UWB-Antennas for Wall Penetrating Radar Systems

OTAR JAVASHVILI

Supervisors:	**Daniel Andersson & Kjell Wallin, *Radarbolaget AB***
Examiner:	**Prof. Claes Beckman**

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ABSTRACT

Basic properties and new design principles of ultra wideband Vivaldi antennas are presented and discussed in this paper. The focus will be on the modeling of Vivaldi antenna design curves, by which it is constructed; its simulation results, realization and the measurements.

According to the aim of this research the discussion starts with the review of the previous researches done for Vivaldi antennas. Introductory part of the report also contains the problem description for the current project and the classification of the goals to be achieved. As a theoretical review, the discussion initiates with the definitions and description of basic parameters of the antennas and covers a short presentation of UWB pulse-based radar system. The attention will be focused on UWB signals behavior and characterization, their propagation principles and basic troubles stands nowadays. As an application the wall penetrating Radar systems will be considered. The major part of the report holds on the investigation of the design principles of Vivaldi Antenna and optimization of the key parameters for achieving the best performance for radar. The ending part of the report shows the simulations and measurement results and their comparisons following with conclusions/discussions.

The report will be supportive for the antenna designers, who work for UWB systems and particularly for Vivaldi antennas, as long as there are showing up detailed descriptions of Vivaldi antenna characteristics depending on its shape and substrate properties. The model for designing Vivaldi antennas, given in this project, can successfully be applied for almost all the cases used in practice nowadays.

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LIST OF ACRONYMS

3D	Three Dimensional
3G	Third Generation
3L	Three Layer
AC	Alternating Current
ADC	Analogue to Digital Converter
BAVA	Balanced Antipodal Vivaldi Antenna
BS	Base Station
DAC	Digital to Analogue Converter
DC	Direct Current
DUT	Device Under Test
FWHM	Full-width at half-maximum
GP	Groundplane
HFSS	High Frequency Structure Simulator
HPBW	Half Power Beam Width
IEEE	Institute of Electrical and Electronics Engineers
PRBS	Pseudo Random Binary Sequence
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RS	Radar System
Rx	Receiver
SFMG	Scattered Field Measurement Gain
TL	Transmission Line
TRP	Total Radiated Power
Tx	Transmitter
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UWB	Ultra-Wideband

KEY WORDS

- ***Vivaldi Antenna***
- ***Ultra WideBand***
- ***Radar Systems***
- ***Wireless Communications***

1. INTRODUCTION

Considering the practical aspects of a current project the major intention of this research is to improve the accuracy of the radar system, used for wall penetrating applications, by improving the characteristics of the radar antennas. The system, built by the company Radarbolaget AB, is based on UWB Pulse-based technology and is developed for supporting the industrial sector, as a civilian application. The system is responsible to observe the processes running inside a furnace made by approximately 2 meters brick walls. The internal temperature is around 1200 ^{0}C. Such a high temperature makes it impossible to use any equipment inside the furnace for monitoring the processes. While, wall-penetrating radar became the only effective solution for salvation of the presented problem.

- **Problem Description**

The most of the factors, essential for the radar, are the resolution of the system and the accuracy. One of the most important advantages for UWB systems is that the UWB signals support ultra-narrow pulse generation, which positively affects the resolution of the radar. As narrow pulses can be generated from the system as high resolution of target detection (even in cm range) can be achieved. For building the high-quality system, the complication appears mostly with the analogue components of the UWB system, such as antennas, filters or etc.; also more complication of the signal generation and signal processing is required. The simplicity of the system and its accuracy will be greatly improved if the number of analogue components is possibly decreased. Although to replace the sensor with the corresponding digital system component seems impossible. Therefore, it is said, that the accuracy of UWB radar is significantly depending on the properties of the sensor.

To achieve pulse reception without considerable damages and generally for optimal wave reception, the linear phase or near to the constant group delay for the UWB antennas is required. Also the ringing, which is one of the most important troubling properties of the UWB antennas, is effecting the UWB behavior of antenna. Ringing limits the accuracy of the system a lot, since the ability of the reception for the adjacent pulses becomes limited; in other words, the detection of the closest “next” target after previous one will be not possible.

More important parameters for the UWB antennas are the impedance bandwidth, usable gain, the radiation efficiency, the directivity, the beamwidth of the main lobe and minimization (zeroing) of the side-lobes and back-lobes. In addition, from the practical side of view, the dimensions of the sensors and their boundaries should be minimized to increase the mobility of the system. It should be mentioned, that the high quality sensor makes whole system simpler, without need of additional analogue system-components implementation and assembles the outcome of the signal processing much more effective.

The radar system which is considered in a current project employed the sensors, which presented two relatively large Vivaldi antennas with the total size of 300x300x300 mm and for the frequency range of 0.7 - 10 GHz. The size of separate Vivaldi antennas was 185x210x1 mm with substrate material FR4. The maximal working temperature is 125^0C.

- ### Goals

The main tasks for the project are to find the limitations for the following key parameters for the Vivaldi antennas: radiation bandwidth, radiation pattern, phase linearity, UWB behavior and the physical dimensions. The goal is to find a new ways of designing Vivaldi antennas so that to improve the outcome of the presented parameters.

- ### Previous Works

Several researches have been done and several works have been reported for the Vivaldi antennas. In all the cases it shows good UWB behavior, mostly for the cases of UWB impulse transmission. The comparisons have been done also between Vivaldi antenna and some of other type of UWB antennas. The table 1.1 shows the comparison of characteristic parameters of bowtie antenna, spiral antenna, log-periodic antenna, monocone antenna and Vivaldi antenna [1]. The observations were done for impulse response of UWB antennas. The detailed parameterization is given in chapter 2.3, section UWB antennas.

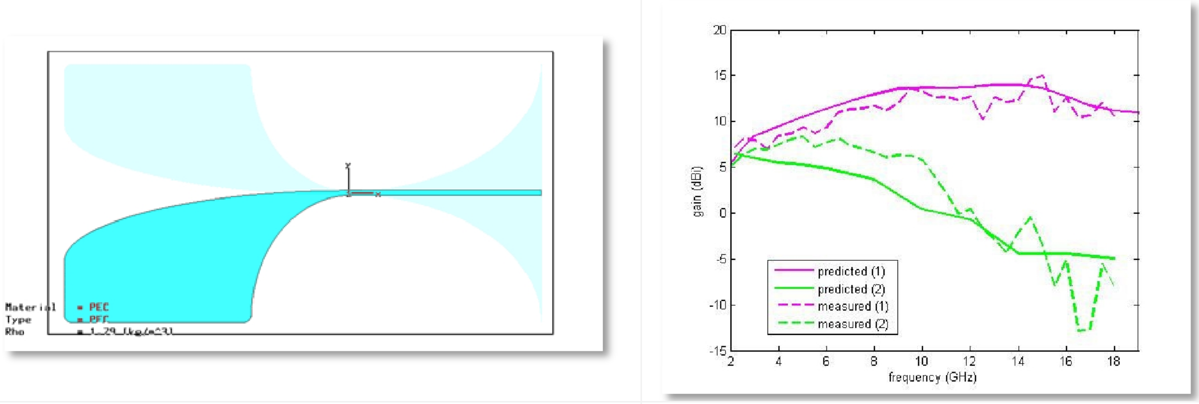
	Vivaldi	**Bowtie**	**Spiral**	**Log-Per**	**Monocone**
Pick Value p in m/ns	0.35	0.13	0.1	0.13	0.23
τ_{FWHM} in ps	135	140	290	805	75
$\tau_{r=0.22}$ in ps	150	185	850	605	130

Table 1-1 Comparison of characteristic parameters of UWB antennas [1].

From the table it is seen that the Vivaldi antenna has rather low impulse distortion compared to other UWB antennas.

Furthermore, several researches have been done lately for improving the characteristic parameters of Vivaldi antennas. Here will be looked a few of the papers to acquire a general inspiration of the newest achievements and the results.

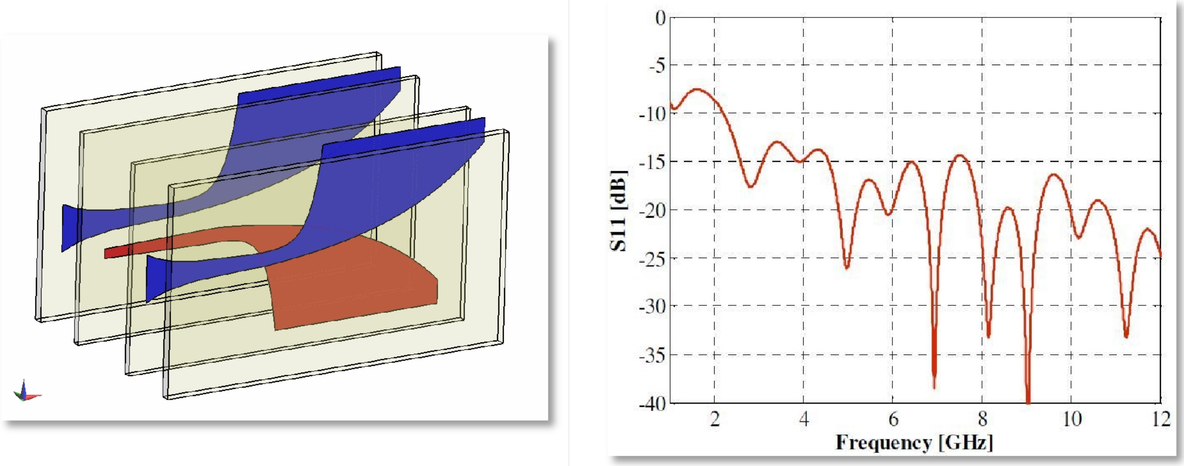
Reference [2] investigates a wideband antipodal Vivaldi antenna to achieve ultra-wideband performance. The attention was directed for antenna shape, the dielectric material and substrate thickness. The total size of antenna was 133x250 mm. Between different substrate materials, different thicknesses of the substrate and different shapes of antenna flare the widest usable bandwidth was achieved for 2-20 GHz frequency range. During observations the high dielectric material of $\varepsilon_r = 6.15$ was used for the substrate (RO3006). The main purpose was to improve the usable gain in a frequency band where S_{11} response was lower then -10dB. Also the restrictive parameter was the radiation pattern, since for the lower frequencies it was not showing functional properties. For constructing antenna design an elliptical flares were used [2] Figure 1-1 shows the prototype of discussed Vivaldi antenna and corresponding gain response along the frequency band.



(a) (b)

Figure 1-1 (a) Vivaldi antenna design; (b) Antenna gain curve 2-20 GHz for: RO3003 (1) and FR4 (2) [2].

Reference [3] considers balanced antipodal Vivaldi antenna (BAVA) constructed with 3 copper layers and 4 dielectric layers. As a substrate material the dielectric, RT/Duroid 6002 from Rogers Corporation with relative permittivity of 2.94, was chosen. The width and the length of the antenna is 44 and 74 millimeters respectively. The simulation shows S_{11} parameter response below -10dB from 2.2GHz (figure 1-2 (b)). No upper limit has been found up to 17GHz, because of the simulation and measurement limits Figure 1-2 (a) shows the design of presented Vivaldi antenna.



(a) (b)

Figure 1-2 (a) BAVA construction with the 3 copper layers and the 4 dielectric layers; (b) Simulated reflection coefficient (S_{11}). [3]

An example of the group delay variations for the typical Aperture Coupled Vivaldi Antenna, taken from the reference [1], is shown on figure 1-3. The same figure demonstrates also the group delay response of the Log-periodic antenna.

