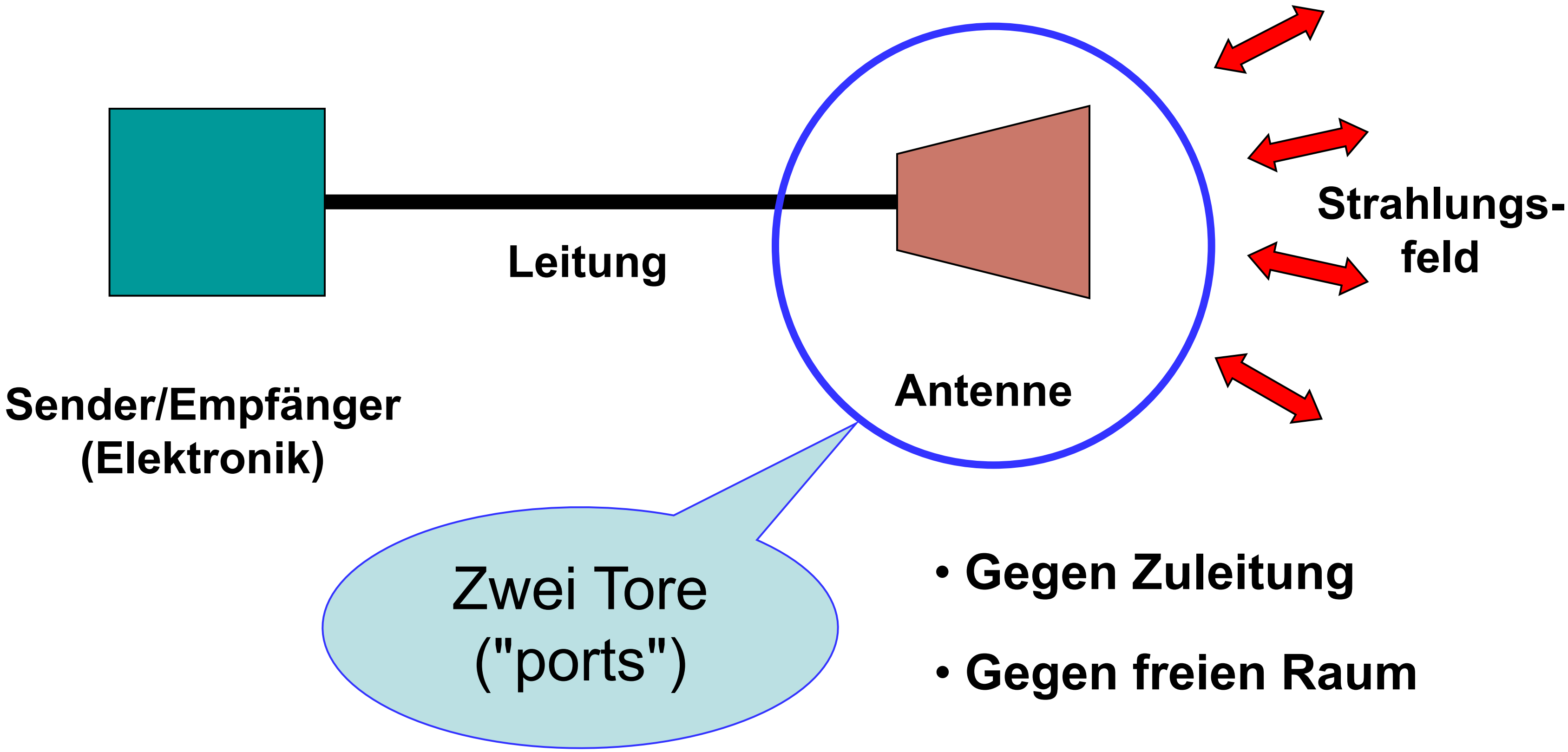
# Übersicht

- Antennen aus der Sicht der Speisung
- Antennen aus der Sicht des Fernfeldes
- Richtdiagramm und Strahldichte
- Wirkungsgrad, Richtfaktor, Gewinn, effektive Sendeleistung (ERP)
- Ersatzschaltung einer Antenne, Strahlungswiderstand
- Hertz'scher Dipol

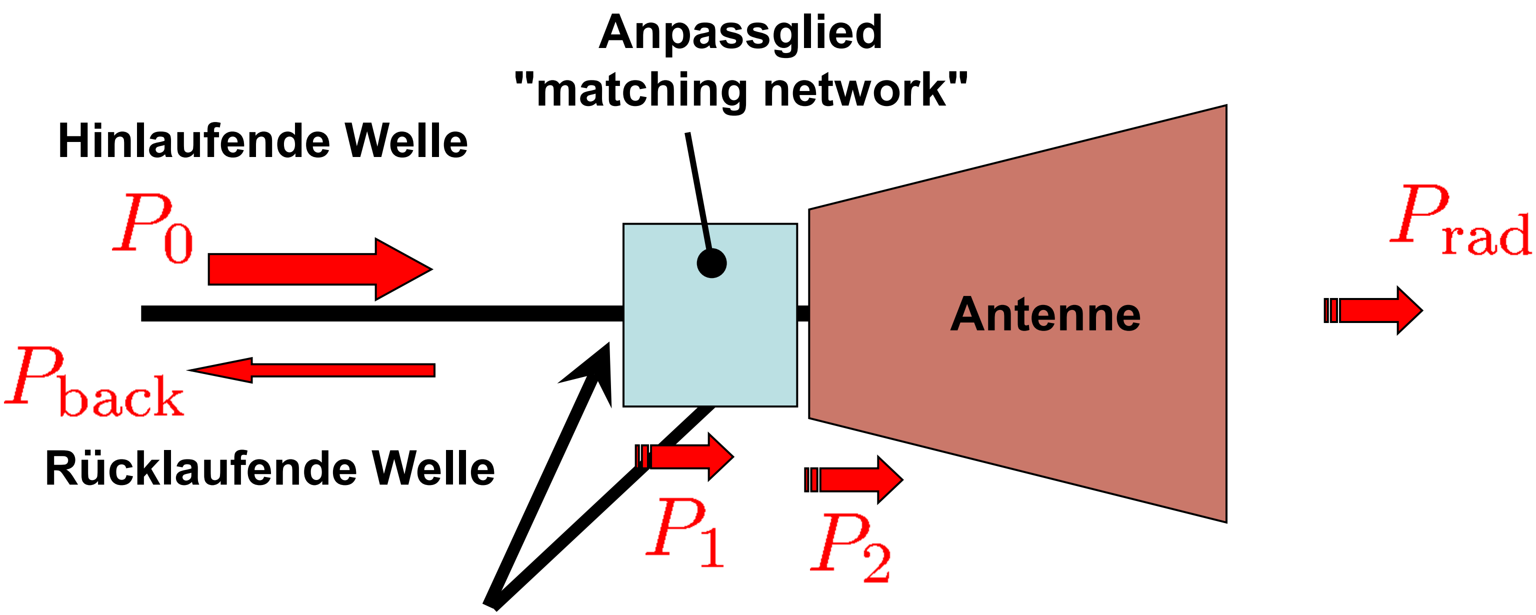
# Antennen

*Es geht darum, elektromagnetische Energie in den freien Raum zu bringen bzw. von dort einzufangen.*




- **Gegen Zuleitung**
- **Gegen freien Raum**

# Beschreibung des Antenneneingangs



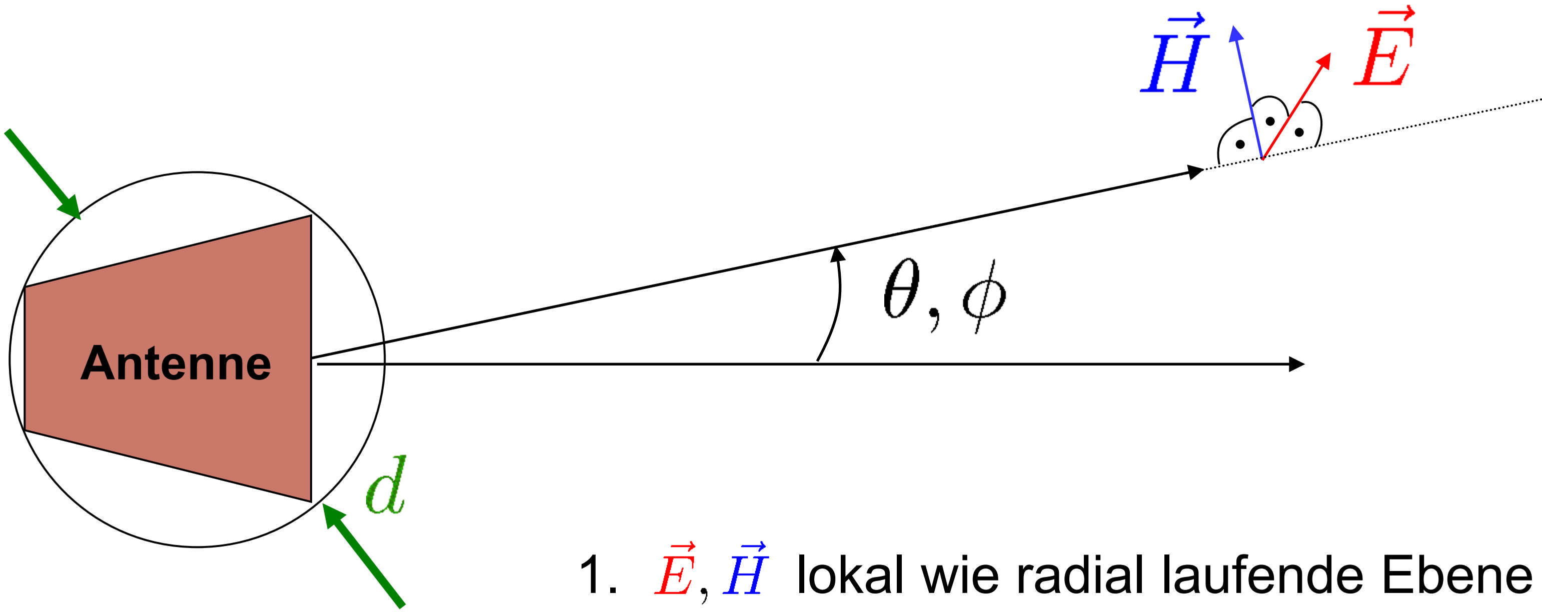

**Impedanz** $Z_{\mathrm{in}}(\omega)$

**bzw. Reflexionsfaktor** $\Gamma_{\mathrm{in}}(\omega)$

$$P_0 \geq P_1 \geq P_2 \geq P_{\mathrm{rad}}$$

**Referenz!!**

# Beschreibung des Fernfeldes




1. $\vec{E}, \vec{H}$ lokal wie radial laufende Ebene Welle

2. $$\vec{E}(r,\theta,\phi) = \frac{1}{r}\widetilde{E}(\theta,\phi)\vec{e}_{\mathrm{pol}}(\theta,\phi)$$

