Related topics

Transmission, reflection, absorption, refraction, phase velocity, total reflection, surface waves, frustrated total reflection, tunnel effect

Principle and task

In the first part, the transmission and reflection characteristics of glass, acrylic glass and metal are studied with a microwave transmitter-receiver pair and are compared to each other.
In the second part, total reflection of microwaves on a prismatic surface is suppressed by bringing a second prism with the same refractive index close to the first one.

Equipment

Microwave transmitter w. klystron	11740.01	1
Microwave receiver	11740.02	1
Microwave power supply, 220 VAC	11740.93	1
Screen, metal, 300×300 mm	08062.00	2
Glass plate, 200×300×4 mm	08204.00	1
Plexiglas plate, 200×200×4 mm	11613.00	1
Barrel base -PASS-	02006.55	4
Plate holder	02062.00	1
Supporting block 105×105×57 mm	02073.00	2
Prism, synthetic resin	06873.00	2
Digital multimeter	07134.00	1
Screened cable, BNC, l 750 mm	07542.11	1
Adapter, BNC-socket/4 mm plug pair	07542.27	1
Vernier caliper, plastic	03011.00	1

Problems

1. Determination of the reflecting and transmitting characteristics of glass, acrylic glass and metal.
2. Observation of the effect of frustrated total reflection and determination of the transmitted irradiance as a function of distance d to the prismatic surface. The refractive index of the prism material can be calculated by determining the attenuation coefficient γ.

