DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

RADIO WAVE PROPAGATION STUDIES THROUGH MODERN WINDOWS

Author	Faisal Rehman
Supervisor	Adj.Prof. Erkki Salonen
Second Examiner	Dr. Markus Berg
(Technical Advisor	Veikko Hovinen)

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ABSTRACT

It is a growing trend in the modern housing construction especially in northern parts of Europe and America to use modern windows with selective glasses in order to achieve the adequate thermal isolation. The idea is to conserve the energy and discourage the excess use of it following the guidelines of European commission, which aims to achieve zero energy buildings by 2020. Even though the use of such windows do address the energy issue at hand, but on the other hand they cause problems to the radio wave propagation through these windows. The reason for this is the use of metallic coating made of titanium oxide or silver oxide in general on these windows because of their good properties to provide thermal isolation, but are susceptible to deterioration of radio wave propagation through them.

Various solutions to this problem have been addressed in this thesis along with their tradeoffs. The previous and current research being carried out to address this issue also have been discussed thoroughly including the research that worked as the motivation to pursue this issue. Amongst others, one solution is the use of passive repeater to achieve the power gain which have been focused on. A prototype repeater antenna developed earlier at CWC and tested through measurements addresses the problem considerably well. Measurements were taken at EMC chamber, University of Oulu, within the frequency range of 700 MHz to 10 GHz, and the results have been compared and analyzed in this thesis. According to our findings, the repeater antenna under the test has shown promising results. In the future work, the proposed repeater can be tested in real life scenarios and its performance can be analyzed within the real life environmental constraints.

Key words: Selective glasses, Passive repeater, Modern windows, Modern buildings, Outdoor-to-indoor propagation.

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FOREWORD

This thesis work has been carried out as a partial requirement for the completion of the degree towards the Master's Degree Programme in Wireless Communication Engineering, at the Center for wireless Communication (CWC), University of Oulu, Finland.

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I dedicate this thesis to my parents for their support and unconditional love.

"In so far as a scientific statement speaks about reality, it must be falsifiable: and in so far as it is not falsifiable, it does not speak about reality."

— *Karl R. Popper, The Logic of Scientific Discovery*

Oulu, August 15, 2017

Faisal Rehman

LIST OF ABBREVIATIONS AND SYMBOLS

Ag	Silver
CST	Computer Simulations Technologies
dB	Decibel
EMC	Electromagnetic Compatibility
EM	Electromagnetic
FBW	Functional bandwidth
FNBW	First null beam width
GSM	Global System for Mobile Communications
HSPA	High-Speed Packet Access
HPBW	Half power beam width
IF	Intermediate frequency
LTE-A	Long Term Evolution-Advanced
LHCP	Left hand circularly polarized
LOS	Line of sight
PIM	Passive intermodulation
RX	Receiver
RF	Radio frequency
RHCP	Right hand circularly polarized
SiO_2	Silicon oxide
SWR	Standing wave ratio
S-parameters	Scattering parameters
S-matrixes	Scattering matrixes
TX	Transmitter
TiO_2	Titanium oxide
UMTS	Universal Mobile Telecommunications System
VSWR	Voltage standing wave ratio
VNA	Vector network analyzer

A_e	Effective aperture
$\boldsymbol{B}$	Magnetic Flux density
B	Bandwidth in Hertz
D	Directivity
$\boldsymbol{D}$	Electric flux density
$\boldsymbol{E}$	Electric field
$\lvert E_X \rvert$	Magnitude of the X component
$\lvert E_Y \rvert$	Magnitude of the Y component
G	Gain
G_t	Gain of the transmitter
G_r	Gain of the receiver
$\boldsymbol{H}$	Magnetic field

k	Boltzmann's constant
P_r	Received power
P_t	Transmit power
R	Resistance in Ohms
r	Distance from the transmitter
$S(t, \tau)$	S-parameter in delay domain
$S(t, f)$	S-parameter in frequency domain
T	Temperature in Kelvin
Γ	Reflection Coefficient
Z_{IN}	Input impedance
Z_0	Characteristic impedance
η_{tot}	Total Efficiency
η_r	Radiation Efficiency
ε	Permittivity
μ	Permeability

1. INTRODUCTION

With the innovation of modern housing construction development towards the energy efficient windows and walls to provide adequate heating within the houses, especially at places which are susceptible to cold winter, the wireless signal propagation through these walls and windows proves to be a pressing problem. Since the construction industry and the cellular industry are separate entities with no direct collaboration with each other so far, it is all the more important to study and find solution to the serious attenuation of the radio signals due to walls and windows in the modern housing structures. The issue needs to be studied exhaustively and the solutions need to be incorporated both from the construction and wireless engineering point of view, and the attention towards that have recently been shifted. The research work on the issue is being carried out in many research faculties, especially in Finland, where the use of energy efficient windows is increasing with the passage of time because of the advantages they provide in terms of heating and overall energy reduction. So, it is about time to also address the radio wave deterioration through such windows. This thesis addresses one solution to the problem which is based on the use of passive repeater antenna as means of addressing the signal propagation issue through selective windows used widely in the modern housing construction to achieve thermal isolation.

1.1. Problem identification & problem extent

The trend of using energy efficient windows and walls structures is global in nature since the problem presented above also affects the places where the isolation is needed for providing the adequate cooling within the houses. However, it is a vital issue in the northern countries, due to the extreme winter these places are susceptible to. The issue particularly affect the northern parts of Europe and America. In order to reduce the overall energy consumption, the European commission aims to achieve zero energy buildings by 2020 [1]. In general, the reduction in energy consumption in houses is applicable to even those places where the extreme winter or summer is not a problem. And to achieve that, the construction companies are bringing some changes in their approach. The modern houses construction uses metal in order to achieve the thermal isolation due to its good properties of achieving thermal isolation. Even though the use of metal is also common in the modern walls structures, and that also affects the signal propagation through them, however, in this thesis the focus is on the issue of selective windows and radio wave propagation problem through them is addressed, and one solution of using passive repeater is proposed. It is also important to notice that the heat losses in case of windows are more than walls, and the use of metal in order to tackle those heat losses is more frequent in the windows. So, it is important to address the radio wave propagation problem in windows caused by the use of metal coatings.

Modern windows use thin metal oxide coating, made of titanium oxide, silver oxide in particular, along with other metals in general. The metal coating on the modern windows help achieve the good thermal isolation, but the effect of these coatings is very strong in impeding the radio wave propagation through them. The signal propagation is also affected on the frequencies the mobile operators operate at, so it is an important aspect to find solutions for. One solution to the problem is the use of passive repeater antenna which we used in our measurements and the results of which are presented and discussed in this thesis. Passive repeater, in simple words, helps increase the gain by passively reflecting or deflecting the radio signal. In our measurements with the proposed passive antenna, we covered the range of frequencies from 700 MHz to 10 GHz in order to understand the effect of selective windows on radio wave propagation, and the improvement our proposed passive antenna brings against them. The details of the measurements and the relative gain achieved are presented and discussed ahead in the relevant sections. Even though our measurements were carried out in EMC chamber using the highly directive antennas, but still the improvement in the gain is evident even if we take the constraints of real life signal reception, such as coming from various angles and based on multipath reflections, into account. However, it could be a further step in this study to carry out the real life experiments with this passive antenna to get more realistic figures of the improvement.

1.2. Related work and literature review

The important factor in the construction of selective windows is the U-value, which is basically the ability of the window and its coating to be able to provide adequate thermal isolation. This is the determining factor in selective windows construction, at least in the Northern Europe [2]. As mentioned before, the kind of coating used in the selective windows is thin metal coating made of tin oxide or silver oxide in general. This metal coating affects the radio wave propagation as reported in [3]. The same study carries out the detailed analysis of the attenuation in the old houses and the modern houses, and finds that there is considerable increase in the attenuation due to the modern construction trends in Finland. The said study was carried out in real life scenarios dealing with the signal propagation from various mobile operators active in Finland. So, it presents quite realistic picture of the radio wave attenuation in modern housing. The study also carries out the individual construction materials effects on the radio wave propagation, and reports that the four layered windows are vulnerable to 20 dB and 35 dB attenuation around 900 MHz and 2100 MHz, respectively. Authors of [4] also confirm that the heat energy double glazing in windows impede the radio wave propagation. Moreover, the use of aluminum frames and four layered windows in order to achieve the strict thermal isolation adds onto the radio wave deterioration through the windows, as aluminum strongly affects the radio wave propagation. For this reason, in our measurements, we used the Aluminum frame for an outside window to see its effect on the radio wave propagation. The problem is also crucial due to the limitations of the operators to deploy the denser networks, its counterproductive nature indoors, and because of likely increase in the data services of UMTS and LTE-A in the future. Keeping this in mind, we carried out our measurements against wide range of frequencies. However, the small cells (micro) or indoor (pico, femto) approach is helpful to achieve more network capacity indoors [5].

Even though the dedicated indoor solutions address the problem to certain extent, but it is not available to the common subscribers because of the financial costs and additional equipment that comes along with it. And even if it does solve the problem for limited number of commercial users, it solves for one particular operator. There have also been efforts to improve the signal coverage in a passive way; that is, using frequency selective surfaces to improve the radio wave propagation which are mentioned further in this chapter. Other methods of improving the signal reception could be the use of RF holes, and using sort of a passive repeater setting with cabling.

The further related work and the work that made us experiment passive repeater option to improve the radio wave propagation through selective windows is as follows; Authors of [6] explore the possibility of using passive repeater for indoor signal improvement by using passive repeaters starting from the underground spaces and later experimented in the office buildings where the signal coverage was non-existent. The paper concludes that the use of passive repeaters in the underground spaces to enhance the signal could be a promising solution commercially. The experiments were focused on 900 MHz frequency. This showed the promising possibility of using the passive repeater for indoor signal improvement through selective windows. Authors in [7] experimented within the pico cell settings using the passive repeater for mobile signal improvement in energy efficient buildings with the outer directional antenna and inner omnidirectional antenna connected with the cable. Authors in [8] reported the difference between the attenuation in the older buildings and modern energy efficient buildings in terms of frequency dependence and material effects within 800 MHz to 18 GHz, and concluded that attenuation in the modern energy efficient buildings is 20-25 dB more than the older buildings. Authors in [9] propose the use of frequency selective windows as the solution of the problem. Authors in [10] again confirm the fact that propagation through the transparent conductors used in the modern housing has negative effect on the radio signal propagation. Authors in [11] and [12], again, propose the use of frequency selective surfaces to solve the radio wave propagation through selective windows. Authors in [13] after acknowledging the issues of RF signal propagation within energy efficient houses, propose a wireless sensor network to assist in the characterization of radio propagation within buildings. Authors in [14] tested the frequency selective surfaces at GSM 900 and UMTS/HSPA 2100 in real life scenarios for the use in the future energy efficient buildings, and concluded that the proposed surfaces showed the improvement of 8-13 dB for GSM, and 2-5 dB for UMTS/HSPA 2100 MHz. Authors in [15] investigate the passive intermodulation from different operators for network planning inside the energy efficient building, and point out that not only the loose cables and connector give rise to the passive intermodulation (PIM), but also the antenna environment within the building plays a significant role in multi-operators indoor distributed antenna systems, and conclude that careful consideration should be given to indoor network planning keeping PIM in consideration. Author in [16] carried out the experiments in the energy efficient building to get the experimental picture of how much signal deterioration takes place because of the materials used for energy consumption in the modern buildings. They came to the conclusion that not only the hindrance is because of the energy efficient glass, but interference is also generated by energy efficient lighting inside the building. Author also notices that the impact of the inner attenuation might not be that much on higher frequencies such as the ones mobile operators and public safety services operate on, but it still has impact nonetheless.

Authors of [17] propose photonic band gap structures composed of SiO_2/TiO_2 with Ag system and experimentally demonstrate that such type of material for the energy efficient windows has the potential ability to control the propagation of electromagnetic waves along with also improving the advantages of energy efficient buildings. Author in [18] conducted experiments on the window panes in order to see the impact of RF signal degradation, and came to the conclusion that various window panes and their corresponding coating is crucial factor in terms of how much attenuation the radio signal goes through. The range of attenuation on various window panes ranged from approximately 10 dB to 30 dB over the 1-18 GHz compared to the

0 dB for traditional clear glass. The author also concludes that modern low-emission window structures attenuate the signal from 15 dB-45 dB over the same frequency range. Authors of [19] tried to see the impact of double gazing on energy efficient windows, and after carrying out experiments within frequency range of 8-12.5 GHz, came to the conclusion that heat energy efficient double glazing attenuates the signal at least 20 dB more than standard double glazing in windows.

2. ANTENNA FUNDAMENTALS AND ELECTROMAGNETIC WAVE PROPAGATION

2.1. Antenna fundamentals

Antennas are the vital and integral part of wireless communications that work as transmitter and receiver of wireless signals. The size, shape, and dimensions of the antennas can vary depending on the desired applications, type of signal, and distance wireless signal is intended to be carried to. In other words, antenna is a device that converts electromagnetic waves into electrical signals within its particular structure made of conductors, or opposite of that, depending upon whether it is being used as transmitter or receiver [20]. In addition to being used as transmitter and receiver, antennas also enhance and direct the radiation energy in desired directions, and limit it in unwanted directions. So, it also works as a directional device along with being a radiating device. It is for the same reason it can have many molds e.g. conducting wire antenna, aperture antenna, patch antenna, array antenna, reflector antenna, lens antenna and others [21].

Some of the fundamental parameters of antennas include radiation pattern, radiation intensity, directivity, gain, polarization, efficiency, reciprocity, bandwidth, effective aperture, and beam width [21].

2.1.1. Radiation pattern

Antenna's radiation pattern, also known as antenna pattern, is basically a geographical representation of the radiation properties of the antenna in terms of the function of the directional coordinates. In most cases, the radiation pattern is determined in the far field region. Radiation properties include power flux density, radiation intensity, directivity, field strength, phase or polarization.

For an antenna, field pattern in linear scale represents a plot of the magnitude of the electric or magnetic field as a function of the angular space. Power pattern, on the other hand, in linear scale, represents a plot of the square of the magnitude of the electric or magnetic field as a function of the angular space. Power pattern, in dB, represents the magnitude of the electric and magnetic field, as a function of the angular space. [21]

2.1.2. Directivity, Gain, and Efficiency

Directivity of an antenna is the measure of how directional antenna's radiation pattern is. An isotropic antenna that radiates equally in all directions has zero directionality, so the directivity of such an antenna would be one or 0 dB [22].

Antenna gain describes how much power is being transmitted in the direction of the peak radiation in reference to the isotropic source. Antenna gain is important since it takes into account the actual losses of the antenna. [22]

The relation between directivity and gain of an antenna is given by;

$$G = \eta_{tot} D \tag{2.1}$$

Where η_{tot} is the total efficiency and D is the directivity of the antenna.

The efficiency of an antenna is the ratio of power delivered to the antenna relative to the power radiated from the antenna. A high efficiency antenna has most of the power present at the antenna's input whereas the low efficiency antenna has most of the power absorbed as losses within the antenna, or reflected away due to impedance mismatch. Efficiency of the antenna is same whether it is being used for transmission or reception [22]. The antenna efficiency or the radiation efficiency can be described by the following expression.

$$\eta_r = \frac{P_{radiated}}{P_{input}} \tag{2.2}$$

Where $P_{radiated}$ is the power radiated by the antenna, and P_{input} is the input power to the antenna.

2.1.3. Beam width

Beam width is basically an aperture angle from where most of the power is radiated. The two main aspects of beam width include Half power beam width (HPBW) and First null beam width (FNBW).

Half power beam width is the angle from the peak of the main beam, in which the radiation pattern decreases by half in magnitude, or by -3dB in power, compared to the peak of the main beam.

First Null beam width is the angular space between the first nulls of the radiation pattern which are adjacent to the main lobe towards either side of it. [23]

2.1.4. Reciprocity

Reciprocity of the antenna means that the transmitting and receiving antennas have the same properties, meaning that we do not have distinct radiation pattern for the each mode, that is, for receiving and transmitting mode. So, the principle of reciprocity states that the radiation pattern of the antenna in the transmitting mode is same as its radiation pattern in receiving mode [22].

2.1.5. Effective aperture

Effective aperture measures the received power of the antenna, and is also known as effective area. Effective aperture parameter describes how much power is received by the receiving antenna from the plane wave travelling towards the direction of its maximum radiation. So, it describes the amount of power captured from the received wave and fed to the receiving antenna.

Effective aperture in terms of the gain of the antenna is given by;

$$A_e = \lambda^2/4\pi * G \tag{2.3}$$

2.1.6. Bandwidth

Bandwidth of any particular antenna is the range of frequencies on which the antenna can operate on. There are variety of antennas having different bandwidths: some having wide bandwidths, while others have narrow bandwidths. Bandwidth is important parameter of the antenna and helps to decide an appropriate antenna for the desired application.

Bandwidth is usually described in terms of the functional bandwidth (FBW) which is the ratio of frequency range difference divided by the center frequency [22].

2.2. ELECTROMAGNETIC WAVE PROPAGATION

Understanding electromagnetic wave propagation is crucial to understand the wireless signal propagation through any medium. It is important to understand the wave behavior in any particular environment for the design and operational purposes.

Maxwell formulated the electromagnetic wave equations in 1865, which led to ground breaking advancements in wireless communications. It can be said that Maxwell's equations are backbone of understanding and planning the electromagnetic wave propagation for any communication model.

The electromagnetic waves equations related to antennas are formulated in the vector form along with the spherical coordinates. They are represented in vector form because of being able to conveniently represent the antenna polarization. Spherical coordinates such as θ and Φ are used in equations in order to cover the movement of antenna in three dimensions. The fundamental electromagnetic equations along with continuity equation are written below:

$$\nabla\times\mathbf{E}=-\partial\mathbf{B}/\partial t \tag{2.4}$$

$$\nabla\times\mathbf{H}=\mathbf{J}+\partial\mathbf{D}/\partial t \tag{2.5}$$

$$\nabla\cdot\mathbf{D}=\rho \tag{2.6}$$

$$\nabla\cdot\mathbf{B}=0 \tag{2.7}$$

$$\nabla\cdot\mathbf{J}=-\partial/\partial t\ \rho \tag{2.8}$$

The above four equations are Maxwell's equation while the last equation is the continuity equation. The above equations along with the continuity equation are very useful, particularly in time varying field problems. [26].

In the above equations, as hinted before: electric field ***E*** and magnetic field ***H*** are vector entities in time and space within a medium, where electric field is generated by time varying magnetic field and magnetic field is generated by time varying electric field [25]. In the above equations ***D*** is the electric flux density, and ***B*** is the magnetic flux density. Equation (2.4) represents the Faraday's law, equation (2.5) represents Ampere's law, equation (2.6) represents the Gauss's law, equation (2.7) represents the Continuity of magnetic flux, and equation (2.8) represents Continuity law.

In a free space environment, the relationship between field strengths and flux densities is given by:

$$\mathbf{D} = \varepsilon\mathbf{E} \tag{2.9}$$

$$\mathbf{B} = \mu\mathbf{H} \tag{2.10}$$

Where ε is the permittivity of the free space and μ is the permeability of the free space [27]. The propagation of electromagnetic waves depend on the medium, for example, media can be free space, lossless dielectrics, lossy dielectrics, and good conductors [28].
Electromagnetic wave carries both electric and magnetic components, and through a vacuum its speed is equivalent to speed of light, that is, $3*10^8$ m/s. They generally require no medium to propagate; however, if the wave is propagating through any medium other than vacuum then its speed is less than speed of light. When electromagnetic waves travel through a medium the wave energy is absorbed and reemitted when the waves hit the atoms of the material they are passing through. Due to this absorption of the wave energy by the atoms of the material, the vibration is induced in the atoms, which in turn give rise to new electromagnetic wave that has the same frequency as the incident wave had. Because of this absorption and reemission of the electromagnetic waves while travelling through any medium other than the vacuum: the collective speed of electromagnetic waves is consequently less than the speed of light. Also, the wave propagation through any medium depends upon the density of the material, and the eventual delay will be dependent on that.

In space, the energy transported by the electromagnetic waves can be understood by the following equation.

$$S = EB/(\mu) = E^2/(\mu c) \tag{2.11}$$

S is the energy flux; μ is the permeability of the free space. E^2 represents the square of the amplitude, to which energy transported by electromagnetic waves is proportional to, as shown in the above equation [29].

The Friis equation is very useful to understand the behavior of electromagnetic waves moving through the free space. The received power decrease by the factor of $1/r^2$, meaning that the waves lose their power inversely proportional to the square of the distance they cover while being propagated. However, this factor doesn't take into account the environmental impeding factors into account. The following expression represents the Friis equation.

$$P_r = P_t\, G_t\, G_r\, (\lambda/4\pi r)^2 \tag{2.12}$$

In the above equation P_r is the received power, P_t is the transmit power, G_t is the gain of the transmitter, G_r is the receiver gain, and r is the distance from the transmitter.

Practically, the electromagnetic waves are affected by variety of obstacles on their way, and go through the phenomena of reflection, diffraction, and refraction. For example, for a GSM communication, the travelling radio waves will get diffracted and reflected by the tall buildings and other obstacles, say in an urban environment, along with various materials with varying densities on their way towards the receiver. The diffraction and reemission of the electromagnetic waves, as mentioned before, depends on the properties of that particular material they'd come across, which can be understood by the permittivity and permeability of those materials. The efficient channel modelling and network planning requires thorough study of the radio channel environment the waves are going to propagate through, and the kinds of attenuation and losses they are likely to face. Such planning also takes into account the particular wavelength of the waves, because attenuation of the electromagnetic waves is dependent upon the frequency of the waves [37].

Hence, the electromagnetic wave propagation depends on the frequency of the waves and the kind of medium they are travelling through along with kinds of obstacles they are likely to encounter. The frequency range that we conducted our experiments in belongs to the microwave frequency range, that is, 300 MHz to 30 GHz. In our measurements, as stated above, we focused primarily at the frequency range of 700 MHz to 10 GHz. Microwave frequencies are suitable for the broadcasting compared to the lower frequencies, and can move through buildings walls efficiently: especially in the lower end of the microwave frequency band. They travel mostly in the line of sight (LOS), and the interference from the ground is not as much as it is in the lower frequencies range, even though it still depends on the surfaces the waves are reflecting from [27].

2.3. Polarization

Polarization, in simple words, can be understood as the polarization induced by the antenna in the radiated electromagnetic wave in any particular direction. In general, the polarization is usually produced in the direction of the maximum gain. The antenna produces polarization in any particular direction from the center of the antenna, so the resulting polarization pattern would vary depending on the part of antenna which radiated it. The polarization of the electromagnetic wave can also be understood by the change in particular direction and magnitude of the generated wave by the radiated antenna. Polarization can be associated with both transmission and reception of the antenna. In terms of the reception, the polarization can be defined as any particular polarization of incident wave from any particular direction which induces maximum power at the terminals of receiving antenna [21].

It is convenient to understand the polarization in terms of electric field vector, since the polarization of the waves is in the direction of electric field [30]. The position of the electric field vector in terms of the direction of propagation defines the polarization of the waves [25]. The polarized waves are knows as plane waves since their electric and magnetic fields lie in a plane [26].

In terms of the antenna, the polarization can be described as the radiated plane wave by the antenna having particular radiation pattern at any given point in the far field. The polarization of antenna is usually depicted in the far field. The polarization pattern of the antenna can be described by spherical coordinates describing the radiation pattern produced by the antenna at any given point. Polarization in the regard, can be described by either cross polarization, or co-polarization. The co-polarization in terms of the reception, means that receiving antenna has the same polarization as the incident wave, whereas the cross polarization is the polarization that is perpendicular to any particular polarization. According to reciprocity principle of antennas, the transmitting

and receiving antenna both should have the same polarization in order to be able to get the full reception. The cross polarization describes the state where the polarization is perpendicular to the required polarization for reception, hence the cross polarization causes loss of power [21].
Below is the description of various kinds of polarizations of electromagnetic waves.

