ALI IHSAN NAJI AL-HUSSEIN

Erciyes Üniversitesi, Fen Bilimleri Enistitüsü
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KISA ÖZET

Mobil iletişim insan hayatının, sosyal, akademik ve ticari faaliyetlerinde önemli bir parçası olmuştur. Özellikle akıllı telefonlar ve netbook'lar, tabletler, dizüstü bilgisayarlar gibi diğer mobil veri cihazlarının yaygınlaşması ile mobil veri trafiği eşi benzeri görülmemiş bir büyüme göstermiştir. Ultra geniş bant ve milimetrik dalga bantları, yeni nesil mobil iletişim sistemleri için iki aday teknolojidir. Bununla birlikte, antenler gibi elektronik bileşenler, ultra geniş bant ve milimetre dalga iletişim sistemlerinde halihazırda kullanılmaktadır lakin boyutları çok büyüktür ve mobil iletişimde kullanılabilmesi için çok fazla güç tüketmektedir. Günümüzde çok sayıda araştırmacı bu teknolojiler kapsamında anten geliştirmeye başlamıştır ve bu konuda büyük miktarda çaba sarf etmektedirler.

Son zamanlarda, Bow-tie ve Quasi-Yagi antenleri, düşük güç spektral yoğunluğu, yüksek hızlı veri hızı, yüksek kazanç, düşük güç tüketimi ve düşük maliyet gibi çekici özelliklerinden dolayı popülerlik kazanmıştır. Bu çekici özelliklerden dolayı, bu antenler yeni nesil mobil iletişim sistemleri için umut verici olmuşlardır.

Bu tez çalışmasında, Quasi-Yagi anten ve iki tip Bow-tie anten, yeni nesil mobil iletişim sistemleri için simüle ve optimize edilmiştir. İki elemanlı bir dizi olan Quasi-Yagi anten ultra geniş bant uygulamaları için tasarlanmıştır. İki tip Bow-tie anteninden, eş düzlemli dalga kılavuzu beslemeli Bow tie anteni, hem ultra geniş bantlı hem de milimetre dalga bandı (X-bandı, Ku-bandı ve K-bandı) ve yivli Bow-tie anteni 5G uygulamalarında kullanılan Ka-band için çalışılmıştır.

Önerilen tasarımlar beş farklı alttabaka malzeme (FR4, Neltec, Nelco, Arlon, Rogers) üzerinde analiz edilmiş ve optimize edilmiştir. Simülasyon sonuçları, önerilen antenlerin yüksek radyasyon verimliliğine, düşük yansıma katsayılarına ve tatmin edici kazançlara sahip olduğunu göstermektedir. Önerilen antenler ultra geniş bant ve milimetre dalga bandı uygulamaları için uygun bir seçim olabilir.

Anahtar kelimeler: Bow-tie anten, Quasi-Yagi anten, Ultra geniş bant, Milimetre dalga bandı, 5G uygulamaları

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THE RESULTS OF THE PROPOSED DESIGNS

CHAPTER 4

LIST OF ABBREVIATIONS

ABC	Absorbing Boundary Condition
BSO	Bacterial Swarm Optimization
CPS	Co-planar strip
CPW	Co-Planar Waveguide
EM	Electro Magnetic
$\boldsymbol{\varepsilon_r}$	Dielectric Constant
FSCBT	Fractal Self-Complementary Bow Tie
G	Antenna gain
GRIM	gradient refractive index metamaterial
h	Substrate Thickness
HFSS	High Frequency Simulation Software
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ISM	Industrial Scientific and Medical Radio
LTCC	Low-Temperature Cofired Ceramic
MIMO	Multiple Input Multiple Output
MS	Microstrip
NM	Nelder-Mead
OAM	orbital angular momentum
PML	Perfectly Matched Layer
RFID	Radio-Frequency Identification
SCBT	Self-Complementary Bow Tie
TV	Television
UWB	Ultra-wideband
VSWR	Voltage Standing Wave Ratio

WIFI	Wireless Fidelity, Wireless Internet
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WRC-19	World Radiocommunication Conference 2019
$\boldsymbol{\Gamma}$	Return Loss
$\boldsymbol{\eta}$	Radiation Efficiency
$\boldsymbol{\eta_r}$	Reflection Efficiency

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INTRODUCTION

Networking area of Computer Engineering focuses on protocols, devices and components that can be used in next generation mobile communication systems. Mobile communication has been one of the most successful technology innovations of our lives especially last two decades [1]. Due to the increasing popularity of smart phones and other mobile data devices like netbooks, tablets, laptops, mobile data demand grows. Almost all wireless commercial applications and systems such as mobile internet, high-definition gaming and video streaming, video sharing, cellular, satellite communication, and global positioning systems, and also Wi-Fi, use below 3 GHz spectrum. So, 3 GHz spectrum has become increasingly crowded. However, a vast amount of spectrum in the 3–300 GHz range remains unexploited. This spectrum represents an ultra-wideband and millimeter waveband mobile broadband system as a hopeful next generation mobile communication system. To meet the unprecedented growth of mobile data traffic and to satisfy the consumers' demand for higher data rates, the use of 3–300 GHz spectrum is of paramount importance [1].

3–12 GHz spectrum is generally referred to as ultra-wideband, this band not only can carry a huge amount of data over a short distance at very low power (less than 0.5 milliwatts), but can carry signals through walls and other obstacles that tend to reflect signals at more limited bandwidths and a higher power, while 12–300 GHz spectrum is referred to as millimeter waveband which is candidate for fifth generation (5G) technology. However, electronic components such as antennas already used in ultra-wideband and 5G technologies are too big in size and consume too much power [2].

Since the inception of short range ultra-wideband and millimeter waveband communication systems the factors like device miniaturization and high-speed data rate create big challenges for antenna designers [1]. Another challenge with millimeter waveband is the low efficiency of antennas devices used. So, it is crucial to design efficient antennas that provide high gain and high bandwidth with reduced antenna size [2].

Antennas work by sending or accepting electromagnetic (EM) waves and it is the last element at the transmission segment and the first element at the receiving end. Therefore, failure in designing an efficient antenna, which can firmly close the link between the endpoints, degrades the system performance. With the rapid increase of Personal Mobile Devices. antennas become more and more important [2].

Engineers are required to design low profile and compact antennas to be accommodated by the miniaturized newly mobile devices. An antenna is usually called low profile if its total height is less than $\lambda/10$. There are numerous antenna configurations such as dipole, horn, microstrip and dielectric resonator antennas [2].

The microstrip patch antenna defined as one of the most interesting developments in antenna and electromagnetic history. Microstrip patch antenna represent the most useful solution to the system that require a radiation element. Of all the printed antennas, including dipoles, slots and tapered slots, microstrip patches are the most popular and adaptable. This is because of all their salient features: including ease of integration, good radiation control and low cost of production [2].

The expression 'patch' is derived from the shape of the printed conductor of the antenna: traditionally rectangular or circular. Microstrip patch antennas are typically resonant in style as opposed to traveling wave and therefore are characterized by being quite efficient over a relatively narrow operation bandwidth. Bow-tie and Quasi-Yagi antennas are the examples of the microstrip patch antenna.

Nowadays, Bow-tie and Quasi-Yagi antennas have become very popular in many applications of next generation mobile communication, radar and sensor systems due to their attractive advantages such as simple geometry, ease of fabrication, low profile with wideband characteristics and high radiation efficiency [3]–[9]. In particular, high gain with low cost property of Quasi-Yagi and Bow-tie antennas make them promising candidates for next generation network systems. Several Bow-tie and Quasi-Yagi antennas designed for next generation network systems; however, they were designed either in a big matrix array or using metamaterials technology [10]–[13].

The aim of this thesis study is to focus on these regions to design an optimal small antennas which can be used for UWB and millimeter waves applications. The Quasi-Yagi, slotted Bow-tie, and CPW fed Bow-tie antennas are selected for them ability to carry high frequencies with small size. These three antennas will investigate, design, simulate, and optimize for ultra-wideband and millimeter waveband applications. Several Quasi-Yagi and Bow-tie has been designed. Of the designed antennas, Quasi-Yagi antenna operate at 10–12 GHz, coplanar waveguide fed Bow-tie antenna operate at three bands (9, 15, and 21 GHz), while slotted Bow-tie antenna operate at 28 GHz, which is the potential frequency of 5G communication applications.

CHAPTER 1

GENERAL INFORMATION AND LITERATURE REVIEW

1.1. Antenna Brief History

The antenna is very important component of the communication systems. By simple definition, it is a device which sends or receives electromagnetic (EM) waves. The antenna has a very old history back to James Clerk Maxwell in 1873 when he presented his antenna for the first time [13]. After the end of World War II, antennas became the main concern of human life through radio and television devices. The United States was one of the first countries give great attention to the antenna industry, where its industry had become a rival to the cars industry there.

In the early 21st century, antennas have witnessed a major development, thanks to mobile devices. Mobile devices are small and accessible to any person and any person can have more than one. Nowadays each mobile device has more than an antenna depending on the applications of the device. So, the strong growth in Radio-Frequency Identification (RFID) devices indicates that the number of antennas used in normal life usage can extend to one antenna per one person in the world or even more than that.

The growth of mobile devices is increasing gradually. Mobile communication systems have become very important part of our daily lives. Also, this phenomenal growth in the use of antennas has prompted a serious search for solutions for the purpose of dwarfing the size of the antenna which is defined as [14].

$$\lambda = \frac{c}{f} \qquad 1.1$$

where c represents the light speed, which is $3x10^8$ m/s in air and f is the frequency (cycles per second). When a radio wave moves through a non-conducting medium other than air, this slows the wave down and results in a shorter wavelength. These factors do not affect the simulated antenna while it affects too much the designed and analyzed antenna [2]. An antenna as a transmitter device is shown in Figure 1.1 [2].

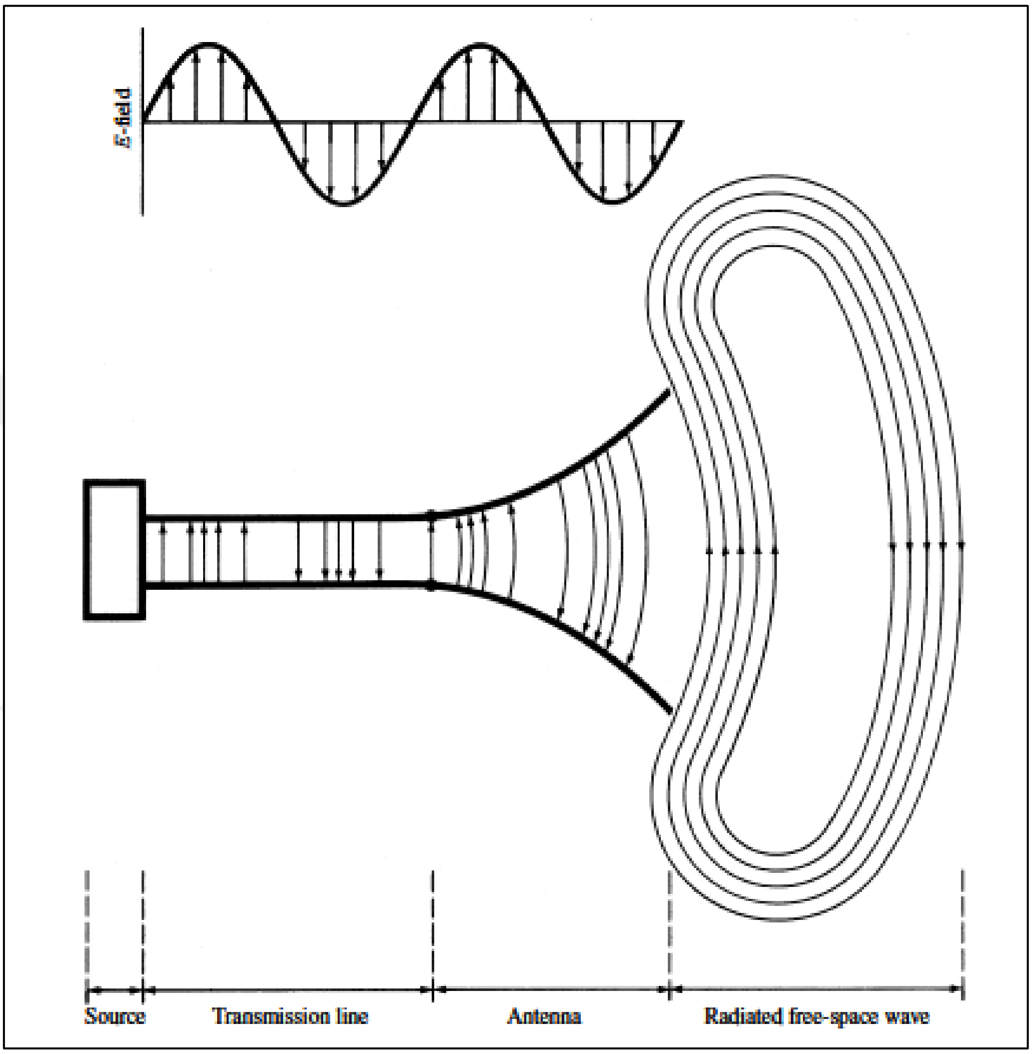


Figure 1.1. Antenna radiation [2]

Before understanding the designing of antenna or types of antenna, the fundamental parameters that characterize an antenna, must be understood.

1.2. Antenna Fundamental Parameters

To understand the challenges facing an antenna designer, some of the fundamental parameters and performance metrics must be known. Fundamental parameters and performance metrics completely control the design geometry and evaluate the performance of the antenna [2]. Some of the antenna parameters are:

- Impedance bandwidth
- S-parameters
- Radiation pattern
- Directivity
- Efficiency
- Gain
- VSWR.

In next subsection, each of these parameters will be explained briefly.

1.2.1. Impedance bandwidth

The impedance bandwidth is a relationship between the current and voltage at the frontend of the antenna is called the antenna. It is the power which is received by the antenna or radiated away from the antenna [2]. The impedance bandwidth can be measured by the characterization of both the Voltage Standing Wave Ratio (VSWR) and Return Loss (RL) at the frequency band of interest. Both VSWR and RL are dependent on measuring the reflection coefficient.

1.2.2. S-Parameters

S- (scattering) parameters are very popular in RF circuit design. They are used for measuring and characterizing the device efficiency. S-parameters include S_{11}/S_{22} (Reflection coefficient), S_{12} (Isolation) and S_{21} (Insertion loss), and are illustrated in Figure 1.2. S_{11}/S_{22} is also named as return loss. If return loss is zero ($S_{11}=S_{22}=0$), then this means that there is no power being reflected back due to a good match to the characteristic impedance of the feeding structures, usually 50Ω for commercial applications and 75Ω for military applications [2].

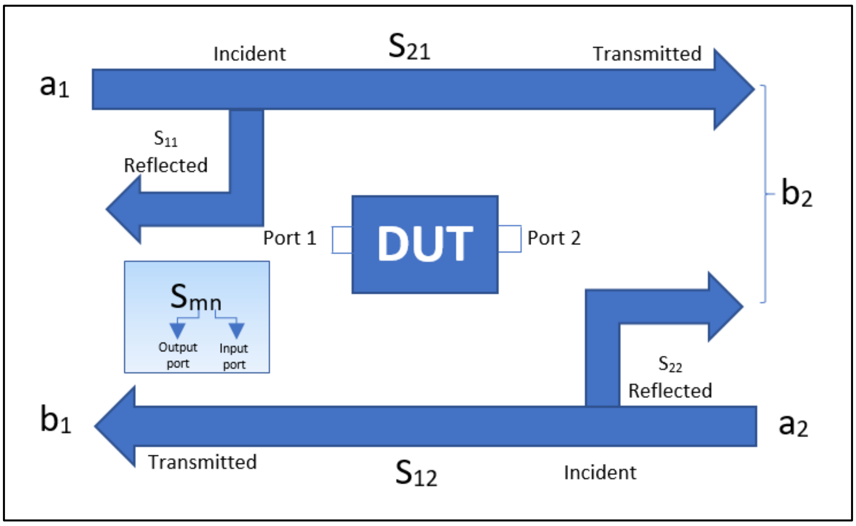


Figure 1.2. S-parameters

In Figure 1.2, DUT is Device Under Test, S_{11} is reflection coefficient at Port1, S_{22} is reflection coefficient at Port2, S_{12} is isolation (reverse), S_{21} is insertion loss (passive device case), a_1 is the signal incident at port 1, b_1 is the signal reflected at port 1, a_2 is the signal incident at port 2, b_2 is the signal reflected at port 2.

1.2.3. Radiation pattern

The radiation pattern is the difference in the power radiated away from the antenna as a function of the direction [14]. Primarily, when measuring the radiation pattern, the property of most interest is the energy radiated relative to the antenna position [2].

1.2.4. Directivity

It is a measure how directional the antenna's radiation pattern. The directivity of the antenna is transmitted evenly in all directions would be 1 or 0 dB and the directionality of the antenna would be definitely zero [14], [15]. So, it is clear that, increased directivity gives a very satisfactory antenna.

1.2.5. Efficiency

The efficiency of an antenna is a ratio of the power received to the antenna relative to the power radiated from the antenna. A high efficient antenna means most of the power at the input ports of the antenna are radiated away and a low efficient antenna means most of the power is not received by the antenna (receive as losses) or reflected away because of the impedance mismatch [16]. If there are no losses due to mismatch or the antenna, then it can be seen, for a given frequency. Also, efficiency depends on the antenna size. If the antenna size is reduced, the efficiency is reduced [2].

1.2.6. Gain

Antenna gain represents the measurement of the power of efficiency and directivity to convert the electricity to radio waves. The most suitable candidate for efficiency and directivity of the antenna is theta. The antenna gain is represented in decibel (dB) and the gain can be define as [2].

$$\text{Gain} = \text{Efficiency} * \text{Directivity} \tag{1.2}$$

1.2.7. VSWR

Voltage Standing Wave Ratio (VSWR) is a function of the reflection coefficient which describes the power reflected from the antenna. VSWR is a measure of how efficiently the power is transmitted from the antenna. VSWR value under 2 is considered suitable for most antenna applications. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna which is ideal [2].

1.3. Antenna Types

The fundamental parameters used to characterize the antenna performance have been discussed in section 1.2. Generally, the size of the antenna starts to occupy a large area of the researchers. The new technological devices are now expected to be lighter, smaller, and more importantly, to be wirelessly networked. Therefore, different types of antennas have been developed, optimized and produced over the years for many different applications like wire, aperture, array, printed, reflector and lens antennas [2].

1.3.1. Wire Antennas

Wire antennas are probably the most recognizable, as they are everywhere. So, they can be seen in TV aerials, car aerials etc. Examples of wire antennas are short dipole antenna, dipoles antenna, loops antenna, half-wave dipole, helical antenna, broadband dipoles, monopole antenna, folded dipole antenna, sleeve dipoles antenna, yagi-uda arrays antenna, and cloverleaf antenna. Generally, wire antennas work at lower frequencies because they have low gain. They have the advantages of low cost, ease of fabrication and design.

1.3.2. Aperture Antennas

Aperture antenna a material has physical slots through which propagate EM wave flow. The slots are several wavelengths long in one or more dimensions. The high gain of the antenna is provided by the narrow main beam. Examples of these antennas are horn, lenses, the slot, slotted waveguide, and circular apertures antennas. These models of antennas are quite useful for many applications of spacecraft or an aircraft.

1.3.3. Array Antennas

Array antenna is a number of elements arranged together individually to create the array matrix. The patterns of the array are defined by the phase of the excitation fields and corresponding amplitude of each source and the geometric spacing of the sources. There are many types can be in array design like dipoles, monopoles, microstrip, slots in waveguides, and open-ended antennas.

1.3.4. Printed Antennas

All the antennas mentioned in sections 1.3.1 to 1.3.3 can be designed as printed antennas. So, the printed antennas are very common. Printed antennas are also called microstrip antenna and uses the photolithographic technique, with both the antenna fabricated on a dielectric substrate and the feeding structure.

1.3.5. Reflector Antennas

Sending or receiving signals over millions of miles need a high gain. The reflector antenna is the biggest size among the other antennas even they can be built with 305 m of diameters or larger than that. This kind of antenna usually used in radar and satellite applications.

1.3.6. Lens Antennas

Lens antennas are usually used for high frequencies to prevent the divergent energy from spreading in unwanted directions. They can be divided into different kinds according to their shapes or their material which made from.

1.4. Antenna Structure

Antennas can have different shapes such as square, rectangular, U shape, E shape, circular and elliptical as shown in Figure 1.3, but any continuous shape can possible and many other shapes can be designed using different simulation software. The designs of the antenna are in high demand and are desirable for many uses like personal mobile devices, small satellite communication terminals and other applications involving wireless communication [17].

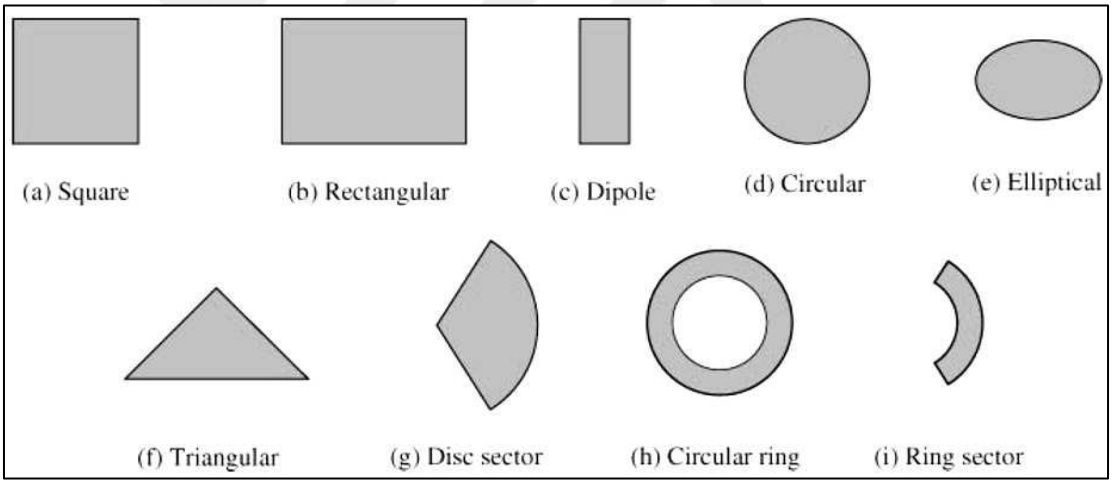


Figure 1.3. Different antenna shapes

1.5. Antenna Substrate Material

Many different substrates materials are used in the design of antennas. The dielectric constant (ε_r) of the substrate materials are generally in the range of $2.2 \leq \varepsilon_r \leq 12$. Low ε_r provides greater efficiency and wider bandwidth, but the antenna should in large size [2]. So, there is a trade-off between ε_r and the antenna size. ε_r is also depends on the type of the design and the bandwidth. Because antenna requires tightly bound fields to minimize undesired radiation, coupling and guide to miniature element sizes, light substrates with higher ε_r which are useful for microwave circuitry [18].

Microstrip patch antenna can be created on a variety of substrate materials with different dielectric constants such as Arlon CuClad 217, FR4_epoxy, Nelco N4000-13, Neltec NH9294 and Rogers RT/duroid 5880. These substrate materials represent the top requested materials for high frequencies designs [19], [20], [21].

Arlon CuClad 217 is one of the Rogers crop. uses a low fiberglass/PTFE ratio to provide the lowest dielectric constant ($\mathcal{E}_r$=2.17) and dissipation factor available in fiberglass reinforced PTFE-based laminates. These properties offer faster signal propagation and higher signal/noise ratios. The general applications of the Arlon material in military electronics (Radars, ECM, ESM) and microwave components (LNAs, filters, couplers, etc.).

Rogers RT/duroid 5880 is designed as a high frequency laminates material with glass microfibers. The dielectric constant of this material is very low ($\mathcal{E}_r$=2.2). So, this material is suitable for high frequency and broadband applications. This material is applied in commercial airline broadband antennas, microstrip and striplines circuits, millimeter wave applications, military radar systems, missile guidance systems, point-to-point digital radio antennas.

