Curs 6

2026/2027

# Dispozitive şi circuite de microunde pentru radiocomunicații

# Disciplina 2026/2027

- 2C/1L/1P, **DCMR (CDM)**
- **Minim 14 prezente (curs+laborator+proiect)**
- Curs - **conf. Radu Damian**
  - Vineri 8-10/**Video (istoric)**, C1, corp C
  - E – **40%** din nota
  - **probleme** + (2p prez. curs) + (3 teste) + (bonus activitate)
    - primul test L1: ~01.10.2025 (t2 si t3 neanuntate la **curs**)
    - 3pz (C) ≈ +0.5p (**2p** max)
  - **toate materialele permise**

# Disciplina 2026/2027

- 2C/1L/1P, **DCMR (CDM)**
- Laborator – **conf. Radu Damian**
  - Miercuri 08-16, **II.13**
  - Joi 12-20, **I.08**
  - L – **30%** din nota
    - ADS, tema personala
    - prezenta + **rezultate personale!**
  - P – **30%** din nota
    - ADS, tema personala
  - S1÷14: 3P, 7L, 4P
    - prezenta cu alte grupe **permisa** in limita numarului de calculatoare disponibile

# Documentatie

- https://rf-opto.etti.tuiasi.ro



# Cuprins

- Linii de transmisie
- Adaptarea de impedanța
- Cuploare direcționale
- Divizoare de putere
- Amplificatoare de microunde
- Filtre de microunde
- Oscilatoare de microunde ?

# Examen: Reprezentare logaritmică

- $\boldsymbol{X[dB] = 10 \cdot log_{10}(X[lin])}$
- $X[B] = log_{10}(X[lin])$
- X[lin] – adimensional
- $log(A \cdot B) = log(A) + log(B)$

- $\boldsymbol{X[lin] = 10^{X[dB]/10}}$

# Examen

- Operatii cu numere complexe!
- $z = a + j \cdot b$ ; $\mathbf{j^2 = -1}$

# IA/AI+ IN/NI

**SUPERVISED LEARNING**



**UNSUPERVISED LEARNING**



**REINFORCEMENT LEARNING**



# IA/AI+ IN/NI

- Într-un bar se aduce un robot pe post de barman. Vine un client, se aşează la tejghea, robotul îi serveşte băutura şi îl întreabă:
  - Ce IQ aveți?
  - **150**…
- Şi robotul continuă conversația despre fizica cuantică, tehnologii medicale avansate şi alte subiecte care necesită un grad ridicat de cunoştințe şi înțelegere. Impresionat, clientul iese din bar, stă două minute şi intră iar. La fel, îl preia robotul şi răspunde acestuia:
  - **100**…
- Şi robotul continuă discuția despre celebre meciuri de box, renumite fabrici de bere şi altele de acelaşi tip uzual. Clientul mai încearcă o dată faza, iese afară, intră şi este întâmpinat de robot:
  - Ce IQ aveți?
  - **50**…
  - Ce spui de echipa noastră de fotbal?

