EE3P11 - EM Practicum, 2024-2025 Q3

Session 2 Free Space Propagation of EM waves

Reports: One report per group. Deadline for report submission**: Check the BS site**

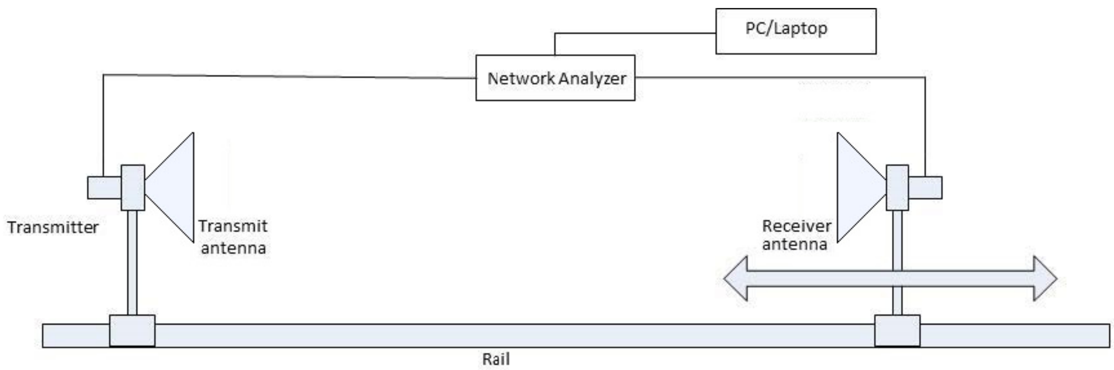
The goals of this practicum session are

1. Extend the basic knowledge on electromagnetic wave propagation in free space including the propagation velocity and propagation loss;
2. get physical insight in multi-path propagation of electromagnetic waves;
3. get practical knowledge on the polarization of electromagnetic waves and antennas, different states of the polarization of the waves, and polarization control;
4. exercise the theoretical knowledge on electromagnetic waves' reflection from a flat boundary between different media.

Assignment 1. Free space propagation. 45 min

Measurement set-up

Check/renew the experiment set up according to the following schema (***antenna large opening vertical is horizontal polarization***)



The experiment equipment includes the rail that supports two horn antennas. They can be used as directive transmit and receive antennas that are connected to the ports of vector network analyser (VNA). This device is capable to measure the amplitudes and phases of received signal in wide frequency band. Such configuration gives a possibility to measure and study many aspects of the electromagnetic wave propagation in free space. It is clear that the experimental area in the laboratory is not a very good approximation of the free space as soon as it includes many reflecting objects, obstacles, and even the air as the propagation medium. But to some extent we can still talk about free space propagation if the close area between and around transmit and receive antennas will be kept free from obstructing objects. The usage of free space propagation model is also supported by the fact that the relative dielectric permittivity of the air in normal condition is very close to the unity, the relative permittivity of the free space (vacuum).

With the provided setup it is possible to move the receive antenna along the rail to measure the range dependence of the received power, to rotate it along the line of sight to change the linear antenna polarization to orthogonally oriented, and to put some objects in between to study their influence on propagating signal's parameters. One of the antennas is also placed on the rotation table, which can be used for brief study of the horn antennas spatial directivity.

As soon as the VNA is measuring the signal parameters in a wide frequency band, every group will be given a specific value of the frequency in X-band (8.0 – 10.0 GHz) to make their measurements. This frequency can be found in the Matlab MAT file with your group number at the session 2 page on TU Delft Brightspace site of the EE3P11 course. This file include one variable ***session2*** with the fields of interest for this assignment: ***session2.task1.frequency.*** Put the frequency marker of the VNA screen to that frequency to read values of amplitude and phases, or use it for data extraction from the recorded frequency profiles.

1.1. Wavelength and propagation velocity in free space using obstructing object

For the experiment setup with horizontally polarized horn antennas, put the array of horizontally oriented wires in position between transmit and receive antennas. Move it horizontally along the line of sight between antennas. As soon as continuous wave is transmitted, between the transmitter and the receiver antennas exists the standing wave, and you will see on the amplitude scope of VNA the changes of received signal's amplitude when the position of array is changing. This effect can be explained as follows. Assume that the array of metal grids reflects back to transmitter some fixed percent of incident wave power. As soon as the power in standing wave antinode is small, placing array in that position will not strongly influence the amplitude of signal that reaches the receiving antenna. When the array is placed in a location with non-zero level of power, it will reflect some fraction of incident power and reduce the level of power that approaches the receiver. Moving array along the line of sight and along the pattern of standing waves result in periodical changes of received signal amplitude at selected for your group frequency. Use this modulation to measure the period of standing wave pattern and, as result, the wavelength of EM wave with a given frequency in free space (in air). Repeat this procedure a few times and estimate improved (averaged) value and precision of your estimation of wavelength.