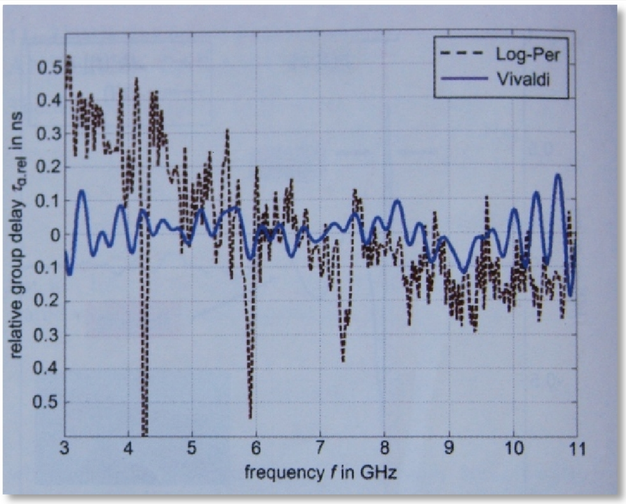


Figure 1-3 The group delay of a Vivaldi antenna and a Log-Per antenna [1].

In general, there are not many works done for improving the low frequency behavior of the Vivaldi antenna. The most of the researches considers the low frequency limit for the operation band as 2 GHz.

- **Current Work**

The improvement of Vivaldi antenna parameters is done during this project for optimizing the radiation bandwidth with usable gain response along the whole operating band. It automatically means the optimization of the size of antenna. An investigation of phase linearity and UWB behavior of the antenna have been accomplished too.

For improving antenna parameters the new solutions for the design implementation were needed, which can be considered as an innovative part of the project. The innovation stands on the formulation of design curves by which antenna is constructed. New design shows the best possible response for any different substrates and different frequency limits, in addition with maintaining the smallest possible dimensions.

Design procedures and the results are illustrated in chapter 3 - Vivaldi Antenna Design and chapter 4 - Vivaldi Antenna Implementation correspondingly.

For constructing and simulating antenna designs the High Frequency Structure Simulator (HFSS) software from Ansoft is used. The research was done as a master’s thesis of University of Gävle in a Radio Center Gävle with collaboration to the company Radarbolaget AB.

2. THEORETICAL REVIEW

2.1 Introduction

The original problem in telecommunications is transferring the information signals from one to another place; in other words, to establish communication between various telecommunication units by and through the communication media, so called transmission interface. Generally, several different natural and manmade transmission interfaces exist nowadays, who have the ability of transporting signals; examples are: twisted wires, coaxial cables, waveguides, fibre optics, air interface or vacuum and etc. Each of them has its own properties and different influences over the signals transmitting through them. Hence it follow that we need to build the information carrying signals to be suitable for transmitting in an exacting transmission interface considering the characteristics of the media. But, when signals pass from one to another transmission interface they become sacrifice from dissimilar transmitting characteristics of the media and they do not feel comfortable without exceptional modification. In most of the cases the communication system uses not only one interface at a time when building a network, which pushes out the need of using the special technique to establish the 'right' communication between different media; i.e. changing signal properties step by step (or interface by interface) properly. Here comes the term of matching, which carries a 'bridge' function between two different interfaces.

To make the concept clear, better to have a simple characterization of the transmitting interface. In electronics point of view it can be thought, that every media have their own characteristic impedance, which describes how resistive it is towards the signal transmission. When signals are passing trough the different transmission interfaces with different characteristic impedances the reflections appear at the connection points and some of the power is reflected back to the source interface, which is perceived as a power loss. To avoid power losses during signal transmission the "perfect" matching between different transmission interfaces are required. Matching networks provide a transformation of impedance so that they maximize the signal transfer and minimize reflections between two communication media. There exists high variety of electrical matching networks used between different communication units to connect them to each other. Here, the focus will be on the communication between wired (coaxial cable) and wireless (free space) interfaces.

As long as the wireless communications come into view, the requirement for signal transmission in the air or in a free space interface becomes extremely important. The idea is to leave the cables and closed transmission interfaces and to go out through the space. An electrical communication unit responsible for the matching between wired and wireless media is called an antenna.

2.2 Antennas

- **Definition**

Antenna is an electrical circuit used in microwave/RF networks to match the signal transmission line (coaxial cable, waveguide, etc.) to the signal propagation interface (air, vacuum, etc.). Antenna transforms the signals formed by the electrical currents inside the cable to the electromagnetic waves propagating in a free space. It's an electrical device that sends or receives radio signals.

By the *IEEE Standard Definitions of Terms for Antennas* (IEEE Std. 145-1993) an antenna is defined as "a part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves".

There are several different sources for the definitions of antennas; all of the definitions come from the functions that antenna curries and from the basic working principles they do. The detailed description of antenna behavior and functionality is discussed in the following part of the report.

In general, antenna in both transmitting and receiving modes acts upon the same principles and obeys the same functionality, that's why the following pages does not show separate discussions for transmission and reception modes of antennas.

- **Propagation Principles**

To clarify the job antenna do we need to go through the theory of electromagnetism, Maxwell's equations and propagation principles. First, describe the signals passing through the cable and signals travelling in free space and then define a theory of signal transformation done by an antenna. Electric and magnetic phenomena at the microscopic level are described by Maxwell's equations, as published by Maxwell in 1873 [4].

In a cable, signals are transmitting by the electric currents moving during it. An electric current presents an electromagnetic field, since the current is the flow of charged particles and any charged particle presents an electromagnetic field itself. Time-varying electromagnetic fields produce electromagnetic waves. Generally, we talk about alternating currents as an information carrying signals and such currents produce time-varying electromagnetic fields. And here we reach the point where we wanted to be, that the alternating currents are the source of radiation; so, any current currying single wire radiates. In a cable, used for signals transmission, simply we keep the two currents close together, to neglect or reduce radiation, because whenever a current becomes separated in a distance from its return current, it radiates [5]. As surprising it can be seen, the more effort is needed to prevent unnecessary radiations from the currents, since the currents are the radiators themselves.

We can agree that it is a simple task to make a device, which radiates; and we call it an antenna. But, the main task of the antenna device is to control propagating electromagnetic waves (or it can be said: to control currents) so, that we can obtain radiation in a desired frequency range, or in a desired direction in a space, or in a certain power levels, or certain polarization and etc. For that entire purposes antenna designers have created thousands of different types and styles of antennas with different practical solutions, different shapes and dimensions, with different functions and etc. But, still the essential part is to achieve specific current distributions through the antenna shape.

Classification of Antennas

Antennas can be classified in several ways, according to the design principles, radiation types and frequency allocations or according to its applications and fields of use.

Currently there are definitions for 95 antenna types [6]. It is suggested that the antenna types be divided into the following classes according to their physical structure. These can be roughly divided into the following categories:

- Wire antennas (dipoles and loops)
- Aperture antennas (pyramidal horns)
- Reflector antennas (parabolic dish antennas)
- Microstrip antennas (patches)
- Dielectric antennas (dielectric resonant antennas)
- Active integrated antennas
- Lens antennas (sphere)
- Leaky wave antennas.
- Antenna arrays (including smart antennas)

Also, antennas can be classified as a narrowband, wideband or ultrawideband depending on the width of the frequency band of their operation. According to the radiation pattern antennas can be considered as omnidirectional, broadside or end-fire, single or multiple directed antennas.

Depending upon the purpose of the current project, we will concern for ultra-wideband microstrip antennas, principally the Vivaldi antenna.

Basic Parameters of Antennas

Antennas can be characterized with the following major parameters: antenna impedance, radiation pattern (power, intensity), gain, directivity and bandwidth. These parameters will be briefly discussed in this part of the report. Although, there exist some more antenna parameters for its characterization, that are not discussed this time.

Antenna Impedance - is defined as the impedance presented by an antenna at its terminals [6]. Also it can be said that it's a ratio of the voltage to current at a pair of terminals. As all the electrical components or devices, antennas have their characteristic impedance, or input impedance at the input port to clarify it in a system.

To understand what antenna impedance Z_A (or Z_{in}) means, better to look through the equivalent electrical circuit of antenna. The antenna equivalent circuit is shown on figure 1. As all the impedances, generally, so the antenna impedance is divided into real and imaginary parts. Real part of the input impedance R_A represents the resistivity of antenna and imaginary X_A represents antenna reactance. Resistivity part itself can be considered as a sum of radiation resistance and loss resistance, since antenna is a radiator device with attenuating properties and dielectric losses.

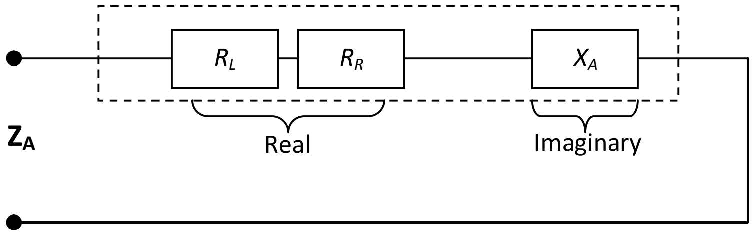


Figure 2.2-1 Antenna equivalent circuit (Thevenin Equivalent).

Radiation resistance R_R is caused because of the radiation from the currents exists through the antenna body. When AC is applied to antenna the conducting electrons become accelerated and they accumulate the energy in face of electromagnetic waves. These energies, spent by electrons as electromagnetic radiation, appear as a resistance for the circuit, which we presented in an antenna circuit. Main time some of the energy is spending because of the ohmic resistance existing in any conducting material and is showing up as a heat. We call it loss resistance R_L, since the energy dissipated as a heat is unusable.

$$\mathrm{Z_A} = \mathrm{R_A} + j\mathrm{X_A}$$

$$\mathrm{R_A} = R_L + R_R \qquad [2.2\text{-}1]$$

$$\mathrm{Z_A} = (R_L + R_R) + jX_A$$

If we assume that the antenna is connected to the system (wired circuit) with characteristic impedance Z_C and applied voltage V_C, we can characterize the current I_C through the circuit loop using Ohm's lows and can also be derive the functions for power distributions.

$$\mathrm{I_C} = \frac{V_C}{Z_C + Z_A} = \frac{V_C}{(R_C + R_A) + j(X_C + X_A)} \tag{2.2-2}$$

$$\mathrm{P_R} = \frac{|I_C|^2 R_R}{2} = \frac{|V_C|^2 R_R}{Z_C + Z_A} = \frac{|V_C|^2 R_R}{(R_C + R_L + R_R)^2 + (X_C + X_A)^2} \tag{2.2-3}$$

$$\mathrm{P_L} = \frac{|I_C|^2 R_L}{2} = \frac{|V_C|^2 R_L}{Z_C + Z_A} = \frac{|V_C|^2 R_L}{(R_C + R_L + R_R)^2 + (X_C + X_A)^2} \tag{2.2-4}$$

Where, P_R is the power delivered to the electromagnetic waves for radiation and P_L is a lost power dissipated in a circuit as a heat.

If we assume that there are no reflections (or there is perfect matching) at the connection point between the wire and antenna, the total power is exhausted for radiation in R_R and also is dissipated as a heat in R_L. The values for designated powers are directly proportional to corresponding resistance values. In real case, the maximum power delivery to the antenna can be achieved during conjugate matching between the cable and antenna, which means equal real and opposite signed imaginary parts of the impedances Z_C and Z_A.

$$\mathrm{Z_A} = conj[\mathrm{Z_C}]$$

$$\mathrm{R_A} = \mathrm{R_C} \tag{2.2-5}$$

$$\mathrm{X_A} = -\mathrm{X_C}$$

From practical side of view it’s essential to know the value of antenna input impedance. It gives information about what value of impedances can be chosen for the wire used to connect it to the antenna for power delivering. Since the wire is used to provide an antenna with information signals it is important to choose it so that it has the same characteristic impedance as antenna input impedance. In that case the power transfer maximizes and power losses turn to zero.