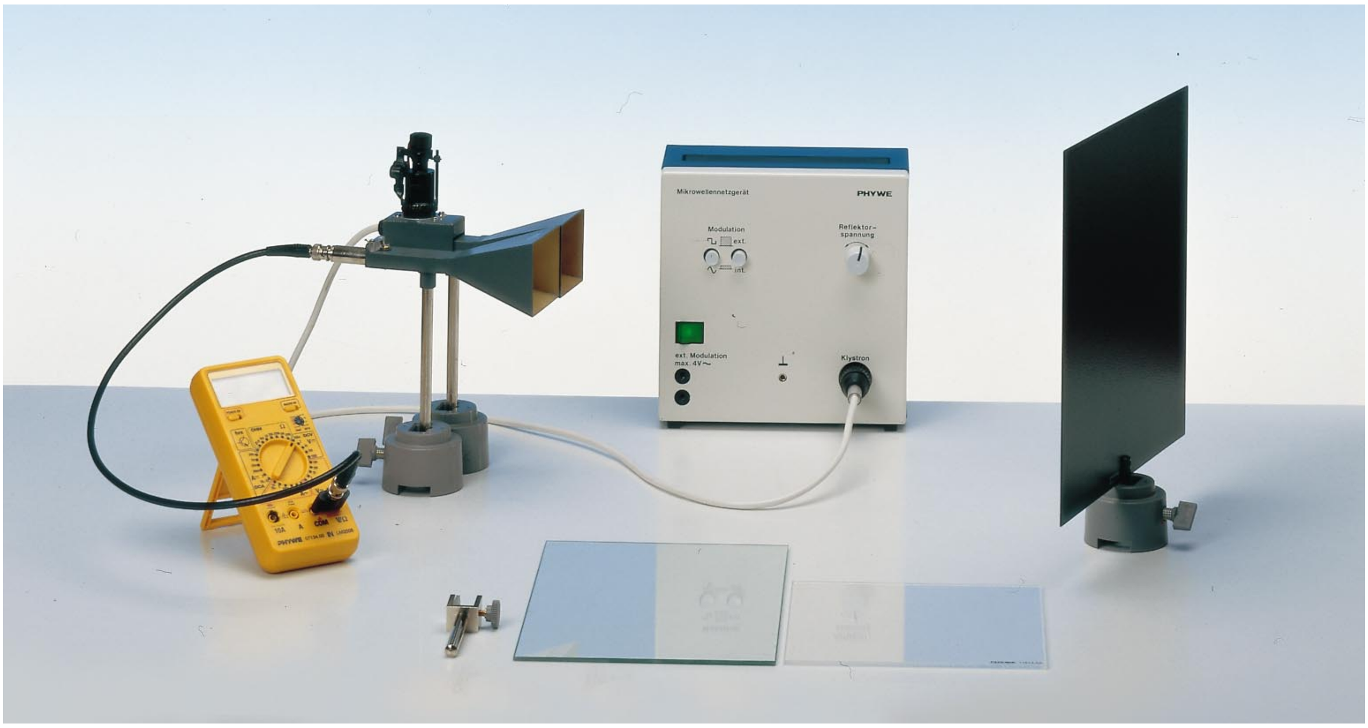
Set-up and procedure

1. To begin with, the reflector voltage of the clystron is adjusted to maximum output (no modulation: "ext" and "~"). Direct voltage on the rectifier of the antenna is proportional to the received irradiance. The experimental set-up required to determine the reflecting characteristics is shown in Fig. 1. Transmitter and receiver antenna are adjusted to the maximum reflection signal, for which the distance between the material plate and the antenna heads should be 40 cm. The reflecting power of glass, acrylic glass and metal plates (screen) are then measured.

To determine the transmission characteristics, the directional receiver is set up at r = 80 cm (distance of the antenna heads) from the transmitter antenna, in order to compensate the loss of irradiance in air due to absorption by water molecules and to the divergence of the emitted microwaves (proportional to r^{-2}). For comparison, the values of irradiance transmitted through air should also be noted along with those for irradiance transmitted through the test material.

2. The experiment for frustrated total reflection is shown in Fig. 2. The microwave transmitter is set up directly in front of the first prism in such a way, that only one half of the back surface of the prism is irradiated. The other half of the prism is covered from the back with a screen, in order to protect the receiver from multiply reflected waves.

Fig. 1: Experimental set-up to determine reflection characteristics.



The radiation characteristic of the microwave emitted by the horn antenna is directed forward and similarly the receiver antenna has the same, narrow reception characteristic. If the sphere function of the microwave field is developed according to plane waves, the plane wave propagated in the main radiating direction of the horn antenna is absorbed better by the receiving antenna than the inclined plane waves, as only this wave impinges again perpendicularly onto the receiving funnel after passing the prisms. If the emitted wave is thus approximated by this plane wave, it impinges on the rear surface of the prism with an angle of 60 °, and total reflection condition is fulfilled. By shifting the receiver perpendicularly to the plane of incidence of the microwaves (which is formed by the directions of polarization and of radiation of the horn antenna), it can be verified that the microwave is actually totally reflected by the second surface of the prism.

The surface of the second prism is then brought into close contact with the reflecting surface of the first prism. To compensate the offset of the beam, it is recommended to shift the directional receiver perpendicularly to the plane of incidence of the microwaves to maximum receiving signal. Using the Vernier caliper, the relationship between transmitted irradiance and the distance from the prismatic surface can be measured in steps of 1 mm *(d* = 0.1…2.0 cm) It must be particularly taken care to maintain the parallelism between the two surfaces during the procedure.

Theory and evaluation

If a plane electromagnetic wave traveling through medium 1 (n_1) meets a second medium (2) ($n_1 \neq n_2$), transmission, reflection and absorption occur (scattering due to material inhomogeneity is considered to be negligible). If transmission coefficient *T*, reflection coefficient *R* and absorption coefficient *A* are defined by the corresponding partial irradiances I_T, I_R and I_A of total irradiance I_1 of the incident beam (e. g. $T = I_T/I_1$), the following relation applies, due to conservation of energy:

$$T + R + A = 1 \quad (1)$$

T, *R* and *A* are functions of the angle of incidence as well as of the electronic and atomic characteristics of the material.