FR4_epoxy is made of alkali-free E-glass cloth impregnated with epoxy resins by processing under heat and pressure. The characters of this material are high temperature resistance, high intensity, high mechanical properties, and dielectric properties ($\mathcal{E}_r$=4.4) and good smoothness, etc. FR4_epoxy substrate materials are using in wireless antenna design, tri-band antenna, millimeter waves technique.

Neltec NH9294 and Nelco N4000-13 with dielectric constant ($\mathcal{E}_r$=2.94, 3.5 respectively) are designed for microwave components like antennas, power amplifiers and subassemblies. Superior mechanical and electrical performance make these two materials the best choice for lowest loss and high frequency applications like cellular base station antennas, wireless communications, power amplifiers, dual band hi power passive circuits, millimeter wave components.

1.6. Microstrip Patch Antenna

Microstrip patch antennas are used in mobile and wireless communication systems because they have low profile, small size, light weight and low cost and provide a high bandwidth [22]. Another advantage of microstrip patch antennas is their feeding. They can be fed in different ways like microstrip feeding, aperture coupling, coaxial probe, coplanar waveguide (CPW), and proximity coupling. A microstrip patch antenna in its simplest form as shown in figure 1.4. It consists of a radiating patch, which is made of metal, on one side of a dielectric substrate and a ground plane on the other side.

For proper design, microstrip patch antenna should not be exceed the required limits for all design parameters and must satisfy the characteristics of components required. The simulation software like HFSS and CST are used to design the microstrip patch antennas.

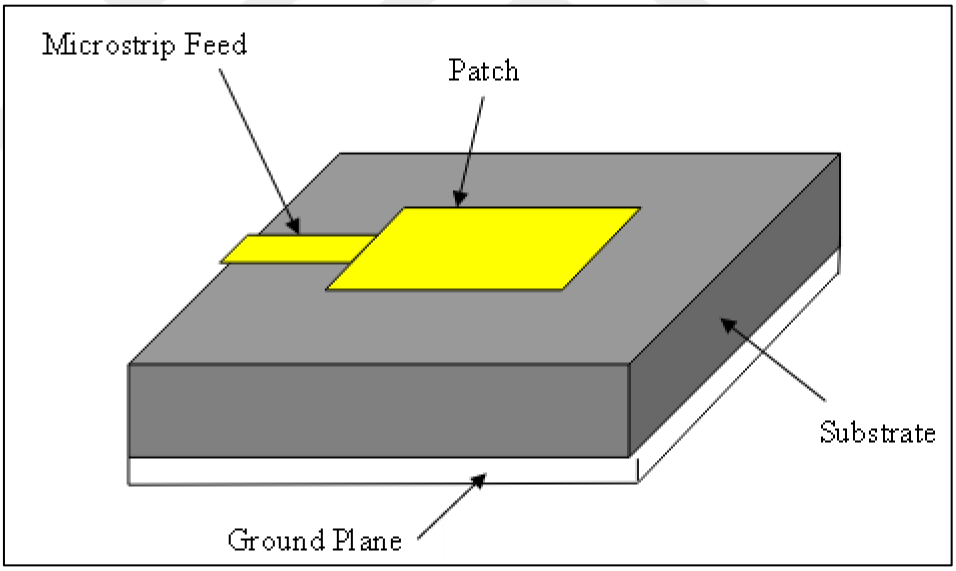


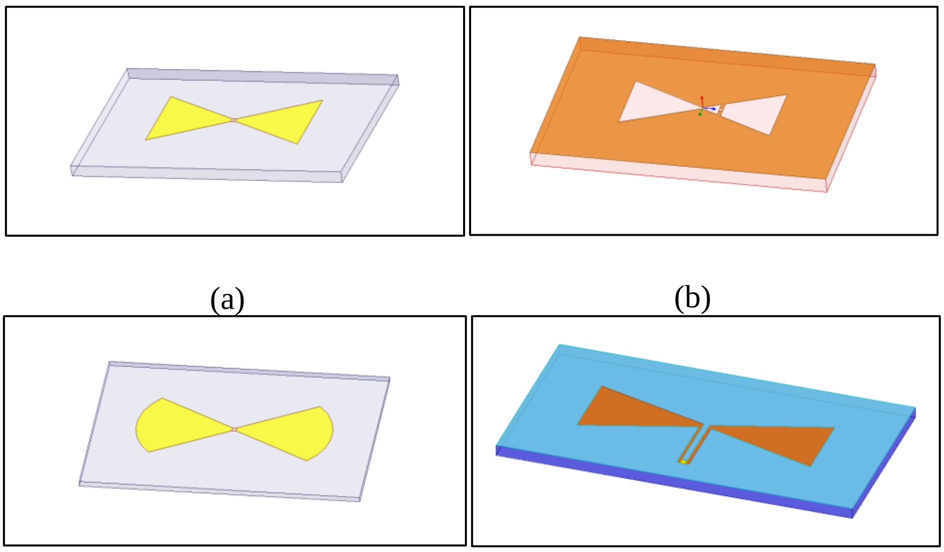
Figure 1.4. Microstrip Patch Antenna

Bow-tie and Quasi-Yagi antennas are the examples of the microstrip patch antenna. Bow-tie and Quasi-Yagi antennas have become very popular in many applications of next generation mobile communication, radar and sensor systems due to their attractive advantages such as simple geometry, ease of fabrication, low profile with wideband characteristics and high radiation efficiency [22]. The configurations of Bow-tie and Quasi-Yagi antennas will be explained briefly in the next subsections.

1.6.1. Bow-tie Antenna Design

Bow-tie antenna is a bi-triangular sheet of metal or two triangles meet from the head in microstrip patch antenna design [17]. Bow-tie antenna has the advantages of low profile antennas with wideband characteristics and high radiation efficiency. Because of the larger radiating area, there is a future vision that the directive of Bow-tie antennas will be better than conventional dipole antenna [23]. The back lobes of the patterns are approximately 10 dB lower compared to the forward lobes. This difference is due to the presence of the ground plane, which “pushes” the radiation pattern against itself and toward the Bow-tie [2].

Bow-tie antenna is used widely in many applications such as ground filtering radar, the mobile devices [3], [24]–[26] and Wi-Fi applications [27]. The Bow-tie antenna can be feed by coaxial line [28], [29], coplanar waveguide [30], [31] and striplines [32]. In the literature, several structures of Bow-tie antenna as shown in Figure 1.5. they are the simple Bow-tie antenna [33], slotted Bow-tie antenna [26], rounded Bow-tie or circular Bow-tie antenna [34], and coplanar waveguide (CPW) fed Bow-tie antenna [35].



(a) (b) (c) (d)

Figure 1.5. Four Bow-tie antenna models (a) Simple Bow-tie, (b) Slotted Bow-tie, (c) Rounded Bow-tie, (d) CPW fed Bow-tie

Slotted Bow-tie and CPW fed Bow-tie antennas are attractive types of Bow-tie antennas for high frequencies with small size, these features are small size, easy to feed, high bandwidth, inexpensive to fabrication, and omnidirectional radiation pattern [36].

1.6.1.1. Slotted Bow-tie Antenna

Slotted Bow-tie antenna is depending on the requirements, and the frequency or time domain usage [37]. In this thesis, the slotted Bow-tie antenna will be designed for frequency domain applications to increase the antenna bandwidth. In this case two parameters are important, the slot width and location [38]. There are no general ratios to determine those parameters because they depend also on the Bow-tie dimensions (outside width, inside width, tri-length, substrate length, substrate width, and substrate thickness) as shown in Figure 1.6. The easiest way to determine the optimal slot width and location for obtaining the best result is by performing a parametric study. The simulation software offers a parametric technique to optimize and get the optimal design.

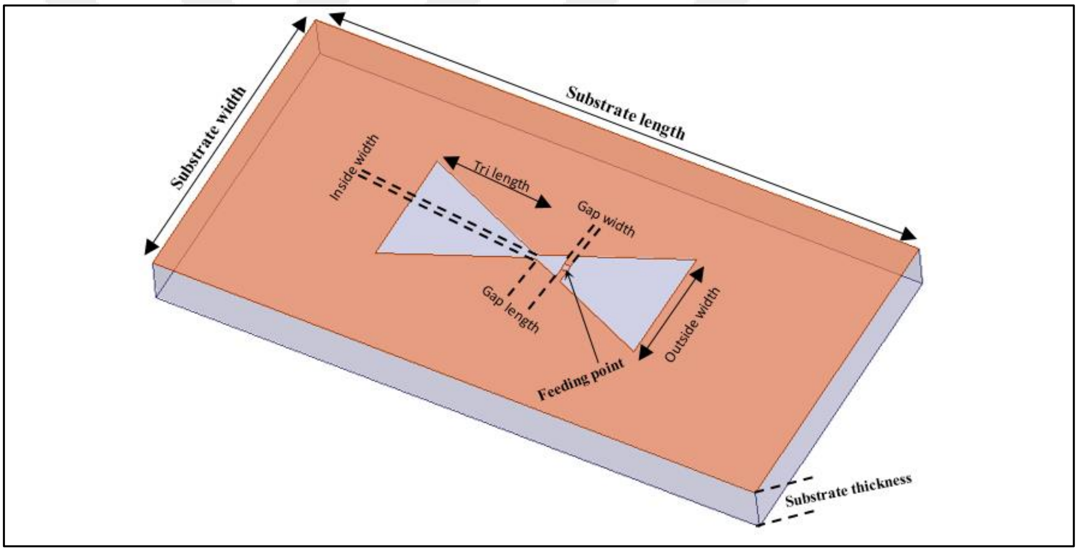


Figure 1.6. The slotted Bow-tie antenna geometry

1.6.1.2. CPW fed Bow-tie Antenna

The name of the CPW fed Bow-tie antenna took from the feeding way [39]. The antenna that fed by CPW has several advantages like, wider bandwidth, lower dispersion, and lower radiation loss. The CPW also presents a parallel and series feeding connection with active and passive elements. This kind of connection are required for impedance matching and gain improvement.

The CPW fed Bow-tie antenna requires a balanced feed network, so the antenna can be fed by coplanar microstrip line. The whole dimension of the antenna and the feeding port is shown in Figure 1.7.

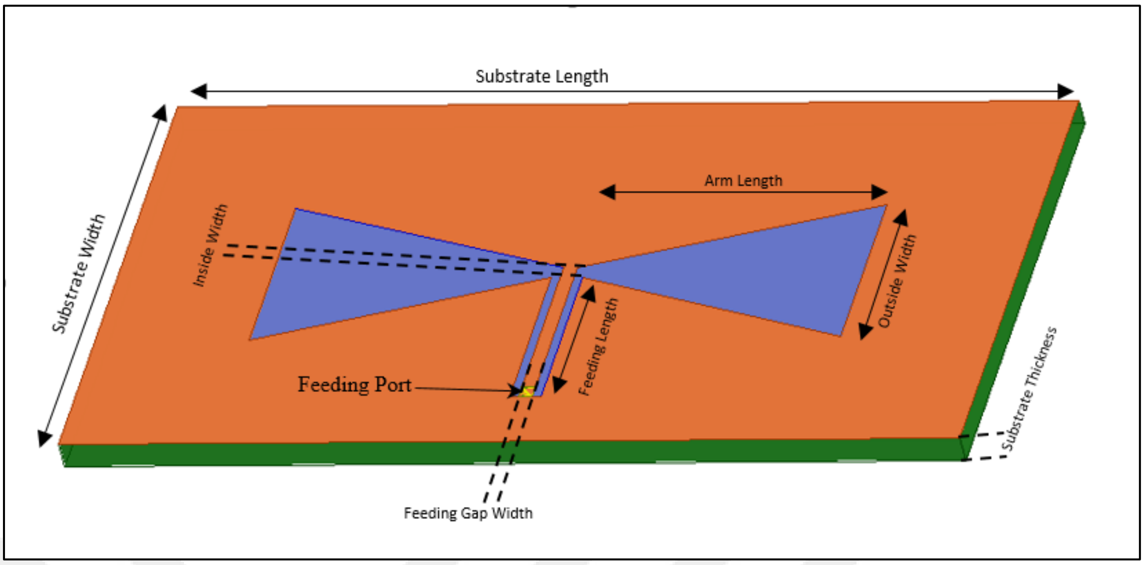


Figure 1.7. CPW fed Bow-tie antenna dimensions

1.6.2. Quasi-Yagi Antenna Design

The Quasi-Yagi antenna usually used for high band frequencies [5], [6], [40], [41]. Quasi-Yagi antenna is one of the useful antennas for broadband and high gain applications. Printed Quasi-Yagi antenna is a kind of broadband antennas [2]. Its advantages contain not only the characteristics of Yagi antenna with high gain, but also the miniature size, realized by the adoption of high permittivity substrate. Hence, Quasi-Yagi antenna has a promising feature. Currently, the Quasi-Yagi antenna can be designed in an array to improve the bandwidth for ultra-wideband communication applications.

The design of Quasi-Yagi antenna is shown in Figure 1.8. The antenna is similar to the traditional Yagi antenna, which is composited by two parts. The upper is the radiation unit, including a printed dipole and one or more directors, which can direct the EM radiation, as well as adjusting the input impedance.

The reflector builds on the back of the microstrip as a ground plane and represents a big advancement in Quasi-Yagi antenna. This kind of reflectors has a decreased backward radiation. Therefore, the direction of the peak gain is away from the ground plane.

The geometry of the single Quasi-Yagi antenna can be shown in Figure 1.8, the director length is (L_{dir}), the director width is (W_{dir}), the director space is (S_{dir}), the driven length is (L_{dri}), the driven width is (W_{dri}), the driven space is (S_{dri}), the feeding length is (L_f), the feeding width is (W_f), the length of the Quasi-Yagi structure is controlled by (L_1, L_2, L_3 and L_4) and the width of the Quasi-Yagi structure is controlled by (W_1).

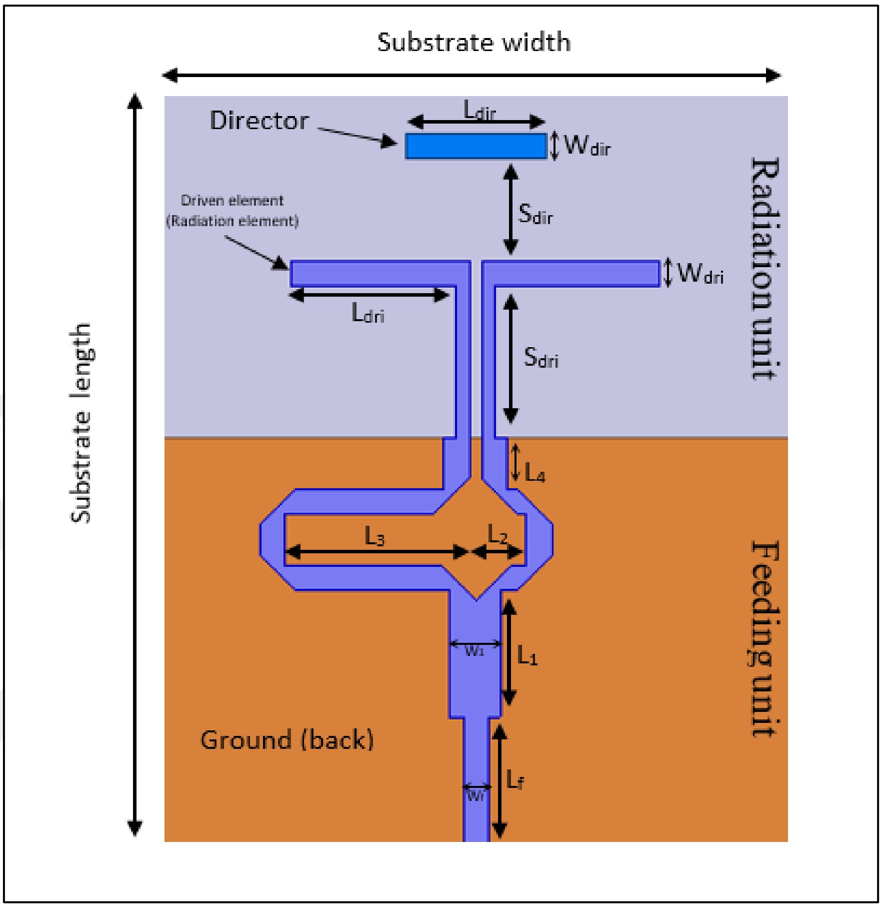


Figure 1.8. The Quasi-Yagi antenna geometry

To create an antenna design, EM spectrum should be known.

1.7. EM spectrum

The EM spectrum consists the waves of all ranges of wavelength or frequency as listed in Table 1.1. It has the harmful rays like IR rays and some useful rays like radio wave for communication, X-rays for medical purpose, microwaves for cooking etc. The wave energy depends on the frequency of the waves and it increases by increasing the frequency, while decreasing with wavelength [42].

Table 1.1. EM spectrum

Name	Wavelength (m)	Frequency (Hz)	Photon Energy (eV)
Gamma ray	$< 6\times10^{-12}$	More than 10 EHz	100 keV–300+ GeV
X – ray	6×10^{-12} - 8×10^{-9}	30 PHz–30 EHz	120 eV–120 keV
Ultraviolet	8×10^{-9} - 3.8×10^{-7}	790 THz–30 PHz	3 eV–124 eV
Visible	3.8×10^{-7} - 7.6×10^{-7}	405 THz–790 THz	1.7 eV–3.3 eV
Infrared	7.6×10^{-7} - 0.001	300 GHz–405 THz	1.24 meV–1.7 eV
Microwave	0.001-0.3	300 MHz–300 GHz	1.24 μeV–1.24 meV
Radio	> 0.3	3 Hz–300 MHz	12.4 feV–1.24 meV

As can be seen in Table 1.1, the Microwave region in the EM spectrum lies between 300 MHz to 300 GHz which roughly comprises of the UHF and EHF bands of the radio waves [43]. The microwaves are defined as wave with the wavelength in the range of micrometers [43]. Microwave bands are illustrated in Table 1.2, which is given by the Royal Society of Great Britain [44].

Table 1.2 Microwave region bands [44]

Letter Designation	Frequency Range
L-band	1 to 2 GHz
S-band	2 to 4 GHz
C-band	4 to 8 GHz
X-band	8 to 12 GHz
Ku-band	12 to 18 GHz
K-band	18 to 26.5 GHz
Ka-band	26.5 to 40 GHz
Q-band	33 to 50 GHz
U-band	40 to 60 GHz
V-band	50 to 75 GHz
E-band	60 to 90 GHz
W-band	75 to 110 GHz

1.7.1. Ultra-wideband Radio Region

Ultra-wideband (UWB) is a radio technology that can use a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum. The general range for the UWB is 3–12 GHz and the traditional applications in non-cooperative radar imaging [45]. UWB radio not only can carry a huge amount of data over a short distance at very low power (less than 0.5 milliwatts), but can carry signals through walls and other obstacles that tend to reflect signals at more limited bandwidths and a higher power [46].

1.7.2. Millimeter Waveband Radio Region

Almost all commercial radio communications including AM/FM radio, high-definition TV, cellular, satellite communication, GPS, and Wi-Fi have been contained in a narrow band of the RF spectrum in 300 MHz–3 GHz [47].

The use of the 57–64 GHz oxygen absorption band is also being promoted to provide multigigabit data rates for short range connectivity and wireless local area networks. On the other hand, there are unexploited spectrum above 3 GHz as shown in Figure 1.9 [1].

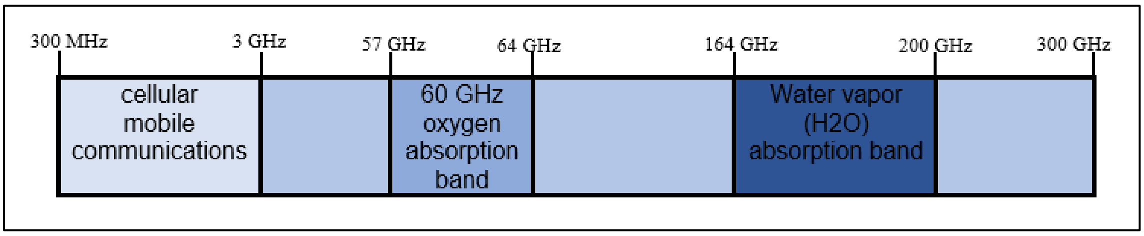


Figure 1.9 RF spectrum from 300 MHz–300 GHz

The three biggest countries of the International Technological Committee: South Korea, Japan, and the United State have accepted to make the 28GHz frequency band as the standard candidate for millimeter waves and 5G networks [48]. Therefore, it represents the gate for the modern technologies and marks the beginning of the revolution in the era of modern communication. This will encourage many researchers to begin the challenging work of designing and making the new world.

1.8. Literature Review for Bow-tie Antenna Design

One of the most common microstrip antenna is the Bow-tie antenna for WLAN applications. The Bow-tie antenna has a big history in wireless communication. The previous Bow-tie antenna designs have been reviewed and presented in this section as follows:

- MKA Rahim *et al*. proposed two Bow-tie antennas with two different angles (40^o and 80^o) as an investigation to the effect of changing the angle on the return loss (S_{11}) and radiation pattern for 2.4 GHz operating frequency. The design was with FR4 substrate where it was very common to use either FR4 substrate or RT/duroid which have high frequency laminates for printed circuit boards. The difference between the frequencies because of the FR4 substrate and its dielectric constant between 4.0 to 4.7 were explained. He explained that the angles of Bow-tie antenna do not effect on the return loss too much where it was –27.71 dB at 2.48 GHz for 40^0 angle and –28.92 dB at 2.48 GHz for 80^0 angle [33].

- Anas Abas and Thiagarajah were designed a slotted L shape of Bow-tie patch antenna for 3G applications. This slotted Bow-tie patch antenna was fed by the coaxial probe at specified location to obtain a 50Ω input impedance. For 3G system application, the antenna was required to operate at the frequency range of 1.950 GHz to 2.025 GHz. The substrate was used a FR-4 double sided board. The narrow L shape slot in the center of the patch improved the bandwidth by four times and it met the requirement of 3G applications [49].

- In [9] a wideband microstrip fed modified printed Bow-tie antenna for wireless applications was designed for C and X-band operations. The obtained modified Bow-tie antenna provided 91% impedance bandwidth that covers C and X bands and part of the Ku band from 5.5 to 12.5 GHz. The substrate of the proposed antenna was Rogers RT/Duroid 6010/6010 LM substrate of a dielectric constant of 10.2, a conductor loss of 0.0023 and a thickness of 1.27 mm. According to the obtained results, the operating bandwidth of the antenna, as a single element, was between 5.3–10 GHz.

- In [50] shorted Bow-tie patch antenna with electric dipole was presented for wideband. Air substrate and zero-thickness metallic layers were assumed for reducing computation time. Different outer width and patch gap dimensions were changed to show various return loss and results. The proposed antenna had a wide impedance bandwidth, which was over 60% for VSWR ≤ 2 ranging from 2.16–4.13 GHz.

- In [25] a Bow-tie antenna was optimized for impulse ground penetrating radar applications. The authors used the technique of choosing an optimal distance between the antenna's feed point and the location of the resistive loading. The antenna was designed without substrate to exhibit an input impedance of around 150Ω in free space. The antenna showed improved properties for ground penetrating radar, which include its compact size and ability to radiate UWB pulses with increased amplitude and very small late-time ringing. The proposed antenna obtained higher amplitude than those transmitted by other commonly used planar ground penetrating radar antennas.

- In [51] the design of Bow-tie antenna for 2.45 GHz for RFID readers was optimized using Bacterial Swarm Optimization (BSO) and Nelder-Mead (NM) algorithms. The antenna was analyzed by using the Method of Moments, and the MATLAB was used for simulates and drawing the results. The dimensions of a Bow-tie antenna were optimized to make it resonant at a center frequency of 2.45 GHz. The obtained input resistance was 50Ω. The BSO-NM algorithm had produced results better than those generated by standalone BFA and BSO. The performance was slightly better than the BFA-NM algorithm. Finally, it was anticipated that the introduced hybrid approach was very efficient and can be applied to other types of antennas and for adaptive arrays.

