Elektromagnetische Feldtheorie I (EFT I) / Electromagnetic Field Theory I (EFT I)

Lecture 5 / 5. Vorlesung

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Exam EFT I / Prüfung EFT I

2511 Elektromagnetische Feldtheorie
23.09.2003, 14:00, R 1603

Field and Circuit Relations / Feld- und Schaltungsrelationen

Field Relation / Feldrelation

$$\oint\!\!\!\oint_{S=\partial V} \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = -\frac{\mathrm{d}}{\mathrm{d}t}\iiint_V \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

(Continuity Equation for Electric Charges / Kontinuitätsgleichung für elektrische Ladungen)

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dR}} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_S \underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}}$$

(Faraday's Induction Law / Faradaysches Induktionsgesetz)

Circuit Relation / Schaltungsrelation

$$\sum_n i_{\mathrm{e}}^{(n)}(t) = -\frac{\mathrm{d}}{\mathrm{d}t}q_{\mathrm{e}}(t) = -C_s\frac{\mathrm{d}}{\mathrm{d}t}u_{\mathrm{e}}(t)$$

(Kirchhoff's Current Law / 1. Kirchhoffsches Gesetz, Knotenpunktregel)

$$\sum_n u_{\mathrm{e}}^{(n)}(t) = -\frac{\mathrm{d}}{\mathrm{d}t}\psi_{\mathrm{m}}(t) = -L_s\frac{\mathrm{d}}{\mathrm{d}t}i_{\mathrm{e}}(t)$$

(Kirchhoff's Loop Voltage Law / 2. Kirchhoffsches Gesetz, Maschenregel)

Field and Circuit Relations / Feld- und Schaltungsrelationen

Field Relation / Feldrelation

$$\oint\!\!\!\oint_{S=\partial V} \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\bullet\underline{\mathbf{dS}} = -\frac{\mathrm{d}}{\mathrm{d}t}\iiint_V \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

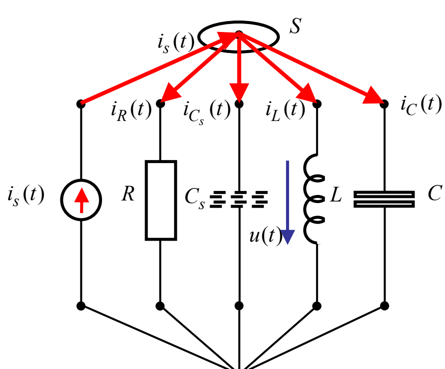
(Continuity Equation for Electric Charges / Kontinuitätsgleichung für elektrische Ladungen)

Circuit Relation / Schaltungsrelation

$$\sum_n i_{\mathrm{e}}^{(n)}(t) = -\frac{\mathrm{d}}{\mathrm{d}t}q_{\mathrm{e}}(t) = -C_s\frac{\mathrm{d}}{\mathrm{d}t}u_{\mathrm{e}}(t)$$

(Kirchhoff's Current Law / 1. Kirchhoffsches Gesetz, Knotenpunktsregel)

RLC Parallel Network / RLC Parallelschaltung
(R, L, C are Lumped Elements / R, L, C sind konzentrierte Bauteile)



$$\sum_n i_{\mathrm{e}}^{(n)}(t) = -i_s(t) + i_R(t) + i_L(t) + i_C(t)$$

$$= \underbrace{-C_s\frac{d}{dt}u_{\mathrm{e}}(t)}_{i_{C_s}(t)}$$

C_s : **Stray Capacitance / Streukapazität**

If C_s and d/dt u(t) are Small / Wenn C_s und d/dt u(t) klein sind

$$-i_s(t) + i_R(t) + i_L(t) + i_C(t) = 0$$

Field and Circuit Relations / Feld- und Schaltungsrelationen

Field Relation / Feldrelation

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)\bullet \underline{\mathbf{dR}} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_S \underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet \underline{\mathbf{dS}}$$

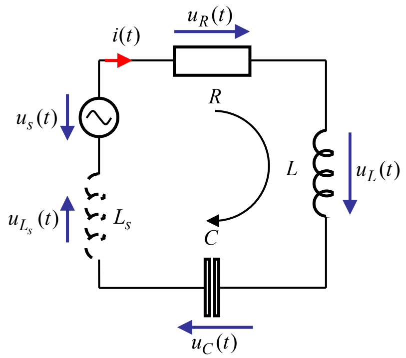
(Faraday's Induction Law / Faradaysches Induktionsgesetz)

Circuit Relation / Schaltungsrelation

$$\sum_n u_\mathrm{e}^{(n)}(t) = -\frac{\mathrm{d}}{\mathrm{d}t}\psi_\mathrm{m}(t) = -L_s \frac{\mathrm{d}}{\mathrm{d}t} i_\mathrm{e}(t)$$

(Kirchhoff's Loop Voltage Law / 2. Kirchhoffsches Gesetz, Maschenregel)

RLC Series Network / RLC Reihenschaltung
(R, L, C are Lumped Elements / R, L, C sind konzentrierte Bauteile)



$$\sum_n u_\mathrm{e}^{(n)}(t) = -u_s(t) + u_R(t) + u_L(t) + u_C(t)$$

$$= -\underbrace{L_s \frac{\mathrm{d}}{\mathrm{d}t} i_\mathrm{e}(t)}_{=u_{L_s}(t)}$$

