POLITECNICO DI TORINO

Master's Thesis

Parametric Study of Tunable Millimeter-Wave Structures based on Metasurfaces for upcoming 5G and 6G Wireless Communication System

Master of Science in Communication and Computer Networks Engineering

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Abstract

The evolutions in the field of wireless communication have a significant impact not only on the environment but also on our daily life. The researchers are working to find the best way to exploit the millimeter-wave band that means frequency from 30-300 GHz, to ensure faster communication in a cheaper way with a higher bit rate and less lossy system. The marvelous artificial material, i.e., Metasurface, is used here to study the mmWave band structures for future generations of wireless technology. Metasurfaces have an ability to regulate EM waves in suitable directions to ensure that communication is happening in a reliable manner; in other words, a completely controlled environment of electromagnetic waves. The tunability feature of metasurfaces can achieve these exceptional outcomes that are controllability and directionality of electromagnetic waves. To observe the performance of the metasurfaces by applying 70 GHz frequency that is lying in the mmWave band, and to find the best results using these materials, Microwave Studio by CST is used for simulation purposes.

The characterization for the different considered structures is carried out in terms of a dispersion diagram. The dispersion diagram shows the frequency behavior of materials; it tells how much phase shift the materials have at a specific frequency when a wave propagates from the input to the output port of the single unit cell. The structures designed for this work are closed by applying the electric boundary conditions from bottom to top, and they are behaving like parallel plate waveguides. The dielectric that is used in the simulation part is Polyimide. It has one of the best thermal expansion coefficients that means a rate at which the dimension of material is growing with an increment of temperature. To check the tunability of metasurface from a physical implementation point of view, here we utilize this dielectric; thus, by changing polyimide thickness/height in the simulator, the observation will be made for the physical execution of self-made materials in terms of tunability or regulation of EM waves by the variations of temperature.

This research is quite helpful for all who have an interest in metasurfaces and also willing to perceive the performance of these artificial materials at the mmWave band and especially at 70 GHz. Here one can find the essential guidance of materials, wireless generations, divergent outcomes, responses of material shapes with multiple thickness/height of substrate material, and the future aspects of these kinds of explorations also. Consequently, the metasurfaces have many more applications, but in this thesis, the focus is only on the high-frequency response around 70 GHz of these remarkable artificial materials using closed structures like parallel plate waveguides.

Acknowledgements

A great experience and skillful knowledge have been obtained from ***Prof. Ladislau Matekovits*** *under his phenomenal supervision. I would like to give special credit to my supervisor whose technicalities, observations and supportiveness were remarkable to achieve this work, without you, it was never possible Sir. The way you encouraged me is beyond explanation, if I get another chance to work with you I will never hesitate to say yes.*

I would like to say Thanks to our ***Politecnico di Torino****, who provided an exceptional opportunity to explore things and also the culture of Italy, before this I never ever had such kind of experience in Europe. My happiness is uncountable to express because I am also a part of one of the best institutes in the world.*

Finally, I would also like to say thanks to my parents, friends, and colleagues, they gave me prayers, support, and encouragement to accomplish this wonderful title.

Acronyms

A/D	Analog-to-Digital
AM/FM	Amplitude Modulation/Frequency Modulation
BSS	Base Station Subsystem
CRAN	Cloud-based Radio Access Network
CST	Computer Simulation Technology
dB	decibels
EM Waves	Electromagnetic Waves
FSS	Frequency Selective Surfaces
Gbps	Gigabits per second
GPS	Global Positioning System
HetNets	Heterogeneous Networks
HSR	Hyper high-Speed Railway
IoE	Internet of Everything
IoT	Internet of Things
LAA	Licensed Assistance Access
LOS	Line Of Sight
LTE	Long-Term Evolution
MIMO	Multiple Inputs and Multiple Outputs
mmWave	Milli-Meter Wave
NFV	Network Functions Virtualization

NR	New Radio
QoS	Quality of Service
RCS	Radar Cross-Sections
RF	Radio Frequency
SDN	Software Defined Networking
S/EHD	Super/Extremely High Definition
TV	Television
UWB	Unlicensed Ultra-Wideband
2D & 3D	Two or Three Dimensionals
5G	Fifth Generation
6G	Sixth Generation

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Chapter 1
Introduction

1.1 Overview/Topic Discussion

The latest findings in wireless communication are marvelous in terms of security, quality of service, reliability, and rapid transmission of data. Whereas, the trade-off between cost and quality is consistent in every field, especially in wireless technology. Nowadays, researchers are working to introduce the latest system for wireless communication, which can be controlled easily and of course less expensive. As of now, mmWave which allows higher bandwidth is a big challenge to deploy and take services without any limitation and significantly lower cost because mmWave can not cover a long distance due to high frequency. Therefore, so many trials have been done so far to overcome these problems in a better way. The title of the thesis defines that if the future belongs to excessive data rate and fast communication, then the better option is tunable metasurfaces to take under consideration. These artificial materials have the stunning qualities to control the waves and beams to transmit in a better and more efficient way under at least a low cost than other solutions. The research is mainly on the tunable mmWave structures based on metasurfaces for future technologies such as 6G and of course, 5G which is nearly to come. This work will be defining the qualities, losses, cost, availability, less power consumption, and future aspects of things that are appreciable. In broad terms, Metasurfaces can be the tool of converting this radio transmission system into a smart or controllable radio environment to manipulate signals and transmit them in an efficient way or basis of demands or needs. As a consequence, these materials have numerous applications but here we are going to check the response of tunable metasurfaces around 70 GHz frequency that is considered as in the mmWave band.

1.2 Motivation/ Background Related Information

Nowadays, the artificial material, i.e., Metasurface, has been under research, and it is being used for many purposes due to its characteristics such as simplicity, easy to fabricate, lightweight comparing the 3D metamaterials, and also reduced profile. The objective and motivation belong to metasurface applications such as control of phase, polarization, and amplitude of EM waves completely; as a result, the appropriate and flexible communication can be possible in wireless technology. As technology is evolving, the wireless networks are required to execute the latest radio environment based on the mmWave frequency spectrum to fulfill the highly demanding capacity. In order to take advantages and implementation point of view the artificial materials such as metasurfaces are also in consideration to utilize in the mmWave band wireless communication systems. In the coming times, metasurfaces are the best possible alternative for copper and optical fiber also, because they are capable of being installed onto the walls to enhance the signal strength for an indoor area of the building.

1.3 Aim/Target

Since the topic of the thesis is to the parametric study of the tunable mmWave structures based on metasurfaces so that they can be used in the future advancement of wireless technology. For considering this, the simulation performance will be applied to get good beneficial outcomes in order to satisfy the main requirements of the implementation of temperature based tunable metasurfaces. These metasurfaces can be able to tune the electromagnetic waves by variations of temperature. The remarkable simulation tool that is the Microwave office by Computer Simulation Technology (CST) is considered to be used for designing and observation of metasurfaces in this regard. Furthermore, we will discuss the results, losses, graphs, and future aspects accordingly. The main focus is to elaborate on the attributes and behavior of tunable metasurfaces that how they control the electromagnetic waves up to 70 GHz, such as the mmWave band.

Chapter 2
Review of Literature

2.1 Initial Information

Based on an intense literature review, some relevant objects have been explained and illustrated with examples to get an idea about things that are major in this thesis. Thus, by following the objective, that is defined in chapter one, some appropriate knowledge is explained here concerning the research. Here, one can obtain all the essential and efficient details about all those topics that are major in the title and work, as the core topics are millimeter wave, 5G, 6G, and metasurfaces. Therefore, in respect of these leading topics, the appropriate guidance has been collected. In the end, the final section of the literature review mainly describes related research.

2.2 Fundamentals

2.2.1 Basics about Metasurfaces

Metasurfaces are two-dimensional (2D) configured materials, these materials are not naturally explored, but they are artificially made up to control and manipulate phenomena such as light, electromagnetic waves, and sound waves [11]. Metamaterials have some limitations from the implementation point of view. Although they are three-dimensional (3D) structures and have difficult micro- and nano-fabrication required and also bulky due to their permittivity, permeability, and refractive index are essential properties of heavy materials [3]. Metamaterials are more diverse than natural materials because of, for instance, a phenomenon called negative refraction, which is allowing the complete control of EM waves and also including light, in all four quadrants of a cartesian coordinate system. It is one of the best properties to be divergent from natural materials and as a result, they are used in so many applications [1].

Metasurfaces are two-dimensional (2D) in nature and promising alternatives, they can work and manipulate waves over a single thin layer. As they are 2D materials, therefore, it makes them less bulky and less expensive materials [1]. From the last two decades, they have been broadly investigated and fabricated due to their lightweight and other abilities such as, blocking, retaining, focusing, scattering, and controlling the waves, first on a superficial level at "touching incidence"(90° short the point of occurrence) and second in space at ordinary (the condition in which a wave-front is parallel to an interface, such that the wave/ray way is perpendicular/normal to the surface), and oblique incidence (a ray may be reflected back to the source, transmitted or 'refract' to the medium), from micro-wave through visible frequencies [2]. Their planar structure is so satisfying; because of that, they can easily be fabricated using fabrication tools. This structure is cost-effective to implement in comparison to complex 3D metamaterials [1]. Metasurfaces are able to exploit both electric and attractive (magnetic) field segments of the EM waves. Hence, they have around trivial/negligible mismatch losses because impedance can be matched by adjusting the electric and magnetic polarizabilities [1].

2.2.2 Types of Metasurfaces

There are a lot of different types of metasurfaces available, according to their work, needs, and applications. We have mentioned some basic types here to get a small idea about their varieties.

1. Non-Linear or Active tunable metasurfaces

From the past few years, the effectiveness of passive metasurfaces has been illustrated, for example, generation of vector beam, holography, deflections of a laser, conversions of polarization, spin-orbit interactions of photonics, and imaging. The flat optics has been publishing some quality papers to focus on passive metasurfaces. In spite of some remarkable qualities and applications of passive metasurfaces in different schemes, they still require tunability to operate appropriately. However, active metasurfaces can be regulated by its refractive indices through electrical, thermal, or optically [17]. This fantastic feature of active metasurfaces allows us to get rapid control of metasurfaces without any reconfiguration at optical frequencies.

Active tunable or nonlinear metasurfaces have an artificial impedance surface which comprises nonlinear circuit components. They are capable of controlling the phase or amplitude of electromagnetic waves dynamically, and also suitable for reconfigurable applications. To achieve desired tunability, they have many approaches to apply tunable elements on the surface with active devices for introducing nonlinearities such as varactor diodes and transistors. Some new researches have explored the unique EM performance and properties that are not accomplished with typical passive metasurfaces [18]. Li et al. (2017) [18] described in his work that recent advancements in tunable metasurfaces, it is possible to acquire their distinctive applications when nonlinearity is present.

Therefore, in conventional metasurfaces, their properties are settled by the plan and course of action of the segments. Whereas, in optic applications, to have active metasurfaces that are controlled dynamically, in light of the fact that various boundaries of the nonlinear optical response, for example, phase, force, and condition of polarization can be significantly constrained by adjusting the geometry and state of a particular metasurface, basically for plasmonic metamaterials [14].

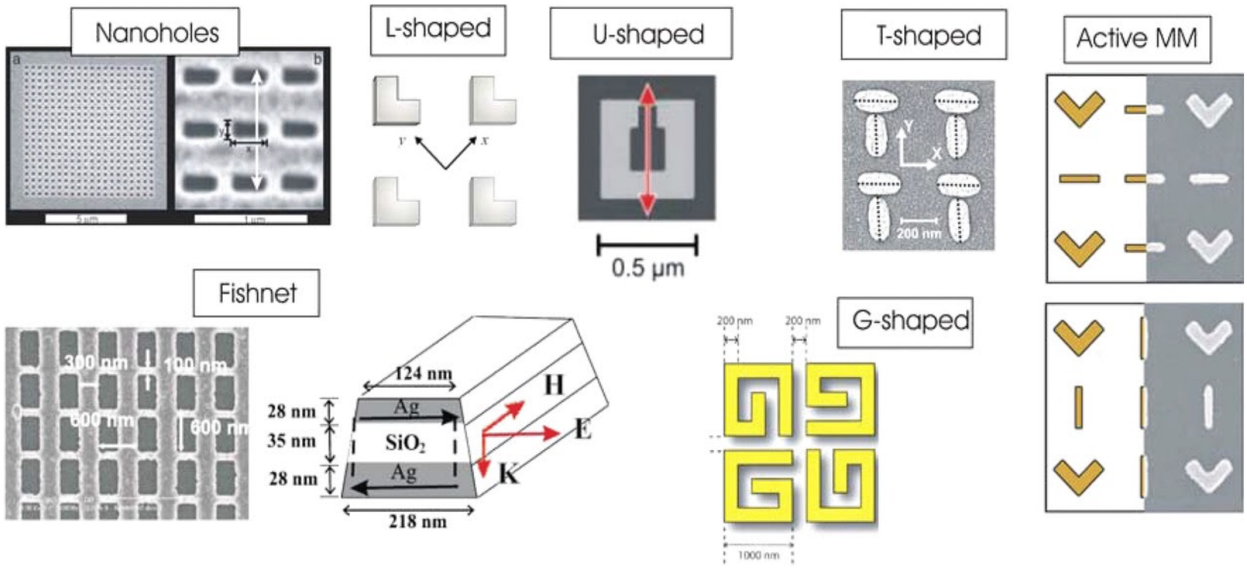

Figure 2.1 *Illustrations of various geometries and placements of meta-particles for nonlinear metasurfaces extending from subwavelength nanohole clusters to varieties of nano-antennas and split-ring resonators [14].*

2. Frequency selective metasurfaces

The most common operation in signal handling systems in both optical ranges and microwaves is the otherworldly sifting. Such kind of administration is given by Frequency Selective Surfaces (FSS) when EM waves are spreading in a homogeneous medium. They have an incredibly dispersive reflection or transmission effects [15].

FSSs have an assortment of microwave and optical structures that are determined after three decades of investigation and inquire about work. All things considered, their primary applications are diplexers for semi visual microwave gadgets, i.e., reflector radio wires, and full bar splitters, likewise spread surfaces for receiving wire radomes. In certain situations, they are executed as occasional varieties of metallic patches or gaps in a metal sheet where a resonant behavior is required. The major part of FSSs design procedure is a choice of opening shape, sizes, and substrate fabric. The dipole sort FSSs are organized/intended to be band-stop channels for occurrence plane waves, i.e., reflection can happen correctly inside a limited recurrence band [15]. Their comparing partners, the FSS that is first sort, present band-pass properties being straightforward for occurrence waves inside the working/activity band (Figure 2).

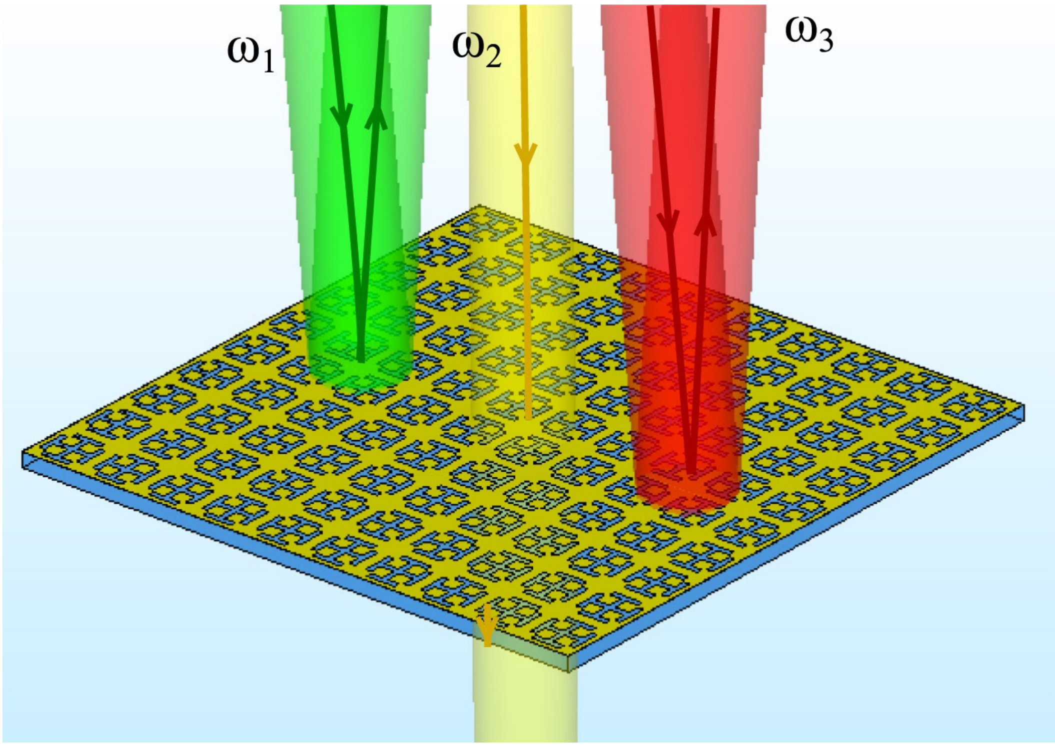

Figure 2.2 *The usefulness of a frequency-specific metasurface is acknowledged as a complimentary self-thunderous framework [15].*

3. Coding Metasurfaces

In 2014 they were proposed; their unique ability is, rather than utilizing compelling medium boundaries, advanced coding unit cells with determined stage reactions are being used to indicate metasurfaces as specified in Figure 3. Coding metasurface provides the connection between the physical and computerized world due to their digitization of the unit cell geometry, and the good thing is their coding representation is more straightforward and makes more comprehensive design and optimization procedures. The coding sequences are used here for the design and the functionalities of metasurfaces, which shows the diverse computerized states for every unit cell [16].