Try to make a simple mathematical model of observed amplitude dependency from the position of interfering array.

From the measured wavelength and known frequency, compute the phase velocity of the traveling wave in free space.

1.2. Wavelength and propagation velocity in free space using phase measurements

The VNA has a capability to measure the phase of received signal, and this capability can be used for the measurement of the propagating wave's wavelength. The idea of this experiment follows from the basic equation of the propagating electromagnetic wave:

$$E(t,r) = E_0(r)\exp\left(-j\left[\omega t + \frac{2\pi}{\lambda}r\right]\right)$$

If we can change the distance between transmit and receive antenna, then the phase of received wave will change as $\varphi = 2\pi r / \lambda$. If we switch VNA scope to the polar mode to see the phase of the received signal (or, actually, the phase difference between transmitted and receive signals), and will slightly move the receive antenna along the rail, we will see how the phase is changing. For the wavelength measurement we will need to measure the distance between two points on the rail when the phase of the receive signal will change for 360 degrees (optionally use polar format). Make such measurement a few times and average the results to improve the accuracy. Use estimated wavelength to derive the propagation velocity of electromagnetic waves in free space (in air).

1.3. Measurement of the relation between the power of received signal and the propagation distance

Put the receiver antenna in a position that is close to transmitter. Both antenna polarizations are horizontal. Measure the distance and the strength of the received signal. Repeat this measurement when moving the receiver antenna on the rail away from the transmitter with steps around 10-20 cm. Process the registered data, assuming that

$$\text{Signal Power} = const\ /\ R^{x}$$

Estimate the value of x and give argumentation for your result.

1.4. The influence of polarization

Put the receiver antenna on the distance about 1.0-1.5 m from the transmitter, rotate receiver antenna 90 degrees. The transmitter now still transmits the signal with horizontal polarization and the receiver antenna has the vertical polarization.

- Measure the polarization isolation (in dB scale) between orthogonally polarized antennas Q (for the fixed distance between antennas)

$$\begin{aligned} Q = &\ \text{Signal power for orthogonal polarizations of antennas, dB} \\ &- \text{Signal power for matched polarizations of antennas, dB} \end{aligned}.$$

- Keeping the array of horizontal wires in hand put it in the beam between mismatched in polarization for 90 degrees (one is horizontal, second is vertical) transmit and receive antennas perpendicular to line of sight. Check the influence of the metallic wires orientation on the value of the received signal (use three cases of wires orientation - parallel to transmitted polarization, parallel to received polarization, 45 degrees to them). Make interpretation of the results assuming that the wires reradiate EM waves with linear polarization, which is parallel to wires.

1.5. Study of the antenna pattern (directivity) of the horizontally polarized horn antenna

Put the receiver antenna on the maximal distance (about 1.5 m) from the transmitter. Set up both antenna polarizations as horizontal again. Using rotation table with azimuthal angle scale estimate the spatial directivity of the horn antennas – the antenna beamwidth that can be defined as the angular difference between directions when the received power decreased to the level of - 3dB from the maximum value of received power.

Assignment 2. Simulation of the measurements of the polarisation state of the EM Wave using the polarization pattern method

The goal of this assignment is deepening your knowledge about electromagnetic waves polarization and effects of reflection of arbitrary polarized waves from metal and dielectric surfaces.