L_s : **Stray Inductance / Streuinduktivität**

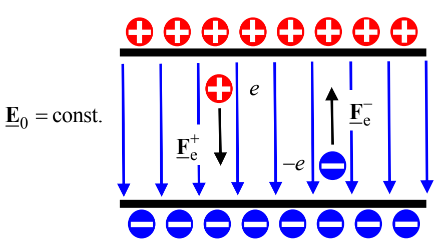
If L_s and $\mathrm{d}/\mathrm{d}t\, i(t)$ is Small / Wenn L_s und $\mathrm{d}/\mathrm{d}t\, i(t)$ klein sind

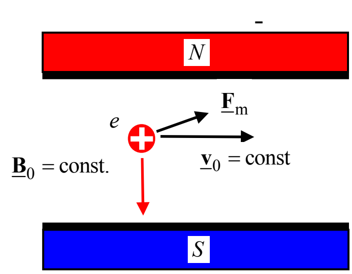
$$-u_s(t) + u_R(t) + u_L(t) + u_C(t) = 0$$

Lorentz Force Law / Lorentzsches Kraftgesetz

$$\underline{\mathbf{F}}(\underline{\mathbf{R}},t) = \underbrace{Q_\mathrm{e}(\underline{\mathbf{R}},t)\underline{\mathbf{E}}(\underline{\mathbf{R}},t)}_{\text{Electric Force / Elektrische Kraft}} + \underbrace{Q_\mathrm{e}(\underline{\mathbf{R}},t)\underline{\mathbf{v}}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)}_{\text{Magnetic Force / Magnetische Kraft}}$$

The electric force is straigtforward, being in the direction of the electric field if the charge Q_e is positive, but the direction of the magnetic part of the force is given by the right hand rule. / Die elektrische Kraft ist einfach, sie zeigt für eine positive elektrische Ladung in Richtung des elektrischen Feldes, die Richtung der magnetischen Kraft ist dagegen über die Rechte-Handregel gegeben.





$$\underline{\mathbf{F}} = Q_\mathrm{e}\underline{\mathbf{E}}_0$$

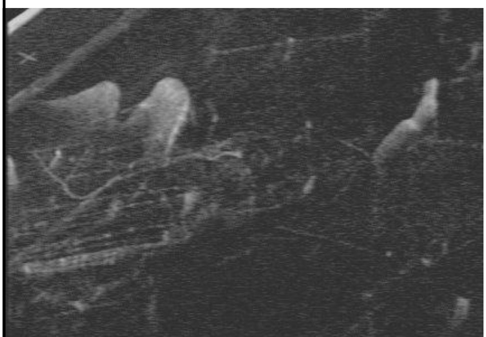
$$\underline{\mathbf{F}}_\mathrm{e}^+ = Q_\mathrm{e}\underline{\mathbf{E}}_0 = e\underline{\mathbf{E}}_0 \qquad \underline{\mathbf{F}}_\mathrm{e}^- = Q_\mathrm{e}\underline{\mathbf{E}}_0 = -e\underline{\mathbf{E}}_0$$

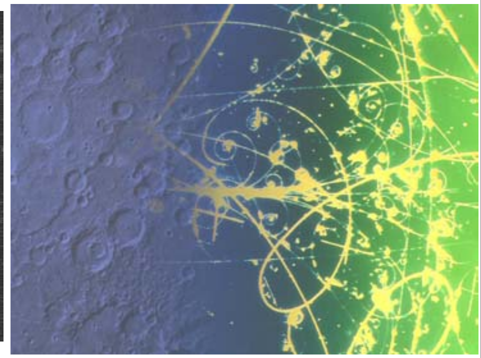
$$\underline{\mathbf{F}}_\mathrm{m} = Q_\mathrm{e}\underline{\mathbf{v}}_0 \times \underline{\mathbf{B}}_0 = e\underline{\mathbf{v}}_0 \times \underline{\mathbf{B}}_0$$

Lorentz Force Law / Lorentzsches Kraftgesetz

$$\underline{\mathbf{F}}_{\mathrm{m}}(\underline{\mathbf{R}},t) = \underbrace{Q_{\mathrm{e}}(\underline{\mathbf{R}},t)\underline{\mathbf{v}}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)}_{\text{Magnetic Force / Magnetische Kraft}}$$

Bubble Chamber / Blasenkammer





Lorentz Force Law / Lorentzsches Kraftgesetz (1)

Electric Charge Density / Elektrische Raumladungsdichte: $\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$ Force Due To / Kraft durch $\underline{\mathbf{E}}(\underline{\mathbf{R}},t)$ and / und $\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$

Electromagnetic Volume Force Density / Elektromagnetische Volumenkraftdichte

$$\underline{\mathbf{f}}(\underline{\mathbf{R}},t) = \underbrace{\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\underline{\mathbf{E}}(\underline{\mathbf{R}},t)}_{\underline{\mathbf{f}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\ [\mathrm{N/m^3}]} + \underbrace{\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)}_{\underline{\mathbf{f}}_{\mathrm{m}}(\underline{\mathbf{R}},t)\ [\mathrm{N/m^3}]}$$

Electric Volume Force Density / Elektrische Volumenkraftdichte; Magnetic Volume Force Density / Magnetische Volumenkraftdichte

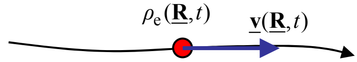
(Hendrik Antoon Lorentz (1853 — 1928))

$$= \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underbrace{\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\underline{\mathbf{v}}(\underline{\mathbf{R}},t)}_{=\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)=\underline{\mathbf{J}}_{\mathrm{ec}}(\underline{\mathbf{R}},t)}\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

$$= \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\left[\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{v}}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\right]$$