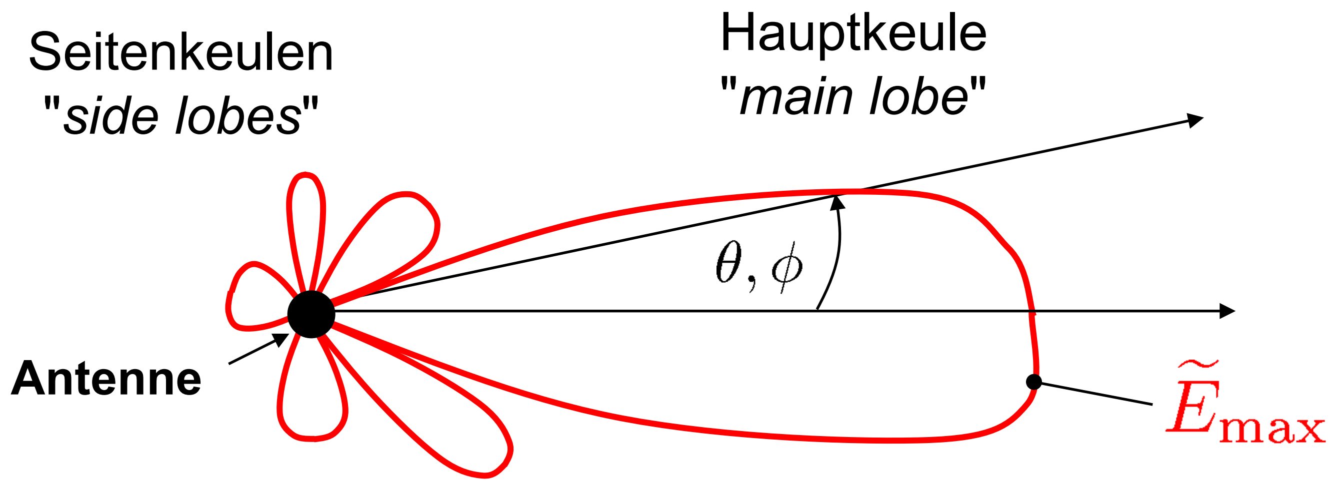
Stärke der Strahlung

Polarisation

nur für

$r \gg d$

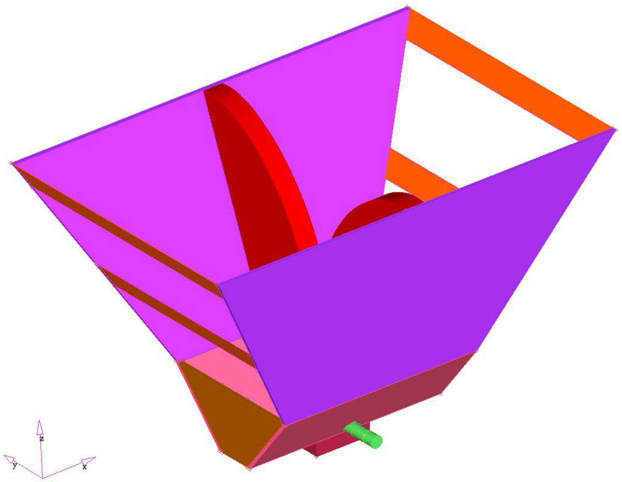
# Beschreibung des Fernfeldes

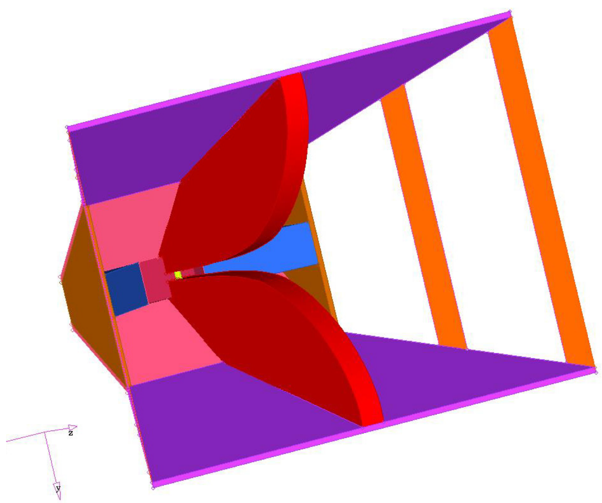


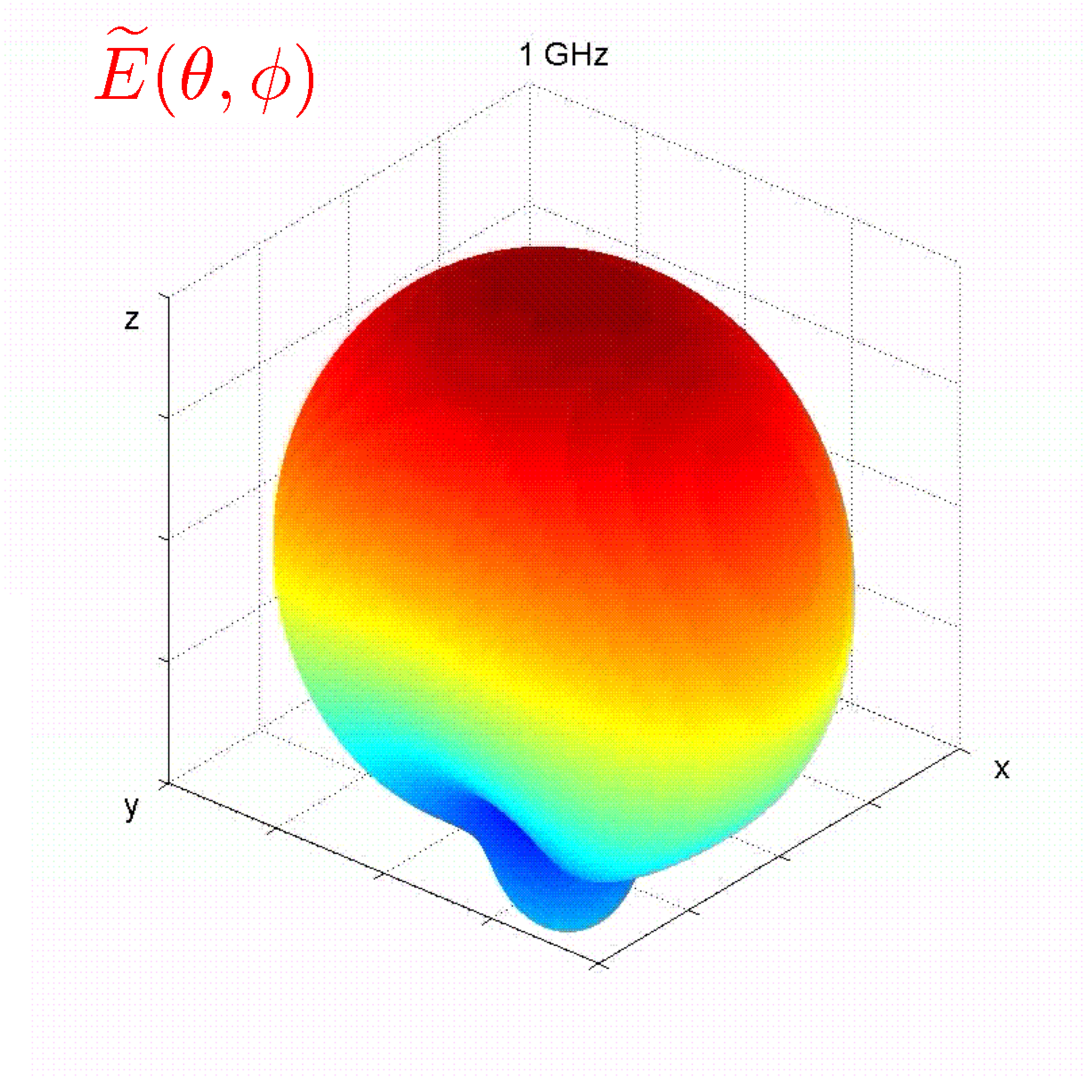

$$\vec{E}(r,\theta,\phi) = \frac{1}{r}\widetilde{E}(\theta,\phi)\vec{e}_{\mathrm{pol}}(\theta,\phi)$$

Strahlungsdiagramm
Richtdiagramm
Antennendiagramm
Richtcharakteristik
Strahlungscharakteristik
Empfangscharakteristik
"*radiation pattern*"

# Beispiel ("double rigded horn antenna")

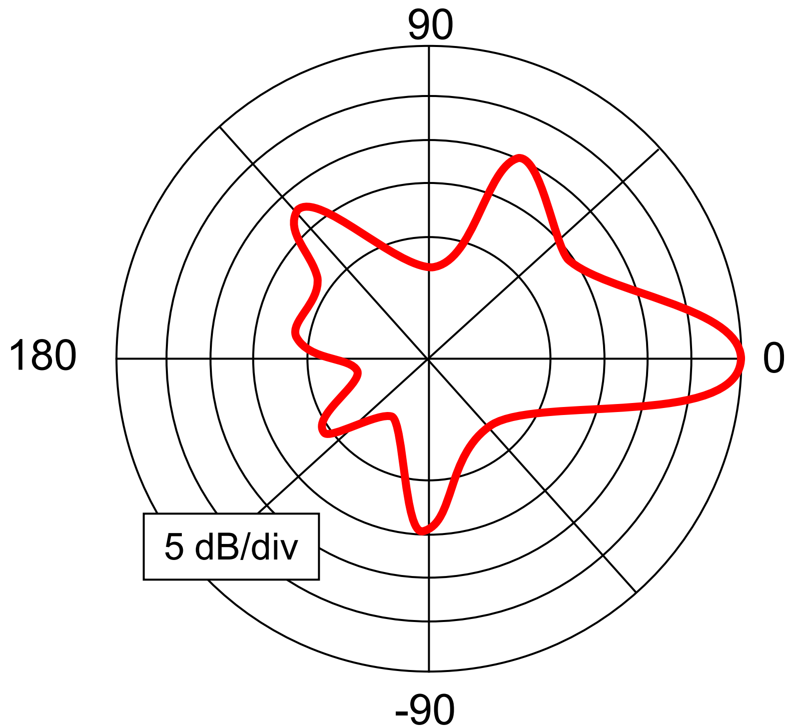






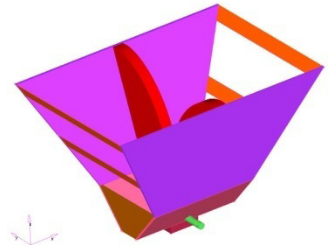
# Weiteres zum Richtdiagramm

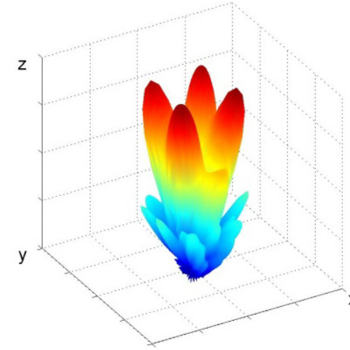
- Enthält (meist) ***keine*** Information zur Polarisation
- 3D-Darstellung gibt nur qualitativen Eindruck
- Darstellung in einzelnen Ebenen: $\left.\widetilde{E}(\theta)\right|_{\phi=\mathrm{const}}$