Short theoretical overview of topics related to the EMW polarization

Read selected chapters from the book Mott, H. *Polarization in Antennas and Radar* (scanned book chapters available on the Brightspace's practicum page)

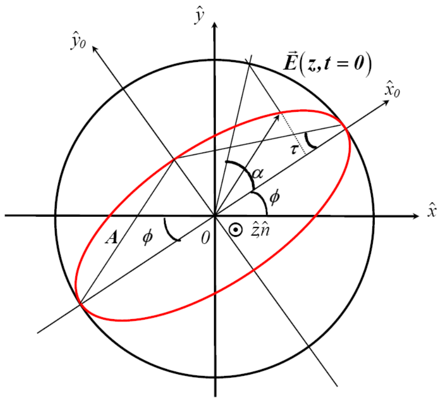


Fig. 1. Polarization ellipse

Any polarized electromagnetic wave that propagate in z direction can be written in a linear polarization basis $\{\mathbf{x},\mathbf{y}\}=\{\mathbf{H},\mathbf{V}\}$ of horizontal and vertical vector components as

$$\mathbf{E}(z,t)=\left(\dot{E}_H\mathbf{x}+\dot{E}_V\mathbf{y}\right)e^{i(\omega t-kz)},$$

or, using a 2 dimensional vector notation as

$$\dot{\mathbf{E}}(z,t)=\begin{Vmatrix}\dot{E}_H\\ \dot{E}_V\end{Vmatrix}e^{j(\omega t-kz)}, \tag{1}$$

Complex values $\dot{E}_H$, $\dot{E}_V$ define amplitudes and phases of horizontally and vertically polarized components of the wave with any arbitrary polarization. In general, the electromagnetic wave on some fixed frequency is fully defined with a value of amplitude A, the absolute phase α and with a shape of polarization ellipse that can be defined with an angle of orientation $\phi\in[-\pi,+\pi]$ and angle of ellipticity $\tau\in[-\pi/4,+\pi/4]$ (see Fig.1). It also can be completely characterized using the complex polarization ratio $\dot{p}$ that is defined as the ratio of orthogonal complex linear components $\dot{E}_H,\dot{E}_V$ and related to the angles ϕ and τ as

$$\dot{p}=\frac{\dot{E}_V}{\dot{E}_H}=\frac{E_{0V}}{E_{0H}}e^{j(\delta_V-\delta_H)}=\frac{\tan\phi+j\tan\tau}{1-j\tan\phi\tan\tau} \tag{2}$$

Eq (1) can be rewritten via complex polarization ratio as

$$\dot{\mathbf{E}}(\mathbf{r},t)=\dot{E}_H\begin{Vmatrix}1\\ \dot{p}\end{Vmatrix}e^{j(\omega t-kr)}=A_H\begin{Vmatrix}1\\ \dot{p}\end{Vmatrix}e^{j(\omega t-kr+\delta_H)} \tag{3}$$

where $\dot{E}_H=A_He^{j\delta_H}$.

The polarization sensitivity of any received antenna is defining by the two-dimensional complex vector of effective length (see provided pages of the Mott's book) that is quite similar to the vector representation of the electromagnetic wave polarization state (1). For linearly vertical polarized antenna the normalized vector of effective length in linear horizontal-vertical polarization basis {HV} can be written:

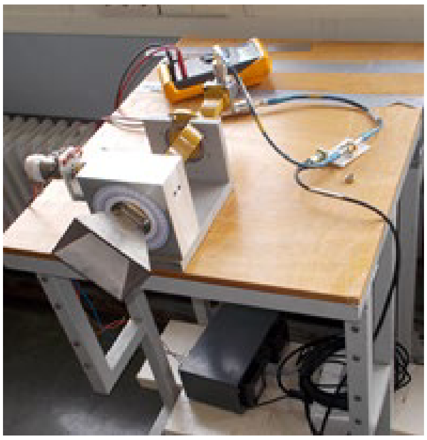


Fig. 2. Experimental setup with rotated linearly polarized antenna

$$\mathbf{h} = \left\| \begin{matrix} \dot{h}_H \\ \dot{h}_V \end{matrix} \right\| = \left\| \begin{matrix} 0 \\ 1 \end{matrix} \right\| \quad (4)$$

The received voltage in the receiver is proportional to the scalar multiplication of the vector of incident field and the receiver antenna's vector of effective length (Mott (3.15)):

$$V = \mathbf{E}_i \cdot \mathbf{h}. \quad (5)$$

The simplest way to measure the polarization state of the received EM wave is to measure its *polarization pattern* (see ch. 8.4. of the Mott's book) using mechanically rotated along the line of sight linearly polarized received antenna.

The rotation of the receiver linear polarization antenna modulates its vector of effective length and for constant polarization state of the incident wave results in so called *polarization pattern*, which is plotted in polar system of coordinates (see provided pages of the Mott's book). The relation between polarization ellipse of the received wave and measured polarization pattern is presented in Fig.3.

