LAB 5: ANTENNA

1. Introduction

An antenna acts to convert guided waves on a transmission structure into free space waves (and vice-versa). Most antennas are reciprocal devices and have exactly the same properties on transmit and receive.

In general, antennas have directional characteristics; that is, electromagnetic power density is radiated from a transmitting antenna with an intensity that varies with angle around the antenna. According to the angular distribution type, we have directive antennas with a narrow beam that are convenient for point-to-point communications, and omnidirectional antennas with constant radiation in one plane that are useful for broadcast situations.

In this laboratory we will characterize parameters of some common microwave antennas, namely a horn antenna, a patch antenna, and a slot antenna.

2. Theoretical reminder

Antenna parameters essential to understand the work in this laboratory session are briefly described in this section. For a full and detailed description of all antenna parameters see for instance [1].

2.1. *Directivity and gain*

Let us assume that the net power into an antenna is P_{in}. A certain part of this power is dissipated in the antenna structure (metals and dielectrics) but the major part is emitted towards the surrounding space as the radiated power $P_r = e_r P_{in}$, e_r being the antenna radiation efficiency. At a large distance from the antenna (far-field), the radiated power within an element of solid angle $d\Omega$ is:

$$U(\theta,\varphi) \cdot d\Omega$$

where $U(\theta,\varphi)$ is the radiation intensity. The ***directivity*** $D(\theta,\varphi)$ is defined as the ratio of the radiation intensity in a certain direction to the average radiation intensity:

$$D(\theta,\varphi) = \frac{U(\theta,\varphi)}{P_r/(4\pi)}$$

The directivity reflects the fact that the power radiated by an antenna is concentrated in certain direction(s). It expresses how much greater the radiated intensity (or power density) is for an antenna than it would be if all the radiated power were distributed uniformly around the antenna. The ***antenna gain*** $G(\theta,\varphi)$ differs from the antenna directivity by the radiation efficiency:

$$G(\theta,\varphi) = e_r \cdot D(\theta,\varphi)$$

The maximum gain is defined as the gain in the direction of maximum radiation:

$$G = \max[G(\theta,\varphi)]$$

2.2. *Polarization*

The ***polarization*** of an antenna is defined by the shape of a curve traced by the electric field vector tip at a fixed distance, when the antenna is transmitting. In general, the antenna polarization is elliptical. However, there are important special cases of the polarization ellipse. If the electric field vector moves back and forth along a line, it is said to be linearly polarized. If the electric field vector remains constant in length, but rotates around in a circular path, it is circularly polarized. The polarization of an antenna always varies with direction. However, usually it remains relatively constant around the direction of maximum radiation and this polarization is typically used to describe the antenna polarization. Again, as antennas are reciprocal devices, the polarization remains the same in the receiving mode.

It should be noticed that, in the ideal case, a receiving antenna does not respond to the orthogonal polarization (horizontally polarized antenna will not receive a signal in vertical polarization; left-hand circularly polarized antenna will not receive a signal in right-handed circular polarisation).

All the antennas under test in this laboratory session are linearly polarized. The polarization of any of these antennas is aligned with the electric field in the waveguide through which they are fed.

2.3. *Radiation pattern, principal planes, and half-power beamwidth*

A ***radiation pattern*** is a graphical description of the angular distribution of radiation level (field or power) of an antenna in the far-field. By definition, it is normalised to the maximum radiation level.

A radiation pattern taken in the plane defined by the electric field vector and the direction of the maximum radiation is called an *E*-plane pattern. A pattern taken in the plane perpendicular to the *E*-plane and cutting through the antenna is called an *H*-plane pattern. These two planes are referred to as principal planes. It should be noticed that this definition is only valid for linearly polarised antennas.

Local maxima of radiation pattern are referred to as *lobes*, which may be subclassified into *major* or *main lobe* and *minor lobes* (*side* and *back*), see Figure.5.4. A ***main lobe*** is the lobe containing the maximum radiation direction. Its width is usually quantified through a half-power (HP) beamwidth, which is the angular separation of the points where the main beam of the power pattern equals one-half of the maximum value. Apart from the main lobe, typically a number of ***side lobes*** exist. A measure of how well the power is concentrated into the main lobe is the *side lobe level (SLL)*, which is the ratio of the side lobe peak level to the main beam level. The radiation pattern also presents a ***back lobe*** which is a minor lobe in a direction opposite to that of the main lobe. The *front back ratio (F/B)* of an antenna is the ratio of power radiated in the main radiation lobe and the power radiated in the opposite direction or back lobe. *SLL* and *F/B* values are normally expressed in dB. *Minor lobes* usually represent radiation in undesired directions, and they should be minimized.