$\underline{\mathbf{v}}(\underline{\mathbf{R}},t)$: **Particle Velocity of the Charged Particle / Teilchengeschwindigkeit des geladenen Teilchens**

$\rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$ $\underline{\mathbf{v}}(\underline{\mathbf{R}},t)$



$$\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = \underline{\mathbf{J}}_{\mathrm{ec}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\underline{\mathbf{v}}(\underline{\mathbf{R}},t)$$

$\underline{\mathbf{J}}_{\mathrm{ec}}(\underline{\mathbf{R}},t)$: **Electric Convection Current Density / Elektrische Konvektionsstromdichte**

Lorentz Force Law / Lorentzsches Kraftgesetz (2)

$$\underline{\mathbf{F}}(t) = \iiint_V \underline{\mathbf{f}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

$$= \iiint_V \left[\rho_\mathrm{e}(\underline{\mathbf{R}},t)\,\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\right]\mathrm{d}V$$

$$= \underbrace{\iiint_V \rho_\mathrm{e}(\underline{\mathbf{R}},t)\,\underline{\mathbf{E}}(\underline{\mathbf{R}},t)\,\mathrm{d}V}_{=\underline{\mathbf{F}}_\mathrm{e}(t)} + \underbrace{\iiint_V \rho_\mathrm{e}(\underline{\mathbf{R}},t)\,\underline{\mathbf{v}}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\,\mathrm{d}V}_{=\underline{\mathbf{F}}_\mathrm{m}(t)}$$

$=\underline{\mathbf{F}}_\mathrm{e}(t)$: Electric Volume Force / Elektrische Volumenkraft

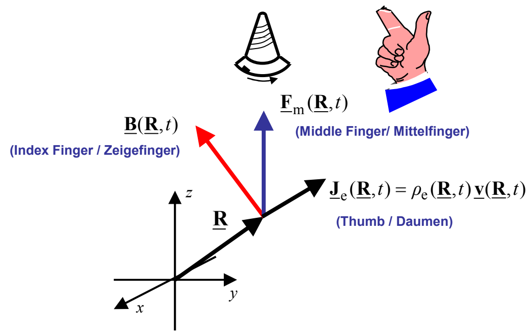
$=\underline{\mathbf{F}}_\mathrm{m}(t)$: Magnetic Volume Force / Magnetische Volumenkraft

$$= \underline{\mathbf{F}}_\mathrm{e}(t) + \underline{\mathbf{F}}_\mathrm{m}(t)$$

$\underline{\mathbf{F}}_\mathrm{e}(t)$:
Points in the Direction of $\underline{\mathbf{E}}(\underline{\mathbf{R}},t)$ /
Zeigt in die Richtung von $\underline{\mathbf{E}}(\underline{\mathbf{R}},t)$

$\underline{\mathbf{F}}_\mathrm{m}(t)$:
Points in the Direction of $\underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$
Zeigt in die Richtung von $\underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$

Right-Hand Rule / Rechte-Hand-Regel



Newton Equation of Motion / Newtonsche Bewegungsgleichung (1)

$$\iiint_V \rho_{\mathrm{m}0}(\underline{\mathbf{R}})\,\frac{\partial}{\partial t}\underline{\mathbf{v}}(\underline{\mathbf{R}},t)\,\mathrm{d}V = \iiint_V \underline{\mathbf{f}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

$$= \iiint_V \left[\rho_\mathrm{e}(\underline{\mathbf{R}},t)\,\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\right]\mathrm{d}V$$

$$\rho_{\mathrm{m}0}(\underline{\mathbf{R}})\,\frac{\partial}{\partial t}\underline{\mathbf{v}}(\underline{\mathbf{R}},t) = \underline{\mathbf{f}}(\underline{\mathbf{R}},t)$$

$$= \rho_\mathrm{e}(\underline{\mathbf{R}},t)\,\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

$\rho_{\mathrm{m}0}(\underline{\mathbf{R}})$: Mass Density of the Charged Particle at Rest /
Ruhemassendichte des geladenen Teilchens

$$\underline{\mathbf{a}}(\underline{\mathbf{R}},t) = \frac{\partial}{\partial t}\underline{\mathbf{v}}(\underline{\mathbf{R}},t) = \frac{\partial^2}{\partial t^2}\underline{\mathbf{u}}(\underline{\mathbf{R}},t)$$

$\underline{\mathbf{a}}(\underline{\mathbf{R}},t)$: Acceleration of the Charged Particle /
Beschleunigung des geladenen Teilchens

$\underline{\mathbf{u}}(\underline{\mathbf{R}},t)$: Particle Displacement of the Charged Particle /
Teilchenverschiebung des geladenen Teilchens

$$\underline{\mathbf{j}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{m}0}(\underline{\mathbf{R}})\,\underline{\mathbf{v}}(\underline{\mathbf{R}},t)$$

$\underline{\mathbf{j}}(\underline{\mathbf{R}},t)$: (Linear) Momentum Density /
(Lineare) Impulsdichte

Newton Equation of Motion / Newtonsche Bewegungsgleichung (2)

$$\iiint_V \frac{\partial}{\partial t} \underline{\mathbf{j}}(\underline{\mathbf{R}},t)\,\mathrm{d}V = \iiint_V \underline{\mathbf{f}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

$$= \iiint_V \left[\rho_\mathrm{e}(\underline{\mathbf{R}},t)\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\right]\mathrm{d}V$$

$$\frac{\partial}{\partial t} \underline{\mathbf{j}}(\underline{\mathbf{R}},t) = \underline{\mathbf{f}}(\underline{\mathbf{R}},t)$$

$$= \rho_\mathrm{e}(\underline{\mathbf{R}},t)\underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{R}},t)\times\underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