2.3.1. Linear polarization

A plane wave is said to be linearly polarized if the electric field vector being the function of time is always along the direction of the line. It also could be magnetic field that is along the same line at every time varying instant, since the electromagnetic wave is comprised of both electric and magnetic components.

The linear polarization can take place if the electric or magnetic field vector has either one component, or two linear components that are perpendicular to each other, and are in time-phase or 180 degree out of phase. In linear polarization, the electric or magnetic field vector moves back and forth along the line.
The following equation represents the time-phase difference requirement for the two components to be linearly polarized [21].

$$\Delta = \Phi y - \Phi x = n\pi, \text{ where } n = 0, 1, 2, 3 \ldots \qquad (2.13)$$

The linear polarization can be further characterized as the horizontal polarization and the vertical polarization. In horizontal polarization, the electric field vector is horizontal to the ground, that is, parallel to the earth. So, in order to produce horizontal polarization, the antenna should be horizontal with respect to the earth. The oscillation of horizontally polarized waves is left to right parallel to the earth, and is mostly used for short distance communication.

Similarly, for a wave to be vertically polarized, the electric field vector needs to be vertical to the ground, that is, perpendicular to the earth. In order to generate the vertical polarization, the antenna should be perpendicular to the earth. The oscillation of vertically polarized signals is top to bottom, and is mostly used for long distance communication because it carries the advantage of minimum attenuation. Moreover, the vertically polarized antenna can propagate signals in all directions, so it offers many advantages over horizontally polarized signals. As stated before, both transmitting and receiving antennas need to have same polarization to receive the transmitted signal, hence horizontally polarized signal cannot be received by vertically polarized receiver antenna.

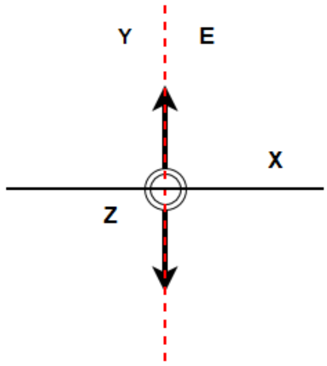


Figure 1: Linear polarization

2.3.2. Circular polarization

A plane wave is said to be circularly polarized when the electric field vector being the function of time draws the figure of a circular path. The linear and circular polarization both are cases of elliptical polarization where, in case of linear polarization, the ellipse drawn by electric field vector becomes a straight line as a function of time, where as in case of circular polarization, the ellipse drawn by the electric field becomes a circle as a function of time.

For the wave to be circularly polarized the electric field vector must have two perpendicular linear components, having the same magnitude, and time phase difference of 90 degrees [21]. The circularly polarization can be further classified as right hand circularly polarized (RHCP), and left hand circularly polarized (LHCP). In case of RHCP, the electric field vector rotates clockwise in reference to the direction of the propagation. While in case of LHCP, the electric field vector moves counter clockwise in reference to the direction of propagation. [25]. In case of circular polarization, the length of the electric field vector remains the same, but it follows a circular path. For circular polarization;

$$| E_X | = |E_Y| \tag{2.14}$$

$$\Delta\emptyset = \emptyset_y - \emptyset_x = +\left(\frac{1}{2} + 2n\right)\pi, n = 0,1,2, \ldots \text{ for Clockwise} \tag{2.15}$$

and

$$\Delta\emptyset = \emptyset_y - \emptyset_x = -\left(\frac{1}{2} + 2n\right)\pi, n = 0,1,2, \ldots \text{ for Counter Clockwise} \tag{2.16}$$

In the above equations $| E_X |$ represents the magnitude of x component, and $|E_Y|$ represents the magnitude of y component. As stated above in circular polarization, the magnitudes of the both components are same, and the time phase difference is 90 degrees.

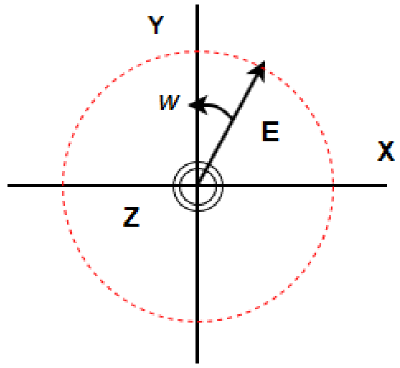


Figure 2: Circular polarization

2.3.3. Elliptical polarization

As mentioned above: A plane wave is said to be elliptically polarized, when the electric field vector being a function of time draws a figure of an ellipse. Linear and circular polarization both are special cases of elliptical polarization. However, the elliptical polarization differs from the circular polarization in a way that, the two perpendicular linear components can have different magnitude or the same magnitude, whereas in case of circular polarization, both need to have the same magnitude. In case, if both linearly polarized components do not have the same magnitude then the time-phase between those components must not be 0 degrees or 180 degrees, because then it would be linear polarization. Similarly, in context to circular polarization, both linearly polarized components must not have phase difference of 90 degrees as this will make it the circularly polarized. Hence for a wave to be elliptically polarized, it should not be linearly or circularly polarized. Elliptical polarization can also be characterized as left hand elliptical polarization, and Right hand elliptical polarization [21]. For Elliptical polarization;

$$| E_X | \neq | E_Y | \quad (2.17)$$

$$\Delta\emptyset = \emptyset_y - \emptyset_x = +(\frac{1}{2} + 2n)\pi, n = 0,1,2, \ldots \text{ for Clockwise} \quad (2.18)$$

$$\Delta\emptyset = \emptyset_y - \emptyset_x = -(\frac{1}{2} + 2n)\pi, n = 0,1,2, \ldots \text{ for Counter Clockwise} \quad (2.19)$$

In the above equations $| E_X |$ represents the magnitude of x component, and $|E_Y|$ represents the magnitude of y component. As hinted above, in elliptical polarization, either the magnitudes of the both components are not same, and the time phase difference is 90 degrees, or irrespective of magnitudes, the time phase difference between both components is not equivalent to the multiples of 90 degrees.

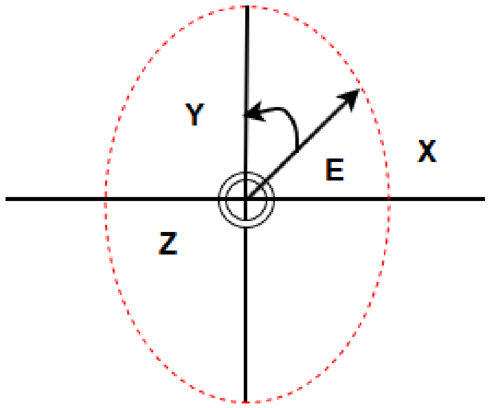


Figure 3: Elliptical polarization

3. RADIO WAVE MEASUREMENTS

The design of the any communication model requires the understanding of the radio channel the signals are going to propagate through, along with the frequency and type of the propagated signals, and the desired operation they are intended to carry out. Radio signal can suffer multiple kinds of losses and attenuation on its way to the receiver, especially when it is being propagated in the free space. Not only does the radio signal suffers loss of power inversely proportional to the distance it travels, it also gets affected by the mechanisms of diffraction from the edges of the surrounding objects and surfaces, reflections from the buildings and other objects, and refraction through various interfaces.

We conducted our measurements up to 10 GHz (from 700 MHz to 10 GHz), because not only microwave frequencies are being focused and researched on for indoor communications, but also the growing trend in research community is to move towards the millimeter waves communication in the future. In the next phase of the project and in the future, the experiments can be conducted beyond 10 GHz frequency range with the proposed passive repeater to know about its effect on those frequencies.

In order to test a measurement system, measurement equipment should be capable of accurately measuring the system output against standard parameters. It should be able to measure the input and output responses from the transmitter to the receiver, taking into account the attenuation the signal goes through while travelling through any given medium.

We used Vector network analyzer (VNA) as a measurement equipment to measure the frequency responses from our transmitter to the receiver through a modern window structure and a wall placed between them. In this chapter the introduction to the VNA along with its important parameters is presented, so that one can get the idea of its basic functions and mode of operation.

3.1. Vector Network Analyzer

VNA measures the S-parameters (Network parameters) of the active and passive devices mainly in the linear mode. It is also capable of measuring the non-linear characteristics and noise parameters. A single connection is enough for the VNA to be able to take multiple measurements. It is a device that can measure the phase and amplitude of the incident and reflected signal from the device that is under test. It is capable of storing the output circuit responses from particular input signal, taking into account the systematic errors, and other factors in order to display the results in the form of standard ratios such as S11, S12, S13, and other S-parameters. Internal function of the VNA is quite complex and performs many mathematical and digital operations in order to produce the accurate output response of devices under the test.

The calibration of the VNA helps take care of the possible negative effects VNA device itself can cause to the accuracy of output responses it stores for any particular device under test, and because of this capability of VNA, the network parameters that VNA measures are quite accurate. VNA has fully working operating system installed on it with serial ports, and displays the network parameters in a very clear way. One can store the previous responses to compare with the responses of the different scenario [31]. In the further sections, brief introduction of S-parameters, and other related aspects of the VNA are presented.

3.1.1. Scattering parameters

S-parameters or scattering parameters are the network parameters described by the scattering matrix of the network. Scattering matrix describes the effects on RF signal propagating through the various ports in a multiport Network in a matrix form. S-parameters depend on the number of ports, and describe the relation between the transmitted, reflected, and incident wave for a given system impedance and the frequency. They are normally presented as the function of the frequency. The change in the magnitude and phase of the incident wave by the network is denoted by S-parameters, which are actually in the form of complex numbers. The matrix format of the S-parameters depicts the number of rows and columns equivalent to the number of ports in the network. The S-matrixes for one, two and three port networks are written below.

$$(S_{11}) \text{ (One port)} \tag{3.1}$$

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \text{ (Two port)} \tag{3.2}$$

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \text{ (Three port)} \tag{3.3}$$

And so on….

The value of reference impedance Z_0 is important to be known for the S-parameters. The two port network with reference impedance Z_0 is shown below in the figure.

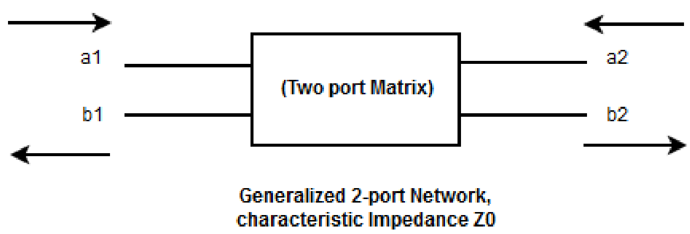


Figure 4: Generalized 2-port Network

The S-parameters of the 2 port network can be defined in the following way

$$S_{11} = b_1/a_1 \tag{3.4}$$

$$S_{12} = b_1/a_2 \tag{3.5}$$

$$S_{21} = b_2/a_1 \tag{3.6}$$

$$S_{22} = b_2/a_2 \tag{3.7}$$

The Matrix algebraic representation of two port S-parameters is;

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} * \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{3.8}$$

S-parameters magnitude formula in decibel is given by:

$$S_{ij}(dB) = 20 * \log10\,[S_{ij}(magnitude)] \tag{3.9}$$

Accordingly, following the same pattern, S-parameters can be obtained for the N-port Network. The scattering Matrix for N ports is [32]:

$$\begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \tag{3.10}$$

In our measurements, we used the four port VNA. Hence, the S-parameter matrix has the default order of 4*4 for 4 ports. However, for our measurements, we focused on three ports of the VNA, as we used one transmitting antenna, and two dual polarized receiving antennas. S-parameters of interest were those of vertically polarized waves travelling from port 1 to port 2; s21, and port 1 to port 3; s31. These transmission coefficients i.e. ratio of incident and reflection wave as defined above, in our scenario, represent the ratio between the incident signal on the selective windows and the reflected radio signal from the selective windows, placed between the transmitting antenna and the receiving antennas.

3.1.2. Time domain and frequency domain measurements

As mentioned above, VNA measures the magnitude and phase of the device or transmission line under the test in the form of S-parameters. The time domain measurements of the VNA are basically the inverse Fourier transform of the measured results. The time domain measurements basically shows the impulse or step response relative to time delay of the device under the test to get the clear representation of its characteristics. The useful time domain filter such as ‘gating’ can be applied to the measured data to limit the unwanted components of the data. This gated data in time domain is then converted to frequency domain, and S-parameters without the unwanted components can be obtained in the frequency domain. Gating will be explained in detail further.

Frequency domain, on the other hand, shows the transfer function of the measured data, that is, along the given set of frequencies, how much signal energy is being carried and propagated relative to each of them. Following equations show the relationship between time-variant impulse response function, and time-variant transfer function [33].

$$S(t, \tau) = \int_{-\infty}^{\infty} S(t, f).\, e^{j2\pi ft}\, df \qquad (3.11)$$

$$S(t, f) = \int_{-\infty}^{\infty} S(t, \tau).\, e^{j2\pi ft}\, d\tau \qquad (3.12)$$

In the above equations, *S(t, τ)* is the S-parameter in delay domain, *S (t, f)* is the S-parameter in frequency domain.

The figure below shows the time domain and frequency domain measurement results plotted in Matlab.

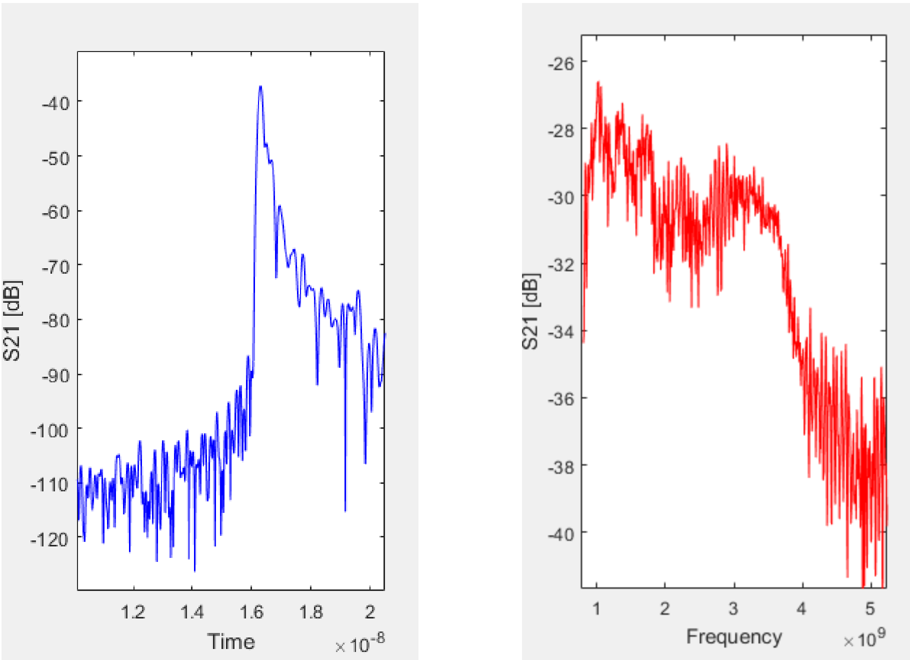


Figure 5: Time domain and frequency domain measurements

There are many advantages and disadvantages associated with each domain. In VNA, time domain analysis is a very good way of looking at reflections, diffractions and other multipath receptions a propagated signal goes through on its way to the receiver, against the function of distance and time. Whereas frequency domain shows the response of the propagated signal at various frequencies within the bandwidth being used. It shows the behavior of propagated signal against specific frequencies within the given bandwidth. However, it is not as efficient in terms of tracking the losses a signal goes through as much time domain analysis is, due to its ability to plot results as a function of propagation delay. The frequency domain signal also carries the information about the phase shift that needs to be applied to all the components of frequency domain signal in order to convert it to the original time domain signal. Hence, the frequency domain signal carries the exact mirror of the demodulation and phase shift in time domain. Both are two different ways of looking at the measurement results, each providing its own advantages and limitations. Signal can be converted from time domain to frequency domain, and vice versa without any information being lost in the process.

3.1.3. Windowing

The Fourier and inverse Fourier transform, shown in the above equations (3.11, 3.12), primarily operates on the continuous data, whereas the VNA operates on the discrete frequency data [34]. It is for that reason the transform of the original signal does not give the appropriate conversion and adds the discontinuities in the converted signal that are not present in the original signal. In order to take care of these discontinuities, windowing is applied. Window function is applied in terms of the certain given or desired interval, with having zero value outside that desired interval. In this way the window function manages to suppress the parts outside of the region of interest, and focuses on the desired interval. After the window function has been applied, it gives rise to the main lobes and many side lobes. The main lobe represent the desired interval we are focusing on, while the side lobes are those unwanted components we want to suppress. The magnitude of the side lobes are the markers of the efficiency of the windowing function; the more smaller the magnitude of the side lobes compared to the main lobe, the better efficiency the windowing function has. The magnitudes of the side lobes are also dependent upon the type of windowing being used.

3.1.4. Gating

Gating is another function that lets us focus on the region of interest. The unwanted data that is not point of interest, contains unwanted components from the environment, or the losses associated with the measuring equipment, can be filtered out by using gating. Regardless of the unwanted components, gating can be used to focus on the specific point in time of particular measured data. It is important to make this distinction that gating is only applied in the time domain, and later the gated response can be converted to the frequency domain. Again, the point of interest signal is referred to the main lobe and other components are referred to the side lobes, and the difference between the magnitudes of the side lobes and the main lobe are important for the effective gating. In a free space propagation being monitored by the VNA, the propagating signal goes through reflections, diffraction, and then we also have the LOS signals. These components are generally visible on VNA in the time domain against different delays, so in order to focus on the data we are interested in, we can isolate the desired point of interest by applying gating. The gated response of particular data in the VNA only shows that particular gated response without having any of the unwanted components. Gating can be applied with different spans in time domain. The following figure shows the gating in time domain and frequency domain.

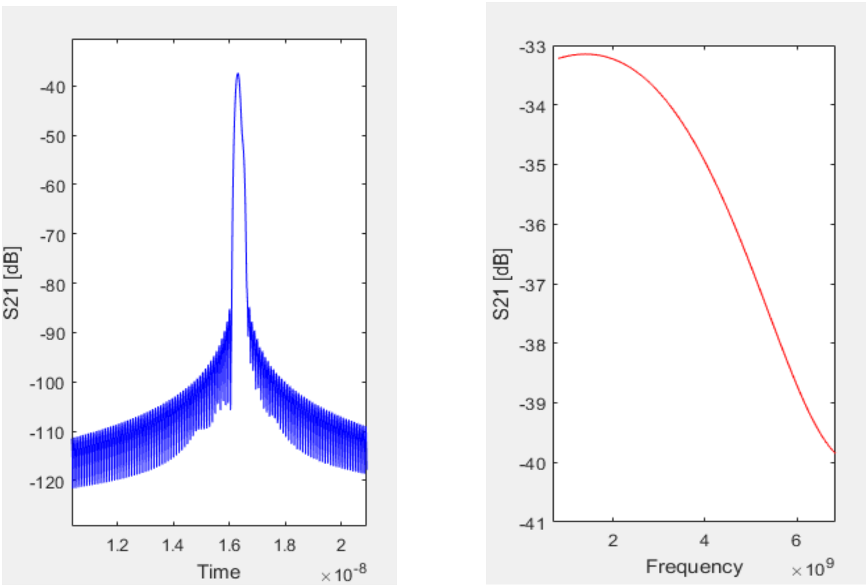


Figure 6: Gating in time domain and frequency domain

3.1.5. Measurement errors

Every kind of measurement is susceptible to errors, both from the measurement equipment used for measurement, and the environmental effects on the measurement. Due to these errors, the accuracy of the measurement results can be impaired and can lead to self-defeating outcomes. Therefore, it is important to minimize the measurement errors coming from the measurement equipment. One way to do this is to calibrate the device, in order to take care of the losses from the connectors and cables connected to the device under test. VNA has this feature of calibrating the device under the test. In order to do this, the response of the connectors and cables is compared with the ideal response of the components being used. Hence, it provides quite accurate standard in order to compensate the measurement impairments that could possibly be induced by the measuring equipment.

There are numbers of errors measurement is vulnerable to, and in order to take care of those errors, it is important to first understand how and why those errors are caused. After that, measures can be taken to minimize the effects of those errors as much as we can. There are also errors that are caused after the calibration of the device under test. For example, drift error occur after the performance of the calibrated device changes, but can be removed by re-calibrating the device. There are certain random errors that cannot be predicted such as instrument noise error, switch repeatability error, and connector repeatability error, but there are measures that can be taken to minimize their impact on the measurement accuracy. The measurement is also susceptible to systematic errors, caused by the losses due to problems with test setup and analyzer. Even though they can be removed significantly by the calibration, but still they are never completely removed because of, or depending upon the limitations of the calibration process. Systematic errors can result from the limitations of the calibration process, interconnecting cables, instrumentation, and the connector interface. The reflection measurements are susceptible to errors like directivity, source match, and frequency response reflection tracking [35].

Thermal noise within the measuring instrument is also source of losses in the measurement equipment. Resistive components are more prone to a sort of thermal noise that proves to be significant factor in the measurement equipment used for RF measurements. Thermal noise is measured in noise power or noise voltage.

The formulas for calculating thermal noise power and thermal noise voltage are given by:

$$\text{Thermal noise power} = P(dBm) = 10.\ lg\ (kTB) + 30 \tag{3.13}$$

$$\text{Thermal noise voltage} = V = \sqrt{4\ kTBR} \tag{3.14}$$

Where T is the temperature in Kelvin, B is the bandwidth in Hertz, R is the resistance in Ohm, and k is the Boltzmann's constant having a value 1.38064852(79) $\times 10^{-23}$ J/K. [36]. It is important to mention that in VNA, the bandwidth is related and limited to the receiver's IF, so this fact helps reduce the noise.

4. PROPAGATION SIMULATIONS

The selective windows model with window frames and wall was designed in the CST, and simulations were run in order to understand how the selective windows, windows frames, and wall affect the propagation of radio waves through them. Various electric field probes were set to see the effect of the radio signal after its propagation through the model. Just like actual measurement scenario, the outer window frame was of Aluminum, and the inner window frame was of wood. 1 mm and 2 mm slots were added for the Aluminum frame from all four sides, so that the waves can penetrate through it because otherwise Aluminum totally blocks the radio wave propagation. The simulations were taken with the actual window size of 120 cm height and 80 cm width, and smaller size of 60 cm height and 60 cm width to compare the results. Vertically polarized plane wave was used as the input excitation signal. The simulations were focused on in the range of 0.7 to 4 GHz. Field monitors for far field were set at 0.7, 0.9, 1.5, 1.8, and 3 GHz. For electric field, they were set at 1, 2, and 2.5 GHz. The model that was used for the simulations is shown in the figures below.

Figure 7 below shows the front view of the windows model with the wall showing wooden frame (inner window), Figure 8 shows the side view of the window model, and Figure 9 shows the back view of the windows model with Aluminum frame(outer window).