Radiation pattern - is the power distribution in a space around antenna radiated from it. According [7] an antenna radiation pattern or antenna pattern is defined as “a mathematical or graphical representation of the radiation properties of the antenna as a function of space coordinates”. In simple words, the radiation distribution in a space is the radiation pattern. When talking about radiated power we mean electromagnetic radiation intensity or field strength in a space.

The value, which expresses the power of the electromagnetic waves, is called the pointing vector (S). Pointing vector carries information about the power density and the direction of wave propagation and can be found from the cross product of the electric and magnetic fields at a point.

$$\vec{\boldsymbol{S}} = \vec{\boldsymbol{E}} \times \vec{\boldsymbol{H}}^{*} \qquad [\mathrm{W/m^2}] \qquad [2.2\text{-}6]$$

Power density is defined as a power per unit volume. The time average power density vector or average pointing vector can be used to express the magnitude of the fields.

$$W_{av} = \frac{1}{2} Re\left[\vec{\boldsymbol{E}} \times \vec{\boldsymbol{H}}^{*}\right] \qquad [2.2\text{-}7]$$

Since the fields are time varying, the instantaneous radiated power at a closed surface S with normal $\hat{\boldsymbol{n}}$ can be expressed using an integral.

$$P(t) = \oiint_{S} \vec{\boldsymbol{E}} \times \vec{\boldsymbol{H}}^{*} \cdot \hat{\boldsymbol{n}} \boldsymbol{dS} \qquad [2.2\text{-}8]$$

and the average power radiated by an antenna can be expressed as:

$$P_{rad} = \oiint_{S} W_{av} \cdot \hat{\boldsymbol{n}} \boldsymbol{dS} = \frac{1}{2} \oiint_{S} Re\left[\vec{\boldsymbol{E}} \times \vec{\boldsymbol{H}}^{*}\right] \cdot \boldsymbol{dS} \qquad [2.2\text{-}9]$$

When talking about radiation pattern and powers assigned from electromagnetic waves we mean that we are in a far field region from the antenna. Far field can be considered when distance from the antenna is greater then $2D^2/\lambda$, where D is the maximum dimension of the antenna and λ is the wavelength of the radiated wave. To read more about field regions visit the reference [7], section 2.2.4.

As mentioned, another value for characterizing radiation pattern is the intensity of radiation. Radiation intensity is the radiation power per unit solid angle. It depends only on the direction of radiation and remains the same at all distances. Mathematically it is expressed as

$$U = r^2 W_{av} \qquad \text{W/unit solid angle} \qquad [2.2\text{-}10]$$

Since the radiation intensity from an isotropic source does not depend on its direction and is uniformly distributed over the spherical surface it can be expressed as

$$U_0 = \frac{P_{rad}}{4\pi} \qquad [2.2\text{-}11]$$

The best way to perceive radiation pattern we chase by its visual demonstration. There exists high variety of the patterns depending of antenna types and their applications. Patterns can be omnidirectional or directed. Omnidirectional radiation means that the power radiated from antenna is equally distributed for all the directions in a space at certain distance from the antenna. Ideal omnidirectional pattern is called an isotropic pattern. Its shape looks like a sphere and can be achieved from the point source radiator, which is only theoretical representation, because it's not practically realizable. According [7], section 2.3, an isotropic radiator is defined as "a hypothetical lossless antenna having equal radiation in all directions". In practice, we call omnidirectional, when power is uniformly distributed at every point of a space in a same distance from the antenna through the certain plane, for example in a horizontal or vertical plane. Directional patterns are represented by the powers distributed (concentrated) only for one or more specific directions in a space from the antenna. Generally, we call broadside having horizontally directed radiation pattern and end-fire when it is vertical.

Gain - is one of the very important parameter which describes the performance and efficiency of antenna. It is the measure of the ability of the antenna to direct the radiated power into specific direction. For the isotropic source radiator the radiated power is distributed equally for all the directions and the power density at distance R can be derived as $S = P_0/4\pi R^2$ when the input power is P_0. It means the radiated power divided by the area of the sphere at distance R. It can be said that the isotropic antenna is 100% efficient. In general case the gain of the antenna increases the power density in the direction of the peak radiation; it sweeps the radiated power from other directions of the radiation sphere and addresses to one particular direction. Efficiency of antenna in that direction is much more then 100%, which is described numerically as a gain. So, the power density of the nonisotropic radiator in a given direction and distance can be derived as $S = P_0 G/4\pi R^2$. Gain is dimensionless quantity and in a common practice it is used in logarithmic form in dB. The gain can be formulated as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained in a case of isotropically radiated power. Both cases the equal input power would be considered [7] [8].

Directivity - is the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. It describes an ability of antenna of directing the power for the specific direction.

Directivity is dimensionless quantity and is defined as $D = U/U_0$, where U is the radiation intensity and U_0 is the intensity of isotropic source. Directivity depends only on the direction of the radiation and does not depend upon the separation from the antenna [9].

- **Microstrip Designs**

Microstrip antenna is the popular type of planar antennas. Microstrip design presents two of the copper (metallic) layers on different sides of the thin dielectric sheet (substrate). Commonly microstrip type of antennas were considered as a narrow frequency bandwidth antennas; although, lately it was perceived that some of the microstrip designs can be suitably utilized even for ultra-wideband applications. The general advantages and disadvantages for the microstrip designs can be shortly formed as given below.

Advantages - low profile, low coast, ease of manufacturing (can be fabricated by photolithographic processes), easy to integrate with other devices in a system.

Disadvantages - low efficiency, low power, poor polarization purity and poor scan performance [10].

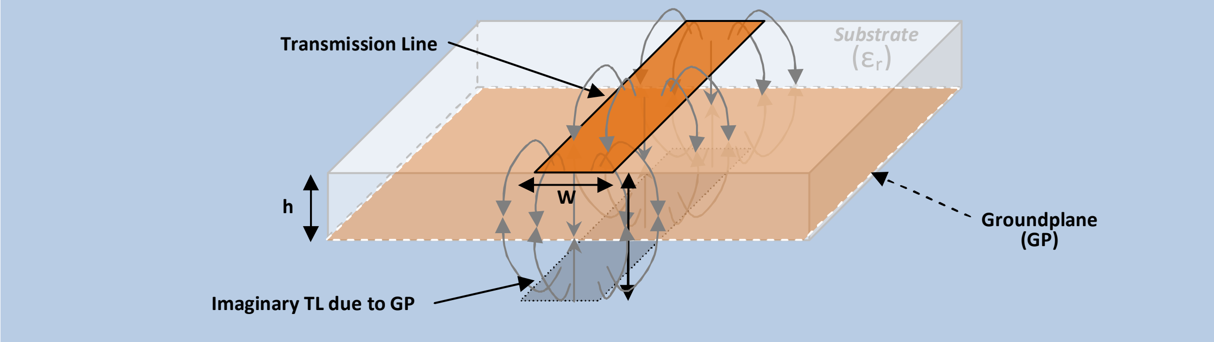


Figure 2.2-2 The graphical representation of microstrip transmission line design and work principle.

The transmission line model for the microstrip design can be considered to describe the general operational principles of microstrip design circuits. The graphical representation of the single transmission line microstrip design is given on figure 2.2-2. The transmission line with the width of W is placed on the one side of the substrate with dielectric constant ε_r and the height of h. The second side of the substrate is covered with massive layer of grounded copper, which is considered as a groundplane. There are presence of the electric field lines between TL and GP when currents appear through the transmission line. In fact the fields are presented between the currents flowing through the transmission line and the currents appearing on the second side of groundplane through the imaginary transmission line. Those two currents are with the same value and opposite direction. Imaginary transmission line, or can be said imaginary currents, are the result of the ground effect, known as image theory in electromagnetism. Even though, later on we will consider only TL and GP and interaction between them. The more discussion about image theory is given in later chapter of the report; chapter 3.2, section matching.

The interaction between TL and GP changes with the dimensions of the TL and the thickness of the substrate. So, it can be said, that the width of the transmission line and its separation from the groundplane identifies the characteristic impedance of the transmission line. Also, the effect of dielectric material must be considered, since without it the dielectric constant ε_r equals to 1 and the later case can be considered as the same as simple two-wire line, known as a TEM transmission line with phase velocity $\upsilon_{\mathrm{p}} = c$ and the propagation constant, $\beta = k_0$. These two values, which characterize the wave propagation through the TL, are different in a presence of dielectric material. Even more, in the case of microstrip design the part of the electric field lines appear above the transmission line outside substrate material in the air, which also has the effect and causes more complications. Due to this reason the term of effective dielectric constant ε_e comes into view and the phase velocity and the propagation constant can be expressed in terms of ε_e as follows (Reference [10]).

$$\upsilon_p = \frac{c}{\sqrt{\varepsilon_e}} \qquad [2.2\text{-}12]$$

$$\beta = k_0\sqrt{\varepsilon_e} \qquad [2.2\text{-}13]$$

Effective dielectric constant depends on the thickness h of the substrate and the width W of the transmission line. The approximation for calculating ε_e is given as:

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/W}} \qquad [2.2\text{-}14]$$

Depending on the dimensions of the transmission line the characteristic impedance Z_0 can be calculated.

For $W/h \le 1$, $$Z_0 = \frac{60}{\sqrt{\varepsilon_e}}\ln\left(\frac{8h}{W} + \frac{W}{4h}\right)$$

[2.2-15]

For $W/h \ge 1$, $$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_e}(\frac{W}{h} + 1.393 + 0.667\ln(\frac{W}{h} + 1.444))}$$

If there is need to calculate the width of the transmission line, when the required characteristic impedance is given the following calculations must be done.

For $W/h < 2$, $$W = h\frac{8e^A}{e^{2A} - 2}$$

For $W/h > 2$, $$Z_0 = \frac{2h}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(\mathrm{B} - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right]$$

[2.2-16]

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}$$

Through the transmission line the phase shift of the transmitting signal is occurring. We can derive the relationship between TL length L and the phase ϕ of the signal. Later on we will need to determine the wavelength of the signal with specific frequency through the substrate dielectric material.

$$L = \frac{\phi}{k_0\sqrt{\varepsilon_e}}$$

$$k_0 = \frac{2\pi f}{c}, or\ k_0 = \frac{2\pi}{\lambda} \qquad [2.2\text{-}17]$$

Where, f is the frequency of the wave, λ is the wavelength and c is the speed of light.

The clearance of the principles of microstrip designs operation is important for the current project, since Vivaldi antenna belongs to the microstrip types of antennas and its operation is strongly depending on the rules of microstrip antenna operation. The calculations developed in this chapter, given as [2.2-14] - [2.2-17], will be used for analysis of the Vivaldi antenna design for the chapter 3.2, section *Radiation Curves*.

2.3 Ultra Wide Band

- **Definition**

Ultrawide bandwidth (UWB) signals are commonly defined as signals that have a large relative bandwidth (bandwidth divided by the carrier frequency) or a large absolute bandwidth [11]. According to the different sources, UWB is defined as the system, with greater then 500 MHz bandwidth, or greater then 25% of the operating center frequency. The commonly used frequency band assigned for UWB applications is 3.1 - 10.6 GHz; although, lately there appear systems with operation bands started from 300 MHz and sometimes up to 20 GHz, depending the applications and the fields of use.