Applications / Anwendungen
(Newton Equation of Motion / Newtonsche Bewegungsgleichung
Lorentz Force Law / Lorentzsches Kraftgesetz)

- **Electron Motion in Vacuum in an Electric Field and/or in a Magnetic Field / Elektronenbewegung in Vakuum in einem elektrischen und/oder magnetischen Feld**
- **Cyclotron (Particle Accelerator) / Zyklotron (Teilchenbeschleuniger)**

Constitutive Equations / Materialgleichungen

$$\underline{\mathbf{D}} = \underline{\mathbf{D}}(\underline{\mathbf{E}})$$
$$\underline{\mathbf{H}} = \underline{\mathbf{H}}(\underline{\mathbf{B}})$$
$$\underline{\mathbf{J}}_\mathrm{e} = \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{E}})$$
$$\underline{\mathbf{J}}_\mathrm{m} = \underline{\mathbf{J}}_\mathrm{m}(\underline{\mathbf{H}})$$

In a material the relations between the vectors $\underline{\mathbf{E}}$, $\underline{\mathbf{B}}$, $\underline{\mathbf{D}}$, and $\underline{\mathbf{H}}$ are generally determined by experiment. These are referred to as the electromagnetic constitutive equations or material equations. /

In einem Material werden den Relationen zwischen den Vektorfeldern $\underline{\mathbf{E}}$, $\underline{\mathbf{B}}$, $\underline{\mathbf{D}}$, und $\underline{\mathbf{H}}$ im allgemeinen experimentell bestimmt. Diese werden dann elektromagnetische konstituierende Gleichungen oder Materialgleichungen genannt.

Constitutive Equations / Materialgleichungen (...)

- linear or nonlinear / linear oder nichtlinear
- homogeneous or inhomogeneous / homogen oder inhomogen
- isotropic or anisotropic / isotrop oder anisotrop
- frequency independent or dependent / frequenzunabhängig oder frequenzabhängig

$$\underline{\mathbf{D}} = \underline{\mathbf{D}}(\underline{\mathbf{E}})$$
$$\underline{\mathbf{H}} = \underline{\mathbf{H}}(\underline{\mathbf{B}})$$
$$\underline{\mathbf{J}}_\mathrm{e} = \underline{\mathbf{J}}_\mathrm{e}(\underline{\mathbf{E}})$$
$$\underline{\mathbf{J}}_\mathrm{m} = \underline{\mathbf{J}}_\mathrm{m}(\underline{\mathbf{H}})$$

(This means, $\underline{\mathbf{D}}$ is a Function of $\underline{\mathbf{E}}$ / Dies bedeutet, dass $\underline{\mathbf{D}}$ eine Funktion von $\underline{\mathbf{D}}$ ist)

- Free Space or Vacuum / Freiraum oder Vakuum
- Linear, Homogeneous, Isotropic, Lossless, and Frequency Independent Material / Lineares, homogenes, isotropes, verlustloses und frequenzunabhängiges Material
- Linear, Inhomogeneous, Isotropic, Lossless, and Frequency Independent Material / Lineares, inhomogenes, isotropes, verlustloses und frequenzunabhängiges Material

Constitutive Equations / Materialgleichungen (...)

Free Space or Vacuum / Freiraum oder Vakuum

$$\underline{\mathbf{D}} = \underline{\mathbf{D}}(\underline{\mathbf{E}}) \quad => \quad \underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon_0\, \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta_0}\, \underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$$\underline{\mathbf{H}} = \underline{\mathbf{H}}(\underline{\mathbf{B}}) \quad => \quad \underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \nu_0\, \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu_0}\, \underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

Speed of Light in Vacuum / Ausbreitungsgeschwindigkeit von Licht in Vakuum

$$c_0 = \frac{1}{\sqrt{\varepsilon_0\, \mu_0}}$$

$\varepsilon_0 = 8.854187817$ pF/m	Permittivity of Free Space (Vacuum) / Permittivität des Freiraumes (Vakuum)
$\beta_0 = 1/\varepsilon_0$ m/F	Impermittivity of Free Space (Vacuum) Impermittivität des Freiraumes (Vakuum)
$\mu_0 = 4\pi \times 10^{-7}$ H/m $= 1.256637061\ \mu$H/m	Permeability of Free Space (Vacuum) Permeabilität des Freiraumes (Vakuum)
$\nu_0 = 1/\mu_0$ m/H	Impermeability of Free Space (Vacuum) Impermeabilität des Freiraumes (Vakuum)
$c_0 = 299\ 792\ 458$ m/s $\simeq 3 \times 10^8$ m/s	Propagation Velocity of Ligth in Free Space (Vacuum) Ausbreitungsgeschwindigkeit von Licht im Freiraum (Vakuum)

Constitutive Equations / Materialgleichungen (...)