Moreover, these arrangements make coding metasurface ready to be executed by advanced rationale gadgets; therefore, just to change the incoming sequence to acquire the different functionalities in real-time. They have the capacity to control the EM waves by using various courses of action of coding unit cells with optimized coding sequences in an entirely more straightforward and systematic way. Coding metasurface has many advantages, but the best is the manipulation of EM waves can be obtained by changing the coding grouping, which appears how the coding unit cells are orchestrated with diverse states on a 2D plane. Comprehensive utilization of coding metasurface is Radar Cross-Sections (RSCs) of metallic articles that can be diminished with irregular coding designs of utilizing 1-piece/bit and 2-piece/bit coding metasurfaces [16].

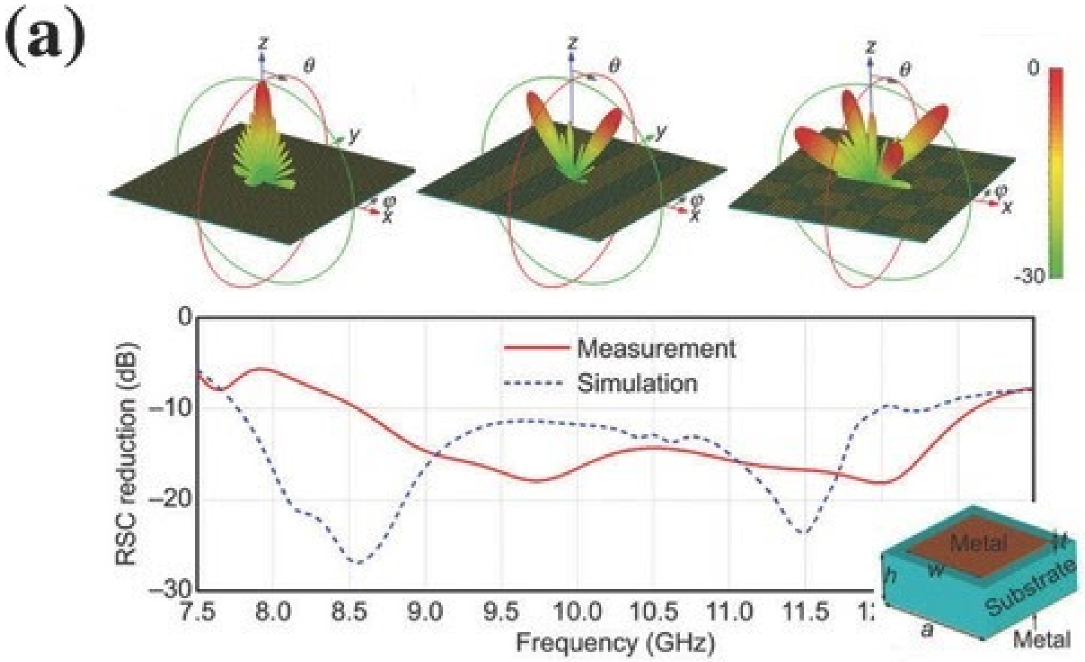

Figure 2.3 *Reenactment outcomes of coding metasurfaces with different coding sequences (upper board), recreation, and estimation outcomes of monostatic RCS depletions of a 1-piece/bit coding metasurface (lower board/panel) [16].*

2.2.3 Applications

In the modern advancement of metasurfaces, many metasurfaces based utilizations are promising choices to supplant customary optical gadgets since they have the advantage of ultrathin, ultra-compact properties, and lightweight, thus, they give the opportunity to overcome the limitations or disadvantages of their conventional counterparts and exhibit flexible novel functionality. The latest progress of metasurface-based utilizations focused on the control of polarization and wavefront control [13].

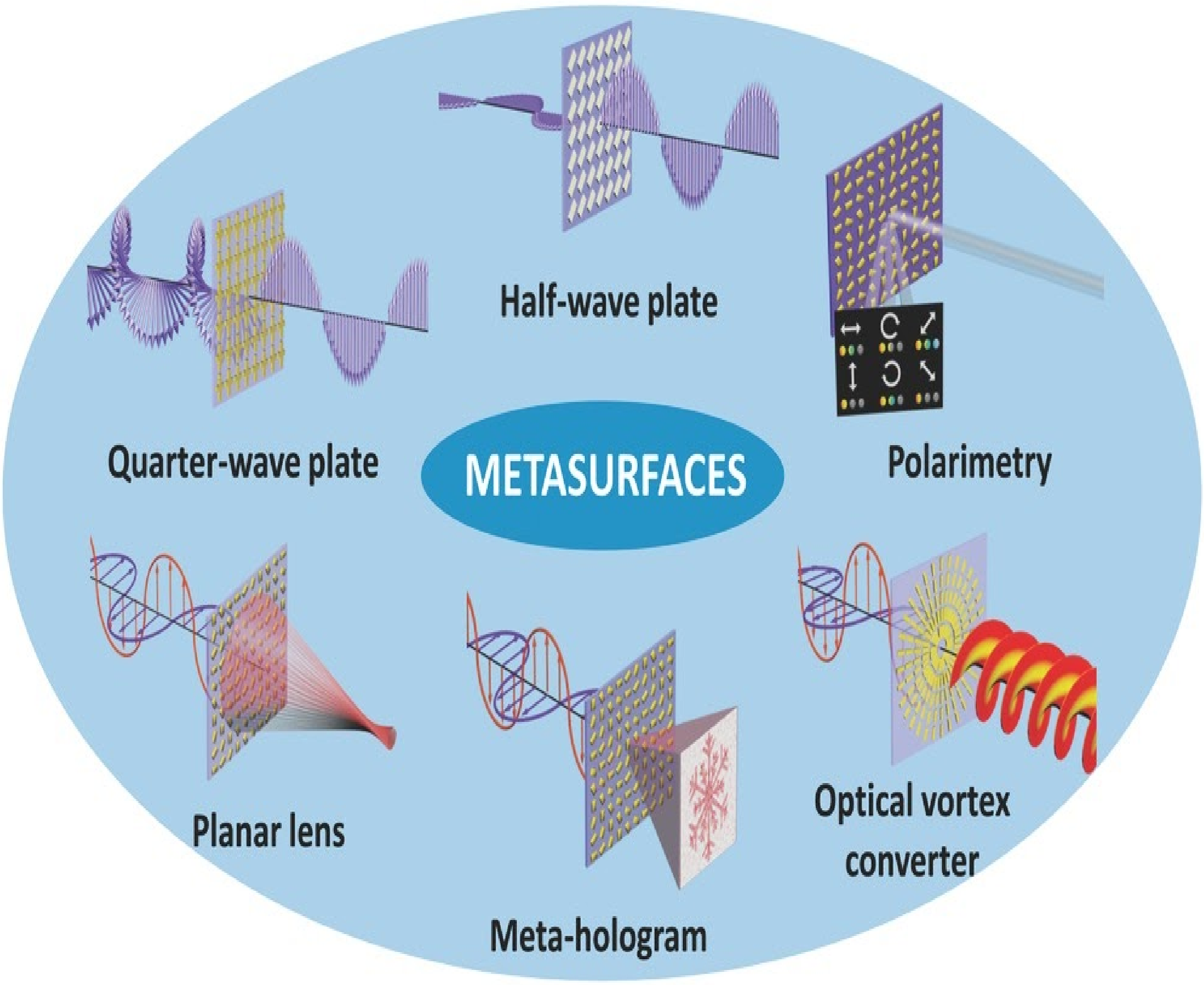

Figure 2.4 *Metasurface-based implementations on polarization manipulation and wavefront model [13].*

2.3 Millimeter Wave

2.3.1 Millimeter-wave range/spectrum and Introduction

The millimeter-wave (mmWave) communication systems have the capability to meet the requirements of the upcoming future ultrahigh bit rate and ultra-low latency. For commercial wireless applications such as AM/FM radio, cellular communication, GPS, top-quality TV, satellite correspondence, and Wi-Fi have been contained in a restricted band of the RF range, i.e., from about 300 MHz-3GHz. Indeed, it is an excellent choice for remote business applications; however, bits of the RF range over 3 GHz have been unexploited. Recently, the interest showed to explore the scope for short-run and fixed remote communication. For example, to empower high information rate availability for individual territory organizations, the Unlicensed Ultra-Wideband (UWB) in the scope of 3.1-10.6 GHz has been suggested [6].

For the support of large bandwidths and high data rates, the high-frequency groups in the range of over 30 GHz were focused on upgrading the limit of remote systems. In reality, these groups are alluded to as "mmWave", on account of their short wavelength, and can be estimated in millimeters. The millimeter-wave groups/bands are extended up to 300 GHz, but as far as the 5G concern, the frequency band from 30 GHz to 100 GHz is anticipated to be utilized. The mmWave groups up to 100GHz can back the transmission capacities up to 2 GHz without the requirement for total bands for higher information throughput [8].

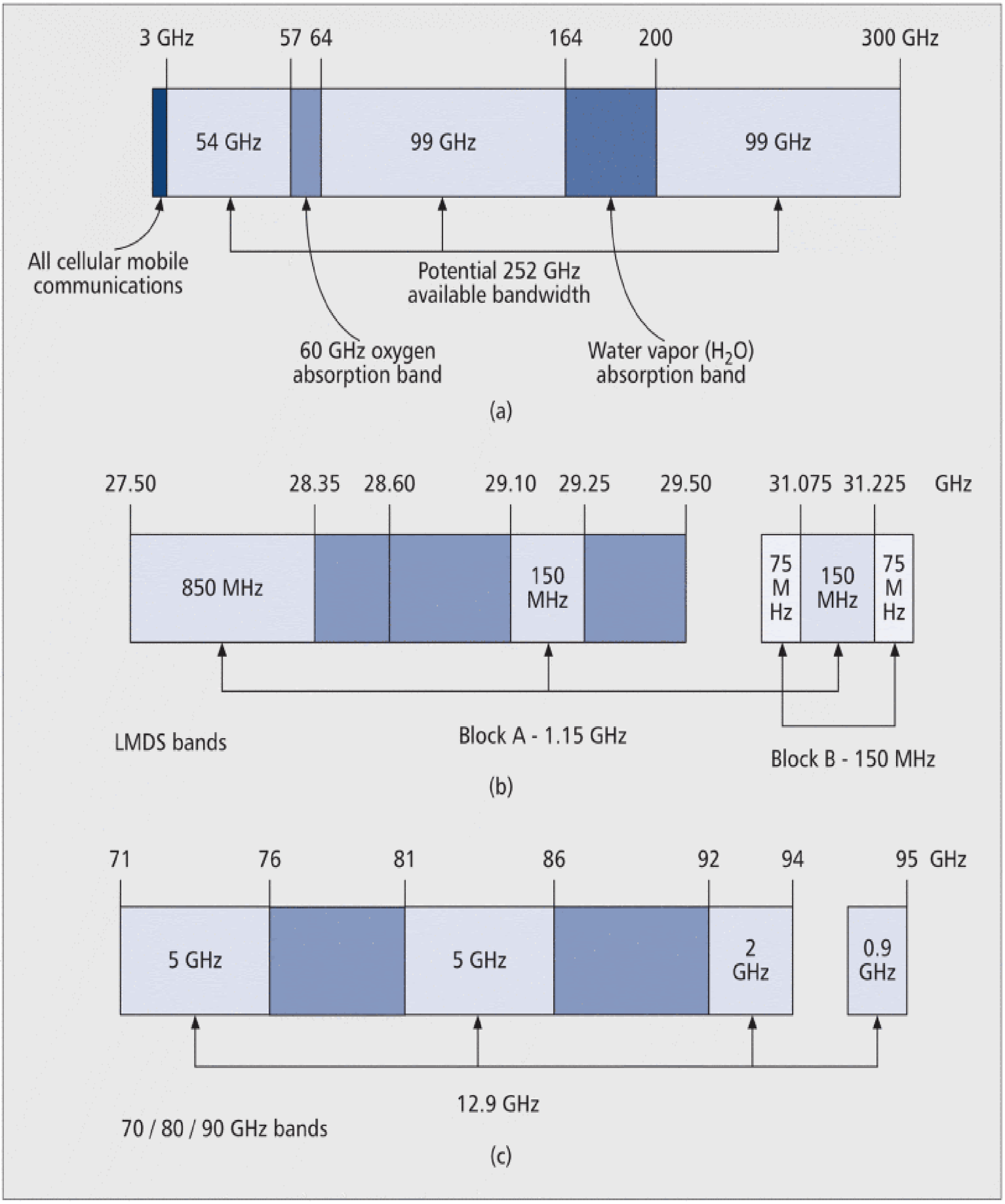

Figure 2.5 *Millimeter-waves spectrum [6].*

2.3.2 Deployment and challenges of mmWave

Earlier, it is considered to be inappropriate usage of frequency groups over 6 GHz for cell correspondences because of the high propagation misfortunes, and the blockage of waves could be possible because of buildings and also the human body. These kinds of challenges set limitations on the deployment of mmWave, but due to the latest radio wire advancements along with a superior comprehension of signal spread and channel attributes, empower various arrangement situations. The blocking and high entrance misfortunes mean the organizations of mmWave will cover outdoor or indoor locations but are not competent in giving open air to indoor networks. That is the reason the cell dimensions of mmWave will be tiny in size and higher in thickness [8].

Nevertheless, the short wavelengths of mmWave frequencies exploit a massive quantity of antennas to be deployed that can hypothetically make up for the isotropic path misfortune, but due to a vast number of antennas a multiple calculations and execution challenges appear to keep going the expected performance gain [5].

Moreover, the other challenge is power consumption in supporting pick up/increase of multi-antenna and wide-transfer speed mmWave within the Analog-to-Digital (A/D) transformation. Notably, the power utilization may scale directly in the inspecting rate and the quantity/number of bits per test, making high-goal/resolution quantization at wide data transmissions and enormous quantities of radio wires restrictive for low-power and ease devices [9]. Furthermore, useful RF power intensification and the mix has been conjured for staged cluster array antennas.

Multiple challenges are forced by client portability additionally in the mmWave communication framework. Primarily, noteworthy changes will be experienced by client portability. The separation between the transmitter and the recipient fluctuates when the client moves. Identically, the channel state encourages shifts appropriately. Client portability will cause critical and quick burden changes in every Basic Station Subsystem (BSS) because of the little inclusion areas [9]. Subsequently, handovers and client affiliation ought to be directed between passages or access points for accomplishing an excellent load balance.

2.3.3 Disadvantages and losses of mmWave

Generally, for a point to point connection, the overall loss in the millimeter-wave is higher than in microwave systems. As mentioned above, the spectrum of mmWave has a frequency range from 30-300 GHz, where about 240-250 GHz transmission capacities are accessible. Even though the convenient data transmission of mmWave frequencies is promising yet the qualities of propagation are notably not quite the same as microwave frequency groups as far as diffraction, path misfortune, blockage, downpour weakening, climatic retention, and foliage misfortune practices [5].

The main disadvantage of mmWave is high attenuation, which is due to loss of signal proliferation, impedance, and blurring, which is absorbed by gases in the air. The two natural elements, the rain, and humidity, affect the performance and the robustness of mmWave. It might likewise pass on and spread by Line-of-Sight (LOS) correspondence because of its short-run frequency, which implies that physical items, for example, (structures, dividers, trees, and so on.) tend to stop and interfere with these signs/waves [9]. In spite of the fact that these waves give the multi GHz data transmissions, which is the primary driver of higher bit rate than traditional microwave communication frameworks, despite what might be expected, mmWave signals experience the ill effects of engendering focused inadequacy.

Furthermore, another critical worry of mmWave waves is tremendously defenseless to shadowing, for example, materials, i.e., the attenuation of waves/signals around 40–80 dB can be done by brick, and also the human body might be involved around 20–35-dB loss. However, these two issues rain facades and humidity are the causes of long-run mmWave backhaul links [9]. The various open-air reflective materials and the human body are significant scatterers for mmWave proliferation.

		Attenuation (dB)		
Material	Thickness (cm)	< 3 GHz [6, 8]	40 GHz [7]	60 GHz [6]
Drywall	2.5	5.4	–	6.0
Office whiteboard	1.9	0.5	–	9.6
Clear glass	0.3/0.4	6.4	2.5	3.6
Mesh glass	0.3	7.7	–	10.2
Chipwood	1.6	–	.6	–
Wood	0.7	5.4	3.5	–
Plasterboard	1.5	–	2.9	–
Mortar	10	–	160	–
Brick wall	10	–	t178	–
Concrete	10	17.7	175	–

Figure 2.6 *Millimeter-waves attenuation due to different materials and blockages [6].*

2.4 5G Technology

2.4.1 Introduction and overview

The high demanding features of wireless communication such as security, education, transportation, shipping, agriculture, smart homes, health care, surveillance, logistics, automotive, and smart cities are the main motive of enhancement in gadgets and traffic. In the research [10], it is to be expected that 45% of machine type traffic will be set up on the internet by 2022. Figure 7 defines how 5G beamforming surroundings show thick and varied smart connectivity.