Due to the ITU and FCC regulations the UWB assigned as unlicensed band in the range of 3.1 - 10.6 GHz with the transmitted power emission limitation of -41.3 dBm/MHz, and the rest of the frequency range with as low power as -75 dBm/MHz. Figure 2.3-1 shows the frequency band allocation for the UWB and some of other licensed and unlicensed bands.

Still, the general definition of UWB is stated as the relative bandwidth. If f_H and f_L are the upper and lower band limits respectively, the UWB definition can be expressed as follows [12].

$$2(f_H - f_L)/(f_H + f_L) > 0.2 \qquad [2.2\text{-}18]$$

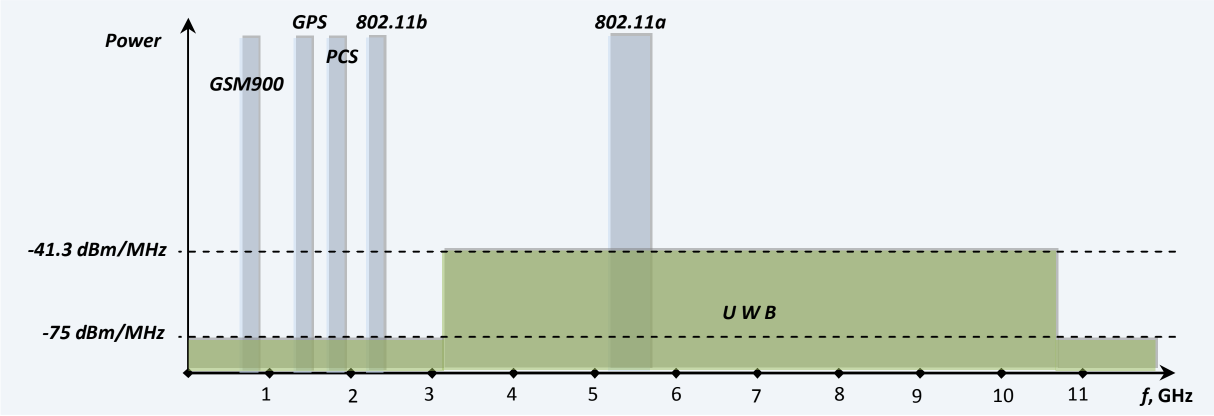


Figure 2.3-1 Frequency band allocation and power limitations for UWB.

UWB signals, which occupy extremely large bandwidths, usually operate as an underlay system with other existing, licensed and unlicensed, NB radio systems. Because of their characteristics, UWB systems are considered among key technologies in the context of cognitive radio. As a result, the deployment of UWB systems requires that they coexists and contend with a variety of interfering signals. Thus, they must be designed to account two fundamental aspects: 1. UWB devices must not cause harmful interference to licensed wireless services and existing NB systems (e.g., GPS, GSM, UMTS, 3G, Bluetooth, and WLAN), and 2. UWB devices must be robust and able to operate in the presence of interference caused by both NB systems and other UWB-based nodes [1].

- **Radar Systems (Basic Principles and Applications)**

Radar, Radio Detection and Ranging, can be considered as the most prevalent system used in a microwave technology nowadays. Radar is a target detection system that uses electromagnetic waves to specify the range, or position, or speed of the target or can be some other applications, since the fields of the use of the Radar systems are quite many and completely different from each other. The typical applications are as civilian (airport surveillance, weather radar, police radar, mapping …) as military (air navigation, tracking of aircraft, missiles, spacecrafts, weapon fuses …) or scientific use (astronomy, mapping and imaging, remote sensing of natural resources, medical applications) [13].

The basic principle of Radar operation depends on the analysis of the initially transmitted signals from the transmitter and then partly reflected back by the target. The method of analysis depends on the application of the Radar. For example, for the range Radar applications, the distance of the target is defined by the time required for the signal to travel forward and backward directions from the transmit/receive antenna. In some of the cases the same antenna is used for transmitting and receiving modes, called mono-static systems, while bi-static systems are using separate antennas for these applications. Bi-static systems characterize better isolation between transmitter and receiver and are more useful for pulse radar systems with requirement of high sensitivity [13]. Reference [13] describes also radar equation, the target properties and discusses some of the common radar system types.

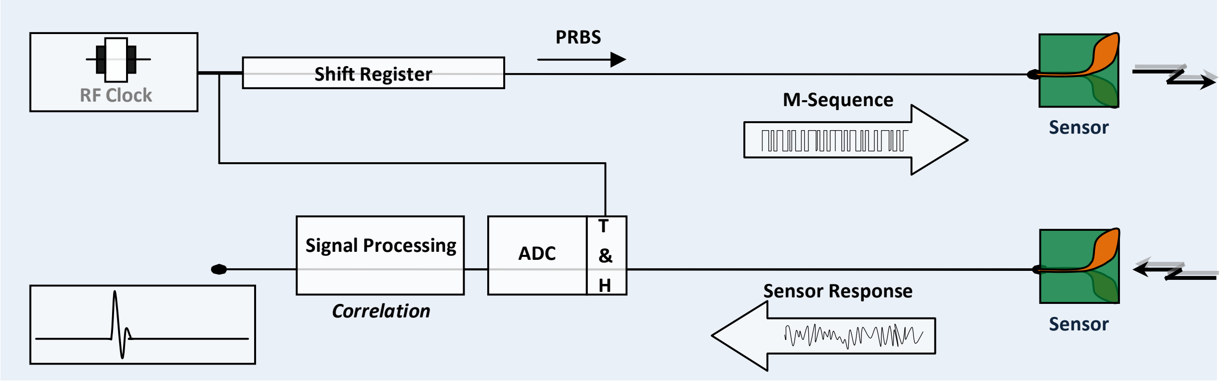


Figure 2.3-2 Pulse Based UWB Radar.

As for ultra-wide bandwidth systems, they are characterized with easy material penetration properties; even through the very thick walls by using the UWB signals. Also they become attractive for the reason that they have the following important properties, such as an accurate position location and ranging due to fine delay resolution, multiple access capability, underlay and covert communications due to low power spectral density, reduced density due to finer multipath resolution [14].

The UWB radar, which is also considered in this project, is based on UWB impulse excitation. Radar transmits a sequence of short pulses and the range of the target is determined by measuring the time delay between emitted and reflected pulses. The basic architecture of the wall penetrating radar system, which is implemented by Radarbolaget, is shown on Figure 2.3-2.

The RF clock is pushes the shift register, which generates the sequence of pulses, in this case PRBS signal, and produced M-sequence signal power is delivered to the sensor, which transmits signals in ultra-wideband analogue form. Sensor presents the Vivaldi Antenna. Reflected signal, received by the same type of receiving sensor, is converted into digital form again in an ADC block and after proper signal processing (correlation with transmitted signal pulses) the measuring of the delay [15].

- **UWB Antennas**

Antennas are essential elements, especially in UWB systems. Not only beam width, gain, and side-lobes, but also their pick amplitude, width of pulses, ringing, and spatial correlation are of major interest. There are several generic ideas for the development of UWB antennas like travelling wave, frequency independent, multiple resonance, or electrically small configurations [16]. UWB type of antennas belong Biconical, Helical, Bow-tie antennas, Rectangular Loop antennas, Diamond Dipole antennas or Vivaldi antennas.

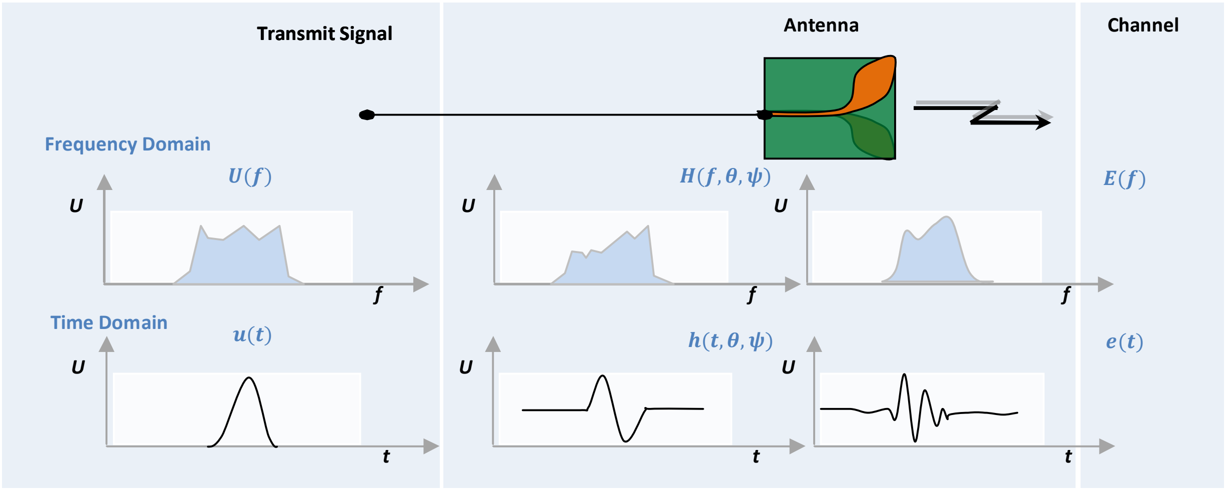


Figure 2.3-3 Frequency and time domain characterization of a pulse entering to the UWB Antenna.

For narrow band antennas the characteristic parameters are assumed to be constant over the whole operational bandwidth; but for UWB antennas the frequency dependency of the antenna characteristics is important to be considered. Also, UWB systems are often based on impulse transmission technologies, which make time-domain characterization of antennas crucial. The complete behavior of the antenna can be described by a time-domain impulse response function $h(t, \theta, \psi)$ or by a frequency domain transfer function $H(f, \theta, \psi)$. Both of them contain full information of the antenna radiation. θ and ψ together with the separation r represent the spherical coordinate system used to describe the fields around antenna [17].

Figure 2.3-3 represents the influence on the wideband pulse by the UWB Antenna given as a frequency and time domain. To switch the functions from time to frequency domain or vice versa the Fourier transforms can be used. Hilbert transform is used for deriving analytic impulse response for analyzing the dispersion of the antenna.

For the typical impulse response of the UWB antenna the main characteristic parameters are the peak value of the envelope, pulse width ($\boldsymbol{\tau_{FWHM}}$), the ringing duration; also gain and the group delay.

The peak value of the envelope is the measure of the maximal value of the strongest peak, while the FWHM describes the broadening of the radiated impulse. The ringing is the undesired behavior of UWB antennas caused by the multiple reflections in the antenna or the resonance due to energy storage. Ringing of the pulse follows to the main peak of the impulse. The energy stored to the ringing by the antenna is unusable and considered as a loss of energy. Figure 2.3-3 presents ringing of UWB antenna and its parameters.