If half-power beamwidths in the principal planes HP_E and HP_H of a directive single beam antenna are known, the gain can be approximated by the following equation:

$$G \approx \frac{26000}{HP_E \cdot HP_H} \ (HP - beamwidths\ are\ expressed\ in\ degrees)$$

There are three main types of radiation patterns: isotropic, directional and omnidirectional. An ***isotropic*** radiator is a hypothetical lossless antenna having equal radiation in all directions, this radiator is often taken as a reference for expressing the directive properties of actual antennas. A ***directional*** antenna has radiation characteristics which are more effective in some directions than in others. An ***omnidirectional*** antenna has an essentially nondirectional pattern in a given plane and a directional pattern in any orthogonal plane.

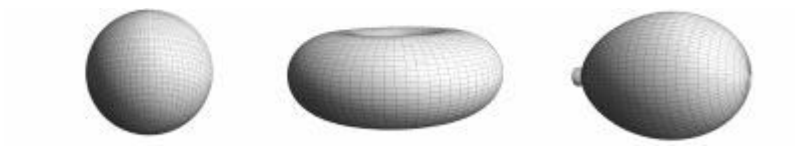


Fig. 5.1. Radiation patterns: isotropic, omnidirectional and directional.

2.4. *Friis transmission formula*

Friis transmission formula is an equation relating the received (RX) and transmitted (TX) power in a basic radio communication system shown in Fig. 5.2. With the variables noted in the figure, it reads

$$P_{RX} = P_0 \cdot G_{RX} \cdot G_{TX} \cdot \left(\frac{\lambda}{4\pi L}\right)^2$$

The following must be fulfilled for a successful application of this equation:

- Antennas are in free space and far from each other ($L \gg \lambda$; $L \gg D$; $L \gg \frac{2D^2}{\lambda}$; D being the maximum extent of any of the two antennas);
- Antennas are well matched to the transmitter/receiver;
- Antennas are aligned in polarisation and point each other with their maximums of radiation.

In the laboratory, we can only approximately satisfy the requirements above. In particular, reflection from the walls and nearby objects can be minimized by high frequency absorbers, but it cannot be fully avoided. This results in a considerable measurement uncertainty. A better facility for antenna measurements is an electromagnetic anechoic chamber, which will be presented during this laboratory session.

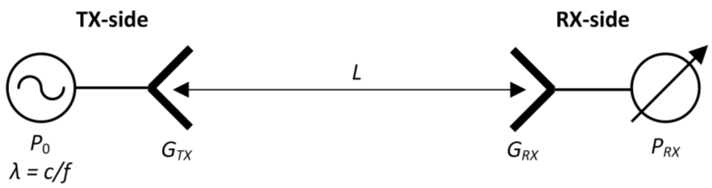


Fig. 5.2. Basic radio communication system.

3. Fundamentals of HFSS: A brief introduction

High Frequency Structure Simulator (HFSS) is a 3D electromagnetic (EM) simulation tool used to design a broad range of high frequency products such as antennas, filters, and IC packages.

The numerical technique used in HFSS™ is the Finite Element Method (FEM). In this method a structure is subdivided into many small subsections called finite elements. In HFSS these finite elements are in the form of tetrahedra. The entire collection of tetrahedra constitutes the finite element mesh. A solution is found for the fields within these tetrahedra. These fields are interrelated so that Maxwell's Equations are satisfied across inter-element boundaries yielding a field solution for the entire original structure. Once the field solution is found, the generalized S-matrix solution is determined. The figure below shows the geometry, mesh, field results, and the S-matrix results of a bandpass cavity filter in HFSS.