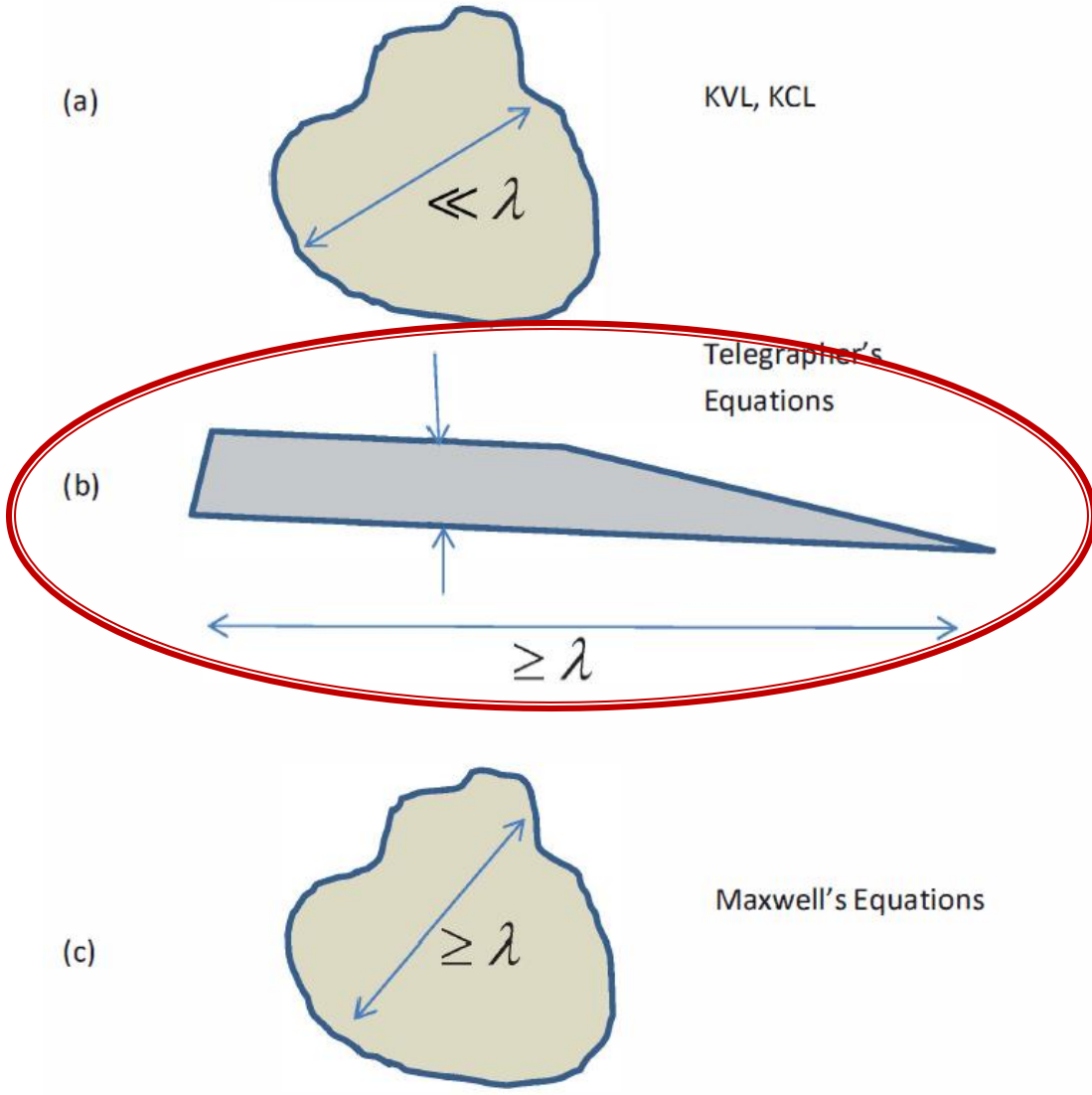
# Cuprins

- Linii de transmisie
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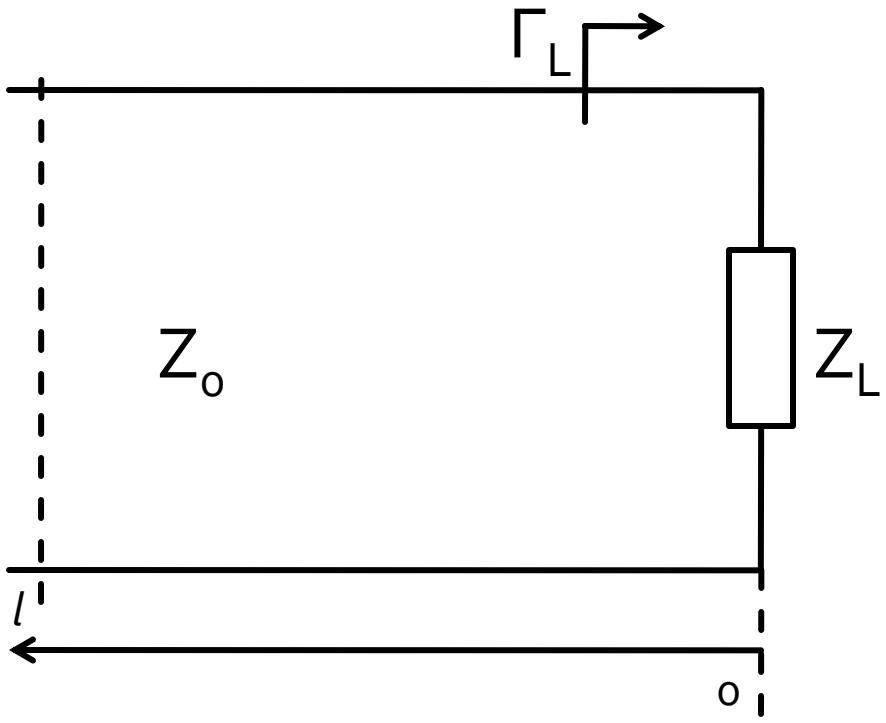
# Lungime electrica