Linear, Homogeneous, Isotropic, Lossless, and Frequency Independent Material / Lineares, homogenes, isotropes, verlustloses und frequenzunabhängiges Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \varepsilon_0 \varepsilon_\mathrm{r} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta_0 \beta_\mathrm{r}} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$$\underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \nu \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \nu_0 \nu_\mathrm{r} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu_0 \mu_\mathrm{r}} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

Speed of Light / Ausbreitungsgeschwindigkeit von Licht

$$c = \frac{1}{\sqrt{\varepsilon \mu}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_\mathrm{r} \mu_0 \mu_\mathrm{r}}} = c_0 \frac{1}{\sqrt{\varepsilon_\mathrm{r} \mu_\mathrm{r}}}$$

ε [As/Vm=F/m] **(Scalar) Permittivity / (Skalare) Permittivität**
ε_r [1] **(Scalar) Relative Permittivity / (Skalare) relative Permittivität**

β [Vm/As=m/F] **(Scalar) Impermittivity / (Skalare) Impermittivität**
β_r [1] **(Scalar) Relative Impermittivity / (Skalare) relative Impermittivität**

μ [Vs/Am=H/m] **(Scalar) Permeability / (Skalare) Permeabilität**
μ_r [1] **(Scalar) Relative Permeability / (Skalare) relative Permeability**

ν [Am/Vs=m/H] **(Scalar) Impermeability / (Skalare) Impermeabilität**
ν_r [1] **(Scalar) Relative Impermeability / (Skalare) relative Impermeabilität**

Constitutive Equations / Materialgleichungen (...)

Linear, Homogeneous, Isotropic, Lossless, and Frequency Independent Material / Lineares, homogenes, isotropes, verlustloses und frequenzunabhängiges Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \varepsilon_0 \varepsilon_\mathrm{r} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta_0 \beta_\mathrm{r}} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$$\underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \nu \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \nu_0 \nu_\mathrm{r} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu_0 \mu_\mathrm{r}} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

Speed of Light / Ausbreitungsgeschwindigkeit von Licht

$$c = \frac{1}{\sqrt{\varepsilon \mu}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_\mathrm{r} \mu_0 \mu_\mathrm{r}}} = c_0 \frac{1}{\sqrt{\varepsilon_\mathrm{r} \mu_\mathrm{r}}}$$

Linear, Inhomogeneous, Isotropic, Lossless, and Frequency Independent Material / Lineares, inhomogenes, isotropes, verlustloses und frequenzunabhängiges Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon(\underline{\mathbf{R}}) \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \varepsilon_0 \varepsilon_\mathrm{r}(\underline{\mathbf{R}}) \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta(\underline{\mathbf{R}})} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \frac{1}{\beta_0 \beta_\mathrm{r}(\underline{\mathbf{R}})} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$$\underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \nu(\underline{\mathbf{R}}) \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \nu_0 \nu_\mathrm{r}(\underline{\mathbf{R}}) \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu(\underline{\mathbf{R}})} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \frac{1}{\mu_0 \mu_\mathrm{r}(\underline{\mathbf{R}})} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)$$

Speed of Light / Ausbreitungsgeschwindigkeit von Licht

$$c(\underline{\mathbf{R}}) = \frac{1}{\sqrt{\varepsilon(\underline{\mathbf{R}}) \mu(\underline{\mathbf{R}})}} = c_0 \frac{1}{\sqrt{\varepsilon_\mathrm{r}(\underline{\mathbf{R}}) \mu_\mathrm{r}(\underline{\mathbf{R}})}}$$

Constitutive Equations / Materialgleichungen (...)

Linear, Homogeneous, Isotropic, Electric Lossy, and Frequency Dependent Material / Lineares, homogenes, isotropes, elektrisch-verlustbehaftetes und frequenzabhängiges Material

$$\underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = \underline{\mathbf{J}}_{\mathrm{e}\sigma}(\underline{\mathbf{R}},t) = \sigma_{\mathrm{e}}\underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$\underline{\mathbf{J}}_{\mathrm{e}\sigma}(\underline{\mathbf{R}},t)$	$[\mathrm{A/m}^2]$	**Electric Conduction Current Density / Elektrische Leitungsstromdichte**
σ_{e}	$[\mathrm{A/Vm{=}S/m}]$	**(Scalar) Electric Conductivity / (Skalare) elektrische Leitfähigkeit**

Linear, Homogeneous, Isotropic, Magnetic Lossy, and Frequency Dependent Material / Lineares, homogenes, isotropes, magnetisch-verlustbehaftetes und frequenzabhängiges Material

$$\underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t) = \underline{\mathbf{J}}_{\mathrm{m}\sigma}(\underline{\mathbf{R}},t) = \sigma_{\mathrm{m}}\underline{\mathbf{H}}(\underline{\mathbf{R}},t)$$

$\underline{\mathbf{J}}_{\mathrm{m}\sigma}(\underline{\mathbf{R}},t)$	$[\mathrm{V/m}^2]$	**Magnetic Conduction Current Density / Magnetische Leitungsstromdichte**
σ_{m}	$[\mathrm{V/Am{=}1/Sm}]$	**(Scalar) Magnetic Conductivity / (Skalare) magnetische Leitfähigkeit**

Constitutive Equations / Materialgleichungen (...)

General Properties of the Material Parameters / Allgemeine Eigenschaften der Material Parameter

$$\varepsilon_{\mathrm{r}} \geq 1$$

$$\mu_{\mathrm{r}} \begin{cases} \leq 1 & \text{diamagnetic / diamagnetisch} \\ \geq 1 & \text{paramagnetic / paramagnetisch} \\ \gg 1 & \text{ferromagntic / ferromagnetisch} \end{cases}$$

$$\sigma_{\mathrm{e}} \geq 0$$

$$\sigma_{\mathrm{m}} \geq 0$$

Constitutive Equations / Materialgleichungen (...)