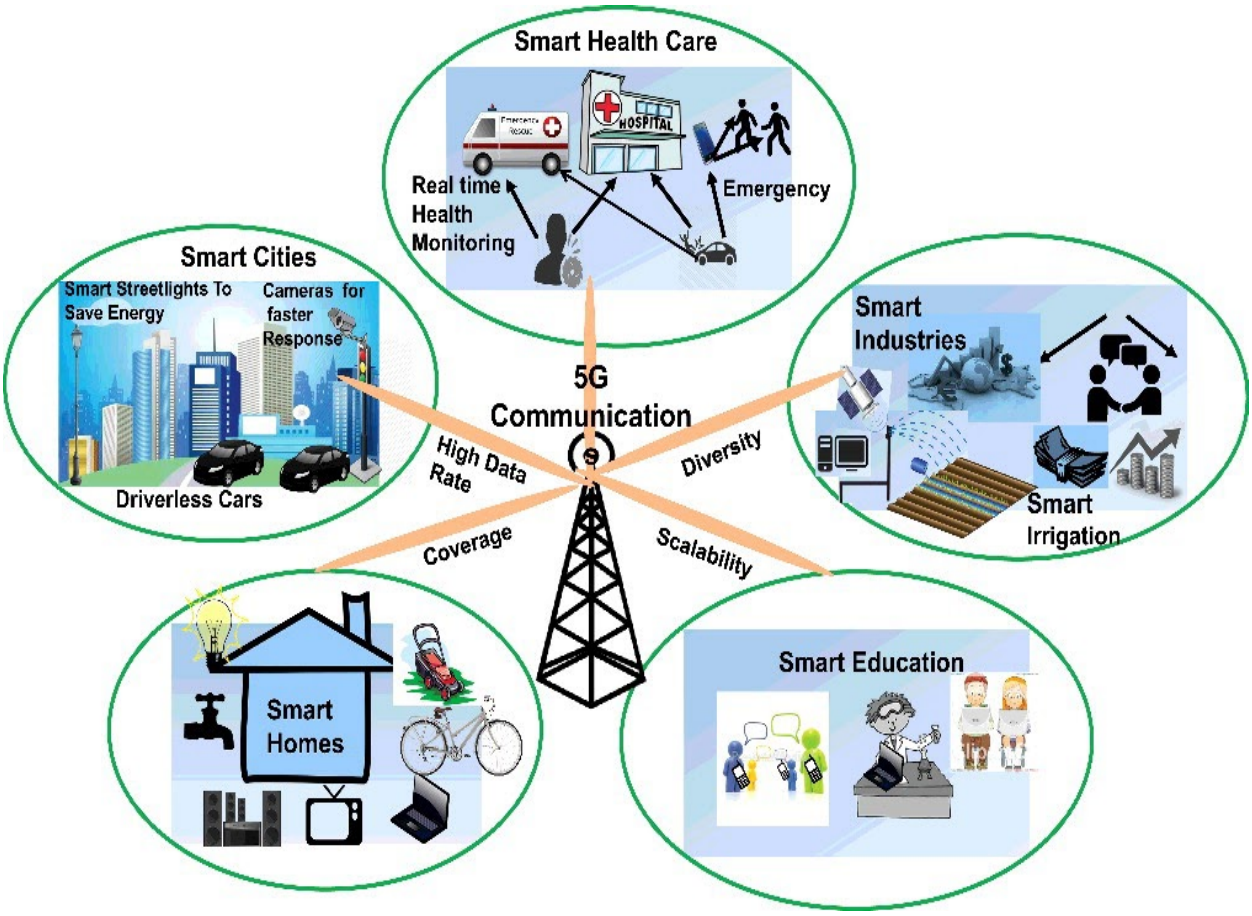

Figure 2.7 *View of 5G beamforming environment [10].*

The Internet of Things (IoT) associates distinctive physical items with the web, to create communication joins for a wide range of purposes. Tendencies of IoT not just stretch out to spare people's and establishments' time and costs yet additionally share some dynamic outcomes in an extensive level of application areas [10]. In the coming time, these kinds of applications of wireless traffic needs can be visualized.

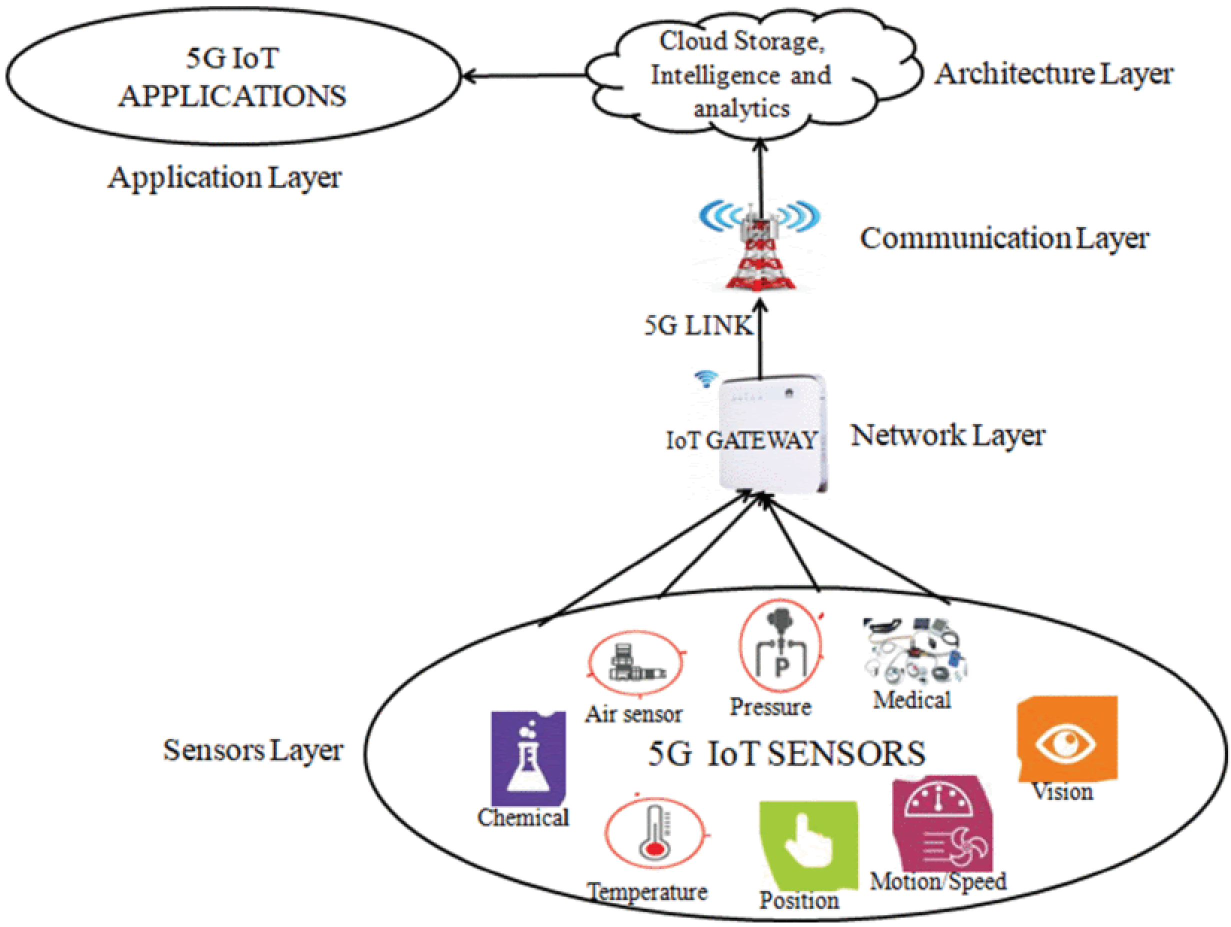

Figure 2.8 *Architecture overview of 5G IoT [20].*

In the environment of wireless advancement, 5G technology is now the most demanding and exciting subject in wireless exploration. The analysis inspiring in the 5G technology is mainly taking an eye on mentioned [20] points,

- In real-time, the flow of data must be ten times greater from 1 to 10 Gbps than the current system.
- Latency should also be ten times less (1ms) than current Long Term Evaluation (LTE) technology.
- 5G needs higher bandwidth by utilizing the Multiple Inputs and Multiple Outputs (MIMO) antenna and efficient spectrum by taking the services of cognitive radio, which gives the consumer to use both spectrum bands one is licensed, and another is unlicensed.
- More and more devices would be connected. In the near future, around 70-80 billion gadgets will append to the system [20].

- A deep-rooted or life-long battery, IoT gadgets are viewed as brilliant; they need extra power. Thus, a battery backup should be more significant.
- Almost 80-90% of energy reduces in 5G. The implementation of green technologies can acquire it.
- The expenses of IoT devices and sensors deployment should be economical.

Moreover, the two leading features in 5G technology will definitely be used, one is Software Defined Networking (SDN), and another one is Network Functions Virtualization (NFV) to give consistent connectivity for consumers [8].

2.4.2 5G and Millimeter Wave

The mmWave is the prime technology to design the communication paths of 5G utilizing the 5G New Radio system. For future 5G heterogeneous systems, MIMO and mmWave can be the central part of the upcoming networks and ultra-fast system. MIMO system's antenna array will be configured wholly digitized and smart. The future technology will acquire the features of a MIMO antenna, which has the ability of beam tracking, spatial multiplexing, and beam tracing. MIMO has excellent advantages such as less delay spread, interference cancellation, less power consumption during transmission, and better spectral efficiency.

The MIMO configuration can fulfill the requirements of IoT in 5G, such as the transmission of massive data without interference, security and excellent efficiency just by increasing the antenna arrays in the MIMO system. Two significant factors of mmWave on which it works, and these are also the features of this technology. One is a considerable amount of bandwidth having more extensive coverage, and second is, small wavelengths can acquire a high number of antennas in specific areas [19]. In addition, another object of using mmWave in the future or the 5G system is, unlike lower frequencies, mmWave radio frequency provides a chance to use the utilized spectrum bands by sensing [20]. Figure 8 shows the HetNets; it provides a dense network for the 5G environment by utilizing the mmWave technology. The NR of 5G has the potential to deploy small cells such as femtocells and Licensed Assistance Access(LAA) [20]. By using mmWave and MIMO central station, the HetNets are shown in Figure 8.

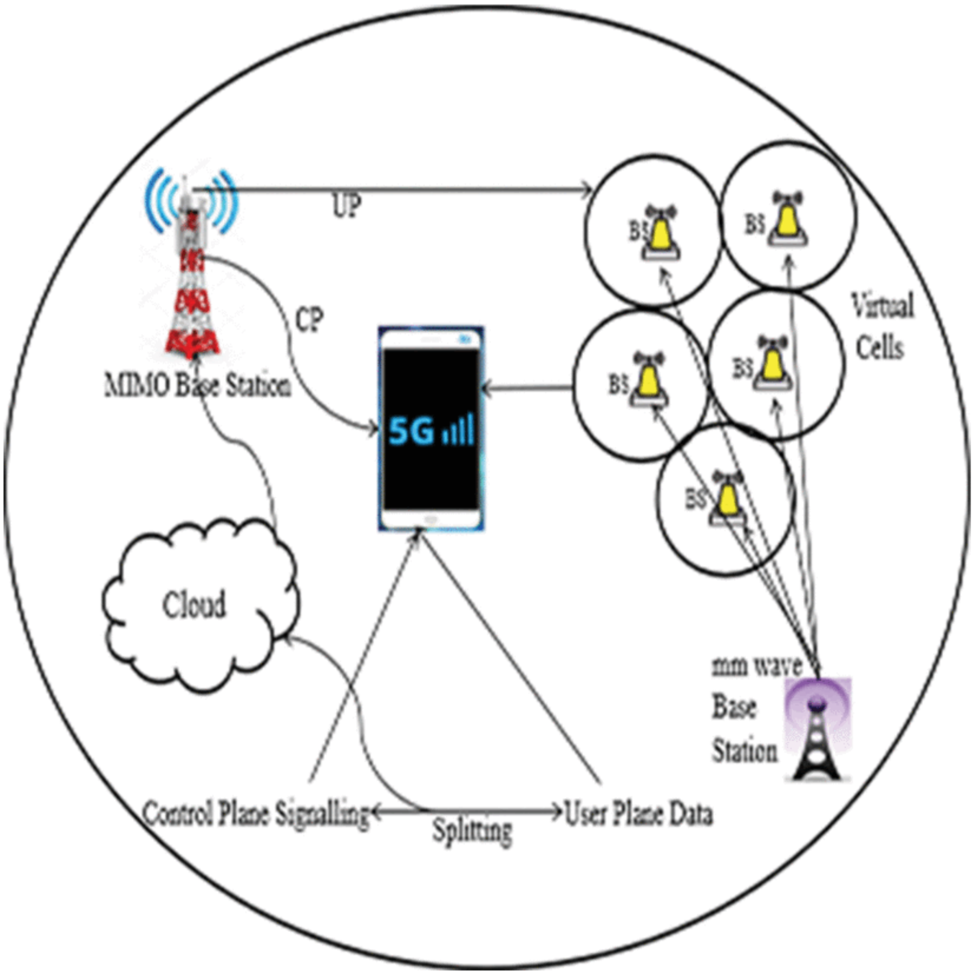

Figure 2.9 *5G HetNets consolidating MIMO and mm-wave communication [20].*

The combined HetNets will acquire a boost from 5G. The combination of mmWave and microwave technology is another feature, mmWave system uses femtocells or small cells that are installed in a base station called 'little cell base station' and exchange the information in low ranges around 1 to 2 km and can transmit the frequency of 2-4 GHz. While the macro-cells with MIMO will be used for the higher distance, and frequency would be above 28 GHz. In dual connectivity, the splitting problem occurs, and this problem is resolved by utilizing a baseband cloud system. By using Cloud-based RAN (CRAN), the splitting of the user and control plane can be possible. Therefore, 5G cellular networks will be more efficient and flexible after exploiting this magnificent technology.

2.4.3 5G and Metasurfaces

In the future technological advancement in telecommunication, reconfigurable metasurfaces will have a crucial role to govern the EM waves and make them efficient in the real-time, because their properties are not fixed, unlike conventional metasurfaces. They are highly demanded material in nowadays research, thanks to their flexibility according to stimuli that are received for the outer world [22]. Some limitations of the current cellular network will be eliminated by exploiting the Reconfigurable Metasurfaces. Generally, 5G communication will implement the massive MIMO antenna array with multiple radio-frequency chains that will cause a complicated system, more expenses, more weight, size and more power will be used. To overcome these kinds of disadvantages, the remarkable structure can be proposed i.e., reconfigurable metasurfaces. At the antenna and RF level, they have an ability to provide active beamforming proficiencies with comparable lower cost and complexity than the conventional systems [21].

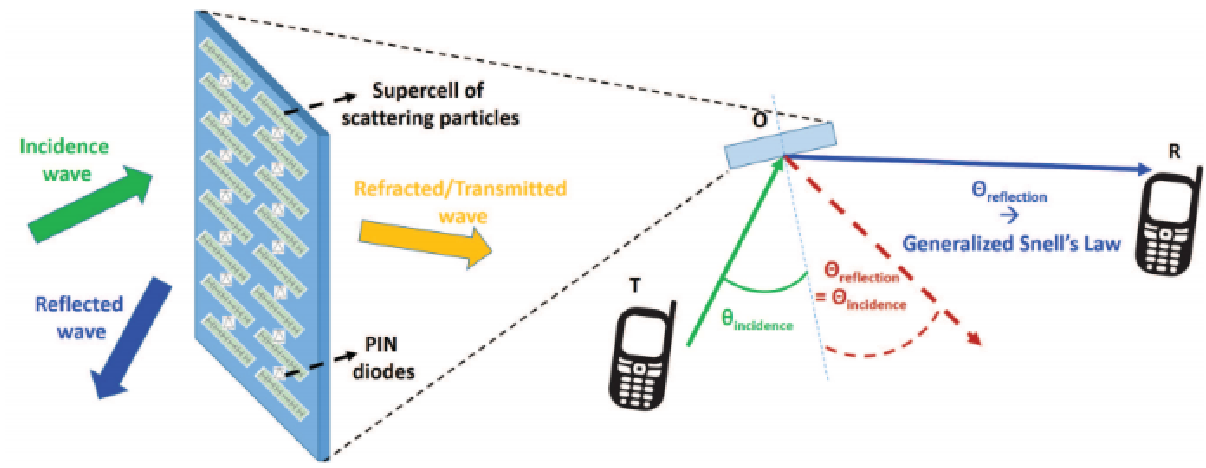

Figure 2.10 *The theoretical idea of reconfigurable metasurfaces functioning [22].*

Another advancement of future communication technology is the smart radio environment. It can be defined as “A turned radio environment that can control and reconfigure a space to transmit the data after smartly processing.” In other words, a radio domain transformed into shrewd and enables uninterruptible communication and guaranteed QoS, and data can be transferred without creating the latest signals but utilizing/ reusing the accessible ones at whatever point it is required [22]. The smart radio environment working and implementation comprises deploying programmable and smart FSS, reflect-arrays, or mirrors. These can be embedded on the building walls, environmental objects with reconfigured metasurfaces to fulfill the future wireless technology demands.

2.5 6G Technology

2.5.1 Introduction

The revolution of 6G technology will be experienced in nearly about 2030-35. It will be a sensational and fantastic insurgence in the field of wireless communication. It will consist of many things that can now only be imagined such as highly digitized, fully wireless coverage, and combine all bases, including positioning, radar navigation, computer, cashing, sensing, and control to provide full applications. The evolution of 6G will be included from human to machine-centric and also merging both, that will give many ways, for instance, through brain signals or mind/neural waves, voice, eyes, faces, and even fingers to transfer and interface with smart entities. Furthermore, the two major key enablers of 6G that will have a quite impressive space for 6G revolution one is cellular internet and the other one is the Internet of Everything (IoE) [23]. They are capable of high-precision and holographic communication for the sense of touching applications such as haptic internet which will give us a complete sensorial namely hearing, vision, touch, and taste experience that will require an extremely high data transferring and huge throughput in the upcoming time.

