Characterization of a Transmitter-Receiver System

Keywords:
Microwaves, transverse waves, plane waves, spherical waves, standing wave, directional characteristic, reflection law and refraction law, index of refraction, polarisation.

Measuring program:

Properties of a transmitter-receiver system for microwaves, measurement of the distance dependence and directional characteristic, index of refraction of PVC for microwaves, reflection of microwaves at a metal plate and a wire grid, polarisation of microwaves.

References:
/1/ DEMTRÖDER, W.: „Experimentalphysik 2 – Elektrizität und Optik“, Springer-Verlag, Berlin among others
/2/ EICHLER, H. J., KRONFELDT, H.-D., SAHM, J.: „Das Neue Physikalische Grundpraktikum“, Springer-Verlag, Berlin among others

1 Introduction

Over the course of your studies of physics you will get to know different transmitter receiver systems, e.g. the system light source / photo detector in optics, or the system loudspeaker / microphone in acoustics. Such systems are generally described by a number of characteristic values. The aim of this experiment is to familiarize you with some of these values by measuring the characteristics of a transmitter receiver system for microwaves[1]. It is to be investigated in particular,

- whether, and if yes how, the intensity of the emitted wave decreases with increasing distance from the transmitter (*distance dependence*),
- in which geometric form (e.g. beam-like, spherical or lobar) the wave propagates (*directional characteristic*),
- by which structures the wave is reflected (*reflection law*),
- whether the wave is refracted at the interface air → PVC (*refraction law and index of refraction*),
- whether the wave is linearly *polarized*.

The system consists of a microwave transmitter and a suitable receiver. Both components are treated as ”black boxes” that serve a certain purpose (emit a wave and detect the intensity of a wave), the construction of which, however, is of no importance for the experiment and is therefore neglected.

Fundamental school knowledge of optics is required to analyse parts of the tasks in this experiment: reflection, refraction, standing wave. In the course of the introductory laboratory course, these subjects will be treated in detail following their presentation in the lecture.

2 Experimental Procedure

Equipment:

Microwave transmitter (Type I with Gunn diode MICROSEMI MO86751A, $P \approx 10$ mW, $\lambda \approx 28.5$ mm; type II with Gunn diode CL 8650 8927 (unknown manufacturer), $P \approx 15$ mW, $\lambda \approx 27.5$ mm), microwave receiver (HEWLETT-PACKARD X424A), 2 triangular rails (lengths 1.5 m and 0.5 m), joint for triangular rails with angle scale indicator, angle-sensor (TWK ELEKTRONIK PBA 12), 3 power supplies (PHYWE (0 – 15 / 0 – 30) V), multimeter (AGILENT U1272A or U1251B), digital oscilloscope TEKTRONIX TDS 1012 / 1012B / 2012C / TBS 1102B - EDU, PVC plate, metal plate, wire grid, transition stage (length 100 mm) with motor and laser distance sensor (BAUMER OADM 12U6460/S35), 2 impedance converters, PC with DAQ device (NATIONAL INSTRUMENTS myDAQ) and BNC-adapter box, metal measuring tape (length 1 m), stand material.

2.1 Set-up of Transmitter and Receiver

Before starting with the experiments the operation of transmitter and receiver has to be learnt. For this purpose, a set-up according to Fig. 1 is constructed. Transmitter S and receiver E are assembled on a triangular rail (about 1.5 m long) adjusted to the same height and arranged centrically to the axis A at a distance of d = 5 cm from each other. The distance between the front edges of the *horns* of transmitter and receiver is defined as distance d.

---

[1] Microwaves are electromagnetic waves in the frequency range between approx. 300 MHz and 300 GHz.

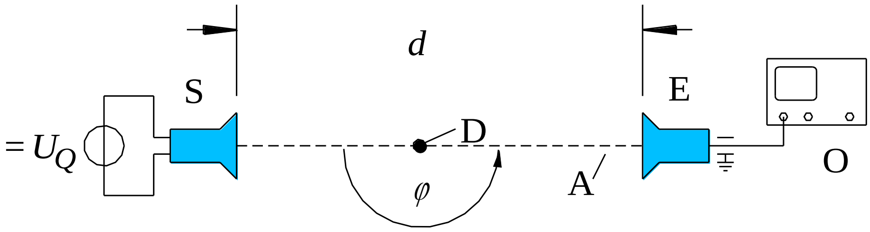

Fig. 1: Schematic set-up of the transmitter S connected to a supply voltage U_Q and the corresponding receiver E. E is connected to the oscilloscope O and/or a data acquisition board via a coaxial cable, the outer conductor of which is grounded. A is the joining axis of S and E. For some experiments, S and E are mounted on a *single* triangular rail, for others *two* rails connected by an angular joint with rotational axis D are used. d is the distance between S and E, while the angular orientation is given by φ. The angle φ is measured using an angle-sensor, which is known from the experiment "*Sensors…*".