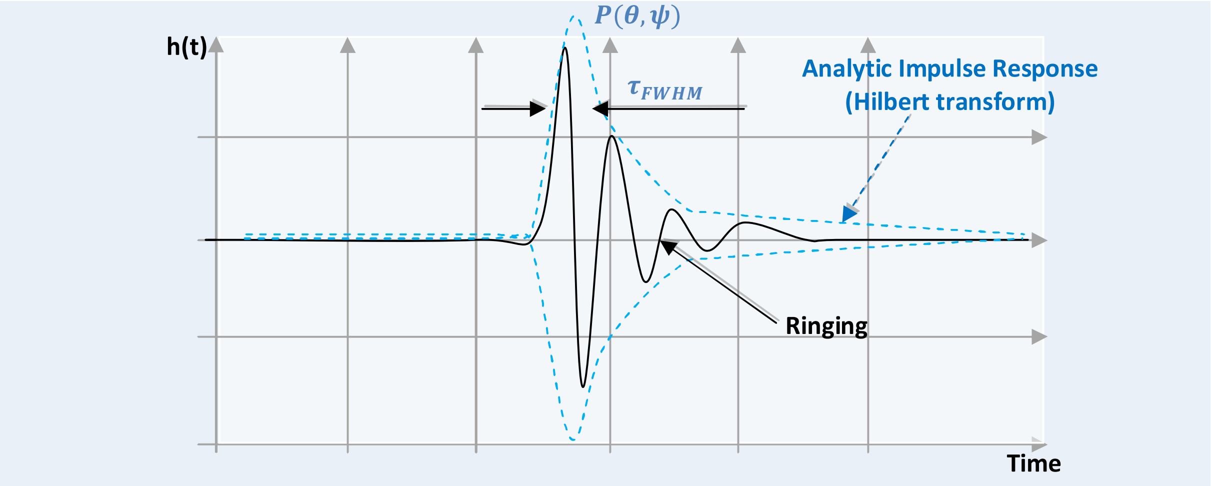


Figure 2.3-4 Ringing of UWB Antenna impulse response.

The group delay of the UWB antenna characterizes the frequency dependence of the time delay of the signal. The stable (close to constant) group delay for the UWB radar sensors are desirable [17].

3. VIVALDI ANTENNA DESIGN

3.1 Design Background

All the benefits, Vivaldi antenna carries, makes it important and interesting objective for the researchers and developers. Most of the studies were done for the analysis of various types of substrates, investigation of radiation and bandwidth dependency for the antenna size and thickness, Vivaldi arrays investigation and time domain behavior characterization for using it in pulse based radar applications.

As it was mentioned in an introduction part of the report, the Vivaldi antennas are used as sensors for the radar system used in a current project. Vivaldi antenna presents the microstrip type of travelling wave UWB antennas, which curries all the benefits microstrip designs have. They are inherently wideband with good RF characteristics, inexpensive and easy to manufacture. Furthermore, as the practical observations show the UWB properties and UWB behavior of the Vivaldi antenna seems one of the attractive for the pulse radar systems. High peak value ($P(\theta, \psi)$) of the pulse envelope, the narrow width of the pulses, short duration of the ringing and stable group delay are the key advantages of the Vivaldi antenna; and those are the essential requirements for the UWB pulse radar.

Vivaldi antennas are travelling wave antennas and there is no accessible design theory that can be used to design the optimum antenna for a particular set of design [2]. This fact became the key objective of the current project, to investigate the design and develop the limits and specific rules for the designing of Vivaldi antenna. Figure 3.2-1 shows the typical Vivaldi antenna design. The radiation plates are constructed by the surrounding curves, which are parts of the arbitrary cylinders, due to the most of the sources of Vivaldi design developers. There is couple of more different Vivaldi designs available, the balanced or with groundplane (unbalanced), designs with three layer metallization, hybrid curvature designs and etc… Also Vivaldi antenna arrays are well-liked to construct.

This chapter expands the particular way of calculating design curves of the Vivaldi antenna, mostly for the radiator part and also for the matching, to increase the effectiveness of the antenna and to reduce the size of the substrate. The main deterministic factor which directly affects the size of the antenna is the dielectric constant of the substrate. Current project contains examples of use of a hybrid substrate designs for improving low frequency radiation by the small-sized antennas.

3.2 Design Procedure

- **Structure**

As most of the antennas, Vivaldi Antenna design consists of two parts: *radiator* - the part of antenna body-shape responsible for creating radiation by the currents flowing through it, and *matching* - the part of antenna which makes impedance transition from radiator to the system impedance for which antenna is designed. Radiator part can also be considered as a matching between transmission line and the free space. So, inside antenna design there are matching between wired and wireless networks and also matching between antenna device and the system it is supposed to be connected. Dissection by parts comes from the functional point of view; otherwise both parts present one unit of continuous metal (copper) plate.

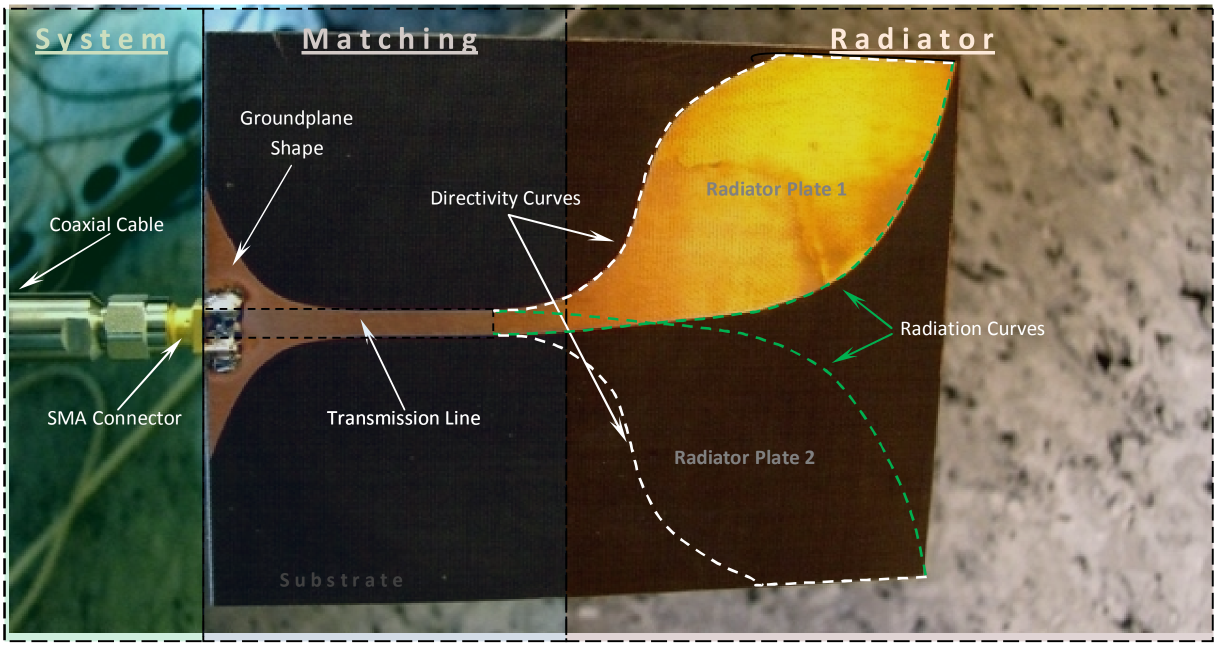


Figure 3.2-1 Structure of Vivaldi Antenna design.

In most of the cases the matching networks between antenna and the system (signal supply cable) are integrated inside the antenna design. It makes the antenna as a device ready to be connected easily with the rest of the system, so that there is the only need to choose the proper impedance cable and connect it to the device. After this discussion we can separate two parts inside antenna design, radiator and matching. Radiator part contains the property of power radiation and has certain radiation resistance for certain frequency and also certain loss resistance. The matching part must be designed to make coincidence of the system and antenna radiator part. Integrated matching networks and the techniques of their implementation will be discussed more extensively in the later parts of this report. As an example UWB antennas and specially Vivaldi antenna will be discussed and spread out.

To make the discussion easier for the later part of the report, and for improved indication of the meanings, we will give particular names to the separate parts of Vivaldi antenna design structure. The radiator part (radiation plates) of antenna presents a plate formation of copper layer. The radiator shape is limited by the surrounding curves. One curve is looking inside towards the body of the substrate and we can call it ‘Inner’ or ‘Radiation Curve’, and the second one placed close to the side edge of the substrate, can be called as ‘Outer’ or ‘Directivity Curve’. The radiator plates are followed with the transmission line (‘TL’) which provides impedance matching between radiator plates and the system (Figure 3.2-1).

‘Radiation curves’ are main contributors of radiation, it means they act as a load in an antenna circuit and provide radiation resistance R_R. As for ‘Directivity curves’, they are in charge of radiation beam formation; controlling main beam-width and its direction. Electrical losses through the copper plates and the substrate dielectric material present loss resistance of antenna circuit (Figure 3.2-1).

There can be considered two types of designs, balanced and unbalanced in terms of impedances. Balanced design means that the impedances through the signal flowing conductors are equal. For unbalanced case, one of the conductors becomes a reference, usually with zero impedance, referred as a ground.

Research shows that the same design of radiators can be used for both balanced and unbalanced Vivaldi designs. The difference appears for the formation of transmission line. For the case of balanced antenna, exactly equal shapes of radiators and transmission lines are used for both sides of the antenna substrate, when the unbalanced system requires whole (or at least part of) groundplane shape for one side of the substrate attached or integrated to the conductor plate. The theory for the transmission line, in the case of balanced and groundplane designs will be given in the following part of the report named “Matching”.

- **Radiation curves**

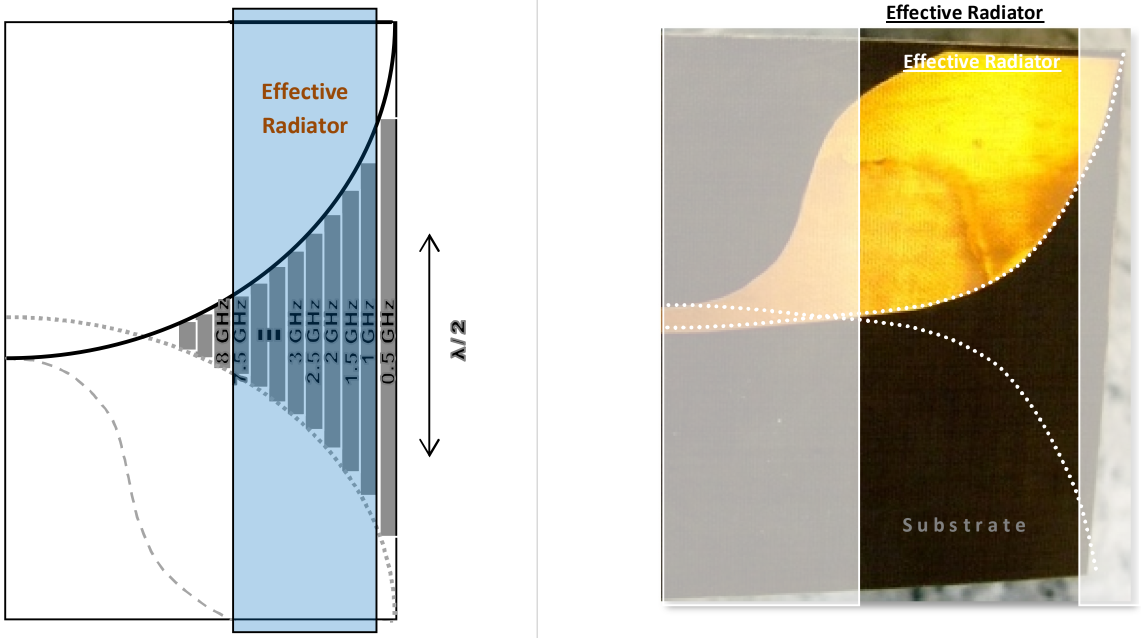


Figure 3.2-2 Radiator part of Vivaldi Antenna and radiation principle.