Moreover, this technology will be able to hold up Super/Extremely High Definition (S/EHD) videos, exceptionally low latency about 10 µs, fully autonomous cars, lengthy distance, and excessive mobility transmissions, Internet of Nano things, Internet of Bodies with deficient power (micro, nano, and picowatts) consumptions, able of consistent service in immediate conditions, for instance, Hyper high-Speed Railway (HSR), and the communication would also be significantly possible underwater, deep sea and space [23]. Figure 11 (a) is showing how 6G will support these kinds of applications and also differentiate with previously mobile or wireless technologies. Also, it can be seen that the performance measures for 6G technology such as the density of devices connections, latency, peak data rate, etc. in Figure 11 (b).

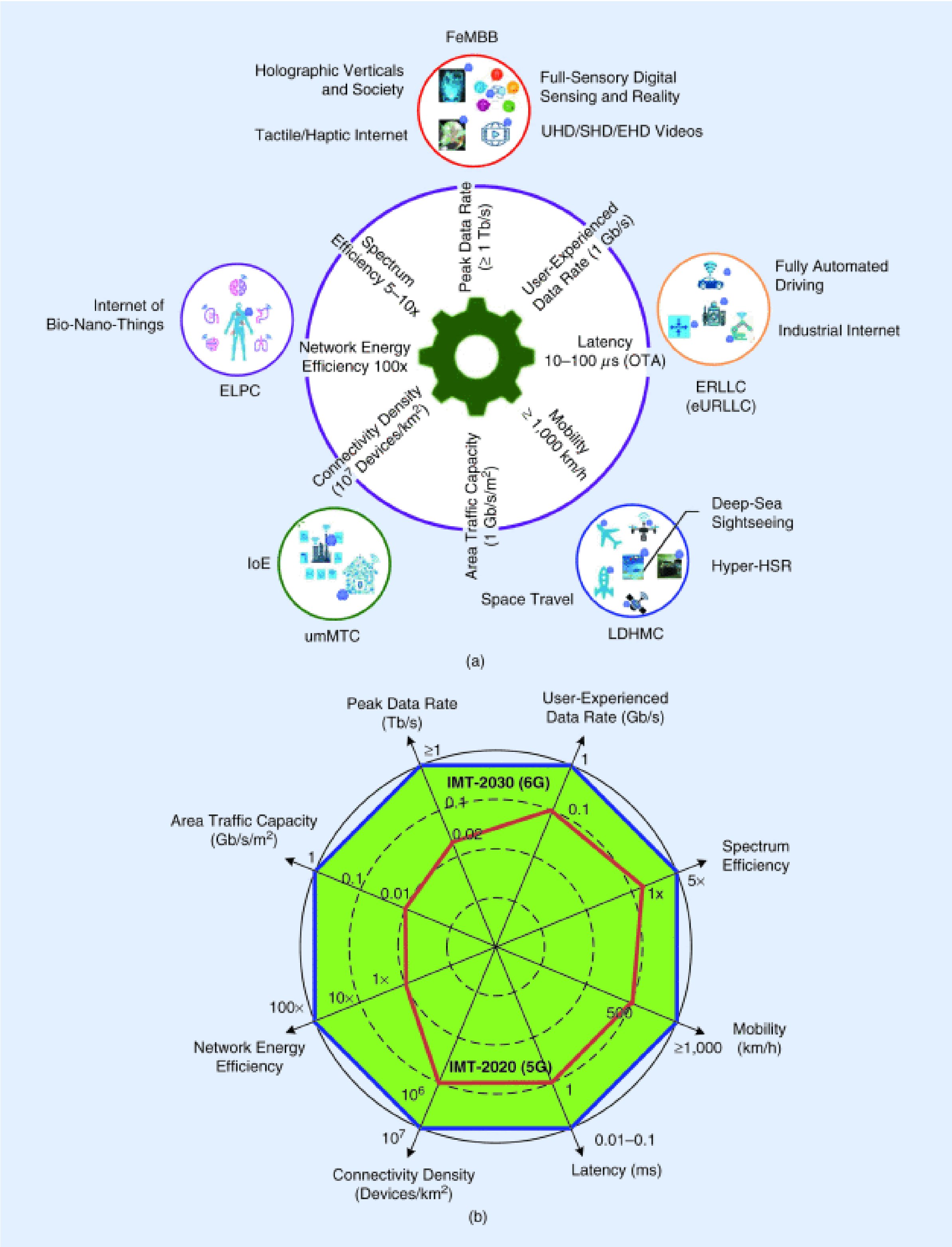

Figure 2.11 *(a)The typical scenario, capabilities of 6G technology(b) [23].*

2.5.2 TeraHertz Communications

In 5G, the mmWave spectrum or band is used, which is good enough from the LTE, whereas, in 6G, the spectrum is beyond these technologies. It will have a rich spectrum that has a range of about 1-10 THz communication band [23]. Thus, this spectrum will provide the Tb/s transmission of data which is enormously higher than past cellular technologies. Due to the multi-Tera bits communication, it is named as THz transmission or communication.

2.5.3 6G and Metasurfaces

The future of wireless is entirely dependent on how to manipulate and control the EM waves in order to satisfy the requirements with low cost, low power, low latency, and efficient output. As we know, one of the essential parts of 6G technology will be THz communication. On the other hand, the scattering properties, the detrimental effect, and attenuation continue a significant challenge in the future of wireless. For instance, objects in an environment such as building walls and furniture usually scatter waves in Omni directions; this will propagate in multipath environments [24]. As a result, the ungovernable climate leads to an unknowing communication process.

In these types of scenarios, the best and ultimate solution will be the usage of tunable or programmable metasurfaces to control and manipulate the wireless environment or waves. Metasurfaces provide all those services that are much needed in future wireless communication. The lower expenses of metasurfaces make them a suitable alternative or choice to utilize their features. Eventually, their flexibility and controllability is a much-needed requirement of wireless environments such as 6G.

2.6 Related Work/Research

Hashemi et al. (2016) [25] in this paper, the author, has designed and fabricated to perform the experiment on a mmWave beam scanner that is fully electronic controlled and made up of VO2 reconfigurable metasurface. The prime object is to manipulate or govern the phase shift electronically by tuning the connected voltage on the lines of the metasurface arrangement. Hence, the point of transmission of an occurrence mmWave is manipulated electronically. The demonstration or experimentation is performed on 44 degrees at 95 GHz of constant beam scanning by a completely integrated device platform.

Jilani et al. (2019) [26] has explained the probable usage of flexible mmWave metasurface as screens or wallpapers, to enhance the power transmission and to make better wave communication for the indoor environments. For the 60 GHz i.e., hugely attenuated frequency band, the screen-printed metasurface has been configured, and the evaluation of its performance is measured or assessed by state-of-the-art testing resources. The observed outcomes portray a group/band of 60 GHz while the transmission is opposite to the metasurface which is wholly blocked. As a result, the signal transmits on the outer part of the configured metasurface and seems as though a waveguide channel/medium to move the information/signal between two focuses with lower misfortune than the conventional wireless data transmission.

Tasolamprou et al. (2019) [27] has proposed in his paper and inspect the issue of intercell remote communication within the complicated scene of smart metasurface textures, where it is imperative to actualize such sort of communication's distinctive advantages or features namely interconnectivity, intelligence, and autonomy. Moreover, the exploration of this paper is based on three possible propagations at mmWave frequencies. The first analysis produces a quite steep path loss of around 40-50 dB at 60 GHz and up to 70 dB at 120 GHz, predominantly because of lossy silicon chips. On the other hand, a chip layer looks like a natural option as the antennas may be consolidated on a controller chip and subsequently don't meddle with metasurface working. The dielectric layer is also introduced, which is mainly used for subsistence of thermal and mechanical and capable of reducing the path loss by 10 dB. In the second exploration, the alternative comprises the insertion of a layer for remote between cell correspondence. To compare with the first, it has a lower loss of about 5-25 dB and has useful security to interfere with all groups. Still, the drawbacks are the cost and spread delay of around 99-100 ps for a coherence transmission capacity of 10 GHz. The final version contains the layer of metasurface that has a relatively low path loss of around 20-40 dB at 60 GHz to the transmission path. The main challenge is to design metasurface properly in order to reduce the leakage signal and interference. Therefore, every alternative has an advantage and disadvantages but consequently, the most effective and impressive solution is the third one which uses the metasurface layer.

Olk et al. (2020) [28] here, the author presents extremely effective metasurfaces for the mmWave band range. An improved/advanced procedure used here that points out the main reasons such as degradation of performance, near field coupling, and the conductor losses. In this paper, the data processing and experimental characterizations are used, which provide a quite impressive determination of the Floquet harmonics over the high range frequencies. The optimal frequency shift form 80-83 GHz was noticed or observed. The achievements were about 80% on the order of -1.0 dB for beam refraction, according to microscopy and a profilometer analysis, which is actually a good agreement between experimental model and simulation. As a result, this finding confirms the author's numerical model and presents the resemblance of containing the subordinate consequences namely roughness of the surface into the metasurface combination. Furthermore, this model confirmed numerically; the information can be calculated that is inaccessible in the observation with high accuracy.

2.7 Conclusive Statement

The literature review's purpose was to identify the research and work that have been done so far with related to the title of the thesis. Most of the papers elaborated that despite the advantages of metasurfaces, they can be lossy, unpredictable, and challenging to implement. To use high frequency such as mmWave in the future technological revolution at a quite low cost, the most prominent material would be tunable/programmable/reconfigurable metasurface that has an ability to control the EM wave effectively. The research papers that are mentioned in this review have tried to reduce the losses so that metasurfaces will get the opportunity to use in upcoming wireless technology. The prime objective of this thesis is to optimize the mmWave by designing the metasurfaces to observe the high frequency so that this material can have the best outcomes in terms of losses and other propagation characteristics, e.g., less dispersion, etc.

Chapter 3
Methodology

3.1 Simulation Tool

3.1.1 Introduction of CST Microwave Studio

The simulation tool which is used for this thesis and numerical simulations in CST Microwave Studio. CST Microwave Studio incorporates devices for the structure, recreation, and improvement of a broad scope of gadgets, from fixed to optical, and electrically large from the nanoscale. The examination is not restricted to unadulterated EM, yet can incorporate thermal and mechanical impacts and circuit reproduction [29]. CST Microwave Studio can offer large items to advertise favorable circumstances, for example, shorter advancement cycles, virtual modeling before physical preliminaries, and streamlining or enhancement rather than experimentation. Gadget execution can be facilitated, potential consistency issues recognized and moderated before the plan procedure, the number of physical models required can be diminished, and the danger of test disappointments and reviews limited [30].

3.1.2 Parallel Plate Waveguide

It is a device that consists of two perfectly conducting plates and a dielectric between them to guide the propagating waves. The basic operation of a parallel plate waveguide is it creates an electric field at a specific voltage, that field is vertical to the plates, electric current flows in the z-direction, the magnetic field is in the y-direction, and the electromagnetic wave propagates in the z-direction as showing in the figure 3.1.

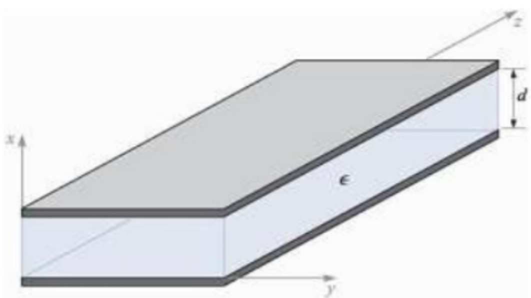

Figure 3.1 *Parallel Plate Waveguide with directions of fields propagation [34].*

In this thesis, the operation of designed structures is the same like a parallel plate waveguide because of applied boundary conditions in the simulator. As in the pictures 3.4, 3,7, and 3.10 below, the boundary conditions are put onto the two distinct geometrical shapes of a unit cell. In the designing part, the whole structure of a parallel plate waveguide is mentioned here in the form of an array of unit cells.

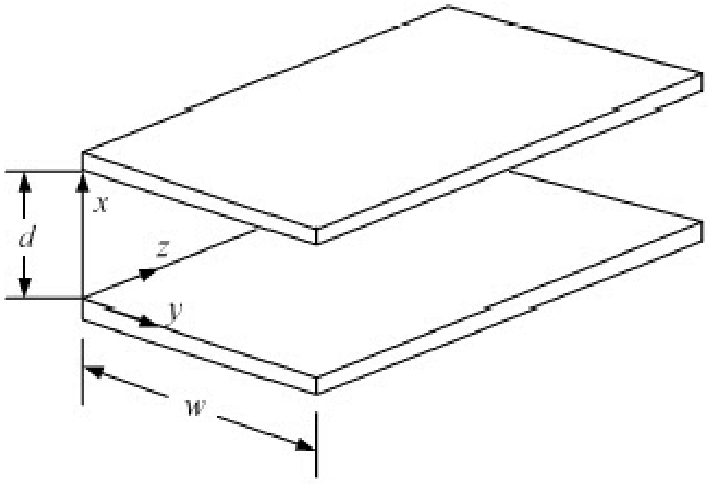

Figure 3.2 *Two parallel plates of conduction material [34].*

In this figure, these two parallel plates show how these plates are places to make a waveguide. Here, d represents the distance between plates, and w shows the width of a plate. If we consider the three directions, here x-direction showing the height, y-direction represents the width, and z-direction is for a length of the parallel plate waveguide.

There are three possible modes of a waveguide;

1. **Transverse Electric (TE):** In this mode, the electric field is purely transverse to the direction of propagation while the magnetic field is not purely transverse which is Ez=0 and Hz≠0.
2. **Transverse Magnetic (TM):** Here, the magnetic field is purely transverse but the electric field is not, which is Hz=0 and Ez≠0.
3. **Transverse Electromagnetic (TEM):** In this type of mode, both field components are transverse/perpendicular to the direction of propagation, meaning both fields are directed components that are Ez=0 and Hz=0.

3.2 Dispersion Diagram

To analyze the left-handed qualities of metamaterial and also the periodic structures, there is the most potent graph or diagram used, which is known as Dispersion Diagram. It has the ability to examine the single unit cell composing any full structure. The diagram is quite useful to plot waves of different frequencies traveling at distinct phase and group velocities. Sometimes, it is called a k-β diagram, where β is phase constant or wave propagation constant, and k is wave number because the dispersion diagram is acquired from the dispersion equation [32]. The k-β layout is quite simple for a 1D periodic structure, while in 2D and 3D or any other kind of geometry, it is complex to plot in a k-β manner. There is an excellent solution available to plan such a complicated diagram for higher dimensions that is known as the Brillouin zone/diagram, and this zone is named after innovation by Leon Brillouin. To follow the propagating directions and constants, besides those directions and network of periodic formation, Brillouin permits to verify zones to cluster propagating directions.

Here a square patch structure of 2D formation is studied concerning both X and Y directions. The best thing is of Brillouin's attempt, all possible directions of propagation in X and Y axes can be merged in an irreducible Brillouin zone. The irreducible is actually a triangular region that is defining the Brillouin zone. One condition is applied for this zone; it is only valid when there are some symmetry axes. In the figure, it can easily be seen how the triangular area is selected for this zone, and that is used to optimize a square patch. The picture is also showing all values of phase constants that are βx and βy along the x and y directions.

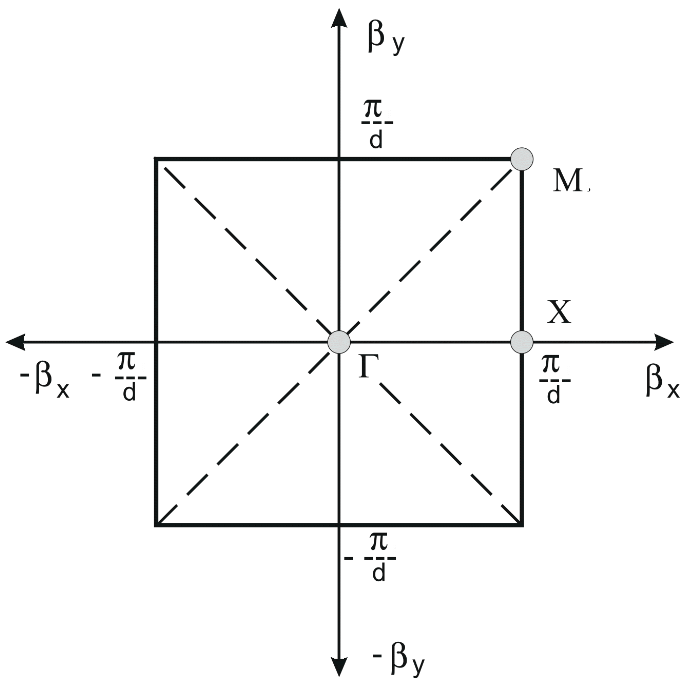

Figure 3.3 *Brillouin zone of any geometry with symmetries [32].*

Here, d denotes the geometrical dimension of a unit cell. Nevertheless, to study the 2D square patch with dispersion diagram in three possible steps, when the frequency dispersion of the wave phase variations "Γ to X," "X to M," and "M to Γ."

1. From Γ to X, it defines the phase constant along x-axes, or it is the base of the Brillouin triangle. It varies from 0 to 180 degrees, while y-direction is fixed at 0 degrees. After setting the values of phase constant, then it can be able to generate the dataset for the wave propagation. This dataset groups the modes, i.e., the solution of the Helmholtz equations - homogeneous, i.e., zero right-hand side equation.