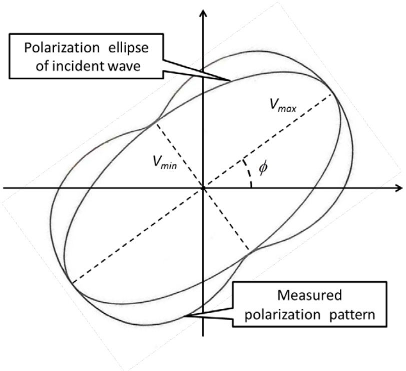


Fig. 3. Relation between polarization ellipse of the received wave and measured polarization pattern

The measured polarization pattern gives us a possibility to estimate:

- the absolute value of the *axis ratio* of polarization ellipse is equals to the ratio of square roots (we assume that the receiver's detector is quadratic) of minimum to maximum values on polarization pattern:

$$|AR| = \sqrt{\frac{|V_{\min}|}{|V_{\max}|}} \quad (6)$$

It equals to 0 and 1 for linearly and circularly polarized waves. This parameter relates to the absolute value of the ellipticity angle of EMW as

$$|\tau| = \arctan(|AR|) \quad (7)$$

Unfortunately, the direction of rotation could not be estimated using this technique.

- The orientation angle of the maximum of the pattern defines the orientation of polarization ellipse ϕ . (counted from the horizontal axis - positive in counter clockwise direction, negative in clockwise direction).
- The amplitude of the received wave is equal to $A = \sqrt{V_{\max} + V_{\min}}$ (remembering about the quadratic detector).

Due to the fact that any transmit and receive antennas have some angular radiation pattern with non-zero beam width, the radiated electromagnetic waves propagate to the receiver using multiple paths. The simplest case presented in Figure 4 where 2 most powerful waves came to the receiver antenna.

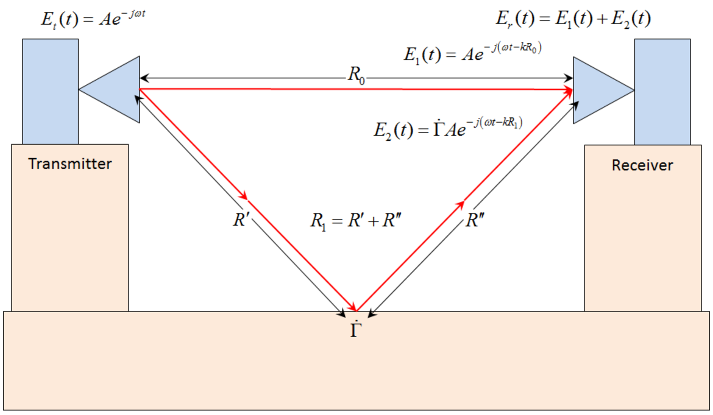


Figure 4

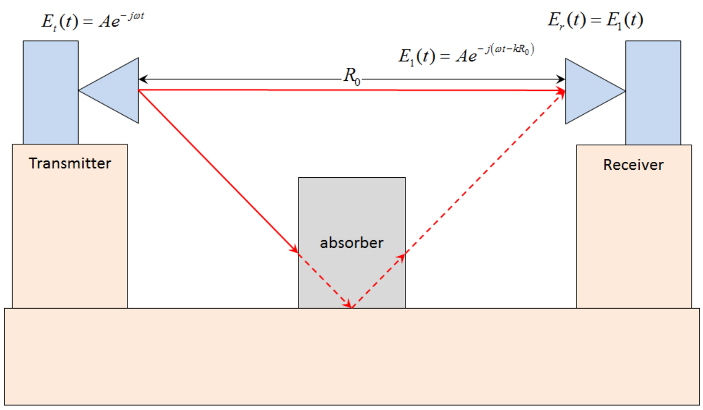


Fig. 5

It is known from the electromagnetic theory that during the reflection of electromagnetic wave from any surface, the wave with arbitrary polarization has to be presented as a vector sum of linearly polarized components that oscillate within the incident plane and in the perpendicular to that plane direction. These components are reflected with its own reflection coefficient that are called the Fresnel coefficient and depends on incident angle, magnetic permeability, conductivity and dielectric permittivity of reflecting surface/medium. Within our experimental setup this components have linear vertical (within incident plane) and horizontal polarizations. As result, the signal at the input of the receiver antenna equals to