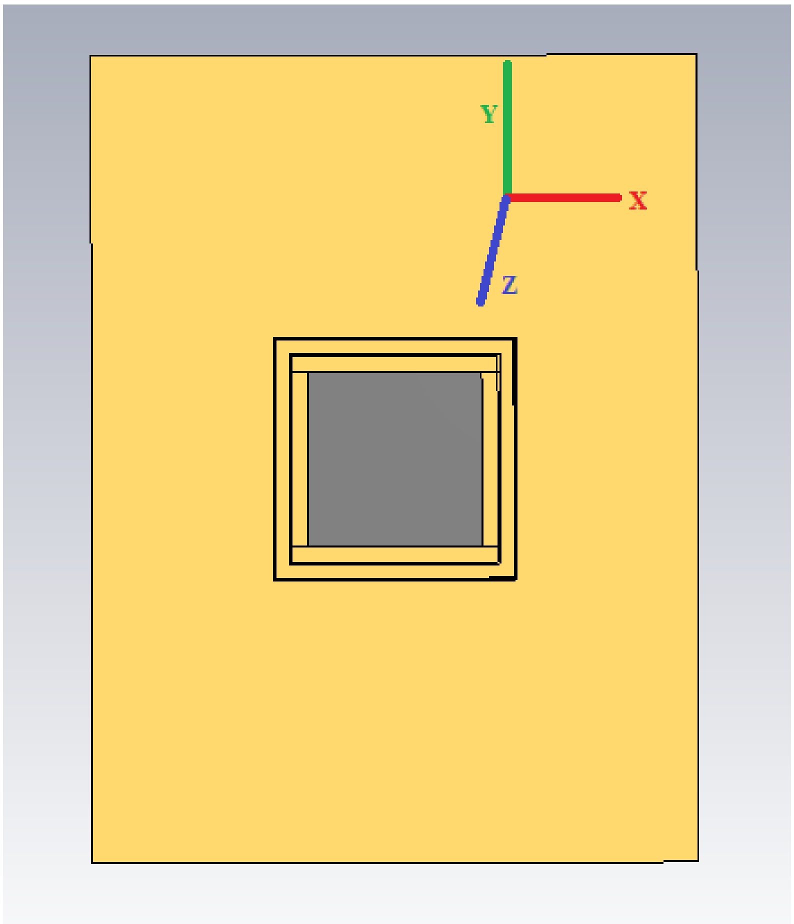


Figure 7: Front view of the windows model with the wall showing wooden frame (inner window)

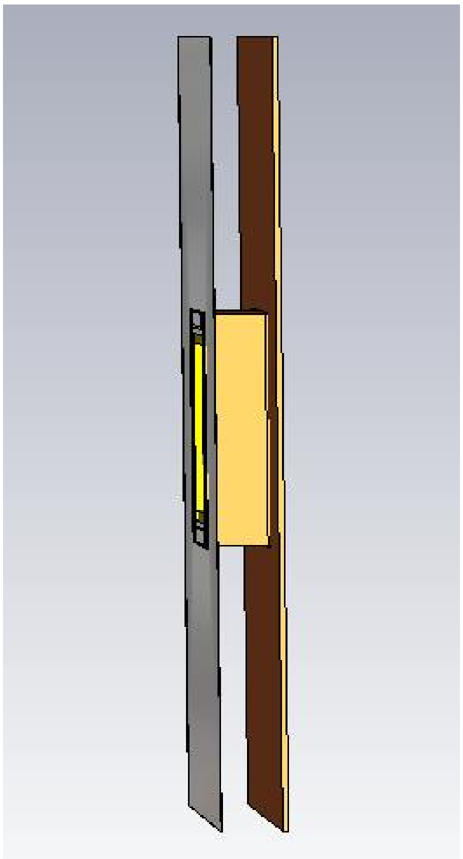


Figure 8: Side view of the windows model

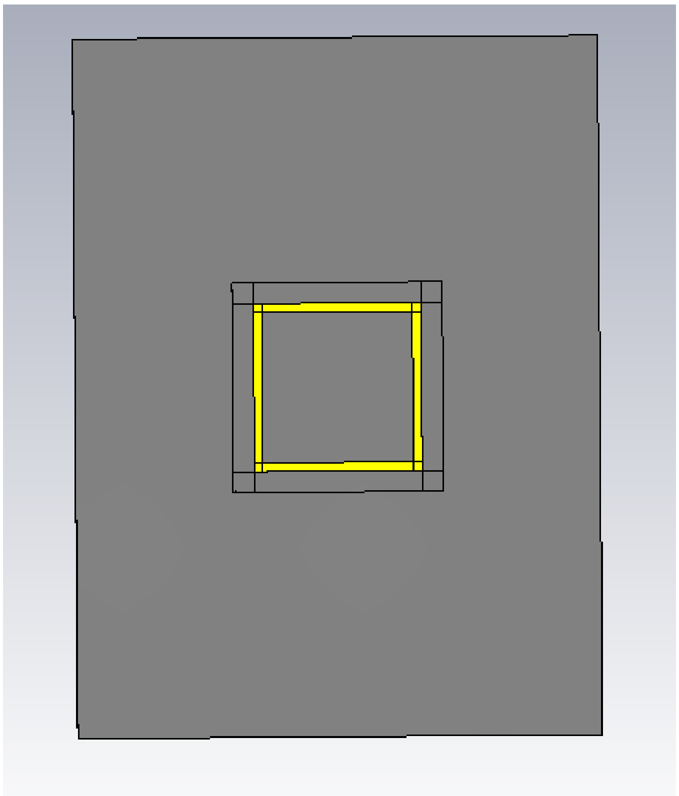


Figure 9: Back view of the windows model showing Aluminum frame (outer window)

4.1. Simulation results

4.1.1. Propagation simulations through slots of the window

The propagation simulations with the 1 mm and 2 mm slots in the outer window were run with a 60 cm*60 cm i.e. smaller window size along with the 120 cm*80 cm i.e. actual window size that we used in our measurements. Following figures show the comparison of 75 cm distance towards the inside of the windows model with 1 mm slot width for both smaller windows size and the actual windows size respectively. Figure 10 below shows the results for the smaller windows size with 1 mm slot width, and Figure 11 shows the results for the actual window size with 1 mm slot width in terms of Y-polarization.

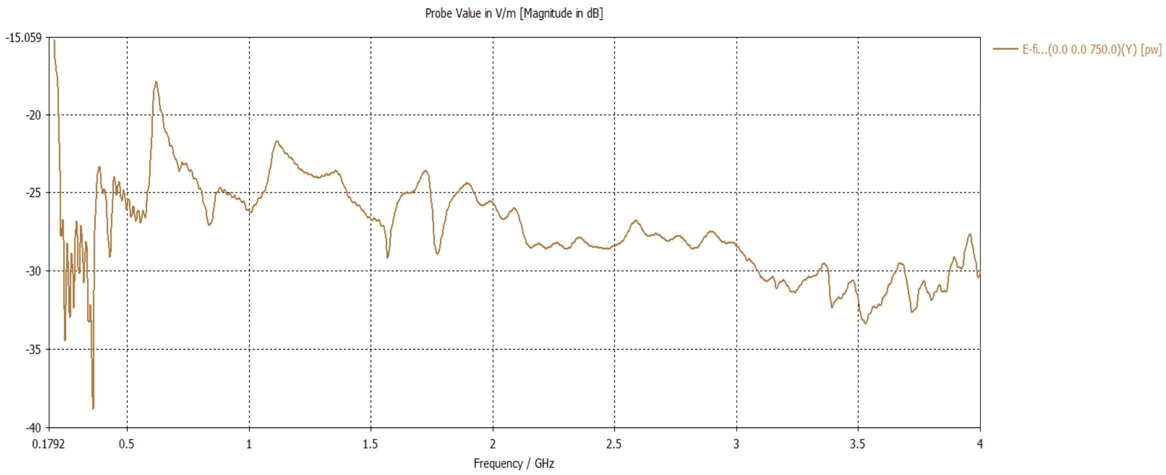


Figure 10: 75 cm distance at receiving end with Y-polarization for 60 cm*60 cm window (Smaller window) and 1 mm slot

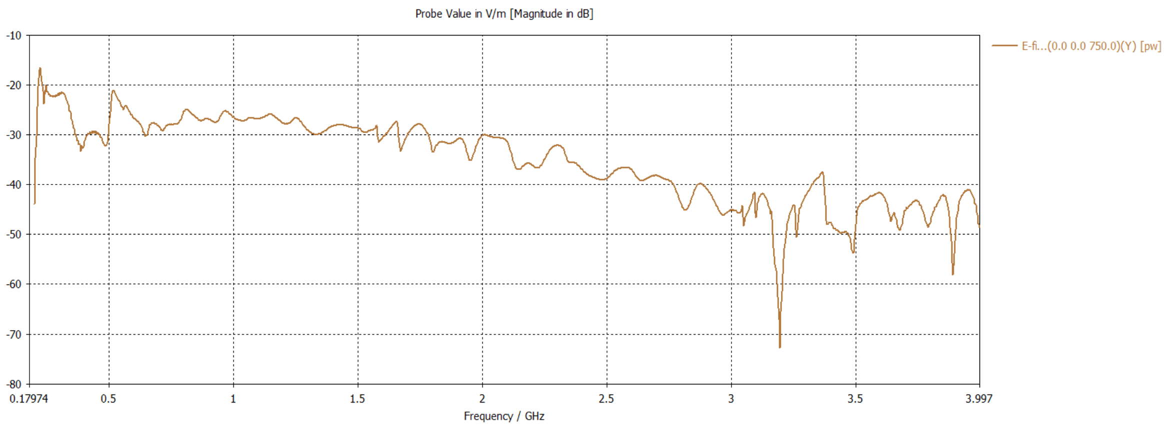


Figure 11: 75 cm distance at receiving end with Y-polarization for 120 cm*80 cm window (actual size) and 1 mm slot

The result shown in the Figure 10 with two peaks around 0.7 GHz and around 1.2 show the resonances of the inner windows. The result presented in the Figure 11 is consistent with the result we received in the actual measurements for the same distance for frame taped vs the case where the frame was not taped shown in Figure 52 ahead.

For the frame not taped case, above result can be compared. However, it should be noted that the above result is for 1 mm slot, and is limited to frequencies up to 4 GHz. Furthermore, the difference between the result of actual windows size and smaller window size is because of the dimensions of the window which also changed the slot width. Hence, the result is better for the actual window size. The peak around 0.5 in Figure 11 shows the resonance of inner windows.

The following figures show the results for the Y-polarized electric field within the double glazed windows, 75 cm, and 100 cm distance at the receiver end for smaller window size and actual windows size respectively with 1 mm slot.

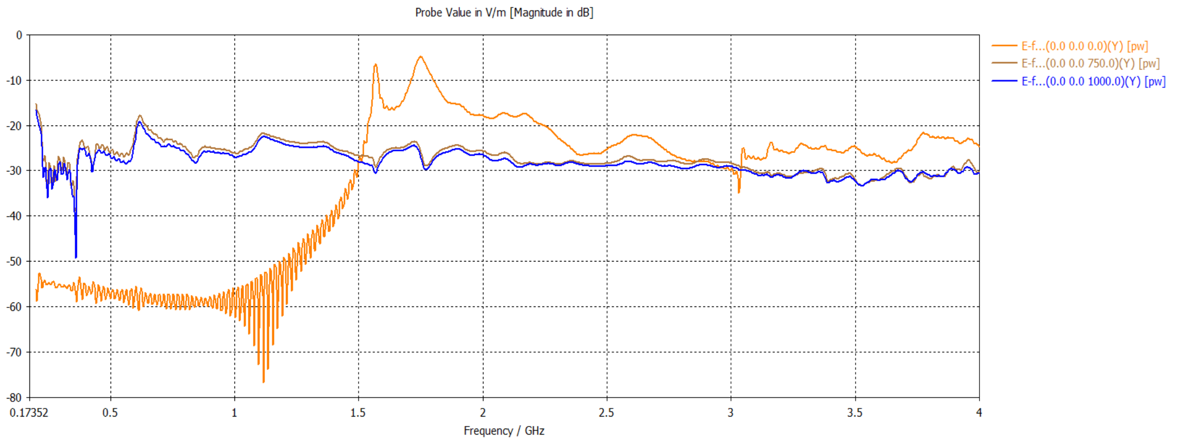


Figure 12: Y-polarized electric field within the double glazed windows, 75 cm, and 100 cm distance for smaller (60*60) windows size with 1 mm slot

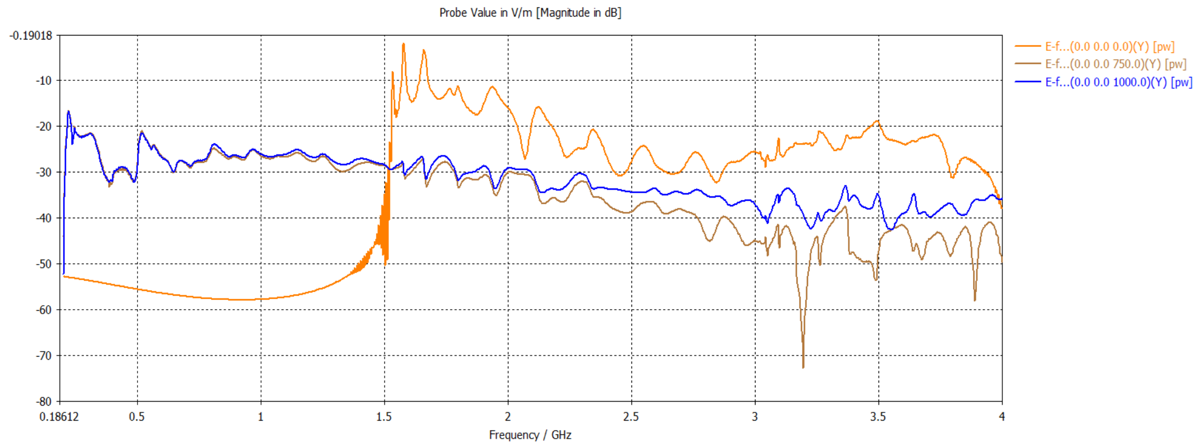


Figure 13: Y-polarized electric field within the double glazed windows, 75 cm, and 100 cm distance for actual (120*80) windows size with 1 mm slot

In the above figures the orange curve shows the electric field within the double glazed windows we used for our measurements. It shows the resonance between the inner windows, which is consistent with the actual measurement results. The results at 75 cm and 100 cm distance are also consistent with the results presented in the actual measurements. However, here the slot size is 1 mm, and the curves are confined to 4 GHz. The size of the windows also changes the slot width, which is why there is difference between the both results shown above.

4.1.2. E-field Results

4.1.2.1. E-field at 1 GHz

Since our plane wave is vertically polarized wave, so the electric field plots are presented in terms of Y-polarization.

Figure 14 below shows the Y-polarized electric field plot for 1 GHz with 1 mm slot for 60 cm*60 cm window size, and Figure 15 shows the Y-polarized electric field plot for the same frequency with 2 mm slot for 60 cm*60 cm window size. As can be seen in the plots below that standing wave when passes through the window model it radiates from the 2 points which act as sort of an antennas and radiate the wave in two patterns further from the window model. Those two points can be seen in the following figures. The reason for having such radiation pattern from the window models is because of the slots we introduced in the model. The effect of the slots in the Aluminum frame can also be confirmed from the actual measurement results shown in the next chapter. There is a minor difference between the pattern of 1 mm and 2 mm slots but nonetheless both follow the same standing wave and slot pattern after passing through the windows model. The results can be seen in the following figures.

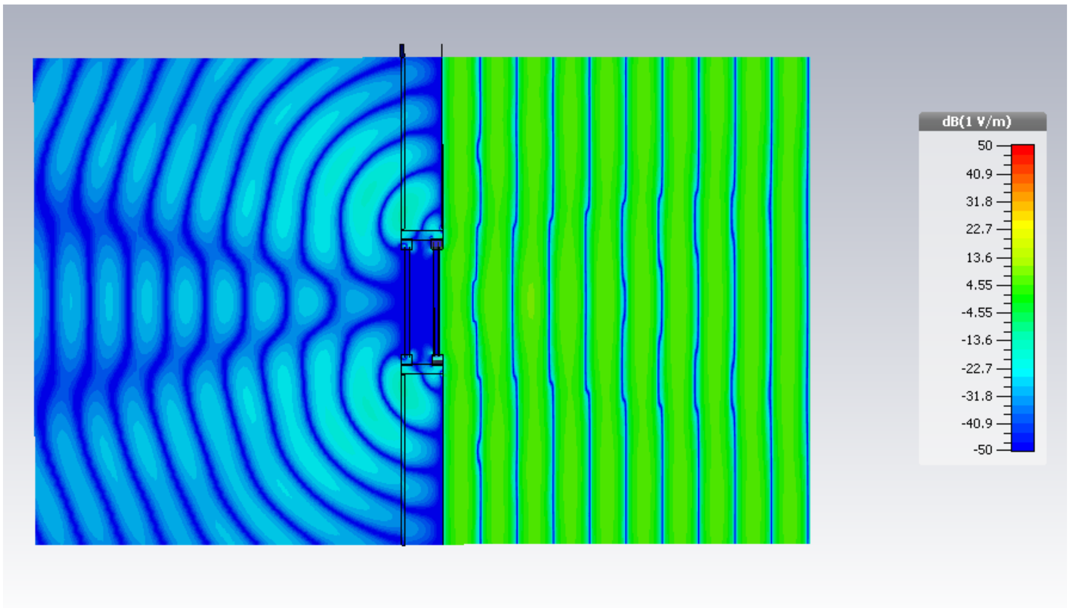


Figure 14: Y-polarized electric field plot at 1 GHz with 1 mm slot for 60 cm*60 cm window (Smaller window)

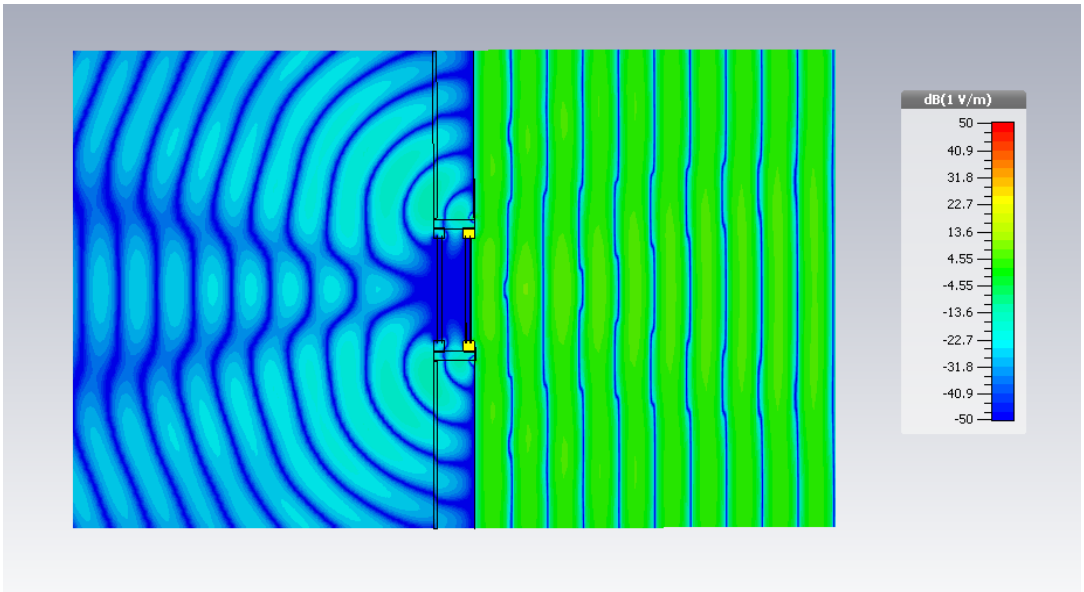


Figure 15: Y-polarized electric field plot at 1 GHz with 2 mm slot for 60 cm*60 cm window (Smaller window)

Figure 16 below shows the Y-polarized electric field plot with 1 mm slot for the actual window size i.e. 120 cm*80 cm. It can be seen that same two points on top and bottom of the frame are radiating the field energy in two dominant patterns.

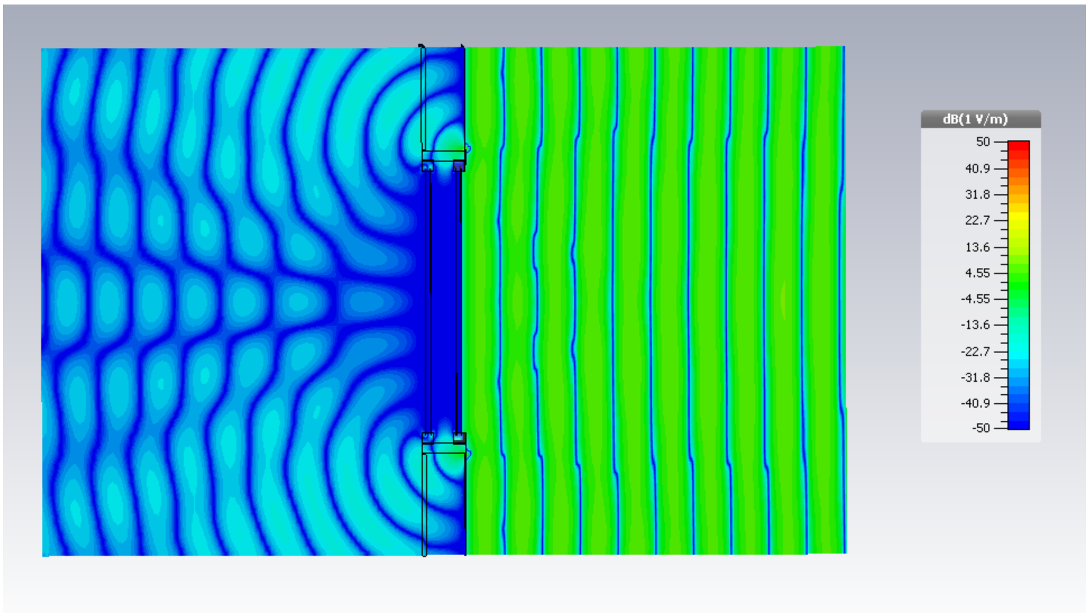


Figure 16: Y-polarized electric field plot at 1 GHz with 1 mm slot for 120 cm*80 cm window (actual size)

4.1.2.2. E-field at 2 GHz

At 2 GHz, the same pattern of the standing wave before passing through the model, and the same two points can be seen radiating the wave energy in two patterns further from the slots. Due to the increase in the frequency range the pattern is becoming denser i.e. drifting towards more attenuation. Figure 17 and Figure 18 below show the Y-polarized electric field plots with 1 mm and 2 mm slots respectively for 60 cm*60 cm window size. As can be seen in the 2 mm slot case for the same frequency, that due to the width of the slot, the field pattern is slightly different from the 1 mm slot case.