2. From X to M, set the x-direction at 180 degrees fixed, and the y-direction varies from 0 to 180 degrees. In this way, the second set of eigenmode frequencies are formed.

3. From M-Γ, in this case, both the segments are varied that are Γ-X and X-M from 180 to 0 degrees. Thus, the last set of frequencies are found for this segment, i.e., M-Γ of the Brillouin triangle.

To acquire the dispersion diagram, here, CST Microwave Studio is used. In which the path is simple, choose a new project>Periodic Structures>Unit Cell>Dispersion Diagram>Eigenmode Solver. Actually, the dispersion diagram is none other than just a graphical representation of eigenmode frequency as a function of the phase constant [32].

In the CST Microwave studio, there is a PathPara selection available by the software. To use this tool, one can easily find the dispersion diagram accordingly. PathPara wipes the whole Brillouin zone with a one-parameter sweep. PathPara is defined as:

0->1: Γ->X
1->2: X->M
2->3: M-> Γ

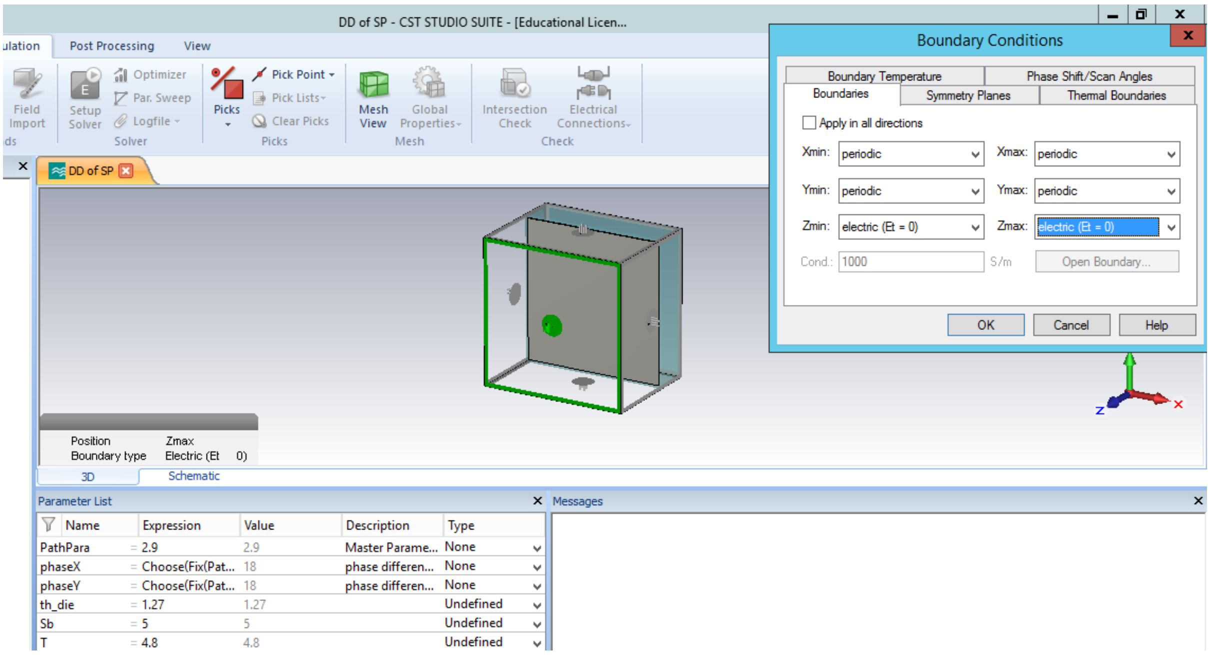

Figure 3.4 *Boundaries setup of a square patch.*

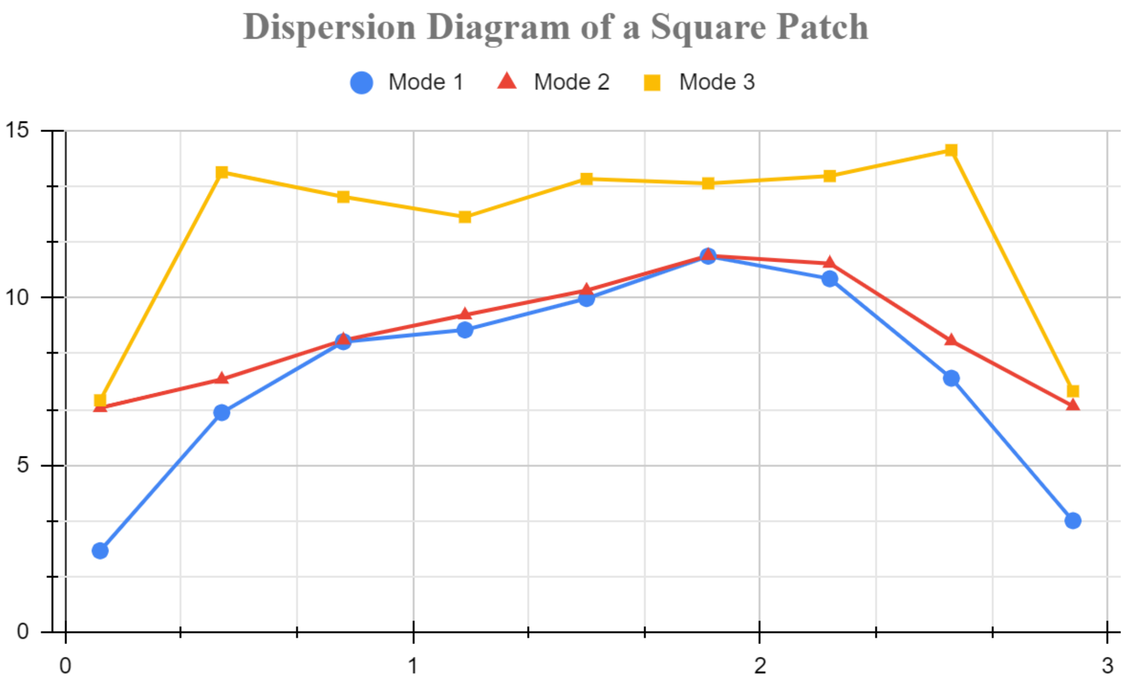

Figure 3.5 *Dispersion Diagram of a square patch with periodic boundaries.*

Here, three frequency modes are used to find the dispersion diagram of a square patch. First of all, the periodic boundaries were set in order to obtain the proper values from the patch. In CST, open limits/boundaries are not acceptable, so for X and Y, periodic boundaries are selected, and Zmin and Zmax electric (Et=0).

In the figure 3.5, a PathPara has swept the irreducible Brillouin zone, respectively. Two modes have around the same frequency, just a minor change, while frequency mode three has quite a different plot than those of two. Here, a bandgap is not formed among these modes, if a band gap is available among modes, which means in a particular range of values, there is no interaction among modes; thus, no frequency mode propagates here. In other words, in the bandgap, there are no eigensolutions; thus, no field can be represented by the eigenmode solver.

3.3 Designing of Metasurfaces

3.3.1 Details of Parameters to Design

3.3.2 Substrate/Dielectric layer in the Designing

For the tunability effect, the most important thing would be the dielectric material to acquire the tunability by changing the dielectric's thickness/height in the Microwave Studio simulator. Therefore, a chosen dielectric is Polyimide, a comparatively good thermal expansion coefficient with other dielectrics. A coefficient of expansion means a rate at which the length of material is growing with an increment of temperature. In other words, a matter has a tendency to change its shape, area, volume, and density by changing in temperature which is known as thermal expansion. The Polyimide has Linear Thermal Expansion Coefficient α 60($x10^{-6}$ C^{-1}) Where C means Celsius [33].

1. ***<u>Square Structure</u>***

The dimensions of a unit cell are selected here after a small calculation; this process includes the resonance frequency and the wavelength. As we have to observe the metasurface is on 70 GHz; therefore, the resonance frequency should be 70 GHz, and 1/10 of a wavelength defines the size of the unit cell. After calculation, the size should be 2.3mm, but by rounding off, we are using a 2mm unit cell.

The first layer of the structure is chosen as a substrate; in this layer, a Polyimide dielectric material is used. Design details are mentioned below:

- **Dielectric**

Length	-1.0 to 1.0	Xmin to Xmax	Total Length is 2mm.
Width	-1.0 to 1.0	Ymin to Ymax	Total Width is 2mm.
Thickness	0.0 to 1.56	Zmin to Zmax	Total thickness is 1.56mm.

- **Perfect Electric Conductor(PEC)**

Length	-1.8/2 to 1.8/2	Xmin to Xmax	Total Length is 2.8mm.
Width	-1.8/2 to 1.8/2	Ymin to Ymax	Total Width is 2.8mm.
Thickness	1.56 to 1.59	Zmin to Zmax	Total thickness is 0.03mm.

- **Air Layer**

The thickness of this layer is 1.5 times greater than the substrate thickness. This layer is used to get the right results from the structure because in CST, the open boundaries are not acceptable; that's why it is used here to set the proper boundary conditions.

2. ***Rectangular Structure***

Here, the materials are the same as before; just the shape has been changed to make a rectangle structure. Design details are mentioned below:

- **Dielectric**

Length	-1.5 to 1.5	Xmin to Xmax	Total Length is 3mm.
Width	-0.9 to 0.9	Ymin to Ymax	Total Width is 1.8mm.
Thickness	0.0 to 1.56	Zmin to Zmax	Total thickness is 1.56mm.

- **Perfect Electric Conductor(PEC)**

Length	-1.2 to 1.2	Xmin to Xmax	Total Length is 2.4mm.
Width	-0.75 to 0.75	Ymin to Ymax	Total Width is 1.5mm.
Thickness	1.56 to 1.59	Zmin to Zmax	Total thickness is 0.03mm.

- **Air Layer**

As mentioned above, the thickness of this layer is 1.5 times greater than the substrate thickness.

