EMF 2 Großübung

Dominik Hölscher
Mitschrift: Marius Geis

5. August 2013

Inhaltsverzeichnis

Allgemeines: Leistungsanpassung, Reflektionsfaktoren

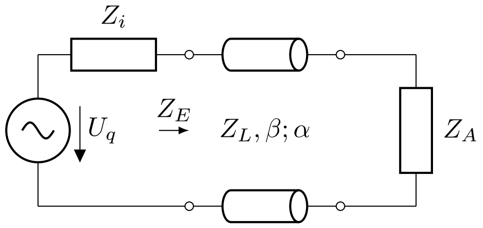
Termin 1: 3.4.2012

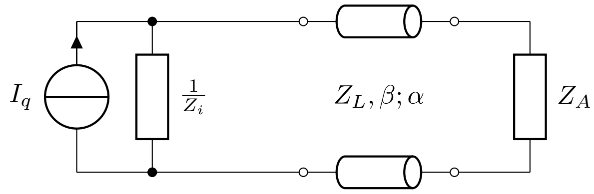
Übung	Di, 14.00 Uhr (ab. 03.04.2012)	FT	(Dominik Hölscher)
Rechenübung	Di, 16.00 (ab 10.04.2012)	FT	(div. Mitarbeiter)
Vorträge Praxissemester	Di, 15.00	FT103	
EMV/EMVU	Mi, 08.15 - 11.30 Uhr (14-tägig) (ab 11.04.2012)	FT103	

KGÜ:

1) Di, 10.00 Uhr (FT103)
2) Do, 9.00 Uhr (FT103)
3) ~~Di 17.30 Uhr (FT103) /~~ Do 13.00 Uhr (FT103)

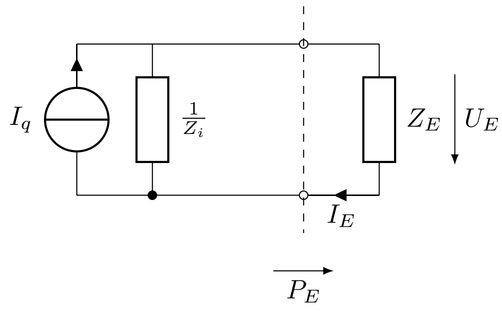
Klausur:
Skript erlaubt, mit eigenen Kommentaren, eigenen Zusammenfassungen, eigene Formelsammlung, mit Heftstreichen o.Ä. zusammengehalten. Nicht erlaubt: Übungen / Klausuraufgaben und deren Lösungen.





Äquivalent mit $U_q = I_q \cdot Z_i$. Aufpassen: Angegeben an Quellen sind immer Spitzenwerte. Alle angegebenen Größen sind komplexe Phasoren.

Vereinfacht:



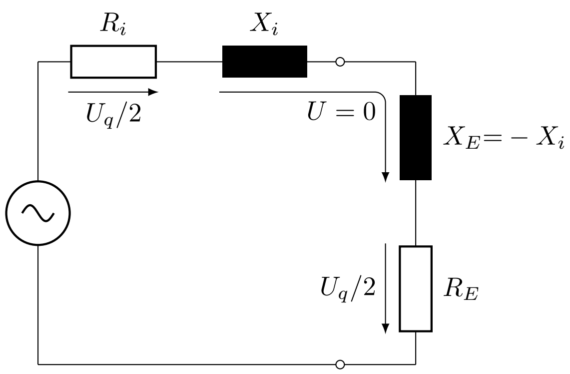
$$
\begin{aligned}
P_E &= \frac{1}{2}\,\mathrm{Re}\{U_E \cdot I_E^*\} \\
&= \frac{1}{2}\,\mathrm{Re}\left\{U_E \cdot \frac{U_E^*}{Z_E^*}\right\} \\
&= \frac{|U_E|^2}{2}\,\mathrm{Re}\left\{\frac{1}{Z_E^*}\right\} \\
U_E &= U_q \cdot \frac{Z_E}{Z_E + Z_i} \\
P_E &= \frac{|U_q|^2}{2} \cdot \frac{|Z_E|^2}{|Z_E + Z_i|^2} \cdot \mathrm{Re}\left\{\frac{Z_E}{Z_E^* \cdot Z_E}\right\} \\
&= \frac{|U_q|^2}{2|Z_E + Z_i|^2} \cdot \mathrm{Re}\{Z_E\}
\end{aligned}
$$

Falls $Z_E = Z_i$ $(= R_i + jX_i)$:

$$P_E = \frac{|U_q|^2}{2 \cdot |2Z_i|^2} \cdot R_i$$

Falls $\boxed{Z_E = Z_i^*}$

$$\boxed{P_E = \frac{|U_q|^2 \cdot R_i}{2 \cdot |2R_i|^2} = \frac{|U_q|^2}{8R_i}}$$



Leistungsanpassung (maximale verfügbare Leistung)

$$P_{\text{verf}} = \frac{|U_q|^2}{8\,\text{Re}\{Z_i\}}$$

Termin 2: 10.4.2012

$$P = \frac{|U_q|^2 \cdot |Z_E|^2}{2 \cdot |Z_i + Z_E|^2} \cdot \text{Re}\left\{\frac{Z_E}{Z_E \cdot Z_E^*}\right\} = \frac{|U_q|^2 \cdot \text{Re}\{Z_E\}}{2 \cdot |Z_i + Z_E|^2}$$

$$P_{\text{verf}} = \frac{|U_q|^2}{8 \cdot \text{Re}\{Z_i\}}$$

$$P = \frac{|U_q|^2}{8 \cdot \text{Re}\{Z_i\}} \cdot \frac{8 \cdot \text{Re}\{Z_i\} \cdot \text{Re}\{Z_E\}}{2 \cdot |Z_i + Z_E|^2} = P_{\text{verf}} \cdot \frac{4 \cdot R_i \cdot R_E}{|Z_i + Z_E|^2}$$

$$= P_{\text{verf}} \cdot \frac{|Z_i + Z_E|^2 - \left[|Z_i + Z_E|^2 - 4 \cdot R_i \cdot R_E\right]}{|Z_i + Z_E|^2}$$

$$= P_{\text{verf}} \cdot \left[1 - \frac{(R_i + R_E)^2 - 4 \cdot R_i \cdot R_E + (X_i + X_E)^2}{|Z_i + Z_E|^2}\right]$$

$$\boxed{\begin{aligned}(R_i + R_E)^2 - 4 \cdot R_i \cdot R_E &= R_i^2 + 2 \cdot R_i \cdot R_E + R_E^2 - 4 \cdot R_i \cdot R_E \\ &= (R_E - R_i)^2\end{aligned}}$$

$$= P_{\text{verf}} \cdot \left[1 - \frac{(R_E - R_i)^2 + (X_E + X_i)^2}{|Z_i + Z_E|^2}\right]$$

$$= P_{\text{verf}} \cdot \left[1 - \left|\frac{Z_E - Z_i^*}{Z_E + Z_i}\right|^2\right]$$

Leistungs-Anpassung wenn $Z_E = Z_i^*$

$$= P_{\text{verf}} \cdot \left[1 - |r_0|^2\right]$$

Eingangsreflektionsfaktor

$$r_0 = \frac{Z_E - Z_i^*}{Z_E + Z_i}$$

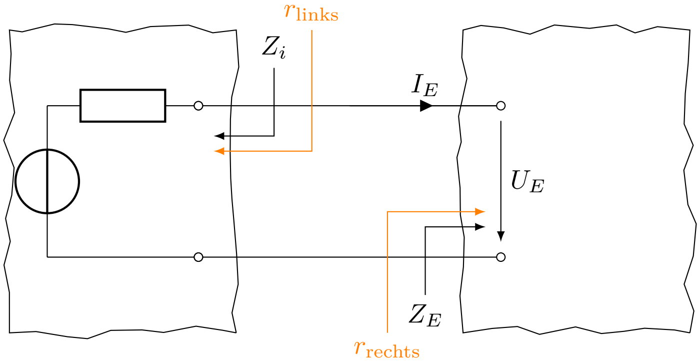
Wenn $Z_i = R_i$ (reell)

$$\Rightarrow r_0 = \frac{Z_E - R_i}{Z_E + R_i}$$

Bei jeder linearer Schaltung definierbar: $Z_E = \frac{U_E}{I_E}$ (Eingangsimpedanz in die Last hinein)