- In [37] the Low-Temperature Cofired Ceramic (LTCC) technology was used to design a Bow-tie slot microstrip patch antenna with an H-type radiation chip and U-type parasitic patches in Ka-band. The material was nine-layer LTCC substrates, which was FerroA6-M (dielectric constant of 5.7, loss tangent of 0.002, one-layer thickness of 0.094 mm after firing process). The overall dimensions of the antenna were 9 mm, 9 mm, 0.846 mm. The design configuration was an array of 4 element on the top layer (layer number 9) and a ground plane with Bow-tie slot located between layer 2 and layer 3 and a 50Ω microstrip line on the underside of layer 1. The obtained antenna results presented a reducing size, expanded bandwidth, and increased the gain where the broadband between 27–34 GHz. It compact millimeter waveband multi-layer integrated circuits using LTCC technologies.

- In [52] two Bow-tie shaped patches separately were slotted to two pairs of T-shaped for Wireless Local Area Network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) applications. This structure changed the path of the current and keeps the cross polarization under –40dB for 1.70–2.73 GHz broadband. The general design look like an array of patches with many slots. The substrate was FR4 and 0.8 mm of thickness with dielectric constant 4.6 and 58×58 mm^2 area over a rectangular ground of the antenna was 160×160 mm^2. The proposed antenna achieved a –40dB cross polarization level for both polarization and –38 dB port isolation in the whole bandwidth 1.8–2.6 GHz. The compact structure with high isolation between the port and the low cross-polarization levels proves it a suitable candidate for base-station antenna applications.

- In [53] a new antenna design was proposed for gain and bandwidth enhancement of the slotted Bow-tie microstrip antenna using the principle of partial substrate removal. The characterizes of this design was a lightweight and compact one that was suitable for broadband communications due to its high gain and wide bandwidth. The design achieved the frequency of more than 5 GHz. The substrate that has dielectric constant $\mathcal{E}_r$=2.2 and thickness 1.57mm was used. The antenna dimensions as well as the feeding lines were designed and optimized to achieve input impedance matching to 50Ω. The obtained results showed that by suppressing surface waves and reducing dielectric loss, the gain of the designed antenna was enhanced by more than 2 dB with an increase of up to 1.5 GHz in the bandwidth from 9–12 GHz where it can be used for UWB applications.

- Khalil H. *et al*. [39] implemented a normal Bow-tie antenna then they improved it by two different ways for UWB applications at 8 GHz, the Self-Complementary Bow-tie Antenna (SCBT) antenna and The Fractal Self-Complementary Bow-tie Antenna (FSCBT) antenna. These two ways proved an enhancement to the Bow-tie gain by using FR4 substrate of 1.6mm thickness, relative permittivity $\mathcal{E}_r$=4.3, dielectric loss tangent=0.025, and simple 50Ω port. The FSCBT antenna showed better return loss curve as compared to that of SCBT antenna. Investigational validations for the return loss and radiation patterns showed good matching with the simulation results.

- In [26] a Bow-tie antennas designed with different slot sizes were presented a new approach for the design of a tri-band Bow-tie antenna for ground penetrating radar and mobile stations. By incorporating slots with triangular shapes on the arms of the Bow-tie, resonance was obtained in the 2.5 GHz, 4.4 GHz, and 6.2 GHz bands. A line fed of 50Ω was given at the meeting point which drives the antenna. The proposed antenna gave a satisfactory results of return loss and tri-band at 2.5, 4.4, and 6.2 GHz.

- HaiWen Liu *et al*. [54] proposed a single feed slotted Bow-tie antenna for triple band wireless applications. The antenna was simulated and implemented to match the results of triband at 3.5, 4.5, and 5.8 GHz applications by using slotting technique. The antenna was fabricated on a Taconic RF-35A2 substrate with a relative dielectric constant ε_r=3.5, loss tangent 0.0018 and thickness 0.8 mm and a microstrip feeding line of 50Ω. Two pairs of slots were etched on the isosceles triangle to change the surface current distributions resulting in triband without increasing the antenna size, thus it was compact in nature. The geometry of the antenna was simple and the obtained result was satisfactory.

- In [24] several planar antenna topologies aimed for application in radar sensor and one of them was the Bow-tie antenna. CPW fed Bow-tie slot antenna on a Rogers RO4003C substrate was proposed. The target frequency band was between 6–7 GHz. Which it was fed by exciting the two respective CPW apertures of 50Ω. The obtained result showed that the most optimal topology for the considered application was the conductor backed CPW fed Bow-tie slot antenna.

- In [55] a dual-polarized self-grounded Bow-tie antenna was proposed for micro-base stations. The 4-petal geometry of the antenna has been optimized for the best matching to 50Ω coax over 1.5–3 GHz. Both simulated and measured results were presented to verify the design. The Bow-tie was placed over the ground plane, with petals making a certain angle with it. After a straight part, the petal was folded down to make a circular bow, and the lower edge connected to the ground plane. The obtained result gave a broadband for the return loss between 1.70–2.51 GHz.

- In [56] an array enhanced end coupled split ring in front of 3 circular Bow-tie antenna to be 4×5 array was proposed for the base station operations. This kind of design resulted an enhancement in the antenna gain performance for 2.5–3.9 GHz. Rogers RT/duroid 5880 substrate with the thickness 1.575 mm was used with dielectric constant of 2.2 and loss tangent of 0.0009. The peak gain of the proposed antenna was 12 dB at 3.85 GHz, and the measured gain of the antenna without enhanced end coupled split ring loading was only 5.2 dB, resulting in gain enhancement of 6.8 dB at 3.85 GHz.

- Naser Ojaroudi Parchin *et al*. [57] were proposed a new design of mm Wave phased array 5G antenna for multiple input multiple output (MIMO). They presented two similar linear phased arrays with eight leaf-shaped (2×8) a half Bow-tie antenna element were used at different sides of the mobile-phone PCB. The substrate was used An Arlon AR 350 dielectric with properties of 0.5 mm of thickness. The frequency range of the antenna was 25–40 GHz. The results of the proposed antenna were a good radiation performance at 28 and 38 GHz which both are powerful candidates to be the carrier frequency of the future 5G cellular networks.

- In [11] a design of millimeter waveband microstrip fed Bow-tie array antenna with beam steering characteristic for 5G applications was proposed. Eight elements of the 17 GHz Bow-tie antennas had been employed to form a linear array with end fire radiation beams on the top region of the cellular handset PCB. The substrate was N9000 PTFE with 0.787 mm thickness and 2.2 dielectric constant and 65×130 mm^2 overall dimensions. The investigated results showed that the proposed phased array antenna provided some attractive features and could be suitable for 5G cellular systems.

- In [4] a Bow-tie antenna in an underwater three dimensional space was examined to establish an underwater localization system. A new study for the underwater environment where the Wi-Fi that used in air and underwater environment using the channels around the 2.4 GHz frequency range that have been standardized worldwide. The authors used a Bow-tie shaped antenna to study the actual signal strength between underwater and air conditions. The antenna gain was –25 dB at 2.4 GHz, which was high value for underwater wireless communication to overcome the high path loss due attenuation.

- In [3] a CPW fed printed Bow-tie slot antenna with loaded stub was presented for different applications in wireless communication systems. The authors studied the effect of changing the slot size and the overall dimensions of the antenna. CPW fed structure provided wider bandwidth with lower dispersion in comparison with Probe fed antennas. The frequency of the proposed antenna was a broadband from 1.7–2.6 GHz. The obtained result showed that increase of the slot size decreases the bandwidth gain and made it closed to –10 dB. The designed antenna in both simulation and measurement presents the reflection coefficient of the feed port at 50**Ω**. The characteristics of the proposed antenna changed by hanging in the dimensions of the designed geometry. The proposed antenna achieved the desired bandwidth. The results were proven through simulation, fabrication, and measurement.

- In [58] A broadband Bow-tie dual-polarized dipole was used as the array element. A broadband dual-polarized dual orbital angular momentum (OAM) mode UCA was simulated, fabricated, and measured. The proposed antenna substrate was Rogers 4350B with dielectric constant of $\mathcal{E}_r$=3.48. The generation of broadband OAM beams from 2.1–2.7 GHz was attributed to the broadband feeding network. The broadband of frequency was used 2.1–2.7 GHz. A digital data communication confirms that the proposed antenna array can be used to generate OAM mode−1 and OAM mode 1 beams for each of two polarizations from 2.1–2.7 GHz.

- In [59] a 2×2 Bow-tie array based on characteristic mode theory was performed. The flat metal pieces of the array elements were simulated as perfect electric conductor. The etched-on top of a printed circuit board with a Rogers substrate RO4003C ($\mathcal{E}_r$=3.38) and loss tangent (δ=0.0021) with a thickness of 1.6 mm. The pair feed points of each Bow-tie were excited 180° out of phase with two coaxial cables of 50**Ω** each. The obtained results showed that the most influential factors on the array bandwidth were the length of the elements and the distance between the array and the ground plane. The bandwidth was calculated with and without the metasurface at 2.1–4.0 GHz broadband. The investigated results showed that the proposed phased array antenna provided some attractive features.

Finally, from the Bow-tie antenna designs were investigated as shown above. Generally, Arlon, Rogers, FR4 or Neltec were used as substrate materials with several thicknesses.

Most of these studies were below 3 GHz, but there were a few studies over the 3 GHz spectrum, especially 28 GHz.

1.9. Literature Review for-Quasi-Yagi Antenna Design

The previous studies of the Quasi-Yagi antennas designs are presented as follows:

- Kan *et al*, presented a CPW fed antenna for broadband applications in wireless communication systems [60]. The antenna was one of the simplest forms of a planar Quasi-Yagi and it did not require any complicated structure. The antenna proposed a novel CPW fed Quasi-Yagi antenna with broadband for covering X band at 8 GHz. The substrate was a Rogers RT6010 with high dielectric constant $\mathcal{E}_r$=10.2 and thickness of 0.64 mm. Two directors were found with 3.73 mm of length and the length of the driven element of the antenna was 11.5 mm. The dimensions of the antenna were improved after the simulation to these values. The simulated result closely resembles the measured result at the lower and upper resonant frequency validating the design of the antenna and the antenna was small indicating that it was a suitable candidate for phased arrays.

- In [61] amplitude and phase balances for the two types of microstrip (MS) to coplanar strip (CPS) baluns were analyzed, and their effected on antenna performance for X-band 5–20 GHz, end-fire antennas were investigated. Two types of Quasi-Yagi were designed and simulated. The antenna design consists of a MS feed, MS to CPS balun, and two dipole elements: one dipole element was a driver dipole fed by CPS and the second strip was a parasitic director. The proposed substrate was RT/duroid 6010 and ground on the bottom plane was truncated and serves as the reflector for the antenna. According to the obtained results, it was shown that the analysis of amplitude and phase imbalances of the balun was effective way to determine the valid bandwidth of the balun and the performance of broadband balanced antennas.

- In [62] a linear array design for wireless communication systems was proposed. The arrays evaluated in the paper were composed of two, four, and eight Quasi-Yagi elements. The array design combined genetic algorithm and sequential quadratic programming because they combine both global and local optimization algorithms. The length of the director was 33.15 mm and the length of the driven element was 54 mm. The design at 2.40 GHz offer a bandwidth from 1.93–2.76 GHz on FR4 substrate. The obtained results showed that a compromise between the number of beam pointing directions and the array size should be taken into consideration for a wireless communication system design. The analysis proved that an amount of beams equivalent to the number of elements in each array was a trade-off in terms of array cost and signal to noise ratio performance.

- In [63] a Quasi-Yagi antenna with a double feed dipole of 5×4 array of Gradient Refractive Index Metamaterial (GRIM) was proposed. Beam deflection mechanism was based on the phase shift phenomena resulted from the interaction of the EM Waves with media of different refractive indices implemented using GRIM unit cells. The result frequency broadband was 57–64 GHz. The structure of GRIM was separated into the top and bottom layers to enhance coupling with the dipole arms and ensure that GRIM effectively interacted with radiation on both sides of the antenna. The GRIM unit cell was constructed on a Rogers RT5870 substrate with a thickness of 0.254 mm, permittivity ε_r=2.3, and loss tangent=0.0009. The measured results confirmed the direction of the main beam to deflect at 60 GHz.

- In [64], the method that used to improve the bandwidth of a double dipole Quasi-Yagi antenna was a stepped slot line structure. Different widths with a stepped slot line were used in the coplanar strip line connecting the two dipoles to improve impedance matching covering a wide frequency band. A prototype antenna operated at 1.60–3.60 GHz frequency range on FR4 substrate. Two directors were proposed with different width and equal length the length of the both director elements were 24 mm and the widths were 10, 5 mm respectively. The length of the driven element was 61.2 mm. The fabricated antenna had the desired impedance properties with a frequency band at 1.59–3.64 GHz.

- In [65], Rezaeieh *et al*. proposed a unidirectional and compact Quasi-Yagi antenna for medical diagnostic applications. The mixture of loop and dipole interleaved structures represented the main part of the antenna that formed from. The antenna was presented for frequency about 0.68 GHz. With the proposed configuration, the antenna acted as an array of two dipoles and a Quasi-Yagi antenna at lower and higher frequencies, respectively, and thus radiates mainly in one direction. The antenna printed on a square epoxy FR4 substrate with a dielectric constant ε_r=4.4, loss tangent=0.02 and a thickness of 0.8 mm. The antenna achieved a wide fractional bandwidth of 55%

(0.65–1.15 GHz), the proposed design could be applied in microwave imaging systems for various medical applications.

- In [66] a helical Quasi-Yagi antenna array with low profile and multi beams at the end fire direction was proposed. To achieve end fire radiation, a planar normal-mode helical Quasi-Yagi antenna designed with top hat loading for low profile. A broadband was achieved by controlling the resonance difference between the parasitic and driven elements. Then a microstrip beamforming network based on Butler matrix was designed to feed a 1 × 4 helical Quasi-Yagi arrays at 1.8 GHz of frequency. The substrate used was Rogers 4003 with a dielectric constant of ε_r=3.38 and thickness=0.813 mm. The frequency band from 1.63 to 1.77 GHz. The proposed antenna and its array showed advantages of low profile, reliable structure, and easy fabrication.

- In [67] the proposed antenna was a novel self-packaged substrate integrated suspended line Quasi-Yagi antenna. The design of the antenna used five substrates with embedded air cavities and transitions for broadband operation for UWB applications of 3.1–10.6 GHz. Quasi-Yagi antenna was proposed and the substrate integrated suspended line structure that had the merits of planar and substrate integrated cavity structure was introduced in the patent. Of the five substrates, 1st, 2nd, 4th, and 5th were FR-4 laminates with thickness=20 mil, dielectric constant ε_{r1}=4.4, loss tangent=0.02 and 3rd substrate was Rogers 4003C laminate with thickness h2=8 mil, dielectric constant ε_{r2}=3.38, loss tangent=0.0027 with 50Ω SMA connector was used to feed the antenna. The Rogers 4003C laminate was used with FR4 to achieve higher antenna gain and radiation efficiency. The maximum measured gain was 8.1dB and the bandwidth of the simulated gain was from 5.2 to 9.5 GHz. The measured results showed that the antenna operates with an UWB frequency.

- In [6] a design of a planar Quasi-Yagi antenna capable of achieving high Front to Back ratio, high gain and relatively wide bandwidth was proposed. The antenna design covered 2.45 GHz ISM band. The antenna was made of seven elements up of 5 director elements and they were different in length, 1 driven dipole like L-shaped dipole antenna printed on both sides of the substrate and a reflector ground plane as usual. The substrate used for the design was the Rogers Duroid RT5880 with an ε_r=2.2 and a loss tangent=0.0009. The thickness of the board was 1.575 mm. The antenna was fed using a simple 50Ω microstrip transmission line printed on the top side of the substrate and a ground plane printed on the bottom side of the substrate. Wide bandwidth was achieved through the strong coupling between both the first director and the driven dipole.

- In [8] a design of 4×4 square structure microstrip Quasi-Yagi beam steering antenna array this array consists of sixteen element antennas operation at 3.5GHz for future 5G vehicle and millimeter waves applications was proposed. the proposed Quasi-Yagi antenna was printed on the FR4 substrate with dielectric constant ε_r=4.4, loss tangent=0.02 and thickness=1.15 mm and fed by 50Ω input impedance. The simulation results showed that the antenna array had high gain and wide bandwidth.

- In [68] a wideband and low-profile monocone Quasi-Yagi antenna was presented to produce a nearly end fire radiation beam. The proposed antenna consists of a driven element, two rows of grounded cones as reflectors, and another two parasitic cones beside the driven element to suppress the sidelobe level and improve the front-to-back ratio of the radiation beams. This original top hat monocone antenna was modified by cutting two slots on the top loaded patch and then adding conducting pins shorted to the ground plate. The antenna was fabricated with copper and tested with and without slots. The obtained measured results show good agreement with simulated ones. The operating frequency band was broadening significantly from 5.5 to 17 GHz with one slot on the top hat and adding the second slot on the top hat was widen the bandwidth further, which covers 5.6–18 GHz. The proposed antenna showed advantages of extremely low profile, broadband, moderate gain, good front-to-back ratio, and sidelobe level.

1.10. Aim of The Study

3–300 GHz is referred to as the extremely unexploited high frequency of UWB or millimeter- wave band [69]. In this thesis, the aim is to focus on these regions to design an optimal small antennas which can be used for UWB and millimeter waves applications [70]. The slotted Bow-tie, CPW fed Bow-tie and Quasi-Yagi antennas are selected for them ability to carry high frequencies with small size. In the next chapters, the proposed antennas will be explained, and simulation of each antenna results will be given.

CHAPTER 2

ANTENNA CONFIGURATION

In this chapter, the simulation program and its components are given in designing and simulating the antennas. The configuration of the designing process is given in details.

2.1. The Simulation Program

Various simulation software is used as an evaluation and configuration tool for the majority of the work carried out in a different research like (CST, HFSS, etc.) [62], [63], [3], [7], [68]. Some of these software deal straightly with the design's elements but the other programs depend on the programming language to design the configuration shape. One of these programs is the HFSS which is a very useful simulation program. To measure the electrical performance of high frequency and high-speed elements, HFSS uses a 3D full-wave Finite Element Method [71]. Models can be built with different geometries, materials, and boundaries [72].

2.2. Antenna Design and Experimental Analysis

The software used to design antennas is High-Frequency Simulation Software (HFSS) it is one of the widely used simulation tool to describe and optimize the performance of antennas [73]. The complete process of antenna design and experimental analysis used to design antennas are shown in the Figure 2.1. the steps of the flowchart given in figure 2.1 are explained in the subsections.

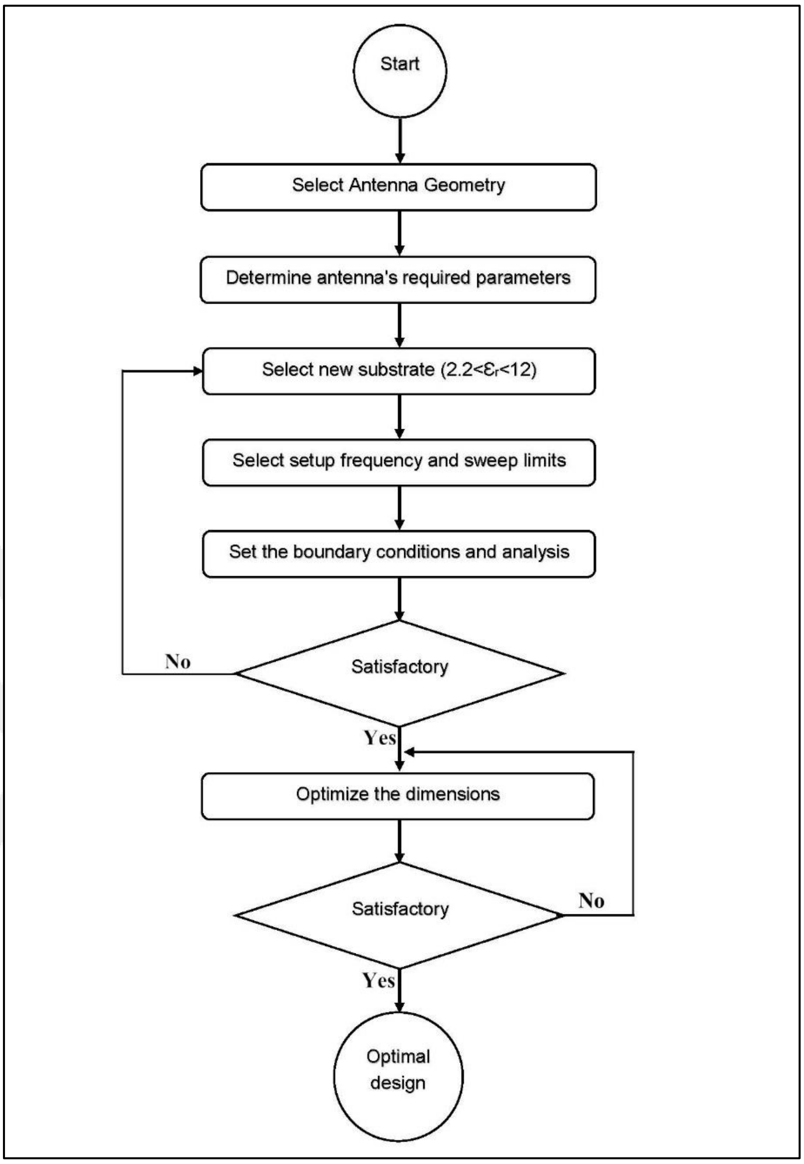


Figure 2.1. Flowchart of the designing process

2.2.1. The Antenna Design

The first step to design an antenna is to determine the required parameter of the antenna. The parameters can be the substrate dimensions, material, and feeding position, etc. according to the coordinate system. HFSS has a huge library of varied materials with different dielectric constant and also new materials can be added normally. The general range of the dielectric constant is between $2.2 \leq \varepsilon_r \leq 12$. All these factors and others depend on which frequency band that the antenna will be operated. These substrate materials are mostly used as a state in the literature review section, six different types of substrates (Arlon CuClad 217, FR4_epoxy, Nelco N4000-13, Neltec NH9294, Rogers

RT/duroid 5880 and RT/6010 LM) will be examined. These materials represent the top requested materials for high frequencies designs [74].

Once the required parameters, dimensions and the material of the substrate are chosen, the second step is to choose the patch antenna design on the top face of the substrate. The most critical point in the patch design is the feeding point. In the designs two kinds of feeding (the microstrip feeding line, and the coplanar waveguide) are dealt. The dimensions of the patch can be controlled to create the desired shape. Then, ground plane is created, which is usually on the back side of the substrate and everything created according to the coordinate system.

2.2.2. The Frequency Setup and Sweep Limits

The third step is called the adaptive frequency (which frequency will be selected to solved the model). The adaptive frequency should be set ‘in band’ at the expected solution frequency, especially for highly resonant structures. If a wideband structure is being analyzed, then the frequency should be set at the highest frequency of expected operation. After selecting the adaptive frequency, the final stage is to choose the frequency sweep. When specifying the frequency sweep there are three options:

- Discrete: This sweep offers the highest accuracy as it performs a full solution at every frequency specified in the sweep. This sweep is best when only a few frequency points are necessary to accurately represent the results in a frequency range.
- Interpolative: Estimates a solution for an entire frequency range. This sweep is best when the frequency range is wide and the frequency response is smooth e.g. a filter.
- Fast: Generates a unique full-field solution for each division within a frequency range. This sweep is best for models that will abruptly resonate or change operation in the frequency band. A fast sweep will obtain an accurate representation of the behavior near the resonance.

Throughout this thesis, the discrete and/or fast sweep are used.

2.2.3. The Boundary Conditions and Analysis Results

In the fourth step, the boundary conditions are set and the analysis is made. With the model created, the boundary conditions need to be specified. Generally, these can be split into excitations or surface approximations. There are many types of excitations possible in the simulation programs, but the main ones used for the models throughout the thesis is lumped ports. Ports are unique types of boundary conditions that allow energy to flow into and out of a structure:

- Wave ports: These ports can be placed internally or externally, and support multiple modes of transmission. They also support reference plane de-embedding and arbitrary mode re-normalization. They are well suited for exciting most transmission lines, though setting them up can be complex.
- Lumped ports: These ports are recommended only for surfaces internal to the geometric model. There is only a single mode excited at the port (TEM) and there is no de-embedding. They are simpler to set up and are ideal for exciting transmission lines such as microstrip.