Linear, Homogeneous, Electric Anisotropic, Lossless, and Frequency Independent Material / Lineares, homogenes, elektrisch-anisotropes, verlustfreies und frequenzunabhängiges Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \underline{\underline{\boldsymbol{\varepsilon}}} \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = \varepsilon_0 \underline{\underline{\boldsymbol{\varepsilon}}}_{\mathrm{r}} \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}},t)$$

$$\underline{\underline{\boldsymbol{\varepsilon}}} = \begin{array}{l} \varepsilon_{xx}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_x + \varepsilon_{xy}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_y + \varepsilon_{xz}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_z \\ +\varepsilon_{yx}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_x + \varepsilon_{yy}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_y + \varepsilon_{yz}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_z \\ +\varepsilon_{zx}\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_x + \varepsilon_{zy}\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_y + \varepsilon_{zz}\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z \end{array} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{yx} & \varepsilon_{yx} & \varepsilon_{zz} \end{bmatrix}$$

If we keep the unit vector of Cartesian coordinate system in mind / Wenn wir die Einheitsvektoren des Kartesischen Koordinatensystems im Hinterkopf behalten

Three Different Cases / Drei verschiedene Fälle:

isotropic / isotrop

$$\underline{\underline{\boldsymbol{\varepsilon}}}^{\mathrm{iso}} = \varepsilon\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_x + \varepsilon\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_y + \varepsilon\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z = \begin{bmatrix} \varepsilon & & \\ & \varepsilon & \\ & & \varepsilon \end{bmatrix} = \varepsilon\,\underline{\underline{\mathbf{I}}}$$

Only 1 material constant / Nur eine Materialkonstante

uniaxial / uniaxial

$$\underline{\underline{\boldsymbol{\varepsilon}}}^{\mathrm{uni}} = \varepsilon_{xx}\underline{\mathbf{e}}_x\underline{\mathbf{e}}_x + \varepsilon_{xx}\underline{\mathbf{e}}_y\underline{\mathbf{e}}_y + \varepsilon_{zz}\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z = \begin{bmatrix} \varepsilon_{xx} & & \\ & \varepsilon_{xx} & \\ & & \varepsilon_{zz} \end{bmatrix} = \varepsilon_{xx}\,\underline{\underline{\mathbf{I}}} + (\varepsilon_{zz} - \varepsilon_{xx})\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z$$

Two material constants / Zwei Materialkonstanten

biaxial / biaxial

$$\underline{\underline{\boldsymbol{\varepsilon}}}^{\mathrm{bi}} = \varepsilon_{xx}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_x + \varepsilon_{yy}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_y + \varepsilon_{zz}\,\underline{\mathbf{e}}_z\underline{\mathbf{e}}_z = \begin{bmatrix} \varepsilon_{xx} & & \\ & \varepsilon_{yy} & \\ & & \varepsilon_{zz} \end{bmatrix}$$

Three material constants / Drei Materialkonstanten

Constitutive Equations / Materialgleichungen (...)

… Electric Anisotropic… Material / … elektrisch-anisotropes ... Material

Example / Beispiel 1

$$\underline{\mathbf{E}}(\underline{\mathbf{R}},t) = E_x(\underline{\mathbf{R}},t)\,\underline{\mathbf{e}}_x$$

$$\underline{\underline{\boldsymbol{\varepsilon}}} = \varepsilon_{xy}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_y = \begin{bmatrix} 0 & \varepsilon_{xy} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{aligned} \underline{\mathbf{D}}(\underline{\mathbf{R}},t) &= \underline{\underline{\boldsymbol{\varepsilon}}} \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}},t) \\ &= \varepsilon_{xy}\,\underline{\mathbf{e}}_x\underline{\mathbf{e}}_y \bullet E_x(\underline{\mathbf{R}},t)\,\underline{\mathbf{e}}_x \\ &= \varepsilon_{xy} E_x(\underline{\mathbf{R}},t)\,\underline{\mathbf{e}}_x \underbrace{\underline{\mathbf{e}}_y \bullet \underline{\mathbf{e}}_x}_{=0} \\ &= 0 \end{aligned}$$

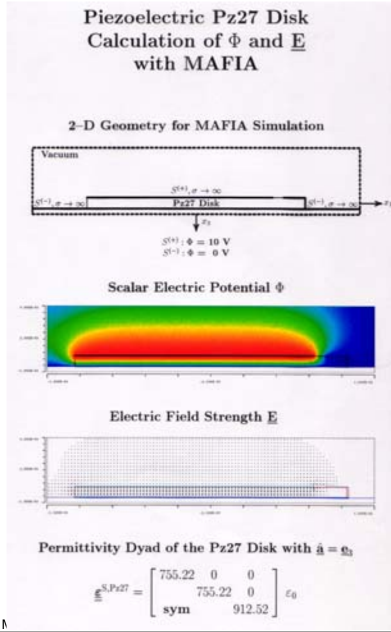
Example / Beispiel 2

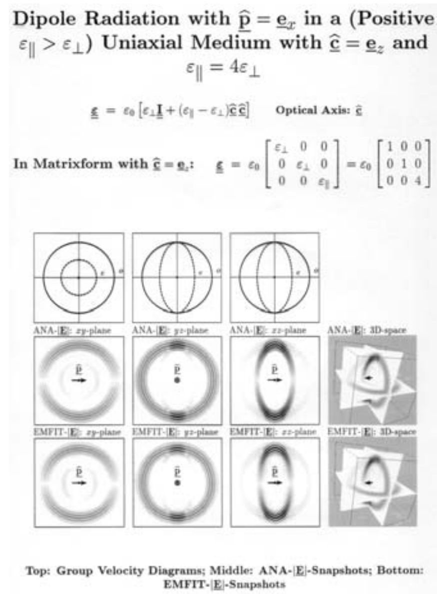
$$\underline{\mathbf{E}}(\underline{\mathbf{R}},t) = E_x(\underline{\mathbf{R}},t)\,\underline{\mathbf{e}}_x$$