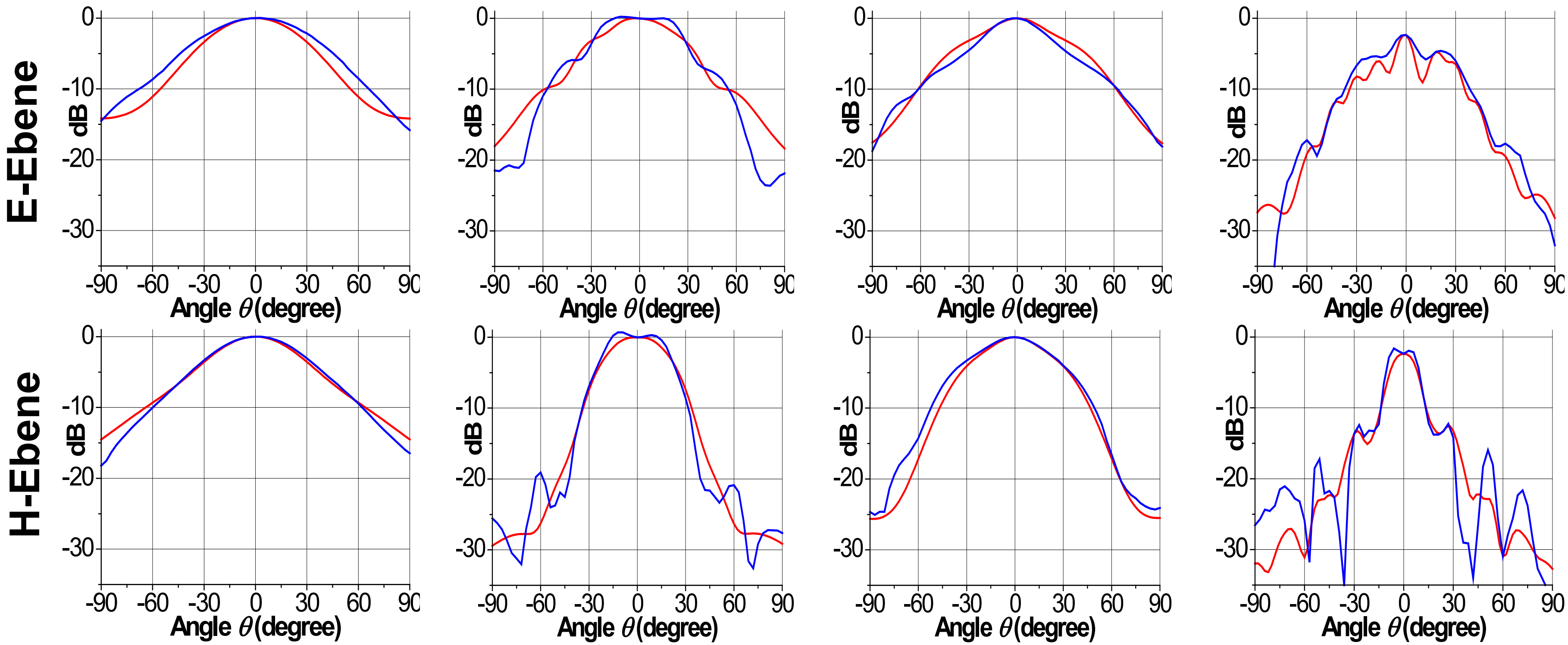

auch kartesische Darstellung!

# Kartesische Darstellung





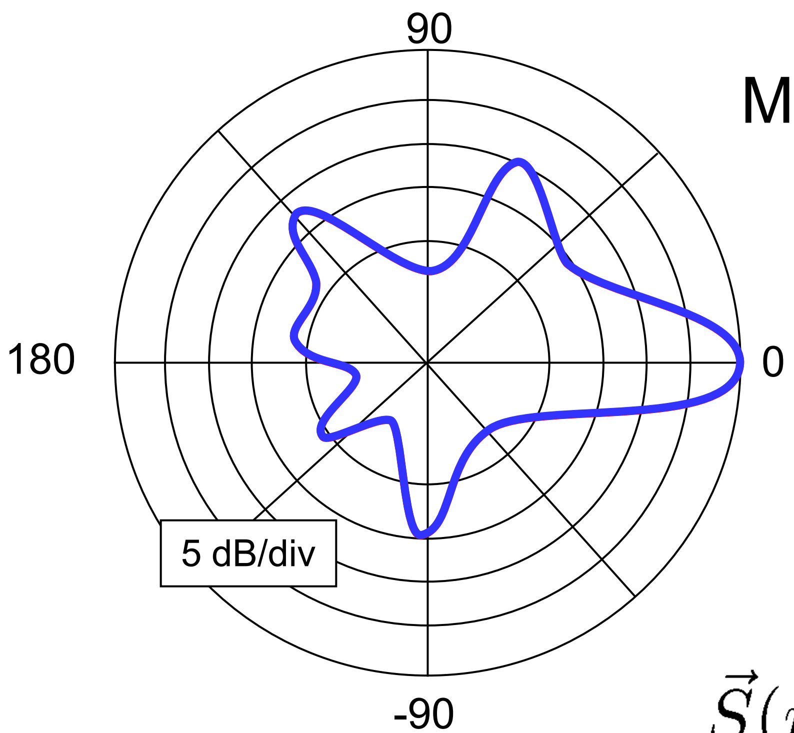

Messung
FVTD




2 GHz 4 GHz 8 GHz 16 GHz

# Weiteres zum Richtdiagramm

Normalerweise bezogen auf $\widetilde{E}(\theta,\phi)\,[\mathrm{V}]$




Manchmal auch auf Strahldichte

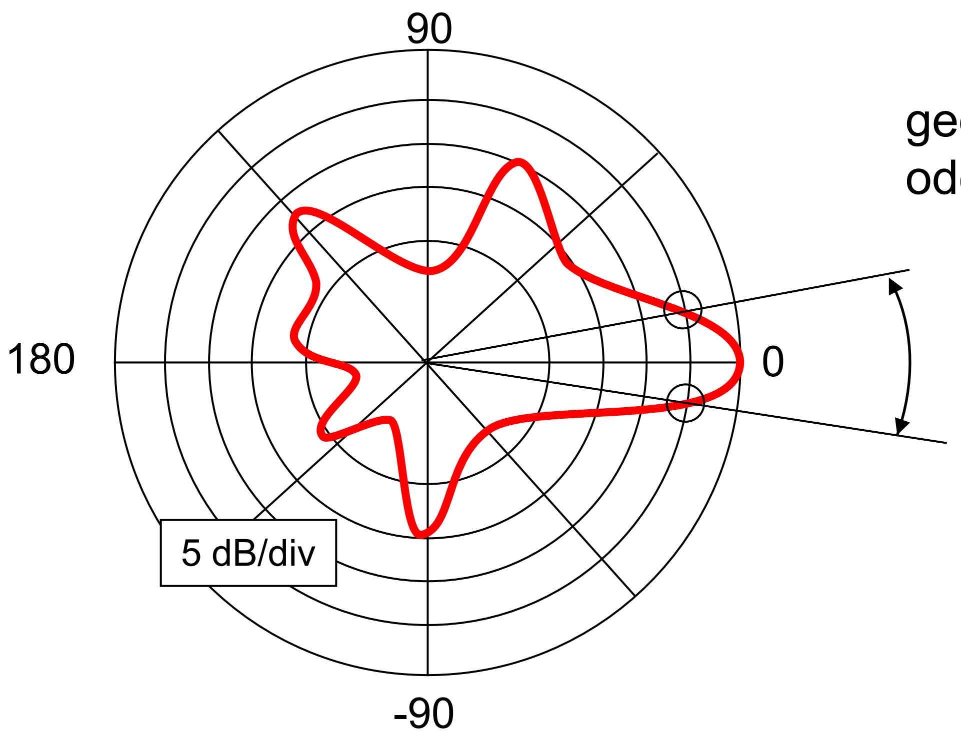
$$S(\theta,\phi) := \frac{\widetilde{E}^2(\theta,\phi)}{Z_{\mathrm{w}}}\,[\mathrm{W}]$$

Achtung:
**Nicht** Poynting-Vektor!

$$\vec{S}(r,\theta,\phi) \mathrel{\widehat{=}} \frac{S(\theta,\phi)}{r^2}\,\vec{e}_r\,[\tfrac{\mathrm{W}}{\mathrm{m}^2}]$$

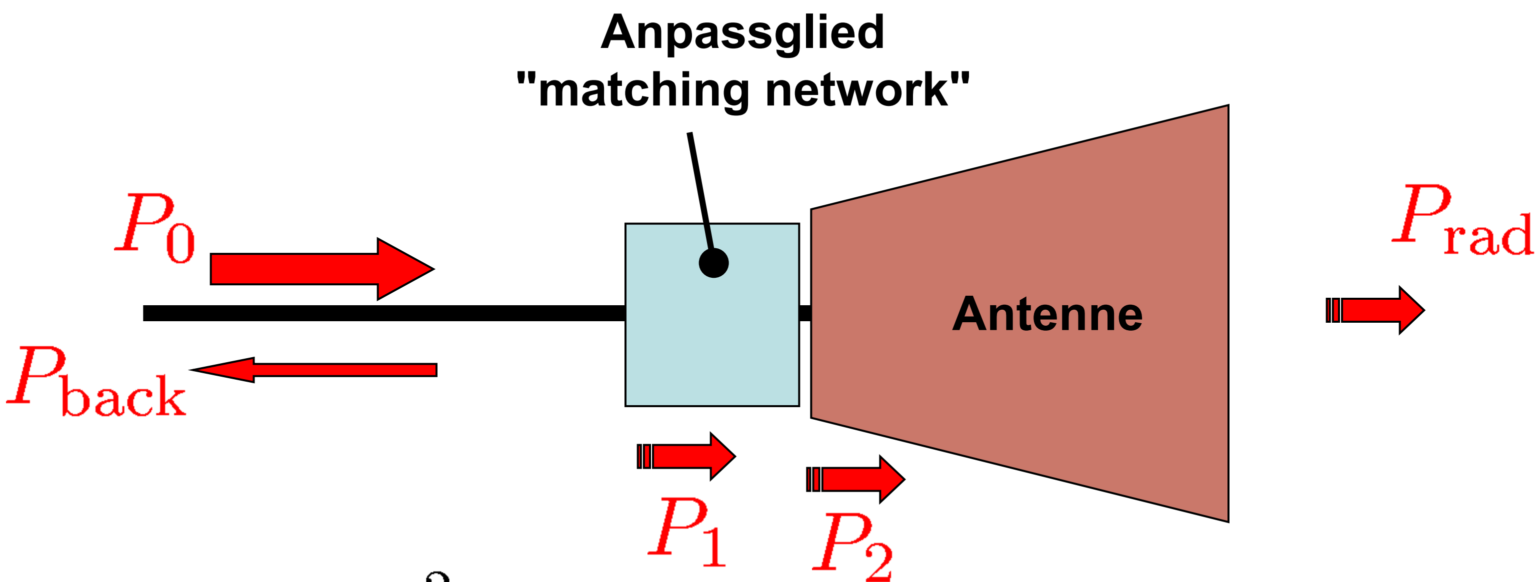
# Weiteres zum Richtdiagramm

- (x-dB-)Keulenbreite ("*beam width*")




gegeben in Grad (2D)
oder Steradiant (3D)

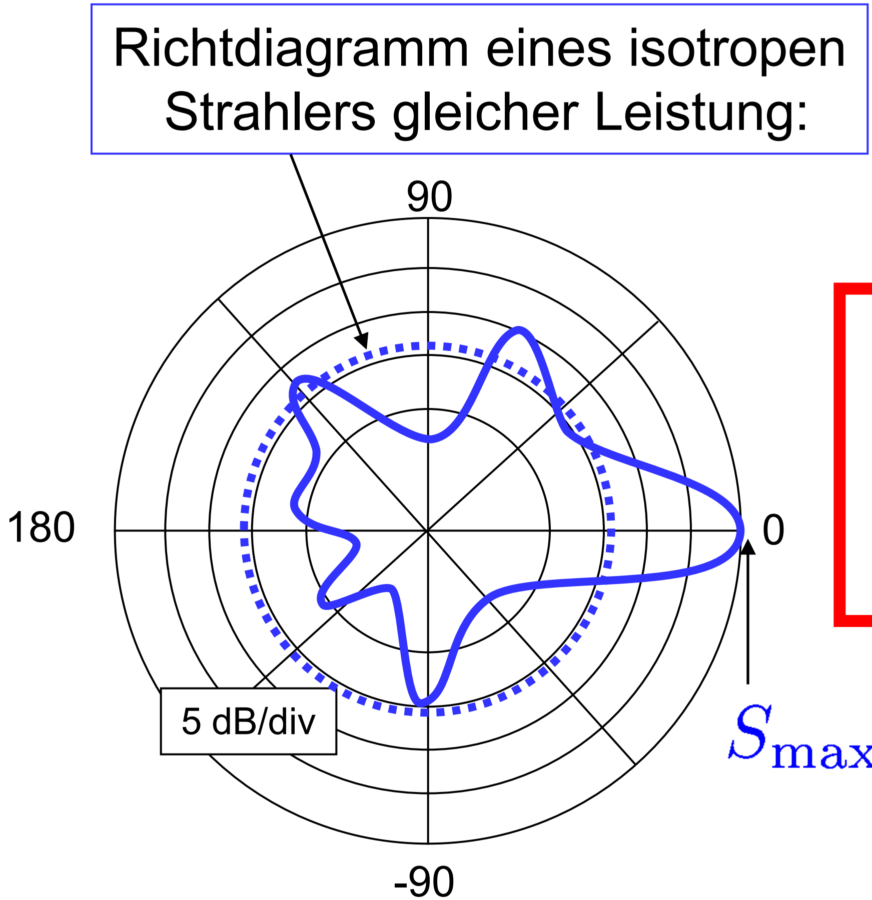
# Strahlungsleistung und Wirkungsgrad




$$P_{\text{rad}} = \int_0^{\pi} \int_0^{2\pi} S(\theta, \phi)\, d\phi \, \sin\theta d\theta \; [\text{W}]$$