If we look for the current distribution over the radiator plates, it's normal that at the edges of the conductor plate the current concentration is much higher then in the middle, as a result, the curves through the edges takes the most of the responsibilities for the radiation. The shapes of inner curves are crucial for antenna performance, since they are the main contributors of the radiation. Subsequently the current strength through the inner curve is the highest. As far we go from the transmission line side of the antenna as more distance appears between the couple of inner curves of the radiators, because of tapering of the conductor shape; and the possibility of generating lower frequency radiation is greater. To reach the lowest possible radiation for a given type (the material with specific dielectric constant) or size of the substrate, there is need to define the right shape of the curves.

We mentioned before, that as most of the researches show, there were no exact formulations for the tapering of the radiation curves and it was suggested the part of arbitrary cylinder shape to be used for constructing inner curve. This fact became the main point of this research and as our investigation shows, there is the only way to reach the lowest frequency radiation with the highest transmission (S_{21}) possibility if we follow the rules stated in a report, which comes from the theory of electromagnetic radiation combined with couple of practical issues. Of course, not only lower frequency radiation is valuable when talking about ultra-wideband antennas, but still, for Vivaldi antennas, the most of the problems appear for the lower frequency radiation. All the benefits of the presented design method will be deeply discussed.

The general idea of radiation, which was already mentioned in previous chapters and we just remind it now, is to place two currents close together. The distance between them identifies the frequency of the radiation, since the frequency depends on the wavelength of radiating wave and radiating wave is formed because of existence of the separation between currents. The tapering of the radiation curves provides almost all the distances between them from very minimum (minimum distance is the thickness of the substrate, which is normally 1 mm range or so) to the maximum distance available from the size of antenna substrate. Also, it is significant that not all the segments of radiators are adequately usable for the radiation we need to achieve.

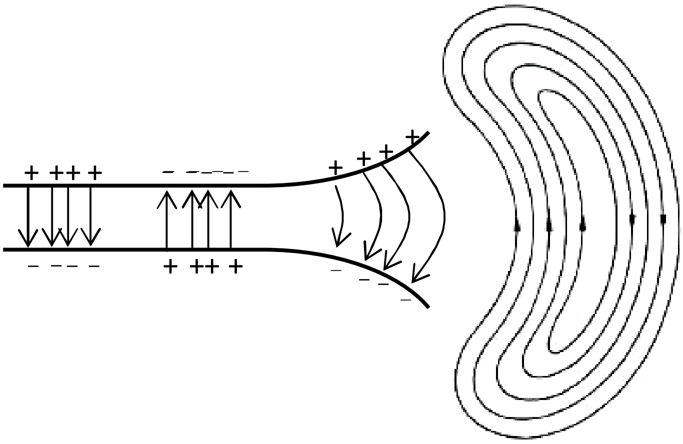


Figure 3.2-3 (a)
Detachment of electric field lines from transmission line.

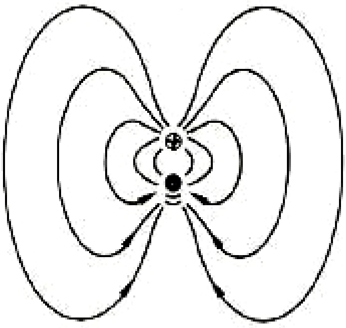


Figure 3.2-3 (b)
Dipole radiation.

The radiation principle depends on two types of radiation through the Vivaldi antenna shape; one is close to the transmission line, small segment of the radiator plates, which acts as a waveguide radiator, and another one is “far away” from transmission line, where the electromagnetic waves obey the principles of dipole radiation. Investigations show that the waveguide segment of Vivaldi radiator is not usable for the radar applications, since it provides multiple beam radiation, or more likely the high frequency scattering of energy for all the directions indefinitely around the antenna; the frequencies we are talking can be considered to belong from the X-band to higher. We will concentrate for the rest part of the radiator, which obeys dipole principle and to be more specific the principle of two wires radiation.

Two wires radiation principle means initially the electromagnetic waves propagation along the transmission line (the conductor wires), called guided waves and then at the open end of the line waves are detached and creating free-space waves. Two wire and dipole radiation principles are given on the figure 3.2-3 (a) and (b) respectively. Electric field lines start on positive and end on negative charges and when the separation between charges becomes more then half of the wavelength they are separating from the charges and travelling independently in a free space. Detailed discussion about two wire and dipole radiation principles is given in a reference [18].

f, GHz	$\lambda/4$, mm		*Required Width of Substrate (mm)*
0.5	82.20	-82.20	164.3938391
1	41.10	-41.10	82.19691957
1.5	27.40	-27.40	54.79794638
2	20.55	-20.55	41.09845979
2.5	16.44	-16.44	32.87876783
3	13.70	-13.70	27.39897319
3.5	11.74	-11.74	23.48483416
4	10.27	-10.27	20.54922989
4.5	9.13	-9.13	18.26598213
5	8.22	-8.22	16.43938391
5.5	7.47	-7.47	14.94489447
6	6.85	-6.85	13.6994866
6.5	6.32	-6.32	12.64567993
7	5.87	-5.87	11.74241708
7.5	5.48	-5.48	10.95958928
8	5.14	-5.14	10.27461495

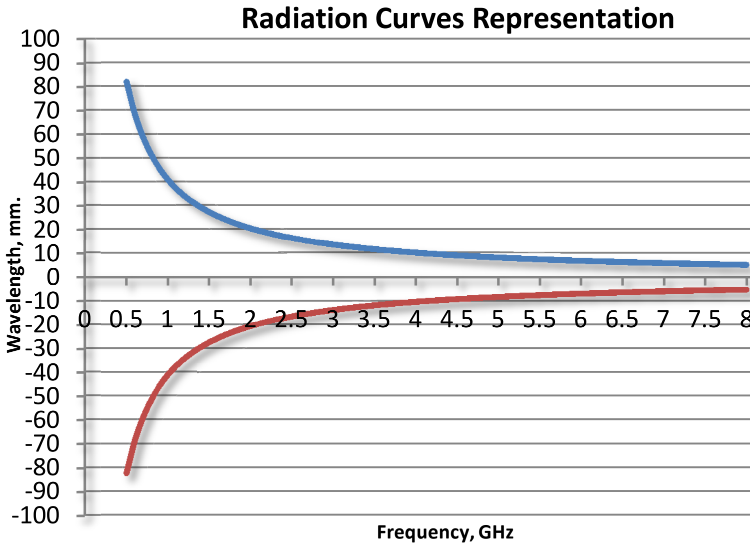


Figure 3.2-4 Radiation Curves shape for the substrate FR4 with dielectric constant 4.4.

The same scheme of radiation can be transferred to the Vivaldi antenna radiation. The distances between the charges (currents) on different parts of the radiator plates present half wavelength of different frequencies and correspondingly the radiating waves at those frequencies. That is the explanation makes Vivaldi antenna wideband radiator. Figure 1.12 shows the principle of Vivaldi radiation at different frequencies. Radiator curves are constructed by marking the points for the separate frequencies with appropriate distances on the substrate and connecting them to each other. The radiation curves can be easily drawn using Matlab or any software with ability of data analysis and graphical representation. Simple X-Y plot with the wavelength as a function of the frequency gives the desired result. Figure 3.2-4 represents the plot using Microsoft Excel software, where the X axis corresponds to the frequency and the Y axis - the wavelength. For better visualization of the couple of Vivaldi radiator curves, we use to column of data, one of which is the quarter wavelength size of appropriate frequencies (the positive side above the X axis) and the second the column contains exactly the same values, but opposite sign (the negative values of Y axis). In this way the distance between two curves points of the same frequencies become half of the wavelength and the curves distribution gives the exact shapes of “inner” of Vivaldi radiator.

For the wavelength calculation the substrate material influence must be taken into account, since the wave propagation in different materials are different and the wavelength changes depending on the dielectric constant of the material of wave propagation. In the case of Vivaldi antenna, wavelength calculations must be made using the formulas [2.2-16] and [2.2-17] evaluated during the discussion of the microstrip antennas in chapter 2.

The aim of these calculations is to define the shape of Vivaldi antenna radiators and their position on the substrate. As we can see the only parameter need to be considered is the distance between the identical points of the radiator curves of two radiators. To make more accurate calculations the thickness of the substrate must be taken into account, since the radiator plates are laying on different planes; it means different sides of the substrate. The rule of right-angled triangular (Pythagoras Theorem) can be used to define the exact position of the plates facing each other on the substrate. Figure 2.3.4 shows the case discussed. For general case it's applicable to neglect the height of the substrate when h<<W.

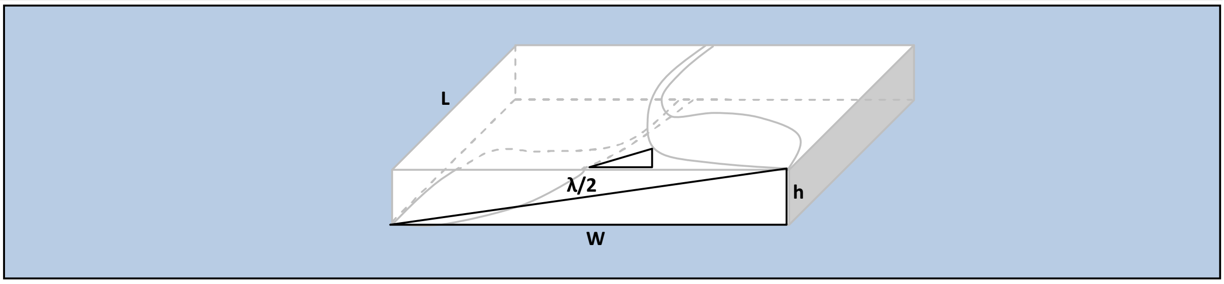


Figure 3.2-5 The scheme of the calculation of the separation of radiation curves of Vivaldi antenna for different frequencies.

After deriving the necessary shape for the inner curve we need to prolong it and connect to the transmission line. The connection must be made as smooth as it is possible to neglect unnecessary radiation and the power loss through it. The prolongation of the radiator can not be predicted and generalized, because it depends upon many different factors, like impedance of the transmission line (width of TL) and also the length of it, or the shape of the radiators and their separation from the TL.

In addition, the later part of the report, named as "HFSS - Designing techniques and Simulations", presents the formulation of the radiation curves implemented inside the HFSS software, which gives great possibility to design Vivaldi antenna in a couple of minutes using the software mentioned.

- **Directivity curves**

The Directivity curves are affecting the radiation beam-width and the direction of radiation. During this project the practical observations were done for investigating the functions of the directivity curves, hence we will not give deep theoretical discussions for it. Still, there were over 300 designs made and observed during the project and quite clear conclusion can be estranged as an outcome. Some of the examples are given as an appendices at the end of the report, where there are shown different designs of Vivaldi antenna with different formation of the outer curves of the Vivaldi radiator and corresponding radiation beam plots.

- **Matching**

The matching is crucial for the operation of an antenna, since antenna is a part of the system and the affective power delivery to the antenna radiator is an essential for successful communication. Matching also is affecting the radiation properties of the radiation part of the antenna. There are a few of the methods for constructing matching networks depending upon the feeding of Antenna. The typical feeding methods for microstrip antennas are the microstrip line feed, probe feed, aperture-coupled feed and proximity-coupled feed [19]. The one used in this project, is the microstrip line feed. It is represented as the transmission line of microstrip design with the SMA connector at one of the end of it. The width of microstrip transmission line is calculated using the method explained in a chapter 2 (microstrip antennas) depending on the required characteristic impedance of the line (Antenna input impedance).