Figure 2.2 shows an example of a Microstrip feeding port. The orientation of the field at the port can clearly be seen to be in a lump port mode.

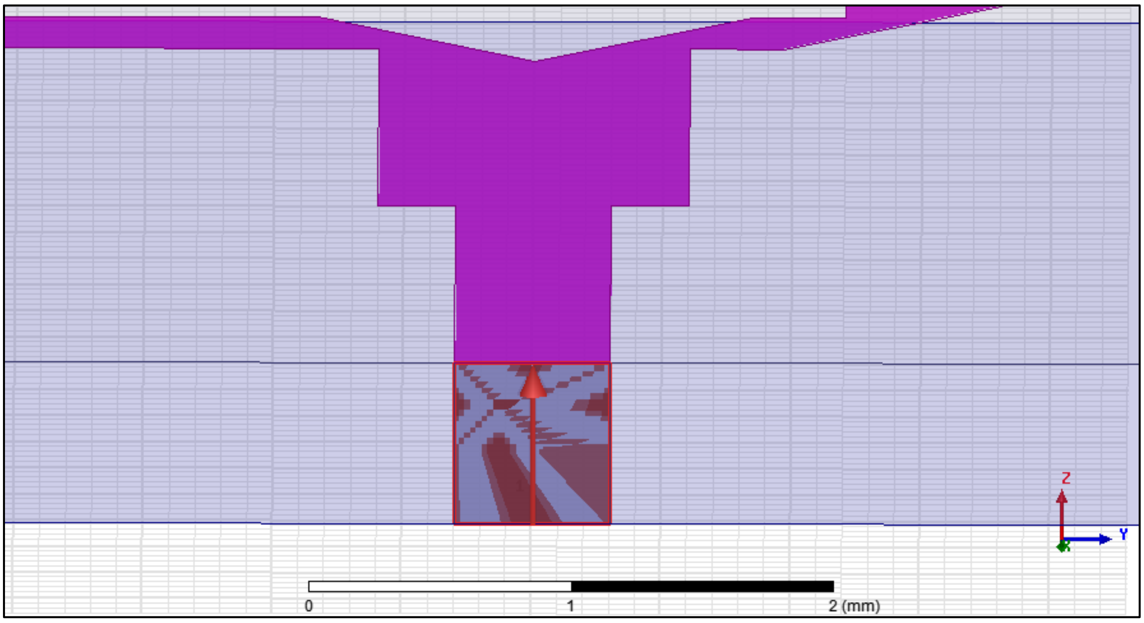
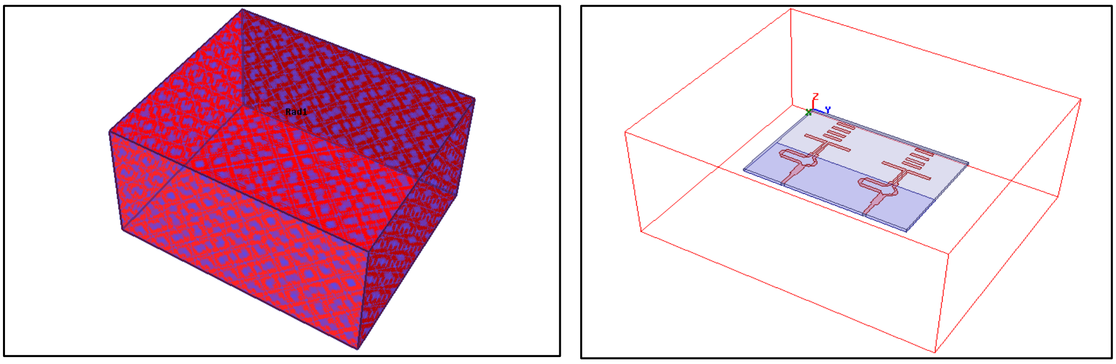


Figure 2.2. Microstrip port as a lump feeding port

With the model created and an excitation specified, then the surface approximation for the radiation boundary is selected. There are two main options for this selection:

- Radiation Boundary – The radiation boundary, also known as the Absorbing Boundary Condition (ABC) allows waves to radiate infinitely far into space. The boundary is normally assigned to an airbox, which is placed at least one quarter of a wavelength, at the lowest frequency of interest, away from any radiating object. A drawback to this boundary is that if there is any energy incident at an angle greater than 30 degrees it will be reflected. This means for curved surfaces; the boundary should follow the shape. For example, a wire dipole should have a cylindrical boundary around it.
- Perfectly Matched Layer (PML) – Like the radiation boundary, the PML allows waves to radiate infinitely far into space. The PML is not strictly a boundary condition but a fictitious, complex, anisotropic material that fully absorbs the EM fields impinging upon the PML boundary. The main advantages of the PML is that there is no angle of incidence problem and the boundary can be placed a minimum of one tenth of a wavelength, at the lowest frequency of interest, away from any radiating object.

Figure 2.3 shows an example to the patch antenna enclosed in an air box with and without the boundary.



(a) (b)

Figure 2.3 Two antenna models (a) with (b) without radiation boundary

Importing and exporting models for analysis and design is also carried out. After choosing the frequency setup and the sweep band configuration, the results are among the most important things to be chosen with caution and care. There are several types of result offered by the simulation programs and all of them depend generally on the fundamental of antenna parameters which mentioned before (Input impedance, S-parameters, Radiation pattern, Directivity, Efficiency, Gain, VSWR) is selected, these parameters represent the base to design any antenna. The most efficient one which controls completely the antenna design is the S-parameter (return loss). This represents the last step before analyzing the design.

2.2.4. The Optimization Methodology

The antenna designs can be improved by optimizing either the dimension or the feeding point of the antenna. These two parameters, completely affected the results and affect them. The lack of closed form formula for the designs and the variety of the designs lead the designer in using optimization methods and algorithms. Therefore, numerical techniques remain another option for analysis and synthesis of the antennas. The simulation program offers an optimization technique that can help with improving the solution result in parametric way. As mentioned before that the proposed antenna designs are CPW fed Bow-tie, slotted Bow-tie, and Quasi-Yagi antennas. Each one of the presented design has a special parameter can be improve and optimize the solution results.

Bow-Tie antennas generally, depends on the designs geometry where the inside width, outside width, and the tri-length control the triangle shape and size while the gap port length and the port gap width control the slot measurement and the feed offset position even the substrate dimensions control the solution frequency result and affect it.

The Quasi-Yagi antenna design has many parameters that control the shape of the Quasi-Yagi like the director length (L_{dir}), the director width (W_{dir}), the director space (S_{dir}), the driven length (L_{dri}), the driven width (W_{dri}), the driven space (S_{dri}), the feeding length (L_f), the feeding width (W_f), the length of the Quasi-Yagi structure is controlled by (L_1, L_2, L_3 and L_4) and the width of the Quasi-Yagi structure is controlled by (W_1). The most effective parameters are the director and driven elements.

The optimization technique for these parameters should not exceed the required limits for all design parameters and must satisfy the characteristics of required components. If the results are satisfied, the design is accepted as the optimal design; otherwise, the dimensions are optimized again.

CHAPTER 3

THE RESULTS OF THE PROPOSED DESIGNS

In this chapter, the optimal designs and the results of each design (Bow-tie and Quasi-Yagi antennas) are given sequentially.

3.1. Bow-tie Antenna Results

Two types of Bow-tie Antennas (CPW fed Bow-tie and slotted Bow-tie antennas) are designed. In the next subsections, each result is obtained with the optimal design.

3.1.1. CPW fed Bow-tie Antenna Results

CPW fed Bow-Tie antenna is designed in tri-band frequencies (9 GHz, 15 GHz, and 21 GHz) for both UWB and millimeter waveband systems.

For this design, five different substrates are used and analyzed to find the optimal design and result. In the design of the antenna, the dimensions values given in Table 3.1 are used.

Table 3.1. Initial values of CPW fed Bow-tie antenna design

The variables	**Elements Values (mm)**
Outside Width	13.3
Inside Width	3.4
Arm Length	21
Feeding length	12
Feeding Gap Width	1.2
Substrate Length	64
Substrate Width	34
Substrate Thickness	1.57

The first substrate is Arlon CuClad 217 which it is one of the Rogers crop. substrates with 1.57mm of thickness and ε_r=2.17. The result of S_{11} for this substrate gives a good tri-band for S-band, C-band, and X-band which are 3.5 GHz at –14.5 dB, 7 GHz at –26 dB, and 10.5 GHz at –16 dB, respectively, as shown in the Figure 3.1.

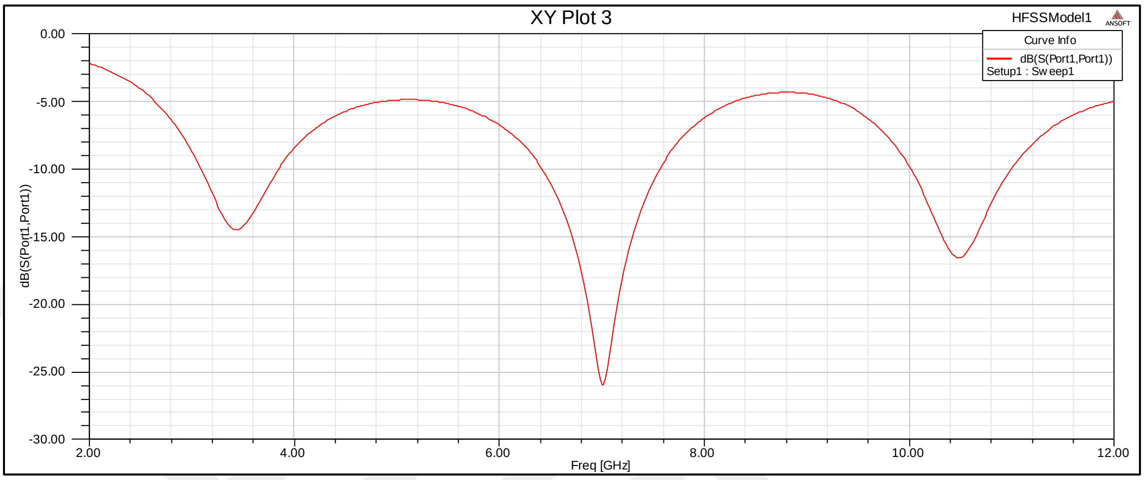


Figure 3.1. The S_{11} result for Arlon substrate with 1.57 mm of thickness

The substrate thickness is changed to 0.635 mm and tested again. The second result shows approximately the same tri-band 3.7 GHz at –17 dB, 7.4 GHz at –30.5 dB and 11.2 GHz at –13 dB with using the same substrate material, as shown in Figure 3.2.

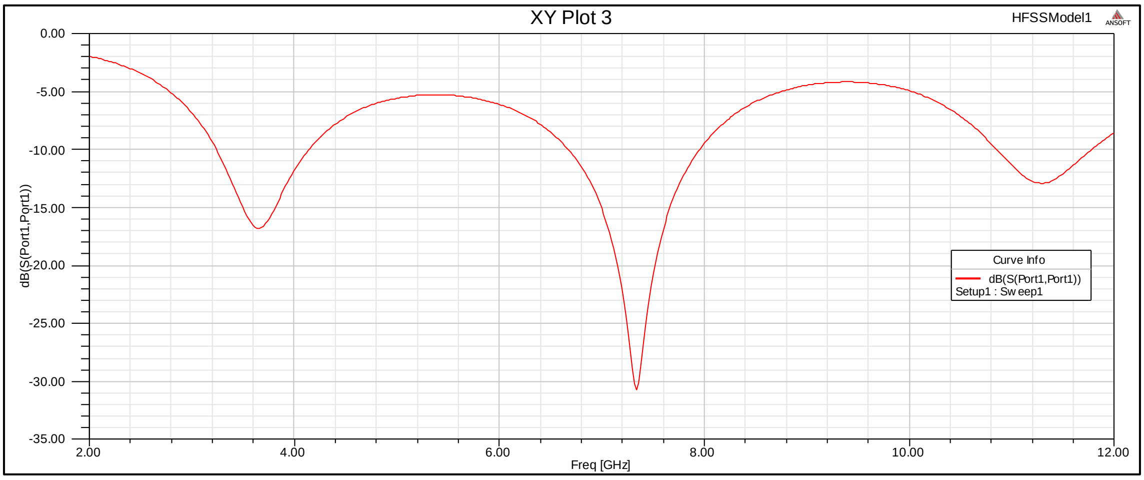


Figure 3.2. The S_{11} result for Arlon substrate with 0.635 mm of thickness

In the next design, the substrate material is changed to Rogers RT/duroid 5880 with a ε_r=2.2 and 1.57 mm of thickness. The result for this substrate is very close to the result of Arlon CuClad substrate. The new S_{11} result in S-band, C-band, and X-band which are

3.5 GHz at –13.6 dB, 7.5 GHz at –27.5 dB, and 10.7 GHz at –16.5 dB, respectively, as shown in Figure 3.3.

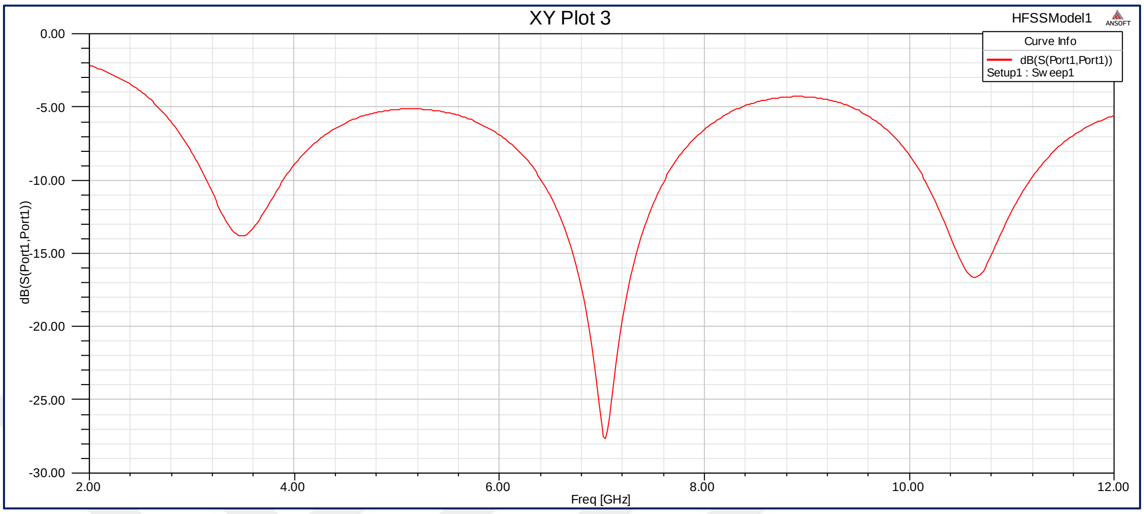


Figure 3.3. The S_{11} result for Rogers substrate with 1.57 mm of thickness

The substrate thickness is changed to 0.635 mm and tested again. The second result shows approximately the same tri-band 3.7 GHz at –20 dB, 7.6 GHz at –26 dB and 11.5 GHz at –11 dB as shown in Figure 3.4.

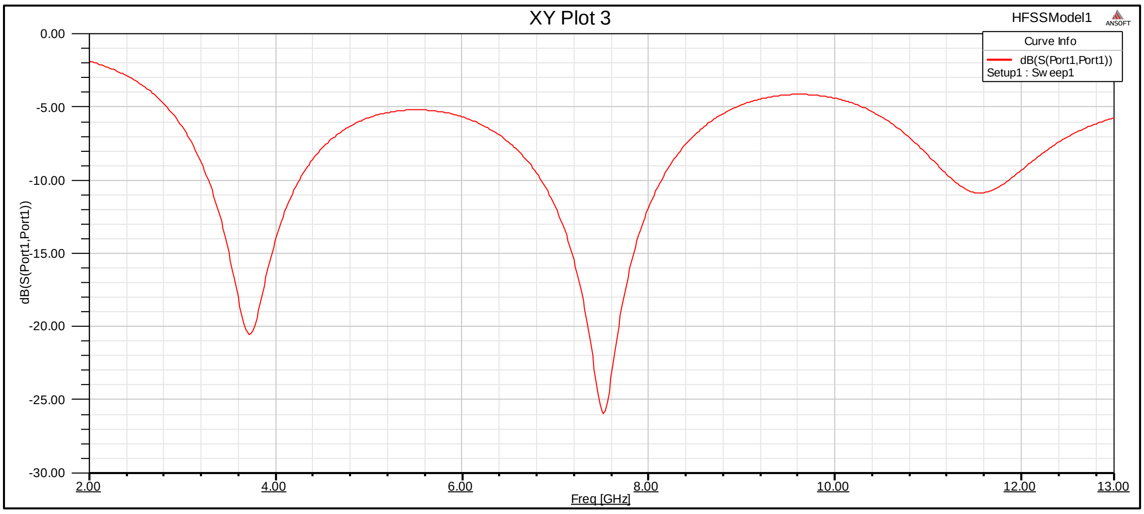


Figure 3.4. The S_{11} result for Rogers substrate with 0.635 mm of thickness

The next step is changing the substrate material to the FR4_epoxy substrate with ε_r=4.4 with 1.57mm of thickness. The result shows an improvement in bandwidth according to the increase in the dielectric constant. The new antenna work for C-band and X-band which are 5.5 GHz at –14.3dB, 8.5 GHz at –17.8dB, and 11.3 GHz at –14dB as shown in Figure 3.5.

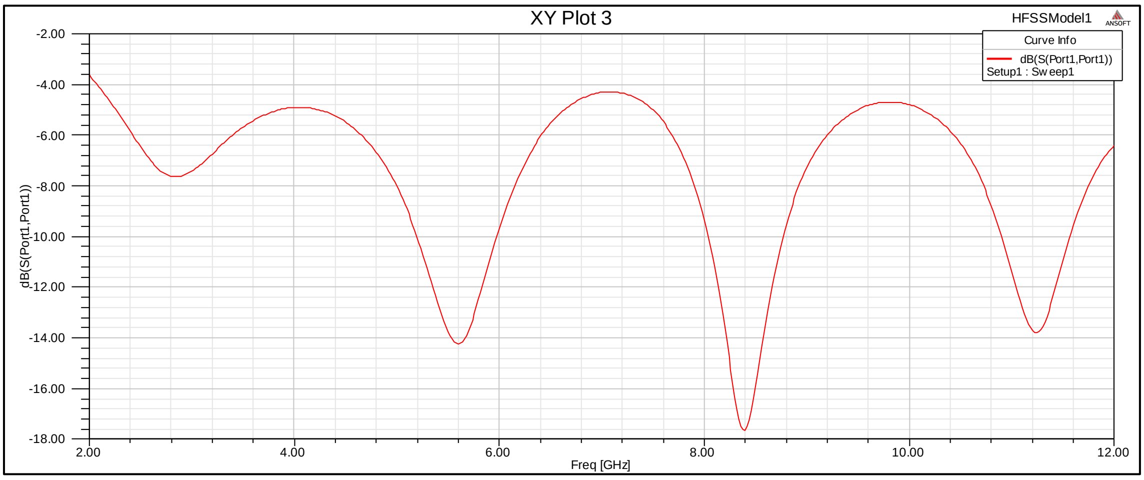


Figure 3.5. The S_{11} result for FR4 substrate with 1.57 mm thickness

After changing the substrate thickness to 0.635mm the antenna improved too much in gain and bandwidth and the antenna approach a better result with the FR4_epoxy substrate. The S_{11} in Figure 3.6 shows that the antenna has a tri-band in C-band, X-band, and Ku-band which are 6.25 GHz at –38dB, 9.8 GHz at –25dB, and 12.7 GHz at –24dB.

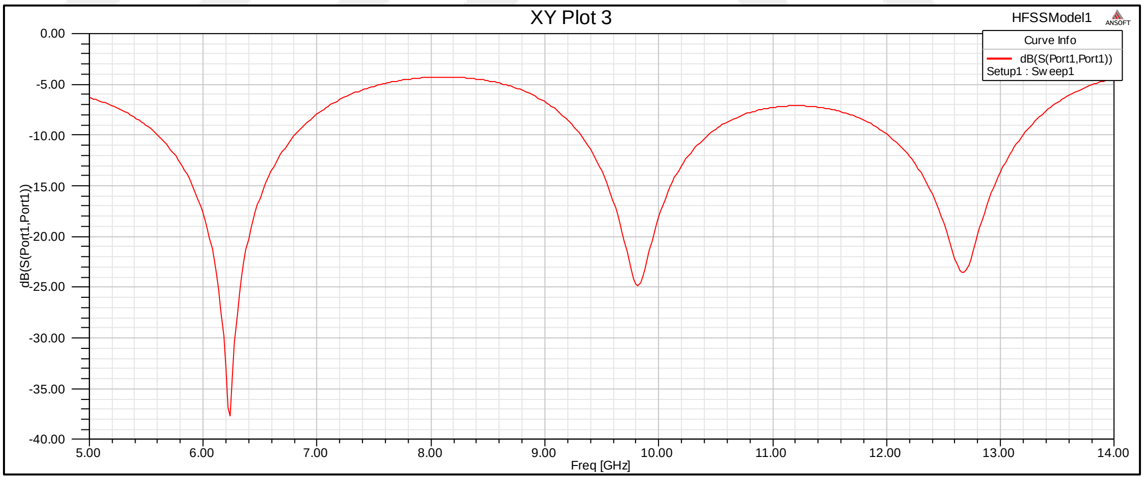


Figure 3.6. The S_{11} result for FR4 substrate with 0.635 mm thickness

In the next design, the substrate material is changed to Neltec NH9294 substrate with ε_r=2.94 with 1.57mm of thickness. The new substrate result in X-band, Ku-band, and K-band which are 9.8 GHz at –27 dB, 16 GHz at –25 dB, and 22.3 GHz at –41 dB as shown in Figure 3.7.

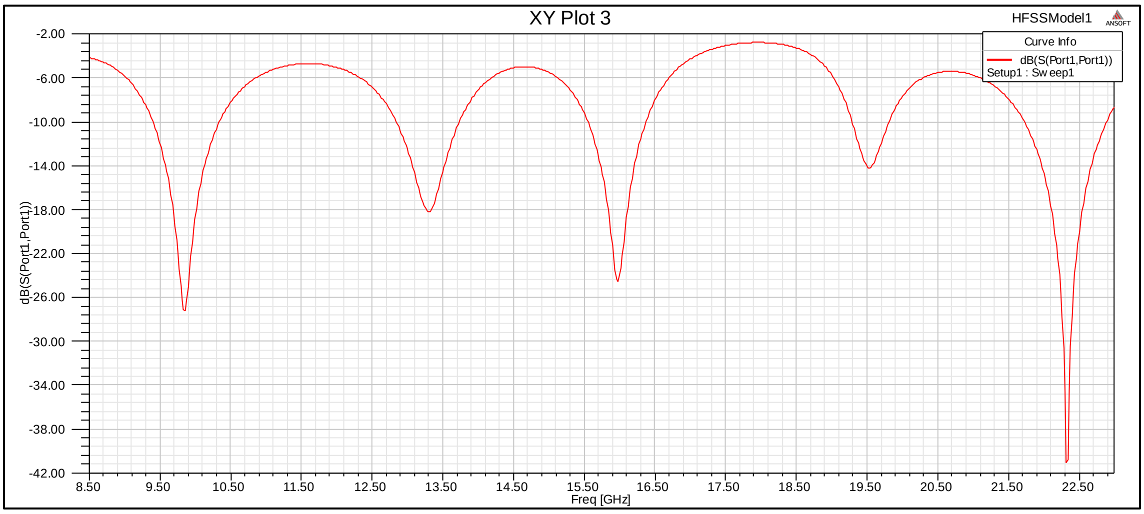


Figure 3.7. The S_{11} result for Neltec substrate with 1.57 mm of thickness

The substrate thickness changed to 0.635 mm and the S_{11} result shows that the antenna has a tri-band in C-band, Ku-band, and K-band which are 7 GHz at –26 dB, 15 GHz at –35 dB, and 22.7 GHz at –16.6 dB as shown in Figure 3.8.