R_i: Innenimpedanz der Ersatzquelle (ET1)

Mit Normierungswiderstand R_N (häufig Z_L):



$$r_{\text{rechts}} = \frac{Z_E - R_N}{Z_E + R_N}$$
$$r_{\text{links}} = \frac{Z_i - R_N}{Z_i + R_N}$$
$$\boxed{r_{\text{rechts}} = r^*_{\text{links}}} \text{ (Anpassung)}$$

Zusammenfassung:
Eingangsreflektionsfaktor:

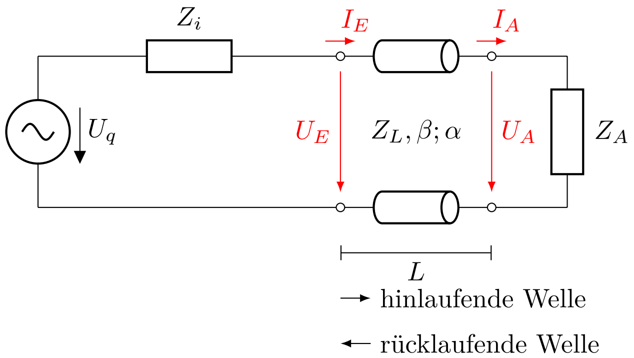
$$r_0 = \frac{Z_E - Z_i^*}{Z_E + Z_i}$$

Anpassungsbedingung:

$$Z_E = Z_i^* \qquad r_{\text{links}} = r^*_{\text{rechts}}$$

üblich: Normierungswiderstand

$$Z_i = R_i = R_N$$

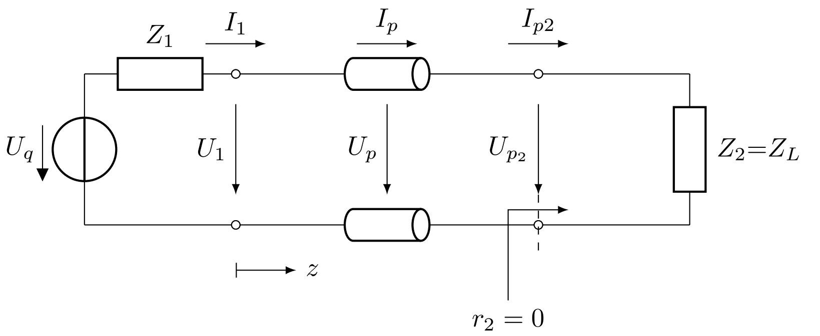


$$Z_E = \frac{U_E}{I_E} = \frac{U_{E_p} + U_{E_r}}{I_{E_p} + I_{E_r}}$$
$$Z_A = \frac{U_A}{I_A} = \frac{U_{A_p} + U_{A_r}}{I_{A_p} + I_{A_r}}$$
$$Z_L = \frac{U_{E_p}}{I_{E_p}}$$
$$-Z_L = \frac{U_{E_r}}{I_{E_r}}$$
$$r_A = \frac{U_{A_r}}{U_{A_p}} = -\frac{I_{A_r}}{I_{A_p}}$$

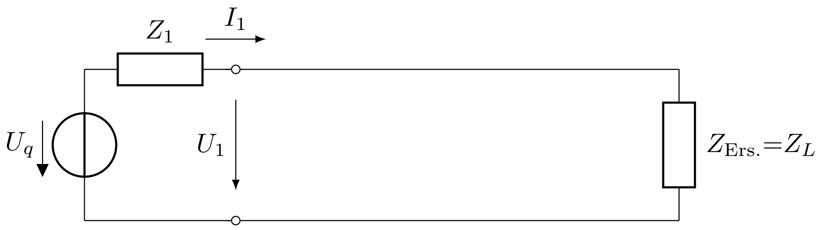
Aufgabe 1

Termin 3: 17.4.2012

1.1.1 Voraussetzung: $Z_2 = Z_L$



ESB:



$$\frac{U_p}{I_p} = \frac{U_{p_2}}{I_{p_2}} = Z_L$$

$$\left.\begin{array}{rcl} U_r(z) & = & 0 \\ I_r(z) & = & 0 \end{array}\right\} \Rightarrow \text{keine rücklaufende Welle}$$

Weil damit auch

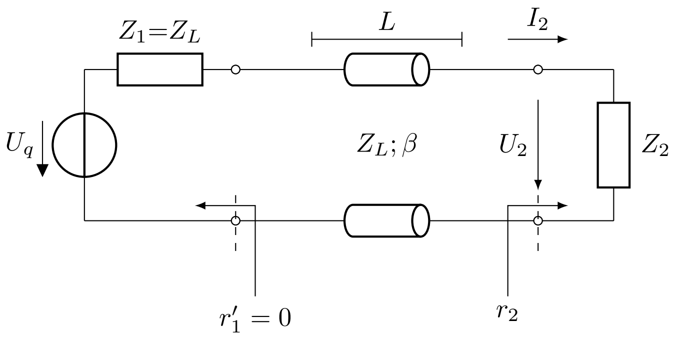
$$U_{1r} = U_r(z=0) = 0$$
$$I_{1r} = I_r(z=0) = 0$$

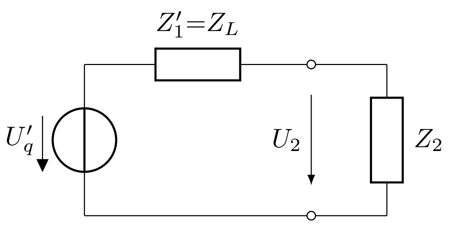
gilt:

$$\left.\begin{array}{rcl} U_1 & = & U_{1p} + 0 \\ I_1 & = & I_{1p} + 0 \end{array}\right\} \Rightarrow \frac{U_1}{I_1} = \frac{U_{1p}}{I_{1p}} = Z_L \Rightarrow Z_{\text{Ers}} = Z_L$$

$$U_1 = U_q \cdot \frac{Z_L}{Z_1 + Z_L}$$

1.1.2





$$Z_2 = \frac{U_2}{I_2} = \frac{U_{2p} + U_{2r}}{I_{2p} + I_{2r}}$$

rücklaufende Welle

$$U_{2r} = r_2 \cdot U_{2p}$$

hinlaufende Welle

$$U_{1p} = U_{\text{gen}} + r_1' \cdot U_{1r}$$

$U_{\text{gen}} =?$

$$\begin{aligned} U_{1p} &= U_{\text{gen}} + \cancel{r_1'}^{\,0} \cdot U_{1r} \\ U_1 &= U_{1p} + U_{1r} \\ &= \frac{U_q}{2} + U_{1r} \end{aligned}$$