The general calculation for the microstrip transmission line is given for the commonly used case, when one of the sides of the substrate is covered by the massive part of the copper layer with 0 impedance named as a groundplane. First we will consider the balanced Vivaldi antenna, where there is no groundplane at all and the transmission line width calculation needs different method.

From the image theory it is well known that the antenna (Ex. Dipole) placed over the groundplane presents its own symmetrical mirror image at the opposite side of the groundplane and acts together with it during the operation. The current flowing through the antenna is considered in the same direction for the image when original antenna is placed vertically towards the groundplane and opposite direction, when it is placed horizontally. The same theory applies for the charged particles and currents placed close to the groundplane. Positive charged particle above the ground demonstrates its negative image on the other side of the ground separated in a same distance as positive particle. This effect is similar to the mirror effect.

For the microstrip transmission line the groundplane has the same effect as mentioned above. But for the balanced case of transmission line the both sides of the substrate identical transmission lines are presented with the currents, flowing opposite directions. If one of the transmission lines be considered as an image of the second, it can be assumed that the groundplane is placed between them in the middle of the substrate. So, the term of imaginary groundplane is turning out. Considering the new circumstances, we can evaluate transmission line width calculations, depending on the required impedance, taking into account only the one of the transmission lines and the imaginary groundplane. The simple modification of the calculations, presented for microstrip design, can be done by replacing the value of the height of the substrate, which was showing the distance between the line and the ground, with the half of the actual height of the substrate, since the imaginary groundplane appears in a middle of the substrate and the distance between them is the half of the actual substrate thickness.

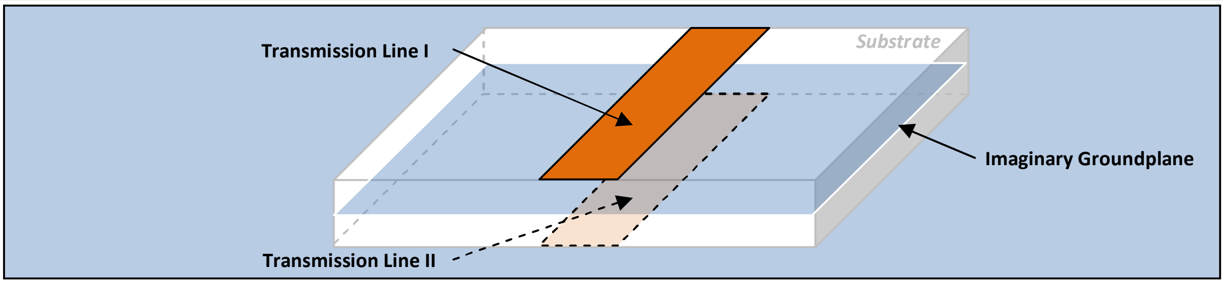


Figure 3.2-6 Imaginary groundplane effect modeling for a microstrip transmission line.

Furthermore, the length of the transmission line involves our attention to be specified. It only affects the phase of the incoming wave. For maximum power delivery to the antenna radiator, the conjugate matching is commonly used for narrowband antennas, since for the specified frequency the specified wavelength is assigned. In the case of ultra-wideband antennas, we are considering the incoming waves with the frequencies from very low (for example 300 MHz) up to high (8 GHz or so) frequencies with corresponding wavelengths from centimeters to millimeters range, which makes it complicated (almost impossible) to calculate the exact phase of the flowing signal.

3.3 The Transitional design from GP to Balanced transmission lines

From the beginning of this chapter it was mentioned, that the radiator part of the Vivaldi antenna stays uniform for both balanced and unbalanced designs. The change requires for the matching transmission line of the antenna.

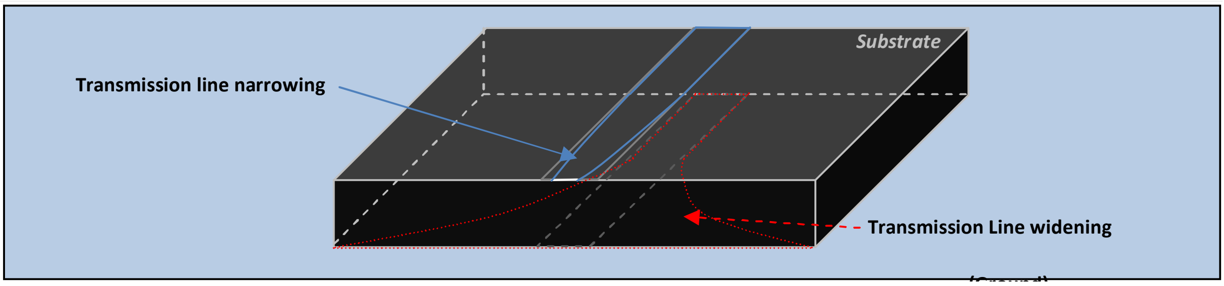


Figure 3.2-7 Transmission lines modification for transitional design.

From the practical point of view the balanced design for the Vivaldi antenna is much easier to implement, since there is no need of complication of matching transmission line. But furthermore, considering practical issues, there is looked-for use of unbalanced designs for most of the systems exist nowadays. In addition, the majority of the measuring devices using for antenna and microwave circuit measurements are intended primarily for the unbalanced networks; and to create an accurate measurement setup for the balanced devices, it requires much more expenses and energy to be spent.

The unbalanced Vivaldi antenna needs to have groundplane for one side of the substrate, or at least a part of the groundplane, which should be united to the transmission line. Transitional design means the modification of the initially constructed design for balanced case. The modification applies not only for one of the transmission lines, which will be the groundplane, but the other one too.

As it is shown in the figure 3.2-7 the transmission line, designed for the balanced Vivaldi antenna, is enlarged, which will be used as a groundplane, and simultaneously and symmetrically the second transmission line is narrowed towards the ending part of the substrate. The enlargement of the groundplane part can be designed arbitrary depending on the size and availability of the transmission line and the substrate. During making design it must be carefully considered that the widening segment is smoothly harmonized with the rest of the design, so that there must not be the edges or hard corners left along the widening. Otherwise it is a possibility of unnecessary power loss and unusable radiation.

As for the narrowing part of the second transmission line, the width of the starting and ending parts of the line must be calculated. Starting part requires the balanced transmission line width calculation depending on the desired characteristic impedance and the ending part can be calculated as unbalanced (standard microstrip line) calculation method.

3.4 Vivaldi Design Summary

Combining the designs for Vivaldi radiator and the matching parts gives the Vivaldi antenna design ready for construction and ready to simulate. The combination of the parts must be done as smoothly as possible to avoid unnecessary concentration of the parasite currents for some segments of the antenna design, which can be result of several disturbances during the antenna operation.

To summarize the discussion about radiation curves and its formulation, there is need to appear the term of effective part of the radiator for the Vivaldi antenna, since not all the parts of antenna is taking responsibility for effective radiation. When talking about radiator plates we already mentioned for the waveguide part of radiators that it was not usable for the radiation. But still, there is the part of the radiator, which follows two wires radiation principle, but can not be considered as an effective radiator too. The figure 2.3-2 shows the area of the radiators generating an effective radiation. This area can be enlarged if the radiation curves are constructed depending on the formulation developed in this project. Otherwise, any type of curves can be considered as a radiator for Vivaldi antenna, but the effective radiation zone can be different, and sometimes very small, which results the large size of antenna, waste of substrate and manufacturing recourses and disturbances due to the unnecessary radiation field components.

Mostly an effective radiation is difficult to assign for lower frequencies, but the observations show that the almost 100 percent of the substrate can be successfully used when making right shapes of Vivaldi radiator; it means the larger effective area of the radiator. To be more specific, better to present an example. The substrate with material Duroid 6010, with dielectric constant 10.2, thickness 1 mm and the width 120 mm, can theoretically radiate the lowest frequency of 0.5 GHz, since the maximum separation of radiator currents can be equal to the maximum width of the substrate and for that separation the 0.5 GHz frequency is theoretically assigned to be radiated. The antenna, which was designed according the way developed in this project, produces the lowest frequency radiation as much as 0.6 GHz, which is very close to the theoretical one. It means that the effective radiator is spread completely over the low frequency radiation part of antenna. This design can be considered as the smallest possible for Vivaldi type of antennas, which are radiating as low frequency as 0.6 GHz for the given substrate material. The design and return loss for the mentioned antenna is given in an appendix VII.

4. VIVALDI ANTENNA IMPLEMENTATION (SIMULATIONS AND MEASUREMENTS)

In this part of the report the presentation of some of the designs will be given as a proof that the method of Vivaldi antenna designation, which developed in a previous chapter, is working as it was expected. Total number of the designs during the project reaches more then 300. Investigations were done for deriving right shape of the Vivaldi radiators and matching designs; also investigations were done for different substrates with different dielectric materials and different dimensions. A few designs were fabricated to show that the simulation results are matched to the real state of fabricated antenna. Designs were done by using HFSS software.

The parameters, which were our interest, are the radiation resistance of the antenna showed by the observing of S parameters, radiation pattern and the linearity of the antenna showed as a group delay response along the whole frequency band of operation. We are looking for the S parameters, since the powers delivered to the antenna and the correspondingly the powers radiated from it are in a range of very low levels, approximately -80dBm and lower.

Vivaldi antenna designs which were simulated successfully and considered as one of the "best" over all other designs were fabricated and tested. The fabrication procedures were proceeded using lithographic printed method (Printed-circuit technology), in a same way as microstrip design fabrication. Test antennas have been fabricated and measured using the fabrication and measurement equipments available in a Radio Center Gavle and tested results have been compared to the simulated test results.

4.1 Test Designs Simulations and Measurements

- **Small Size Design - *RT/Duroid 2.2 by Rogers* $\boldsymbol{\varepsilon_r = 2.2}$ (100x71x0.8)**

One of the test designs, presented in the appendix II, were fabricated and measured. The dimensions of the substrate are 100x71x0.8 in millimeters, with the material of dielectric constant $\varepsilon_r = 2.2$. The bandwidth of the antenna is considered as the range of S_{11} less then -10dB. Furthermore the frequency dependency of the radiation pattern is also essential. According to it the bandwidth of the presented test antenna belongs to the frequencies from 1.25 to 7.5 GHz range.

It is valuable to underline, that the simulated results of the test Vivaldi antenna (by HFSS) is clearly matched to the result of the fabricated antenna measurement. For better pragmatic simulations, the SMA connector was designed in HFSS with soldering segments on it, by which almost all the possible losses were taken into account during simulations.

The figure 4.1-1 (a) and (b) shows the design made in HFSS software and simulated radiation pattern at 3 GHz. The table 4.1-1 represents the parameters of the Antenna substrate and the lowest frequency component values depending on the theoretical calculations and simulation and measurement results. The theoretical lowest frequency radiation is derived depending on the two wire radiation principle by the Vivaldi antenna radiators.

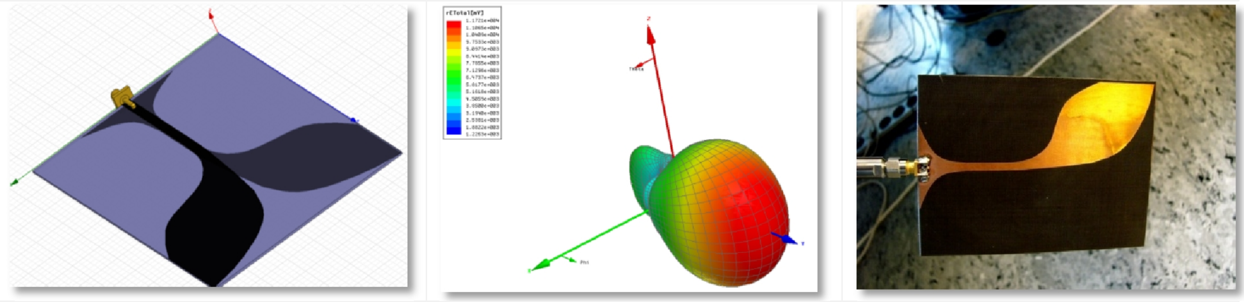

(a) (b) (c)

Figure 4.1-1 (a) The HFSS design of the test Vivaldi antenna; (b) The simulated 3D radiation pattern of the antenna at 3 GHz; (c) Fabricated antenna under test.