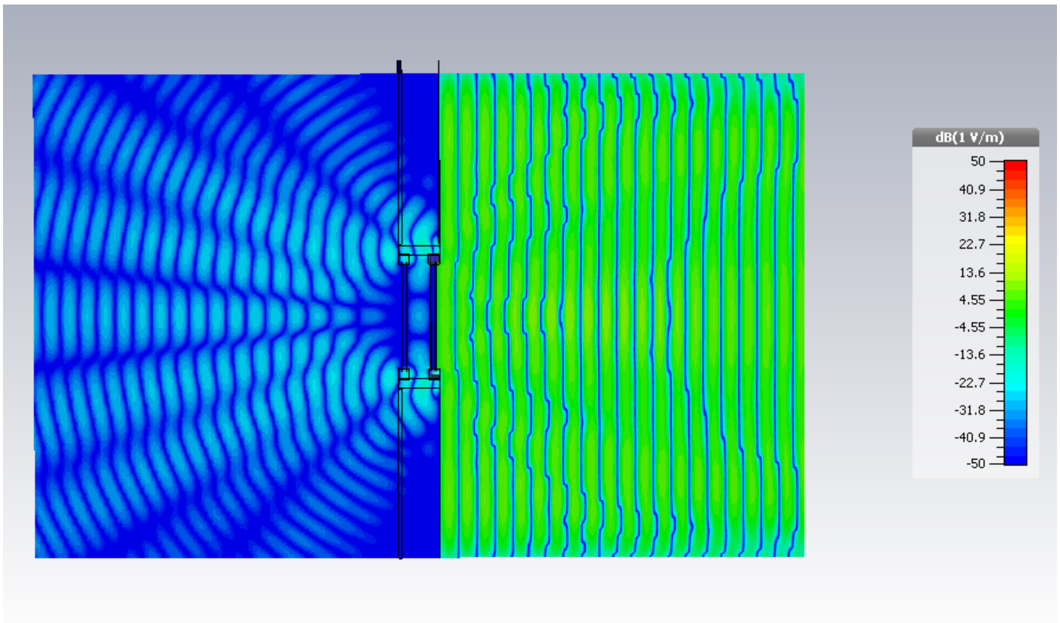


Figure 17: Y-polarized electric field plot at 2 GHz with 1 mm slot for 60 cm*60 cm window (Smaller window)

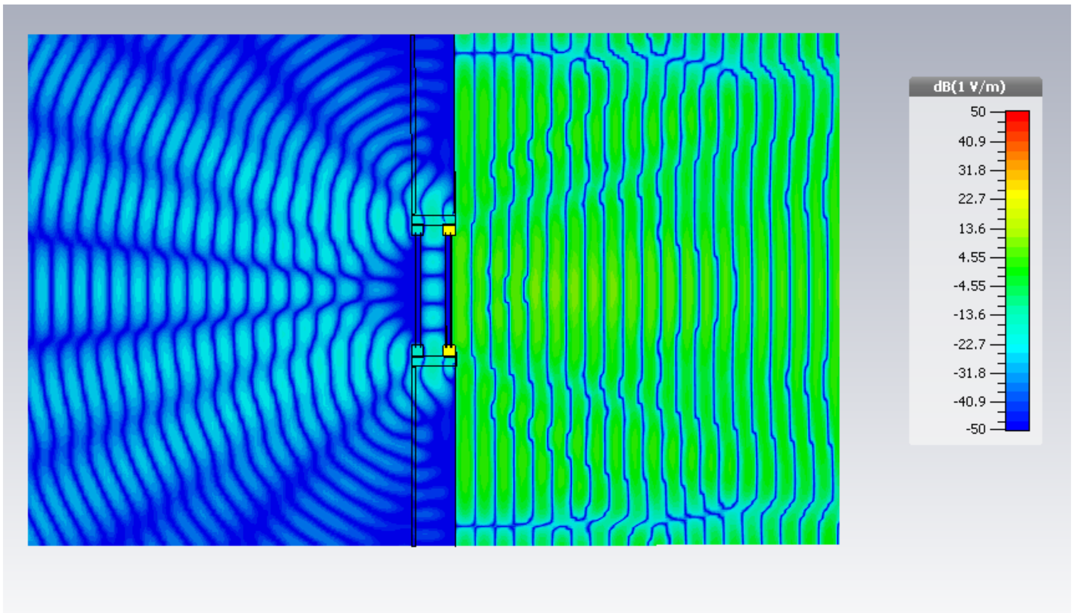


Figure 18: Y-polarized electric field plot at 2 GHz with 2 mm slot for 60 cm*60 cm window (Smaller window)

Figure 19 below shows the Y-polarized E-field plot for 2 GHz with 1 mm slot and 120 cm*80 cm window size. Because of the size of the window model, the slot width also varies along with the radiation pattern further inside from the windows model. But nonetheless those two points can be seen radiating two dominant patterns.

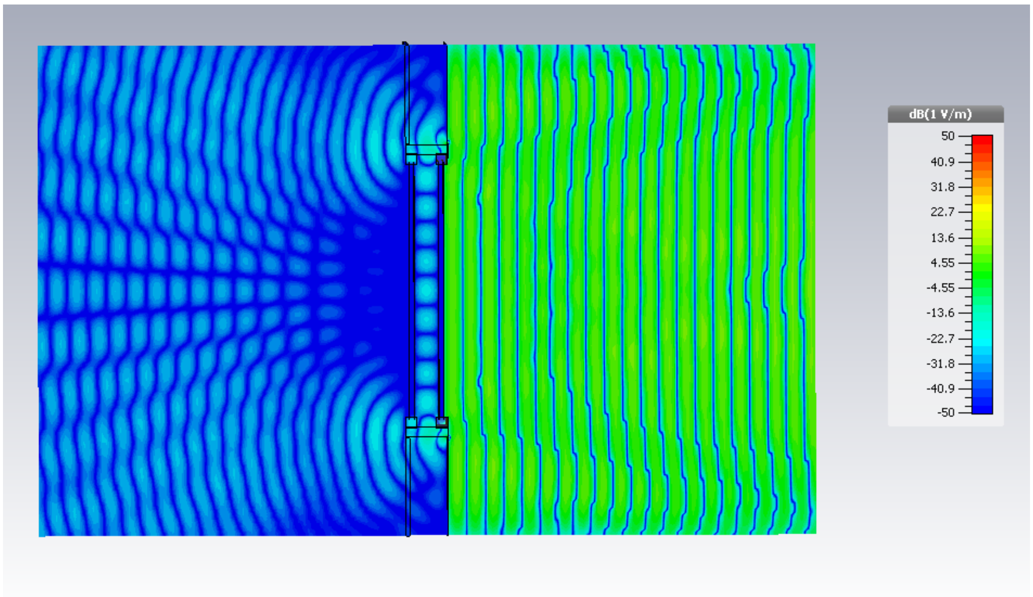


Figure 19: Y-polarized electric field plot at 2 GHz with 1 mm slot for 120 cm*80 cm window (actual size)

4.1.2.3. E-field at 2.5 GHz

Figure 20 and Figure 21 below shows the plots for the Electric field at 2.5 GHz with 1 mm and 2 mm slots respectively for 60 cm*60 cm window size. With the higher frequencies the field pattern is getting denser, but those two points at top and bottom of the window frame acting as sort of antennas radiating the energy in two patterns can be seen in the following figures.

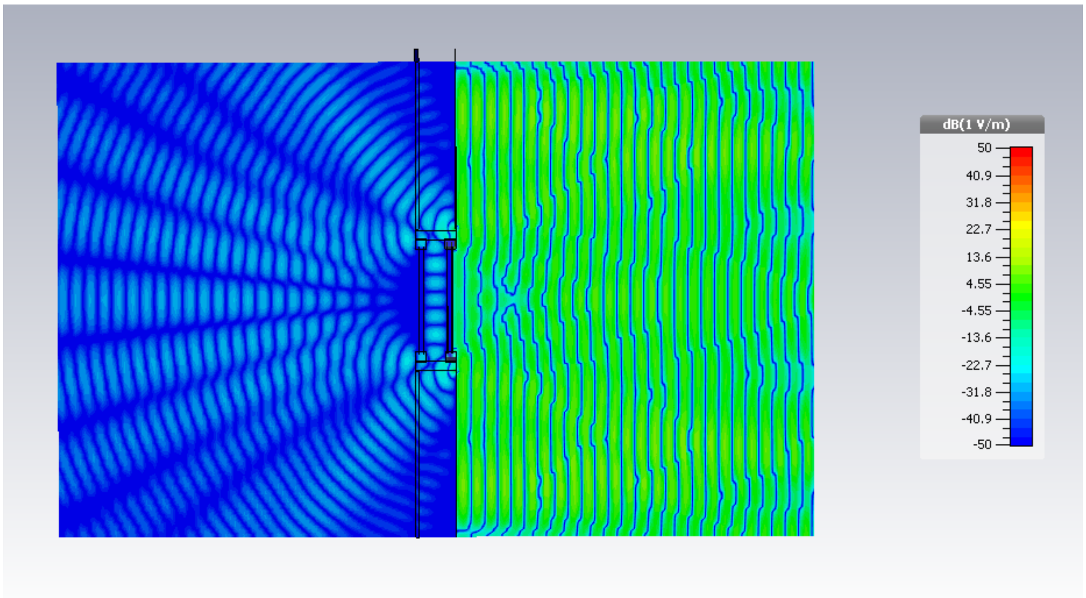


Figure 20: Y-polarized electric field plot at 2.5 GHz with 1 mm slot for 60 cm*60 cm window (Smaller window)

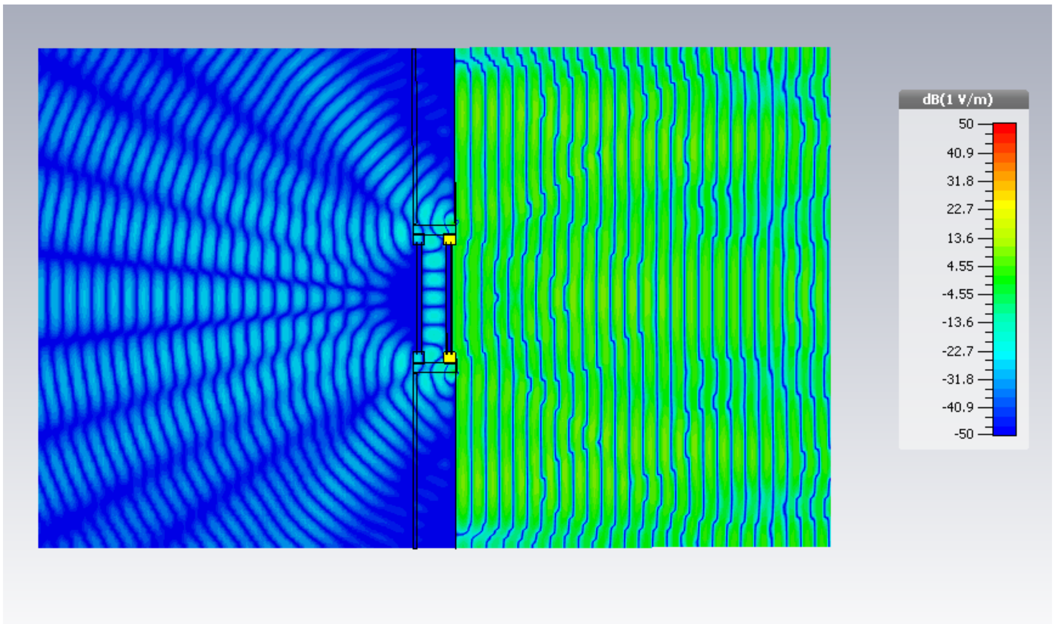


Figure 21: Y-polarized electric field plot at 2.5 GHz with 2 mm slot for 60 cm*60 cm window (Smaller window)

Figure 22 shows the Electric field plot for 2.5 GHz with 1 mm slot width and 120 cm*80 cm window size. Because of the size of the windows and the higher frequencies the radiation pattern is different from the windows model onwards.

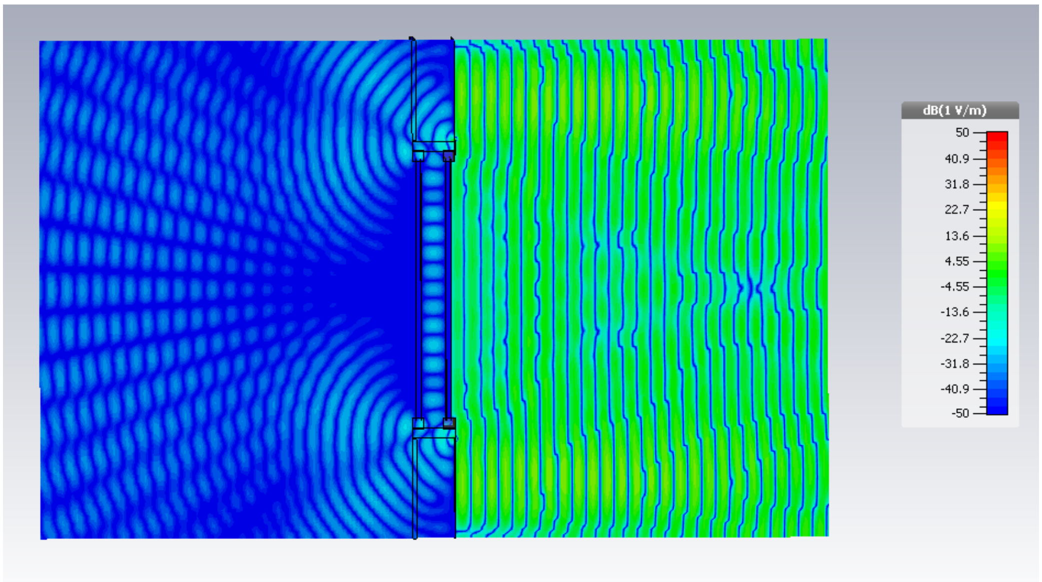


Figure 22: Y-polarized electric field plot at 2.5 GHz with 1 mm slot for 120 cm*80 cm window (actual size)

It is clear from the above figures that vertically polarized plane wave after going through the windows model, spreads in the shown directions (two points in particular top and bottom of the windows model) after losing energy. With the increase in the frequencies the same phenomenon gets intensified as can be seen in the above plots.

The dimensions of the window also affects the slot width, and the resultant pattern. But in general, the same principle is followed which is consistent with our measurement results.

4.1.3. Far field results

The following set of plots are the far field results for the 2 mm slots for 60 cm*60 cm window size (Smaller window). These results are not very different from the 1 mm slot for the same size of the window. The far field patterns against the given frequencies are same as was the case in the 1 mm slot case. However, there is very minor difference between both set of plots.

The far field results for 2 mm slots are presented and discussed in the sections ahead.

4.1.3.1. Far field at 0.7 GHz

The following far field plot at 0.7 GHz shows the attenuation of around 20 to 30 dB, as can be seen by the far field plot below in Figure 23 below. The lobes of the far field pattern below correspond to the same two points mentioned from the windows model that radiated the signal energy in two dominant patterns.

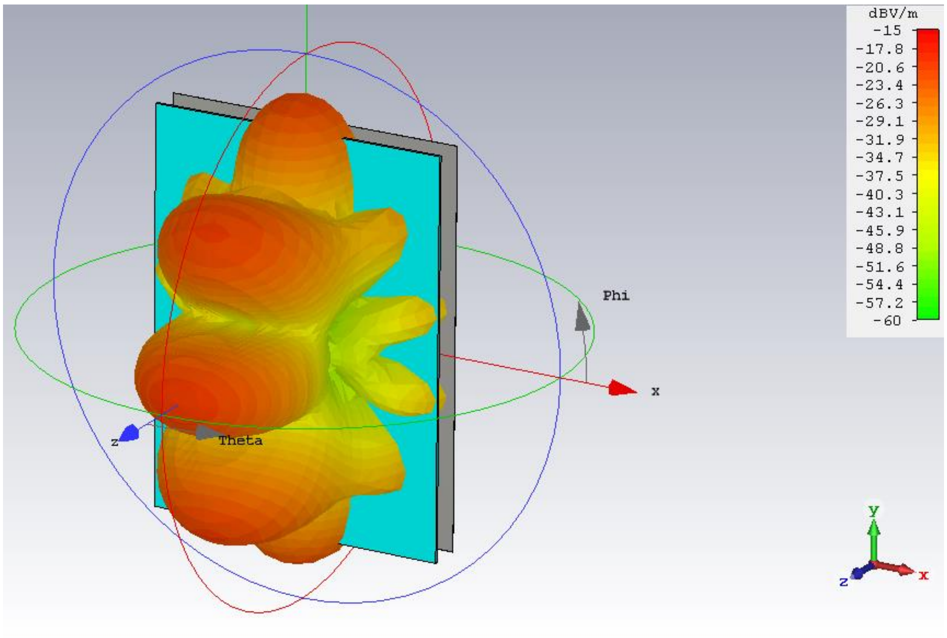


Figure 23: Far field at 0.7 GHz with 2 mm slot and 60 cm*60 cm window (Smaller window)

4.1.3.2. Far field at 0.9 GHz

Figure 24 below shows the attenuation around the same range, but the field pattern is bit different because of the slightly higher frequency range.

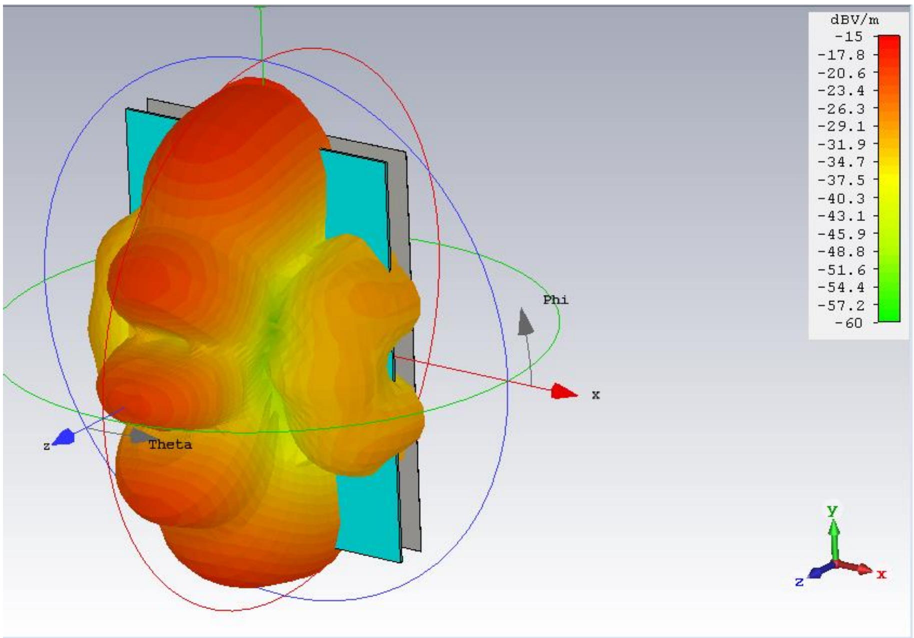


Figure 24: Far field at 0.9 GHz with 2 mm slot and 60 cm*60 cm window (Smaller window)

4.1.3.3. Far field at 1.5 GHz

Figure 25 below shows the far field at 1.5 GHz. With higher frequencies, there is a slight increase in the attenuation than the previous case, but still follows the same range of attenuation as mentioned before. Again, the various lobes in the far field pattern are because of the window slots radiating energy further from the windows model. With the increase in the frequency the lobes will become more dominant, along with more attenuation at higher frequencies.

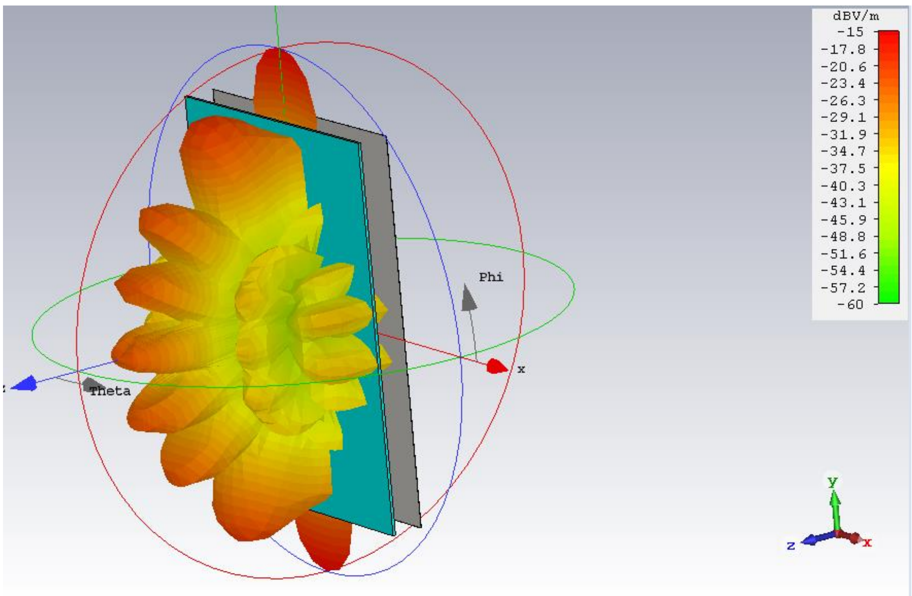


Figure 25: Far field at 1.5 GHz with 2 mm slot and 60 cm*60 cm window (Smaller window)

4.1.3.4. Far field at 1.8 GHz

As can be seen in the figure 26 below that the range of attenuation is almost same as before, but the far field pattern is different from the previous case because of the higher frequencies and the windows slot.

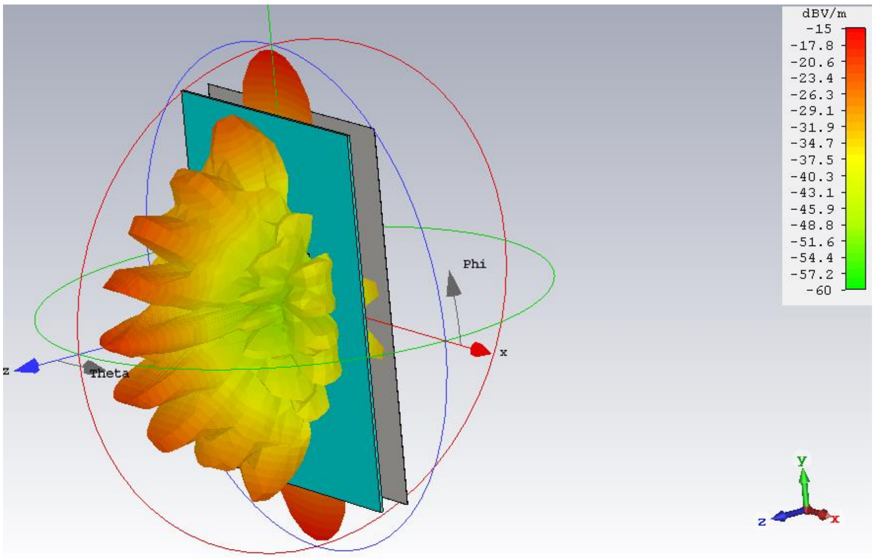


Figure 26: Far field at 1.8 GHz with 2 mm slot and 60 cm*60 cm window (Smaller window)

4.1.3.5. Far field at 3 GHz

Figure 27 shows that as we move towards the higher frequencies the attenuation increases along with the far field pattern. The increment in the lobes and attenuation is because of the higher frequencies and the slots with two dominant points that are producing two dominant radiation patterns.

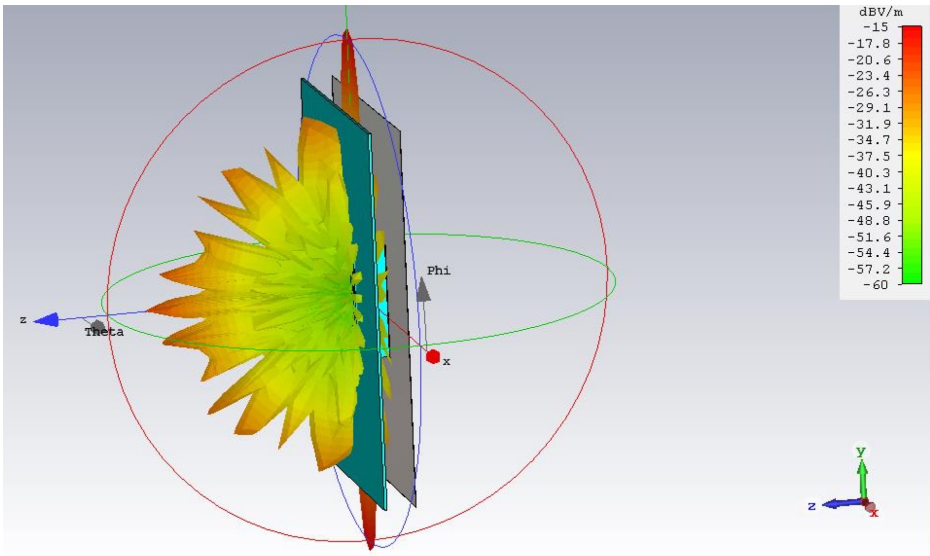


Figure 27: Far field at 3 GHz with 2 mm slot and 60 cm*60 cm window (Smaller window)

These propagation simulation results are consistent with the amount of attenuation the real life scenario presents as mentioned in the first chapter, and as the next chapter will show in the form of measurement results.