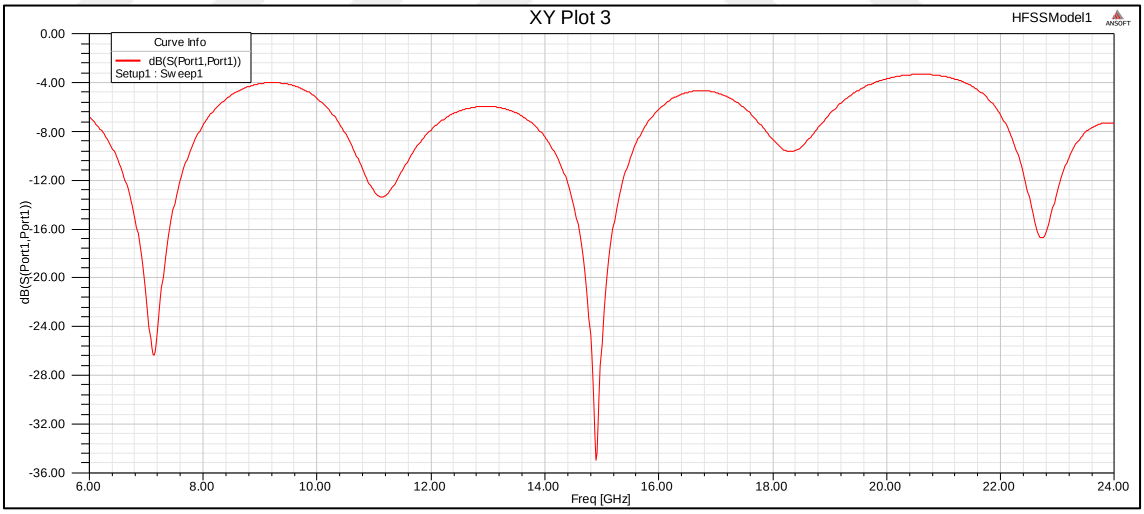


Figure 3.8. The S_{11} result for Neltec substrate with 0.635 mm thickness

The last substrate in this thesis for this design is Nelco 4000-13 with ε_r=3.5. The result is shown in Figure 3.9 and gives a good impression about using this kind of substrate metal. Before optimization, the Nelco N4000-13 substrate with 1.57mm of thickness has a tri-band in X-band, and Ku-band which are 9.4 GHz at –27 dB, 15.1 GHz at –36 dB, and 21 GHz at –37 dB.

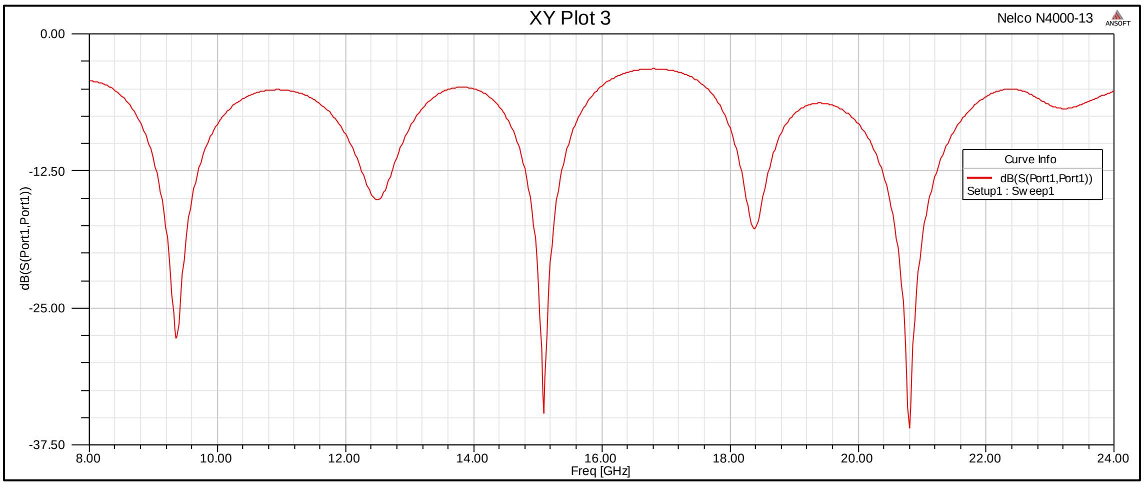


Figure 3.9. The S_{11} result for Nelco substrate at 1.57 mm of thickness

After the substrate thickness changed and reduced to 0.635mm, the result improved and it reached the 21 GHz. The antenna also has a tri-band in Ku-band, and K-band which are 13.5 GHz at –23dB, 16.9 GHz at –14dB (a little bit critical), and 20.6 GHz at –50dB. The S_{11} result is shown in Figure 3.10.

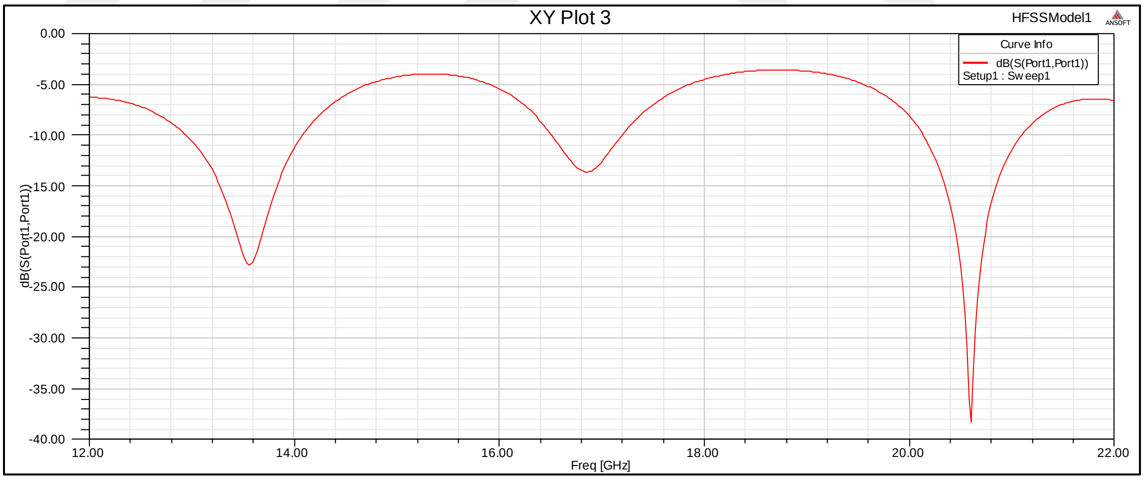


Figure 3.10. The S_{11} result for Nelco substrate at 0.635 mm of thickness

The last step for this design is to optimize the last result. In the next step, the design optimized by controlling the dimension of the antenna. The values of the last dimensions obtained for Nelco N4000-13 substrate with 0.635mm of thickness is given in Table 3.2.

Table 3.2. The CPW fed Bow-tie antenna final dimensions

The variables	Elements Values (mm)
Outside Width	13
Inside Width	1
Arm Length	20.8
Feeding length	12
Feeding Gap Width	1
Substrate Length	56
Substrate Width	34
Substrate Thickness	0.635

Antennas always prefer to be in spherical coordinate systems. rEtotal give the total radiated E-field, so theta and phi are the most suitable candidate for efficiency and directivity of the antenna. The optimal antenna result has a tri-band in X-band, Ku-band, and K-band which are 9.1 GHz at –27 dB, 14.5 GHz at –40 dB, and 20.5 GHz at –34 dB; the VSWR < 2. These S_{11} result, VSWR result, Radiation directivity and also the total radiated E-field results are shown in Figure 3.11–3.14.

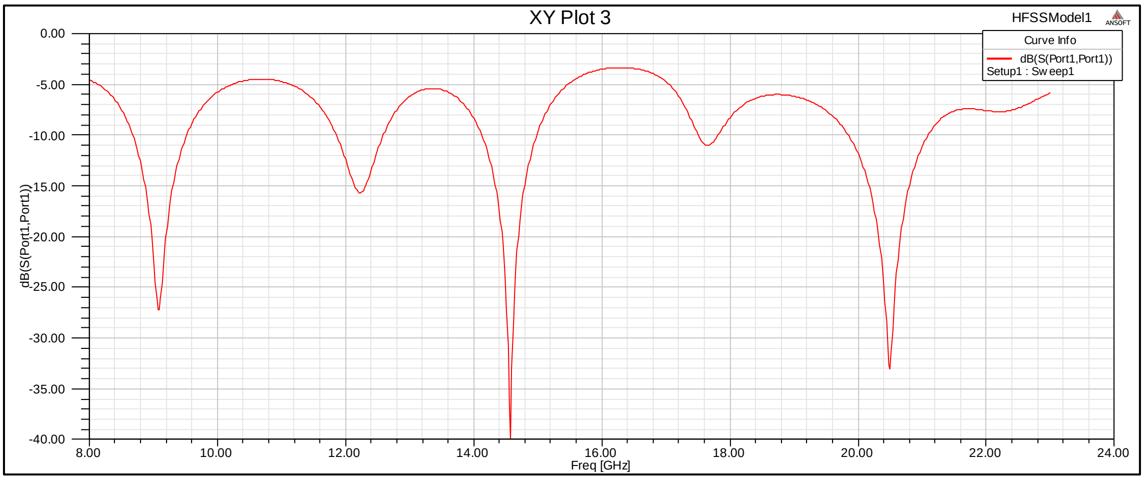


Figure 3.11. The S_{11} result for Nelco substrate with optimization

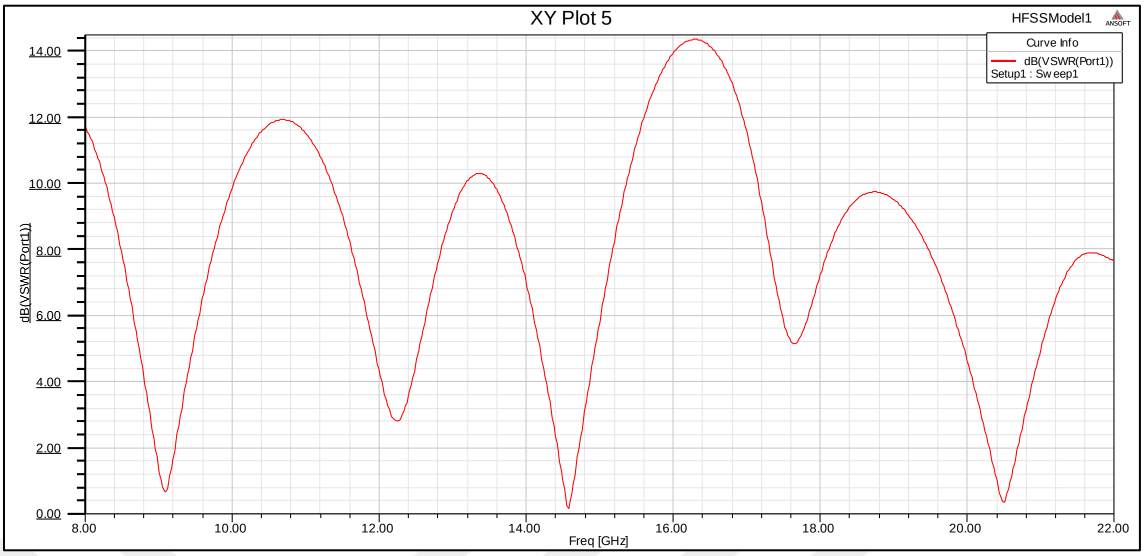


Figure 3.12. The VSWR result for the optimal design

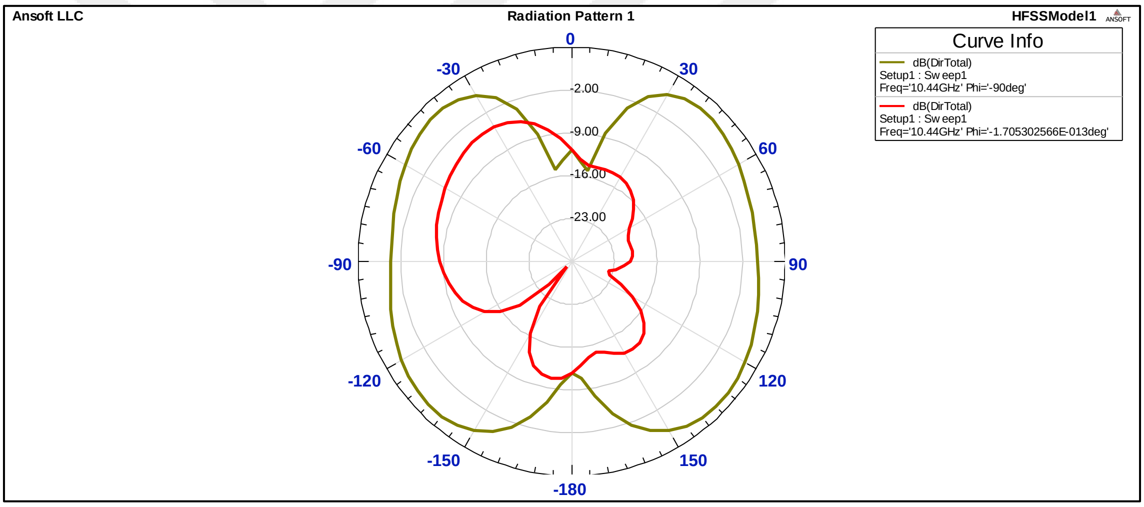


Figure 3.13. Directivity result for the optimal design

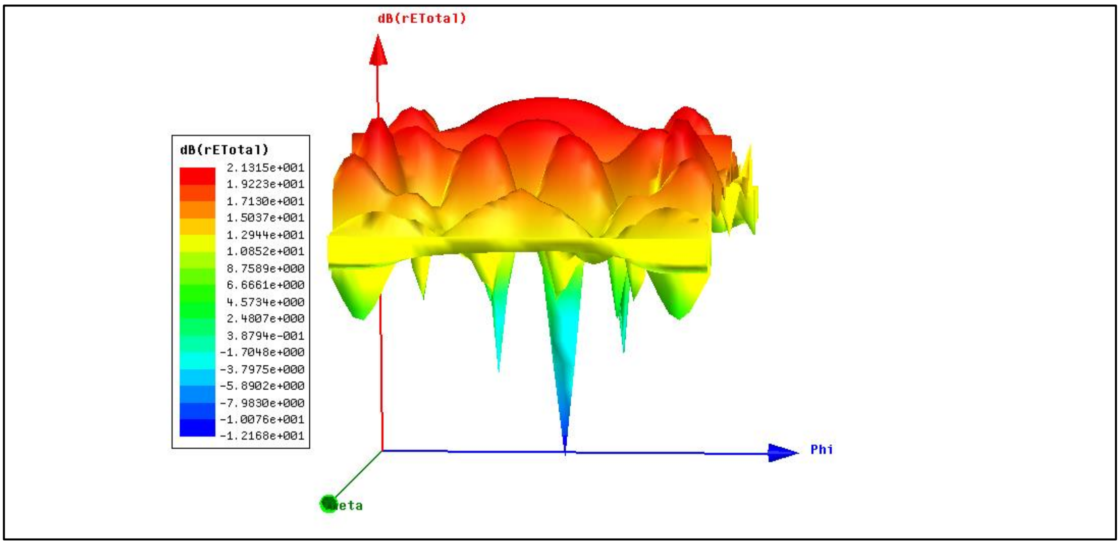


Figure 3.14. rEtotal result for the optimal design

These solution results represent the optimal result for this kind of antenna and it covered different spectrum starting from the UWB to millimeter waveband regions.

3.1.2. Slotted Bow-tie Antenna Results

In this thesis study, slotted Bow-tie antenna designed and optimized for millimeter waves and 5G applications. The frequency band of original Bow-tie antenna design is between 6 and 7 GHz. The dimensions values and the S_{11} result is shown in Table 3.3 and Figure 3.15 [24].

Table 3.3. The dimensions of original design

The variables	Elements Values (mm)
Outside Width	11.5
Inside Width	0.5
Arm Length	16.75
Feeding Gap Width	2.7
Substrate Length	23
Substrate Width	37
Substrate Thickness	19.5

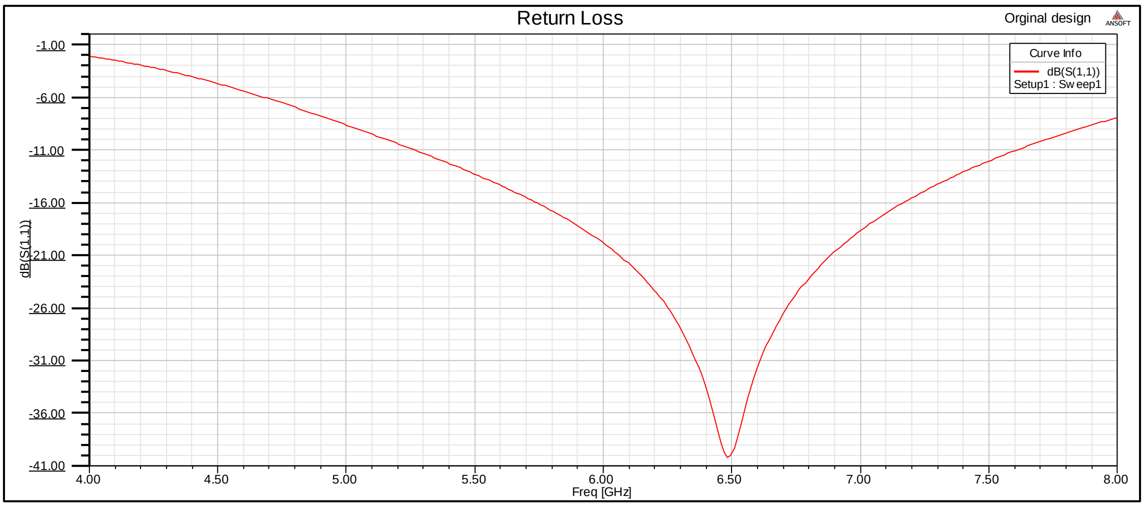


Figure 3.15. The S_{11} result for the original design

The purpose is to improve this antenna by using the slot technique for higher frequency bandwidth. The frequency region that looking for in this design is 28 GHz which represent the candidate for next generation of communication for 5G applications. The geometry of the proposed antenna is optimized and improved in various times until it reaches the optimal design. The same of the CPW fed Bow-tie antenna, five substrate materials are used to reach the optimal antenna design.

For this design, five different substrate materials are designed and simulated to find the optimal substrate for slotted Bow-tie Antenna design. The first optimized dimensions values given in Table 3.4. These dimensions test with the same five substrates but the results are unsatisfactory. The solution results are critical at 28 GHz frequency can be seen in Figure 3.16.

Table 3.4. The first dimension of the proposed antenna

The variables	Elements Values (mm)
Outside Width	2.9
Inside Width	0.2
Arm Length	3.1
Feeding Gap Width	0.2
Feeding Gap Length	0.6
Substrate Length	10
Substrate Width	10
Substrate Thickness	1.57

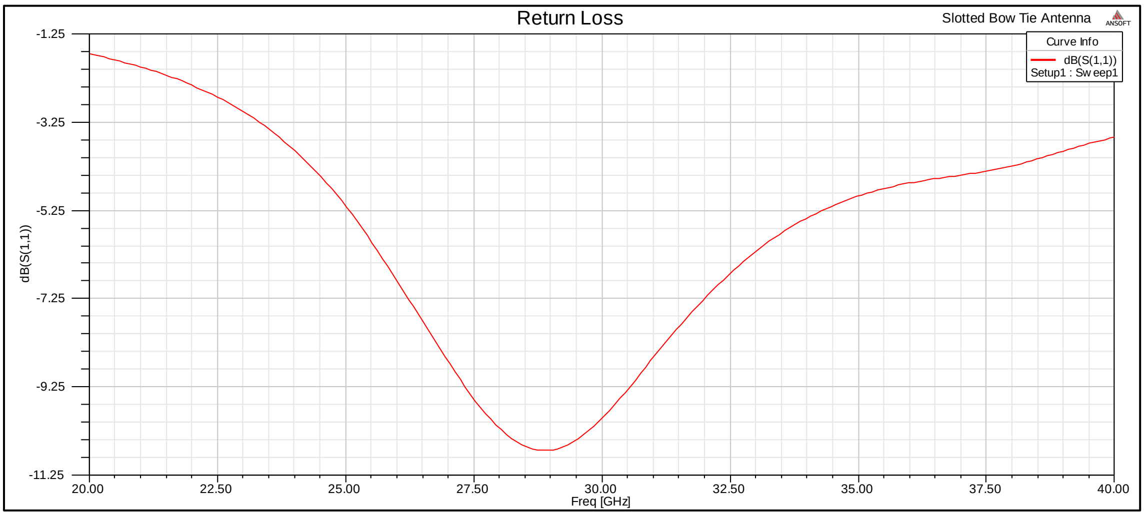


Figure 3.16. The first design of slotted Bow-tie antenna

The dimensions of the antenna optimized again are listed in Table 3.5. The new values show a very promising solution results with the five type of substrate materials.

Table 3.5. The first optimization values

The variables	Elements Values (mm)
Outside Width	1.9
Inside Width	0.1
Arm Length	2.1
Feeding Gap Width	0.1
Feeding Gap Length	0.5
Substrate Length	10
Substrate Width	10
Substrate Thickness	1.57

Using Arlon CuClad 217 substrate material with ε_r=2.17 the result is 32 GHz at –40 dB as shown in Figure 3.17.

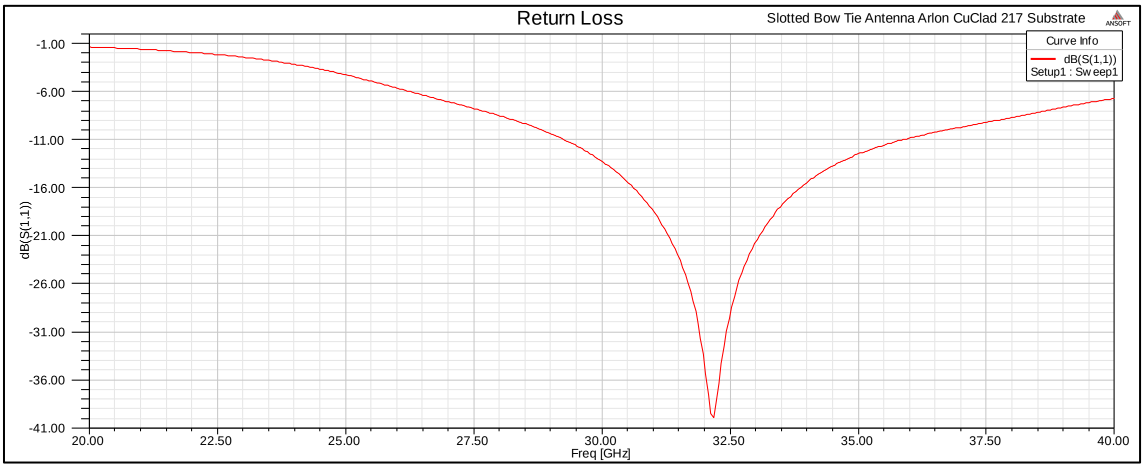


Figure 3.17. The S_{11} result using Arlon CuClad 217 substrate

Using Rogers RT/duroid 5880 substrate material with ε_r=2.2 the result is 32 GHz at –38 dB as shown in Figure 3.18.