From the table 4.1-1 it seems that for this particular antenna the simulated and measured radiation bandwidth is better then the theoretical one, but it's not so. For UWB systems the antennas are considered as effective radiators when the S_{11} parameter response is less then -10 dB. The value for the simulated lowest frequency radiation was taken considering definition of -10 dB. Although in a real case, the radiation is characterized not only considering S_{11}, but also the radiation pattern, since the S_{11} parameter shows only reflections coming back towards the antenna port. It does not give any information about the rest of the power, which is pushed out from the antenna.

Table 4.1-1 Test Vivaldi antenna parameters (Rogers).

Substrate	**Dimensions (mm)**	**Theoretical minimum for low frequency radiation**	**Simulated/measured lowest frequency radiation**
Rogers (Er=2.2)	100x71x0.8	1.54 GHz	1.25 GHz

The time domain measurements of the test antenna were done to observe the antenna influence for the pulse transmission. In a test setup the same PRBS stream were used through the different branches simultaneously. One of them was presented as the direct cable link connection, while the other branch was built by the link of two similar Vivaldi antennas. Appendix V shows the measurement results, where the ringing of the antenna is clearly visible. The ringing is the individual property of the UWB antenna, which seems impossible to stay away from. Still, measurement shows that the ringing duration of the test antennas is short and the main pulse widths are narrow, which underlines the accuracy of the test Antenna.

The simulated and the measurement results of the presented test Vivaldi antenna are given in appendices III, IV and V. The group delay variation through the operational bandwidth of the antenna was simulated in the HFSS and is represented in an appendix VI.

- **Large Size Design - *RT/Duroid 6010* $\varepsilon_r = \mathbf{10.2}$ (201x120x1)**

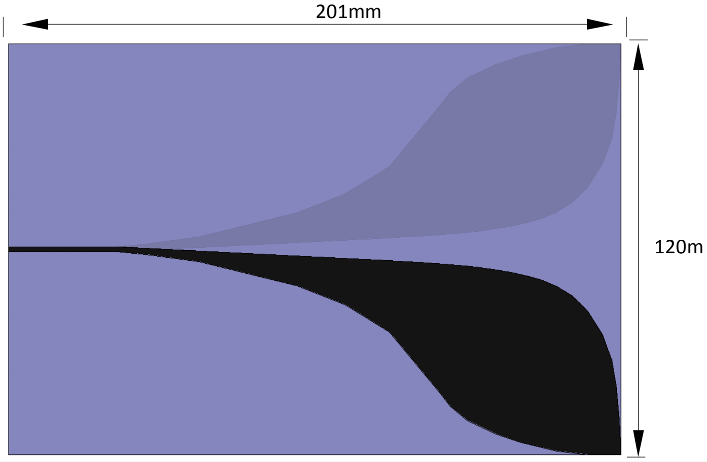


Figure 4.1-2 The HFSS design of the test Vivaldi antenna.

The next test design simulated in HFSS was built on the substrate RT-Duroid with dielectric constant $\varepsilon_r = 10.2$ and the dimensions of 201x120x1 in millimeters. The simulation result of S11 parameters of HFSS simulations is given in appendix VII. The table 4.1-2 shows the brief summary of the parameters of the presented test antenna.

The radiation bandwidth for this antenna is defined as the range of the frequencies between 610 MHz and 8 GHz. It means that the effective radiation for the radiator part of the antenna is very wide, i.e. almost all the segments of the antenna radiator shape are participated for the radiation.

Table 4.1-2 Test Vivaldi antenna parameters (RT/Duroid 6010).

Substrate	Dimensions (mm)	Theoretical minimum for low frequency radiation	Simulated/measured lowest frequency radiation
RT/Duroid 6010/6010LM(tm) - [Er = 10.2]	201x120x1	0.48 GHz	0.61 GHz

- **Hybrid (3L Substrate) design, *FR4/Ceramic/FR4* (160x100x1.635)**

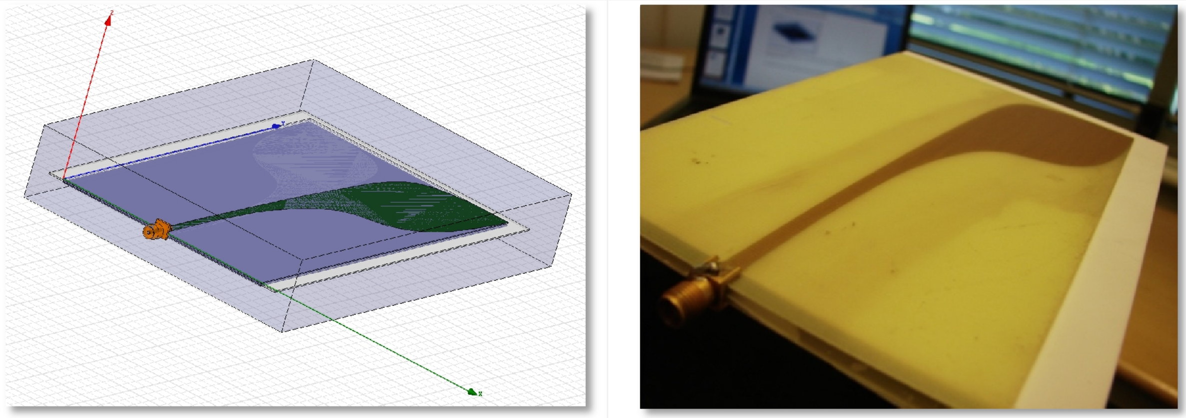

(a) (b)

Figure 4.1-3 (a) The HFSS design of the 3-layers design test Vivaldi antenna; (b) Fabricated design.

Presented test antenna was developed to achieve the compact size of the design with relatively low frequency radiations (Figure 4.1-3). The substrate is constructed with three separate layers of different materials. Two of the layers are FR4 type microstrip substrates with dielectric constant $\varepsilon_r = 4.4$. Each of them is used to fabricate the one-side shape of the Vivaldi antenna. Between FR4 layers the ceramic plate is placed. The dielectric constant for the Ceramic material is $\varepsilon_r = 9.5$. Such a hybrid design of the substrate gives the possibility to increase the operation bandwidth of the Vivaldi antenna towards the low frequencies; while, the Vivaldi radiator and matching design calculations is becoming much more complicated.

Such a hybrid designs and generally the high dielectric materials present higher dielectric losses, which makes antenna less efficient. On the other hand, pulse based UWB radar systems require very low power radiation and the energy saving problem is not essential, since the antenna satisfies the requirements of high bandwidth and high performance during pulse transmission and reception.

The table 4.1-3 demonstrates the parameters of the 3-layers hybrid substrate design antenna. Lowest limit of the operation frequency band is achieved by HFSS simulations. The range is defined from 350 MHz up to 8 GHz. The return loss of the antenna is presented as an appendix VIII.

Table 4.1-3 Test Vivaldi antenna parameters (3L hybrid).

Substrate	**Dimensions (mm)**	**Theoretical minimum for low frequency radiation**	**Simulated lowest frequency radiation**
FR4/Ceramic/FR4 Er[4.4/9.5/4.4]	FR4 - 100x160x0.5 Ceramic - 100x160x0.635	0.27 GHz	0.35 GHz

5. CONCLUSIONS/DISCUSSIONS

The main goal of the current project was to improve the performance and the operational parameters of the Vivaldi antenna, which is utilized for the pulse-based UWB radar. The application for the radar is the wall penetration. Initially the only ambition was to simulate current sensor design and to improve it as far as it could be possible. During the working on it has been explored that the Vivaldi antenna is the most suitable for the UWB pulse transmission and the most of the designs proposed by other sources are acceptable. The problems appeared for the low frequencies of the operational bandwidth of the Vivaldi antenna, so that the radiation bandwidth efficiency was low. To achieve lower frequency radiation the large size of antenna was needed. The part of antenna, responsible for the radiation, was not completely participated during the radiation, so only the part of it was effective. The figure 3.2-2 clearly represents the aim of the given discussion. The large antenna means waste of manufacturing resources, more operational losses and high probability of disturbances during the radiation, less mobility and etc. Also, for the wall penetration systems the low frequencies are essential to be radiated. It seemed the new methods were needed to design the radiator shapes of the antenna.

The method proposed in chapter 3 of the current paper develops the new technique of designing the Vivaldi antenna. The radiator and the matching sections were separately investigated and combined for the final outcome. With this method we achieved to spread out the effective radiation section of the antenna radiator towards the low frequency radiation so, that almost all the segments of Vivaldi radiator were engaged in an effective radiation. It automatically means the smaller size of antenna design.

The bandwidth of the UWB radiation, observed as a return loss of antenna is directly connected to the design of the inner curves of the radiators. They are the main contributors of antenna radiation and correspondingly the decisive factor for the size of antenna, but they require effective power delivery from the system to work themselves effectively. The matching section of the antenna is responsible for that. During the project, the matching drawings for balanced and unbalanced designs of Vivaldi antennas were developed and tested successfully.

- **Future Work**

Furthermore, there are the issues, which need more observations and investigation to make them clear and develop additionally. Since the time factor is decisive for any projects, so we have left some more questions without the proper answers. For example the outer curves of the Vivaldi radiator, which we call the directivity curves, are affecting the radiation pattern of the antenna radiation. Knowing it, and the developing the theory or the practical approaching for the influence of outer curves on the antenna behavior, gives the possibility to control the radiation process desirably.

More investigations are needed for the hybrid designs, which were given in the project as one of the test designs, seeing as they are very coast effective and the most compact-sized antennas. The complication appears during the estimation of the TL and Radiator designs. For calculating effective dielectric constant of the hybrid substrate the effect of the different materials and in addition the effect of the air boundary must be taken into account. Also, the practical effective solutions are needed to be proposed the construction for the 3L design and to attach the layers together properly and connect the connector to the transmission line.

During the radar operation the influence on the antenna radiation were observed by the boundary box, where sensors are placed. Because of that, one of the very important subjects is to investigate the close environmental influence on the antenna behavior. As a method, the simulations of the designed Vivaldi antenna placed close to the different materials can be considered. The analysis of simulation results can be helpful for designing the shell of the antenna and for choosing the proper material for it.

At the end, although there are several intentions to be evaluated and considered, still, as a summary of the current project it can be conclude that: we “forced” Vivaldi antenna to work for us effectively as much as it could be theoretically possible.

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7. APPENDICES

Appendix I	Wavelength, characteristic impedance and TL dimensions calculations;
Appendix II	Small-size antenna design (Rogers 2.2);
Appendix III	Return loss; simulation and measurement results;
Appendix IV	Transmission parameter, Link Measurements;
Appendix V	Time domain signal measurements through the link;
Appendix VI	Group Delay simulations;
Appendix VII	Large-size antenna design and simulations (RT/Duroid 10.2);
Appendix VIII	Hybrid design. Return loss simulations;