$$\dot{\mathbf{E}}_r(t) = \begin{Vmatrix} \dot{E}_{rH}(t) \\ \dot{E}_{rV}(t) \end{Vmatrix} = \dot{\mathbf{E}}_0(t) + \dot{\mathbf{\Gamma}} \cdot \dot{\mathbf{E}}_1(t) = \begin{Vmatrix} \dot{E}_{0H}(t) \\ \dot{E}_{0V}(t) \end{Vmatrix} + \begin{Vmatrix} \dot{\Gamma}_H & 0 \\ 0 & \dot{\Gamma}_V \end{Vmatrix} \begin{Vmatrix} \dot{E}_{1H}(t) \\ \dot{E}_{1V}(t) \end{Vmatrix}. \tag{8}$$

To prevent this effect it is necessary to use the absorbing material that drastically reduces the amplitude of second wave, reflected from the ground surface (floor) – see Figure 5.

It is impossible to use this technique widely in most practical cases for the suppression of multipath propagation, most of the time we have to analyse the general case, considering the presence of both waves. As soon as $R_1 \approx R_0$, we can assume equality of the amplitudes of waves that propagate through both paths and the equation for received wave has to be rewritten in more detailed form:

$$\begin{aligned} \dot{\mathbf{E}}_r &= \frac{A_0}{R_0} \mathbf{P}_1 e^{-j(\omega t - kR_0)} + \frac{A_0}{R_1} \dot{\mathbf{\Gamma}} \cdot \mathbf{P}_1 e^{-j(\omega t - kR_1)} \\ &= \frac{A_0}{R_0} e^{-j(\omega t - kR_0)} \left(\mathbf{I} + \dot{\mathbf{\Gamma}} \cdot e^{jk\Delta R} \right) \cdot \mathbf{P}_1 \end{aligned} \tag{9}$$

where $\mathbf{P}_1$ is the polarization vector of transmitted wave in the polarization basis {H,V} (similar to Eq.(1)), $\mathbf{I}$ is the 2x2 unit matrix.

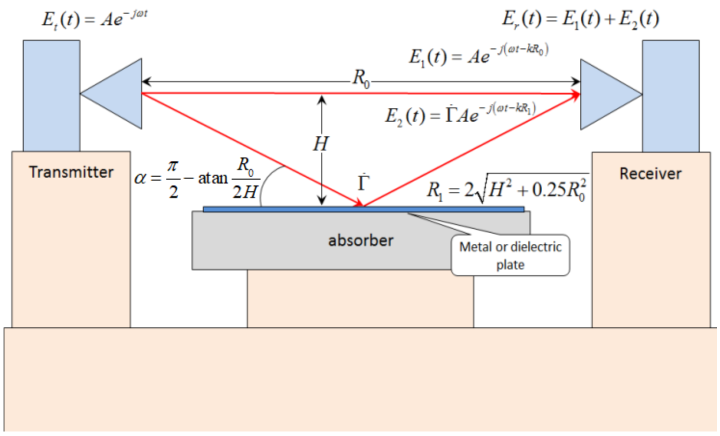


Figure 6

If we will transmit vertically or horizontally polarized waves, the amplitudes of the received waves with the same polarizations will be equal to

$$\begin{aligned} E_{rH} &= A_H \left| 1 + \dot{\Gamma}_H e^{jk\Delta R} \right| \approx A_H \left| 1 + \dot{\Gamma}_H e^{-j2kh_1h_2/d} \right| \\ E_{rV} &= A_V \left| 1 + \dot{\Gamma}_V e^{jk\Delta R} \right| \approx A_V \left| 1 + \dot{\Gamma}_V e^{-j2kh_1h_2/d} \right| \end{aligned} \tag{10}$$

where $A_{H,V} = A_0 P_{H,V} / R_0$, h_1, h_2 - heights of transmit and receive antennas above the reflecting surface, d is the distance between antennas, $k = 2\pi / \lambda$, λ - wavelength of propagating electromagnetic wave. This equation derived for the case $h_{1,2} / d \ll 1$. For a case that will be studied during the practicum and is presented in Figure 6, $h_{1,2} = H$, $d = R_0$.