Allgemein:

$$U_{\text{gen}} = \frac{Z_L}{Z_L + Z_1} \cdot U_q$$

Termin 4: 24.4.2012

Achtung: Zählpfeil von r_1 ist r_1' entgegengesetzt

1.1.2 Skizze 1

$$\left.\begin{array}{lcl} U_{1p} &=& U_{1,Gen} + r_1' \cdot U_{1r} \\ U_{2r} &=& r_2 \cdot U_{2p} \\ U_{2p} &=& e^{-\mathrm{j}\beta L} \cdot U_{1p} \\ U_{1r} &=& e^{-\mathrm{j}\beta L} \cdot U_{2r} \end{array}\right\} \text{1.1.3 und 1.1.4}$$

hier: $Z_1 = Z_L \Rightarrow r_1' = 0$

$$\begin{aligned} U_1 &= U_{1p} + U_{1r} = U_{\text{Gen}} + r_1' U_{1r} + U_{1r} \\ U_2 &= U_{2p} + U_{2r} = U_{2p} \cdot (1 + r_2) \\ U_{2p} &= e^{-\mathrm{j}\beta L} \cdot \underbrace{U_{1\text{Gen}}}_{=U_q/2} = \underbrace{e^{-j\beta L} \cdot \frac{U_q}{2}}_{=U_q'/2} \\ U_q' &= U_q \cdot e^{-\mathrm{j}\beta L} \\ U_2 &= \frac{U_q}{2} \cdot e^{-\mathrm{j}\beta L}(1 + r_2) \end{aligned}$$

1.1.5 Einführung: Infinitesimal kurzes Leitungsstück im ESB

$$\begin{aligned} \frac{U_2}{\frac{1}{2}U_q} &=? \\ U_2 &= U_{2p} + U_{2r} = U_{2p} \cdot (1 + r_2) \\ U_{2p} &= e^{-\mathrm{j}\beta L} \cdot U_{1p} = e^{-\mathrm{j}\beta L} \cdot \left(U_q \cdot \frac{Z_L}{Z_1 + Z_L} + r_1' \cdot U_{1r} \right) \\ U_{1r} &= e^{-\mathrm{j}\beta L} \cdot U_{2r} = e^{-\mathrm{j}\beta L} \cdot r_2 \cdot U_{2p} \\ U_{2p} &= e^{-\mathrm{j}\beta L} \cdot \left(U_q \cdot \frac{Z_L}{Z_1 + Z_L} + r_1' \cdot r_2 \cdot e^{-\mathrm{j}\beta L} \cdot U_{2p} \right) \end{aligned}$$

$$
\begin{aligned}
&= U_q \cdot \frac{Z_L}{Z_1 + Z_L} e^{-\mathrm{j}\beta L} + r_1' r_2 e^{-2\mathrm{j}\beta L} \cdot U_{2p} \\
\Rightarrow U_{2p} &= U_q \cdot \underbrace{\frac{Z_L}{Z_L + Z_1}}_{=\frac{1}{2}\frac{Z_1+Z_L-(Z_1-Z_L)}{Z_1+Z_L}=\frac{1}{2}(1-r')} \cdot \frac{1}{1 - r_1' r_2 e^{-2\mathrm{j}\beta L}} \\
\Rightarrow \frac{U_2}{\frac{1}{2}U_q} &= \frac{(1-r_1')(1+r_2)e^{-\mathrm{j}\beta L}}{1 - r_1' r_2 e^{-2\mathrm{j}\beta L}}
\end{aligned}
$$

1.2.1

$$
\begin{aligned}
P_2 &= \frac{|U_2|^2}{2} \cdot \mathrm{Re}\left\{\frac{1}{Z_2*}\right\} \\
P_\text{verf} &= \frac{|U_q|^2}{8 \cdot \mathrm{Re}\{Z_1\}} \\
\left|\frac{U_2}{\frac{1}{2}U_q}\right|^2 &= \frac{|1-r_1'|^2 |1+r_2|^2}{|1 - r_1' r_2 e^{-2\mathrm{j}\beta L}|^2} \\
\frac{P_2}{P_\text{verf}} &= \frac{|U_2|^2}{2} \cdot \frac{8}{|U_q|^2} \cdot \mathrm{Re}\left\{\frac{1}{Z_2^*}\right\} \cdot \mathrm{Re}\{Z_1\} \\
&= \frac{|U_2|^2}{\left|\frac{1}{2}U_q\right|^2} \cdot \mathrm{Re}\left\{\frac{1}{Z_2^*}\right\} \cdot \mathrm{Re}\{Z_1\} \\
\text{Zähler} &= |1-r_1'|^2 \cdot |1+r_2|^2 \cdot \mathrm{Re}\left\{\frac{1}{Z_2^*}\right\} \cdot Z_L \cdot \frac{\mathrm{Re}\{Z_1\}}{Z_L} \\
|1-r_1'|^2 \cdot \mathrm{Re}\left\{\frac{Z_1}{Z_L}\right\} &= \left|1 - \frac{Z_1 - Z_L}{Z_1 + Z_L}\right|^2 \cdot \mathrm{Re}\left\{\frac{Z_1}{Z_L}\right\} \\
&= \left|\frac{2Z_L}{Z_1 + Z_L}\right|^2 \cdot \mathrm{Re}\left\{\frac{Z_1}{Z_L}\right\} \\
&= \frac{4\,\mathrm{Re}\{Z_L \cdot Z_1\}}{|Z_1 + Z_L|^2} \qquad (*) \\
1 - |r_1'|^2 &= 1 - \left|\frac{Z_1 - Z_L}{Z_1 + Z_L}\right|^2 \\
&= \frac{|Z_1 + Z_L|^2 - |Z_1 - Z_L|^2}{|Z_1 + Z_L|^2} \\
&= \frac{\cancel{|Z_1|^2} + \cancel{Z_L^2} + 4\,\mathrm{Re}\{Z_1 Z_L\}}{|Z_1 + Z_L|^2} \text{ vgl. } (*)
\end{aligned}
$$

1.2.2

$$
\begin{aligned}
P_{2,\min} &= \frac{(1-|r_1'|^2)(1-|r_2|^2)}{(1+|r_1' r_2|)^2} \cdot P_\text{verf} \\
\text{Nenner} &= \left|1 - |r_1'| \cdot e^{\mathrm{j}\,\mathrm{arc}\{r_1'\}} \cdot |r_2| \cdot e^{\mathrm{j}\,\mathrm{arc}\{r_2\}} \cdot e^{-\mathrm{j}2\beta L}\right|^2 \\
P_{2,\max} &= \frac{(1-|r_1'|^2)(1-|r_2|^2)}{(1-|r_1' r_2|)^2} \cdot P_\text{verf}
\end{aligned}
$$

1.2.3 $\dfrac{P_{2,\max}}{P_{2,\min}} = \left(\dfrac{1+|r_1' r_2|}{1-|r_1' r_2|}\right)^2$

Termin 5: 8.5.2012

Zu 1.2.3:

Beispiel: Quelle $|r_1'| \approx 0{,}5$, Spektrumanalystor $|r_2| \approx 0{,}2$

Damit

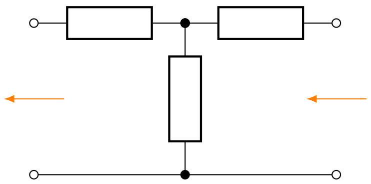
$$
\begin{aligned}
|r_1'||r_2| &= 0{,}1 \\
V &= \frac{1{,}1}{0{,}9} \approx 1{,}2^2 \approx 1{,}4
\end{aligned}
$$

1.3.1 Ziel: $|r_1''| \overset{!}{\leq} |r_1'|$

z.B.

$$\begin{aligned} |r_1''| &= 0{,}02 \\ \Rightarrow |r_2| \cdot |r_1''| &= 0{,}01 \\ V &= \left(\frac{1{,}01}{0{,}99}\right)^2 = |1{,}02|^2 \approx 1{,}04 \end{aligned}$$