Antennenwirkungsgrad $\quad \eta = \dfrac{P_{\text{rad}}}{P_{1,2}}$

# Richtfaktor D ("directivity")




$$S_{\mathrm{iso}}\cancel{(\theta,\phi)} = \frac{P_{\mathrm{rad}}}{4\pi}$$

$$S_{\max} > S_{\mathrm{iso}}$$

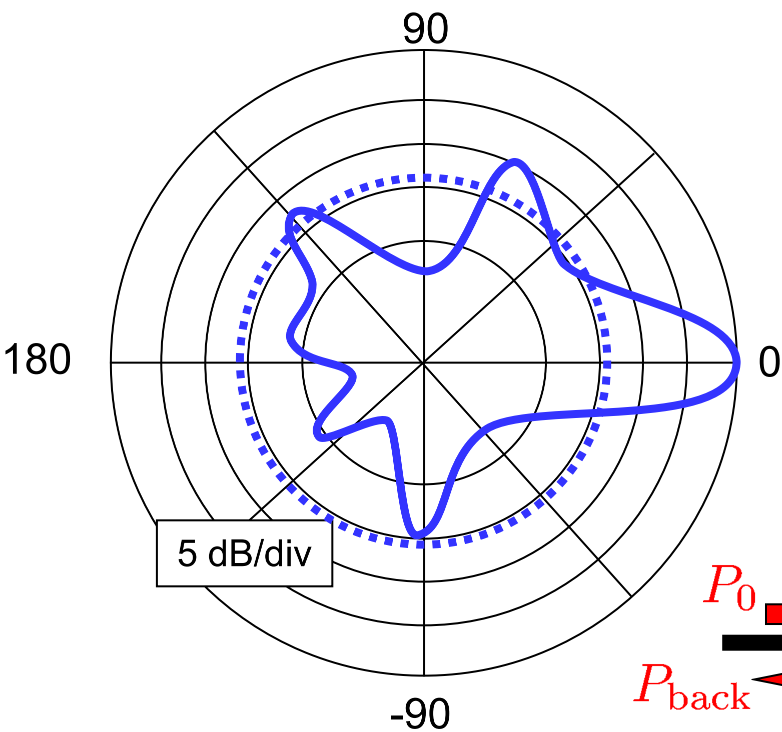
**Richtfaktor:**

$$D = \frac{S_{\max}}{S_{\mathrm{iso}}} = 4\pi \frac{S_{\max}}{P_{\mathrm{rad}}}$$

# Antennen-Gewinn G ("gain")

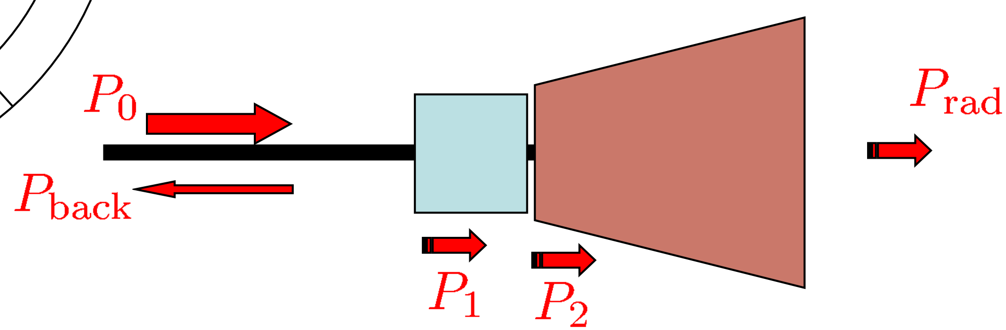
$$D = \frac{S_{\mathrm{max}}}{S_{\mathrm{iso}}} = 4\pi \frac{S_{\mathrm{max}}}{P_{\mathrm{rad}}}$$

$$\eta = \frac{P_{\mathrm{rad}}}{P_{1,2}}$$




**Antennen-Gewinn:**

$$\boxed{G = 4\pi \frac{S_{\mathrm{max}}}{P_{1,2}} = \eta \cdot D}$$



# Antennen-Gewinn: Beispiel 1

**Horn mit Spiegel**: gemäss Hersteller **G = 42 dB**

$$f = 1 \ldots 18\,\mathrm{GHz}$$

gemessen: **G = 32 dB**

Nur 10% der erwarteten Leistung
im Bereich der Hauptkeule!

# Antennen-Gewinn: Beispiel 2

$$f = 380 \ldots 400\,\mathrm{MHz}$$

**Undercover-Antenne**: Bestehendes System **G = – 26 dB**
(Draht-Dipol, fast auf der Haut)

Prototyp: **G = – 12 dB**

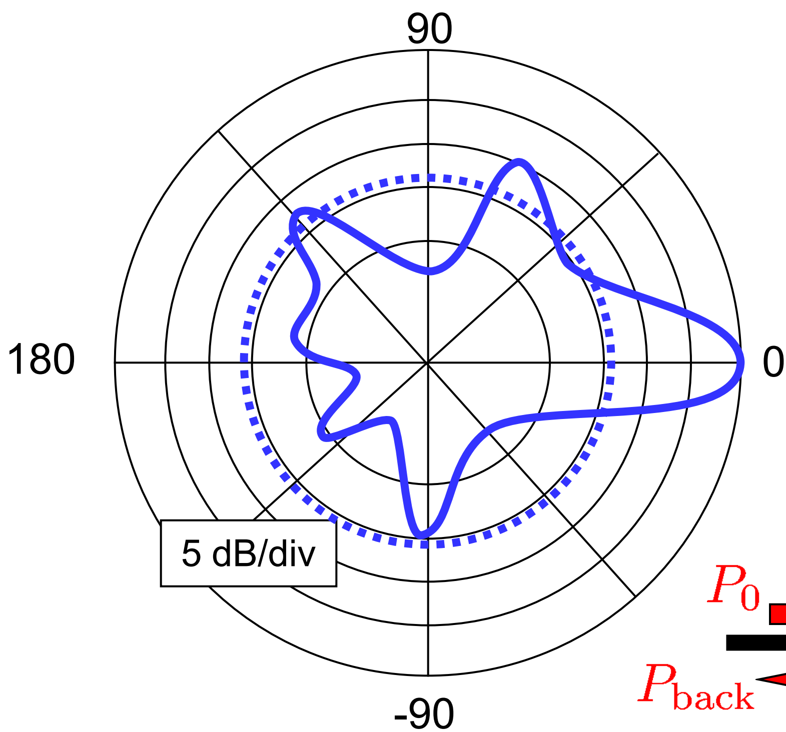
Ideale Antenne hätte
**G = 0 dB** wegen
Rundstrahlcharakteristik!

# Effektive Sendeleistung ("effective radiated power", ERP)

Welche Leistung wäre nötig, wenn die tatsächli… Antenne ein Kugelstrahler wäre, de… …ahlen würde wie die gegebene A… …auptstrahlrichtung?

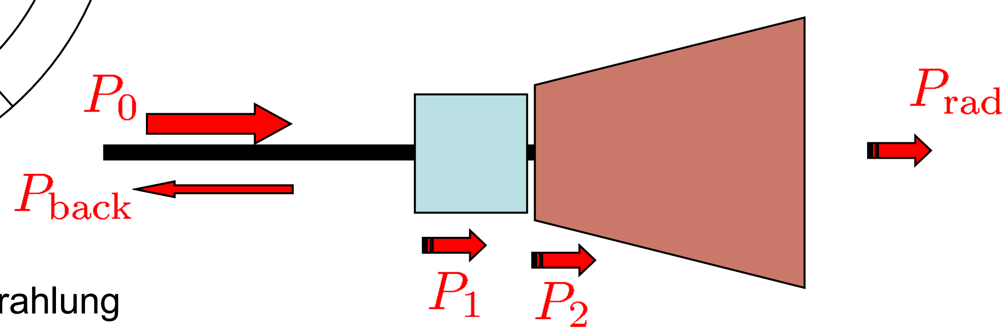
**Juristenfutter bei NISV***

$$G = 4\pi \frac{S_{\max}}{P_{1,2}}$$




$$\frac{P_{\text{eff}}}{4\pi} = S_{\max} = \frac{G P_{1,2}}{4\pi}$$

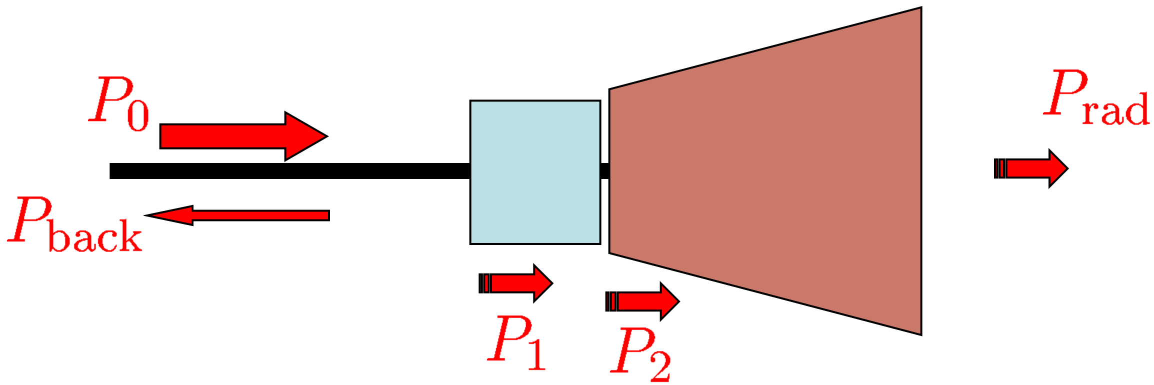
$$\boxed{P_{\text{eff}} = G \cdot P_{1,2}}$$