$$\underline{\underline{\boldsymbol{\varepsilon}}} = \varepsilon_{yx}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_x = \begin{bmatrix} 0 & 0 & 0 \\ \varepsilon_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{aligned} \underline{\mathbf{D}}(\underline{\mathbf{R}},t) &= \underline{\underline{\boldsymbol{\varepsilon}}} \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}},t) \\ &= \varepsilon_{yx}\,\underline{\mathbf{e}}_y\underline{\mathbf{e}}_x \bullet E_x(\underline{\mathbf{R}},t)\,\underline{\mathbf{e}}_x \\ &= \varepsilon_{xy} E_x(\underline{\mathbf{R}},t)\underline{\mathbf{e}}_y \underbrace{\underline{\mathbf{e}}_x \bullet \underline{\mathbf{e}}_x}_{=1} \\ &= \underbrace{\varepsilon_{xy} E_x(\underline{\mathbf{R}},t)}_{=D_y(\underline{\mathbf{R}},t)}\underline{\mathbf{e}}_y \\ &= D_y(\underline{\mathbf{R}},t)\underline{\mathbf{e}}_y \end{aligned}$$

Examples for Anisotropic Media / Beispiele für anisotrope Medien





Constitutive Equations / Materialgleichungen (...)

Linear, Inhomogeneous, Electric Anisotropic, Lossless, and Dispersive Material / Lineares, inhomogenes, elektrisch-anisotropes, verlustfreies und dispersives Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon_0 \int_{t'=-\infty}^{t} \underline{\underline{\boldsymbol{\varepsilon}}}_{\mathrm{r}}(\underline{\mathbf{R}},t-t') \cdot \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t'$$

$$\underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = \underline{\underline{\boldsymbol{\varepsilon}}}_{\mathrm{r}}(\underline{\mathbf{R}},t) - \underline{\underline{\mathbf{I}}}\delta(t)$$

$$\underline{\underline{\boldsymbol{\varepsilon}}}_{\mathrm{r}}(\underline{\mathbf{R}},t) = \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t) + \underline{\underline{\mathbf{I}}}\delta(t)$$

$$\begin{aligned}\underline{\mathbf{D}}(\underline{\mathbf{R}},t) &= \varepsilon_0 \int_{t'=-\infty}^{t} \left[\underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t-t') + \underline{\underline{\mathbf{I}}}\delta(t)\right] \cdot \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t' \\ &= \underbrace{\varepsilon_0 \int_{t'=-\infty}^{t} \underline{\underline{\mathbf{I}}}\delta(t-t') \cdot \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t'}_{=\varepsilon_0 \underline{\mathbf{E}}(\underline{\mathbf{R}},t)} + \varepsilon_0 \int_{t'=-\infty}^{t} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t-t') \cdot \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t' \\ &= \varepsilon_0 \underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \varepsilon_0 \int_{t'=-\infty}^{t} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t-t') \cdot \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t'\end{aligned}$$

Constitutive Equations / Materialgleichungen (...)

Linear, Inhomogeneous, Electric Anisotropic, Lossless, and Dispersive Material /
Lineares, inhomogenes, elektrisch-anisotropes, verlustfreies und dispersives Material

$$\underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \varepsilon_0 \underline{\mathbf{E}}(\underline{\mathbf{R}},t) + \varepsilon_0 \int_{t'=-\infty}^{t} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t-t') \bullet \underline{\mathbf{E}}(\underline{\mathbf{R}},t')\,\mathrm{d}t'$$

Fourier Transform with Regard to Time /
Fourier-Transformation bezüglich der Zeit

$$\underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega) = \int_{t=-\infty}^{\infty} \mathrm{e}^{\mathrm{j}\omega t} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}t$$

$$\underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},t) = \frac{1}{2\pi} \int_{\omega=-\infty}^{\infty} \mathrm{e}^{-\mathrm{j}\omega t} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega)\,\mathrm{d}\omega$$

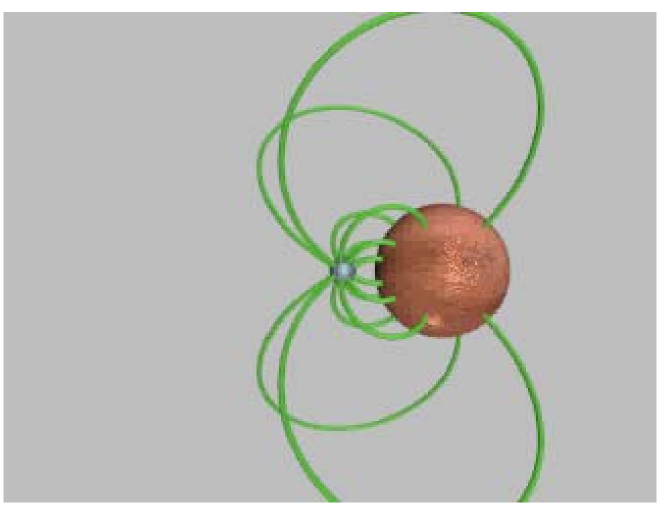
Causality Principle ➡ Kramer-Kronig Relations /
Kausalitätsprinzip ➡ Kramer-Kronig Relationen