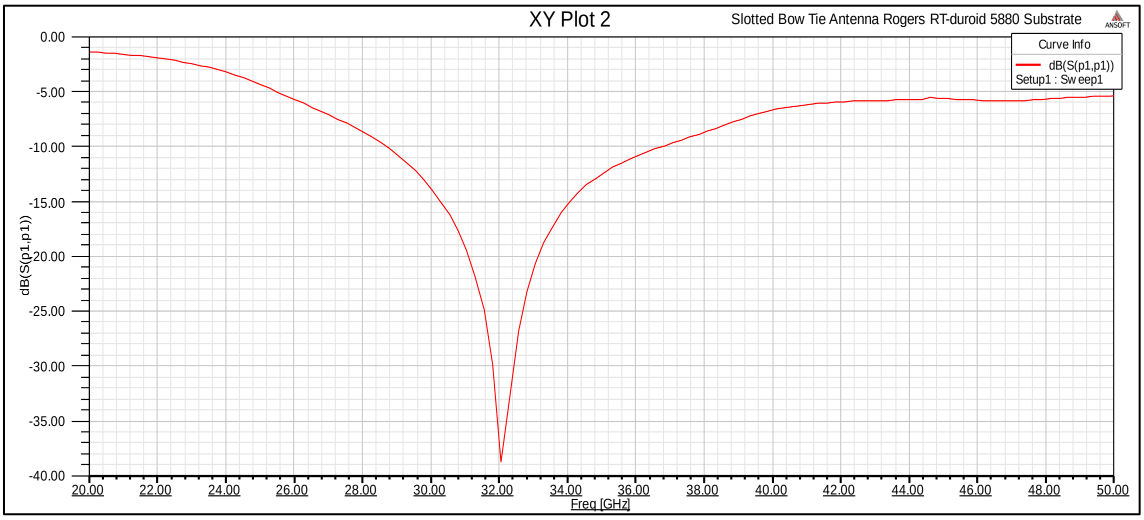


Figure 3.18. The S_{11} result using Rogers RT/duroid 5880 substrate

Using FR4_epoxy substrate material with ε_r=4.4 the result is 24.3 GHz at –54 dB as shown in Figure 3.19.

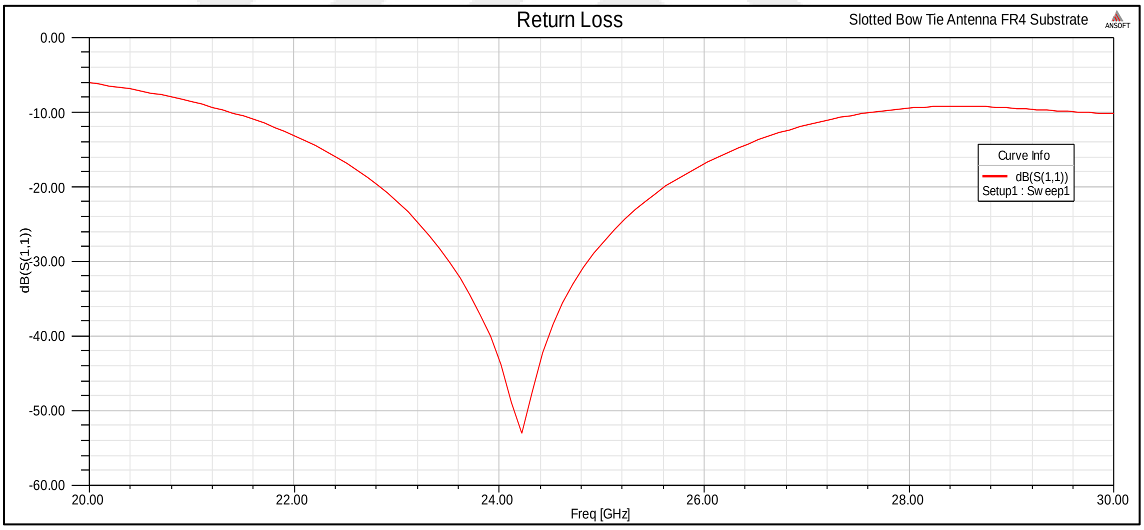


Figure 3.19. The S_{11} result using FR4 substrate

Using Neltec NH9294 substrate material with ε_r=2.94 the result is very close to the aim of this antenna of 28GHz for 5G applications and millimeter waves bands. The result is 28.72GHz at –33 dB as shown in Figure 3.20.

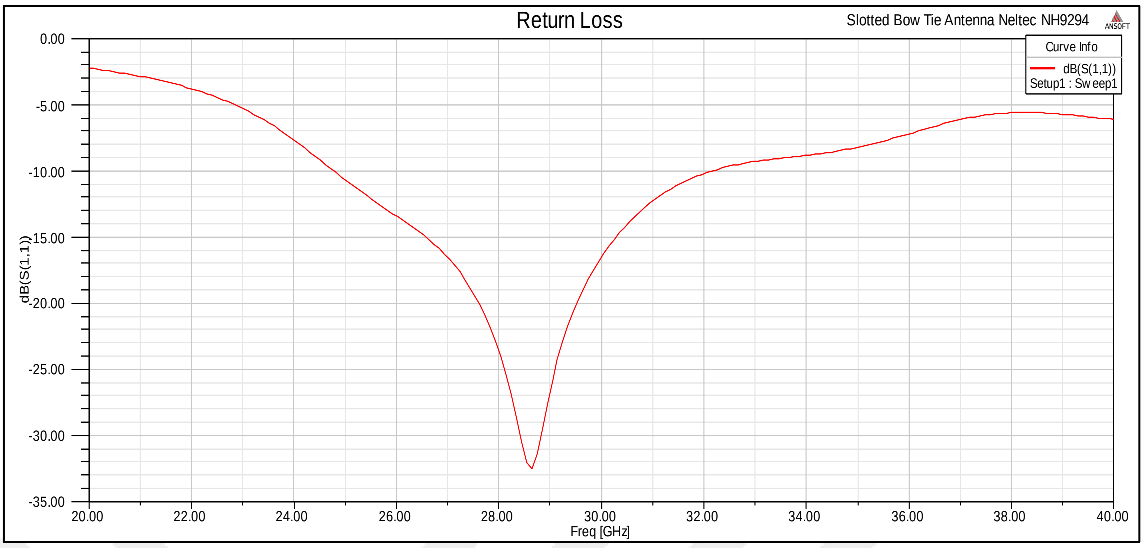


Figure 3.20. The S_{11} result using Neltec NH9294 substrate

Using Nelco N4000-13 substrate material with ε_r=3.5 the result is 24.8 GHz at –45 dB as shown in Figure 3.21.

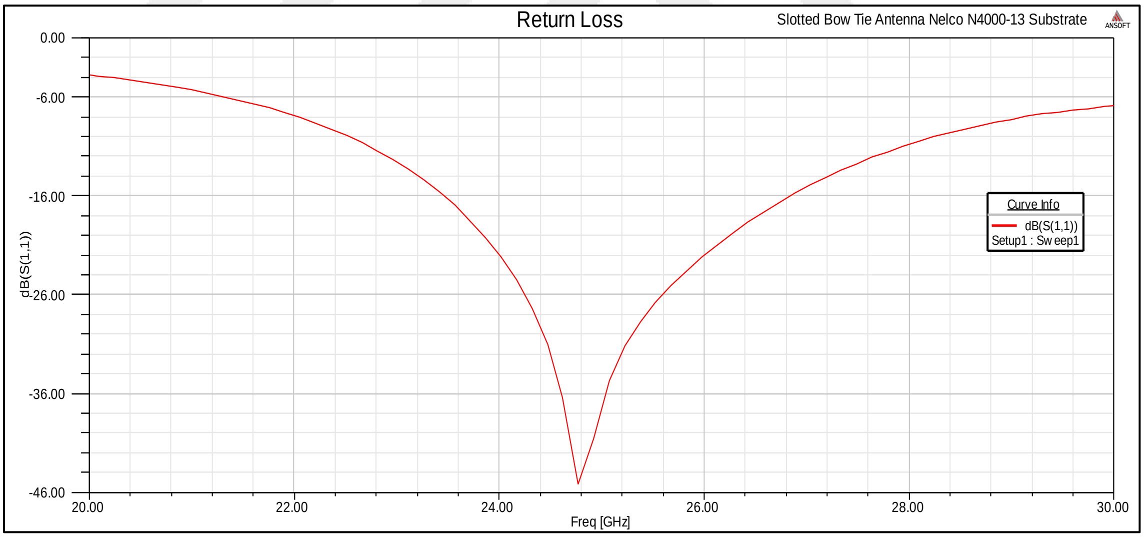


Figure 3.21. The S_{11} result using Nelco N4000-13 substrate

With changing the substrate thickness to 0.635 mm all the antennas improved them frequency but lost them gain except Nelco N4000-13 as can be shown in the Figures 3.22–3.26.

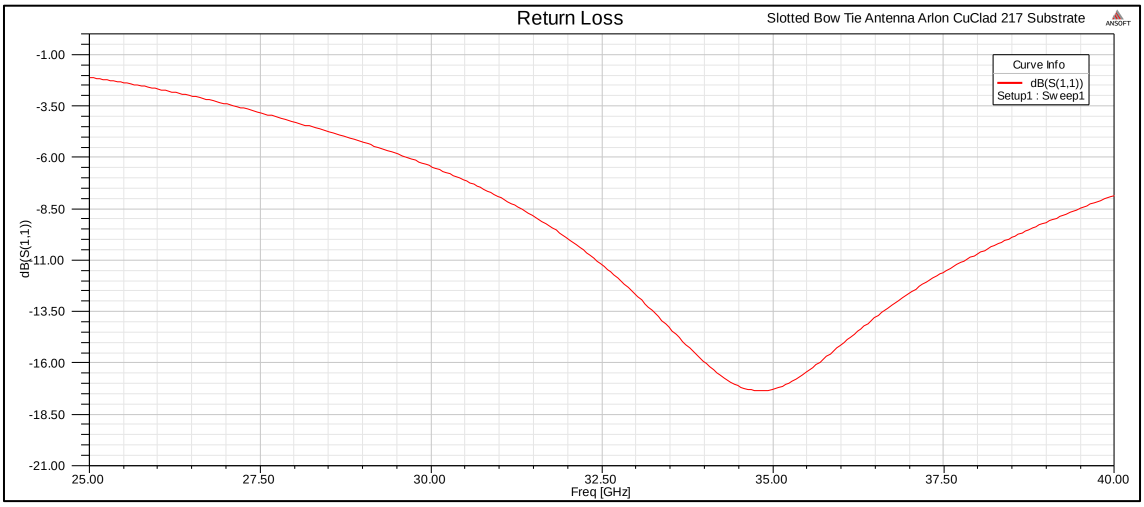


Figure 3.22. The S_{11} result for Arlon CuClad substrate

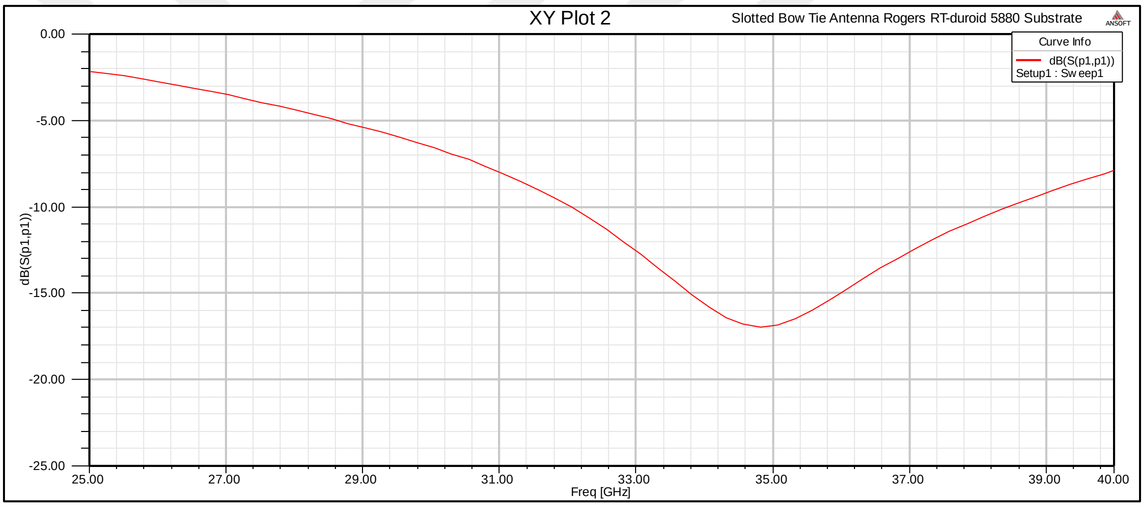


Figure 3.23. The S_{11} result for Rogers substrate

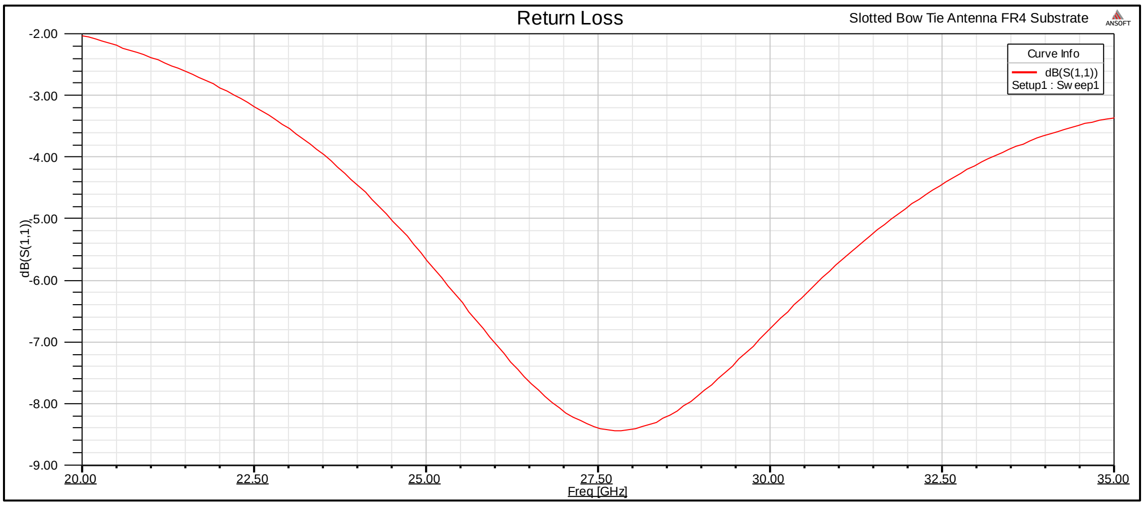


Figure 3.24. The S_{11} result for FR4 substrate with 0.635mm thickness

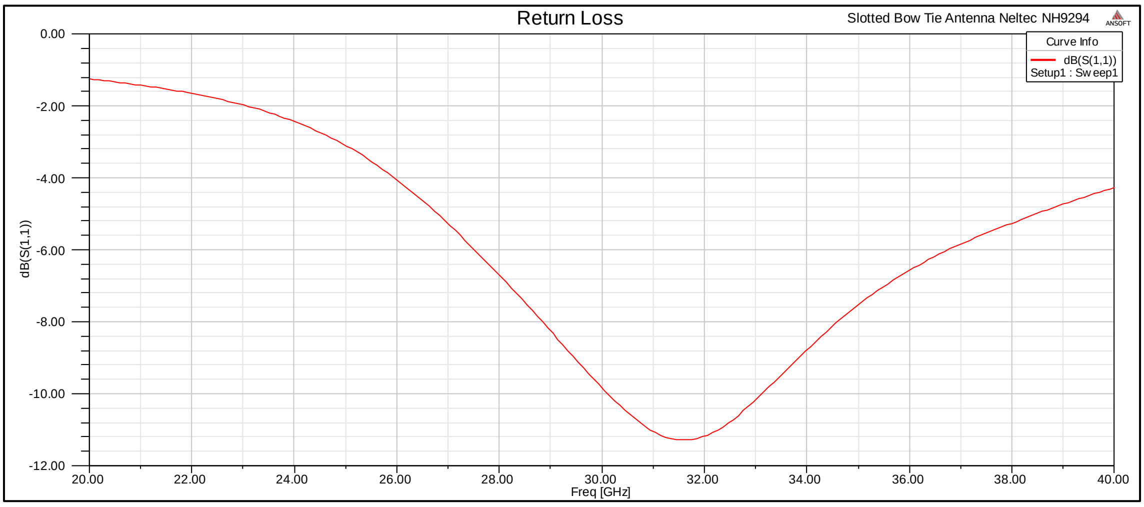


Figure 3.25. The S_{11} result for Neltec substrate

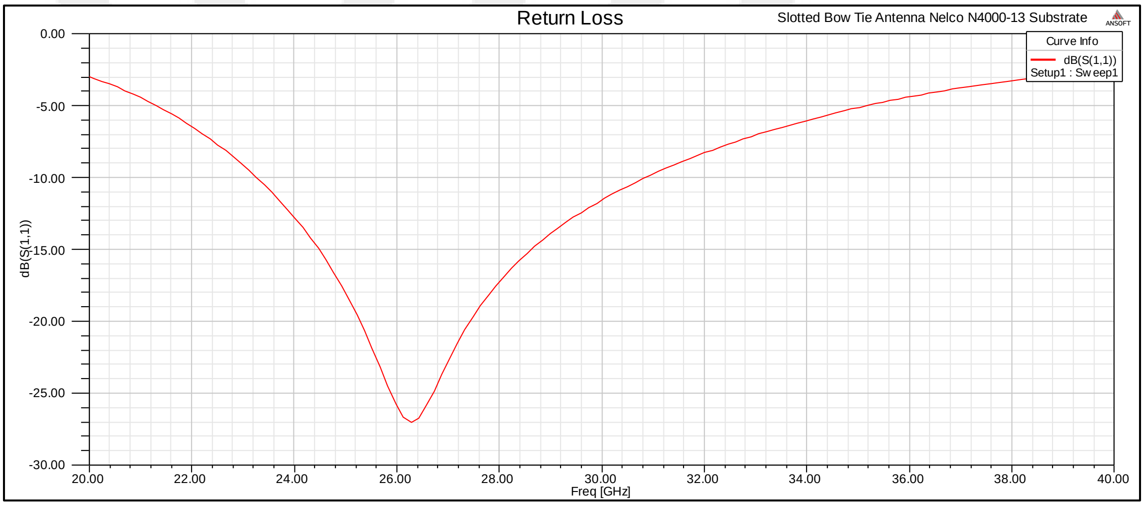


Figure 3.26. The S_{11} result for Nelco substrate

The previous results showed that Nelco substrate was the best results when using 0.635 thickness. The next step is to optimize the dimensions again for Nelco substrate to get the closest value to 28 GHz frequency and without crossing the limits of slotted Bow-tie antenna shape. As done before with CPW fed Bow-tie Antenna, the simulation program offers an optimization technique can help with improving the solution result. The dimension values of the antenna control completely the solution results. Changing these values affect the solution result as shown in the Figure 3.27, where changing the substrate width three times give three different S_{11} results.

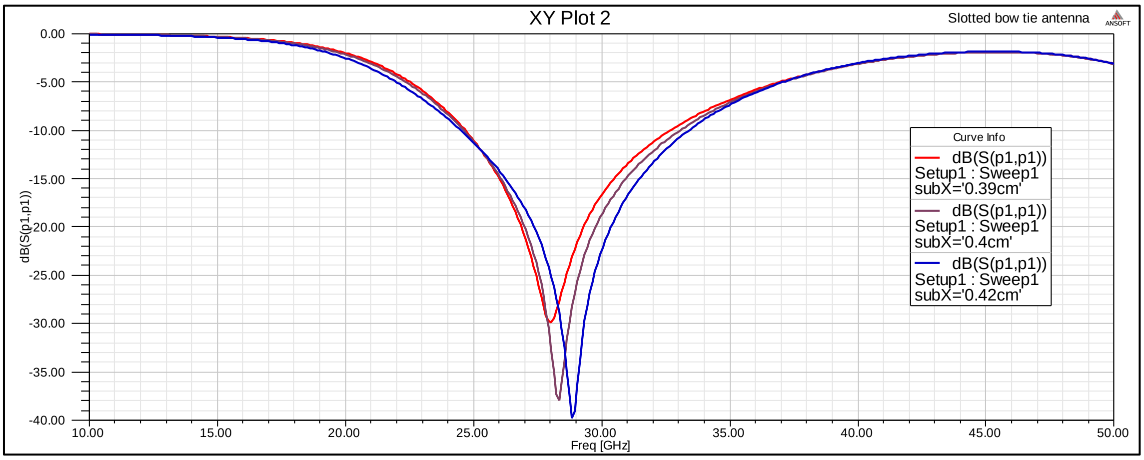


Figure 3.27. Three different results with three different substrate widths

As it clears from Figure 3.27. above, changing the dimensions give different results. So, the new dimensions that give a sharp 28 GHz with Nelco N4000-13 substrate and $\mathcal{E}_r$=3.5 at 0.635 mm of thickness which represent the next generation substrate of communication are given in Table 3.6.

Table 3.6. The final dimensions value

The variables	Elements Values (mm)
Outside Width	1.9
Inside Width	0.1
Arm Length	2.1
Feeding Gap Width	0.1
Feeding Gap Length	0.5
Substrate Length	3.9
Substrate Width	6
Substrate Thickness	0.635

The S_{11} solution result for sharp 28 GHz at –30 dB, VSWR result, radiation pattern and 3D gain Total are shown in Figures 3.28–3.31 which represent the optimal solution result for this kind of slotted Bow-tie Antenna.