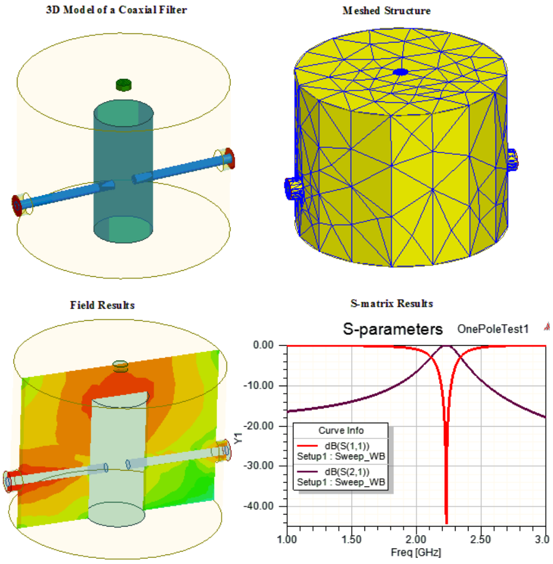
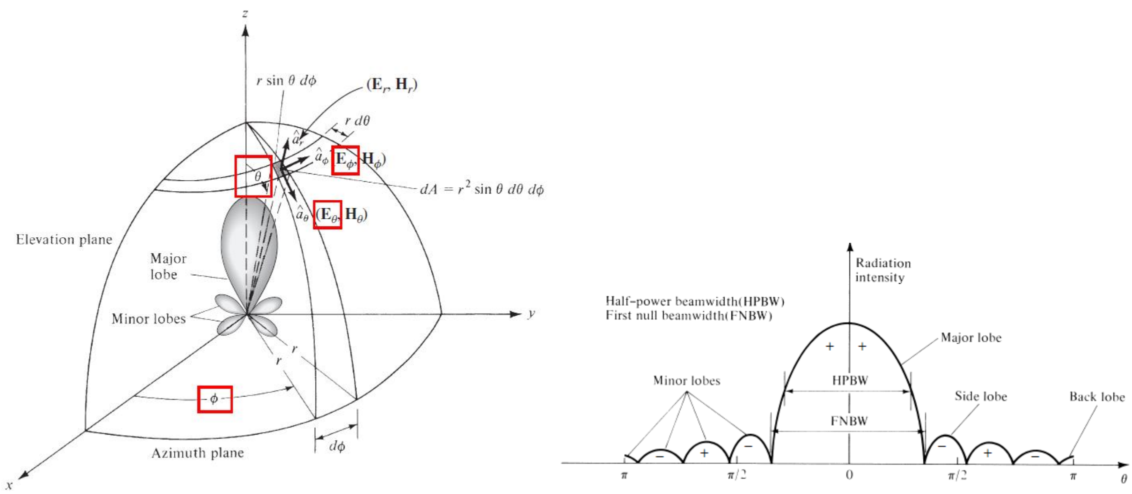


Fig. 5.3. Geometry, mesh, field results, and the S-matrix results of a bandpass cavity filter in HFSS. [taken from Ansys Electronics]

4. Measurements

4.1 Radiation patterns

The simulator also allows us to compute the far field radiation patterns. Before looking at the results for our antenna, it is important to have a clear picture of the definition in spherical coordinate used to represent the fields:



from Modern Antenna Handbook, Balanis.

Fig. 5.4. Spherical coordinates

The 3D radiation pattern (rE) can be obtained in HFSS, however we will stick to 2D cuts to simplify the visualization and understanding of each pattern. The pattern in the phi plane (rEPhi) is a sweep of phi when theta = 90°. The pattern in the theta plane (rETheta) is a sweep of theta when phi = 90°. The same procedure can be realized for measuring the rest of the radiation parameters, such as the realized gain.