- Comportarea (descrierea) unui circuit depinde de lungimea sa electrica la frecventele de interes
  - E≈o → Kirchhoff
  - E>o → propagare

$$E = \beta \cdot l = \frac{2\pi}{\lambda} \cdot l = 2\pi \cdot \left( \frac{l}{\lambda} \right)$$



# Linie fara pierderi




$$V(z) = V_0^+ e^{-j\cdot\beta\cdot z} + V_0^- e^{j\cdot\beta\cdot z}$$

$$I(z) = \frac{V_0^+}{Z_0} e^{-j\cdot\beta\cdot z} - \frac{V_0^-}{Z_0} e^{j\cdot\beta\cdot z}$$

$$Z_L = \frac{V(0)}{I(0)} \qquad Z_L = \frac{V_0^+ + V_0^-}{V_0^+ - V_0^-}\cdot Z_0$$

- coeficient de reflexie in tensiune

$$\Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

  - $Z_o$ real

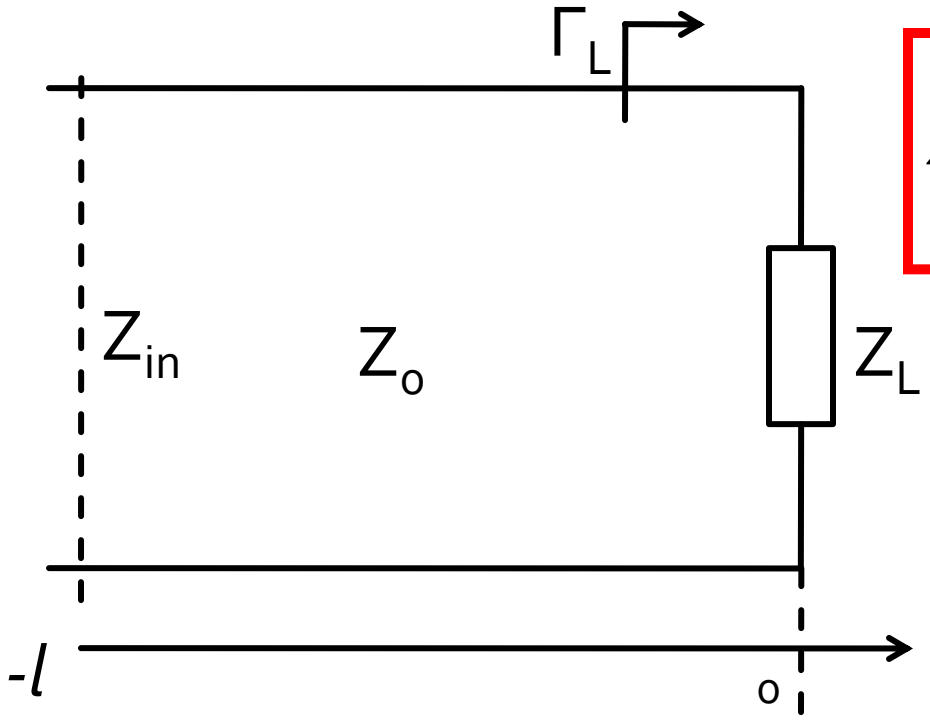
# Linie fara pierderi

$$P_{avg} = \frac{1}{2} \cdot \frac{\left|V_0^+\right|^2}{Z_0} \cdot \left(1 - \left|\Gamma\right|^2\right)$$

- Puterea medie e constanta in lungul liniei
  - ( **fara** $P_{avg}$(~~≠~~) )
  - poate fi masurata
- Se utilizeaza puterea pentru a caracteriza amplitudinea semnalului
  - un punct de vedere "energetic" (fizica)
  - energie mai mare = semnal "mai mare"

# Linie fara pierderi

- impedanta la intrarea liniei de impedanta caracteristica $Z_o$, de lungime $l$, terminata cu impedanta $Z_L$