Thus, for example, in metals, the valence electrons can move freely within the solid. The incident electromagnetic wave excites the electrons into oscillating motion along the $\vec{E}$ Field. Charge carriers thus accelerated (Hertzian dipoles!) produce an opposite phase wave which has the same frequency: during transmission, interference between the primary and secondary waves is destructive and they annihilate each other. This is why a large proportion of the irradiance of the incident wave is reflected in metals, independently from frequency. Collisions between electrons and lattice disturbances cause part of the incident radiation energy to be converted to Joule heat, which means that it is absorbed. The measurement per-

Fig. 2: Experimental set-up for frustrated total reflection.

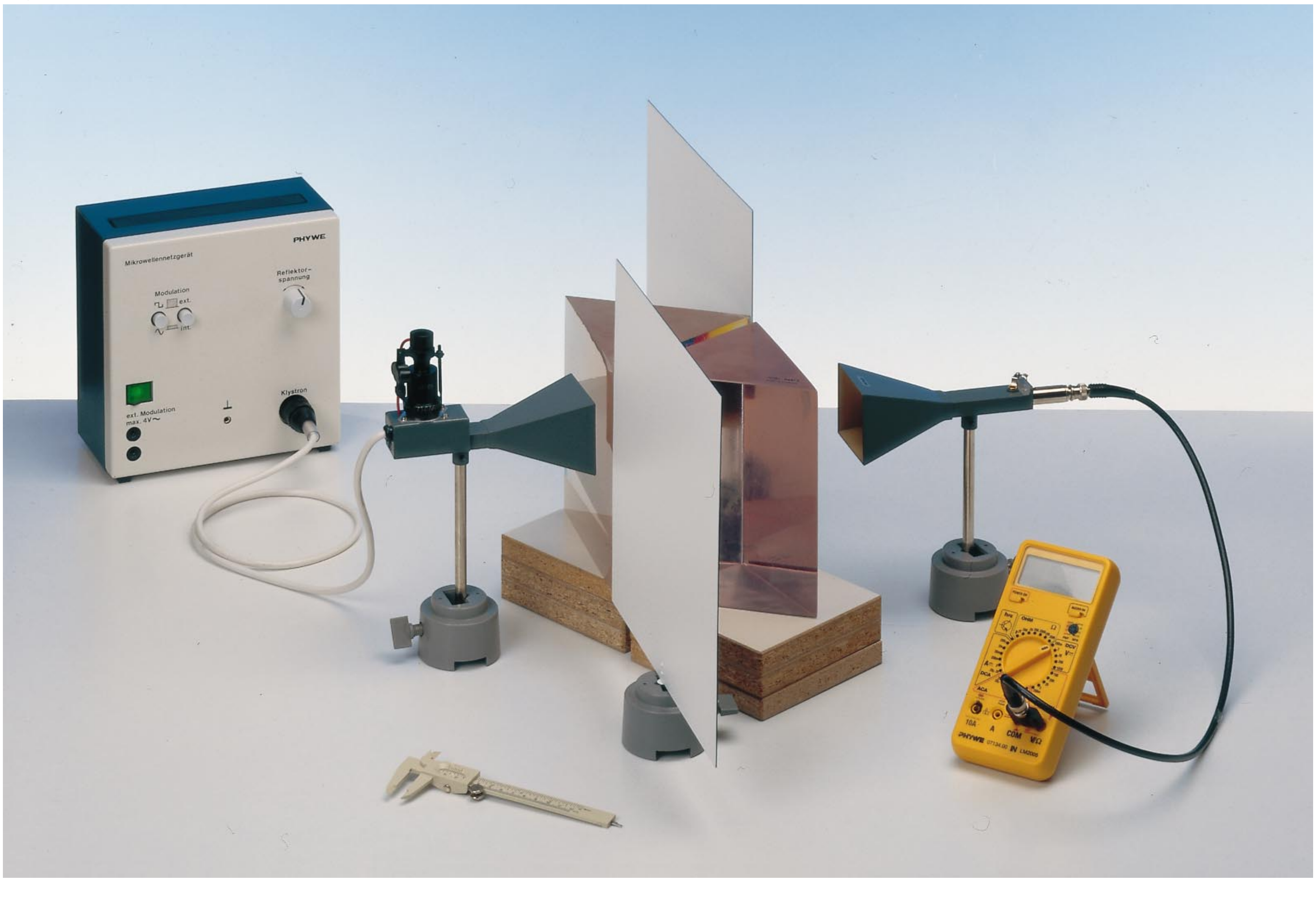


Fig. 3: Refraction in an optically thin medium.