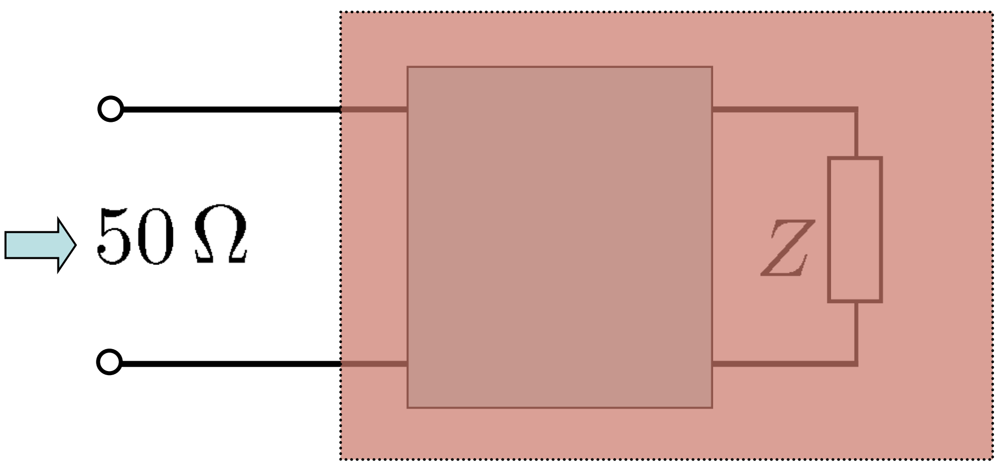

*Verordnung über die Nicht ionisierende Strahlung

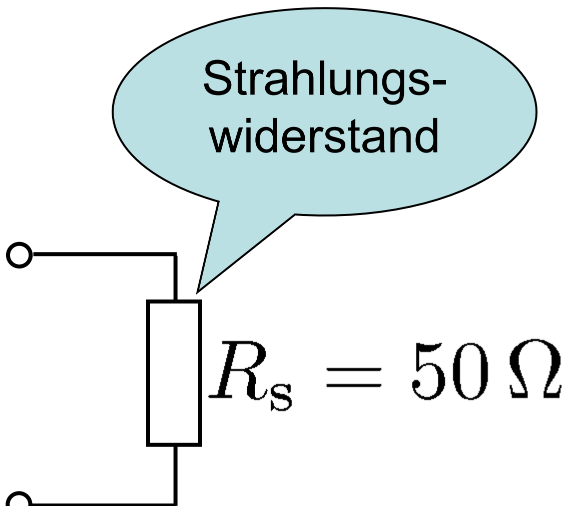
G = 20dB → 10 W reale Leistung ergeben 1 kW ERP

# Ersatzschaltung einer Antenne



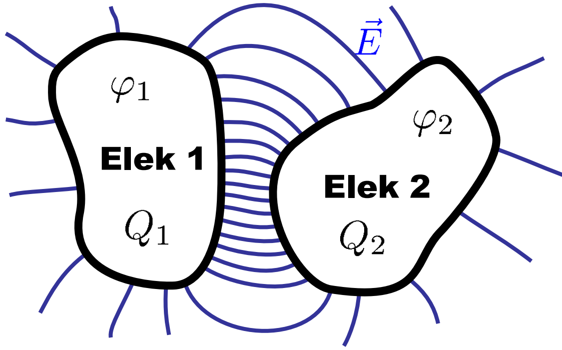

**1. Ideale Antenne:** $P_0 = P_1 = P_2 = P_{\mathrm{rad}}$



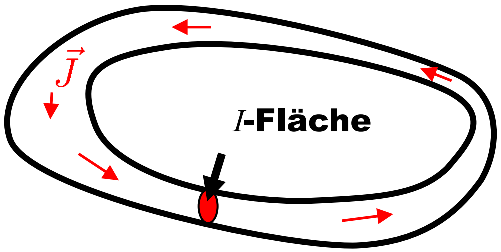



# Feld ⟺ Netzwerk

$$C = \frac{1}{U^2} \iiint_{V_\infty} \vec{D}\cdot\vec{E}\, dV = \frac{1}{U^2} \iiint_{V_\infty} \varepsilon |\vec{E}|^2 dV$$




$$L = \frac{1}{I^2} \iiint_{V_\infty} \vec{B}\cdot\vec{H}\, dV = \frac{1}{I^2} \iiint_{V_\infty} \mu |\vec{H}|^2 dV$$




$$R = \frac{1}{I^2} \iiint_{V_J} \vec{J}\cdot\vec{E}\, dV = \frac{1}{I^2} \iiint_{V_J} \sigma |\vec{E}|^2 dV$$

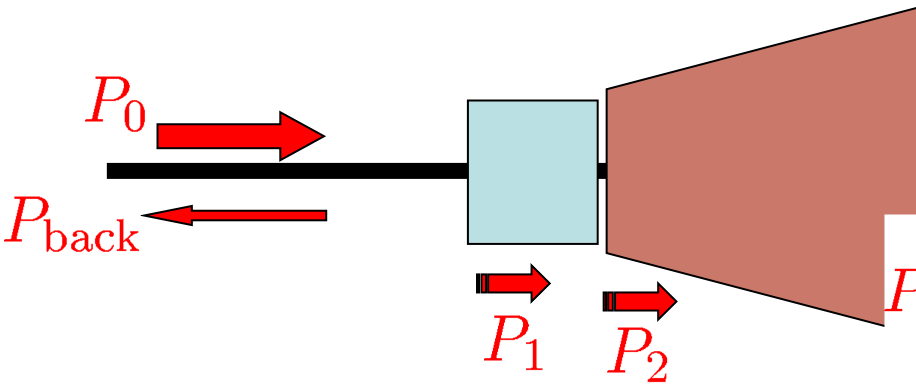
# Poynting-Theorem (Phasor)

$$\boxed{-\oiint\limits_{\partial V} \vec{S}\cdot d\vec{F} = \iiint\limits_{V} \left( \mu \vec{H}\cdot \frac{\partial \vec{H}}{\partial t} + \varepsilon \vec{E}\cdot \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E}\cdot \vec{E} \right) dV}$$

$$-\oiint\limits_{\partial V} \underline{\underline{\vec{S}}}^{\sim}\cdot d\vec{F} = \frac{1}{2} \iiint\limits_{V} \left\{ j\omega \left( \mu \underline{\vec{H}}\cdot \underline{\vec{H}} + \varepsilon \underline{\vec{E}}\cdot \underline{\vec{E}} \right) + \sigma \underline{\vec{E}}\cdot \underline{\vec{E}} \right\} dV$$

$$-\oiint\limits_{\partial V} \underline{\underline{\vec{S}}}\cdot d\vec{F} = \frac{1}{2} \iiint\limits_{V} \left\{ j\omega \left( \mu \underline{\vec{H}}\cdot \underline{\vec{H}}^{*} - \varepsilon^{*} \underline{\vec{E}}\cdot \underline{\vec{E}}^{*} \right) + \sigma^{*} \underline{\vec{E}}\cdot \underline{\vec{E}}^{*} \right\} dV$$

# Ersatzschaltung einer Antenne

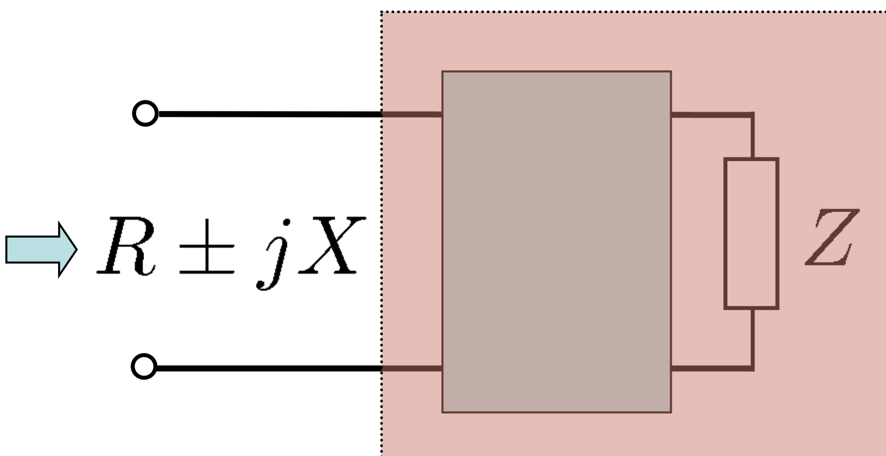


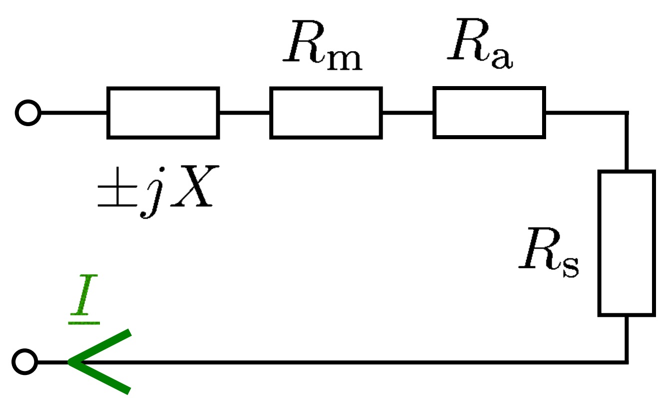

$$P_{\mathrm{rad}} = \frac{|\underline{I}|^2}{2} R_{\mathrm{s}}$$

$$P_2 - P_{\mathrm{rad}} = \frac{|\underline{I}|^2}{2} R_{\mathrm{a}}$$

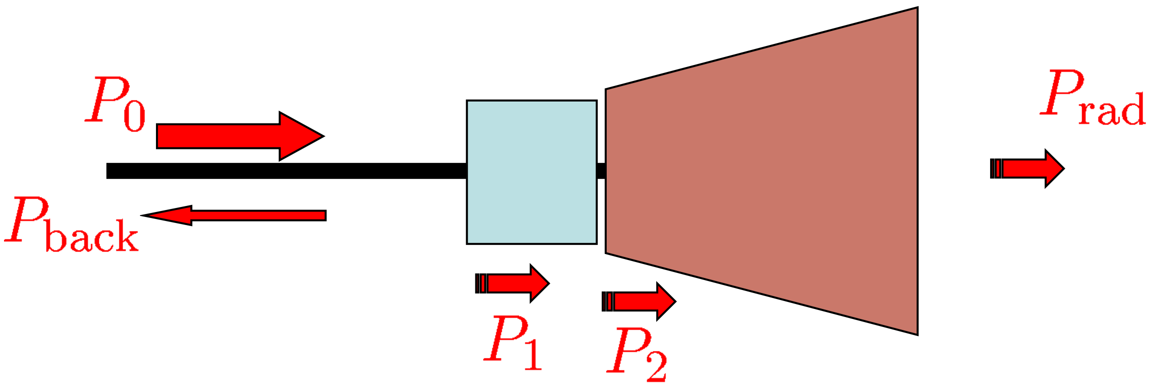
$$P_1 - P_2 = \frac{|\underline{I}|^2}{2} R_{\mathrm{m}}$$