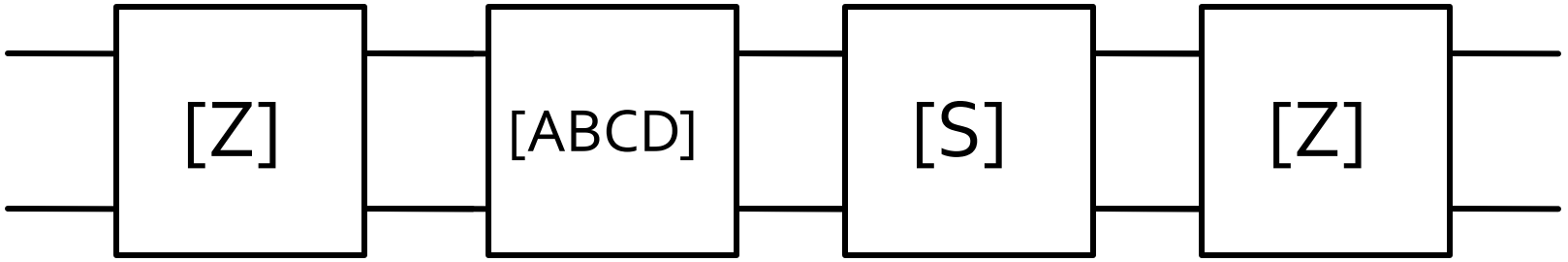



$$Z_{in} = Z_0 \cdot \frac{Z_L + j \cdot Z_0 \cdot \tan \beta \cdot l}{Z_0 + j \cdot Z_L \cdot \tan \beta \cdot l}$$

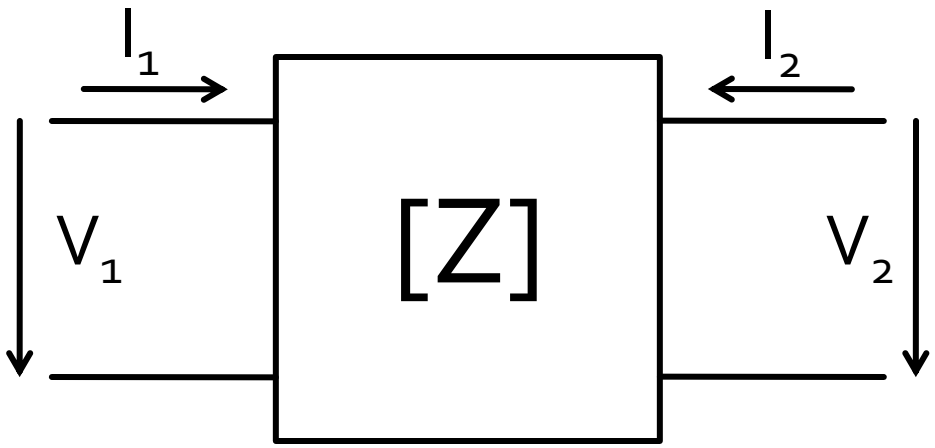
# Analiza la nivel de rețea a circuitelor de microunde

# Analiza la nivel de bloc

- are ca scop separarea unui circuit complex in blocuri individuale
- acestea se analizeaza separat (decuplate de restul circuitului) si se caracterizeaza doar prin intermediul porturilor (**cutie neagra**)
- analiza la nivel de retea permite cuplarea rezultatelor individuale si obtinerea unui rezultat total pentru circuit



# Matricea impedanta




$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2$$
$$V_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2$$

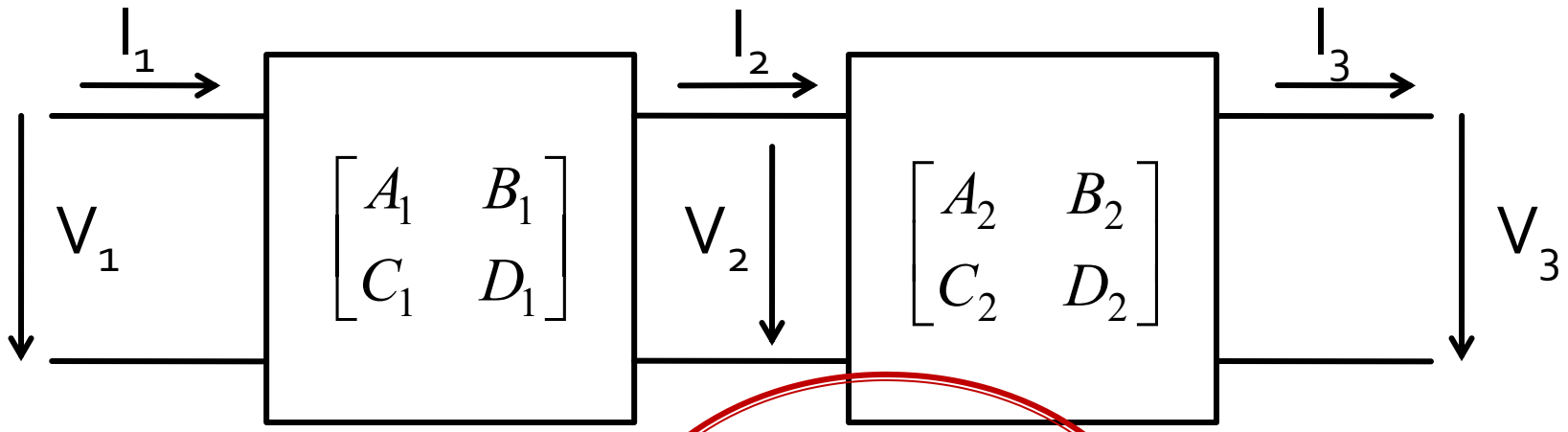
$$V_1 = Z_{11} \cdot I_1\big|_{I_2=0} \qquad Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$$