5. MEASUREMENT SCENARIOS AND RESULTS

Measurements were taken at EMC lab at University of Oulu, Finland, in order to understand the effects of radio waves propagation through modern windows. We used 4 antennas to take the measurements in the first setup of measurements. One was used for the transmission, and three were used for the reception. Antenna number one was SH800, which was the transmitting antenna, antenna number 2 was HF906, antenna number 3 was Vivaldi 5, and antenna number 4 was Vivaldi 6. Various scenarios and combinations were taken into account in order to understand the radio wave propagation effects through windows having wooden (Inner window) and aluminum (Outer window) frames. In the second setup of measurements, we used two antennas; one for the transmission, and second for the reception for the same windows setup. The antennas number one, and number two, which were used for transmission and reception for the first setup of measurements, were also used for the second setup of measurements, in order to draw the consistent results and comparisons.

Vertical and horizontal polarizations were used for the transmitting and receiving antennas. Measurements were taken with zero, one, and two passive repeaters inserted vertically in the slot. Window scenarios such as windows non-existent, inner and outer window open, inner window open and outer closed, outer open and inner closed, inner window closed and outer non-existent, outer window closed and inner non-existent, inner window open and outer non-existent, and outer window open and inner non-existent, were used for measurements.

5.1. Calibration

5.1.1. First setup

For the first setup of measurements, we calibrated the cables for 800 MHz to 10800 MHz, using Agilent PNA-X (10 MHz to 63 GHz) VNA, and took the reference measurements followed by the actual measurements. For calibration of first phase, we took 1601 points corresponding to 50 m distance limit for VNA in which we can detect the reflections and losses. Our measurements deductions and analysis is mainly focused on this calibration and frequency range for the first phase of measurement.

Calibration= 800-10800 MHz

Bandwidth= 10 GHz

d_{tau}= 0.1 ns

N= 1601= 160 ns= 50 meter

5.1.2. Second setup

For the second setup of measurements, we calibrated the cables for the same frequency range, and took approximately same points, in order to keep our measurements consistent with the previous setup of measurements so that the appropriate comparisons can be made.

5.2. Measurement setups

5.2.1. First setup

In the first setup of measurements, we used four antennas; one for transmission, and three for reception. The heights and distances of the transmitting antenna and receiving antennas from the window, and from each other are shown in the figures below.
The Figure 28 below shows the antennas used for the first setup of measurements.

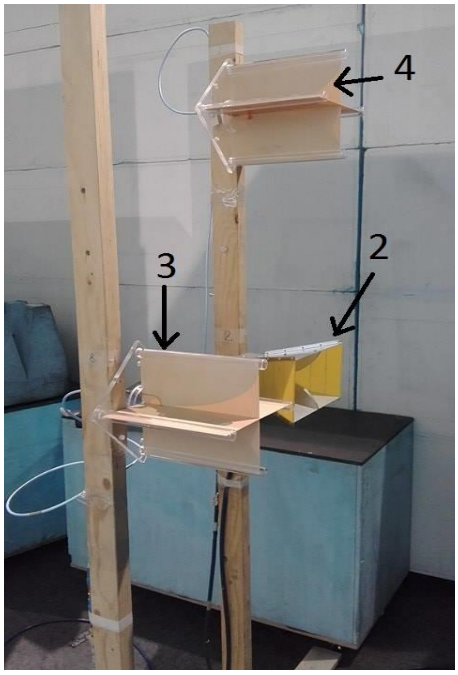


Figure 28: Transmitting antenna with vertical polarization on the left, 3 receiving antennas on the right

Figure 29 shows the operational diagram of the measurement setup with the antennas heights and distances from the respective windows, while the Figure 30 shows the dimensions of the aluminum and wooden window frames.

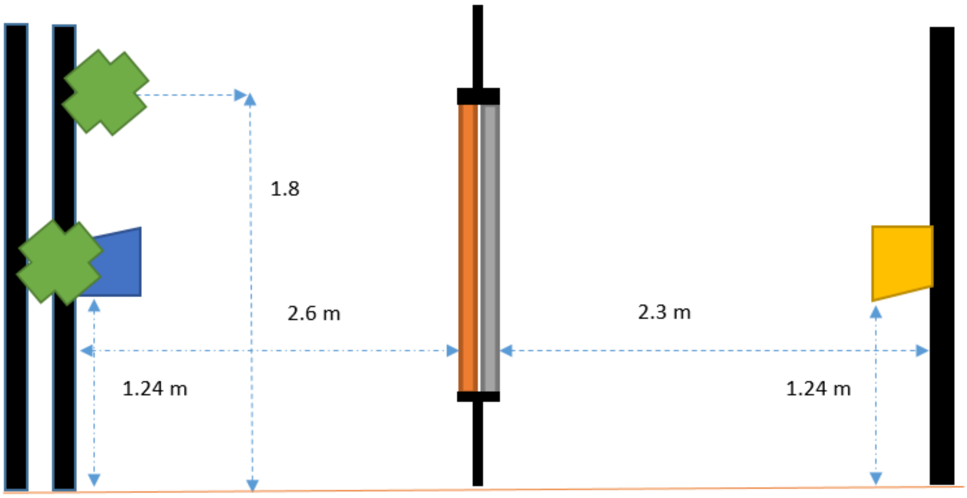


Figure 29: Operational diagram of the first measurement setup

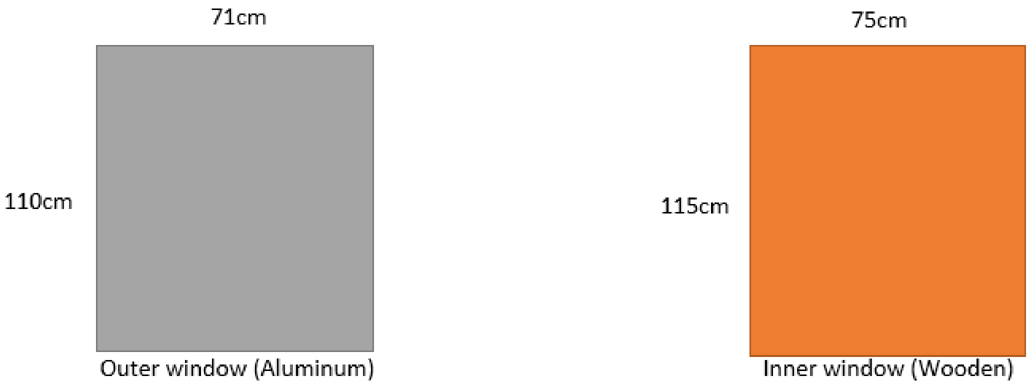


Figure 30: Dimensions of the windows

Figure 31 below shows the detailed operational diagram of the first measurement setup, with the information about the thickness of the window elements and the wall, along with other important parameters related to the measurement setup.

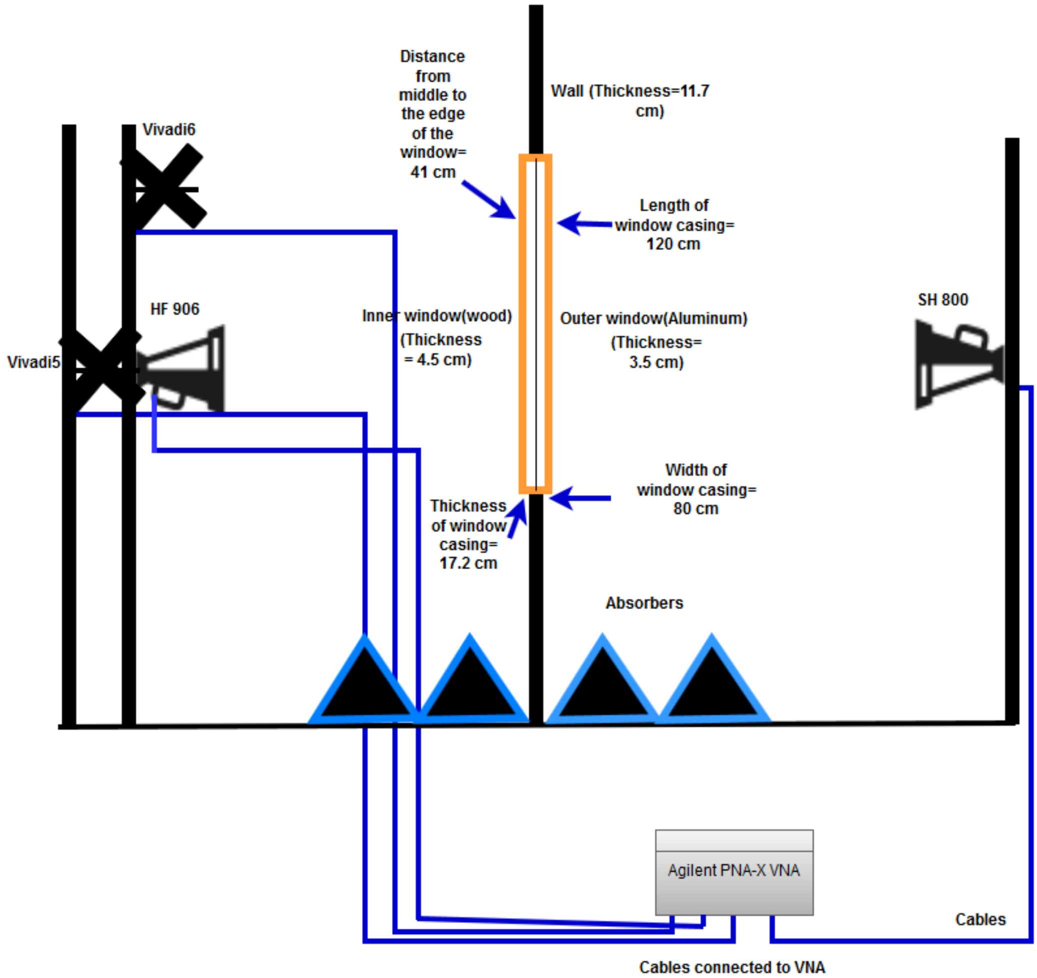
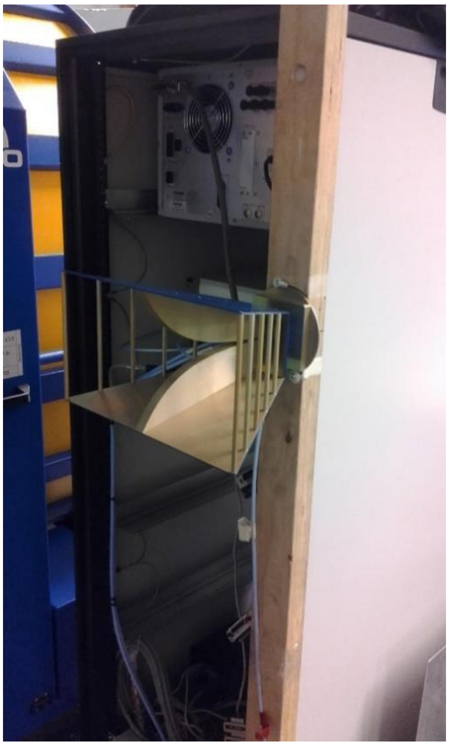


Figure 31: Detailed operational diagram of first measurement setup

The passive antennas that we used had a length of 32.5 cm and width of 18 cm. When one passive antenna in the center was inserted; it was inserted at a position of 50 cm from the top of the window, and 50 cm from the bottom of the window. When two passive antennas (1 cm apart) were inserted; they were placed 40.8 cm from the top, and 40 cm from the bottom. The total length of window frame was 120 cm, and width was 80 cm.

5.2.2. Second setup

In the second setup of measurement, as mentioned before, we used two antennas, one for transmission, and second one for reception. Figure below shows the both antennas used in second setup of measurements.



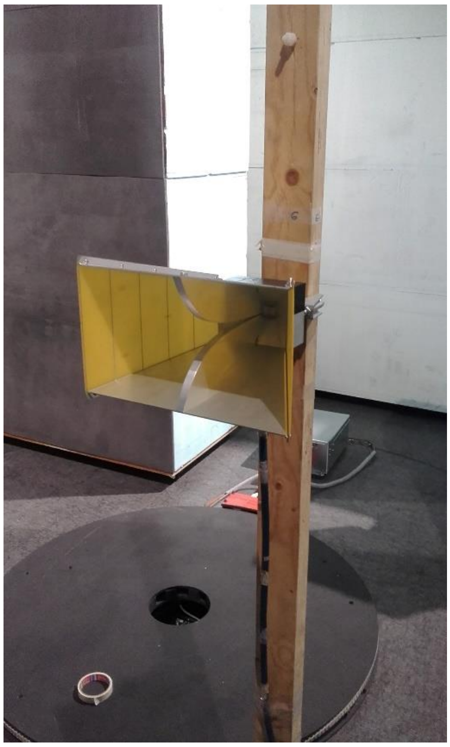


Figure 32: Transmitting (left) and receiving (right) antennas used in second setup

Figure 33 shows the operational diagram of the second setup of the measurements. It shows the two receiving antennas positions that were used i.e. position 'A' and position 'B' along with the description of horizontal and vertical shifts from either of these two positions. Figure 34 shows the detailed operational diagram of the second measurement setup.

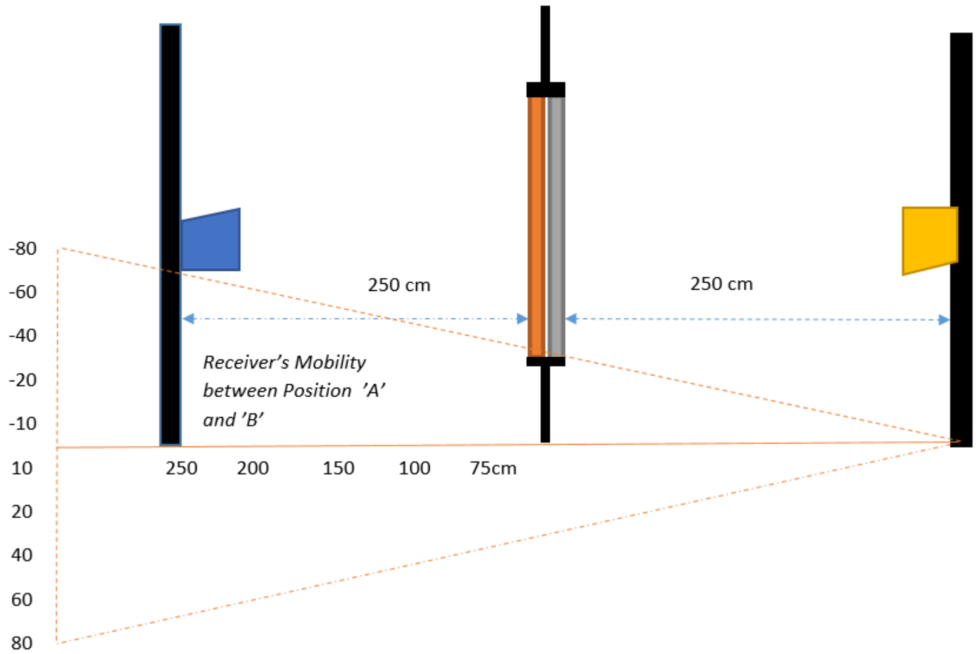


Figure 33: Operational diagram of second setup

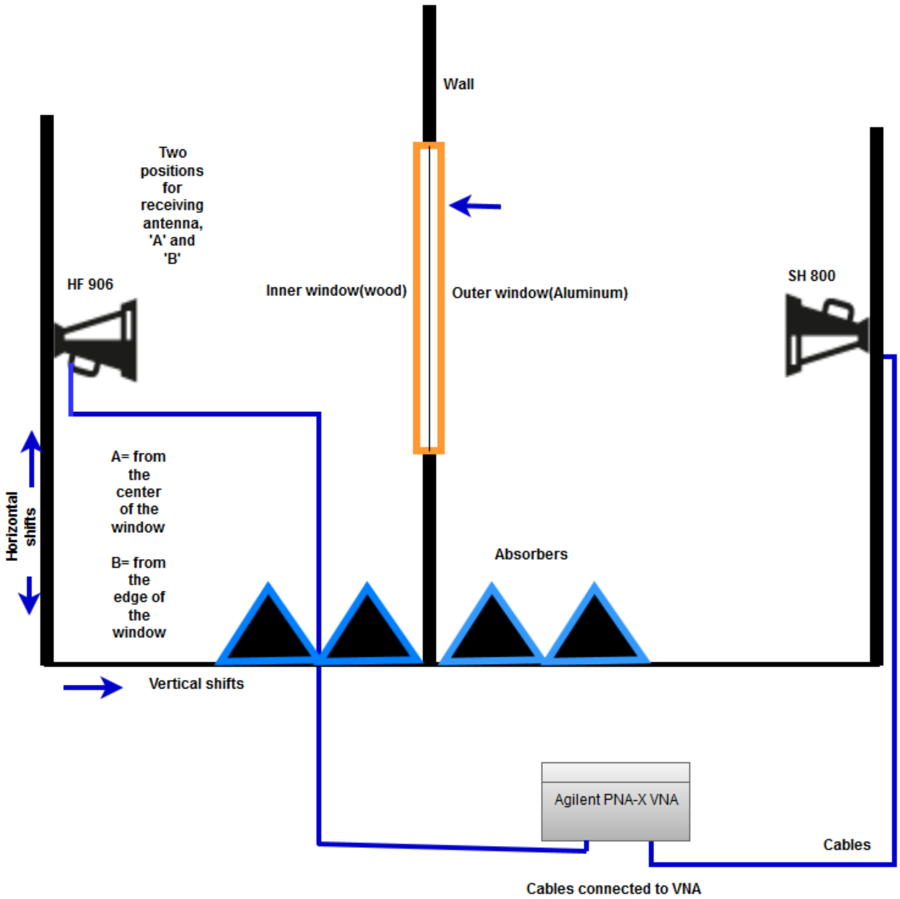


Figure 34: Detailed operational diagram of second setup

Most of the measurement facts associated with second setup are same as first setup of measurements, but still there were few differences mainly in the procedure we adapted to take measurements. The heights and widths along with thicknesses of both windows and window frames were same. The transmitting antenna was same as the setup one, and the receiving antenna number 2 was used for this case, rather than 3 receiving antennas, as shown in the figures above, which was same as the first setup.

Even though the distance from the windows to the transmitting and receiving antennas was 250 each, the offset distance was compensated from the middle of the window frame to the each window, and that offset (inner and outer; corresponding to middle to the inner window, and middle to the outer window) was subtracted from the 250 cm distance from each side. Inner offset was 80 mm, and the outer offset was 37 mm. So, the receiver Antenna was placed at 245 (+8 cm offset), and transmitter antenna was placed at 250 (including the offset). The cable difference for receiver was 5.8 cm, and for transmitter was 3.7 cm. So, 5 meters distance in total from cable to cable. The heights of the both antennas were same as was in setup one. Line of sight (LOS) measurements within the chamber were taken with a distance of 5 meters between both antennas. For the horizontal polarization, the total distance was 5.013 minus the offset.

5.3. Results

The structures of the passive repeaters used are not shown in the following figures because of the pending patent application.

5.3.1. Impact of windows

In order to see the impact of windows on the propagating signal, the combinations such as; Inner window closed outer closed(Ic/Oc), inner open outer closed(Io/Oc), and inner closed outer open(Ic/Oo), have been taken into account without any passive repeater for vertical and horizontal polarizations both. For vertical polarization, as expected, both windows closed affect the transmission strongly, while the inner closed and outer open has lower attenuation than the outer closed and inner open for vertical polarization. It is because outer window is of aluminum which affects the radio signals more than the wooden window frame for the vertical polarization. There is not much of a difference between the s21 and s31 in this case. For the horizontal polarization, the inner closed and outer open has lesser impeding than the outer closed and inner open for both s21 and s31.

5.3.1.1. Vertical Polarization

Figure 35 shows the comparison of the various windows scenarios for the s21 and vertical polarization, and Figure 36 shows the comparison of the various windows scenarios for the s31 and vertical polarization.

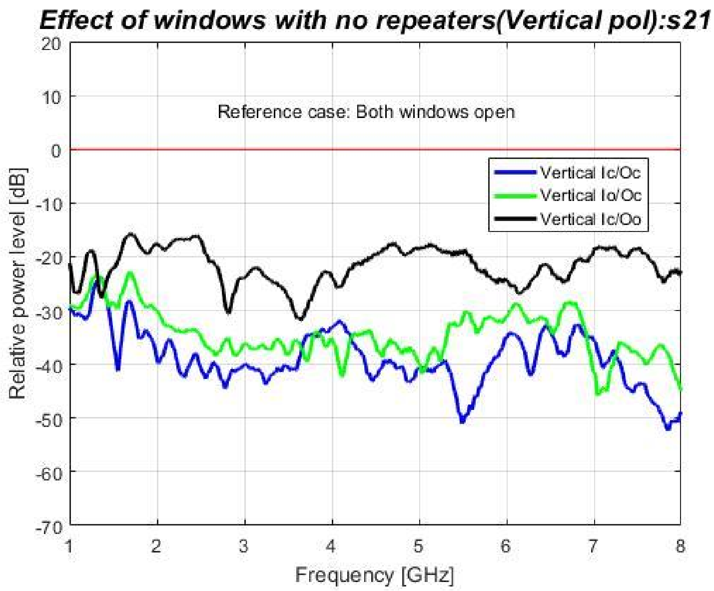


Figure 35: s21 comparisons of windows combinations vertical polarization

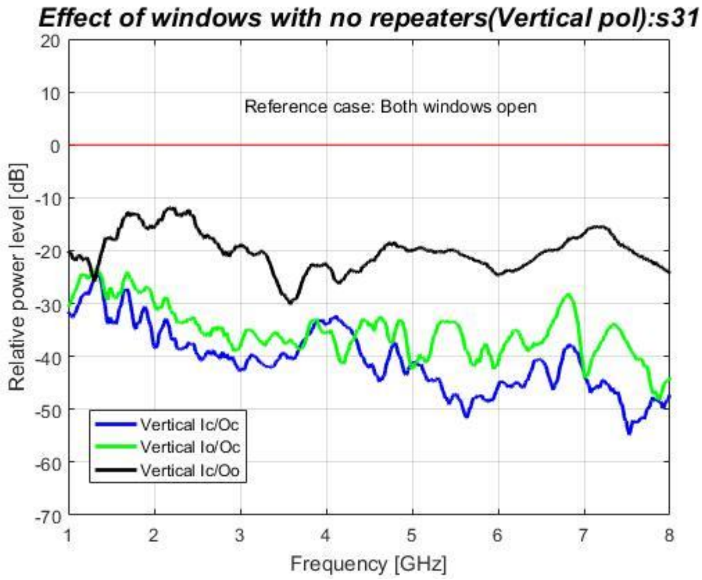


Figure 36: s31 comparisons of windows combinations vertical polarization

Figure 37 below shows the receiver antenna in a vertically polarized state being placed at the position ‘A’.

Figure 37: Receiver antenna in vertically polarized state placed at point A

Figure 38 below shows the comparison between the both windows closed Aluminum frame taped vs the case where the both windows were closed and frame was not taped for the vertical polarization. We took both windows non-existent as a reference for this measurement.