In case of complex polarization state of the transmitted wave that is presented using the complex polarization ratio, the equations for received wave become vector and complex:

$$\begin{aligned}\dot{\mathbf{E}}_r &= A_H\begin{bmatrix}1\\ \dot{p}_t\end{bmatrix}e^{-j(\omega t-kR_0)} + A_H\begin{bmatrix}\dot{\Gamma}_H & 0\\ 0 & \dot{\Gamma}_V\end{bmatrix}\begin{bmatrix}1\\ \dot{p}_t\end{bmatrix}e^{-j(\omega t-kR_1)}\\ &= A_H e^{-j(\omega t-kR_0)}\left(\begin{bmatrix}1\\ \dot{p}_t\end{bmatrix}+\begin{bmatrix}\dot{\Gamma}_H & 0\\ 0 & \dot{\Gamma}_V\end{bmatrix}\begin{bmatrix}1\\ \dot{p}_t\end{bmatrix}e^{jk\Delta R}\right)\end{aligned}, \tag{11}$$

where $\dot{p}_t = \dot{A}_V / \dot{A}_H$ is a complex polarization ratio (2) of transmitted wave. Finally, the amplitude and polarization structure of the received EMW defined as

$$\dot{\bar{E}}_{0r} = A_H\begin{bmatrix}1+\dot{\Gamma}_H e^{jk\Delta R}\\ \dot{p}_t\left(1+\dot{\Gamma}_V e^{jk\Delta R}\right)\end{bmatrix}. \tag{12}$$

The complex polarization ratio of the received wave in this case defined as

$$\dot{p}_r = \dot{p}_t \cdot \frac{1+\dot{\Gamma}_V \cdot e^{jk\Delta R}}{1+\dot{\Gamma}_H \cdot e^{jk\Delta R}}. \tag{13}$$

Here $\dot{\Gamma}_H$ and $\dot{\Gamma}_V$ are the Fresnel reflection coefficients for EM waves with horizontal and vertical polarizations:

$$\dot{\Gamma}_H = \frac{\cos\theta_i - \sqrt{\dfrac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\dfrac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} - \sin^2\theta_i}}, \quad \dot{\Gamma}_V = -\frac{\dot{\varepsilon}_2\cos\theta_i - \dot{\varepsilon}_1\sqrt{\dfrac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} - \sin^2\theta_i}}{\dot{\varepsilon}_2\cos\theta_i + \dot{\varepsilon}_1\sqrt{\dfrac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} - \sin^2\theta_i}} \tag{14}$$

The ratio of dielectric permittivities in these equations equals to the relative dielectric permittivity of the second media as soon as the relative dielectric permittivity of the air is very close to unity.

Short notes on demo hardware

This practicum session includes two sets of experiments with monochromatic (single frequency) microwaves in X frequency band (8 – 12 GHz). For both assignments we do not use any equipment, which can resolve the temporal structure of the EM waves.

For the transfer of the monochromatic (one frequency only, low frequency ($f_{\text{modulation}} \ll f_{\text{carrier}}$) amplitude modulation –e.g., for visualization on oscilloscope– can be neglected from consideration) EM waves from generator via transmission lines (coaxial and, on final stage, waveguide) to free space for these assignments we are using different types of horn antennas.

The electric vector $\mathbf{E}$ at the output of rectangular waveguide at given setup is linearly polarized and perpendicular to wide side of waveguide. The rectangular horn antenna matches impedances of transmission line (waveguide) and free space, narrows down the radiation patterns and keeps the linearly polarized state and the orientation of $\mathbf{E}$ vector.

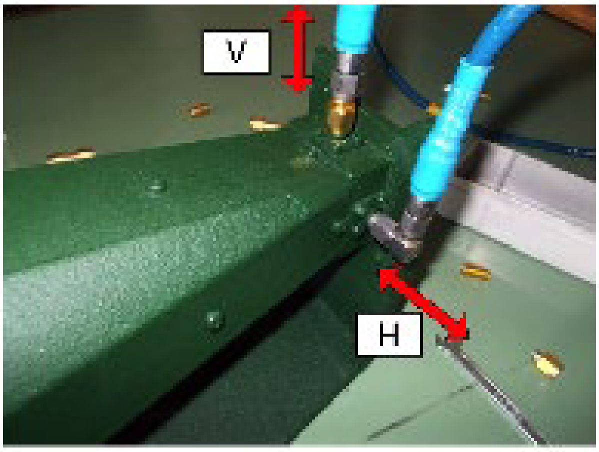


Figure 7.