$$\Re \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega) = -\frac{1}{\pi} \int_{\omega'=-\infty}^{\infty} \frac{1}{\omega-\omega'} \Im \mathrm{d} \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega')\,\mathrm{d}\omega' = H\left\{\Im \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega')\right\}$$

$$\Im \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega) = \frac{1}{\pi} \int_{\omega'=-\infty}^{\infty} \frac{1}{\omega-\omega'} \Re \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega')\,\mathrm{d}\omega' = H^{-1}\left\{\Re \underline{\underline{\boldsymbol{\chi}}}_{\mathrm{e}}(\underline{\mathbf{R}},\omega')\right\}$$

Boundary Conditions = ? / Randbedingungen = ?

**Point Charge Attracted to a Electrically Charged Sphere /
Punktladung angezogen von einer elektrisch geladenen Kugel**



http://web.mit.edu/jbelcher/www/att.html

Transition and Boundary Conditions / Übergangs- und Randbedingungen

Governing Equations in Integral Form / Grundgleichungen in Integralform

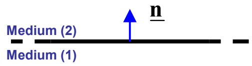
$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{R}} = -\iint_S \frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}} - \iint_S \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}}$$

$$\oint_{C=\partial S} \underline{\mathbf{H}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{R}} = \iint_S \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}} + \iint_S \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}}$$

$$\oiint_{S=\partial V} \underline{\mathbf{D}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}} = \iiint_V \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,dV$$

$$\oiint_{S=\partial V} \underline{\mathbf{B}}(\underline{\mathbf{R}},t)\bullet d\underline{\mathbf{S}} = \iiint_V \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)\,dV$$

Transition Conditions / Übergangsbedingungen



$$\underline{\mathbf{n}}\times\left[\underline{\mathbf{E}}^{(2)}(\underline{\mathbf{R}},t)-\underline{\mathbf{E}}^{(1)}(\underline{\mathbf{R}},t)\right]=\begin{cases}-\underline{\mathbf{K}}_{\mathrm{m}}(\underline{\mathbf{R}},t) & \text{ws / mq}\\ \underline{\mathbf{0}} & \text{sf / qf}\end{cases}$$

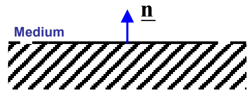
$$\underline{\mathbf{n}}\times\left[\underline{\mathbf{H}}^{(2)}(\underline{\mathbf{R}},t)-\underline{\mathbf{H}}^{(1)}(\underline{\mathbf{R}},t)\right]=\begin{cases}\underline{\mathbf{K}}_{\mathrm{e}}(\underline{\mathbf{R}},t) & \text{ws / mq}\\ \underline{\mathbf{0}} & \text{sf / qf}\end{cases}$$

$$\underline{\mathbf{n}}\bullet\left[\underline{\mathbf{D}}^{(2)}(\underline{\mathbf{R}},t)-\underline{\mathbf{D}}^{(1)}(\underline{\mathbf{R}},t)\right]=\begin{cases}\eta_{\mathrm{e}}(\underline{\mathbf{R}},t) & \text{ws / mq}\\ 0 & \text{sf / qf}\end{cases}$$

$$\underline{\mathbf{n}}\bullet\left[\underline{\mathbf{B}}^{(2)}(\underline{\mathbf{R}},t)-\underline{\mathbf{B}}^{(1)}(\underline{\mathbf{R}},t)\right]=\begin{cases}\eta_{\mathrm{m}}(\underline{\mathbf{R}},t) & \text{ws / mq}\\ 0 & \text{sf / qf}\end{cases}$$

ws: with sources; sf = source-free /
mq = mit Quellen; qf = quellenfrei

Boundary Conditions / Randbedingungen



$$\underline{\mathbf{n}}\times\underline{\mathbf{E}}(\underline{\mathbf{R}},t)=\begin{cases}\underline{\mathbf{0}} & \text{pec / iel}\\ -\underline{\mathbf{K}}_{\mathrm{m}}(\underline{\mathbf{R}},t) & \text{pem / iml}\end{cases}$$

$$\underline{\mathbf{n}}\times\underline{\mathbf{H}}(\underline{\mathbf{R}},t)=\begin{cases}\underline{\mathbf{K}}_{\mathrm{e}}(\underline{\mathbf{R}},t) & \text{pec / iel}\\ \underline{\mathbf{0}} & \text{pem / iml}\end{cases}$$

$$\underline{\mathbf{n}}\bullet\underline{\mathbf{D}}(\underline{\mathbf{R}},t)=\begin{cases}\eta_{\mathrm{e}}(\underline{\mathbf{R}},t) & \text{pec / iel}\\ 0 & \text{pem / iml}\end{cases}$$

$$\underline{\mathbf{n}}\bullet\underline{\mathbf{B}}(\underline{\mathbf{R}},t)=\begin{cases}0 & \text{pec / iel}\\ \eta_{\mathrm{e}}(\underline{\mathbf{R}},t) & \text{pem / iml}\end{cases}$$

pec = perfectly electric conducting; pmc = perfectly magnetic conducting / iel = ideal elektrisch leitend; iml = ideal magnetisch leitend

End of 5th Lecture / Ende der 5. Vorlesung