The transmitter is connected to a DC power supply U_Q that has been adjusted to an output voltage of 10 V beforehand (to be checked with a multimeter). It then emits a microwave with constant power P with the wavelength λ (P and λ see equipment).

The receiver is connected to an oscilloscope O (DC coupling) and/or a data acquisition (DAQ) device via a coaxial cable. It measures the intensity I of the incident microwave. Intensity means the temporal average of energy of a wave per time and area, the unit of intensity thus being $[I]$ = J s^{-1} m^{-2} = W m^{-2}. (The detector cannot directly follow the high-frequency course of the electric field **E** of the microwave (frequency approx. 10.5 GHz[2]).[3])

The receiver is constructed so that it converts the intensity I of the received wave into a *negative* voltage signal U: $I \sim -U$. For the following experiments only the magnitude $|U|$ of the voltage is decisive.

Hints:
- The outer conductor of the coaxial cable is grounded (connection with the ground terminal (⏚) of the laboratory), as to prevent the possible destruction of the semiconductor diode in the receiver by electrostatic discharge.
- Since, to an extent, the microwaves can also be scattered by, and reflected from experimenting persons, all of the following measurements should always be done under the same conditions (same standing place of persons etc.).

2.2 Distance Dependence

First, the *distance dependence* is measured. For this purpose, the transmitter and receiver are mounted on one triangular rail (length about 1.5 m) according to Fig. 1 and the voltage U at the receiver is measured as a function of the distance d (5 cm $\leq d \leq$ 1 m) with the oscilloscope. With varying d, an oscillation of the detected signal will occur, which is superimposed to the distance dependent course of the signal. This oscillation (period length $\lambda/2$) is due to the fact that part of the emitted wave is reflected by the receiver, interferes with the emitted wave and forms a standing wave. Since the amplitude of the reflected wave is significantly smaller than the one of the emitted wave, a standing wave with a weak modulation forms (cf. Fig. 2).

For measuring the distance dependence it must be ensured that the measuring points are always at the distances d_i where the magnitude of the receiver signal, $|U|$, is maximal. The distance between measuring points should be 2λ. After a measuring point is adjusted, the measured value for U can be obtained from the oscilloscope by using the operation mode Measure → Average. For U, no error must be stated. The maximum error for d_i results from the restricted precision in determining the position of measuring points. For the analysis, $|U|$ is plotted against d (with maximum error Δd) once in a semi-log plot ($|U|$ on logarithmic axis) and once in a double logarithmic plot. Additionally, the curves that would result for the following cases are plotted into the diagrams:

---

[2] For comparison, frequencies of other microwaves: Digital-satellite TV approx. 12 GHz, microwave oven approx. 2.5 GHz.

[3] This is analogous to a photo detector, which also can measure only light *intensities*, but not the temporal course of the electric field of a light wave in the frequency range of 10^{14} Hz.

a) The transmitter emits a strongly restricted ray which is not damped between S and E: $|U| = |U_0| = \text{const.}$ with the initial voltage $|U_0|$.

b) Like in a), but with exponential damping by absorption between S and E: $|U| = |U_0|\,\mathrm{e}^{-\alpha d}$ with the damping coefficient α (0,02 cm^{-1} has proven to be a good value).

c) The transmitter emits a spherical wave which is not damped between S and E by absorption: $|U| = |U_0|\,k / d^2$. k is a scaling factor to be chosen so that $|U| = |U_0|$ for $d \to 0$.