3.3.3 Pictures of Designed Metasurfaces

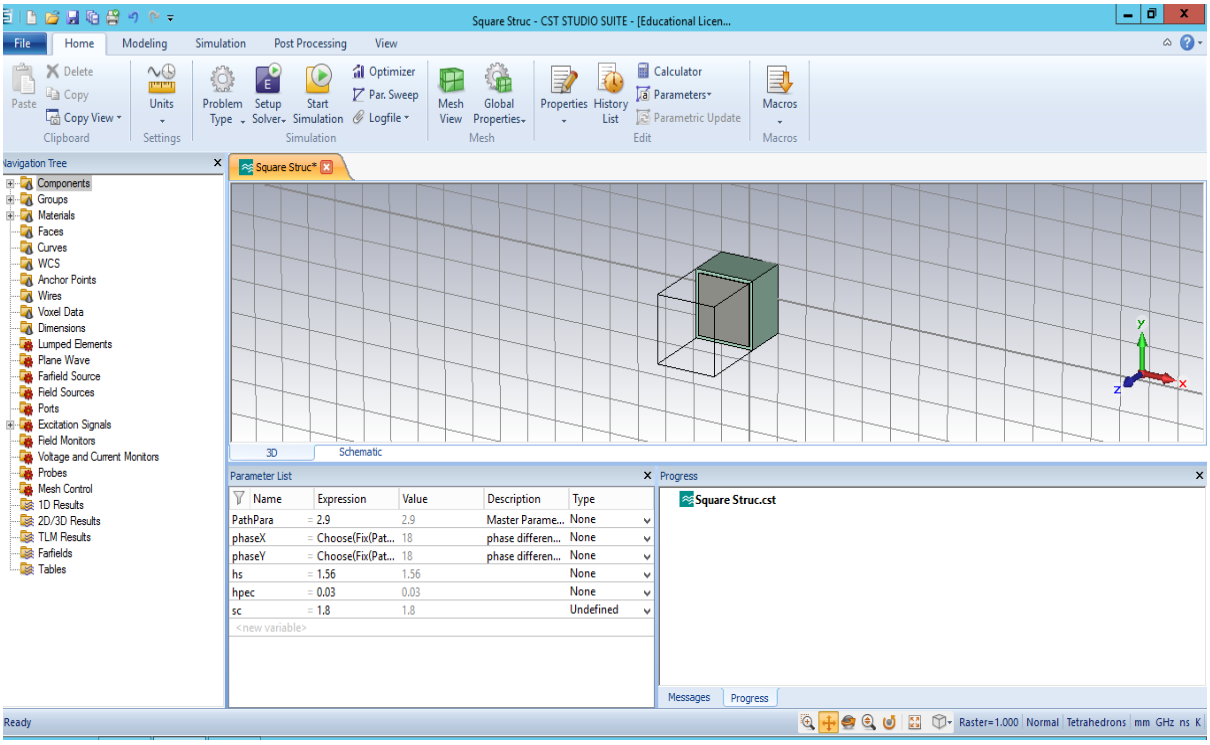

Figure 3.6 *A unit cell with a square structure.*

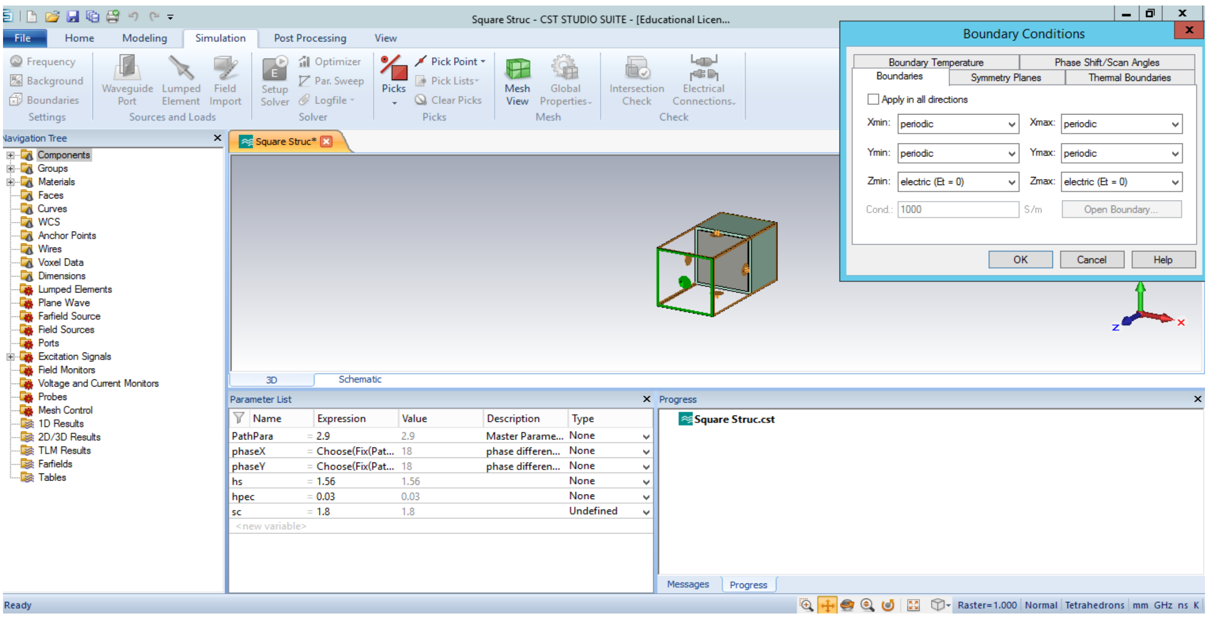

Figure 3.7 *A unit cell with boundary conditions.*

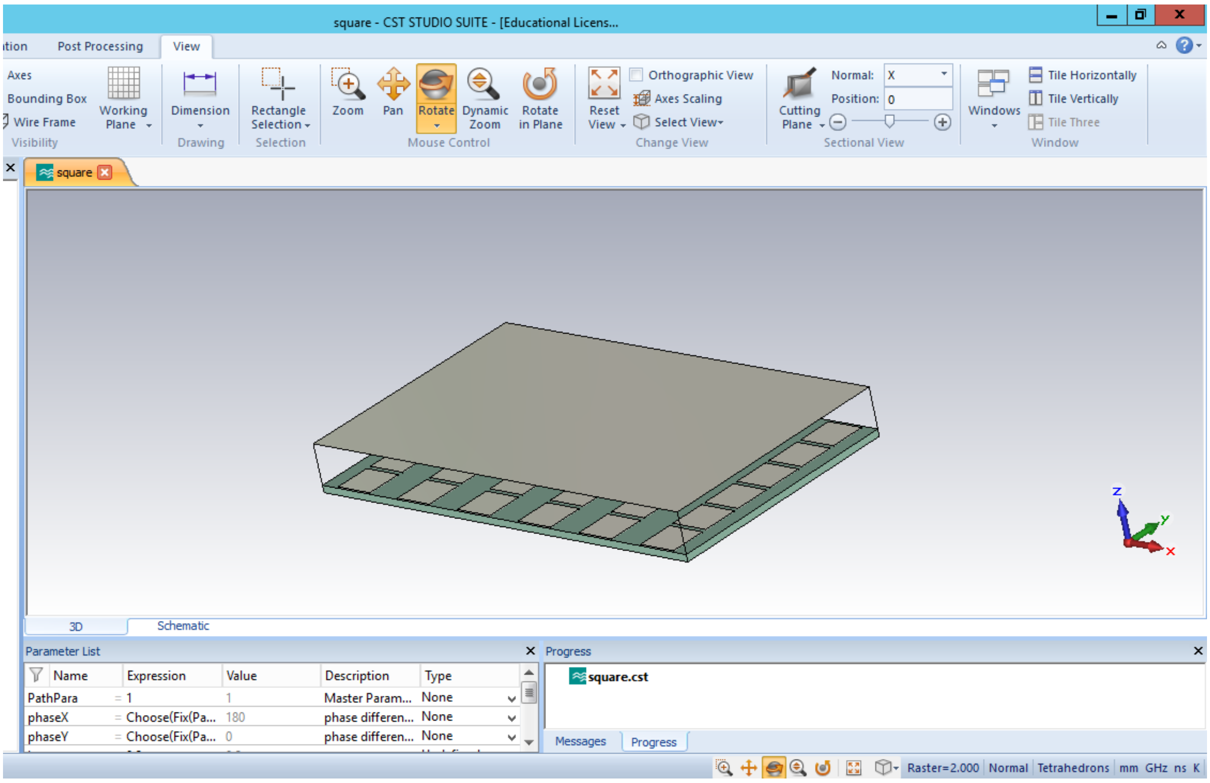

Figure 3.8 *Array of unit cells of a square shape.*

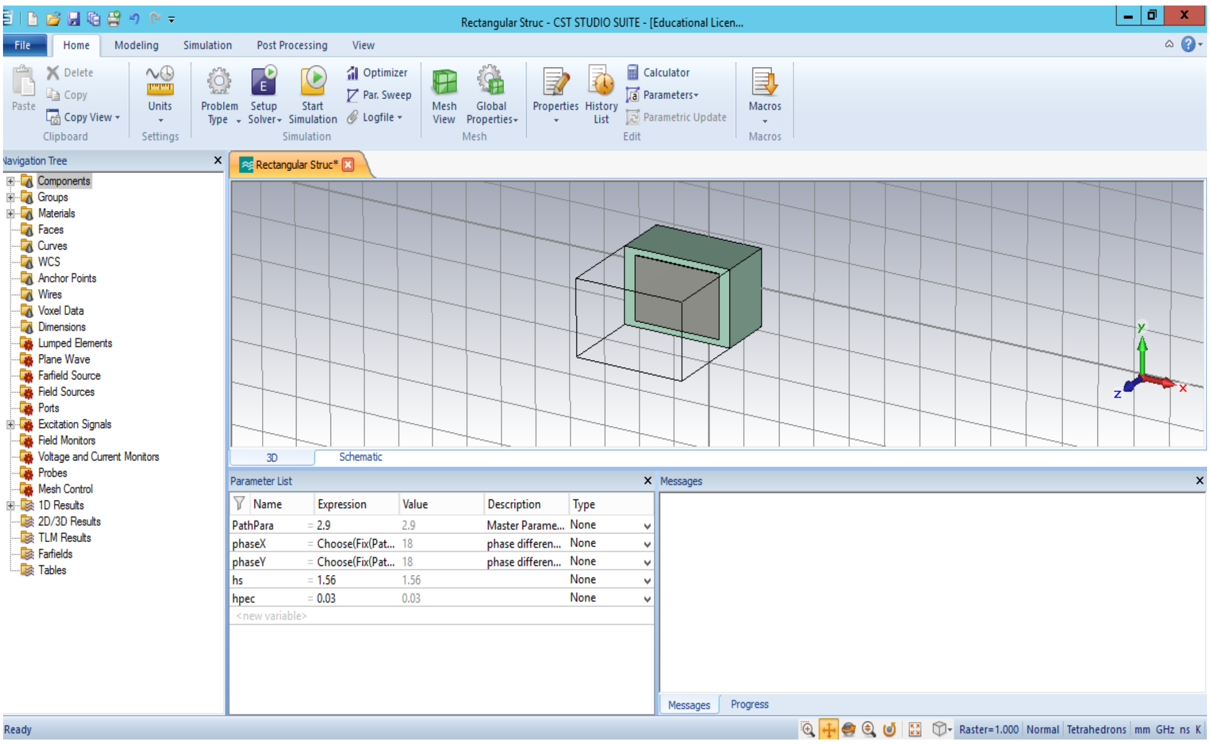

Figure 3.9 *A unit cell with a rectangular structure.*

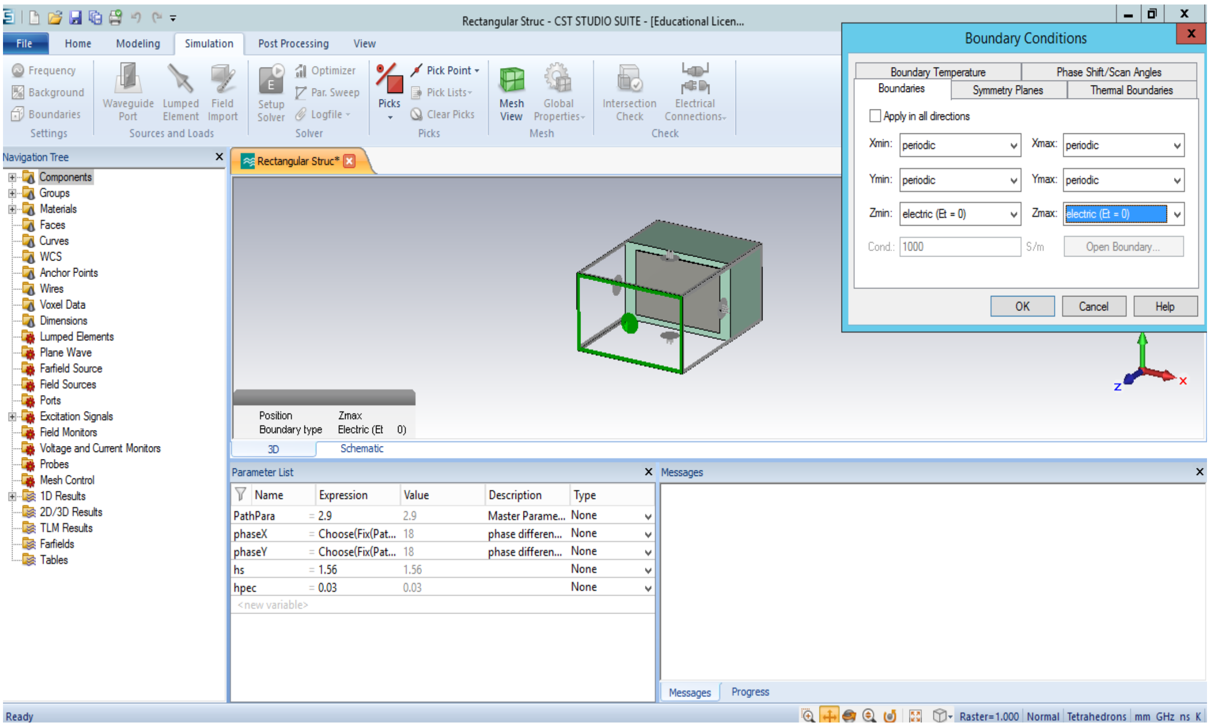

Figure 3.10 *A unit cell with boundary conditions.*

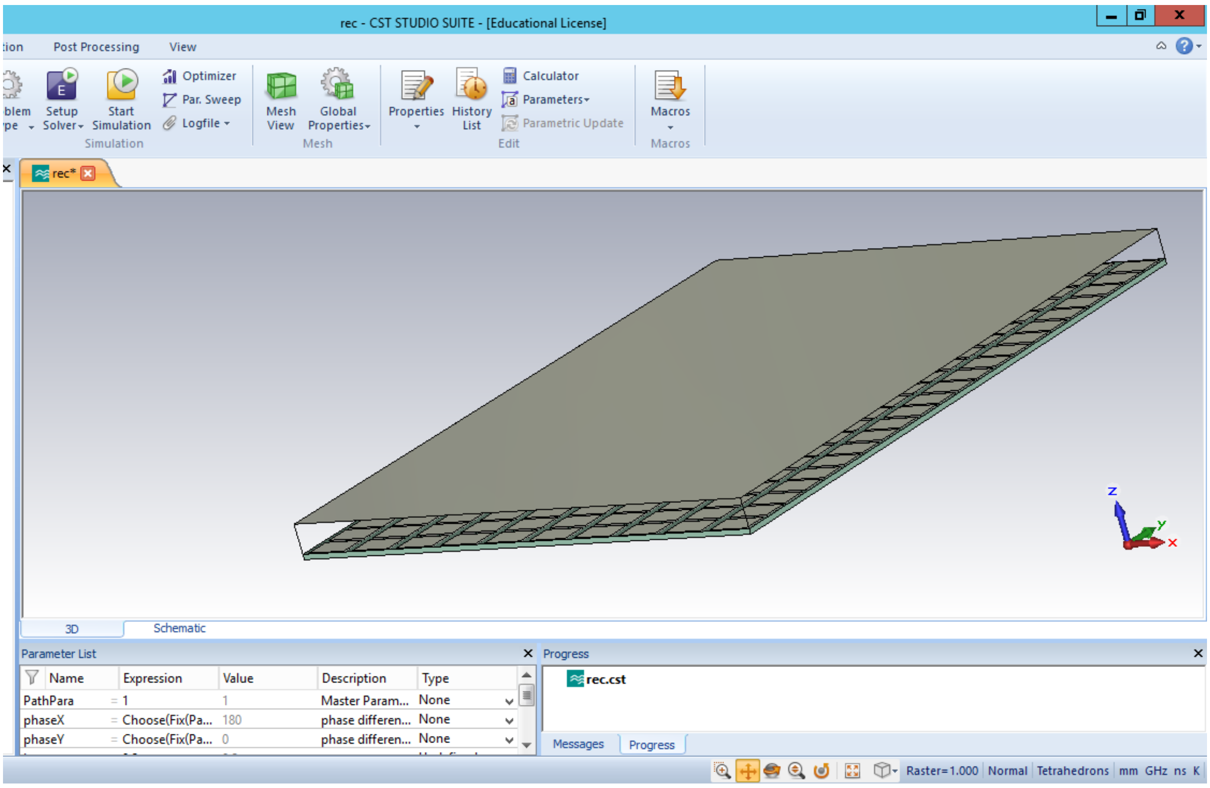

Figure 3.11 *Array of unit cells of a rectangular shape..*

Chapter 4
Results and Discussions

4.1 Overview of Obtained Results

By utilizing the Microwave Studio by CST, the simulation results around 70 GHz were acquired for different geometries of a unit cell. The geometrical structures work as a parallel plate waveguide after applying electric boundary conditions at the ground and the upper layer of both shapes. As mentioned in previous chapters, the target is to determine how electromagnetic waves propagate at the high-frequency band in different directions by using metasurfaces. The remarkable feature of tunable metasurfaces that has been applied here is the controllability of EM waves by tuning a metasurface. In the simulation, this feature is achieved by changing the thickness/height of the dielectric. In this chapter, the metasurface behavior is described by finding dispersion diagrams. Two structures of a unit cell are present here, one is a Square structure, and another one is a Rectangular structure. Thus, the following pictures show the dispersion diagram of distinct geometrical designs, and it can be easily seen there how waves are propagating and how they can be regulated by changing the height of the dielectric. In all dispersion diagrams that are mentioned below, ending points of mode 4 or mode 5 may belong to high-frequency modes such as the mode 6 or mode 7. But, in this work, those modes are not calculated because the tunability is observed up to 70 GHz.

The reason behind the use of only these two geometrical shapes is quite simple; the target of this thesis is to find a better way of implementation of the tunable metasurfaces after observing the behavior of EM waves. The design of these two shapes that are Square and Rectangular is simpler than other geometrical shapes such as star shape, pentagon, and hexagon. In the simulator that is Microwave Studio by CST, the controllability of waves or tunability effects can be acquired by changing the thickness/height of a dielectric substrate. In the different scenarios, the height is increasing according to the impact of temperature on a dielectric. Thus the observation can be made of how the behavior of EM waves is diverse by finding the dispersion diagram of distinct heights.

4.1.1 Height selection of a dielectric

The height of a dielectric is selected according to the temperature applied to the dielectric. Here, polyimide dielectric is used, and its range of temperature is from -270 to 320 degrees celsius, and the linear thermal coefficient of expansion α is 60 ($\times 10^{-6}$ C^{-1}). Thus, by applying the temperature to its initial height, we can identify or find out the next increased height to put the value in the simulator.

$\Delta L = \alpha \times L \times \Delta T$

ΔL represents change in length

L represents an initial length

Alpha α represents the thermal coefficient value of Polyimide

ΔT represents a change in temperature

After calculations, the values of the height of a dielectric are found using the above equation. Those values are used here to obtain the different dispersion diagrams of a unit cell. The temperature affects the materials according to their properties and the value of the thermal coefficient of expansion. Here, in our case, the Polyimide dielectric is used as a substrate layer, and its thermal coefficient of expansion is 60, as mentioned above. For analysis, first, we have to select the initial height of a dielectric that is 1.56mm in our simulation, then variations of height are changed according to the temperature such as 120ºC, 220ºC, and last 320ºC to acquire the tunability effect of metasurfaces.

4.1.2 Light Line

In the dispersion diagram, a light line represents the phase difference of a specified frequency propagating in a vacuum/free space along with the distance concerning the length of a unit cell. The usage of a light line mainly defines the guided and unguided propagating frequency modes, such as if modes are below the light line, then they are guided, and if modes are above the light line, they are considered to be unguided or leaky waves. Here, in our designed structures the energy is not leaking because these are closed structures, so, in our case the energy is just exchanging/transferring between the modes propagating in the dielectric and the air.

4.2 A Square Structure of a unit cell

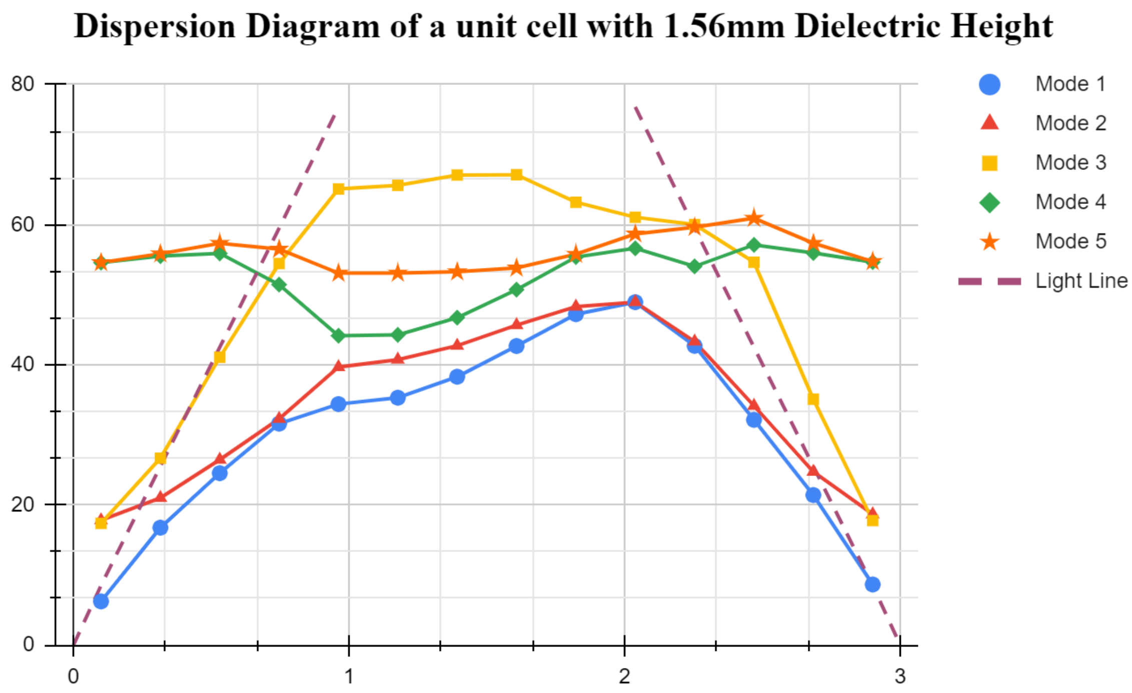

Figure 4.1 *The Square structure of a unit cell with 1.56mm thickness of a dielectric.*

In Fig. 4.1, the dispersion diagram of five different frequency modes is propagating as a function of frequency and propagating directions (Γ to X, X to M, and M to Γ). These define the values from 0 to 1, 1 to 2, and 2 to 3, respectively. Here, the initial height is selected to obtain the dispersion diagram. The blue line i.e., Mode 1, has reached its maximum value 48 GHz between X to M direction of the irreversible Brillouin Zone. The second mode is propagating on a higher frequency than the first but the maximum reached frequency point is the same at 48 GHz. The third mode changes the values in the Γ to X direction frequently, so the maximum frequency is much higher than all modes about 8 GHz. The green line represents the frequency mode 4; it is more diverse than the first three modes because it starts at 54.5 GHz and the maximum obtaining frequency is 57 GHz. The last frequency mode has the starting point is almost similar to mode 4 but the maximum frequency is 60 GHz. The fourth and the fifth modes have received the maximum frequency value from M to Γ direction.