- Z11 – impedanta de intrare cu iesirea in gol

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \qquad Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0} \qquad Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

# Matricea ABCD – de transmisie

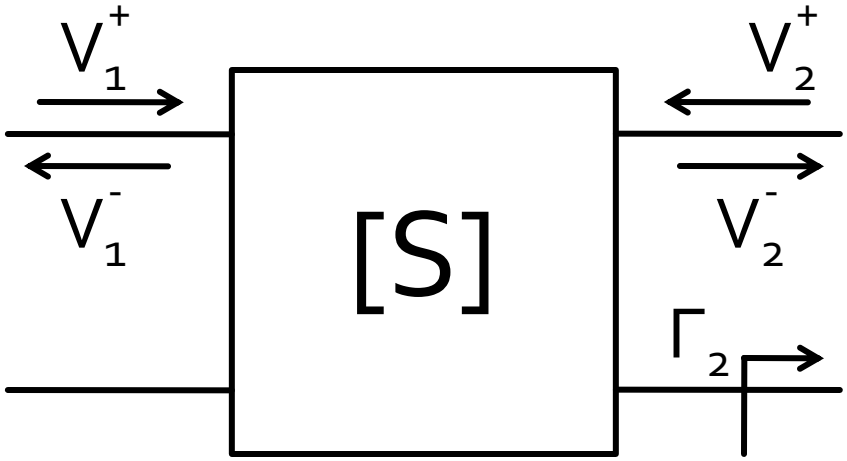
- introduce o legatura intre "intrare" si "iesire"
- permite inlantuirea usoara intre mai multe blocuri




$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \cdot \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \cdot \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}$$

# Matricea S (repartitie)

- Scattering parameters




$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

$$S_{11} = \left.\frac{V_1^-}{V_1^+}\right|_{V_2^+=0} \qquad S_{21} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0}$$

- $V_2^+ = 0$ are semnificatia: la portul 2 este conectata impedanta care realizeaza conditia de adaptare (complex conjugat)

$$\Gamma_2 = 0 \rightarrow V_2^+ = 0$$

# Proprietati [S]

- Circuite reciproce (fara circuite active, ferite)

$$Z_{ij} = Z_{ji}, \forall j \neq i$$

$$Y_{ij} = Y_{ji}, \forall j \neq i$$

$$S_{ij} = S_{ji}, \forall j \neq i \qquad [S] = [S]^t$$

- Circuite fara pierderi

$$\mathrm{Re}\{Z_{ij}\} = 0, \forall i, j$$

$$\mathrm{Re}\{Y_{ij}\} = 0, \forall i, j$$

$$\sum_{k=1}^{N} S_{ki} \cdot S_{kj}^{*} = \delta_{ij}, \forall i, j$$

$$[S]^{*} \cdot [S]^{t} = [1]$$

$$\sum_{k=1}^{N} S_{ki} \cdot S_{ki}^{*} = 1$$

$$\sum_{k=1}^{N} S_{ki} \cdot S_{kj}^{*} = 0, \forall i \neq j$$

# Matricea S generalizata

- Definim undele de putere

$$a = \frac{V + Z_R \cdot I}{2 \cdot \sqrt{R_R}}$$ unda incidenta de putere

$$b = \frac{V - Z_R^* \cdot I}{2 \cdot \sqrt{R_R}}$$ unda reflectata de putere

$$Z_R = R_R + j \cdot X_R$$

O impedanta de referinta oarecare, complexa

- Tensiuni si curenti

$$V = \frac{Z_R^* \cdot a + Z_R \cdot b}{\sqrt{R_R}}$$

$$I = \frac{a - b}{\sqrt{R_R}}$$

# Unde de putere

- Daca in plus generatorul este adaptat conjugat cu sarcina

$$Z_g = Z_L^* \qquad P_{L\max} = \frac{1}{2}\cdot|a|^2 = \frac{V_0^2}{8\cdot R_L}$$