**2. Reale Antenne:**

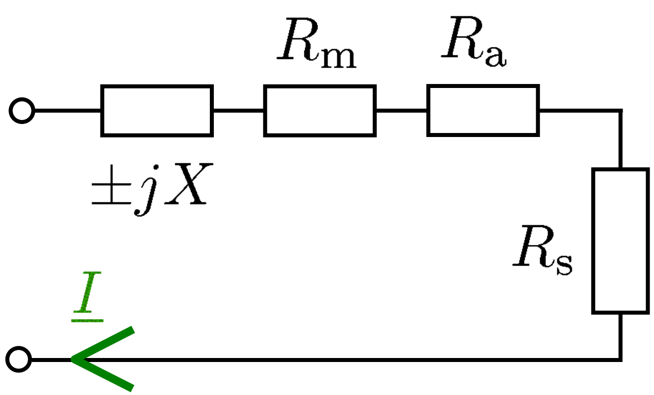


# Ersatzschaltung einer Antenne

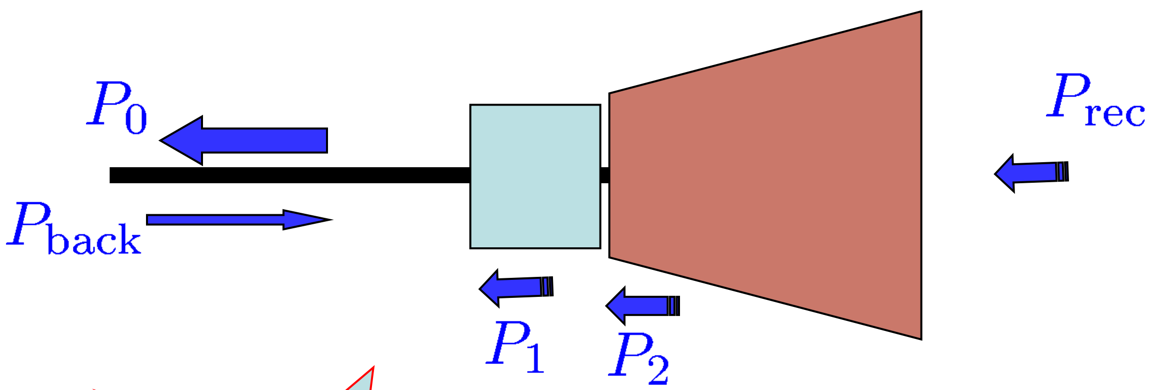


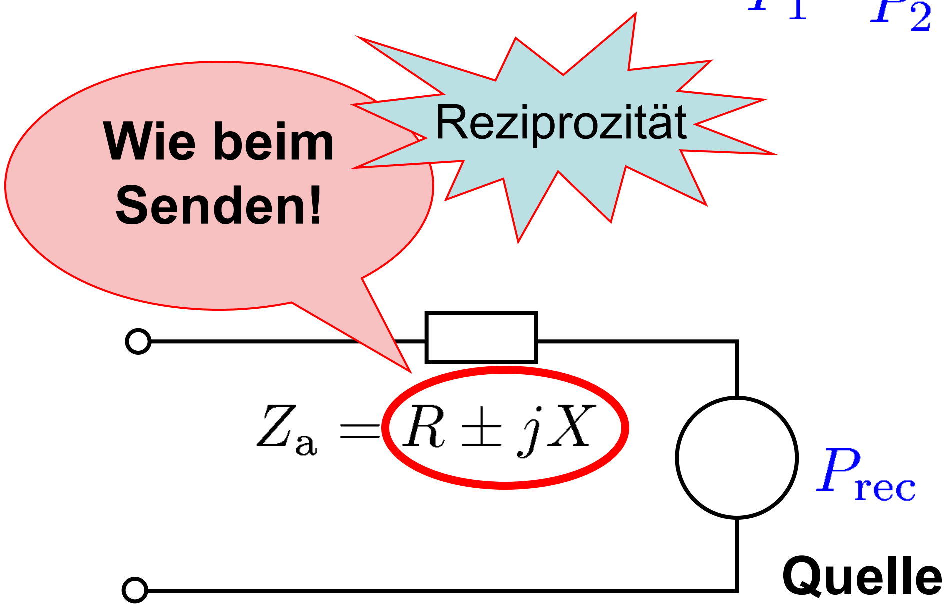

## 2. Reale Antenne:




komplizierter Ersatzschaltungen sind möglich!
(z.B. um grösseren Frequenzbereich abzudecken)

# Antenne beim Empfangen

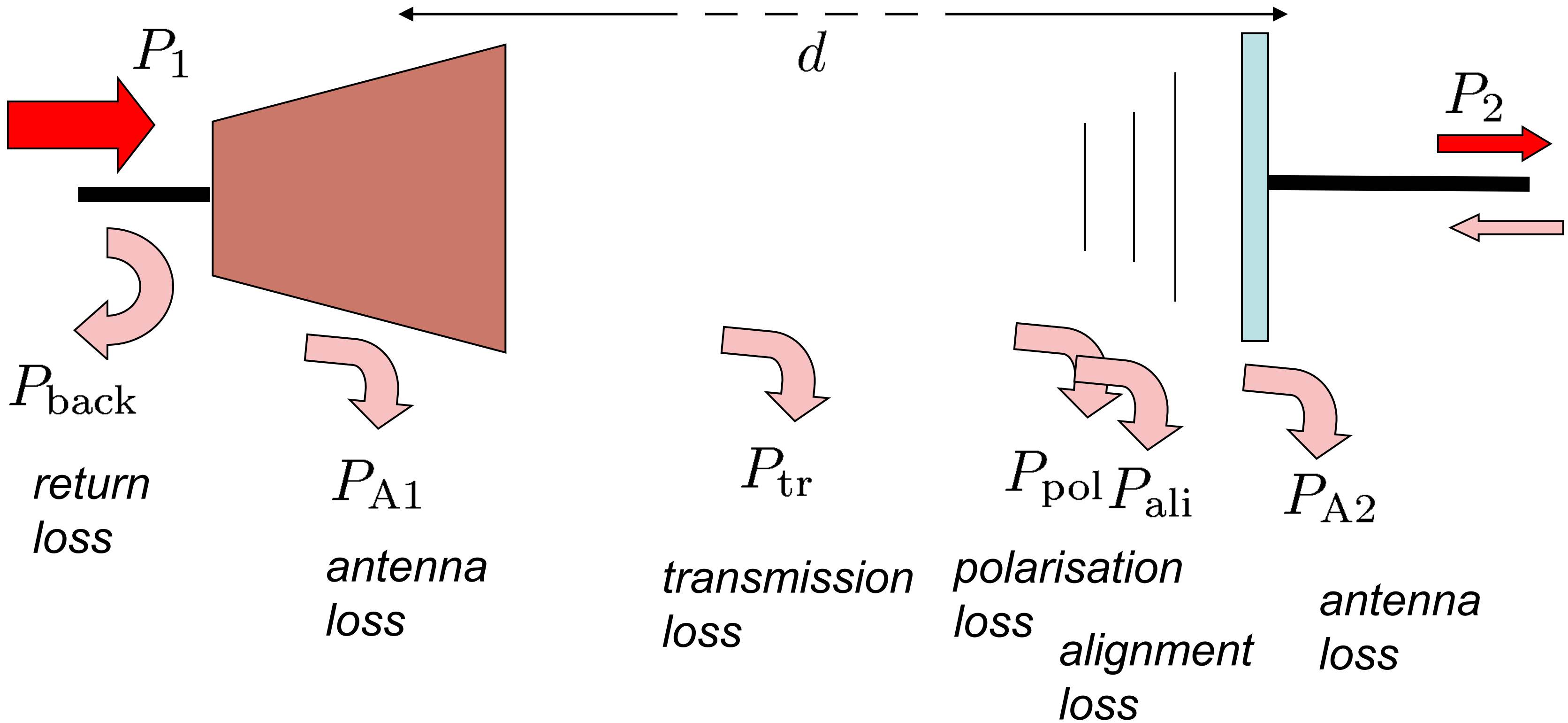



**Empfangscharakteristik**
**=**
**Sendecharakteristik**

Gewinn G
Richtfaktor D

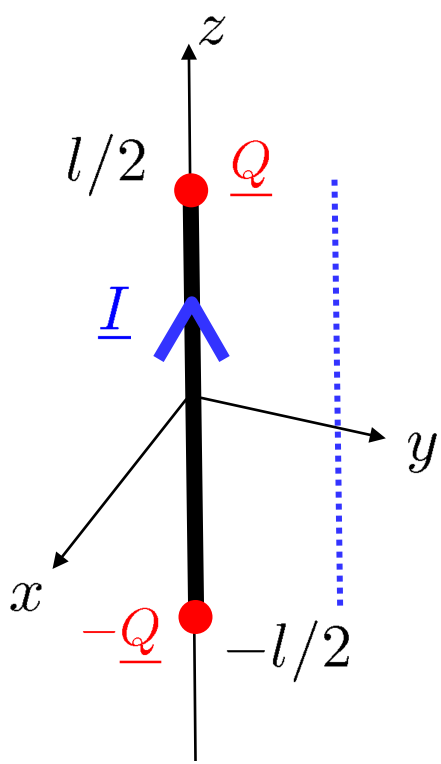
# Drahtlose Übertragungsstrecke




Leistungsanpassung wo immer möglich!!

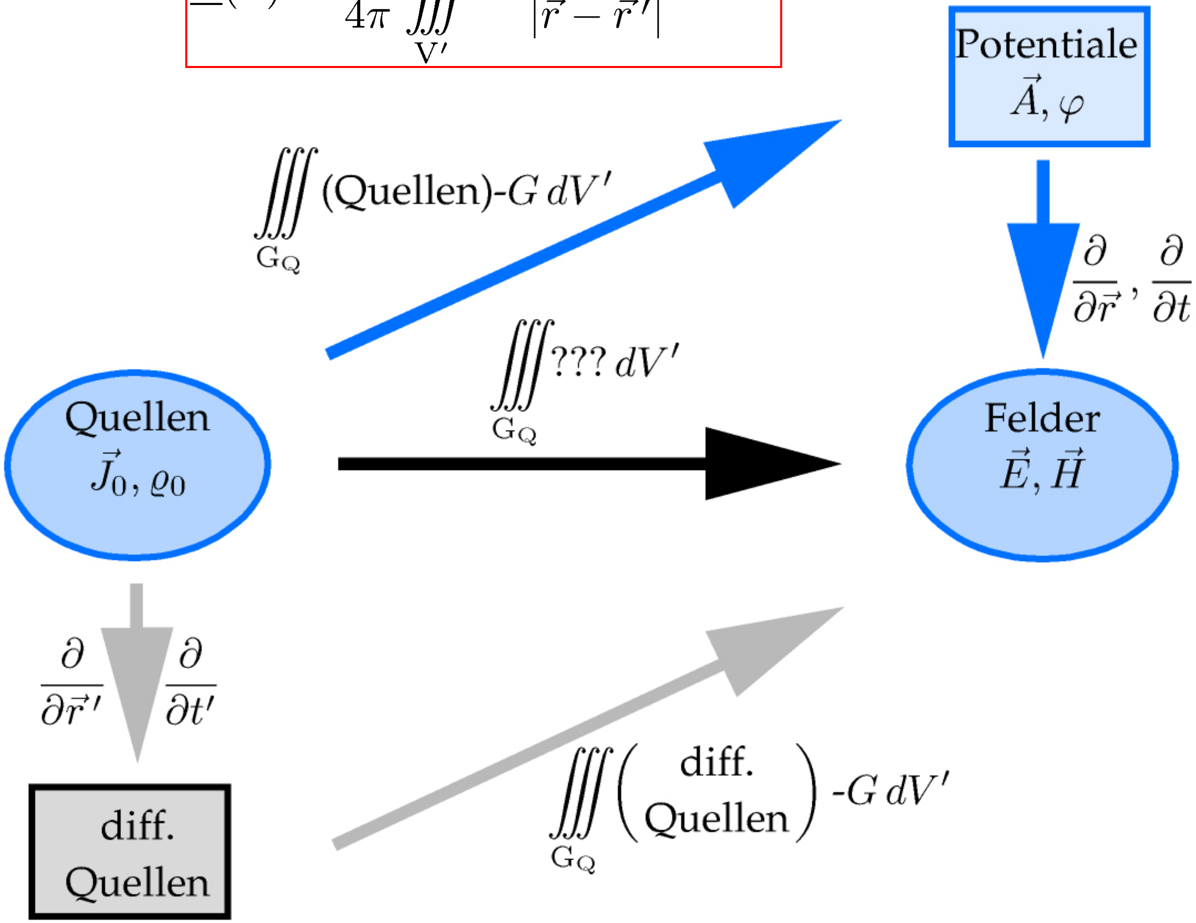
# Hertz'scher Dipol

Siehe auch im Buch, Abschnitt 12.1.4




**Berechnung des Feldes explizit und analytisch möglich!**

$$\underline{\vec{A}}(\vec{r}) = \frac{\mu}{4\pi} \iiint\limits_{V'} \frac{\underline{\vec{J}} \cdot e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dV'$$




$$\underline{\vec{E}} = -\operatorname{grad} \underline{\varphi} - j\omega \underline{\vec{A}}$$

$$\underline{\vec{H}} = \frac{1}{\mu} \operatorname{rot} \underline{\vec{A}}$$

(Kapitel 6, Fuk I)

Bild aus dem Buch!