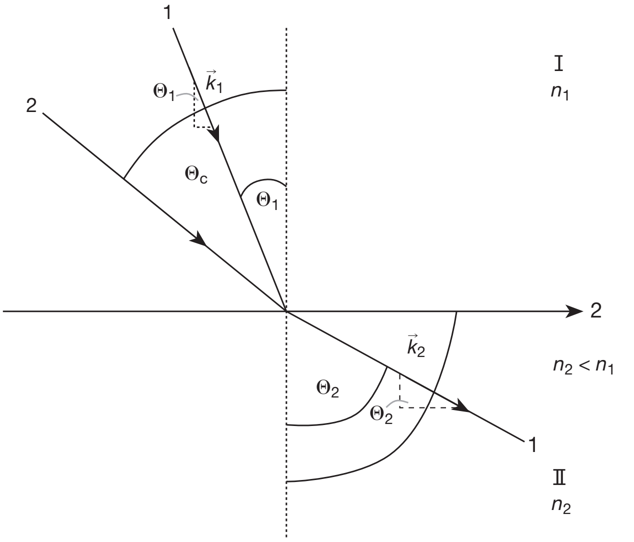
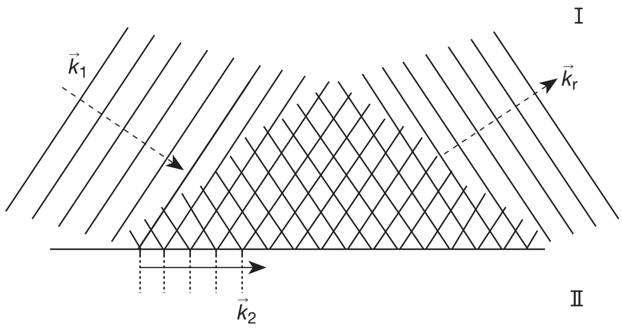


Fig. 4: Production of surface waves.



Tab. 1: Reflection, transmission and 1-reflection-transmission measurements of different probes.

	Reflection	Transmission	1-Reflection-Transmission
Metal	0.88	0.00	0.12
Glass	0.38	0.60	0.02
Plexiglas	0.16	0.83	0.01

formed on the metal screen (table 1) verifies that the microwave is not transmitted, but that a small part is absorbed and a significantly larger part is reflected. Deviations from this model occur for wavelengths which are not distinctly larger than the atomic lattice distances, because the oscillating amplitudes of the accelerated free electrons are drastically reduced with increasing frequency.

Non conductors or dielectric materials have no free charge carriers. However, charge transfers occur in the material in an electric field, due on the one hand to permanent dipole momenta which may be present, and on the second to the shifting of the valence electrons in relation to the molecular body (induced dipole momentum), whose restoring forces $\vec{F}$ can be described as elastic in a first order approximation:

$$\vec{F} \sim -\vec{r}$$

The resulting dipole momentum per unit volume is called dielectric polarization $\vec{P}$ and is usually proportional to the electrical field intensity:

$$\vec{P} = \varepsilon_0 (\varepsilon - 1) \vec{E}, \text{ where } \varepsilon = \text{permittivity}$$
$$\varepsilon_0 = \text{permittivity of vacuum}$$

The phase shift of the forced oscillations of a damped harmonic oscillator – and thus also that of the resulting secondary waves – related to the incident waves depends on the frequency of the exciting waves ω related to the resonance frequency of the oscillator. The result is a strong frequency dependence of the transmission, reflection and absorption characteristics of dielectric materials. The transmission and reflection characteristics of light compared to those of microwaves (table 1) for glass as well as for Plexiglas clearly demonstrates this fact. A further consequence of the phase shift of the secondary waves in relation to the primary waves is the change of phase velocity (which in turn causes refraction) of the resulting electromagnetic wave.