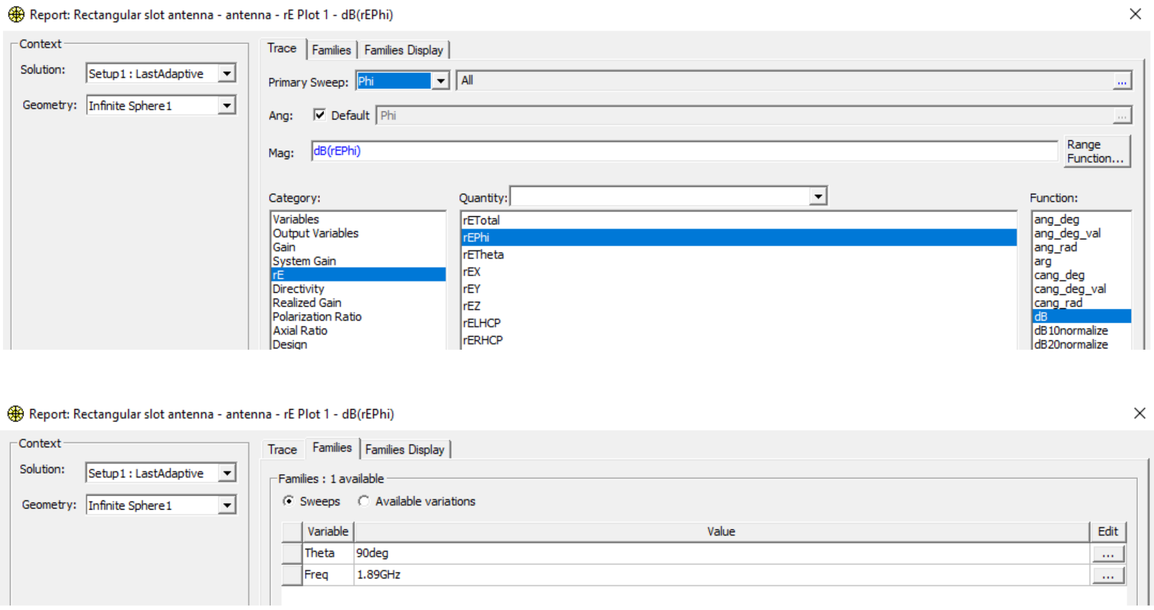


Fig. 5.5. Example of configuration of the radiation pattern in HFSS.

We will start by measuring the radiation pattern (rE) of three different antennas, a slot, a horn and a patch.

ANTENNA 1 (A_1): SLOT ANTENNA

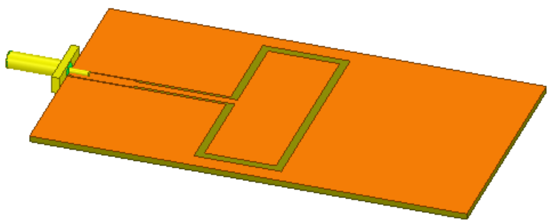


Fig. 5.6. Slot antenna.

Measure the radiation patterns of the slot antenna in the principal planes. From the obtained results, determine the HP beamwidths, F/B in both principal planes, maximum gain and the type of radiation pattern.

Max(Gain) _______ dB. *E*-plane: HP-beamwidth = _______ °

F/B = _______ dB. *H*-plane: HP-beamwidth = _______ °

Type of radiation pattern = ___________________________

ANTENNA 2 (A_2): HORN ANTENNA

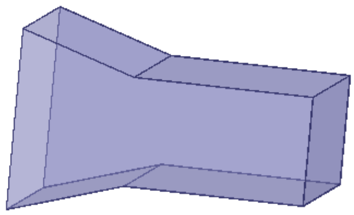


Fig. 5.7. Horn antenna.

Perform the same measurement for the horn antenna. From the obtained results, determine the HP beamwidths, F/B in both principal planes, maximum gain and the type of radiation pattern.

Max(Gain) = _______ dB. *E*-plane: HP-beamwidth = _______ °

F/B = _______ dB. *H*-plane: HP-beamwidth = _______ °

Type of radiation pattern = ___________________________

ANTENNA 3 (A_3): PATCH ANTENNA

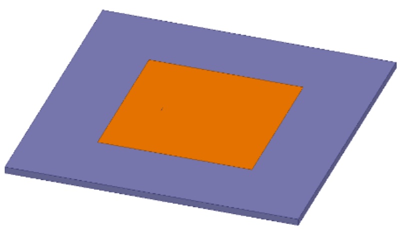


Fig. 5.8. Patch antenna.

Perform the same measurement for the patch antenna. From the obtained results, determine the HP beamwidths, F/B in both principal planes, maximum gain and the type of radiation pattern.

Max(Gain) = _______ dB. *E*-plane: HP-beamwidth = _______ °

F/B = _______ dB. *H*-plane: HP-beamwidth = _______ °

Type of radiation pattern = ___________________________

4.2 Gain measurement

In the antenna design process, once the simulated antenna is optimized, the antenna is fabricated. It is essential to verify that the fabricated prototype fulfils the design requirements. With that aim, different parameters (e.g. S11, radiation pattern and gain) of the fabricated prototype are measured, depending on the application. Those parameters are compared with the simulated results.