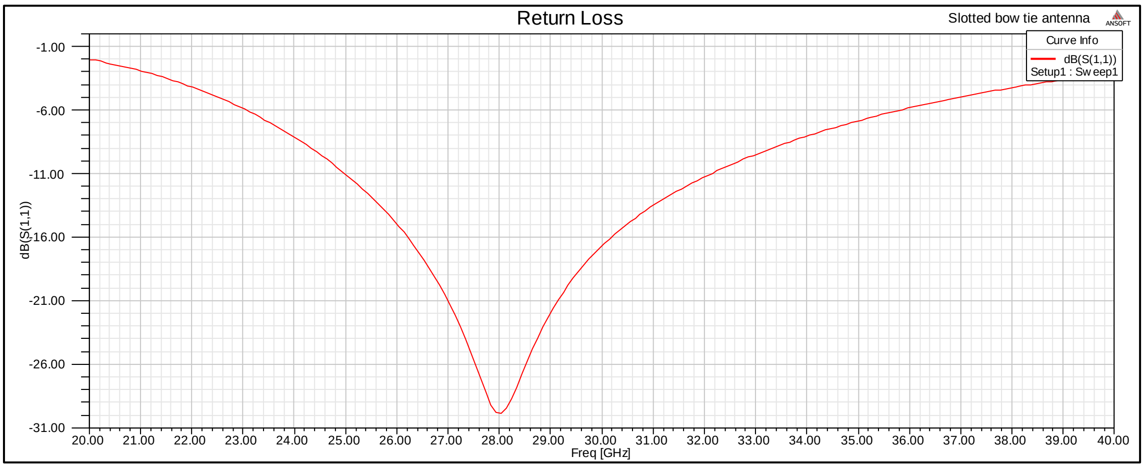


Figure 3.28. The S_{11} result for the optimal design

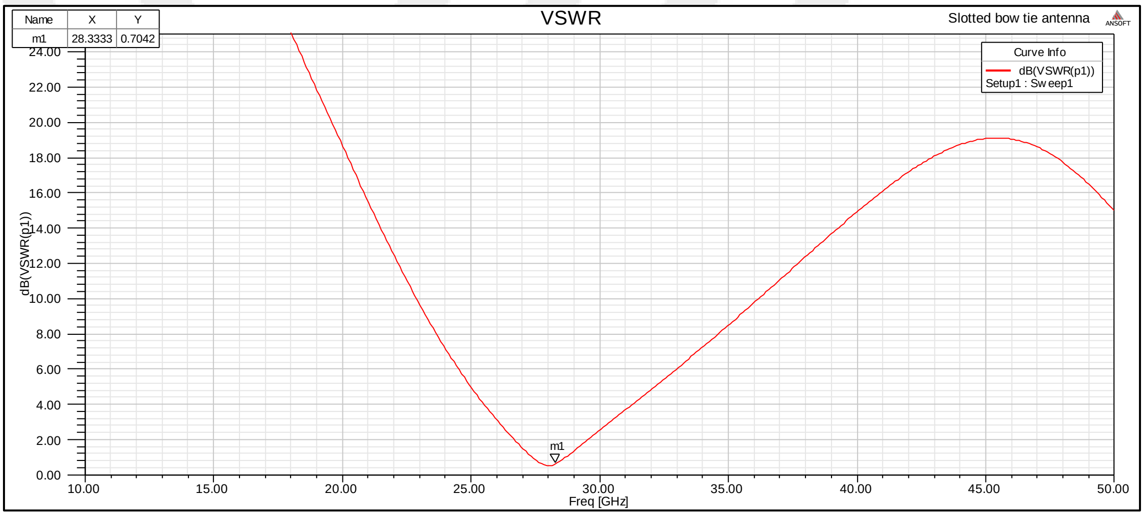


Figure 3.29. VSWR result for the optimal design

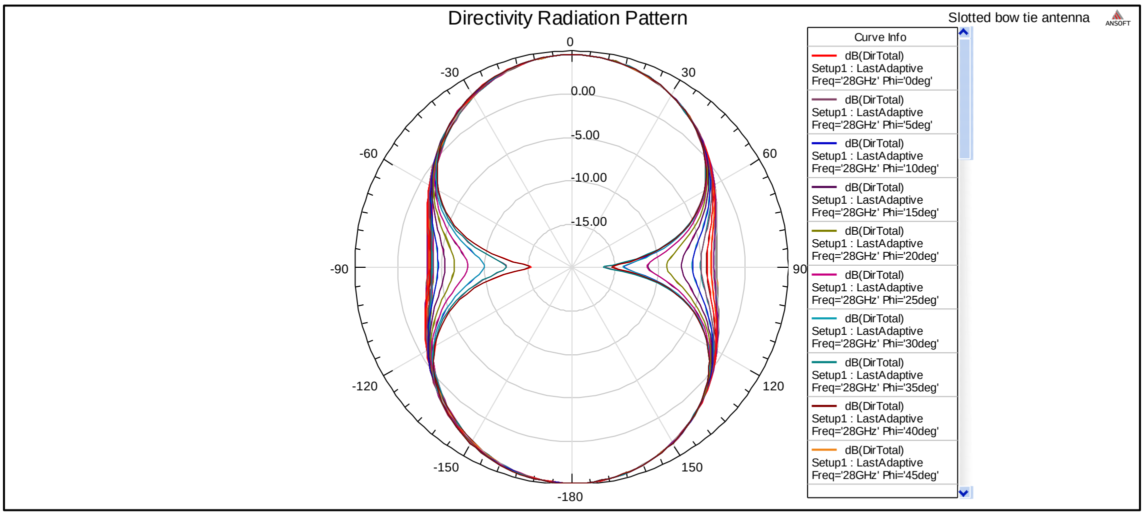


Figure 3.30. Radiation pattern result for the optimal design

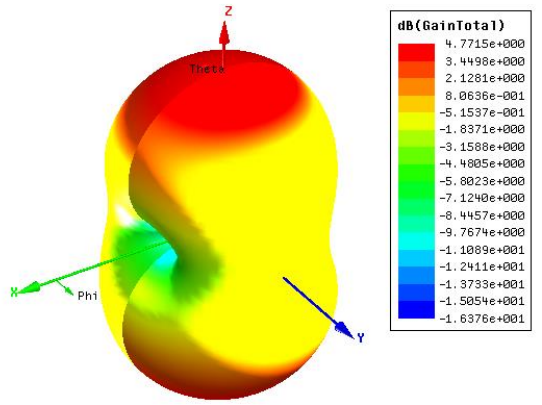


Figure 3.31. Gain Total result for the optimal design

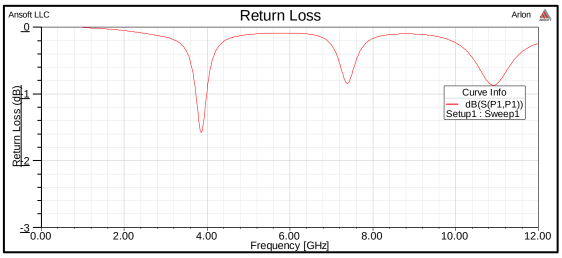
3.2. Quasi-Yagi Antenna Results

The proposed antenna started with designing a single element of Quasi-Yagi Antenna on a different substrate like Arlon CuClad, Rogers RT/duroid 5880, FR4_epoxy, Neltec NH9294 and Nelco N4000-13, substrate width, length, and thickness are 15, 18, and 0.635 mm, respectively with the dimensions values as given in Table 3.7.

Table 3.7. The elements values of Quasi-Yagi antenna

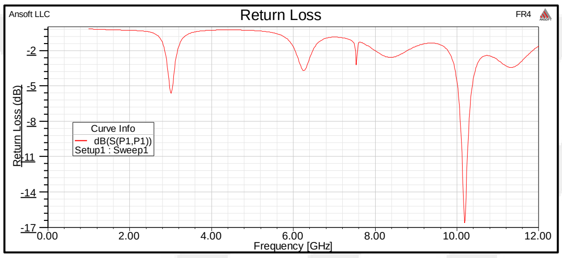
The variables	Elements Values (mm)
L_{dir}	3.7
W_{dir}	0.6
S_{dir}	2.4
L_{dri}	4.2
W_{dri}	0.6
S_{dri}	3.6
L_1	3
L_2	1.2
L_3	4.5
L_4	1.2
L_f	3
W_1	1.2
W_f	0.6

The director works as a parasitic element, generating mutual coupling with an active element, and then realizes the function of adjusting the input impedance. But the S_{11} results for the five substrates are unsatisfactory as shown in Figure 3.32.

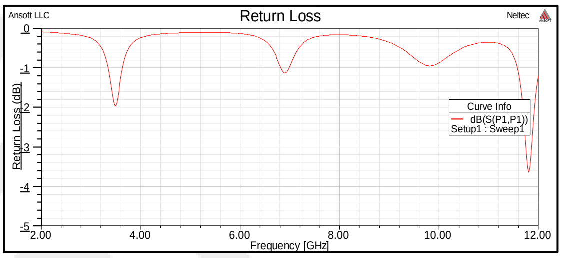


(a)

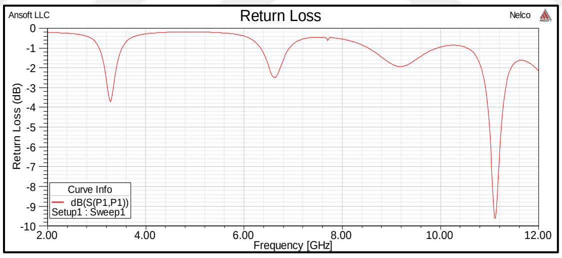
(b)



(b)



(d)



(e)

Figure 3.32. The S_{11} result with using different substrates materials, (a) Arlon, (b) Rogers, (c) FR4, (d) Neltec and (e) Nelco

From the figures above, the best result is FR4 substrate because the FR4 material has the higher ε_r than the other substrates. After that level the constraint on a high ε_r and a good substrate which it should be used for higher frequencies like RT/duroid 6006 & 6010 Laminates which used usually for UWB communication design [67], [75]. This material has been designed for the demand of high ε_r from microwave circuit applications requiring. ε_r of RT/duroid 6010LM laminate=10.2 and its feature ease of fabrication and stability in use [76]. Therefore, it used in the design of Quasi-Yagi Antenna and it improved the gain and the bandwidth. The first design is a single element of Quasi-Yagi Antenna on RT6010LM for UWB applications. The new substrate is proved an improvement in the frequency and gain at 10 GHz with the above elements values as shown in Figure 3.33.

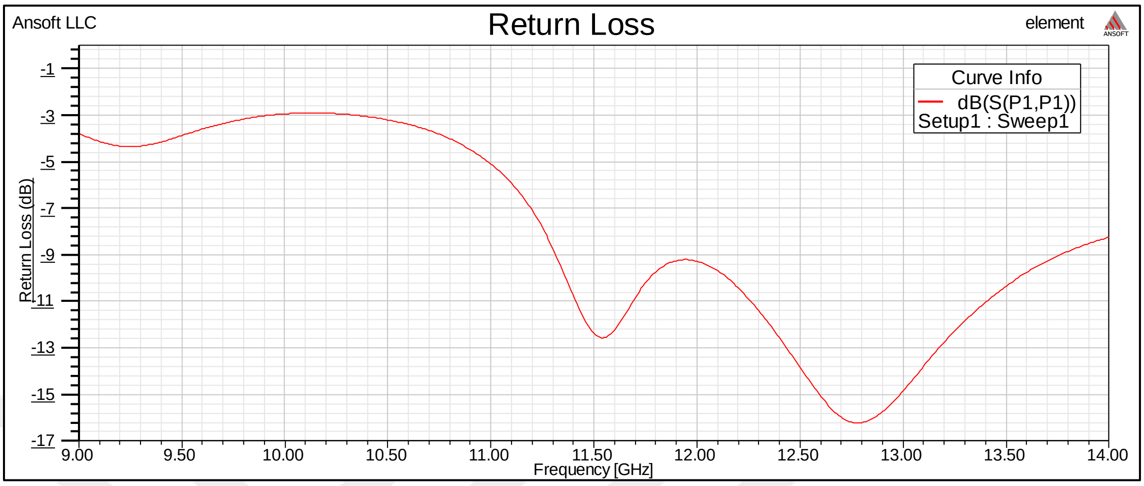


Figure 3.33. The result for the first Quasi-Yagi Antenna

The dimensions values are changed, optimized, and examined the new substrate width, substrate length, and substrate thickness are 30, 21, and 0.635 mm, respectively and the other dimensions values are given in Table 3.8.

Table 3.8. The final dimensions value

The variables	Elements Values (mm)
L_{dir}	3.3
W_{dir}	0.6
S_{dir}	2.4
L_{dri}	3.9
W_{dri}	0.6
S_{dri}	3.6
L_1	3
L_2	1.2
L_3	4.5
L_4	1.2
L_f	3
W_1	1.2
W_f	0.6

For single Quasi-Yagi antenna, the S_{11} final result can be shown in Figure 3.34.

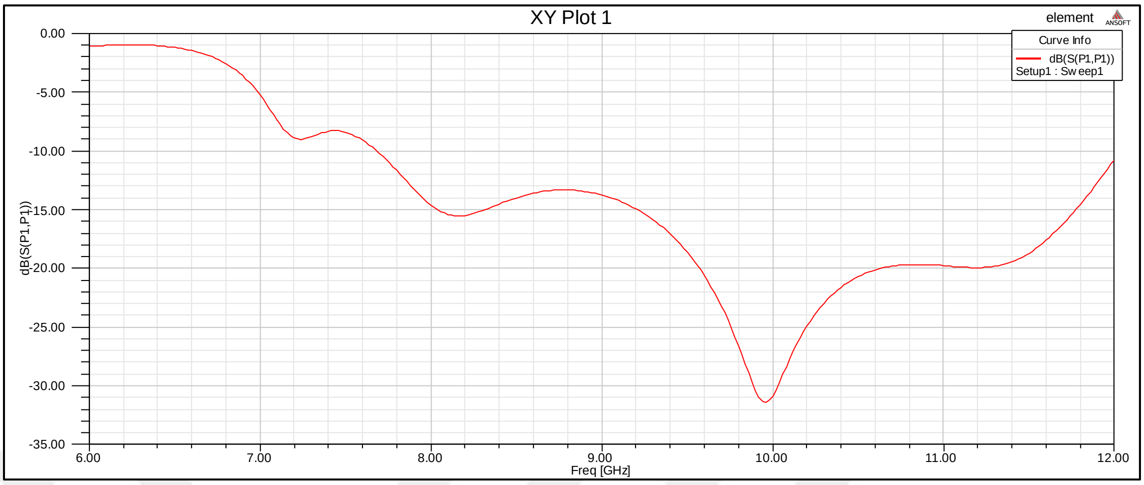


Figure 3.34. The result of Quasi-Yagi antenna after optimization

The next step is to design an array of two Quasi-Yagi Antenna and test the result. Using the same element values and substrate of the above antenna. The antenna has a broadband in C-band and X-band which it is 8.2 GHz at –18 dB, and 10.3 GHz at –28 dB. The S_{11} result is shown in Figure 3.35.

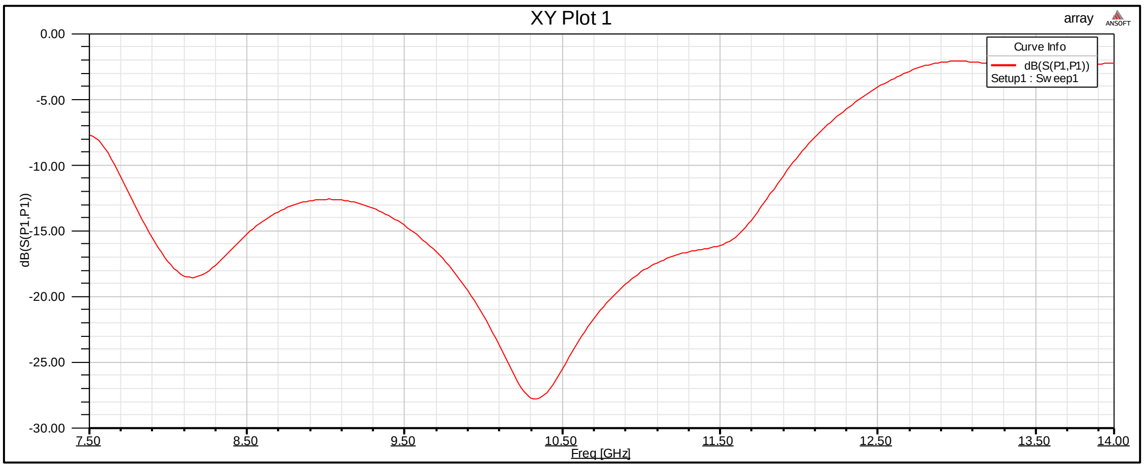


Figure 3.35. The S_{11} result of two Quasi-Yagi antenna array

In this design, two 1×4 uniforms linear array (subarray) of an antennas director have been used as shown in Figure 3.36, where each radiating element of them is excited by signals with equal magnitude.

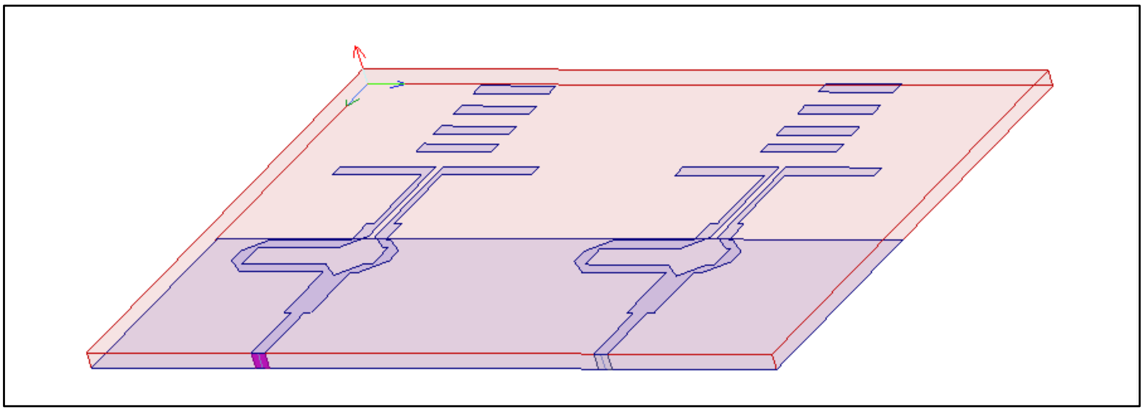


Figure 3.36. The Quasi-Yagi antenna design with the subarray

The return loss, VSWR, Radiation pattern and Gain Total results improved and as shown in Figures 3.37–3.40, the last antenna design has a broadband in X-band which it is 10 GHz at –21.5 dB, and 11.9 GHz at –22.5 dB. This broadband generally used for UWB Applications.

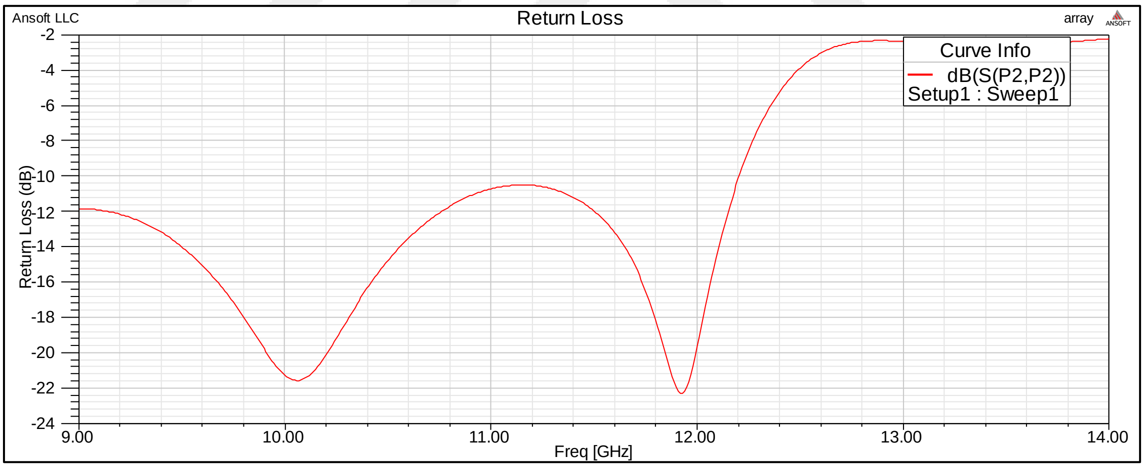


Figure 3.37. The S_{11} result after adding the subarray

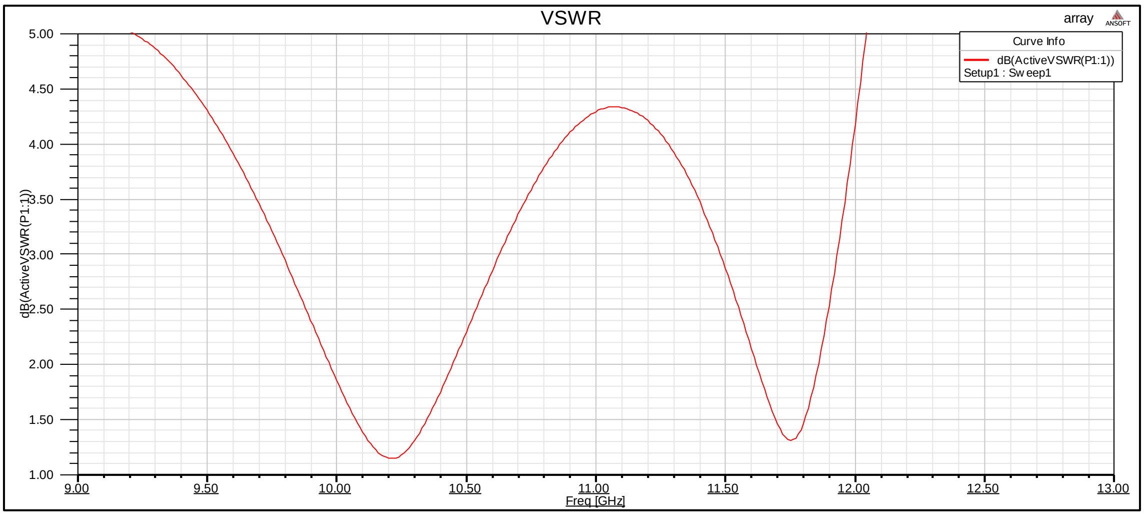


Figure 3.38. VSWR result after adding the subarray

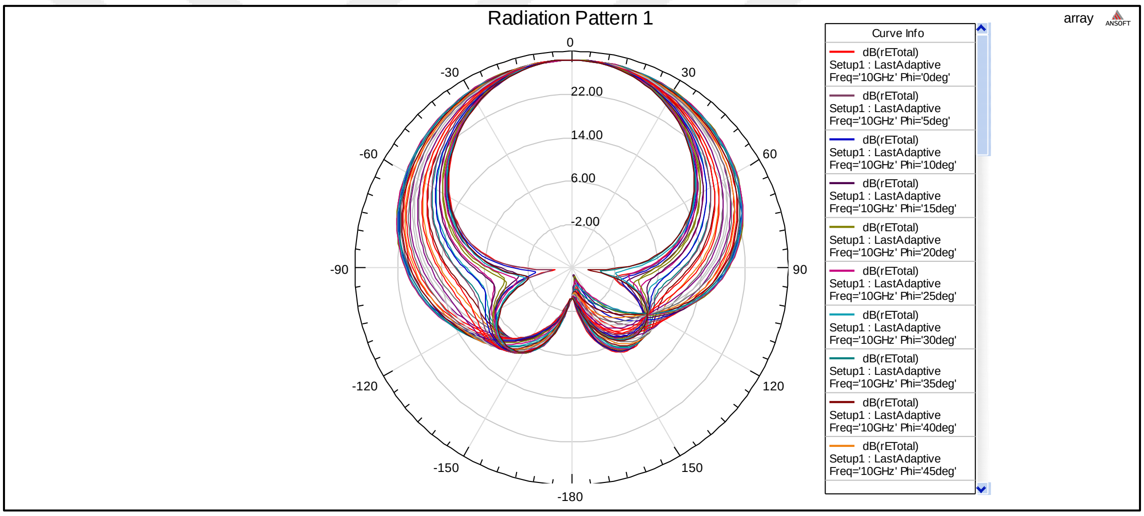


Figure 3.39. Radiation pattern directivity result after adding the subarray

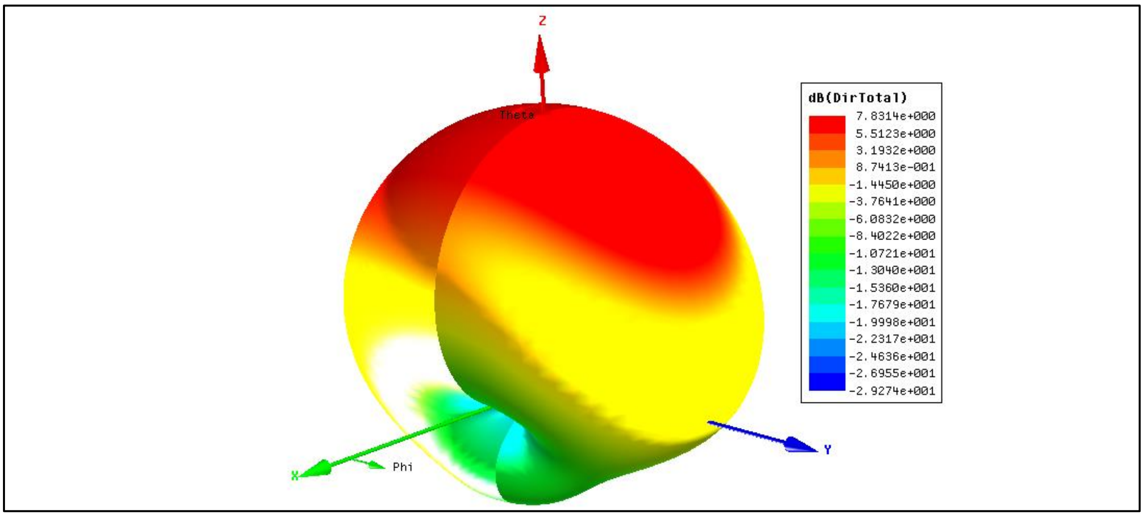


Figure 3.40. The Gain Total result after adding the subarray

As mentioned before in the Bow-tie Antenna to use the optimization techniques that given in the simulation program. In Quasi-Yagi Antenna, this optimization technique cannot help to improve the solution result anymore. Many different times, the dimensions of the antenna are changed and tested but the results do not improve and it is unsatisfactory to get a broadband for X-band spectrum as shown in the Figure 3.41.