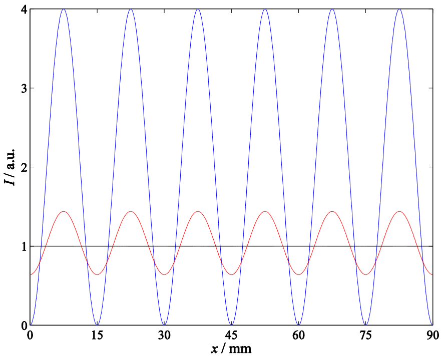

Fig. 2: Spatial course of the intensity I of a standing wave caused by interference of two plane microwaves propagating in opposite directions with a wavelength of $\lambda = 30$ mm[4]. Blue: Course of the intensity for the case, that the amplitude E of the incident wave (E_a) is equal to the amplitude of the reflected wave (E_r): $E_r = E_a$. Red: $E_r = 0{,}2\, E_a$. Black: $E_r = 0$. The maxima and minima of the intensity are spaced by a distance of $\lambda/2$ each, “a.u.” stands for *arbitrary units*.

By comparing the course of measured data with theoretically expected courses according to a) to c) it is to be determined, in which way the wave propagates. For presentation of the theoretical curves, suitable values have to be inserted for α, k and $|U_0|$ so that the expected course of the curve is clearly visible. In order not to draw false conclusions, the measured directional characteristic (Chapter 2.3) must be considered as well!

2.3 Directional Characteristics

For the measurement of the *directional characteristics* the transmitter is mounted on the long rail, so that the front edge of the horn lies right on the rotation axis D (Fig. 1). The receiver is placed at a distance of about 40 cm behind the rotation axis on a second rail (about 0.5 m in length). Both rails are connected by a swivel joint. The angle φ can be read off from an angular scale and simultaneously be measured with the aid of an angle-sensor, which is already known from the experiment “*Sensors...*”. While adjusting the distance between E and D, it must be ensured that the receiver signal $|U|$ shows a maximum for an angular orientation of $\varphi = 180°$. The angle $\varphi = 180°$ is set by aligning the rails along their common axis A with the aid of a metal measuring tape.

By rotation of the arm with the receiver E, the angle is increased from $\varphi = 150°$ to $\varphi = 210°$. During the rotation, the output voltage U_W of the angle-sensor and the voltage U at the receiver are measured and recorded with a DAQ device (see below *Note for data acquisition with the DAQ device*).

Subsequently, $|U|$ is presented as a function of φ (calculated from U_W) in a *polar diagram*[5] with the aid of `Origin` (cf. Fig. 3). No errors must be stated for $|U|$ and φ. The polar diagram is presented as a *line diagram* instead of a *point diagram*, in order to account for the large amount of measured data, In addition, the curves which would result in cases a) and c) are drawn into this diagram.

---

[4] The intensity I of an electromagnet wave is proportional to the square of the amplitude E of its electric field: $I \sim E^2$.

[5] To create a polar diagram with `Origin`: → Plot → Specialized → Polar

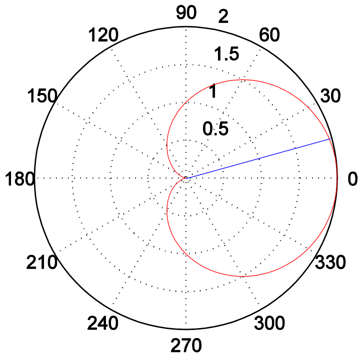

Fig. 3: Example of a polar diagram for the function $r(\alpha) = 1 + \cos\alpha$ (red curve). The angle α runs counter-clockwise. For every angle α, the function value $r(\alpha)$ is represented as the distance from the centre of the diagram (exemplarily marked by a blue line for $\alpha = 15°$.

Note for data acquisition with the DAB

The voltage U_W of the angle-sensor and the voltage U at the receiver are measured and recorded simultaneously by a NI myDAQ device in the PC in an analogue manner to the experiment "*Data acquisition with the PC...*". U_W and U are fed to the connectors AI 0 und AI 1 resp., each via an *impedance converter*[6] for reasons of signal matching. The `MATLAB`–*m*-file from that experiment "*Data acquisition…*" might be extended in order to allow recording both signals simultaneously. Alternatively, a new `MATLAB`–*m*-file *"DatenEinlesen.m"* with a graphical user interface is provided.

A sampling rate of $R = 100/\text{s}$ is sufficient for recording the measured data. The data are read out following the end of the measurement and the data file holds the voltage values from both channels in the form of an $(N, 2)$-matrix having N rows and 2 columns, where N is the number of recorded values. The first column holds the values measured at channel 0, thus the values of U_W, the second column hold the values measured at channel 1, thus the values of U, if not chosen otherwise. The data for the time t are not needed for further analysis. The data for U_W and U are exported into an ASCII-file (here: MD.dat) for further processing by `Origin` later on.