The parameters associated to the radiation characteristics of the fabricated antenna - Antenna Under Test (AUT) - are usually measured in anechoic chambers.

It provides an environment that is free from echoing or other radiated signals during the testing of a given antenna.

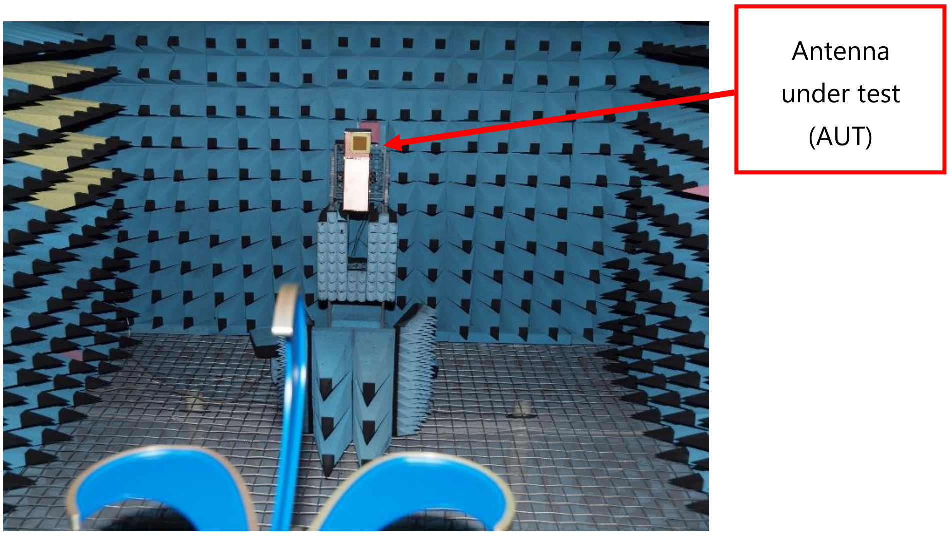


Fig. 5.9. Antenna under test (AUT) in the anechoic chamber (an-echoic = "echo-free").

Radiation pattern measurement in the anechoic chamber: The AUT is positioned in the receiving end (RX) in LOS with the TX antenna. While power is radiated by the TX antenna module (with a fixed position), the RX module is rotated in the theta and phi planes. The received power is normalized with respect to the transmitted power in order to obtain the AUT radiation pattern.

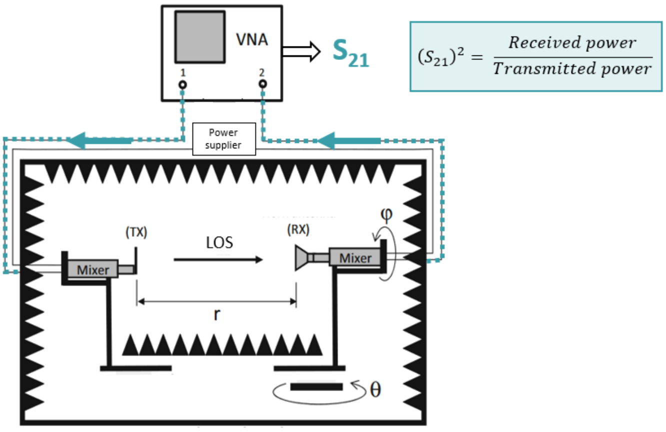


Fig. 5.10. Radiation pattern measurement in the anechoic chamber.

Gain measurement in the anechoic chamber. Substitution method: There are different methods for measuring the AUT gain. We will use the substitution method, using three antennas (slot, patch and horn) for solving three equations with three unknowns in the Friis formula.