1.3.2

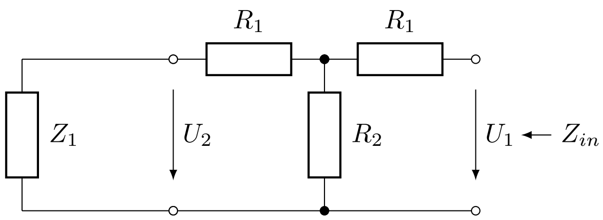


z.B. 10 dB Dämpfungsglied

1) Für $|r_1'| = 0 \Rightarrow |r_1''| = 0$

2) $|r_1''| = 10^{-\frac{a}{10\,\mathrm{dB}}} \cdot |r_1'|$

Ausblick: HF-Technik



1) $Z_1 = Z_L \Rightarrow Z_{in} = Z_L$

2) $\left|\frac{U_2}{U_1}\right|^2 = 10^{-\frac{a}{10\,\mathrm{dB}}}$ für $Z_1 = Z_L$

1.3.3
- EMV-Messtechnik
- Breitband-Messtechnik

Aufgabe 2

2.1.1 $P_2(f_2) = 0$

$P_1(f_2) = 0$

$$P_1(f_1) = \frac{U_{q1}^2}{8R_i}$$

$P_2(f_1) = P_1(f_1)$

2.1.2 $Z_1(f_1) = R_i$

$Z_1(f_2) = R_1 + jX_1$ mit $R_1 = 0$ und X_1 beliebig

$|r_1(f_1)| = 0$ (Bezugswiderstand R_i)

$|r_1(f_2)| = 1$

Termin 6: 22.5.2012

2.2.1 $\frac{L_1}{\lambda_2} = \frac{1}{2}$

2.2.2 $$\frac{L_1}{\lambda_1} = \frac{L_1}{\lambda_2} \cdot \frac{\lambda_1}{\lambda_2} = \frac{L_1}{\lambda_2} \cdot \frac{f_1}{f_2} = \frac{1}{4}$$

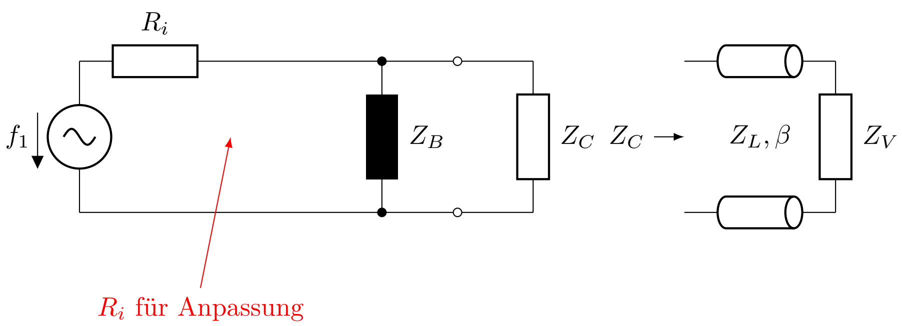
$Z_A(f_1) = 0$

$Z_A(f_2) \to \infty$

$r_A(f_1) = -1$

$$r_A(f_2) = \frac{Z_A - R_N}{Z_A + R_N} = +1$$

2.2.3



$$Z_B = -\mathrm{j} Z_L \cdot \cot(\beta L_2) \Rightarrow \frac{1}{Z_B} \cdot Z_L = +j\tan(\beta L_2)$$

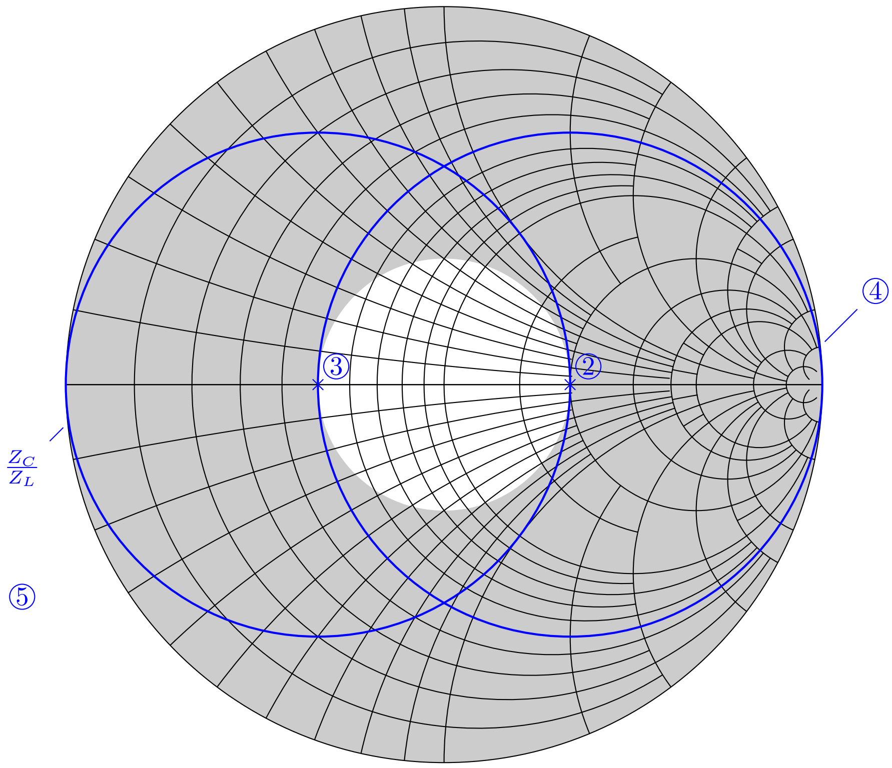
(1) $R_N = Z_L$

(2) $\frac{R_i}{R_N} = 2$

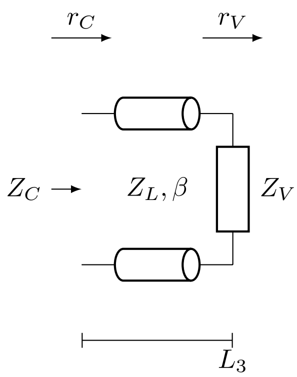
(3) $Z \mapsto Y$

(4) $Y_C \cdot R_N = \frac{1}{R_i} \cdot R_N - \frac{1}{Z_B} \cdot R_N = \frac{1}{Z_C} R_N$

(5) $Y \mapsto Z$



2.2.4



$$r_V = r_C \cdot e^{+2\mathrm{j}\beta L_2}$$

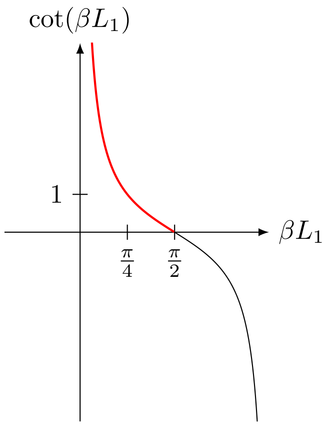
2.2.5 $\frac{1}{3} \leq |r_3| < 1$

2.3.1
$$\frac{L_2}{\lambda_2} = \frac{1}{4}, Z_B(f_2) = 0, r_B(f_2) = -1$$
$$\frac{L_2}{\lambda_1} = \frac{1}{8}$$
$$\frac{Z_B(f_1)}{Z_L} = -\mathrm{j}$$
$$r_B(f_1) = -\mathrm{j}$$