The transmission and reflection coefficients T and R also depend on the angle of incidence Θ_1 of the incident beam (cf. Fig. 3). A peculiarity occurs during the passage from an optically dense to an optically thin medium for a large angle Θ_1: considering Snell's law (with phase velocity v and wave number k)

$$n_{1,2} = \frac{n_1}{n_2} = \frac{v_2}{v_1} = \frac{\mathrm{k}_1}{\mathrm{k}_2} = \frac{\sin \Theta_1}{\sin \Theta_2} \quad (2)$$

light with the critical angle of incidence

$$\Theta_C = \arcsin \left(\frac{n_2}{n_1}\right) \quad (3)$$

is refracted parallel to the surface ($\Theta_2 = 90°$) and can therefore not pass into the optically thin medium (cf. Fig. 3). Glass with $n = 1.5$ has a critical angle Θ_C of 42°. Finally, for $\Theta_1 > \Theta_C$, no real value for the exiting angle can be determined: the trans-

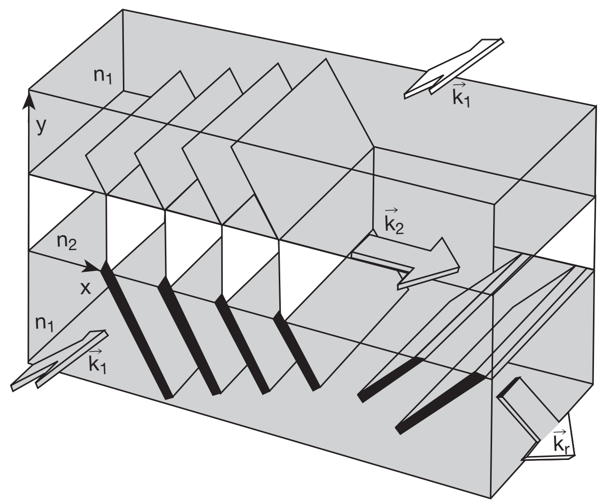
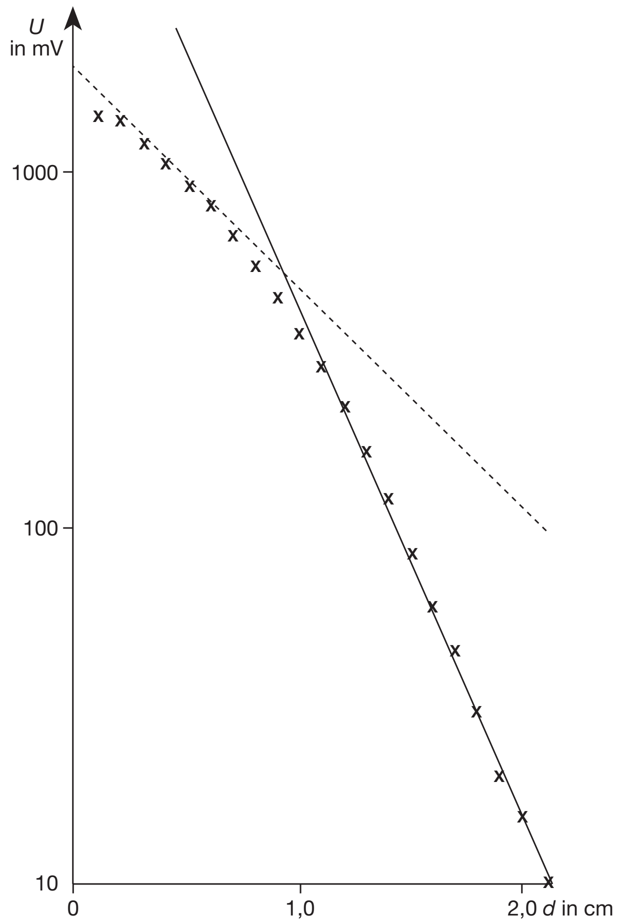


Fig. 5: Frustrated total internal reflection.