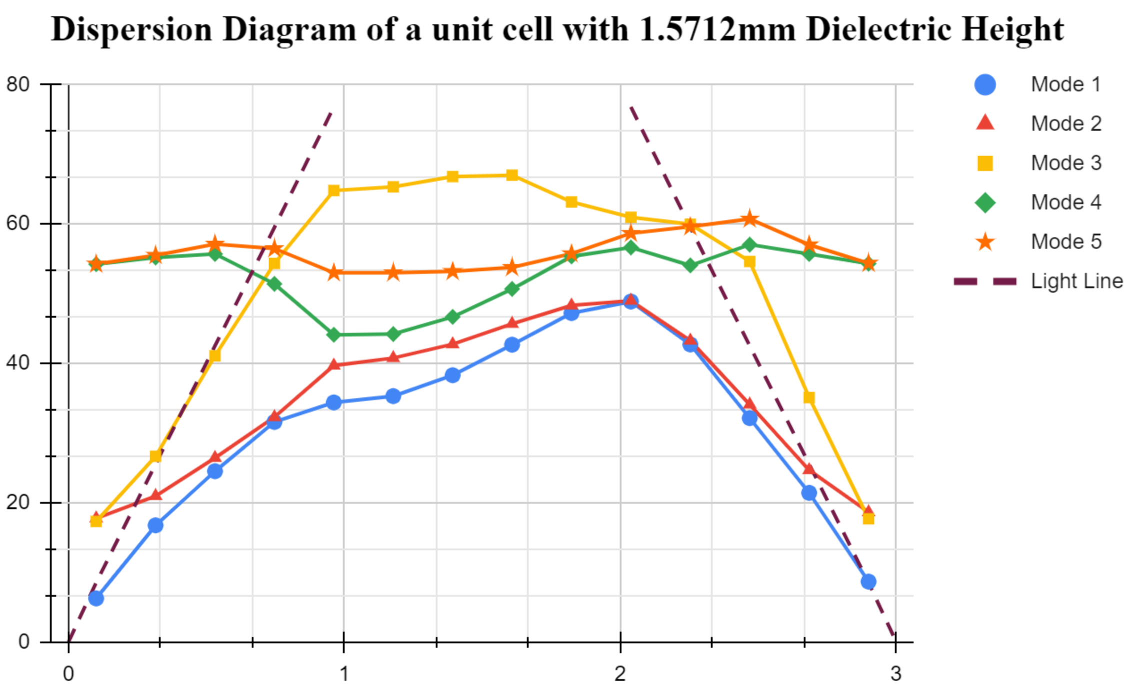

Figure 4.2 *The Square structure of a unit cell with 2.06mm thickness of a dielectric.*

In Fig. 4.2, the thickness/height of the dielectric increases by 0.011232mm at the temperature of 120ºC. The increment of height will observe the tunability effect or also a good feature of the metasurface. Now, it can be seen how these waves have changed their values and directions comparative to the previous one. Although, the difference is small around 0 to 1 GHz because it is directly proportional to the increment of the temperature. If the initial height is small then the change would be minor respectively. In Fig. 4.1, the third mode has reached 67.1 GHz, while in this figure, the maximum value of mode 3 has reached 66.9 GHz. Hence, the tunability is acquired here concerning the previous one by changing the height of a dielectric, but the effect is small at this temperature. The all other modes also have decreased their maximum values; the observation is apparent by comparing these two different heights; that is, by increasing the height, the propagating modes reduce the highest value of frequency.

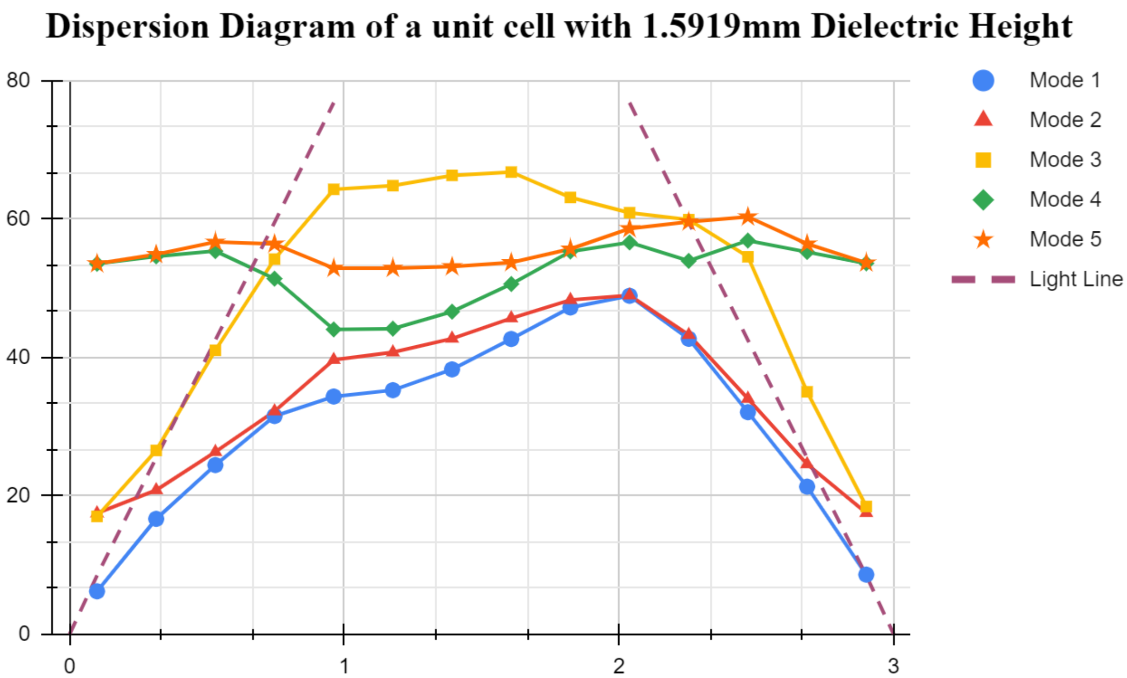

Figure 4.3 *The Square structure of a unit cell with 2.56mm thickness of a dielectric.*

In Fig. 4.3, in this case, the applying temperature is 220ºC; thus, with respect to this, the height is changed by 0.020mm. Therefore, the observed height is 1.5919mm of a dielectric. Here, all frequency modes have decreased their maximum values by about 0.2 to 0.3 GHz at different values of the horizontal axes. Consequently, the conclusion can be made like the previous one; that is, by increasing the height of a dielectric, a decreasing frequency value is observed.

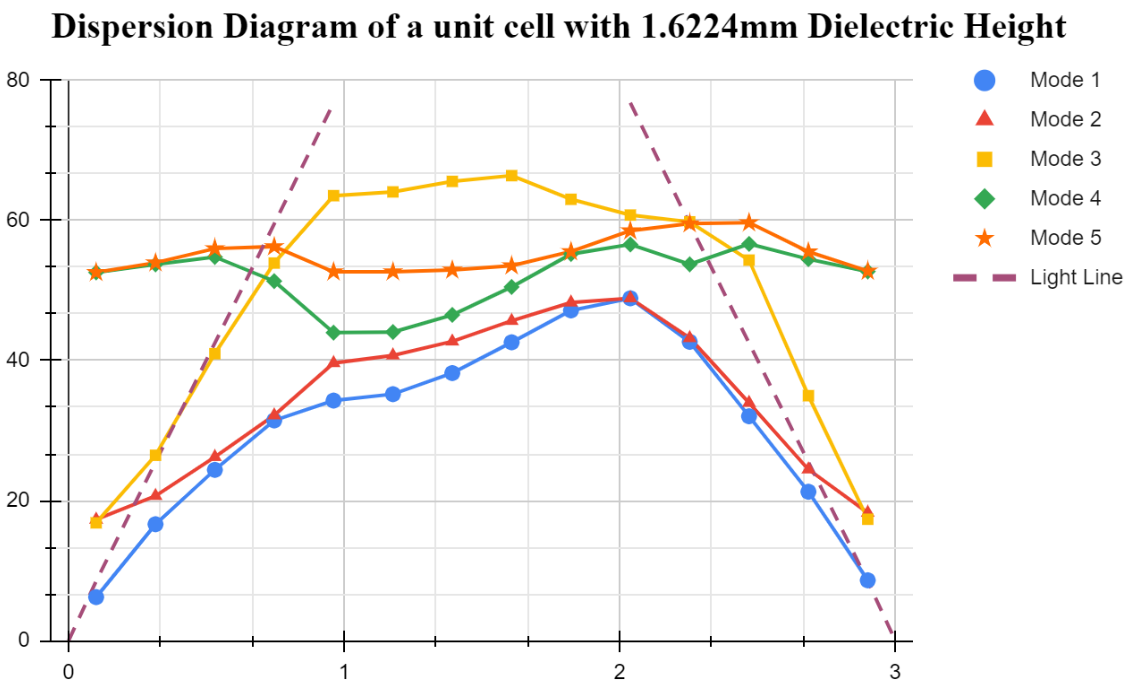

Figure 4.4 *The Square structure of a unit cell with a 3.06mm thickness of a dielectric.*

In Fig. 4.4, The last case with the highest temperature value is applied that is 320ºC at which the dielectric can work. Here, the height of the dielectric is increased by 0.03mm. The dispersion diagram showing here the different frequency modes are propagating in the directions of the Brillouin zone. The last figure of a square geometrical shape shows the dispersive behavior of EM waves. The irreversible Brillouin zone combined all possible directions of propagation in x and y directions. Therefore, the dispersion diagram indicates the potential actions of EM waves using metasurfaces and the tunability effect by changing the height of a dielectric. Here, the decrement is around 0.6 GHz concerning the previous height result.

4.2.1 Two combined Results of a Square shape

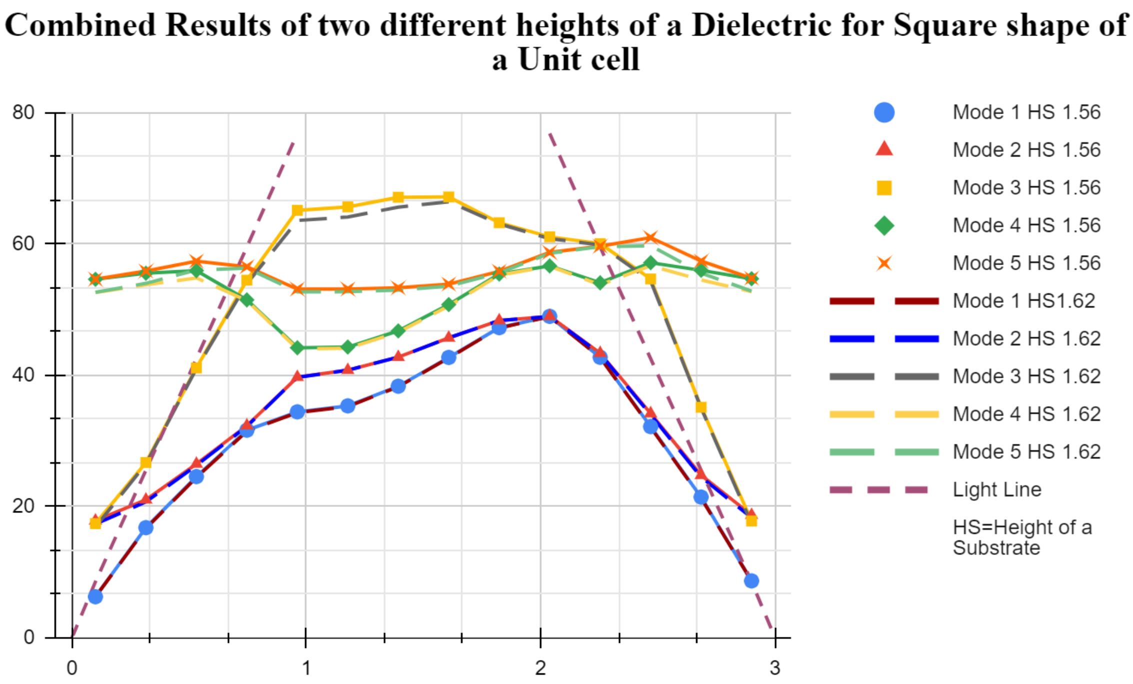

Figure 4.5 *The combined graph of Square structure of a unit cell with distinct heights.*

In Fig. 4.5, this particular graph shows the merged result of two different heights of the square shape of a unit cell. In this graph, the initial height is utilized with the changed height concerning the temperature value of 320ºC. However, the difference is not more significant because of the height and size of a unit cell. If the height is substantial, the change in height will be more significant by applying the positive value of temperature. Mode 3 of the initial height of 1.56mm has reached a little higher frequency value than the other height that (1.6224mm) is being changed according to the temperature. All different modes also have a small difference concerning their heights; this is the tunability effect and also the feature of a metasurface that has to be observed here by changing the height of a dielectric in a simulator.

4.3 A Rectangular Structure of a unit cell

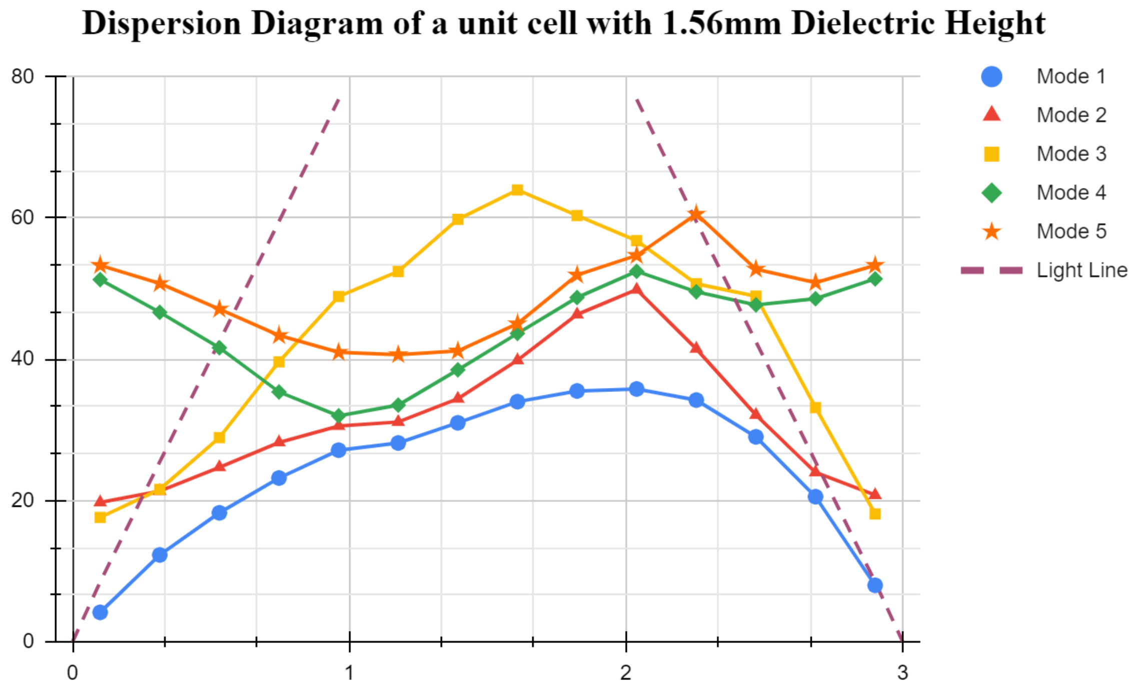

Figure 4.6 *The Rectangular structure of a unit cell with 1.56mm thickness of a dielectric.*

In Fig. 4.6, the rectangular shape of a unit cell has been made to observe the behavior of EM waves. Here, the initial height is the same as the square shape, but in the first frequency mode, there is a big difference in the maximum value of frequency around 12 GHz by comparing the identical height of a square structure. While other modes have a small difference in frequency values in this Brillouin zone combined propagating directions. The third mode has reached 64 GHz at 1.6 values in this shape; on the other hand, the square structure of the previous mode has reached 67 GHz at the same value. Thus, the observations can be made here; the EM waves are propagating at high frequency in square structure, while in a rectangular shape, the waves can not achieve a more prominent value like the square one.

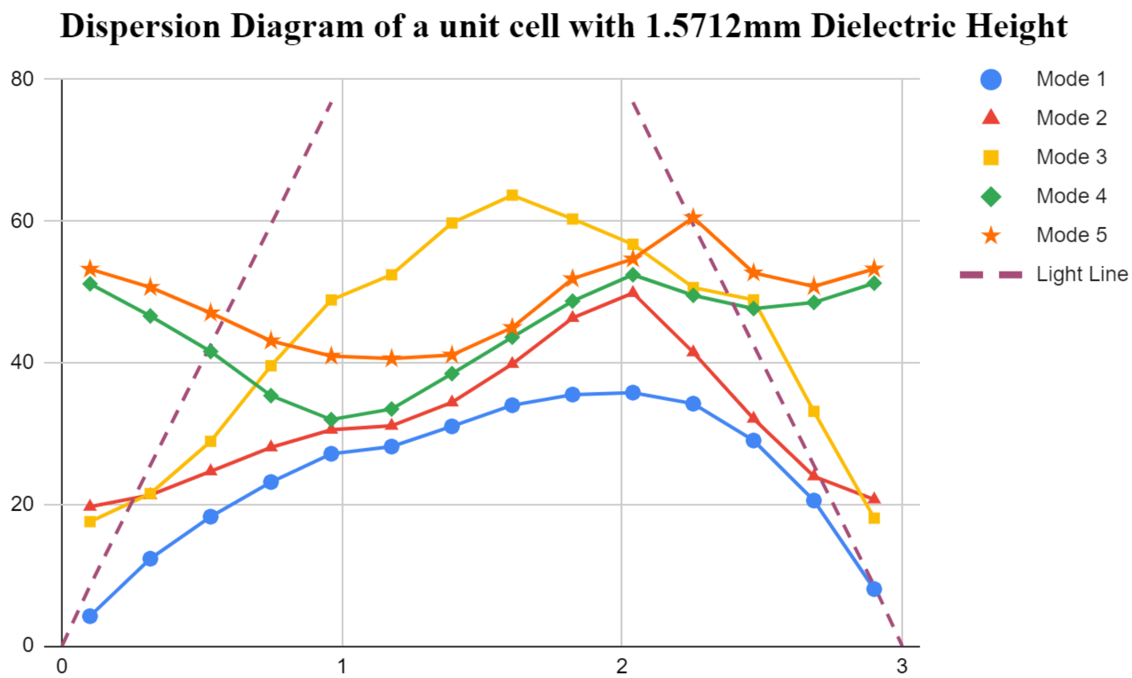

Figure 4.7 *The Rectangular structure of a unit cell with 1.5712mm thickness of a dielectric.*

In Fig. 4.7, the height of a dielectric is changed to see the effect of tunability of a metasurface by using this geometrical shape. In this shape, the change of height is also the same as the square structure at the temperature value of 120ºC. The comparison is with the previous picture; it can be seen here how waves behave in this diagram. The first mode is almost the same as the previous one but the maximum value is a little bit decreased around 0.12 GHz. In contrast, other frequency modes also have a smaller diversity than the last height of the same rectangular structure. This is how height/thickness can be affected by the metasurfaces; to do so, we can achieve the regulation or control of EM waves in metasurfaces.