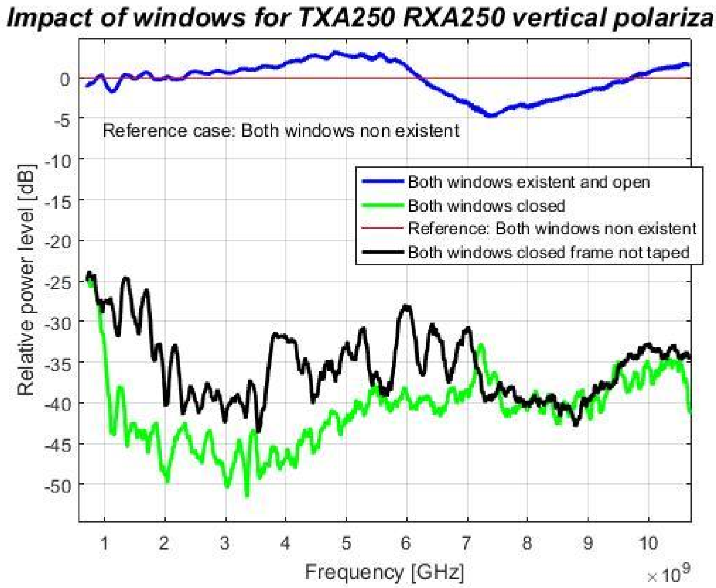


Figure 38: Impact of windows for TXA250 RXA250 vertical polarization

5.3.1.2. Horizontal Polarization

Figure 39 shows the comparison of the various windows scenarios for the s21 and horizontal polarization, and Figure 40 shows the comparison of the various windows scenarios for the s31 and horizontal polarization.

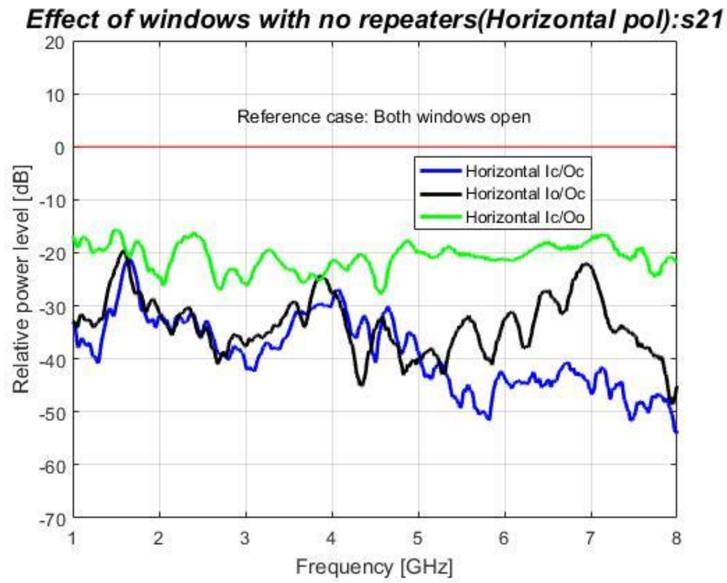


Figure 39: s21 comparisons of windows combinations horizontal polarization

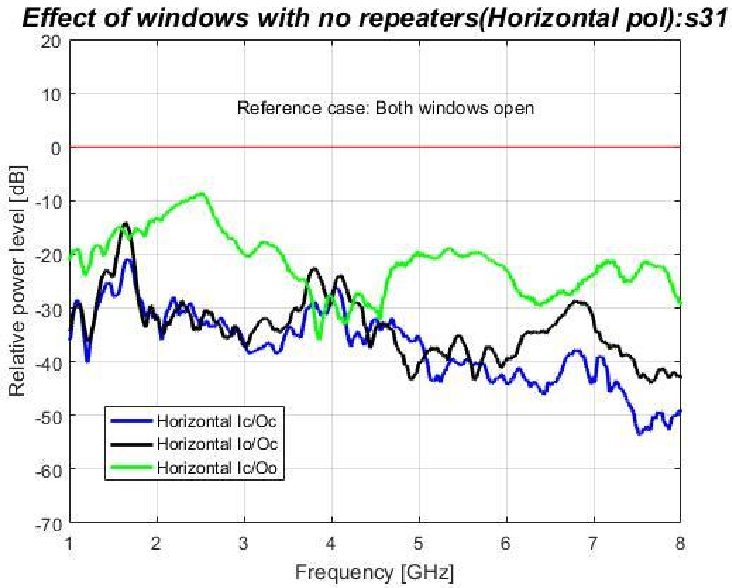


Figure 40: s31 comparisons of windows combinations horizontal polarization

Figure 41 below shows the receiver antenna in a horizontally polarized state being placed at the position ‘A’.

Figure 41: Receiving antenna in Horizontal position placed at point A

Figure 42 below shows the comparison between the both windows closed Aluminum frame taped vs the case where the both windows were closed and frame was not taped for the horizontal polarization. We took both windows non-existent as a reference for this measurement.

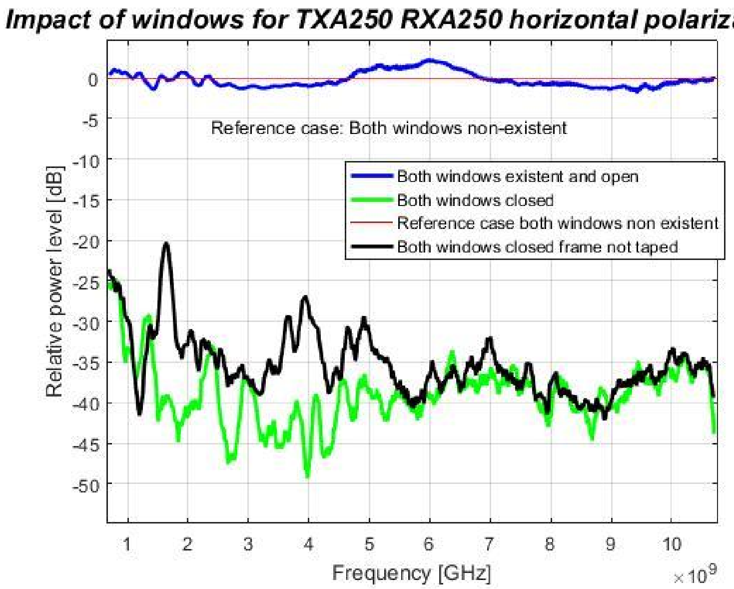


Figure 42: Impact of windows for TXA250 RXA250 horizontal polarization

TXA250 in the above comparisons refers to the Transmitter antenna placed at point 'A' with 250 cm distance from the windows. RXA250 refers to the receiver antenna placed at point 'A' with 250 cm distance from the windows. Point 'A' is the position of the transmitting and receiving antenna from the center of the windows, while point 'B' is in line with the position of the passive repeater i.e. side of the window.

At the 250 cm distance of transmitter and receiver from the windows, taping the frame with aluminum has a considerable impact on the radio wave propagation, as not taping the frame shows better results for frequencies 0.7 GHz to 7 GHz. However, at higher frequencies the impact is insignificant. This considerable effect of taping will be further analyzed in this chapter to have detailed analysis.

5.3.1.3. For horizontal shifts in centimeters with vertical polarization

The horizontal shifts of 10 cm, 20 cm, 40 cm, 60 cm, and 80 cm show the shift on either side of the point B from a particular distance from the side of the window where passive antenna is inserted for our measurements. The positive 10, 20 and so on represent the shift towards the right side from the point, while the negative 10, 20, and so on represent the distance towards the left side from the particular point, in this case, B. For the following comparisons, both windows open case was taken as reference, and both windows closed with no shift was compared in every comparison to draw accurate result. Figure 43 below shows the horizontal shift of receiving antenna towards the positive side.

Figure 43: Horizontal shift relative to point B towards right side

Following set of figures show comparison of varying horizontal shifts from the point B for vertical polarization.

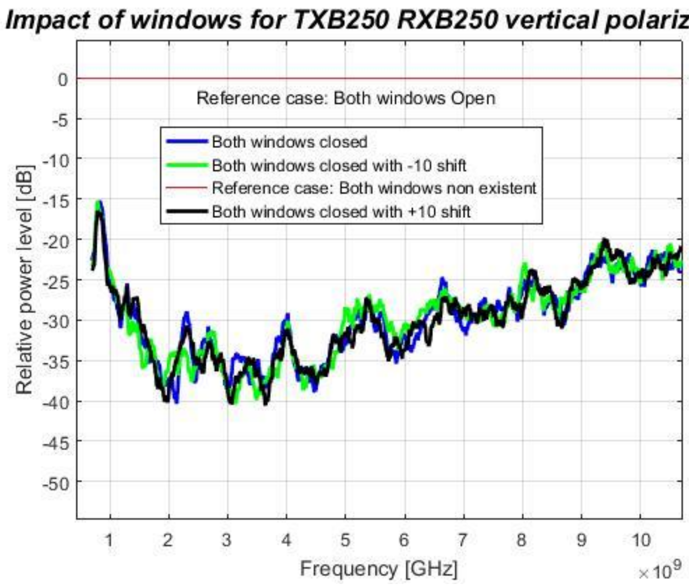


Figure 44: Impact of windows for TXB250 RXB250 vertical polarization varying shifts

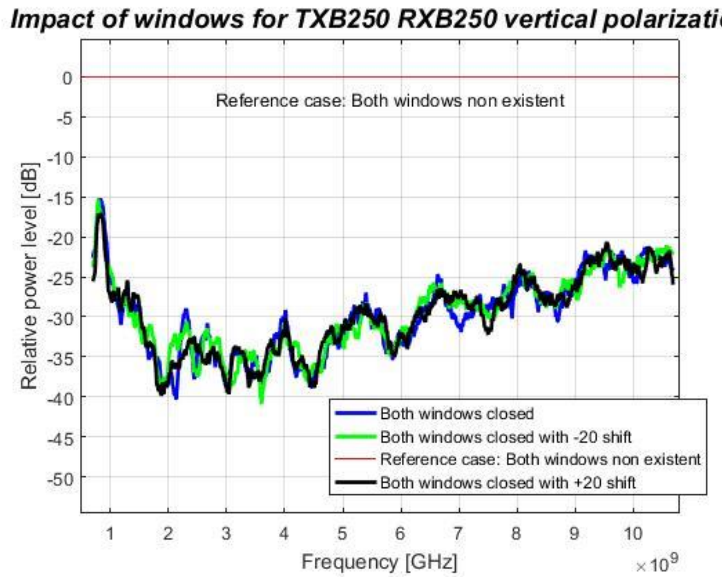


Figure 45: Impact of windows for TXB250 RXB250 vertical polarization varying shifts

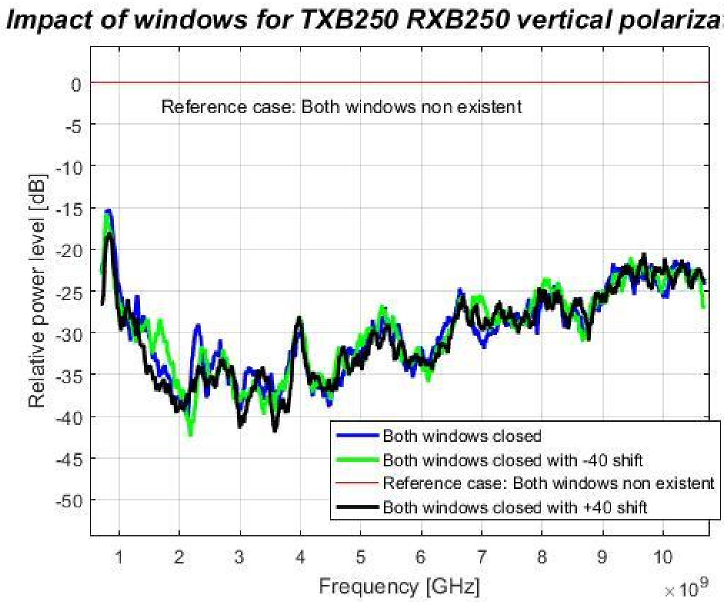


Figure 46: Impact of windows for TXB250 RXB250 vertical polarization varying shifts

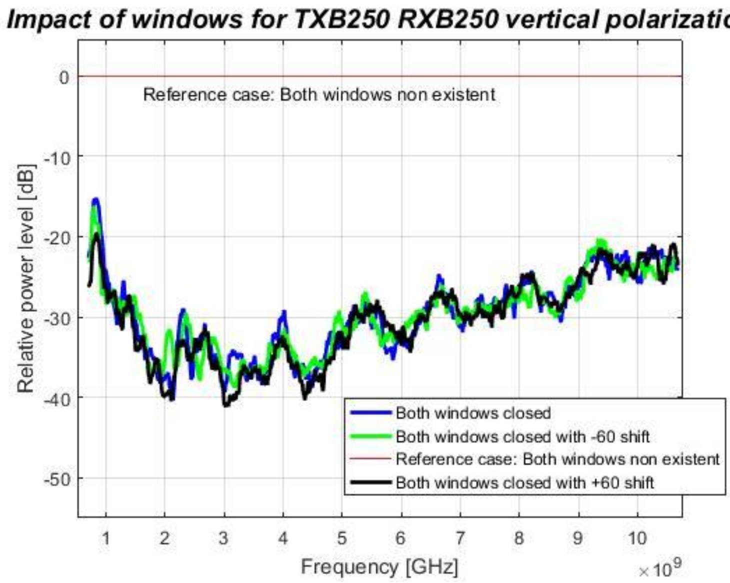


Figure 47: Impact of windows for TXB250 RXB250 vertical polarization varying shifts

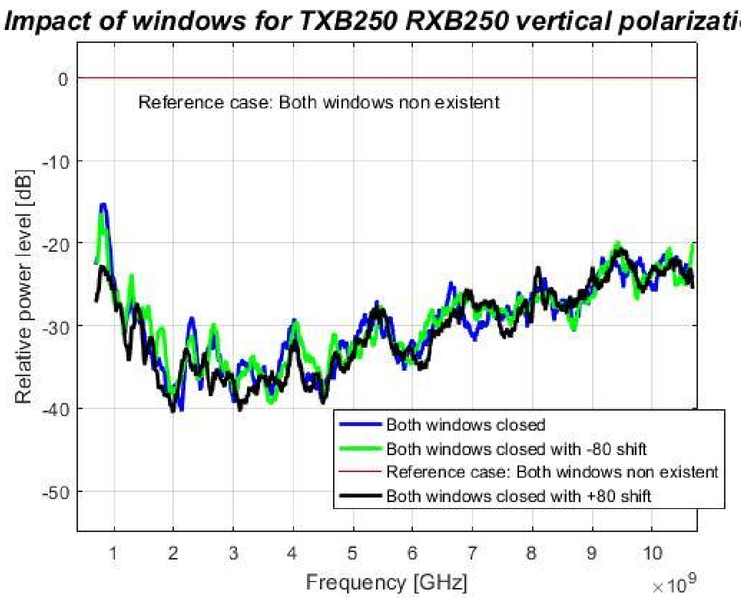


Figure 48: Impact of windows for TXB250 RXB250 vertical polarization varying shifts

Along all these shifts at TXB250 AND RXB250, the impact of these shifts seems to be negligible and the results vary insignificantly as can be seen in the above comparisons.

5.3.1.4. For varying RXB

Vertical shift refers to the movement of the receiving antenna from particular point, in this case, “B” towards the windows. The points taken were 75 cm, 100 cm, 200 cm, and 250 cm, which refer to the distances in centimeters from the windows to the receiving antenna. The Figure 49 below shows the vertical shift at 75 cm from the windows.

Figure 49: Receiving antenna moving vertically from point B

In the following comparison, TXB250 refers to the transmitter antenna at point B with 250 cm distance from the windows, and the RXB75, refers to the receiver antenna at point B having 75 cm distance from the windows, and so on. Both windows closed with TXB250 and RXB250 is taken as reference for this comparison. It is clear from the following comparison that there is slight variation between the results for the vertical polarization and if we compare the RXB75 with RXB200, the former shows slightly better curves than the latter and that’s because of it being closer to the windows. However, for the higher frequencies the impact gets even more insignificant.

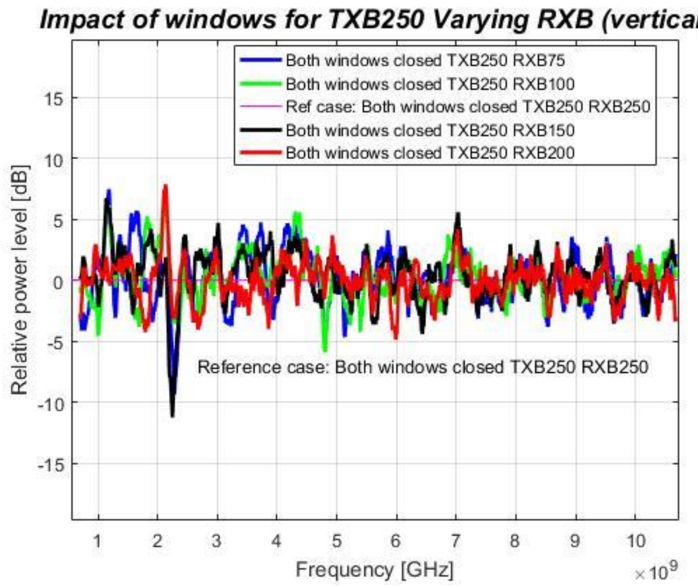


Figure 50: Impact of windows for TXB250 Varying RXB (Vertical)

5.3.2. Radiation measurements through slots of the window

As was seen earlier that taping the Aluminum frame had significant impact on the gain of the repeater. We further carried out the comparisons to see the trend, if any, these comparisons follow.

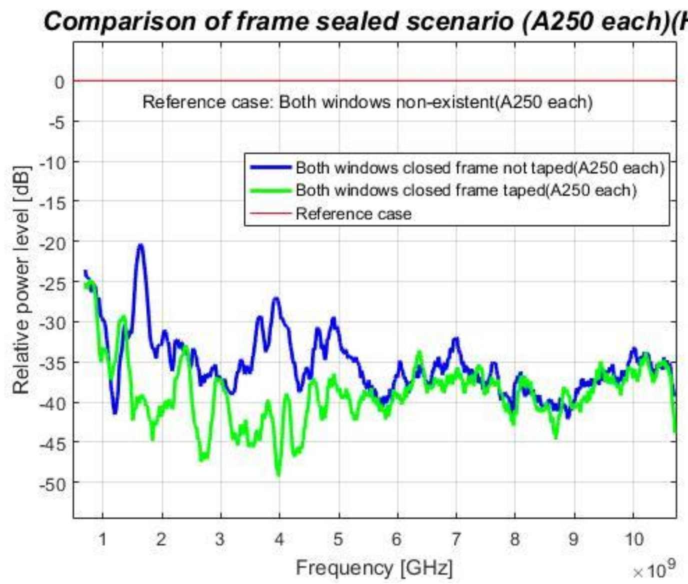


Figure 51: Comparison of frame taped case for horizontal polarization

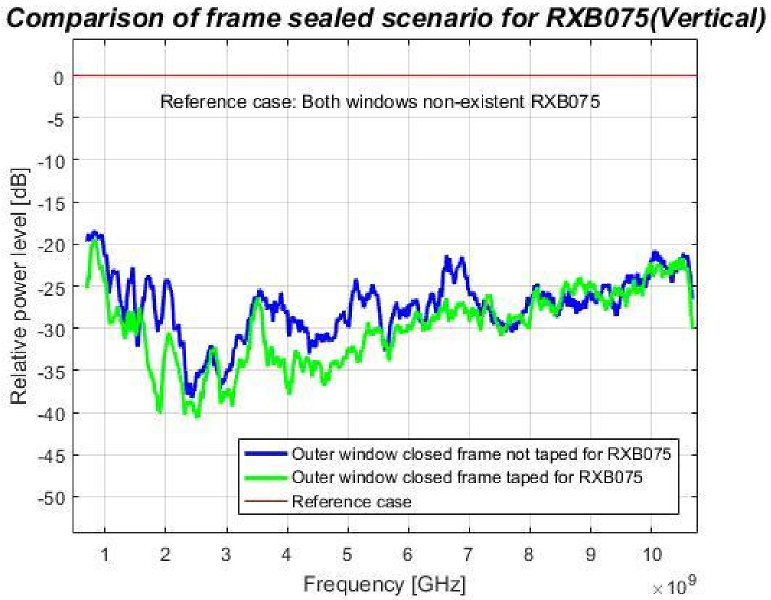


Figure 52: Comparison of frame taped case vertical polarization when TXB250 and RXB075

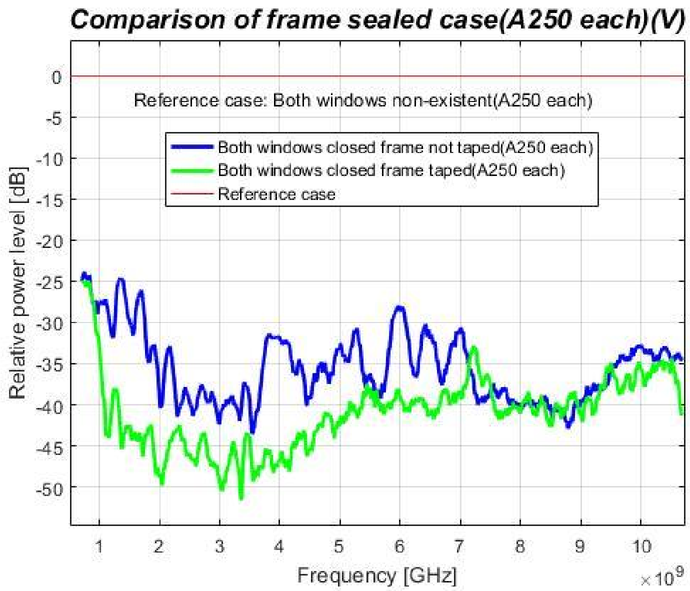


Figure 53: Comparison of framed taped case vertical pol when TXA250 and RXA250

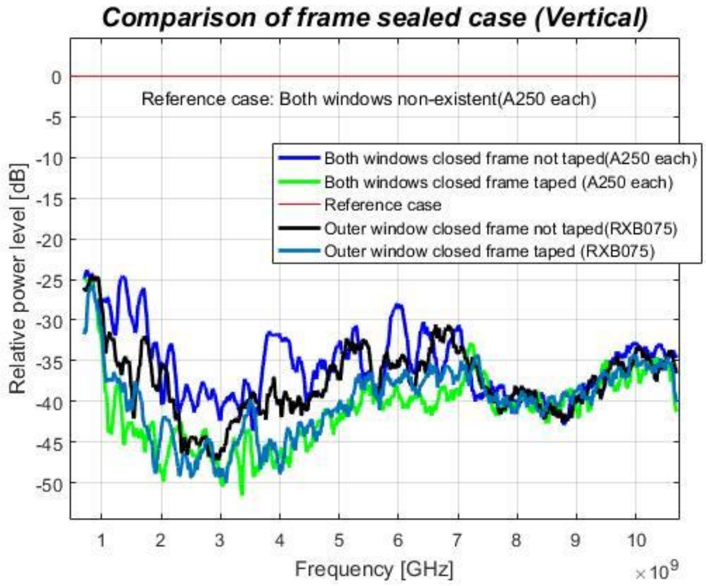


Figure 54: Comparison of frame taped cases for vertical polarization

In the above comparisons the noticeable fact is that even though taping the frame slots affects the performance compared to the cases where the frame is not taped, the effect at higher frequencies is insignificant. It could be the case that because of the radiation pattern of the antenna there is less power in the frame slots for the higher frequencies, and hence the insignificant effect of taping at higher frequencies.

5.3.3. One passive repeater

5.3.3.1. One passive repeater at upper position

It can be seen in the following comparison that one passive antenna in the upper position shows 10 to 15 dB gain around the frequencies ranging from 1 GHz to 3 GHz. and then at higher frequencies ranging from 7 to 8 GHz. The center and right position of the receiving antenna shows minimum variation between them as shown in the Figure 55 below.

