Electromagnetic Waves

The discovery, investigation and application of electromagnetic waves is no doubt among the most important contributions of physics to our knowledge. Applications of electromagnetic waves cover a wide range of wavelengths, e.g. gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, radio waves, …

Propagation of electromagnetic waves

Electromagnetic waves are transverse waves of electric and magnetic fields. The fields and the propagation of the wave obey the right hand rule:

$$\vec{E} = \vec{B} \times \vec{c}$$

The speed of electromagnetic waves in vacuum is a fundamental constant. It can be expressed by the field constants of the electric and magnetic fields:

$$c_{vac} = \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}}$$

In matter, the propagation speed is always less than in vacuum. Its value depends on the electric (dielectric constant) and magnetic (magnetic permeability) properties of the material:

$$c_{med} = \frac{c_{vac}}{n} = \frac{c_{vac}}{\sqrt{\kappa \cdot \mu_r}}$$

These properties depend on the wavelength, causing the dispersion in matter.

Intensity

The energy carried by an electromagnetic wave can be expressed by the *Poynting vector*:

$$\vec{S} = \frac{1}{\mu} \cdot \vec{E} \times \vec{B}$$

The magnitude of the Poynting vector corresponds to the intensity, i.e. the power per unit area. In most practical applications, the area covered by the wave increases with the square of the distance to the source, leading to an inverse square law for the intensity.

Dipole antennas

The most basic antenna to either emit or receive electromagnetic waves is a straight metallic rod (*Hertz dipole*). Due to reflexions at the ends, a standing wave can build up if the boundary conditions (nodes at the ends for the magnetic field, antinodes for the electric field) are met. The minimum length of a dipole antenna is therefore half the wavelength.

For other arrangements, the boundary conditions can be switched, allowing for even shorter $\lambda/4$ antennas.

In a standing wave, there is a phase shift of $\pi/2$ between the electric and magnetic fields.

Polarisation

Depending on the orientation of the magnetic and electric field vectors in an electromagnetic wave, the wave is said to be unpolarised (no preferred orientation), partially or completely polarised (preferred orientation).

Examples: Lasers produce completely polarised light, whereas incandescent lamps and the sun produce unpolarised light.

Unpolarised waves can be polarised with polarisation filters (e.g. Polaroid®) or by reflexion (*Brewster's angle*).

Example: In liquid crystal displays (LCDs), applying a voltage to the crystals changes their polarising properties.

Projection and rotation

Polarised light passing through a polarisation filter decreases in intensity by a factor $\cos\vartheta$ (ϑ being the angle between the two directions) and the intensity drops to

$$S' = S \cdot \cos^2 \vartheta$$

Unpolarised light loses half of its intensity in a polarisation filter.

Even in a setup where the polarisation of the incoming light and the filter are perpendicular, inserting an additional filter in between can let some of the intensity pass.

Doppler effect

The frequency of an electromagnetic wave depends on the *relative* motion between the source and the observer. For a source moving radially toward or away from the observer, the measured frequency is

$$f_o = f_s \cdot \sqrt{\frac{c - v}{c + v}} .$$

The symmetry between observer and source reflects the fact that there is no absolute carrier medium for electromagnetic waves, a fact leading to the development of the Theory of Relativity by Albert Einstein. This is not true in acoustics. Refer to the corresponding formula (Formeln und Tafeln, p. 151) to see the difference.

Huygen's principle

In order to understand some typical wave properties, it is useful to use a model proposed by Christian Huygens: *Every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a later instant is the envelope to the wavelets.*

Huygens can be used to explain the laws of ray optics (reflection, refraction), but also to give a qualitative understanding of diffraction.

Diffraction

If the wavelength is comparable to the dimensions of an object hit by an electromagnetic wave, the wave can enter the region behind the object which is not accessible according to the laws of ray optics. An intensity pattern characteristic for the shape and size of the object can be observed.

Single slit

The intensity pattern behind a single slit with width d has minima for angles obeying the relation

$$\sin\vartheta_m = m \cdot \frac{\lambda}{d} \quad (m = 1, 2, 3, \ldots).$$

Grating

The intensity pattern behind a diffraction grating (parallel slits with mutual distance d) has maxima for

$$\sin\vartheta_m = m \cdot \frac{\lambda}{d} \quad (m = 0, 1, 2, \ldots).$$

The condition for the maxima can be found from the superposition of elementary waves behind the slits.