Termin 7: 5.6.2012

2.3 $0 \leq \dfrac{L_1}{\lambda} \leq \dfrac{1}{4}$

$$Z_A = -\mathrm{j} Z_L \cot(\beta L_1)$$



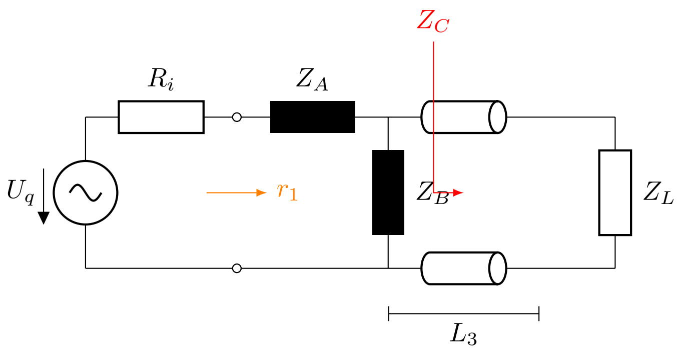
2.3.1 $Z_B \overset{!}{=} 0$

$$L_2 = \frac{\lambda_2}{4}$$

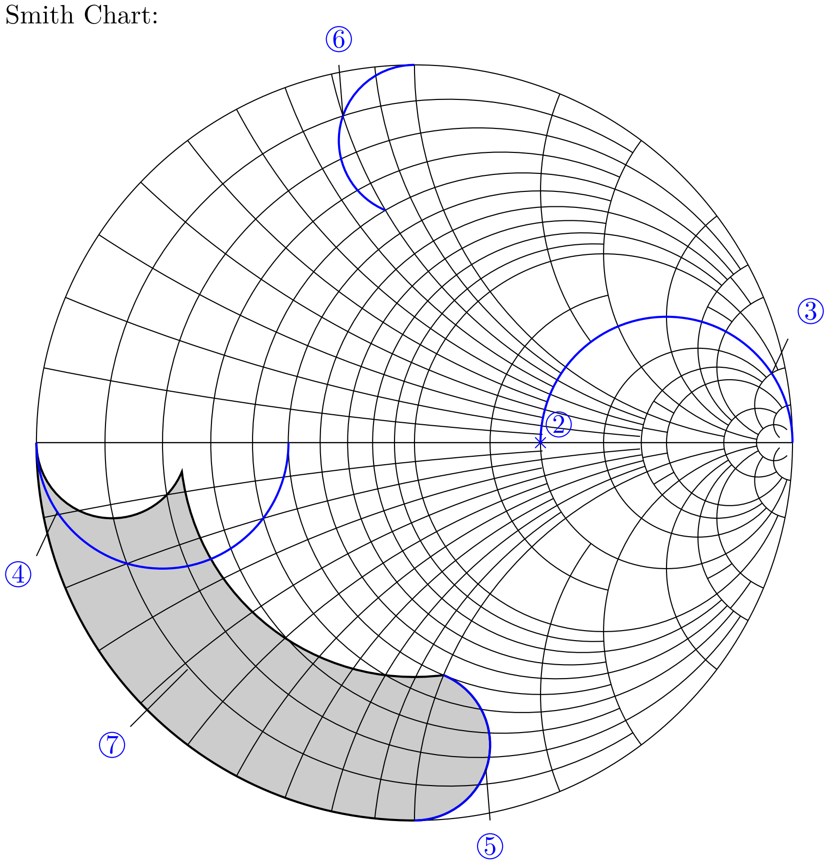
2.3.2

$$\begin{aligned} L_2 &= \frac{\lambda_1}{8} \\ Z_B &= -\mathrm{j} Z_L \cot(\beta_1 L_2) = -\mathrm{j} Z_L \\ Z_B(f_2) &= 0 \\ r_B(f_1) &= -\mathrm{j} \\ r_B(f_2) &= -1 \end{aligned}$$

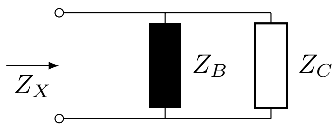
2.3.3 f_1:



Smith Chart:



1) $R_i = R_N$
2) Anpassungsbedingung an den Generatorklemmen!
   $\frac{R_i}{Z_L}$ eintragen
3) $\frac{Z_A}{Z_L}$ abziehen
4) $Z \mapsto Y \ (Y_A \cdot R_N)$
5)



$$\frac{1}{Z_C} \cdot R_N = Y_X \cdot R_N - \underbrace{\frac{1}{Z_B} \cdot R_N}_{+\mathrm{j}}$$
$$= Y_X \cdot R_N - \mathrm{j}$$

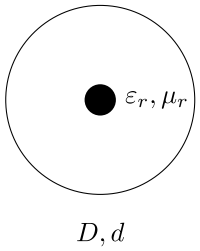
6) $Y \mapsto Z$

2.3.4 7) $r_V = r_C \cdot e^{+2\mathrm{j}\beta L_3}$

Allgemeines: TEM-Leitungen

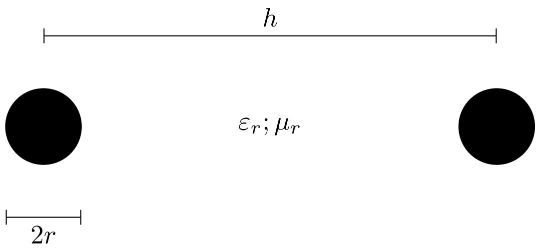
Termin 8: 12.6.2013

Koaxialleitung



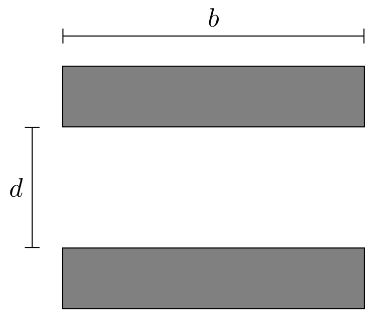
$$Z_L = \frac{Z_0}{2\pi}\sqrt{\frac{\mu_r'}{\varepsilon_r'}}\ln\left(\frac{D}{d}\right)$$

Paralleldrahtleitung



$$Z_L = \frac{Z_0}{\pi}\sqrt{\frac{\mu_r'}{\varepsilon_r'}}\ln\left(\frac{h}{r}\right)$$

Bandleitung



$$Z_L = Z_0\sqrt{\frac{\mu_r'}{\varepsilon_r'}}\cdot\frac{d}{b}$$

Mikrostreifenleitung

`Skizze mit Feldlinien`

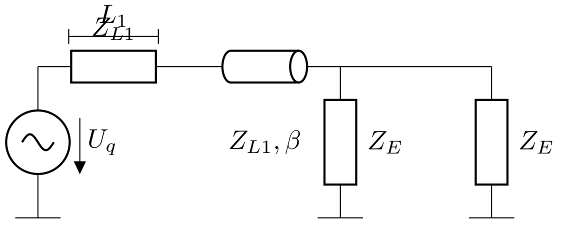
geschichtetes Dielektrikum, Substrat (ε_r) und Luft

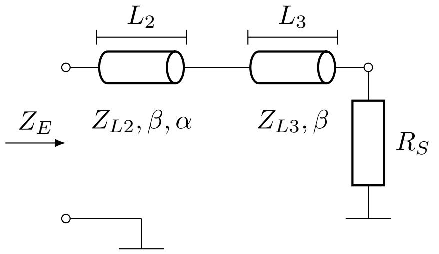
$$|E_z| \ll |E_{\text{trans}}|$$

Quasi-TEM-Wellen

Aufgabe 3

3.1.1 Einpoliges ESB.





3.1.2 $\delta = \frac{1}{\sqrt{\pi \cdot \kappa \cdot \mu \cdot f}} = 0{,}66\,\mu\text{m}$

$Z_{L1} = 50\,\Omega \Rightarrow$ Wellenanpassung bei $Z_E = 100\,\Omega$

$$Z_E = \frac{Z_{Ab} + Z_{L2}\tanh(\gamma L_2)}{1 + \frac{Z_{ab}}{Z_{L2}}\tanh(\gamma L_2)} \neq f(L_2) \text{ wenn } \boxed{Z_{Ab} = Z_{L2} = Z_E}$$