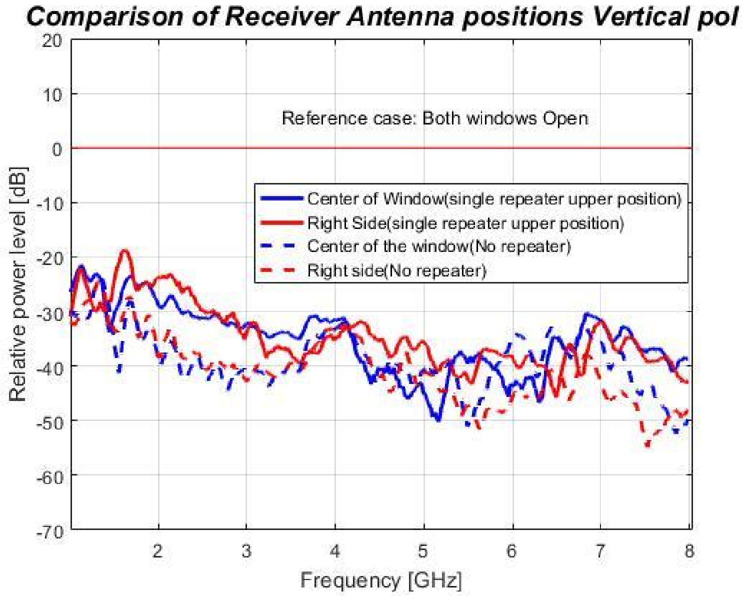


Figure 55: Comparison results of one passive repeater at upper position

5.3.3.2. One passive repeater at central position:

In the comparison of receiver antenna positions involving one passive antenna in the central position, it is clear from the figure 56 below, that it again shows the gain of 10 15 dB around the same frequencies mentioned above, and there is little variation in terms of the right and center of reception relative to the passive repeater position and windows.

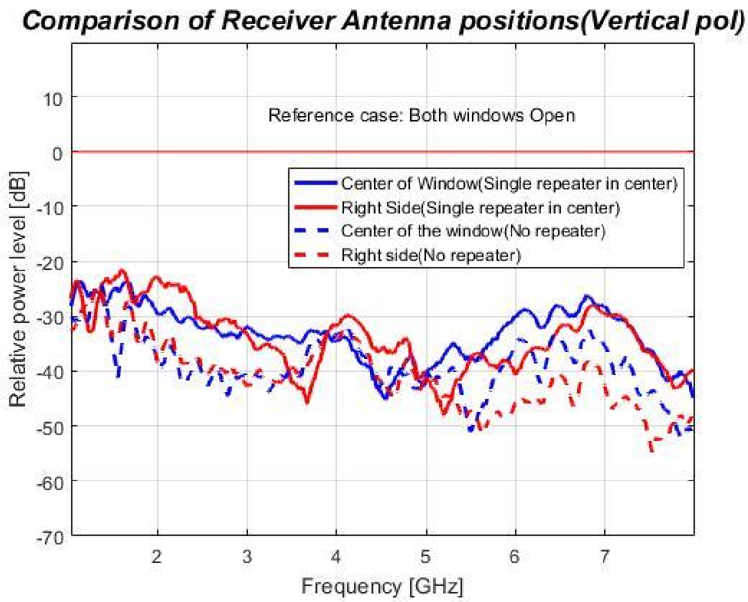


Figure 56: Comparison results of one passive repeater at central position

Figure 57 shows one passive antenna covered with metal guide in the central position.

Figure 57: One passive antenna at the center covered with metal

As can be seen in the Figure 58, one passive antenna in the center covered with metal show the same result as in the case not covered with metal, however, at higher frequencies the impact is very little, and that's because of the metallic covering of the passive repeater. The following comparison shows the results for the vertical polarization.

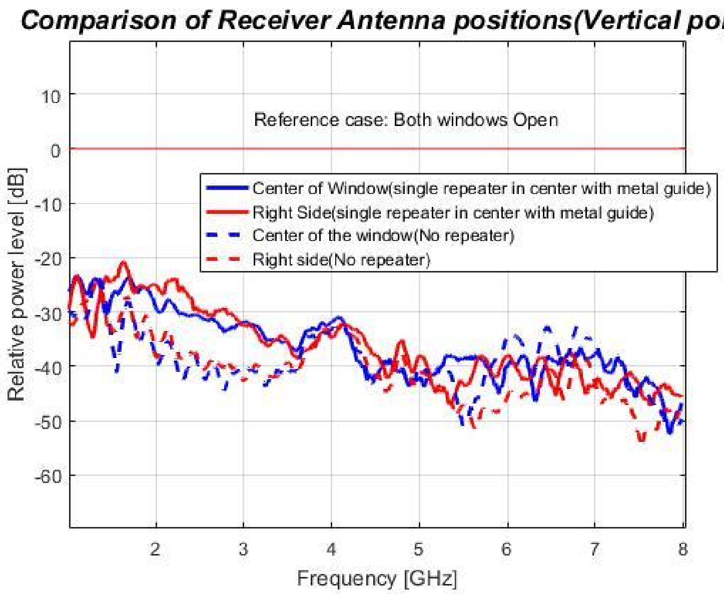


Figure 58: Comparison results of one passive antenna at center covered with metal for vertical polarization

For Horizontal polarization, as shown in Figure 59, the same case shows the opposite result from the vertical polarization, by showing the considerable gain at the higher frequencies, and that's because of the horizontally polarized waves radiated by the transmitting antenna.

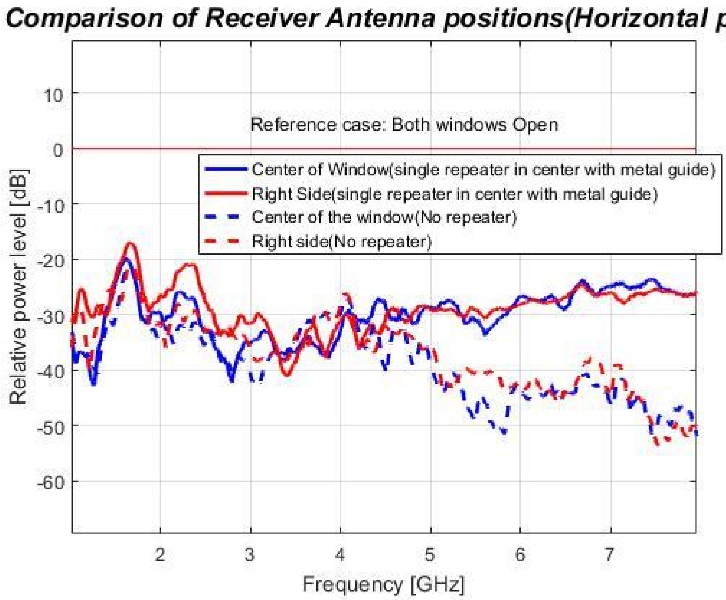


Figure 59: Comparison results of one passive antenna at center covered with metal for horizontal polarization

Four passive repeaters of the same type were used for the measurements. A1 and A2 were same and factory manufactured, while A3 and A4 were made of cardboard with metal strips. Figure 60 shows the A1/A2 passive repeater placed at central position.

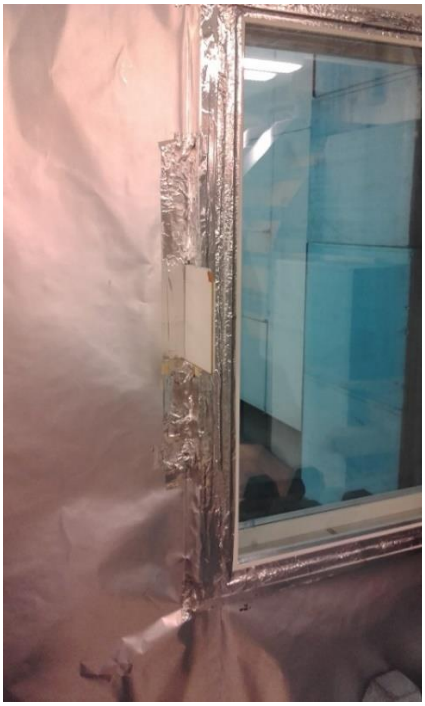


Figure 60: A1/A2 in center

Figure 61 compares the results of various passive repeaters used for the measurements with TXB250 and RXB150, and Figure 62 shows the comparison of various passive repeaters with TXB250 and RXB250 for vertical polarization.

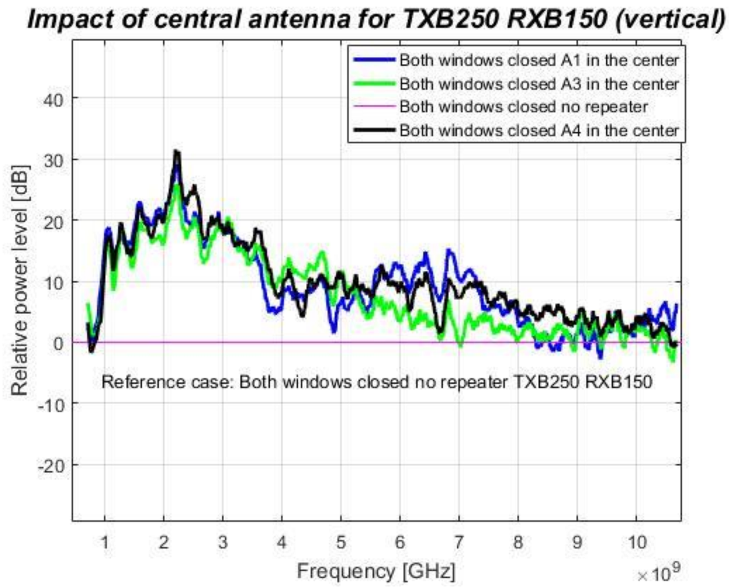


Figure 61: Impact of central antenna for TXB250 RXB150 (vertical)

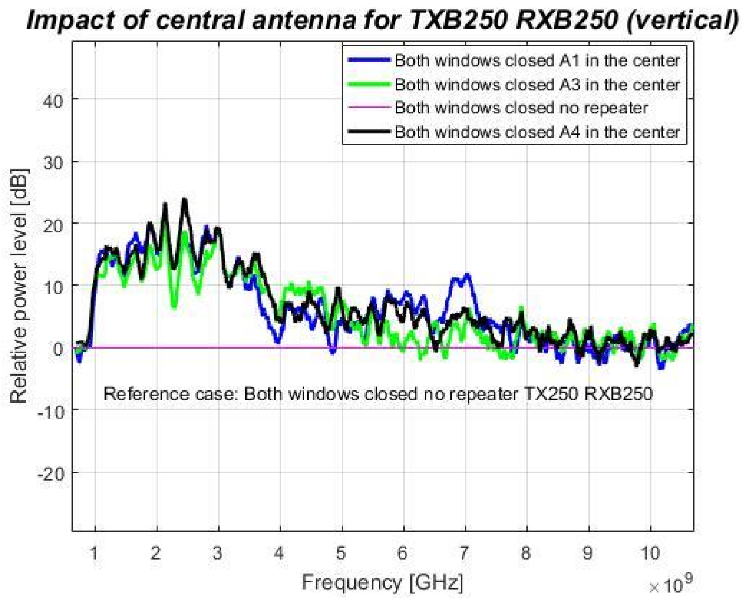


Figure 62: Impact of central antenna for TXB250 RXB250 (vertical)

For the central position of the passive antenna, all passive antennas showed good gain compared to the reference case where both windows were closed and no passive repeater in place, but the antenna A4 showed relatively better results than others. For RXB150 and TXB250, the gain ranging from 1 to 4 GHz has been around 20 dB on average with highest peaks at 2-3 GHz. The higher frequencies showed little improvement. For RXB250, the gain was slightly lower than the RXB150 case, but still considerable amount of improvement for vertical polarization.

Figure 63, Figure 64, and Figure 65 show the comparison of horizontal shifts with one central passive repeater in place.

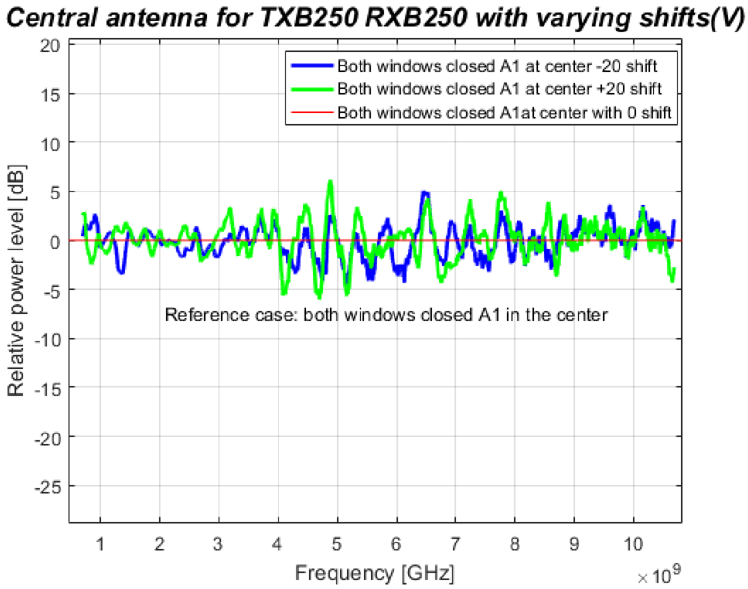


Figure 63: Central antenna for TXB250 RXB250 with varying shifts (V)

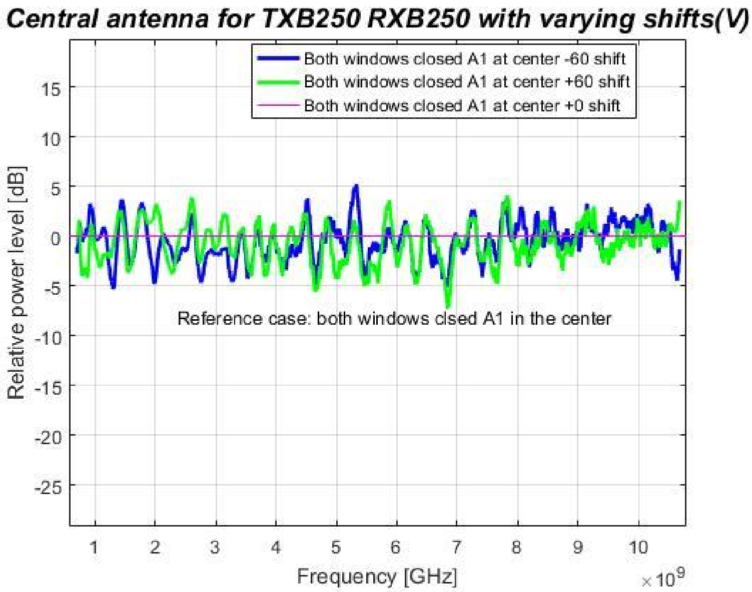


Figure 64: Central antenna for TXB250 RXB250 with varying shifts (V)

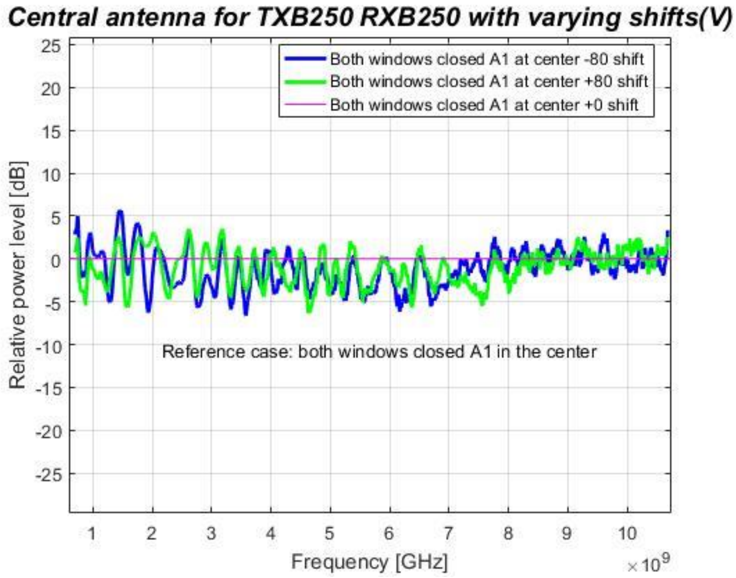


Figure 65: Central antenna for TXB250 RXB250 with varying shifts (V)

As can be seen in the results above that the horizontal shift with one central passive antenna, doesn't seem to show much of a difference amongst the horizontal shifts for TXB250 RXB250 and vertical polarization.

The passive antenna A3 was then folded towards the outside, inside, and both sides to see the effect. It can be seen in the following results that compared to non-folded case the combination didn't show any improvement, but they did vary relative to each other in the lower frequencies, but not significantly.

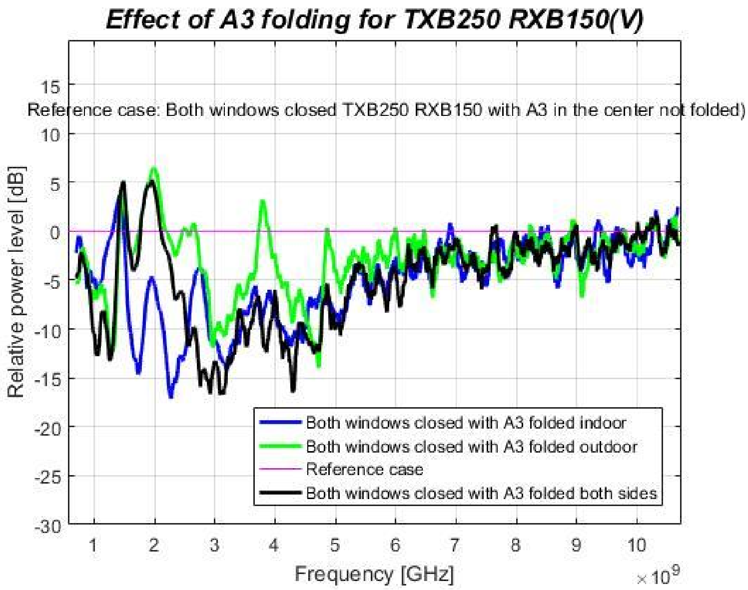


Figure 66: Effect of A3 folding for TXB250 RXB150 (V)

5.3.4. Two passive repeaters

The comparison of the antenna positions for two passive repeaters is shown below in the Figure 67. It is clear from the following comparison that two passive antennas 20 cm apart show considerable gain from frequencies ranging from 1 GHz to 3 GHz, and then the higher frequencies ranging from 7 to 8 GHz. The right side and the center position of the receiving antennas show slight variation between each other as shown in the figure below.

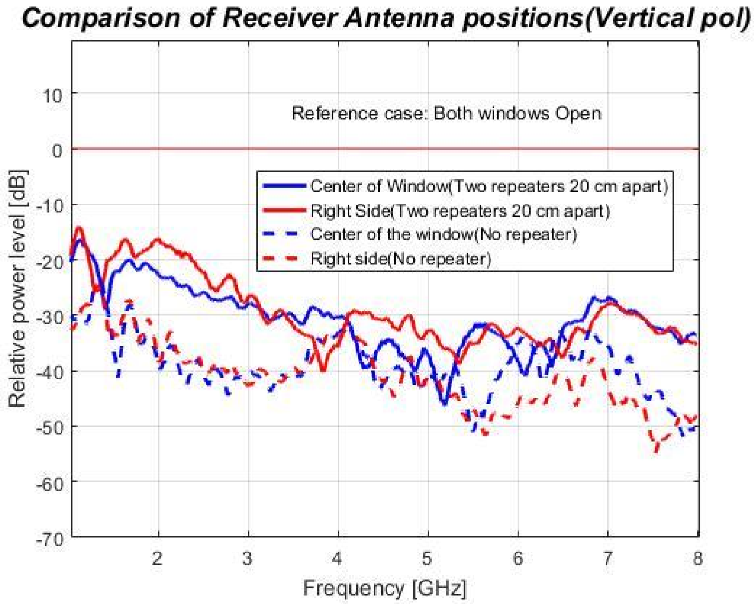


Figure 67: Comparison results of two repeaters 20 cm apart

The Figure 68 below shows the comparison of receiver antenna positions for vertical polarization for the passive repeaters with the separation of 1 cm between them. Again the repeaters show almost the same results as the previous case, and the trend between the right and center is the same i.e. insignificant. The 1 cm and 20 cm separation between the antennas adds a little difference to the gain, and both separations show the identical gain of 15 dB. In order to make this comparison, both windows open case was taken as reference in order to remove the impact of windows from the equation, so that we can get the accurate results.

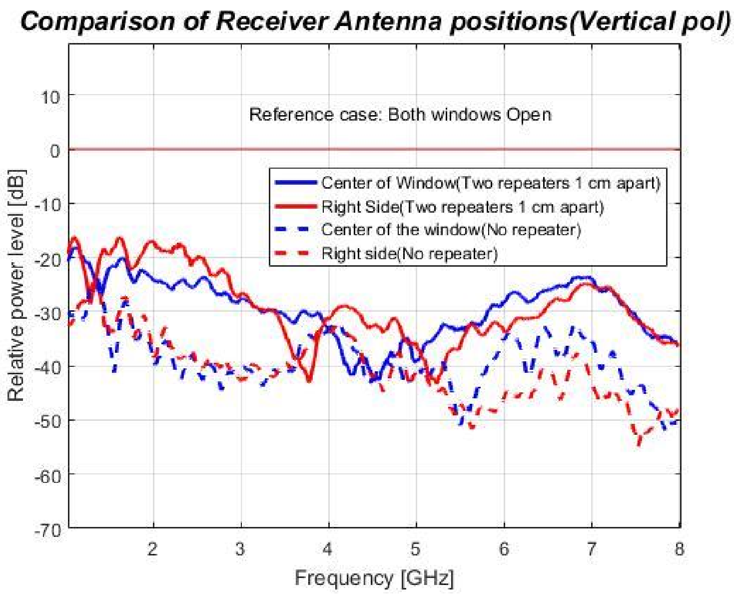


Figure 68: Comparison results of two repeaters 1 cm apart

5.3.4.1. For varying RXB

Figure 69 shows the two passive repeaters placed with 1 cm distance between them. We carried out a comparison with two passive repeaters 1 cm apart with varying vertical shifts to see the effect.

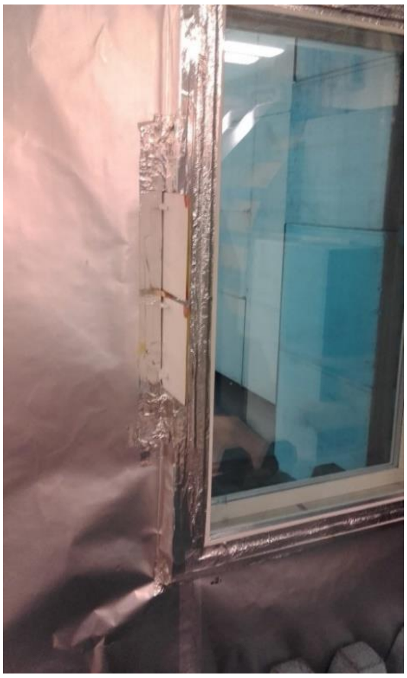


Figure 69: Two passive repeaters in the center

Figure 70 below shows the comparison for TXB250 and varying RXB for vertical polarization with two passive repeaters 1 cm apart.