- Reflexie in putere C4

$$Z_L = Z_i^* \qquad P_{L\max} \equiv P_a \qquad \Gamma = \frac{Z - Z_0^*}{Z + Z_0}$$

$$Z_L \neq Z_i^* \qquad P_r = P_a\cdot|\Gamma|^2 \qquad P_L = P_a - P_r = P_a - P_a\cdot|\Gamma|^2 = P_a\cdot\left(1-|\Gamma|^2\right)$$

- Reflexie in putere C5

$$P_{L\max} \equiv P_a = \frac{1}{2}\cdot|a|^2 \qquad P_L = \frac{1}{2}\cdot|a|^2 - \frac{1}{2}\cdot|b|^2 \qquad \Gamma_p = \frac{b}{a} = \frac{V - Z_R^*\cdot I}{V + Z_R\cdot I} = \frac{Z_L - Z_R^*}{Z_L + Z_R}$$

$$P_L = \frac{1}{2}\cdot|a|^2 - \frac{1}{2}\cdot|a|^2\cdot|\Gamma_p|^2 \qquad P_L = P_a\cdot\left(1-|\Gamma_p|^2\right) \qquad P_r = P_a\cdot|\Gamma_p|^2 = \frac{1}{2}\cdot|b|^2$$

# Unde de putere pentru multiporti

$$[b]=[F]\cdot\left([Z]-[Z_R]^*\right)\cdot\left([Z]+[Z_R]\right)^{-1}\cdot[F]^{-1}\cdot[a]$$

- legatura intre undele de putere incidenta si reflectata

$$[b]=[S_p]\cdot[a]$$

$$[S_p]=[F]\cdot\left([Z]-[Z_R]^*\right)\cdot\left([Z]+[Z_R]\right)^{-1}\cdot[F]^{-1}$$