$\Rightarrow Z_{L2} = Z_{Ab} = Z_E = 100\,\Omega$

$\frac{L_3}{\lambda} = \frac{1}{4}; Z_{L3} = \sqrt{R_S \cdot Z_{Ab}}$

3.2.1 $\frac{w_1}{h} = 3{,}086 (\approx 3{,}1)$
$\Rightarrow w_1 = 5{,}09\,\text{mm}$

3.2.2 $$\frac{w_2}{h} \approx 0{,}9$$

$\Rightarrow w_2 = 1{,}485\,\text{mm}$

$$\frac{w_3}{h} \approx 0.4$$

$\Rightarrow w_3 = 0{,}66\,\text{mm}$

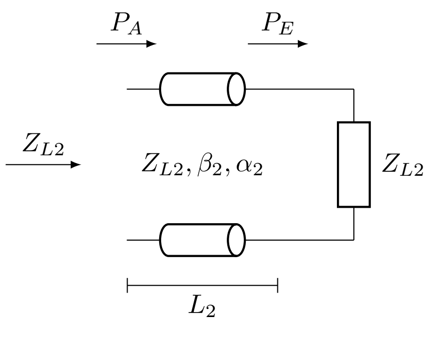
Termin 9: 19.6.2012

3.2.4 $$L_3 = \frac{\lambda_{\varepsilon_3}}{4} = \frac{1}{4} \cdot \frac{c_0}{f \cdot \sqrt{\varepsilon_{r,eff,3}(0)}} = 5{,}725\,\text{mm}$$

$$\varepsilon_{r,eff,3}(f=0) = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} F\left(\frac{w_3}{h}\right)$$
$$= 1{,}7164$$

3.2.5 $$\alpha_2 = \alpha_R + \alpha_G = \frac{1}{\kappa \cdot \delta \cdot w_2 \cdot Z_{L2}} = 0{,}176\,\frac{\text{Np}}{\text{m}} \mathrel{\hat{=}} 1{,}528\,\frac{\text{dB}}{\text{m}}$$

3.2.6



Nur hinlaufende Welle! $|U_{P_E}| = |U_{P_A}| \cdot e^{-\alpha_2 L_2}$

$$P_E = \frac{|U_{p_E}|^2}{2Z_{L2}} - \cancel{\frac{|U_{r_E}|^2}{2Z_{L2}}}$$

$$P_E = P_A \cdot \underbrace{e^{-2\alpha_2 L_2}}_{10^{-\frac{\alpha_2 \cdot L_2}{10\,\mathrm{dB}}}} = 0{,}9826$$

3.3.1 $$\varepsilon_{r,eff}(f) = \varepsilon_r + \frac{\varepsilon_{r,eff}(f=0) - \varepsilon_r}{1+p}$$

$$p \approx \left(\frac{\frac{h}{\mathrm{mm}}}{\frac{Z_L}{\Omega}}\right)^{\frac{4}{3}} \left[0{,}43 \cdot \left(\frac{f}{\mathrm{GHz}}\right)^2 - 0{,}009 \left(\frac{f}{\mathrm{GHz}}\right)^3\right]$$

$\varepsilon_{r,eff1}(f = 10\,\mathrm{GHz}) \approx 1{,}96$

$\varepsilon_{r,eff3}(f = 10\,\mathrm{GHz}) \approx 1{,}76$

`mgeis: Die Werte hier stimmen nicht.`

3.3.2 $$Z_L(f) = Z_L(0) \cdot \sqrt{\frac{\varepsilon_{r,eff}(0)}{\varepsilon_{r,eff}(f)}} \cdot \frac{\varepsilon_{r,eff}(f) - 1}{\varepsilon_{r,eff}(0) - 1} \cdot \underbrace{k(f)}_{\approx 1}$$

$\frac{Z_{L1}(f) - Z_{L1}(0)}{Z_{L1}(0)} \approx 6\,\%$

$\frac{Z_{L3}(f) - Z_{L3}(0)}{Z_{L3}(0)} \approx 4{,}4\,\%$

`Bis 3-5 Gigahertz kann man auch ohne Dispersion rechnen`

`mgeis: Die Werte hier stimmen nicht.`

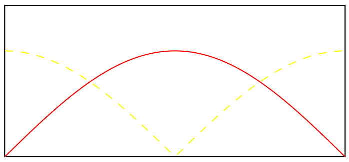
3.3.3 $\frac{L_3}{\lambda_{\varepsilon 3}} = \frac{1}{4}$ ohne Berücksichtigung der Dispersion

$$\begin{aligned}
\left.\frac{L_3}{\lambda_{\varepsilon 3}}\right|_{\mathrm{Disp.}} &= \left.\frac{L_3}{\lambda_{\varepsilon 3}}\right|_{\mathrm{o.Disp.}} \cdot \frac{\lambda_{\varepsilon 3}|_{\mathrm{o.Disp.}}}{\lambda_{\varepsilon 3}|_{\mathrm{Disp.}}} \\
&= \frac{1}{4} \cdot \frac{\frac{c_0}{f\sqrt{\varepsilon_{r,eff}(f=0}}}{\frac{c_0}{f\sqrt{\varepsilon_{r,eff}(f)}}} \\
&= \frac{1}{4} \cdot \sqrt{\frac{\varepsilon_{r,eff}(f)}{\varepsilon_{r,eff}(0)}} = \frac{1}{4} \cdot 1{,}0116
\end{aligned}$$

Aufgabe 4

Termin 10: 26.6.2012

4.1.1 a) $\frac{a}{b} = 2{,}25$

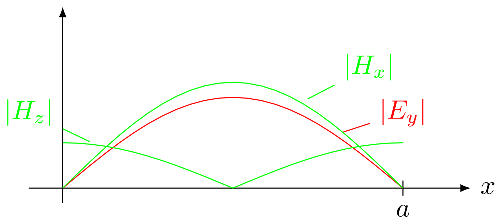


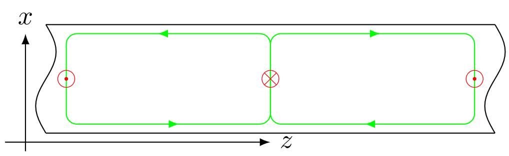
H_{10}

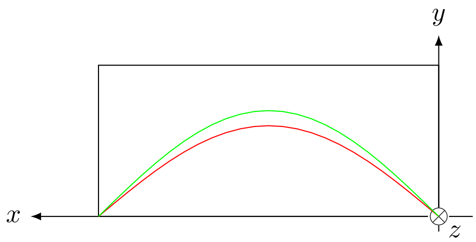
- $H_z \neq 0$, $E_z = 0$
- Feldabhängigkeit von x-Koordinate: 1 sin/cos-Halbwelle
- Keine Feldabhängigkeit in y-Richtung

X_{mn}

$$f_c = \frac{c_0}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$





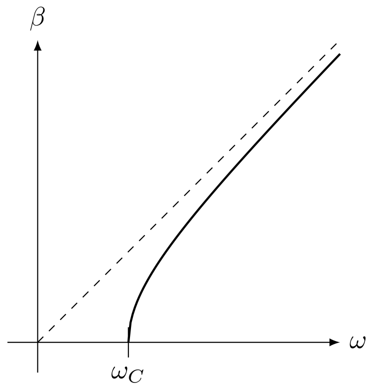


b) $\frac{a}{b} = 1$:
H_{10}, H_{01} sind Grundmoden (entartet)
Feldbilder analog zum Fall $\frac{a}{b} = 2{,}25$

4.1.2 a) $\frac{a}{b} = 2{,}25$: $f_{C,H20} = 2 \cdot f_{C,H10}$
$f_{C,H01} = 2{,}25 \cdot f_{C,H10}$
$f_{C,H11} = f_{C,E11} = 2{,}46 f_{C,H10}$ (Entartet)