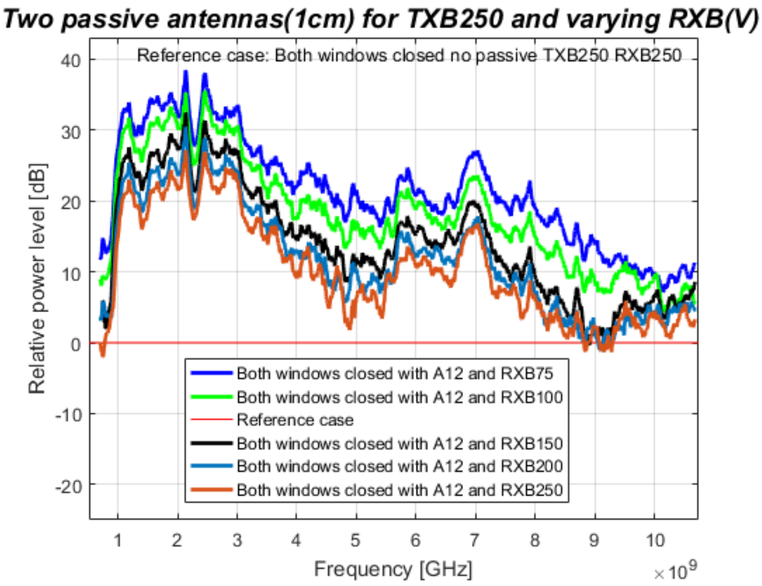


Figure 70: Two passive antennas (1 cm) for TXB250 and varying RXB (Vertical)

It is clear from the above comparison carried out in order to see the impact of two passive antennas being 1 cm apart, the distance from the windows seems to effect the power gain from the perspective of point B and TX fixed at 250. The 75 cm on the receiver end gives the highest gain improvement relatively. The separation of 20 cm between the repeaters was not used in this comparison, as the separation seemed to produce negligible difference.

The following figure 71, shows the two passive repeaters plot relative to the distance, and it is clear from the result that with the increasing distance the relative power level is dropping, as can be seen in the following figure.

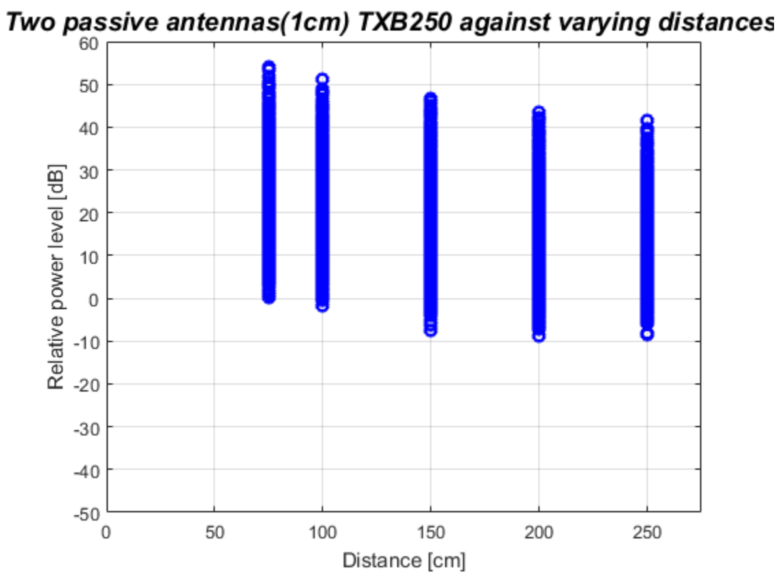


Figure 71: Two passive antennas (1 cm) TXB250 against varying distances

5.3.4.2. For varying horizontal shifts

The following two figures, Figure 72 and Figure 73 show the comparison for two passive repeaters 1 cm apart for TXB250 and RXB250 with varying horizontal shifts. It is clear from the following results that the varying horizontal shift has insignificant effect on the gain of the repeaters.

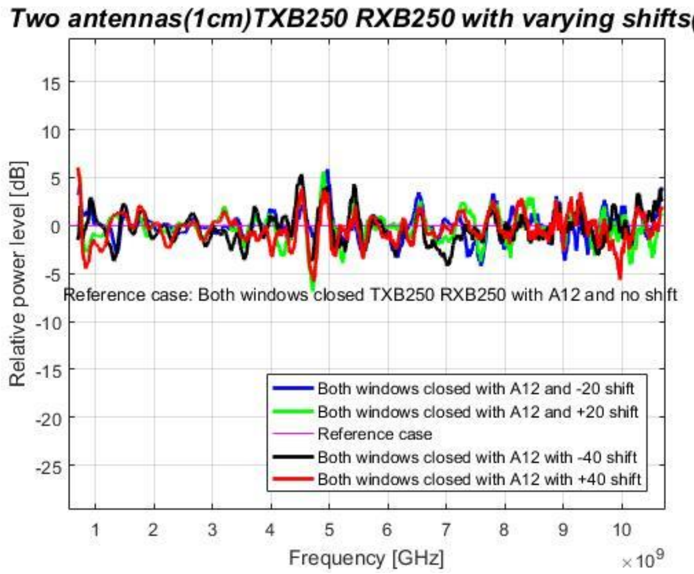


Figure 72: Two passive antennas (1 cm) TXB250 RXB250 with varying shifts (V)

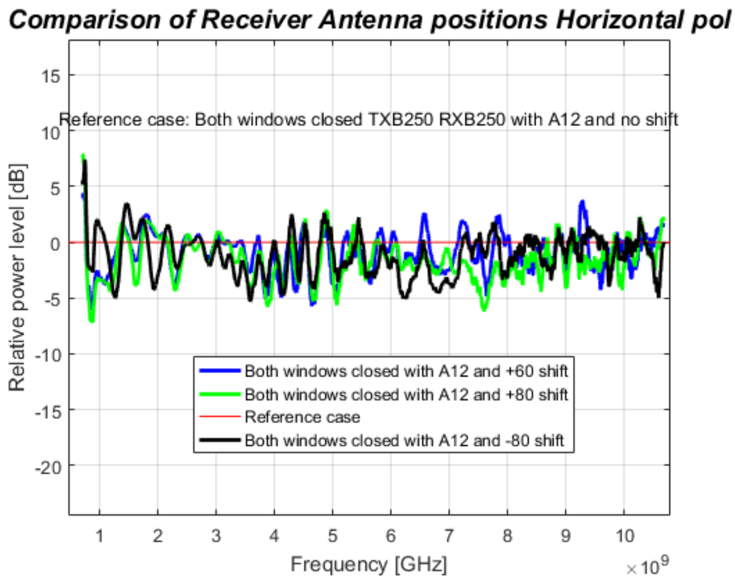


Figure 73: Two passive antennas (1 cm) TXB250 RXB250 with varying shifts (V)

5.3.4.3. For varying repeaters protrusions

Figure 74 below shows the varying passive antenna protrusions in centimeters towards inside. The figure particularly shows 0 cm protrusion of the two passive antennas.

Figure 74: Varying passive antennas protrusions, in this case 0 cm

It can be seen in the following comparison that protrusion of 4 cm shows better results than all the other protrusions especially in the middle frequencies. However, there is a trend in the comparison that with increasing protrusions the gain keeps improving until 5 cm.

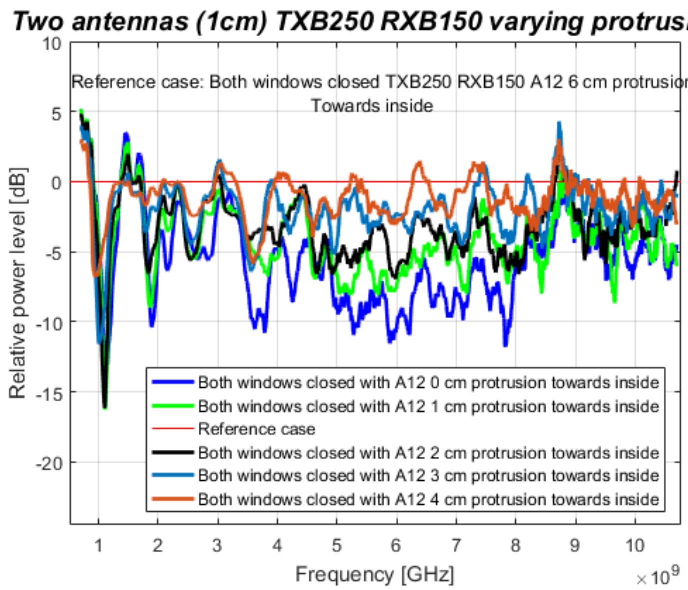


Figure 75: Two passive antennas (1 cm) TXB250 RXB150 varying protrusions (V)

For the protrusions beyond 5 cm as shown in the Figure 76, the difference between them till 9 cm is insignificant.

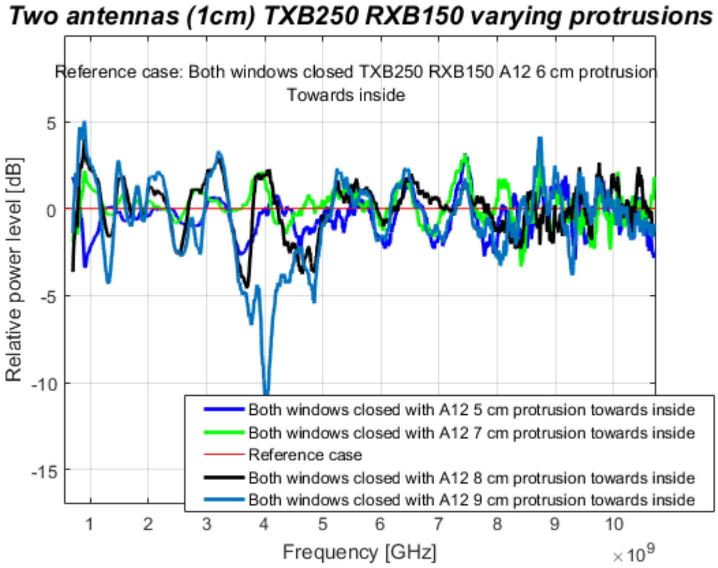


Figure 76: Two passive antennas (1 cm) TXB250 RXB150 varying protrusions

5.3.5. Repeaters combinations effect

Figure 77 and Figure 78 show more focused comparison of repeater combinations. Scattering parameter s21 is taken into account for Figure 77, which is related to the receiving antenna placed relative to the center of the window. Figure 78 shows the comparison of all the repeaters combination in terms of s31 which is related to the receiving antenna relative to the right side of the window in line with the position of the passive repeater.

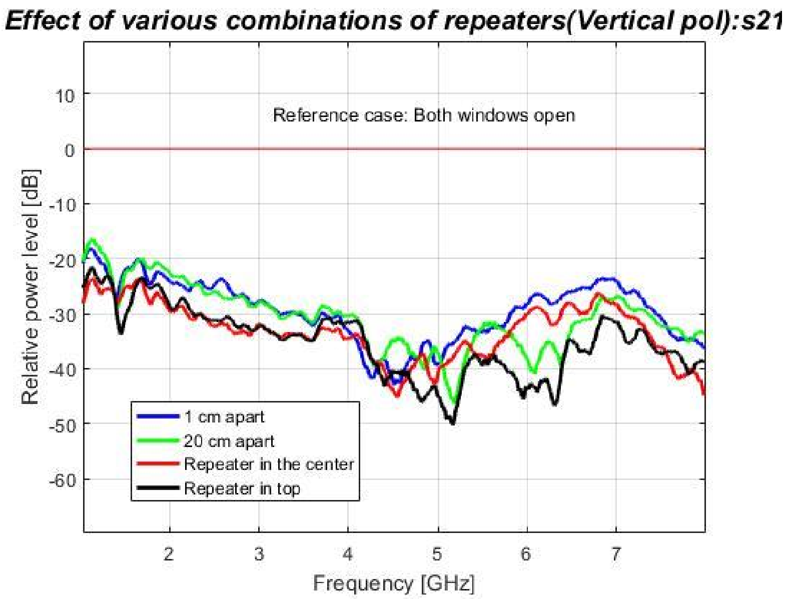


Figure 77: Comparison for the s21 of various repeaters combinations

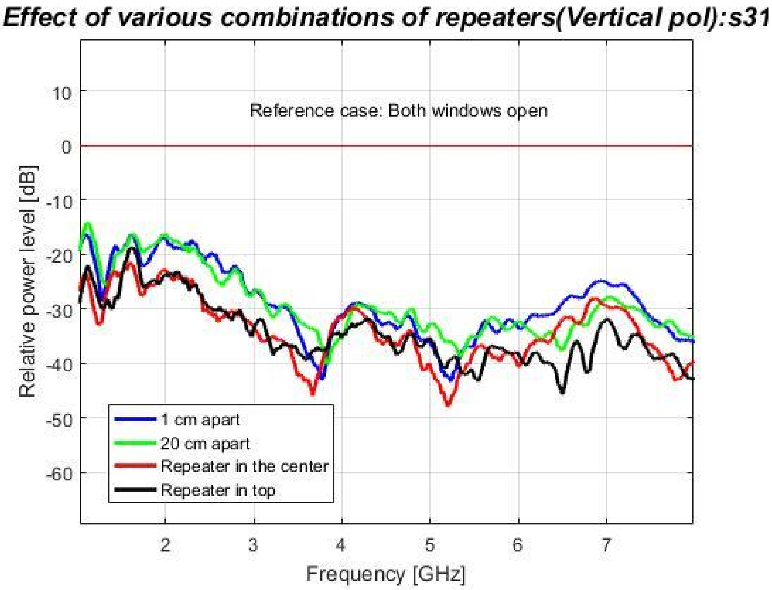


Figure 78: Comparison of the s31 of various repeaters combinations

In terms of the position, and separation of the passive repeater, two passive repeaters with 1 cm and 20 cm apart distance show more gain than the one passive antenna in the center and upper position. Repeater at the upper position seems to perform relatively low at the higher frequencies than the other repeater combinations for vertical polarization because of the heights of transmitting and receiving antennas.

6. DISCUSSION

The metal coating used in the modern windows to achieve the thermal isolation, causes serious impeding of the radio wave propagation through them. One solution to the problem based on the use of passive repeater antenna is designed by Adj.Prof. Erkki Salonen, the patent application for which was pending when this thesis is published. That antenna structure was radiated by measurements, and in this thesis results of those measurements are presented and discussed. The measurements results we received are quite promising, and show that the use of the designed passive antenna adds considerable improvement to the gain of the propagated radio signals. We conducted our measurements within the frequency range of 700 MHz to 10 GHz.

However, in the CST, the propagation simulations were focused in the range of 700 MHz to 4 GHz. The main idea behind the simulations was to see the effect on the propagation of the plane wave through the window model mimicking the real measurement scenario, and the wall. It is clear from the simulation results that the electric field varies across the probes markers placed to see the effect of the electric field. The far field results show the attenuation of 20 to 30 dB against given frequencies which is consistent with the problem mentioned in the first chapter. The propagation results are also consistent with the results of actual measurements. Since the variations in the electric field around different probes vary across the distance; it led us to carry out the second setup of the measurements, where the receiving antenna was placed at various positions horizontally, and vertically to see the actual effect on reception due to varying nature of the field beyond the selective windows towards the indoor reception.

In the first setup of the measurements, various combinations of the passive antennas with varying distances relative to each other have been used and compared with the cases where we didn't have any passive antenna in place. On the receiving end 3 different receiver antennas were used at various heights and relative to right side of window and the center of the window. However, the results of the antenna number four are not presented in this thesis. Also, the results presented above mainly focus on the vertical polarization for practical purposes, and the frequency domain representations of the results have been focused on, to see the impact on propagation at various frequencies.

In order to see the impact of windows on the propagating signal, the window combinations such as; Inner closed and outer closed(Ic/Oc), inner open and outer closed(Io/Oc), and inner closed and outer open(Ic/Oo), have been taken into account without any passive repeater for vertical and horizontal polarizations. For vertical polarization, as expected, both windows closed affect the transmission strongly, while the inner closed and outer open has lower attenuation than the outer closed and inner open for vertical polarization. It is because outer window is of aluminum which affects the radio signals more than the wooden window frame. There is not much of a difference between the s21 and s31 in this case. For the horizontal polarization, again the inner closed and outer open has lesser impeding than the outer closed and inner open for both S21 and S31.

It is clear from our results that two passive antennas show considerable gain from the frequencies ranging from 1 GHz to 3 GHz, and then at the higher frequencies ranging from 7 to 8 GHz. The 1 cm and 20 cm separation between the antennas adds a little difference to the gain, and both separation show the identical gain of around 15 to 20 dB. One passive antenna at the center also shows the gain of around 10 to 15 dB around the same frequencies mentioned above, and there is a little variation in terms of the right side and center of reception relative to the passive repeater position. Repeater in the center show better results than the repeater at upper position. Repeater at the upper position seems to perform relatively low at the higher frequencies than the other repeater combinations for vertical polarization because of the heights of the transmitting and receiving antennas relative to the repeater's position.

We took several antenna locations vertically and horizontally, to compare the effect of the movement of the receiver. The details are presented in the previous chapter. At the 250 cm distance of transmitter and receiver from the windows, the effect of taping the frame with aluminum has a considerable impact on the radio wave propagation, as not taping the frame shows better results for frequencies 0.8 GHz to 7 GHz because of of the open slots in the windows frame. The reason for no effect on the higher frequencies could be because of the radiation pattern of the transmitting antenna at higher frequencies because of which there is less power in the frame slots, and hence the insignificant change at higher frequencies because of taping.

It is important to notice that 'A' point of say; TXA250 represents the 250 cm distance of transmitting antenna from the center of the windows, while the 'B' point of say; TXB250 represents the distance of 250 cm in line with the position of the passive antenna from transmitting antenna as mentioned in the previous chapter. Same goes for the RXA250 and RXB250. The horizontal shifts show the shift on either side of the point B with a particular distance from the side of the window where passive antenna is inserted for our measurements. Along all the horizontal shifts at TXB250 and RXB250, the effect of these shifts seems to be negligible and the result varies insignificantly. In case of vertical movement of the receiving antenna from the point B, such as, at 75 cm, 100 cm, 150 cm, 200 cm, and 250 cm, while the transmitter antenna being fixed at 250 cm at point B; at lower frequencies the closer the receiver is to the windows the attenuation is slightly lower than the other cases.

Four passive antennas of the same type were used, including the one made by cardboard and the metal strip (A3), and were named A1/A2, A3, and A4. For the central position of the passive antenna, all passive antennas showed good gain compared to the reference case where both windows were closed and no passive repeater in place, but the antenna A4 showed relatively better results at lower frequencies than others. For RXB150 and TXB250, the gain ranging from 1 to 4 GHz has been around 20 dB on average with highest peaks at 2-3 GHz. The higher frequencies showed little improvement. For RXB250, the gain was slightly lower than the RXB150 case because of the effect of distance.

The horizontal shift with one central passive antenna, doesn't seem to show much of a difference amongst the shifts for TXB250 RXB250. For two passive antennas being 1 cm apart, the distance from the windows affect the power gain from the perspective of point B and TX fixed at 250, the 75 cm on the receiver end gives the highest gain improvement relatively. The gain of two passive antenna is also more than the one passive antenna. The separation of 20 cm between the repeaters was not used in this case, as the separation seemed to produce negligible difference. In case of varying horizontal shifts when two passive antennas used, and distance fixed at 250 cm from point 'B' on both ends, the impact is again insignificant. The most probable cause for insignificant variations for the horizontal shifts could be the radiation pattern of the transmitting antenna not being wide enough.

Antenna protrusions represent the two passive antennas (A1 and A2) sticking out of the wall towards the inside in centimeters; 1, 2, 3, and 4, so on represent the centimeters of antennas sticking out from the inside. These measurements were taken with zero horizontal shift and TXB250 and RXB150. The result show that up to 5 cm the relative gain keeps improving. 5 cm protrusion shows slight improvement in the middle frequencies in particular i.e. ranging from 3 to 8 GHz. However, from 6 cm to 9 cm, there is no significant difference. Compared to 0 cm and 4 cm protrusion, the 4 cm shows around 10 dB gain in the frequencies ranging from 3 to 8 GHz. The improvement of gain is noticeable till 5 cm as can be seen in the results in the previous chapter. Antenna protrusions were measured to see the effective position of the passive repeater that could give us the maximum performance. For these measurements, 6 cm protrusion was taken as a reference which corresponds to the actual position of the repeater we used in our measurements.

The passive antenna number A3 was folded towards the outside, inside, and both sides to see the effect. It was found that compared to non-folded case the combination didn't show any improvement, but they did vary relative to each other in the lower frequencies, but not significantly.

The antennas used for the measurements have been highly directional, and the measurements were taken in an EMC chamber at University of Oulu with absorbers placed to avoid the ground reflections on both sides. Proposed passive repeater could be further experimented in the real life scenario to see how much improvement in the gain the proposed passive antenna brings, especially on the frequencies commercial mobile phone operators carry out their transmission, along with other indoor communication.

In terms of the implementation, it is hard for the passive antenna to be inserted in already manufactured buildings that aim at thermal isolation as their foremost requirement. The passive antenna can be implemented during the manufacturing process of the building, and need to be fixed in such a way that the thermal isolation is not compromised, and the advantages of it can be utilized.

7. CONCLUSION

This thesis addresses the radio wave propagation issues put forth by the metallic coating on the glasses of the windows being widely used in modern housing construction to achieve thermal isolation. The thermal isolation is the advantage that these selective metal coating windows provide, but they also put constraints on the radio wave propagation through them. The amount of attenuation induced by these windows have been mentioned in the first chapter. Various solutions to the problem that are currently being incorporated, and those that could possibly be implemented to address the issue at hand were also mentioned. Out of those many solutions, passive antenna solution had been addressed, and verified in this thesis.

The propagation simulations in the CST were run with a window model focusing on the real measurement scenario within the frequency range of 0.7 GHz to 4 GHz. The idea of these simulations was to see the effect of the signal propagation through the wall and window structure, and also the deviation of electric field beyond the window model towards inside reception.

The measurements were conducted in the EMC chamber first with three receiving antennas, and one transmitting antenna. The receiving antennas were positioned on the basis of either being in line with the position of passive antenna, that is, the edge of the window, or from the center of the window. In the second setup of the measurements, one transmitter antenna and one moving receiver antenna were used.

In one passive repeater case, the improvement in gain of about 10 to 15 dB is seen at frequencies ranging from 1 GHz to 3 GHz and 6 GHz to 8 GHz. The repeater in center has better results than repeater at upper position because of the heights of the transmitting and receiving antennas.

In case of two passive repeaters case, regardless of 1 cm and 20 cm separation between the two passive repeaters, they show identical gain of around 15 dB at frequencies ranging from 1 GHz to 3 GHz and 7 GHz to 8 GHz. There is not much improvement in the gain at other frequencies. Two passive antennas regardless of the separation between them improve the gain more than the one passive antenna. The average improvement is close to theoretical 6 dB of two element array. Receiver being at center or in line with the window corner, makes little difference.

The movement through the horizontal shifts makes little difference in the reception, however, the vertical movement has effect on the gain. The antenna protrusion towards inside shows a difference, in particular at 5 cm, the result is better than all the others. The folding of the passive antenna again doesn't bring much of a relative gain compared to non-folded case.

It is also clear from our findings that passive repeater transmits the spherical waves which are dependent upon the distance by the factor $1/r^{2,}$ which is shown in the measurement chapter with the relative power gain plot against the distance. The signal propagation through windows from the outside are affected by the aluminum frame as well as the selective glasses. Taping the frame slots totally blocks the signal propagation through the aluminum frame, and if the slots are not sealed waves propagate through them. Using the Aluminum foil for taping further adds to the signal deterioration. As mentioned, taping the frame doesn't affect the higher frequencies compared to untapped cases, and the most probable reason for that is the radiation pattern of the transmitting antenna. The distance dependence of taping the frame is same as the case of not taping the frame, but only the results vary at lower frequencies, and higher frequencies remain indifferent.

In general, the proposed antenna clearly shows considerable improvement in the gain of the propagated radiated signal which is clear from the results presented and discussed in this thesis.

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