$$[S]=\left([Z]-[Z_0]\right)\cdot\left([Z]+[Z_0]\right)^{-1}$$

- tipic

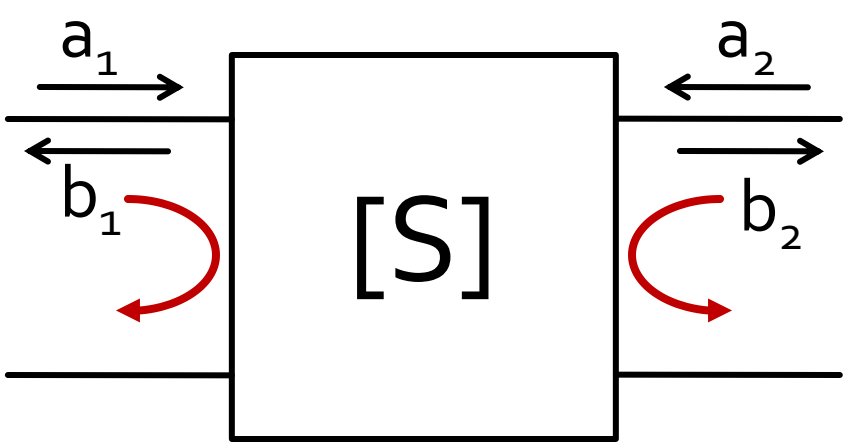
$$Z_{0i}=Z_{Ri}=R_0,\forall i$$

$$R_0=50\Omega$$

$$\boxed{[S_p]\equiv[S]}$$

- **coincid!!!**

# Matricea S (repartitie)

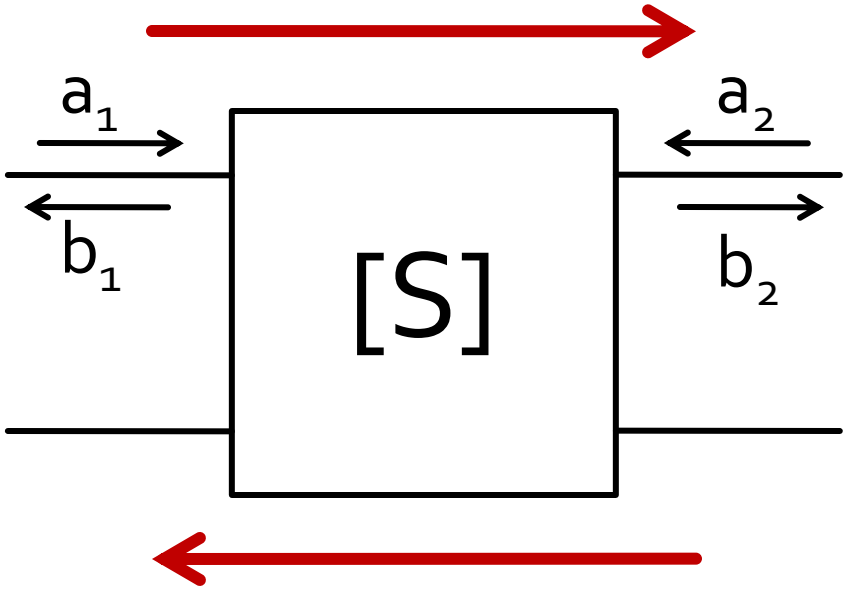



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

- $S_{11}$ si $S_{22}$ sunt coeficienti de reflexie la intrare si iesire cand celalalt port este adaptat

# Matricea S (repartitie)

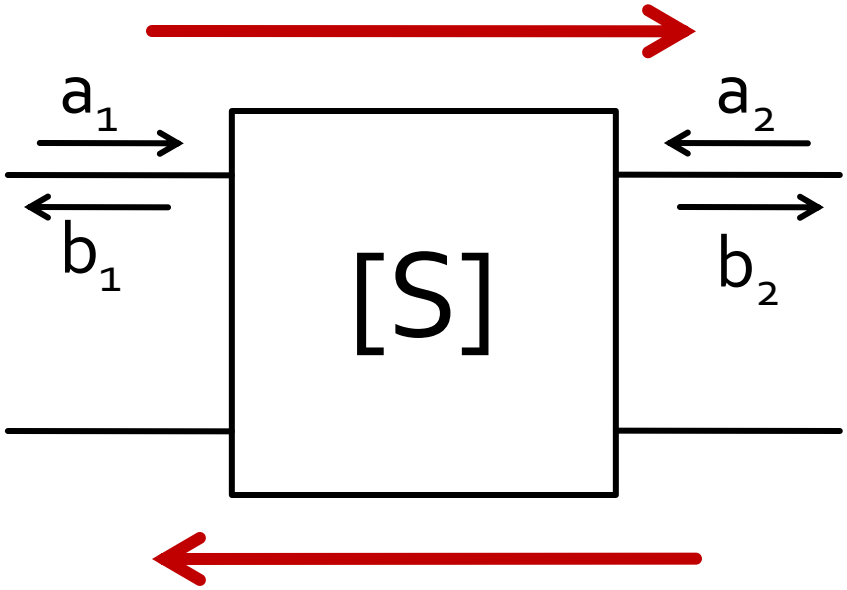



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

- $S_{21}$ si $S_{12}$ sunt amplificari de semnal cand celalalt port este adaptat

# Matricea S (repartitie)




$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$|S_{21}|^2 = \frac{Putere\ sarcina\ Z_0}{Putere\ sursa\ Z_0}$$

- a,b
  - informatia despre putere **SI** faza
- $S_{ij}$
  - influenta circuitului asupra puterii semnalului incluzand informatiile relativ la faza