Entartete Moden:

$$\beta = \frac{\omega}{c_0} \cdot \sqrt{1 - \left(\frac{f_c}{f}\right)}$$



b) $\frac{a}{b} = 1$:

- H_{11}, E_{11} $(f_{C,11} = \sqrt{2} \cdot f_{C,H10})$ (entartet)
- H_{20}, H_{02} $(f_{C,H02} = 2 \cdot f_{C,H20})$ (entartet)

4.1.3 + Verluste geringer

+ höhere Leistung

- Preis

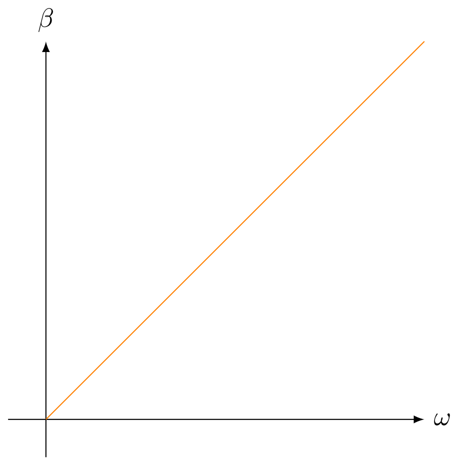
- Integrierbarkeit von Bauteilen

4.1.4 $\lambda_H = \frac{\lambda_0}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$

Mode	$\frac{f_c}{\text{GHz}}$	$\frac{\lambda_H}{\text{cm}}$
H_{10}	7,5	1,83
H_{20}	15	3,44
H_{01}	16,875	8,2
H_{11}/E_{11}	18,47	↯

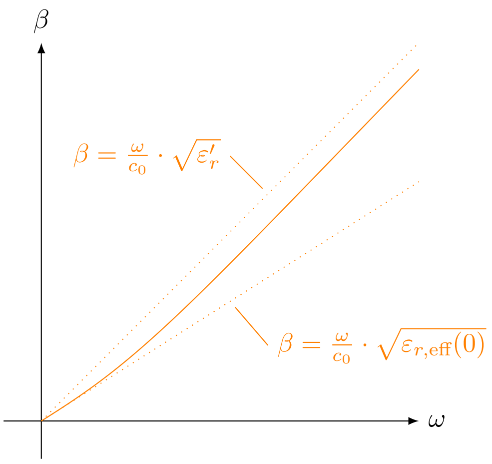
Termin 11: 3.7.2012

4.1.5 a) TEM Welle:



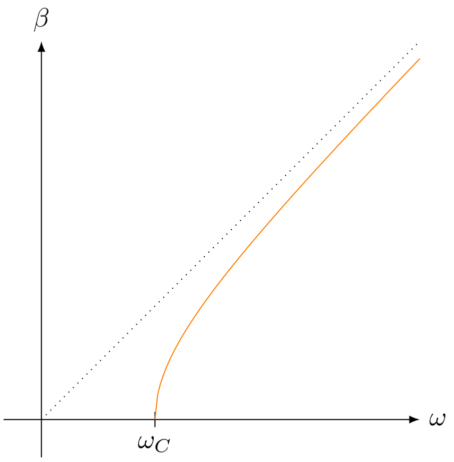
$$\beta = \frac{\omega}{c_0}\sqrt{\varepsilon_r}$$

b) Quasi-TEM-Welle (Mikrostreifenleitung):



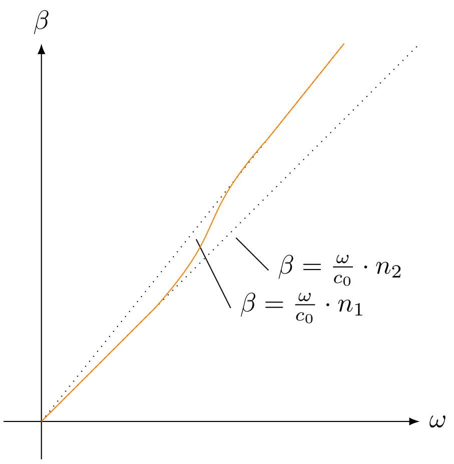
$$\beta = \frac{\omega}{c_0} \cdot \sqrt{\varepsilon_{r,\text{eff}}(f)}$$

c) H-/E-Welle (Hohlleiter):



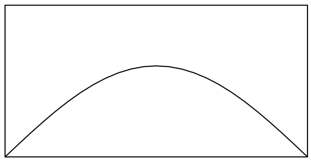
$$\beta = \frac{\omega}{c_0} \sqrt{1 - \left(\frac{f_c}{f}\right)^2}$$

d) Glasfaser:



$$\beta = \frac{\omega}{c_0} \cdot \underbrace{n_{\text{eff}}}_{\sqrt{\varepsilon_{r,\text{eff}}}}$$

e)



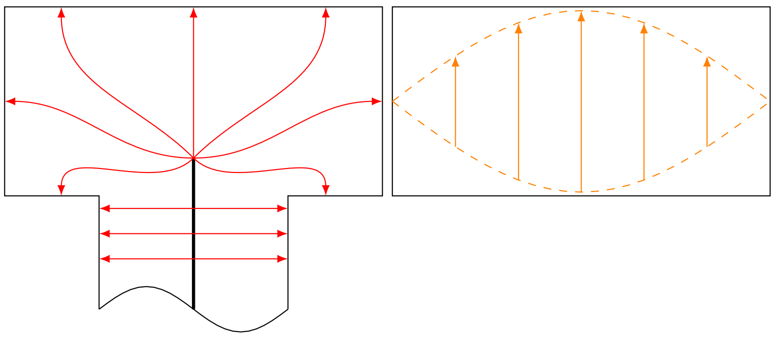
$$E_y = E_{\max} \cdot \sin\left(\pi \frac{x}{a}\right) \cdot 1$$

$$P = \frac{1}{2} \operatorname{Re} \left\{ \int\limits_A (E_y \cdot H_x^*) \, \mathrm{d}A \right\}; \qquad H_x = \frac{E_y}{Z_F^H}; Z_F^H = \frac{Z_0}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}$$

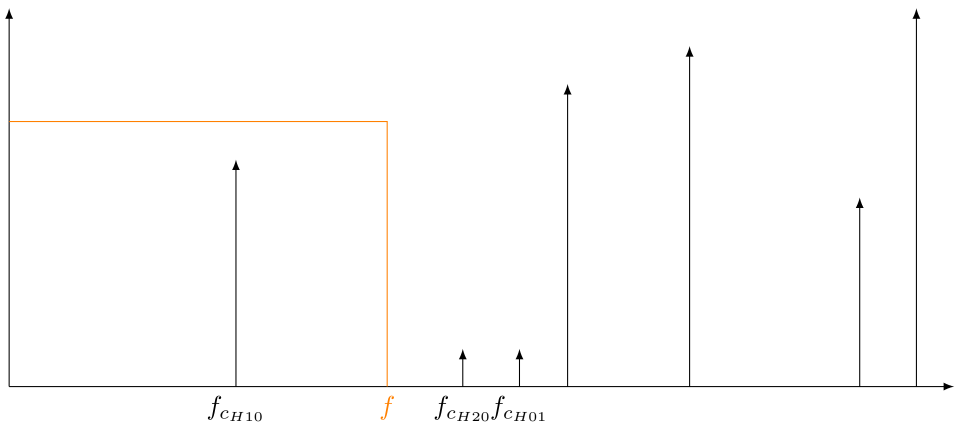
$$= \frac{1}{2} \int\limits_0^a \int\limits_0^b \left(\frac{E_y \cdot E_y^*}{Z_F^H} \right) \mathrm{d}y \, \mathrm{d}x$$

$$= \frac{E_{\max}^2}{2 Z_F^H} \cdot b \cdot \int\limits_0^a \sin^2\left(\pi \frac{x}{a}\right) \mathrm{d}x = \frac{E_{\max}^2}{4 \cdot Z_F^H} \cdot a \cdot b$$