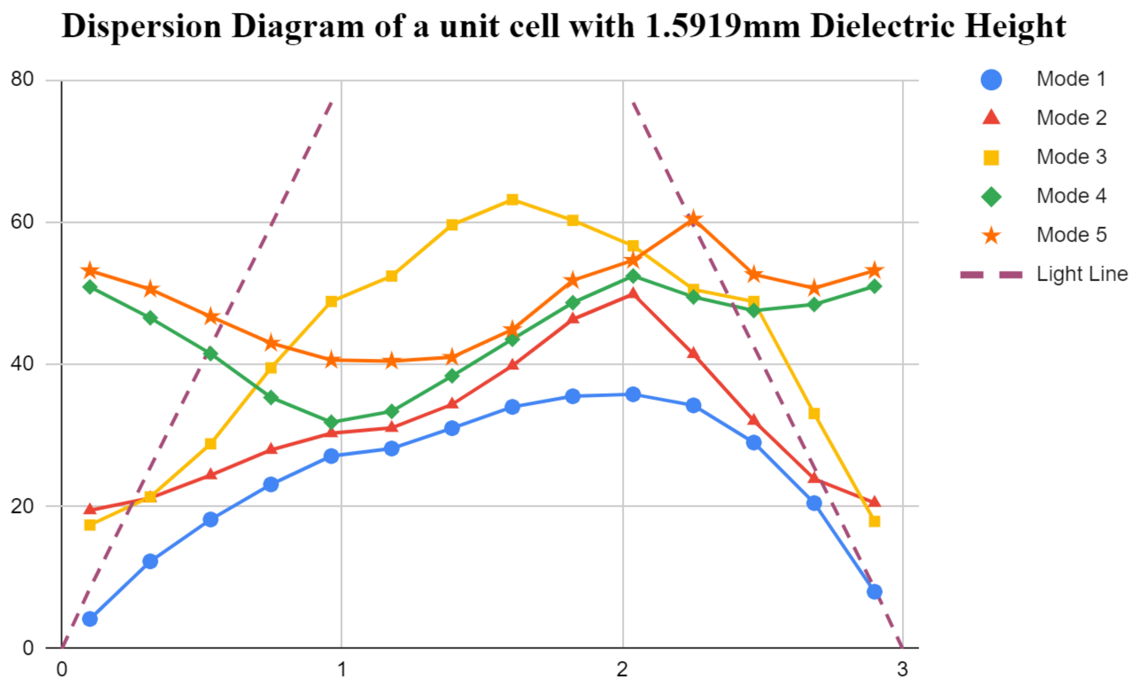

Figure 4.8 *The Rectangular structure of a unit cell with 1.5919mm thickness of a dielectric.*

In Fig. 4.8, the height of a dielectric increases by 0.02mm by changing the value of temperature by 100ºC; now, the applied temperature is 220ºC. Here, the waves are almost the same. However, in the deep, a little bit difference is present here because as the propagating modes are increasing from 1 to 5, the value of maximum frequency is declining tiny concerning the last figure that is 4.7, where the thickness of a dielectric was 0.02mm lesser than this one. The difference among the all modes except three according to the value of frequency is just 0.1 to 0.2 GHz, while in the mode 3, the difference is 0.4GHz concerning 1.5919mm thickness.

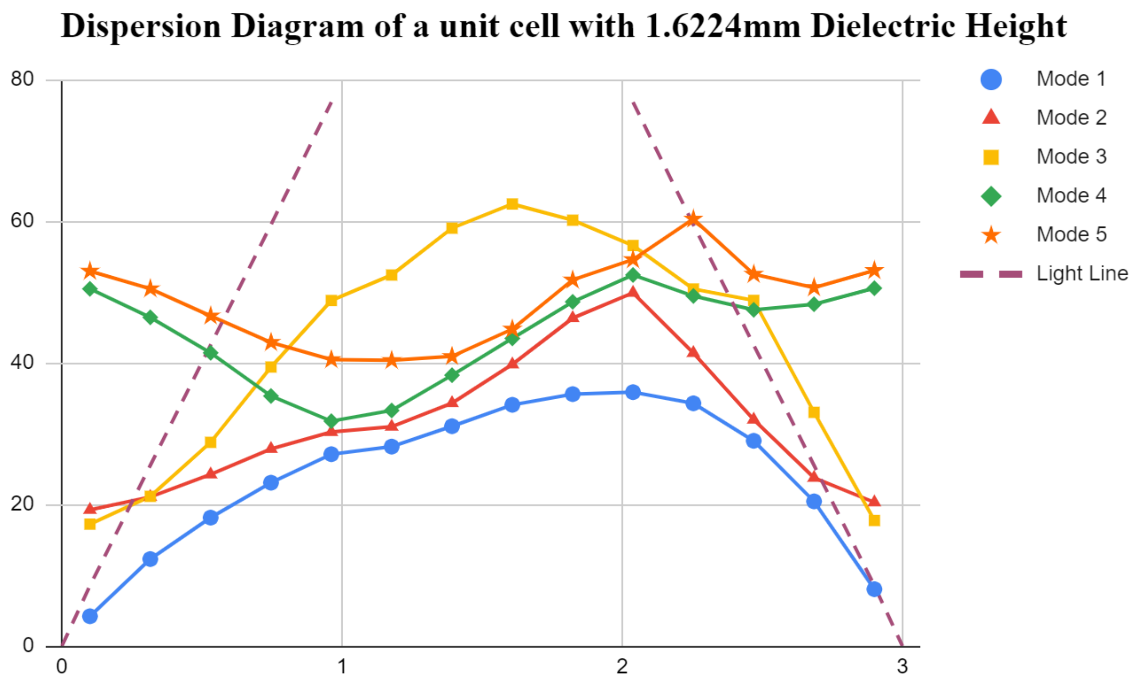

Figure 4.9 *The Rectangular structure of a unit cell with 1.6224mm thickness of a dielectric.*

In Fig. 4.9, the thickness of the dielectric increases by 0.03mm concerning the last one; because here, the applied temperature is 320ºC now, the height is 1.6224mm. In this figure, the tunability effect is obtained by changing the height in the simulator. The overall observation can be explained such as, while we increase the thickness of a dielectric, the maximum value of frequency is decreased of the EM wave. By comparing the square shape, the rectangular shape has significantly lower frequency values than that shape, as tunability is small. Therefore, it can be utilized in some applications where we need a little effect by regulating the waves by changing its height.

4.3.1 Two combined Results of a Rectangular shape

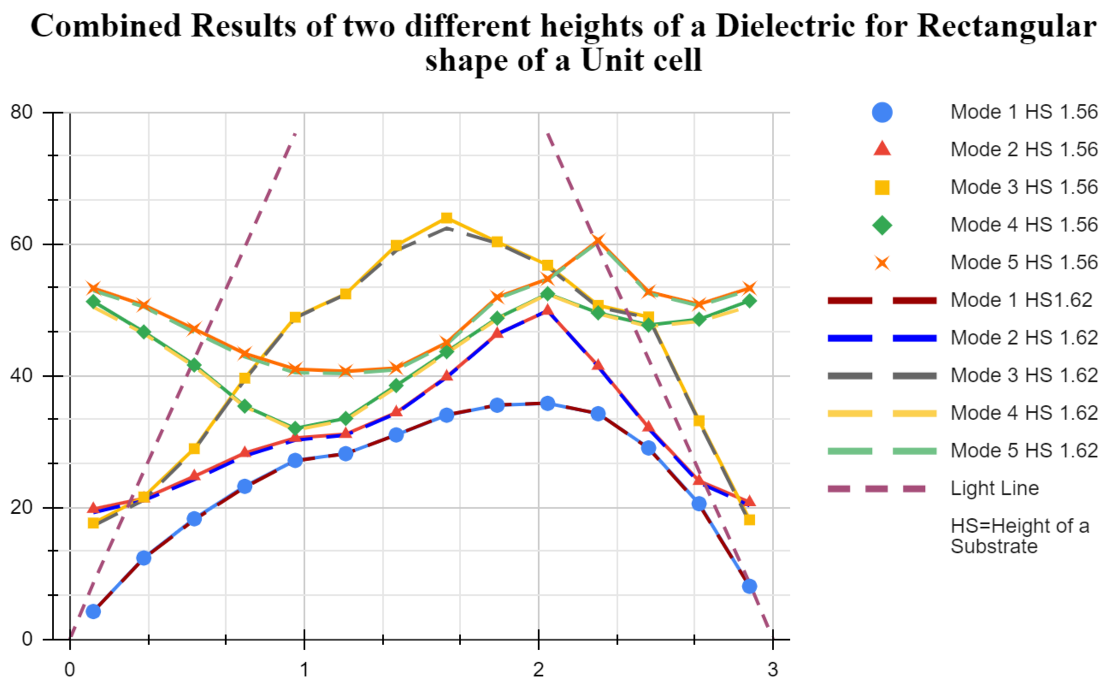

Figure 4.10 *The combined graph of Rectangular structure of a unit cell with distinct heights.*

In Fig. 4.10, the merged graph is presented here to elaborate on the tunability effect clearly according to the change of heights. In this graph, the rectangular-shaped structure is observed by applying the mmWave band frequency. The initial height is utilized with the changed height concerning the temperature value of 320ºC. As mentioned above, the difference is not bigger because of the height and size of a unit cell. If the height is significant, the change in height will be bigger by applying the positive value of temperature. Mode 3 of the initial height of 1.56mm has reached a little higher frequency value than the other height that (1.6224mm) is being changed according to the temperature. All different modes also have a small difference with respect to their heights; this is the tunability effect and a good feature of a metasurface that has to be observed here by changing the height of a dielectric in a simulator.

4.3.2 Two combined Results of Two Geometrical Shapes

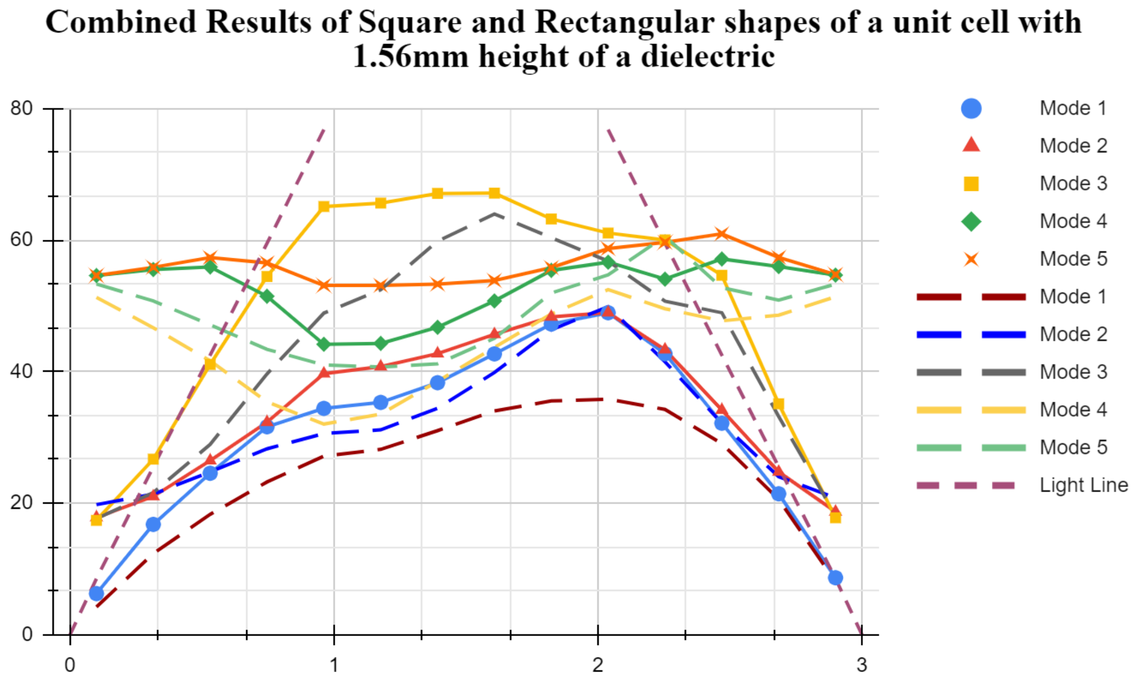

Figure 4.11 *The combined graph of two geometrical shapes of a unit cell.*

In Fig. 4.11, here, two geometrical shapes are merged in order to see the difference in terms of wave propagation at distinct frequencies. Furthermore, both structures have the same material, same height, boundary conditions and frequency, but just because of the change of a shape of a unit cell, it shows a big difference in values and directions. All modes also have an incredible visual difference with respect to their geometrical shapes; this is the tunability effect that has to be observed here by changing the height of a dielectric in a simulator, but in this graph, height is constant but the shape is changed.

Chapter 5
Conclusion

As the title of the thesis is the parametric study of the tunable millimeter-wave structures based on metasurfaces for the wireless communication system. Here, the simulation work has been performed to observe the tunability feature of the metasurface at a high frequency such as 70 GHz. The Microwave Studio by CST is used here for designing and executing the simulations. The results have been carried out in the form of a dispersion diagram. The main objective was to propose the tunable millimeter-wave structures based on metasurfaces to observe the tunability feature. In the dispersion diagram, the multiple numbers of frequency modes can be used to show the dispersion behaviour of electromagnetic waves, but here in our case, the frequency is restricted to 70 GHz that's why only five frequency modes are used here to acquire the results around 70 GHz. By following the concept of tuning, here in simulation, the work is done through the change of thickness/height of a dielectric. The two geometrical shapes of a unit cell have been designed to acquire the results and to notice how EM waves are propagating in different forms of a unit cell.

The polyimide dielectric is used here as a substrate layer, and for the conduction layer, the PEC has been utilized in both geometrical structures. The selection of the height of a dielectric is calculated by a linear thermal coefficient expansion equation in order to increase the height of a dielectric with proportional to the increment of temperature. In results, three different heights are used for both structures of a unit cell by an increment of a 100ºC, respectively. The multiple dispersion diagrams show in the results chapter that how heights are so affecting the propagation of electromagnetic waves. In our case, the dimensions of a unit cell are so small because of a high frequency; that's why the change of height is not so significant with an increment of temperature. The height and the temperature are directly proportional to each other; thus, if the height is substantial, the change in height will be more significant by applying the temperature. Nevertheless, the target of a thesis has been done by observing the tunability effect of a tunable metasurface at 70 GHz by changing the heights of a dielectric in the simulator. Thus, in the coming times, these temperature-based tunable metasurfaces can be used at the millimeter-wave frequency band.

Chapter 6
Future Aspects

This thesis is based on the simulations; thus, the first thing could be the implementation of tunable metasurfaces for the observation of millimeter waves structures. As we know, the future belongs to the high data rate transmissions typically in multi gigabits; that's why we have to think of a cheaper and less lossy system to introduce for the upcoming time. To deploy the mmWave, many types of research and works are under experimentation; on account of this, the tunable metasurfaces are also under consideration and demonstration. Because they are capable of regulating electromagnetic waves in desirable directions according to the needs and requirements, here, this thesis has observed the tunability feature of metasurface on multi gigahertz to obtain the response and propagation of waves in different directions using metasurfaces. The physical design can be the part of the near future to observe tunable metasurfaces on 70 or 130 GHz frequency. Many advantages of metasurfaces put them in a unique category to utilize in the near future of wireless technology such as, less bulky, low cost, easy to design, and physical implementation is more straightforward than 3-Dimensional metamaterials. Secondly, to enhance the coverage in 5G technology, metasurfaces can be implemented on the walls of the building to guarantee the full range in the basements and car parking area.

The sixth-generation 6G technology would be the revolution in the wireless communication system because of the Internet of Everything (IoE). That means almost all devices, industries, institutions, transportation, shipping through water, every single thing will be connected to the internet. In the last, here, reconfigurable metasurfaces can be an essential part of the system. Because to govern the electromagnetic waves and make them efficient in transferring the data in real-time could be the challenge. For this reason, the tunable metasurfaces are proficient in shaping the propagation of EM waves in a customizable way. The idea of a smart radio environment is proposed by many researchers, which will be one of the essential parts of upcoming 6G wireless technology. The intelligent radio environment can be defined as the transmission of electromagnetic waves or signals without generating new ones to recycle the existing one whenever the network needs. To follow this idea, tunable metasurfaces are the most prominent alternative to control, absorb, and regulate the EM waves in the necessary directions whenever the system needs. As a consequence of this, the metasurfaces are flexible, controllable, and provide the services that will be part of the future wireless environment.

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