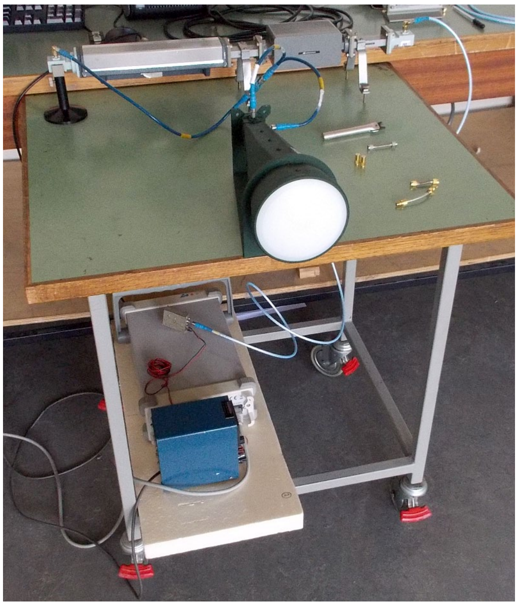


Figure 8.

For the polarization-isotropic circular horn with coaxial connectors the output polarization of the radiated EM wave is defining as a vector sum (keep in mind possible phase difference) of waves with linear polarization, which are parallel to the central wires of feeding coaxial cable connectors. If only one connector is in use, another one has to be loaded with the matched load. In Figure 7 the orientations and related transmitted polarization components of signals are shown that came from coaxial cable to different ports of the circular horn antenna. By changing amplitudes and phase difference between two polarization components it is possible to form an arbitrary polarization of radiated field. By exciting only one antenna port either horizontal (H) or vertical (V) polarization can be transmitted. By exciting both ports by both cables with a phase difference 0 rad, a linearly polarized wave with 45 degrees orientation will be transmitted. The phase shift between feeding ports of 180 degrees will result in -45 degrees orientation of linear polarization. By providing a phase difference between signals in the feeding coaxial cables of 90 degrees a circular polarization will be formed (rotation direction (right or left) can be controlled with selection in which channel (H or V) insert such 90 degrees phase shifter). Arbitrary phase shift results in elliptic polarization of the transmitted wave.

(visit the online demos (links are also provided at the BS page), to experiment with amplitudes of orthogonal components and phase difference between them in relation to the final polarization ellipse of electromagnetic wave, to see the influence of the random noise, and to experiment with the observed shape of the polarization pattern for different polarization states of EM wave)

Practical tasks

1. Implement Matlab functions for the calculations:

1.1. polarization phasor of EMW as function of ellipticity and orientation angles (according to (2))

1.2. complex Fresnel reflection coefficients (14) as function of dielectric permittivity and incident angle

1.3. polarization state of the received wave in multipath propagation case (Fig. 6) as function of EMW frequency, polarization parameters of transmitted wave, scene geometry (distance between antennas, their heights and height of reflection plate, incident angle) and related reflection coefficients of the reflection plate

1.4. illustrate your implementations with plots of expected functional dependencies (or specific interesting cases) and give their brief analysis.

1.5. Plot Fresnel reflection coefficients vs incident angle for the provided dielectric permittivity (see below) and find the Brewster angle.

2. Develop Matlab script for the simulation of the measurements of the polarisation state of the EM Wave using the polarization pattern method:

Based on the materials in the above section "Short theoretical overview" and provided on Brightspace site pages of the Mott's book, develop a simulator of the measurements of the polarisation state of the EM Wave using the polarization pattern method.

Show resulting angular patterns (similar to the Fig. 3) for the cases of transmitting vertical, horizontal and circular polarizations in following setups:

2.1. free space case (Fig. 5)

2.2. multipath case (Fig. 6) for the metallic reflecting plate for different heights H

2.3. multipath case (Fig 6) for the dielectric reflecting plate for different heights H

2.4. analyse the case of transmitted circular polarization when the incident angle of the reflected from dielectric plate wave equals to the Brewster angle (defined in 1.5)

and briefly analyse them in the report.

Parameters for these simulations can be found in the variable *session2.task2*, which you can find in the file with materials for your group at the Brightspace site (see Instructions for previous assignment):

- *session2.task2.frequency* – in Hz
- *session2.task2.dielectric_prermittivity* - complex value of the dielectric reflecting plate's relative permittivity
- *session2.task2.antennas_distance* - distance between transmit and received antennas, in meters
- *session2.task2.reflection_height* - vector of height differences between line of sight and reflection point (H in Fig. 6), in meters