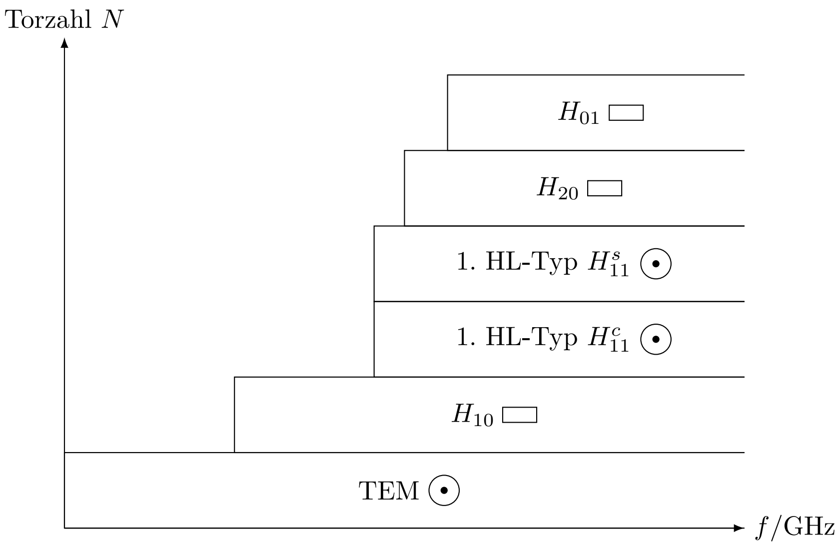
4.2.1



4.2.2



Koax	**HL**
TEM($f_c = 0$)	$H_{10}(f_c = 7{,}5\,\mathrm{GHz})$
1. HL-Typ ($f_c = 13{,}66\,\mathrm{GHz}$)	$H_{20}(f_c = 15\,\mathrm{GHz})$
2. HL-Typ ($f_c = 27{,}26\,\mathrm{GHz}$)	$H_{01}(f_c = 16{,}9\,\mathrm{GHz})$
	H_{11} / $E_{11}(f_c = 18{,}666\,\mathrm{GHz})$



Termin 12: 10.7.2012

`Probeklausur Einsicht Do 15.00 Hörsaal FT`

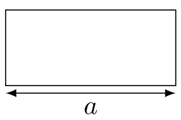
ideale Streuparameter TEM-HL-Übergang

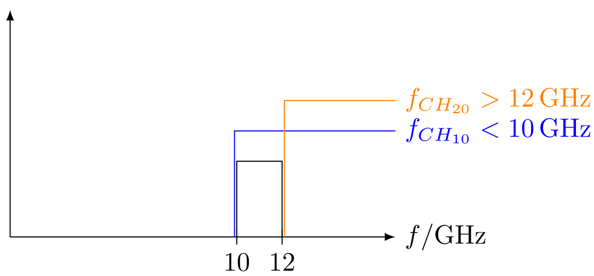
$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

4.2.3 $$\alpha = \alpha_R + \cancel{\alpha_G} = \frac{R'}{2Z_L} \overset{\text{Koax}}{=} \frac{\frac{1}{\kappa\pi\delta}\left(\frac{1}{D}+\frac{1}{d}\right)}{2\cdot\frac{Z_0}{2\pi}\cdot\ln\left(\frac{D}{d}\right)} = 0{,}0272\,\frac{\text{Np}}{\text{m}}$$

$$\alpha_{HL,H10} = \ldots = 0{,}0156\,\frac{\text{Np}}{\text{m}}$$

4.3.1





$$\begin{aligned}
\frac{c_0}{2a} &= f_{CH10} \leq 10\,\text{GHz} \\
\Rightarrow a &\geq \frac{c_0}{2f_{CH10}} = 15\,\text{mm} \\
\frac{c_0}{a} &= f_{CH20} \geq 12\,\text{GHz} \\
\Rightarrow a &\leq \frac{c_0}{12\,\text{GHz}} = 25\,\text{mm}
\end{aligned}$$

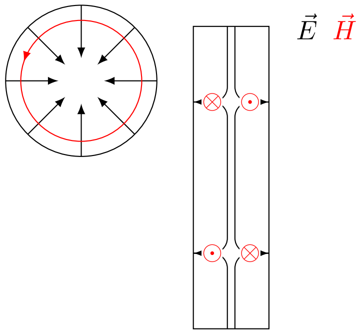
4.3.2 $H_{11}^{c,s}$ (entartet)

$m \neq 0$

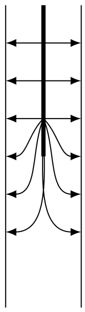
$$H_z \sim J_1\left(\eta'_{11}\frac{\rho}{R}\right)\cdot \begin{matrix}\sin(1\cdot\varphi)\\ \cos(1\cdot\varphi)\end{matrix}$$

$\Rightarrow$ φ-Abhängigkeit

4.3.3 E_{01} $(m \neq 0)$



4.3.4 Ja.



4.3.5 $f_{CE_{01}} \leq 10\,\text{GHz}$
$f_{CH_{21}} \geq 12\,\text{GHz}$

$$\boxed{\Rightarrow 1{,}148 \leq \frac{R}{\text{cm}} \leq 1{,}214}$$

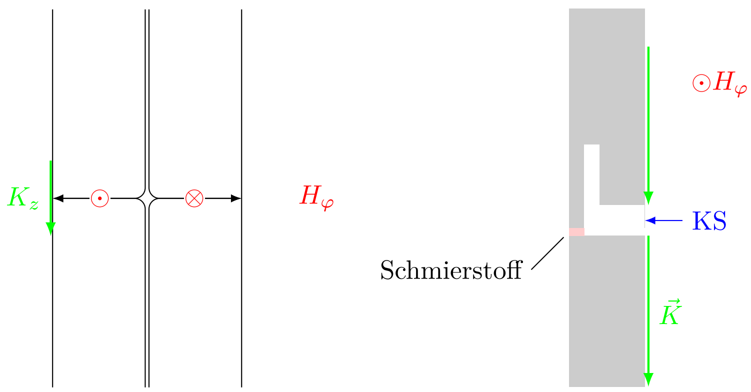
wegen

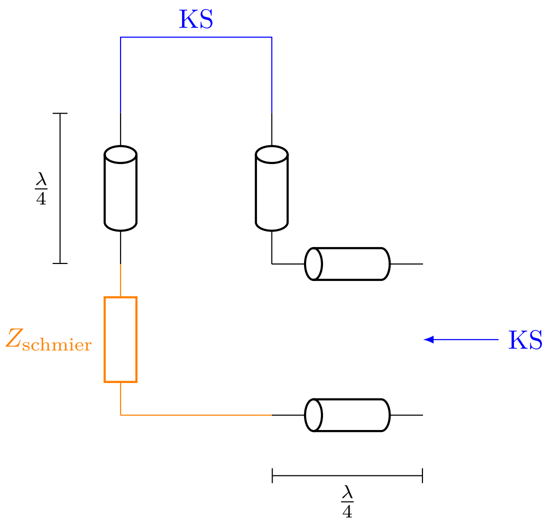
$$\frac{c_0}{2\pi R} \cdot 1{,}84 \cdot 1{,}306 \leq 10\,\text{GHz}$$

$$\frac{c_0}{2\pi R} \cdot 1{,}84 \cdot 1{,}658 \geq 12\,\text{GHz}$$

4.3.6 $\Delta z = \frac{\lambda_H}{4}$

4.3.7




KS
$\frac{\lambda}{4}$
Z_{schmier}
KS
$\frac{\lambda}{4}$