Note for avoidance of interfering voltages:

> This part of the experiment requires connecting the ground-wires (0 V) of the voltage supplies for the impedance transformer and angle-sensor to the ground terminal (⏚) of the power supplies, in order to prevent disturbing voltages from the ground loops.

2.4 Refraction

The aim of this partial experiment is the determination of a rule-of-thumb value for the refractive index n_PVC of PVC for the used microwave[7].

The propagation velocity of electromagnetic waves depends on the index of refraction n of the medium through which the waves propagate. In vacuum, $n = 1$; in this case, the waves propagate at the speed of light in vacuum c. c is a universal constant (cf. back envelope of this script). In media (index M) with $n > 1$, the propagation velocity is lower. It holds:

(1) $$c_\mathrm{M} = \frac{c}{n_\mathrm{M}}$$

In vacuum, the following relation between the propagation velocity c, the wavelength λ and the frequency ν of an electromagnetic wave holds:

(2) $$c = \lambda\,\nu$$

---

[6] The composition and function of impedance transformers are treated in the experiment "*Operational Amplifier*" later on (summer semester).

[7] In the following description it is presupposed that the microwave propagates like a plane wave. Following the results from Chap. 2.3 this is not the case. Furthermore, the measurement is influenced by scattering and reflection at surrounding materials. Therefore, it is not possible to measure n_PVC precisely with the used set-up. However, the measurement delivers a usable rule-of-thumb value.

In a medium with $n_{\mathrm{M}} > 1$ it holds likewise:

$$(3) \qquad c_{\mathrm{M}} = \lambda_{\mathrm{M}}\, \nu$$

The propagation velocity and the wavelength are reduced inside a medium, while the frequency of the wave remains unchanged. The combination of (1) to (3) yields:

$$(4) \qquad \frac{c}{n_{\mathrm{M}}} = \frac{\lambda}{n_{\mathrm{M}}}\, \nu$$

For air, $n_{\mathrm{M}} \approx 1$, and hence, $c_{\mathrm{M}} \approx c$ and $\lambda_{\mathrm{M}} \approx \lambda$.

The contraction of the wavelength in a medium with $n_{\mathrm{M}} > 1$ can be exploited in order to measure the index of refraction n_{M}. For this purpose, we consider a cut-out of the standing wave previously known from Chap. 2.2 as depicted on the top in Fig. 4. Between S and E there is air with $n_{Air} \approx 1$. Along a distance of length *L*, *M* maxima of intensity form, separated by *λ/2* from each other. It thus holds:

$$(5) \qquad L = M\, \frac{\lambda}{2}$$

Now, we insert a plate of thickness *D between* S and E according to Fig. 4 bottom. Let the index of refraction of the plate's material be $n_M > 1$. This causes the wavelength inside the plate to be contracted:

$$(6) \qquad \lambda_{\mathrm{M}} = \frac{\lambda}{n_{\mathrm{M}}}$$

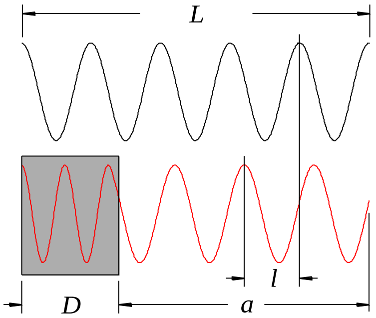

Fig. 4: Standing waves between S and E. The top shows the case where S and E are separated by air. The bottom shows the case where a plate of thickness *D* with the index of refraction n_{M} is inserted into the air between S and E, which shifts the maxima of intensity towards the plate within the range *a*. For other labels refer to the text.

and the number of antinodes along the distance *L* to increase by *m*. It holds:

$$(7) \qquad \frac{D}{\frac{\lambda_{\mathrm{M}}}{2}} + \frac{a}{\frac{\lambda}{2}} = M + m$$

The increase of the number of maxima of intensity by *m* is, outside the plate, accompanied by an offset of the maxima by a distance *l*, for which holds:

$$(8) \qquad l = m\frac{\lambda}{2}$$

Additionally, it holds according to Eq. (5):

$$L = D + a = M\,\frac{\lambda}{2} \tag{9}$$

By inserting M from Eq. (9) into Eq. (7) and together with Eqs. (6) and (8), it follows:

$$\frac{2\,n_{\mathrm{M}}\,D}{\lambda} + \frac{2\,a}{\lambda} = \frac{2\left(D + a\right)}{\lambda} + \frac{2\,l}{\lambda} \tag{10}$$