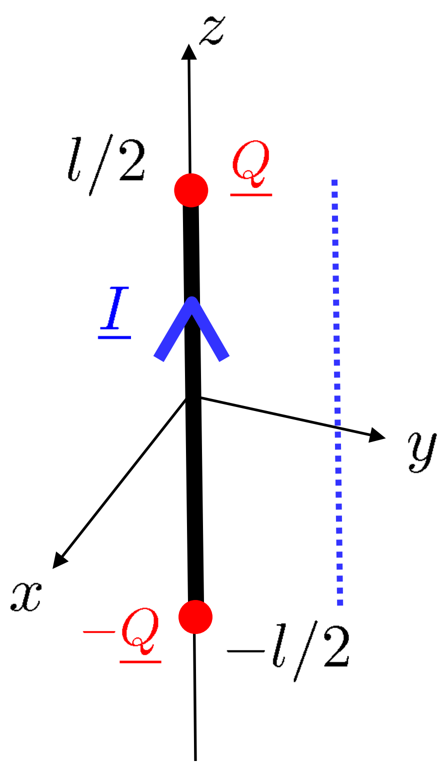
Quellpunkt $\vec{r}', t'$

$R := |\vec{r} - \vec{r}'|$

$t' := t - \frac{R}{v}$

Aufpunkt $\vec{r}, t$

# Hertz'scher Dipol




1. Berechnung des Vektorpotentials $\underline{\vec{A}}(\vec{r})$ für alle "fernen" Punkte $\vec{r}$
2. Berechnung der Felder aus $\underline{\vec{A}}(\vec{r})$
3. Diskussion des Feldverlaufs
4. Berechnung der Antennenparameter (soweit sinnvoll)

# Spezielle (partikuläre) Lösungen im stationären Zustand

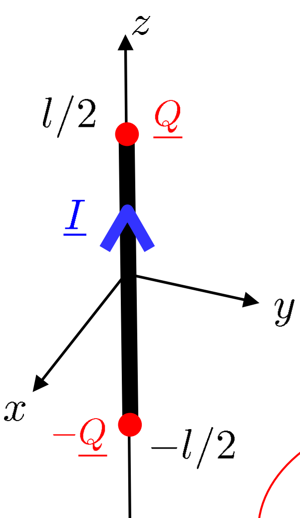
$$\underline{\vec{E}}(\vec{r}) = \frac{-1}{4\pi\varepsilon} \iiint\limits_{V'} \frac{\left(j\omega\mu\varepsilon \underline{\vec{J}}(\vec{r}\,') + \mathrm{grad}'\, \underline{\varrho}(\vec{r}\,')\right) \cdot e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} dV'$$

$$\underline{\vec{H}}(\vec{r}) = \frac{1}{4\pi} \iiint\limits_{V'} \frac{\mathrm{rot}'\, \underline{\vec{J}}(\vec{r}\,') \cdot e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} dV'$$

$$\underline{\varphi}(\vec{r}) = \frac{1}{4\pi\varepsilon} \iiint\limits_{V'} \frac{\underline{\varrho}(\vec{r}\,') \cdot e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} dV'$$

$$\underline{\vec{A}}(\vec{r}) = \frac{\mu}{4\pi} \iiint\limits_{V'} \frac{\underline{\vec{J}}(\vec{r}\,') \cdot e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} dV'$$

# Hertz'scher Dipol: Vektorpotential $\underline{\vec{A}}(\vec{r})$




$$\underline{\vec{A}}(\vec{r}) = \frac{\mu}{4\pi} \iiint\limits_{V'} \frac{\underline{\vec{J}} \cdot e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|} dV' \qquad (7.34)$$

$$= \frac{\mu \underline{I}}{4\pi} \vec{e}_z \int\limits_{-l/2}^{l/2} \frac{e^{-jk\sqrt{x^2+y^2+(z-z')^2}}}{\sqrt{x^2+y^2+(z-z')^2}} dz'$$

$$dV' = dF \cdot dz'$$

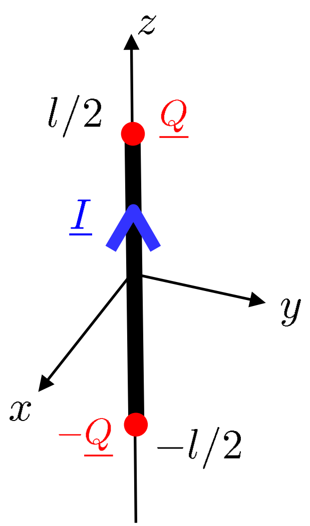
$$\iint \underline{\vec{J}}\, dF = \underline{I} \cdot \vec{e}_z$$

$$= \frac{\mu \underline{I} l}{4\pi} \vec{e}_z \frac{e^{-jk\sqrt{x^2+y^2+z^2}}}{\sqrt{x^2+y^2+z^2}} = \frac{\mu \underline{I} l}{4\pi} \vec{e}_z \frac{e^{-jkr}}{r}$$

$$x^2+y^2+z^2 \gg l^2$$

$$kl \ll 1$$

# Hertz'scher Dipol: Felder aus $\underline{\vec{A}}(\vec{r}\,)$




$$\underline{\varphi} = \frac{\operatorname{div}\underline{\vec{A}}}{-j\omega\mu\varepsilon}$$

Lorentz-Eichung (6.103)

$$\underline{\vec{E}} = -\operatorname{grad}\underline{\varphi} - j\omega\underline{\vec{A}} = \frac{\operatorname{grad}\operatorname{div}\underline{\vec{A}}}{j\omega\mu\varepsilon} - j\omega\underline{\vec{A}}$$

$$\underline{\vec{H}} = \frac{1}{\mu}\operatorname{rot}\underline{\vec{A}}$$

$$\underline{\vec{A}}(\vec{r}\,) = \frac{\mu\underline{I}l}{4\pi}\vec{e}_z\frac{e^{-jkr}}{r}$$

$$\vec{e}_z = \vec{e}_r\cos\theta - \vec{e}_\theta\sin\theta$$

$$\underline{A}_r(r,\theta) = \underline{A}_z(r)\cos\theta = \frac{\mu\underline{I}l}{4\pi}\frac{e^{-jkr}}{r}\cos\theta$$

$$\underline{A}_\theta(r,\theta) = -\underline{A}_z(r)\sin\theta = -\frac{\mu\underline{I}l}{4\pi}\frac{e^{-jkr}}{r}\sin\theta$$

# Koordinatenformen

$$\vec{v} = v_x\vec{e}_x + v_y\vec{e}_y + v_z\vec{e}_z \qquad \text{z.B.} \quad v_y = v_y(x,y,z)$$

$$\mathrm{rot}\,\vec{v} = \left(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}\right)\vec{e}_x + \left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right)\vec{e}_y + \left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right)\vec{e}_z$$

$$\mathrm{div}\,\vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$

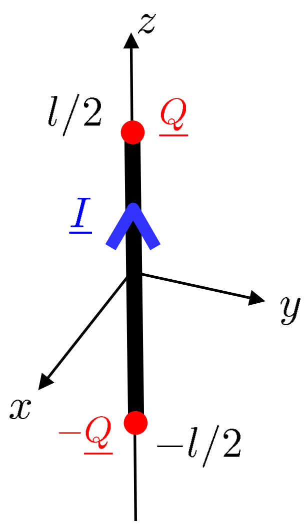
Vgl. S. 154 im Buch

$$\vec{v} = v_\rho\vec{e}_\rho + v_\phi\vec{e}_\phi + v_z\vec{e}_z$$

$$\mathrm{rot}\,\vec{v} = \left(\frac{1}{\rho}\frac{\partial v_z}{\partial \phi} - \frac{\partial v_\phi}{\partial z}\right)\vec{e}_\rho + \left(\frac{\partial v_\rho}{\partial z} - \frac{\partial v_z}{\partial \rho}\right)\vec{e}_\phi + \frac{1}{\rho}\left(\frac{\partial(\rho v_\phi)}{\partial \rho} - \frac{\partial v_\rho}{\partial \phi}\right)\vec{e}_z$$

$$\mathrm{div}\,\vec{v} = \frac{1}{\rho}\frac{\partial(\rho v_\rho)}{\partial \rho} + \frac{1}{\rho}\frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_z}{\partial z}$$

# Hertz'scher Dipol: Felder aus $\underline{\vec{A}}(\vec{r}\,)$




$$\underline{A}_r(r,\theta) = \frac{\mu \underline{I} l}{4\pi}\frac{e^{-jkr}}{r}\cos\theta$$

$$\underline{A}_\theta(r,\theta) = -\frac{\mu \underline{I} l}{4\pi}\frac{e^{-jkr}}{r}\sin\theta$$

$$\underline{\vec{A}}(\vec{r}\,) = \frac{\mu \underline{I} l}{4\pi}\vec{e}_z \frac{e^{-jkr}}{r}$$

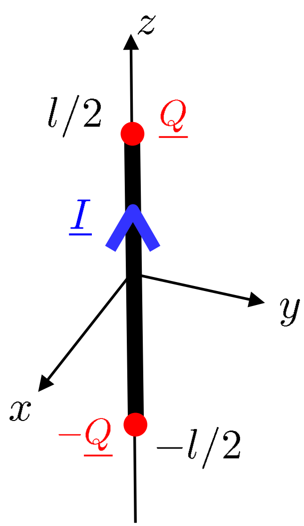
$$\operatorname{rot}\underline{\vec{A}} = \frac{\mu \underline{I} l}{4\pi}\left(jk + \frac{1}{r}\right)\vec{e}_\phi \frac{e^{-jkr}}{r}\sin\theta$$

$$\operatorname{div}\underline{\vec{A}} = -\frac{\mu \underline{I} l}{4\pi}\left(jk + \frac{1}{r}\right)\frac{e^{-jkr}}{r}\cos\theta$$

$$\underline{\vec{E}} = \frac{\operatorname{grad}\operatorname{div}\underline{\vec{A}}}{j\omega\mu\varepsilon} - j\omega\underline{\vec{A}}$$

$$\underline{\vec{H}} = \frac{1}{\mu}\operatorname{rot}\underline{\vec{A}}$$

# Hertz'scher Dipol: Felder aus $\vec{\underline{A}}(\vec{r})$




$$\vec{\underline{A}}(\vec{r}) = \frac{\mu \underline{I} l}{4\pi} \vec{e}_z \frac{e^{-jkr}}{r}$$

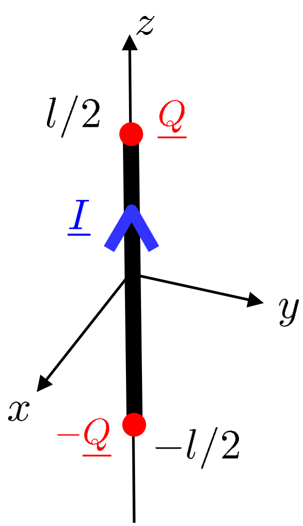
$$\underline{E}_r = \frac{\underline{I} l}{2\pi j \omega \varepsilon} \frac{e^{-jkr}}{r^3} (1 + jkr) \cos\theta$$

$$\underline{E}_\theta = \frac{\underline{I} l}{4\pi j \omega \varepsilon} \frac{e^{-jkr}}{r^3} (1 + jkr - k^2 r^2) \sin\theta$$

$$\underline{H}_\phi = \frac{\underline{I} l}{4\pi} \frac{e^{-jkr}}{r^2} (1 + jkr) \sin\theta$$

weitere Komponenten verschwinden!