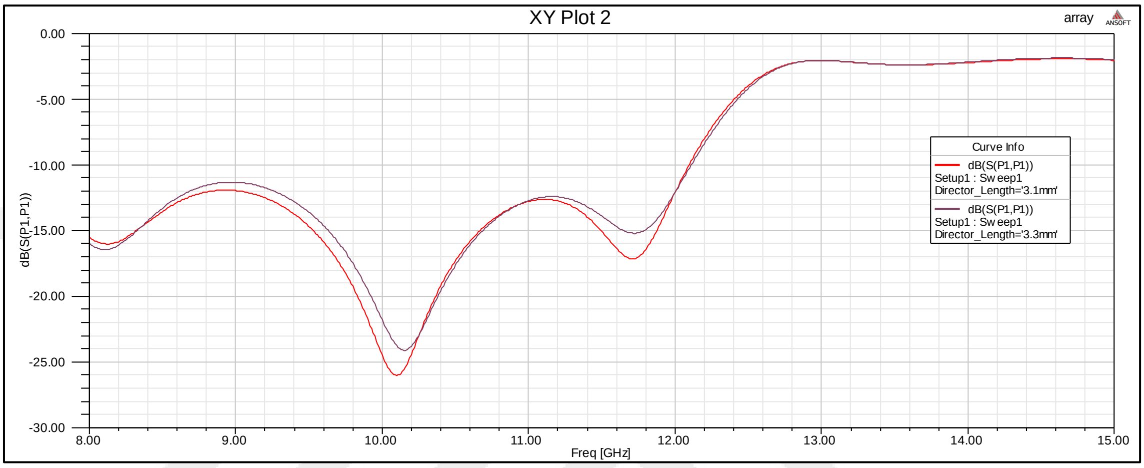


Figure 3.41. The S_{11} result with two different director length values

CHAPTER 4

CONCLUSION, DISCUSSION, AND FUTURE WORK

In this thesis, CPW fed Bow-tie, Slotted Bow-tie, and Quasi-Yagi patch antennas have been proposed and designed for UWB and millimeter waveband communication systems and applications. Different substrates materials have been used in the designs, to make a comparison and to investigate their performance to reach the optimal result. The designs are also optimized in order to get smaller antenna size for next generation mobile communication systems with the high frequencies.

In the first antenna design, CPW fed Bow-tie antenna is simulated for tri-bands in UWB and millimeter waveband spectrums. Five different substrates (Arlon CuClad 217, FR4_epoxy, Nelco N4000-13, Neltec NH9294 and Rogers RT/duroid 5880) used. The result of Arlon substrate and Rogers substrate are very close to each other even with changing the substrate thickness from 1.57 mm to 0.635 mm. The tri-band results are S-band, C-band, and X-band (3.5 to 3.7 GHz at –13 to –17 dB, 7 to 7.6 GHz at –26 to –30 dB and 10.5 to 11.5 GHz at –11 to –16.5 dB).

The substrate changed to FR4_epoxy and investigated with changing the substrate thickness from 1.57 mm to 0.635 mm. The tri-band results are C-band, X-band, and Ku-band (5.5, 6.25 GHz at –14, –38 dB, 8.5, 9.8 GHz at –17.8, –25 dB and 11.3, 12.7 GHz at –14, –24 dB).

The last two substrates are Neltec NH9294 and Nelco N4000-13. The simulation results show a great competition between them, where both belong to the same material's crop. The Neltec substrate also is investigated in two different thickness of substrate 1.57 mm and 0.635 mm. The tri-band results are C-band, X-band, Ku-band, and K-band (9.8, 7 GHz at –27, –26 dB, 16, 15 GHz at –25, –35 dB and 22.3, 22.7 GHz at –41, –16.6 dB).

The Nelco substrate tri-band results are X-band, Ku-band, and K-band (9.4, 13.5 GHz at –23, –23 dB, 12.5, 16.9 GHz at –15, –14 dB and 15.1, 20.6 GHz at –50, –50 dB).

The dimensions of this antenna are optimized and tested again with different substrate materials. The only best results are obtained by using Nelco N4000-13. This substrate expressed as a next generation high Tg FR-4 dielectric substrate, where it is very promising for the new technologies with a high-frequency band for either UWB applications or millimeter wavebands applications.

The CPW fed Bow-tie antenna optimal result for the optimized substrate is tri-band in X-band, Ku-band, and K-band (9.1 GHz at –27 dB, 14.5 GHz at –40 dB and 20.5 GHz at –34 dB), the VSWR < 2 and the Gain Total gave good radiation toward theta.

The second antenna design is slotted Bow-tie antenna for millimeter waveband at 28 GHz which represent the candidate for 5G technology. The slot design is an old technique that used in antenna configuration to improve better gain and bandwidth. In this thesis, the same five substrates (Arlon CuClad 217, FR4_epoxy, Nelco N4000-13, Neltec NH9294 and Rogers RT/duroid 5880) used to investigate the optimal design and to reach the ideal result at sharp 28 GHz. The dimensions of the proposed antenna are improved in different times until it reaches the optimal design.

The Arlon CuClad substrate result is 32 GHz at –40 dB with 1.57 mm and 35 GHz at –17 dB with 0.635 mm. The Rogers substrate result is 32 GHz at –38 dB with 1.57 mm and 35 GHz at –16 dB with 0.635 mm. The FR4 substrate result is 24.3 GHz at –54 dB with 1.57 mm and 27.6 GHz at –8.5 dB with 0.635 mm. The Neltec NH9294 substrate result is 28.7 GHz at –33 dB with 1.57 mm and 31 GHz at –11 dB with 0.635 mm. The Nelco N4000-13 substrate result is 24.8 GHz at –45 dB with 1.57 mm and 26.5 GHz at –27 dB with 0.635 mm.

After optimizing the antenna substrate thickness from 1.57mm to 0.635 mm, it is clear that the Nelco substrate still the best choice to optimize again until it will reach the optimal solution at sharp 28 GHz. The dimensions values of the antenna optimized again with Nelco substrate, where the result of the return loss, VSWR and radiation pattern showed a good match with the required frequency 28 GHz at –30 dB, VSWR < 2 and good directivity results.

The last proposed antenna is Quasi-Yagi Antenna design in an array of two elements and sub-array of 1×4 directors to enhance the gain and radiation pattern. The substrate is RT/duroid 6010LM with high ε_r=10.2 which usually used for UWB frequencies. All the elements of Quasi-Yagi antenna control the results but the most affected parameters are the director length and the driven length.

The first result for the antenna without the subarray design shows broadband in C-band and X-band which it is 8.2 GHz at –18 dB and 10.3 GHz at –28 dB. After adding the subarray, the return loss, VSWR, Radiation pattern and the Gain Total results greatly improved. These results show a broadband in X-band which it is 10 GHz at –21.5 dB and 11.9 GHz at –22.5dB. This broadband generally used for UWB applications.

The results of the three designs reach the aim of this thesis which it is the optimal result for each antenna. The results are very promising to open the gate for the next generation of communication systems.

Many issues related to antennas design have been addressed in this thesis. However, other issues may be considered for further investigations like implementation of these antennas and comparing the measurement results with the simulation results. While valuable results about using metamaterials, antennas are obtained at different modern studies, more related structures could be developed. The recommended structures should be optimized to reduce the electric field intensity around the most effective radiating parts and increase the magnetic field. This can be another future path for antennas design of further larger radiation. It could also be beneficial to investigate the effect of metamaterials on the radiation pattern of the proposed antenna designs. As a future work, the proposed design will be optimized by using different metaheuristic techniques.

REFERENCES

1. Pi, Z. and Khan, F., 2011. An introduction to millimeter-wave mobile broadband systems. **IEEE communications magazine, 49** (6): 101-107.

2. Balanis, C.A., 2016. Antenna Theory: Analysis and design. Fourth edition. John Wiley & Sons, New Jersey, Canada, 1095 pp.

3. Shafiei, M.M., Moghavvemi, M., Mahadi, W.N.L.W., 2017. The parametric study and fine-tuning of Bow-tie slot antenna with loaded stub, **journal pone 0169033**, PloS one, **12** (1): 1-16.

4. Alvertos, K.N., Karagianni, E.A., Vardakis, K.D., Mpountas, T.K., Kaklamani, D.I., 2017. Bow-tie antenna for underwater Wireless Sensor Networks, pp. 323-326. In Antenna Technology: *Small Antennas, Innovative Structures, and Applications (iWAT),* 2017 International Workshop on March 1-3, 2017, Athens, Greece.

5. Gong, Z., Ge, S., Guo, T., Zhang, Q., Chen, Y., 2017. A compact planar 24GHz quasi-Yagi antenna for unmanned aerial vehicle radar applications, pp. 104-105, *In Computational Electromagnetics (ICCEM), 2017 IEEE International Conference*. March 8-10, 2017, Kumamoto, Japan.

6. Wahib, M., Freundorfer, A., Antar, Y., 2017, March. A planar wideband Quasi-Yagi antenna with high gain and FTBR, pp. 42-45, In Antenna Technology: *Small Antennas, Innovative Structures, and Applications (iWAT), 2017 International Workshop*, March 1-3, 2017, Athens, Greece.

7. Jehangir, S.S., Sharawi, M.S., 2017. A highly miniaturized loop excited Quasi-Yagi antenna with high front-to-back ratio, pp. 1976-1979 In Antennas and Propagation (EUCAP), *2017 11th European Conference*, March 19-24, 2017, Paris, France.

8. Wang, H., Yang, G., 2017. Design of 4× 4 microstrip Quasi-Yagi beam-steering antenna array operation at 3.5 GHz for future 5G vehicle applications, pp. 331-334, In Antenna Technology: *Small Antennas, Innovative Structures, and Applications (iWAT), 2017 International Workshop* March 1-3, 2017, Athens, Greece.

9. Eldek, A.A., Elsherbeni, A.Z., Smith, C.E., 2005. A microstrip-fed modified printed bow-tie antenna for simultaneous operation in the C and X-bands, pp. 939-943 *In Radar Conference, 2005 IEEE International Conference*, May 9-12, 2005, Arlington, VA, USA

10. Khodier, M., Al-Aqil, M., 2010. Design and optimisation of Yagi-Uda antenna arrays. **Journal of IET microwaves, antennas & propagation, 4** (4): 426-436.

11. Ojaroudiparchin, N., Shen, M., Pedersen, G.F., 2016. Beam-steerable microstrip-fed bow-tie antenna array for fifth generation cellular communications, pp. 1-5, In Antennas and Propagation (EuCAP), *2016 10th European Conference*, April 10-15, 2016, Davos, Switzerland.

12. Deal, W.R., Kaneda, N., Sor, J., Qian, Y., Itoh, T., 2000. A new quasi-Yagi antenna for planar active antenna arrays. **Journal of IEEE transactions on Microwave Theory and Techniques, 48** (6):910-918.

13. Maxwell, J.C., 1954. Summary for Policymakers. A treatise Electrical magnetism, Macmillan and co., Oxford, London **53** (9): 1–30.

14. Elliott, R.S., Gillespie, E.S., Villeneuve, A.T., Rusch, W.V.T., Alexopoulos, N.G., 1983. IEEE standard definitions of terms for antennas, New York, USA, **145** (31), 29 pp.

15. Koziel, S., Bekasiewicz, A., 2016. Multi-objective design of antennas Using Surrogate Models, World Scientific, Reykjavik University, Iceland, 360 pp.

16. Levin, B., 2017. Antenna Engineering: Theory and problems, Taylor & Francis group, CRC Press, London, 406 pp.

17. Zhang, Z., 2017. Antenna design for mobile devices. John Wiley & Sons, IEEE Press, Singapore, 320 pp.

18. Cheng, Y.J., 2015. Substrate integrated antennas and arrays, Taylor & Francis group, CRC Press, London, 260 pp.

19. Microwave printed circuit board substrate, 2012. CuClad Series ® PTFE/Woven Fiberglass Laminates Typical Properties, CuClad.

20. Coonrod, J., 2012. March, April, Selecting PCB materials for high-frequency applications *Microwave Engineering Europe. Rogers Corporation*, 10-13 pp.

21. Haugan, E., Dalsjo, P., 2014. Characterization of the material properties of two FR4 printed circuit board laminates. *Norwegian Defence Research Establishment (FFI)*, 40 pp.

22. Waterhouse, R.B., 2003. Microstrip patch antennas: a designer's guide. Springer Science & Business Media, RMIT University, New York, 421 pp.

23. Eldek, A.A., Elsherbeni, A.Z., Smith, C.E., 2004. Wideband microstrip- fed printed bow- tie antenna for phased- array systems. **Journal of Microwave and optical technology letters, 43** (2): 123-126.

24. Pandey, G., Soh, P.J., Mercuri, M., Beyer, A., Vandenbosch, G. Schreurs, D., 2013, March. EM-based antenna optimization for health monitoring radar sensor, pp. 632-637, *In The 29th Annual Review of Progress in Applied Computational Electromagnetics*, March 24-28, 2013, Monterey, CA.

25. Lestari, A.A., Bharata, E., Suksmono, A.B., Kurniawan, A., Yarovoy, A.G. Ligthart, L.P., 2010. A modified bow-tie antenna for improved pulse radiation. **International Journal of IEEE Transactions on Antennas and Propagation, 58** (7): 2184-2192.

26. Murugan, S.A.S., Karthikayan, K., NA, N., 2013. A triband slotted Bow-tie antenna for wireless applications. **International Journal of Computational Engineering Research (IJCER), 3** (7): 1658 - 1661.

27. Kaswiati, W.S., Suryana, J., 2012. Design and realization of planar bow-tie dipole array antenna with dual-polarization at 2.4 GHz frequency for Wi-Fi access point application, pp. 218-222, In Telecommunication Systems, Services, and Applications (TSSA), *2012 7th International Conference*. Bali, Indonesia.

28. Lestari, A.A., Yarovoy, A.G., Ligthart, L.P., 2004. RC-loaded bow-tie antenna for improved pulse radiation. **International Journal of IEEE transactions on antennas and propagation, 52** (10): 2555-2563.

29. Lee, J.Y., Hwang, S.N., 2008. A High-Gain Boost Converter using Voltage-Stacking Cell. **Journal of The Transactions of The Korean Institute of Electrical Engineers, 57** (6): 982-984.

30. Eldek, A.A., Elsherbeni, A.Z., Smith, C.E., 2004. Wideband bow-tie slot antenna with tuning stubs, pp. 583-588, In Radar Conference, 2004. *Proceedings of the IEEE, Philadelphia,* April 29, 2004, Philadelphia, PA, USA.

31. Chen, S.Y., Hsu, P., 2004. A modified bow-tie slot antenna fed by a coplanar waveguide, pp. 799-802, *In Antennas and Propagation Society International Symposium,* June 20-25, 2004, Monterey, CA, USA.

32. Lin, Y.D., Tsai, S.N., 1998. Analysis and design of broadside-coupled striplines-fed bow-tie antennas. **Journal of IEEE Transactions on Antennas and Propagation, 46** (3): 459-460.

33. Rahim, M.K.A., Abdul Aziz, M., Goh, C., 2005. Bow-tie microstrip antenna design, pp. 17-20, jointly held with *2005 IEEE 7th Malaysia Int. Conf. Commun*., November 16-18, 2005, Malaysia.

34. Ozturk, M.E., Korkmaz, E., Kebeli, M., 2015. Rounded-edge bow-tie antenna for wideband mobile direction-finding system. **Journal of IET Microwaves, Antennas & Propagation, 9** (15): 1809-1815.

35. Danideh, A., Sadeghzadeh, R.A., 2013. CPW-fed slot antenna for mimo system applications. **Indian Journal of Science and Technology, 6** (1): 3872-3875.

36. Mehdipour, A., Mohammadpour- Aghdam, K., Faraji- Dana, R., Sebak, A.R., 2008. Modified slot bow- tie antenna for UWB applications. **Journal of Microwave and Optical Technology Letters**, **50**(2): 429-432.

37. Li, Y.X., 2012. A bowtie-slot microstrip patch antenna with an H-type radiation chip and U-type parasitic patches in Ka-band using LTCC technology, pp. 434-436, In Computational Problem-Solving (ICCP), *2012 International Conference* on Octtober 19-21, 2012, Leshan, China.,

38. Yurduseven, O., Smith, D., Elsdon, M., 2013. Printed slot loaded bow-tie antenna with super wideband radiation characteristics for imaging applications. **Journal of IEEE Transactions on Antennas and Propagation, 61** (12): 6206-6210.

39. Sayidmarie, K.H., Fadhel, Y.A., 2013. A planar self-complementary bow-tie antenna for UWB applications. **Journal of Progress in Electromagnetics research, 35**: 253-267.

40. Grajek, P.R., Schoenlinner, B., Rebeiz, G.M., 2004. A 24-GHz high-gain Yagi-Uda antenna array. **Journal of IEEE Transactions on Antennas and Propagation, 52** (5): 1257-1261.

41. Alhalabi, R.A., Rebeiz, G.M., 2009. High-gain Yagi-Uda antennas for millimeter-wave switched-beam systems. **Journal of IEEE Transactions on Antennas and Propagation, 57** (11): 3672-3676.

42. Koziel, S., Ogurtsova, S., Leifssona, L., 2011. Simulation-driven design of antennas using coarse-discretization electromagnetic models. **Journal of Procedia Computer Science, 4**: 1252-1261.

43. Benech, P., Duchamp, J.M., Ferrari, P., Kaddour, D., Pistono, E., Vuong, T.P., Xavier, P., Hoarauand, C., Arnould, J.D., 2010. Microwave and millimeter wave technologies from photonic bandgap devices to antenna and applications. In-Teh, pp. 478, Vukovar, Croatia.

44. https://royalsociety.org/. Access date: June.2017.

45. Nikookar, H., Prasad, R., 2008. Introduction to ultra wideband for wireless communications. Signals and Communication Technology, Springer Science & Business Media. Netherlands, 188 pp.

46. Nekoogar, F., Dowla, F., 2011. Ultra-wideband radio frequency identification systems. Springer Science & Business Media. Information technology transmission Springer Link, Bücher, 160 pp.

47. Gaucher, M.B., Pfeiffer, U., Grzyb, J., 2009. Advanced millimeter-wave technologies, 850 pp.

48. Pressure building for 5G to use 28GHz band as the standard: http://www.fudzilla.com/news/42431-pressure-building-for-5g-to-use-28ghz-band-as-the-standard. Access date: June.2017.

49. Abas, A., Thiagarajah, S., 2005, November. Slotted bowtie patch antenna for 3G system, pp. 225-228, In Networks, 2005. Jointly held *with the 2005 IEEE 7th Malaysia International Conference on Communication*, November 16-18, 2005, Kuala Lumpur, Malaysia.

50. Wong, H., Mak, K.M., Luk, K.M., 2008. Wideband shorted bowtie patch A broadband dual-polarized dual-OAM-mode antenna with electric dipole. **Journal of IEEE Transactions on Antennas and Propagation, 56** (7): 2098-2101.

51. Mahmoud, K.R., 2010. Design optimization of a bow-tie antenna for 2.45 GHz RFID readers using a hybrid BSO-NM algorithm. **Progress Journal in Electromagnetics Research, 100**: 105-117.

52. Khoo, K.W., Guo, Y.X., Ong, L.C., 2006. Wideband dual-polarized patch antenna, pp. 1-5, In Communication systems, *ICCS 2006. 10th IEEE Singapore International Conference*, 30 October-1 November 2006, Singapore.

53. Foul, M.K.A., Ouda, M., 2012. Bandwidth and gain enhancement of a slotted Bow-tie antenna using partial substrate removal, pp. 1–7, *The 4th International Engineering Conference*, October 2012, Gaza, Palastine.

54. Liu, H., Jiang, H., Guan, X., Lei, J. and Li, S. 2013. Single-feed slotted Bow-tie antenna for triband applications. **IEEE Antennas and Wireless Propagation Letters, IEEE Antennas and Propagation Society, 12**: 1658-1661,

55. Raza, H., Hussain, A., Yang, J., Kildal, P.S., 2014. Wideband compact 4-port dual polarized self-grounded bowtie antenna. **IEEE Journals & Magazines, IEEE transactions on antennas and propagation, 62** (9): 4468-4473.

56. Dadgarpour, A., Zarghooni, B., Virdee, B.S., Denidni, T.A., 2015. High-gain end-fire bow-tie antenna using artificial dielectric layers. **IET Journal for Microwaves, Antennas & Propagation, 9** (12): 1254-1259.

57. Parchin, N.O., Shen, M., Pedersen, G.F., 2016, October. End-fire phased array 5G antenna design using leaf-shaped bow-tie elements for 28/38 GHz MIMO applications, pp. 1-4, *In Ubiquitous Wireless Broadband (ICUWB), 2016 IEEE International Conference,* October 16-19, 2016, Nanjing, China.

58. Liu, B., Cui, Y., Li, R., 2017. A Broadband dual-polarized dual-OAM-mode antenna array for OAM communication. **IEEE Journals & Magazines, IEEE Antennas, and Wireless Propagation Letters, 16**: 744-747.

59. Salih, A.A., Chen, Z.N., Mouthaan, K., 2017. Characteristic mode analysis and metasurface-based suppression of higher order modes of a 2×2 closely spaced phased array. **IEEE Journals & Magazines, IEEE Transactions on Antennas and Propagation, 65** (3): 1141-1150.

60. Kan, H.K., Waterhouse, R.B., Abbosh, A.M., Bialkowski, M.E., 2007. Simple broadband planar CPW-fed Quasi-Yagi antenna. **IEEE Journals & Magazines, IEEE Antennas and Wireless Propagation Letters, 6**: 18-20.

61. Woo, D.S., Cho, Y.K., Kim, K.W., 2013. Balance analysis of microstrip-to-CPS baluns and its effects on broadband antenna performance. **International Journal of Antennas and Propagation, 2013**: 9 pp**.**

62. Ludwig-Barbosa, V., Schlosser, E., Machado, R., Guterres Ferreira, F., Müller Tolfo, S., Heckler, M.V.T., 2015. Linear array design with switched beams for wireless communications systems. **International Journal of Antennas and Propagation**, **2015**: 9 pp.

63. Dadgarpour, A., Zarghooni, B., Virdee, B.S., Denidni, T.A., 2015. Beam-deflection using gradient refractive-index media for 60-GHz end-fire antenna. **IEEE Transactions on Antennas and Propagation, 63** (8): 3768-3774.

64. Yeo, J., Lee, J.I., 2016. Bandwidth enhancement of double-dipole quasi-Yagi antenna using stepped slotline structure. **IEEE Antennas and Wireless Propagation Letters, 15**: 694-697.

65. Rezaeieh, S.A., Bialkowski, K.S., Zamani, A., Abbosh, A.M., 2016. Loop-dipole composite antenna for wideband microwave-based medical diagnostic systems with verification on pulmonary edema detection. **IEEE Antennas and Wireless Propagation Letters, 15**: 838-841.

66. Hu, Z., Wang, W., Shen, Z., Wu, W., 2017. Low-profile helical Quasi-Yagi antenna array with multibeams at the endfire direction. **IEEE Antennas and Wireless Propagation Letters, 16:** 1241-1244.

67. Yan, N., Ma, K., Zhang, H., 2016. A novel self-packaged substrate integrated suspended line quasi-Yagi antenna. IEEE Transactions on Components, **Packaging and Manufacturing Technology, 6** (8): 1261-1267.

68. Zhao, Y., Shen, Z., Wu, W., 2017. Wideband and low-profile monocone Quasi-Yagi antenna for endfire radiation. **IEEE Antennas and Wireless Propagation Letters, 16**: 325-328.

69. Aluf, O., 2017. Microwave Rf Antennas and Circuits. Springer International Publisher, Switzerland, 466 pp.

70. Vannithamby, R., Talwar, S. eds., 2017. Towards 5G: Applications, Requirements and Candidate Technologies. John Wiley & Sons, 472 pp.

71. Park, Y.J., Herschlein, A., Wiesbeck, W., 2001. A photonic bandgap (PBG) structure for guiding and suppressing surface waves in millimeter-wave antennas. **IEEE Transactions on Microwave Theory and Techniques, 49** (10): 1854-1859.

72. Ansys, 2009. User Guide 12, ANSYs Inc.

73. Hfss Design, 2014. Workshop 6-1: Introduction to Optimetrics: Example, 1–15.

74. Park Advanced Circuitry Materials, 2017. NL9000-Typical Engineering Values, **7117**: 6-13.

75. Abbosh, A.M., Bialkowski, M.E., 2008. Design of ultra-wideband planar monopole antennas of circular and elliptical shape. **IEEE Transactions on Antennas and Propagation, 56** (1): 17-23.

76. RT/duroid® 6006 & 6010 Laminates. [Online]. Available: https://www.rogerscorp.com/acs/products/36/RT-duroid-6006-6010-Laminates. aspx. Access date: June.2017.

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