It thus follows for n_M :

$$n_{\mathrm{M}} = \frac{D + l}{D} \tag{11}$$

By measurement of D and l, it is thus possible to determine n_M . However, the method described above is only unambiguous, if $m < 1$. This is equivalent to $l < \lambda/2$. According to Eq. (11) this means:

$$l = D\left(n_{\mathrm{M}} - 1\right) < \frac{\lambda}{2} \tag{12}$$

and hence

$$D < \frac{\lambda}{2\left(n_{\mathrm{M}} - 1\right)} \tag{13}$$

In this experiment, the index of refraction of PVC, n_{PVC}, for a microwave with $\lambda \approx 28.5$ mm and $\lambda \approx 27.5$ mm, respectively, shall be determined with the aid of Eq. (11). The index of refraction for PVC is in the order of magnitude of $n_{\mathrm{PVC}} \approx 1.6$. Thus it follows for both values of λ: $D < 23$ mm. Here, $D \approx 10$ mm is used.

In order to measure l, we proceed as follows: S and E are mounted on both triangular rails symmetrically to the rotating axis D at a distance of $d_0 = 500$ mm. The receiver is mounted on a motorized translation stage V which allows it to be displaced along the axis A by 100 mm in the direction of S (Fig. 5). The motor is operated by a direct current. The speed of displacement depends on the height of the applied voltage (maximum 24 V), the direction of movement (forwards / backwards) is governed by the polarity. Both ends of the translation stage are fitted with micro-switches which cause the motor to stop upon reaching either endpoint.

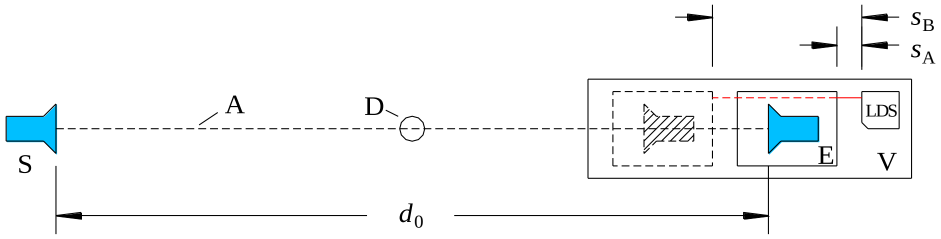

Fig. 5: Set-up of transmitter S and receiver E on a motorized translation stage V. With this translation stage E can be moved forwards from the right to the left stop position and backwards from the left to the right stop position. In the stop positions s_A and s_B are the corresponding distances between the LDS and the ground plate on which E is mounted.

A laser distance sensor LDS that is known from the experiment "*Sensors…*" is mounted on the translation stage. Its output voltage U_L changes linearly with the translation of E. The sensor is calibrated by measuring the distances s_A and s_B (definition see Fig. 5) for both stop positions and the corresponding output voltages U_{LA} and U_{LB}. If E is at any position between the two stop positions during the translation, it follows for the momentary distance s of the receiver from the right stop position:

$$s = \left(U_{\mathrm{L}}\left(s\right) - U_{\mathrm{LA}}\right)\frac{s_{\mathrm{B}} - s_{\mathrm{A}}}{U_{\mathrm{LB}} - U_{\mathrm{LA}}} \tag{14}$$

and thus for the decisive distance d between S and E:

$$d = d_0 - s \tag{15}$$

The motor is started at the right stop position and driven forward in the direction of S up to the left stop position. During the translation, the voltage U_L and the voltage U at E are measured with the data acquisition board and saved (analogue to the procedure for the measurements of Chap. 2.3).
Subsequently, the measurement is repeated with the PVC plate of thickness D_0 (measure with caliper) inserted between S and E. The plate is mounted centric to the rotating axis D. In order to prevent the measurement from being disturbed by signal reflections, the plate is orientated in an angle of $\alpha = 45°$ to the axis A. Thus, the microwave propagates the distance

$$D = D_0 \,/\, \cos\left(\alpha\right) \tag{16}$$

in PVC[8]. After that, the motor is started in the left stop position and moves backwards to the right stop position. During the movement U_{L} and U are recorded again and then stored.
From the two datasets the distances d are calculated using Eqs. (14) and (15) with the aid of `Origin`. Subsequently, $|U|$ is plotted over d in *one* diagram for both datasets. With the `Origin`-tool “`Data coordinates / Data Reader`“[9], it is possible to determine the position of a selected maximum of intensity in both curves and its offset l from this. Finally, the index of refraction n_{PVC} is determined from the values for l and D.