# Hertz'scher Dipol: Feldverlauf




Dipolmoment $\underline{p} := -\frac{\underline{I}l}{4\pi j\omega\varepsilon} = -\frac{\underline{I}lZ_\mathrm{w}}{4\pi jk}$

$$\underline{E}_r = -2\underline{p}\frac{e^{-jkr}}{r^3}(1 + jkr)\cos\theta$$

$$\underline{E}_\theta = -\underline{p}\frac{e^{-jkr}}{r^3}(1 + jkr - k^2r^2)\sin\theta$$

$$\underline{H}_\phi = -\underline{p}\frac{jk}{Z_\mathrm{w}}\frac{e^{-jkr}}{r^2}(1 + jkr)\sin\theta$$

# Hertz'scher Dipol: Nahfeld

$kr \ll 1$

$$\underline{E}_r = -2\underline{p}\frac{e^{-jkr}}{r^3}(1+jkr)\cos\theta \qquad = -2\frac{\underline{p}}{r^3}\cos\theta$$

Elektrisches Feld dominiert!

$$\underline{E}_\theta = -\underline{p}\frac{e^{-jkr}}{r^3}(1+jkr-k^2r^2)\sin\theta \qquad = -\frac{\underline{p}}{r^3}\sin\theta$$

$$\underline{H}_\phi = -\underline{p}\frac{jk}{Z_\mathrm{w}}\frac{e^{-jkr}}{r^2}(1+jkr)\sin\theta \qquad = -\underline{p}\frac{jk}{Z_\mathrm{w}}\frac{1}{r^2}\sin\theta$$

90º phasenverschoben

"keine" radiale Leistung im Mittel?! $\Re\underline{\underline{\vec{S}}} = \frac{1}{2}\Re(\underline{\vec{E}}\times\underline{\vec{H}}^*)$

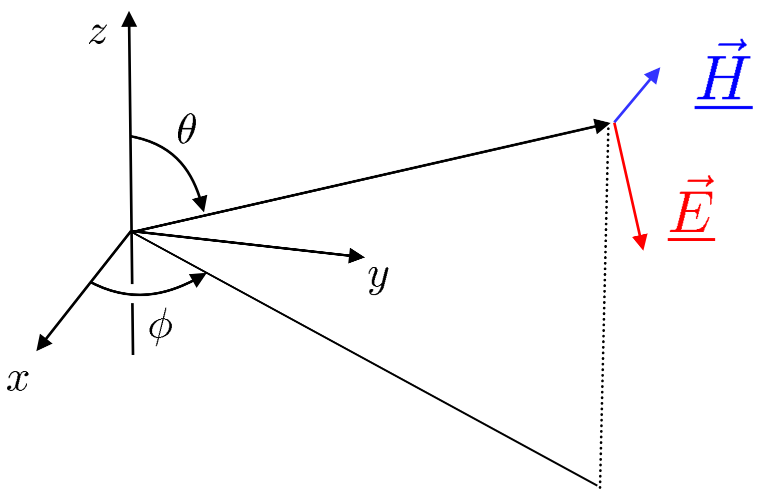
# Hertz'scher Dipol: Fernfeld

$$kr \gg 1$$

$$\underline{E}_r = -2\underline{p}\frac{e^{-jkr}}{r^3}(1 + jkr)\cos\theta \qquad = \underline{0}$$

$$\underline{E}_\theta = -\underline{p}\frac{e^{-jkr}}{r^3}(1 + jkr - k^2r^2)\sin\theta \quad = \underline{p}k^2\frac{e^{-jkr}}{r}\sin\theta$$

$$\underline{H}_\phi = -\underline{p}\frac{jk}{Z_\mathrm{w}}\frac{e^{-jkr}}{r^2}(1 + jkr)\sin\theta \qquad = \underline{p}\frac{k^2}{Z_\mathrm{w}}\frac{e^{-jkr}}{r}\sin\theta = \frac{1}{Z_\mathrm{w}}\underline{E}_\theta$$




Ebene Welle in radialer Richtung!

# Hertz'scher Dipol: Strahldichte

$$\underline{E}_\theta = \underline{p} k^2 \frac{e^{-jkr}}{r} \sin\theta$$

$$\underline{p} := -\frac{\underline{I} l}{4\pi j \omega \varepsilon} = -\frac{\underline{I} l Z_\mathrm{w}}{4\pi j k}$$

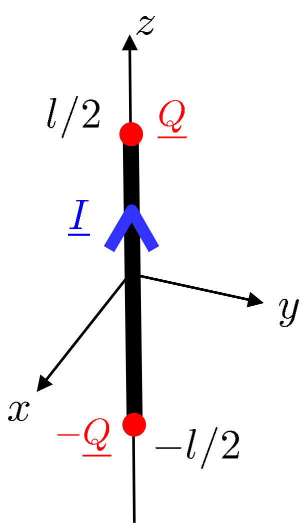
$$\underline{H}_\phi = \underline{p} \frac{k^2}{Z_\mathrm{w}} \frac{e^{-jkr}}{r} \sin\theta = \frac{1}{Z_\mathrm{w}} \underline{E}_\theta$$

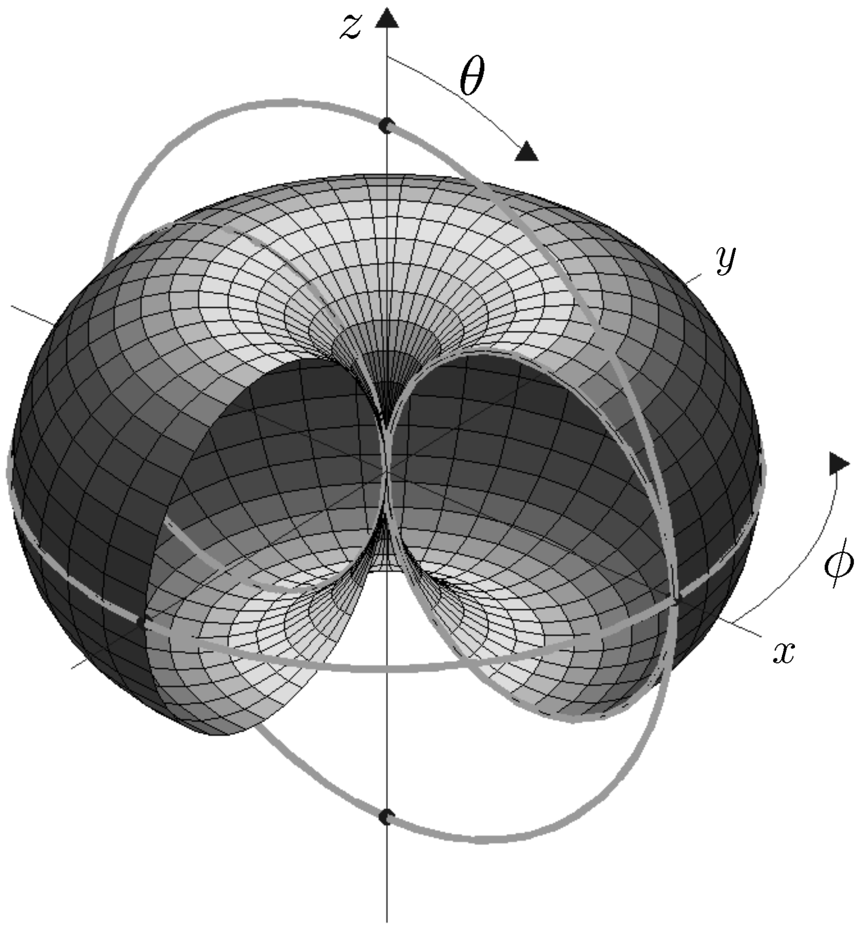
$$\boxed{S = \frac{|\underline{I}|^2 Z_\mathrm{w}}{8} \left(\frac{l}{\lambda}\right)^2 \sin^2\theta}$$

Nur für $\frac{l}{\lambda} \ll 1$

$$S = r^2 \frac{1}{2} \Re\left\{\vec{\underline{E}} \times \vec{\underline{H}}^*\right\} \cdot \vec{e}_r = \frac{r^2}{2} \Re\left\{\underline{E}_\theta \underline{H}_\phi^*\right\} = \frac{|\underline{p}|^2 k^4}{2 Z_\mathrm{w}} \sin^2\theta$$

# Hertz'scher Dipol: Strahlungsdiagramm




$$\boxed{S = \frac{|\underline{I}|^2 Z_{\mathrm{w}}}{8} \left(\frac{l}{\lambda}\right)^2 \sin^2\theta}$$

# Hertz'scher Dipol: Abgestrahlte Leistung

$$\underline{E}_\theta = \underline{p} k^2 \frac{e^{-jkr}}{r} \sin\theta$$

$$\underline{H}_\phi = \frac{1}{Z_\mathrm{w}} \underline{E}_\theta$$

$$\boxed{S = \frac{|\underline{I}|^2 Z_\mathrm{w}}{8} \left(\frac{l}{\lambda}\right)^2 \sin^2\theta}$$

$$S_\mathrm{av} = \frac{P_\mathrm{rad}}{4\pi} = \frac{|\underline{I}|^2 Z_\mathrm{w}}{12} \left(\frac{l}{\lambda}\right)^2$$

Abgestrahlte Leistung

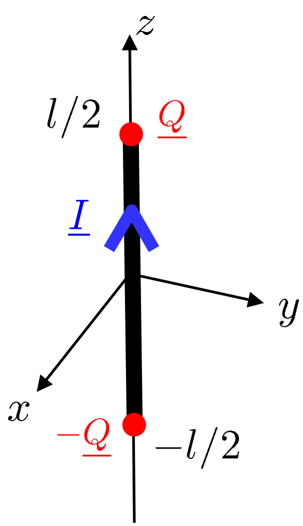
$$P_\mathrm{rad} = \int_0^\pi \int_0^{2\pi} S(\theta)\, d\phi \, \sin\theta \, d\theta = \frac{|\underline{I}|^2 Z_\mathrm{w} \pi}{3} \left(\frac{l}{\lambda}\right)^2$$

$$\int_0^\pi \sin^3\theta \, d\theta = \frac{4}{3}$$

$$\boxed{D = \frac{S_\mathrm{max}}{S_\mathrm{av}} = \frac{3}{2}}$$

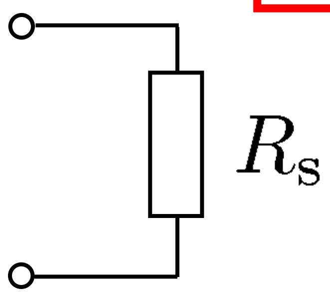
Richtfaktor ("*directivity*")

# Hertz'scher Dipol: Strahlungswiderstand




$$P_{\mathrm{rad}} = \frac{|\underline{I}|^2 Z_{\mathrm{w}} \pi}{3} \left( \frac{l}{\lambda} \right)^2 = \frac{|\underline{I}|^2}{2} R_{\mathrm{s}}$$

$$\boxed{R_{\mathrm{s}} = Z_{\mathrm{w}} \frac{2\pi}{3} \left( \frac{l}{\lambda} \right)^2}$$




Sehr viel kleiner als die Wellenimpedanz des Raumes!

# Hertz'scher Dipol

## E-Feld: Pfeile

## H-Feld: Dreiecke