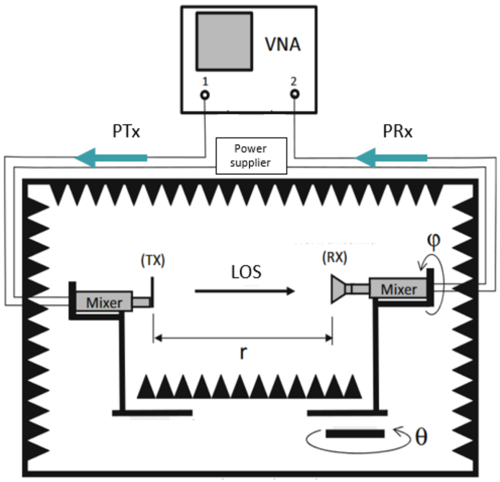


Fig. 5.11. Gain measurement in the anechoic chamber. Substitution method.

Looking at the Friis formula applied to the current experiment setup, it is clear that only the antenna gains are unknowns while all the other parameters (received and transmitted powers, distance R, lambda) are already known or can be readily measured. Having the three antennas at hand, we will create three combinations of the RX/TX antenna and each time measure the received power. Mathematically, we will be creating the system with three equations and three unknowns.

We will recreate this measurement in HFSS. Let us call the three antennas A_1 (the slot antenna), A_2 (the horn antenna), and A_3 (the patch antenna).

- ***Scenario A_{12}:*** Use the Scenario_A12 file containing the slot antenna on the TX-side and the horn antenna on the RX-side. Measure the distance between them. Measure the received power level P_{12}.
- ***Scenarios A_{13} and A_{23}:*** Keeping the TX-power constant (check each time and re-adjust if necessary), measure the received power levels P_{13}, and P_{23} corresponding to antenna combinations A_1-A_3, and A_2-A_3 (the first letter indicates the RX-antenna, the second TX-antenna). Close formed relations for the gain of each antenna are given below:

$$G_1 = \frac{4\pi L}{\lambda}\sqrt{\frac{P_{12}\,P_{13}}{P_{23}\,P_0}}$$

$$G_2 = \frac{4\pi L}{\lambda}\sqrt{\frac{P_{12}\,P_{23}}{P_{13}\,P_0}}$$

$$G_3 = \frac{4\pi L}{\lambda}\sqrt{\frac{P_{13}\,P_{23}}{P_{12}\,P_0}}$$

L = _______ m	S_{21} = ________ dB	P_{12} = _______ mW	**G_1 = _______ dB**
λ = _______ m	S_{21} = ________ dB	P_{13} = _______ mW	**G_2 = _______ dB**
P_0 = 1 mW	S_{21} = ________ dB	P_{23} = _______ mW	**G_3 = _______ dB**

5. Questions

1. Show the radiation patterns in H and E planes of each antenna, together with the values of HPBW, F/B and maximum gain. Explain the relation between the type of ration pattern and the F/B parameter. How does it compare the simulated gain and the approximated gain by using the HPBW?
2. Compare the gains obtained in the simulations for the single antennas with the values obtained using the substitution method.
3. Why is an anechoic chamber useful in the design process of an antenna?
4. What happens if the distance between the antenna elements Scenario A_{12} is doubled?

5. What is the received power if the patch antenna in the Scenario A_{23} is rotated 90°? Explain the reason for this result.

6. References

[1] Warren L. Stutzman and Gary A. Thiele, *Antenna Theory and Design*, 2nd edition, John Wiley & Sons, 1998.

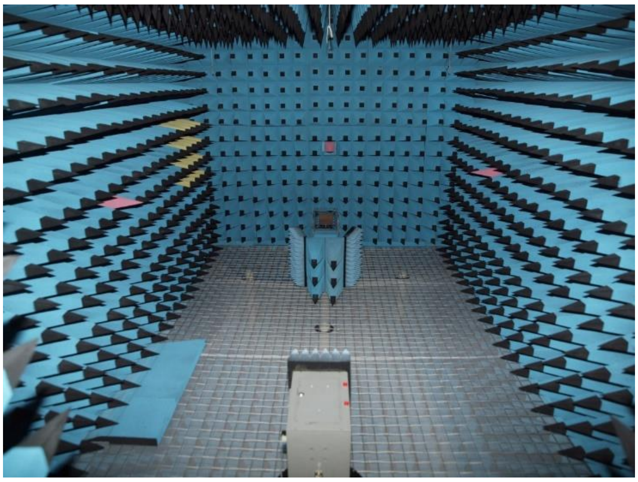


Fig. 5.11. Electromagnetic anechoic chamber of MAG, EPFL.