Note for avoidance of interfering voltages:

> This part of the experiment requires connecting the ground-wires (0 V) of the voltage supplies for the impedance transformer and laser distance sensor to the ground terminal (⏚) of the power supplies, in order to prevent disturbing voltages from the ground loops.

2.5 Polarization

In a linearly polarized microwave beam, the electrical field **E** of the wave oscillates in only one spatial direction (e.g. y-direction, cf. Fig. 6). If such a wave is incident on a metal wire grid oriented in the same direction, currents are induced in the rods, causing them to act as a HERTZian dipole.
The wave emitted by the dipoles is phase shifted to the incident wave by 180°. Behind the grating, destructive interference occurs between the incident and the emitted waves. A receiver placed behind the grating will thus (if at all) measure only a weak signal.

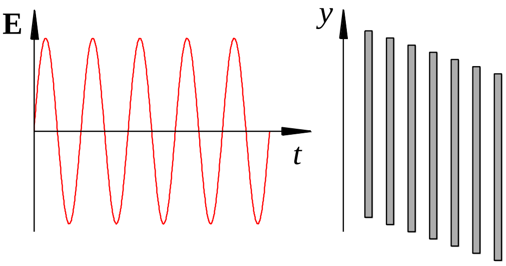

Fig. 6: Interaction of a linearly polarized wave **E** with a wire grid whose thin rods are oriented in the direction of polarization of the wave.

---

[8] Approximation for a plane wave.

[9] The graphical symbol for the tool `Data Reader` is ⊞.

In front of the grating the wave emitted backwards by the dipoles interferes with the incident wave. If the grating is tilted towards the incident wave as in the experiment on reflection (Chap. 2.6.2), the wave emitted backwards (the reflected wave) can propagate without interference from the incident wave.

If the linearly polarized wave is incident on a grating where the rods are oriented perpendicular to the direction of polarization, no appreciable currents are induced (assuming the diameter of the rods is small). In this case, no HERTZian dipole radiation is emitted, allowing the incident wave to pass the grating nearly undisturbed.

To analyse the polarization characteristics of the microwaves used in this experiment, S and E are mounted at a distance of $d \approx 5$ cm ($\varphi = 180°$) from one another. A wire grid is held between S and E the rods of which are in the vertical direction one time and in the horizontal direction the next. The voltage U at the receiver is measured with the oscilloscope for each line orientation.

Question 1:

- Is the wave linearly polarized? If so: In which direction?

2.6 Reflection

2.6.1 Reflection at a Metal Plate

To measure the *reflection* at a metal plate MP, S and E are mounted at a distance of about 20 cm from the rotation axis and the angle between S and E is set to $\varphi = 90°$ (Fig. 7). The metal plate is mounted so that the rotation axis D lies along its surface area. Now, the angle γ is incremented in eight steps of 3° each, starting from $\gamma = 35°$ and the voltage U at the receiver is measured for each angle with the oscilloscope. $|U|$ is plotted over γ and the angle of maximum reflection is determined with a regression curve through the measured data. For the regression curve, a polynomial fit of degree 2 is used, which is calculated and drawn[10] using `Origin`.

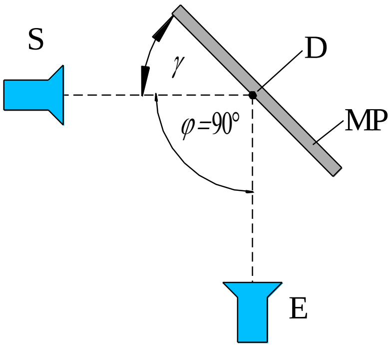

Fig. 7: Set-up for measuring the reflection at a metal plate MP. S and E are mounted at an angle of $\varphi = 90°$, while the angle γ is varied.

Question 2:

- Is the law of reflection valid?

2.6.2 Reflection at a Wire Grid

The same measurement as in Chap. 2.6.1 is repeated with a wire grid with vertically orientated rods. The measured data $|U(\gamma)|$ are added to the diagram created in Chap. 2.6.1. In order to interpret the results of the measurements, refer to the notes on polarization in Chap. 2.5.

---

[10] Polynomial fit with `Origin`: → Analysis → Fitting → Fit Polynomial