Fig. 6: Transmitted radiation intensity as a function of distance.



mission condition cannot be fulfilled and the beam is totally reflected due to conservation of energy *(total reflection)*.
The general wave function of the transmitted wave is:

$$\vec{E}_2(\vec{r},t) = \vec{E}_0\, e^{(i(\vec{k}\vec{r}-\omega t))} = \vec{E}_0\, e^{(i(k_2 \sin\Theta_2 x + k_2 \cos\Theta_2 y - \omega t))} \quad (4)$$

With Snell's law (2) and

$$\cos\Theta_2 = \pm\sqrt{1-\sin^2\Theta_2}$$

the following relation is obtained:

$$\vec{E}_2(\vec{r},t) = \vec{E}_0\, e^{(i(k_2 n_{12} \sin\Theta_1 x \pm k_2\sqrt{1-n_{12}^2 \sin^2\Theta_1}\; y - \omega t))} \quad (5)$$

In case of total reflection ($n_{12} \cdot \sin\Theta_1 > 1$) equation (5) becomes:

$$\vec{E}_2(\vec{r},t) = \vec{E}_0\, e^{(-\gamma y)} \cdot e^{(i(k_2 n_{12} \sin\Theta_1 x - \omega t))} \quad (6)$$

with the attenuation coefficient

$$\gamma = k_2\sqrt{n_{12}^2 \sin^2\Theta_1 - 1} \quad (7)$$

In equation (6), the '+' was left out, because an exponentially increasing field amplitude makes no sense physically.

The non reflected wave thus travels with the following wavelength:

$$\lambda = \frac{2\pi}{k_1 \sin\Theta_1} = \frac{2\pi}{k_{1,x}}$$

along the surface (in $\vec{e}_x$ -direction), whereas the electric field intensity amplitude E_y decreases exponentially, perpendicular to the boundary surface (cf. Fig. 4). The wave is thus called a surface wave. It remains limited mostly to the surface as compared to the wavelength scale.

The surface wave may be "questioned" by a second prism ($n_3 = n_1$). If the distance d between the prismatic surfaces is small enough to allow the residual field intensity E_2 to induce oscillating dipole momenta in the molecules of the second prism, the secondary waves in the second prism can again travel in the original direction ($\vec{k}1$) (cf. Fig. 5). In spite of the condition of total reflection, a part of the incident irradiance is thus transmitted through the gap in the optically thin medium and correspondingly reflected to a lesser extent. The field intensity, and thus the irradiance of the transmitted light, decreases exponentially with prismatic distance *d*.

$$I_{trans} = I_0\, e^{(-2\gamma d)} \quad (8)$$

This process is known as *frustrated total reflection* and is analogous to the tunnel effect of quantum mechanics. Observing the dependence between transmitted irradiance and prism distance d on semi-logarithmic paper (cf. Fig. 6), experimental deviations from exponential decrease are found for irradiance if distance d is small. This is due to the fact that a microwave emitted by the horn antenna deviates from a plane wave as well as to interference between the transmitted wave and the reflected wave. The attenuation coefficient γ obtained from the full drawn line (slope between the values of d = 1.0 cm till 2.0 cm),

$$\gamma = 1.64\ \text{cm}^{-1}$$

yields the following value for the refractive index of synthetic resin for frequency f = 9.45 GHz:

$$n_{12} = \frac{\sqrt{k_2^2 + \gamma^2}}{k_2 \sin\Theta_1} = 1.50 \quad (9)$$

with $\Theta_1 \approx 60°$, $n_{air} \approx 1$ and $k_2 = 2\pi f/c$ = 1.98 cm

The dotted line on the graph, which represents the lower error of the refractive index, corresponds to a value of n = 1.23.

The principle exposed above can be used to design radiation dividers with variable radiating relation. Furthermore, this experiment clearly shows why glass fiber surfaces must be free of impurities, in order to minimize losses of light due to frustrated total reflection.

Caution

Although the clystron only has low power, one must avoid looking directly into the microwave.