# Masurare S - VNA

- Vector Network Analyzer

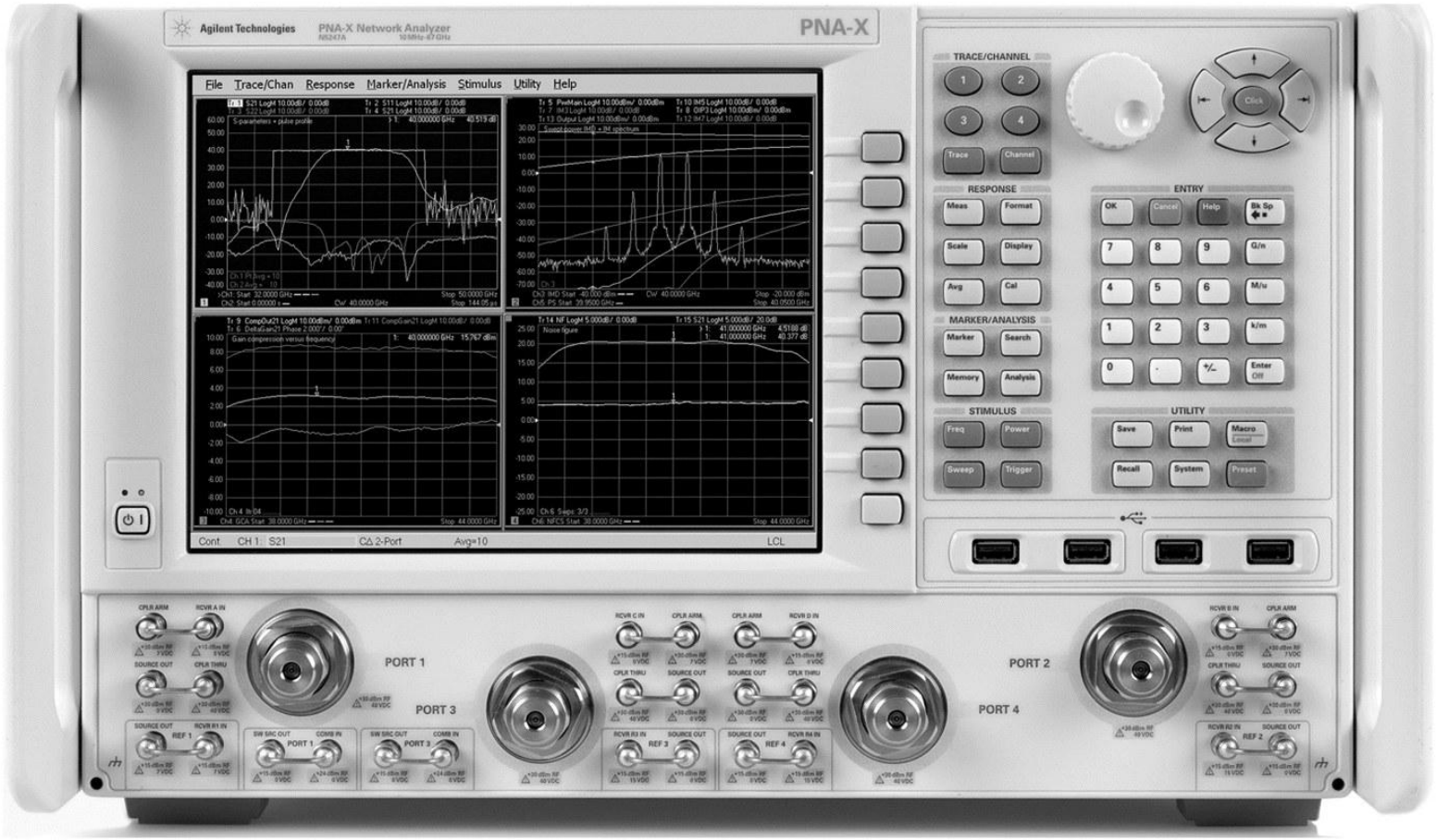


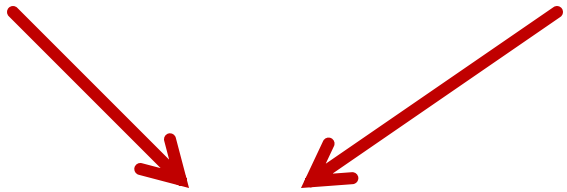

**Figure 4.7**
**Courtesy of Agilent Technologies**

# Analiza pe mod par/impar

# Analiza pe mod par/impar (even/odd)

- In circuite liniare putem aplica suprapunerea efectelor
- avantaje
  - reducerea complexitatii circuitului
  - reducerea numarului de porturi (**principalul** avantaj)

**Efect ( PAR + IMPAR ) = Efect ( PAR ) + Efect ( IMPAR )**



**Putem beneficia de avantajele simetriilor!!**

# Continuare

# Cuploare directionale si divizoare de putere

# Cuprins

- Linii de transmisie
- Adaptarea de impedanța
- Cuploare direcționale
- Divizoare de putere
- Amplificatoare de microunde
- Filtre de microunde
- Oscilatoare de microunde ?

# Cuploare/Divizoare

- Funcționalitatea dorită:
  - divizarea
  - combinarea
- puterii semnalului

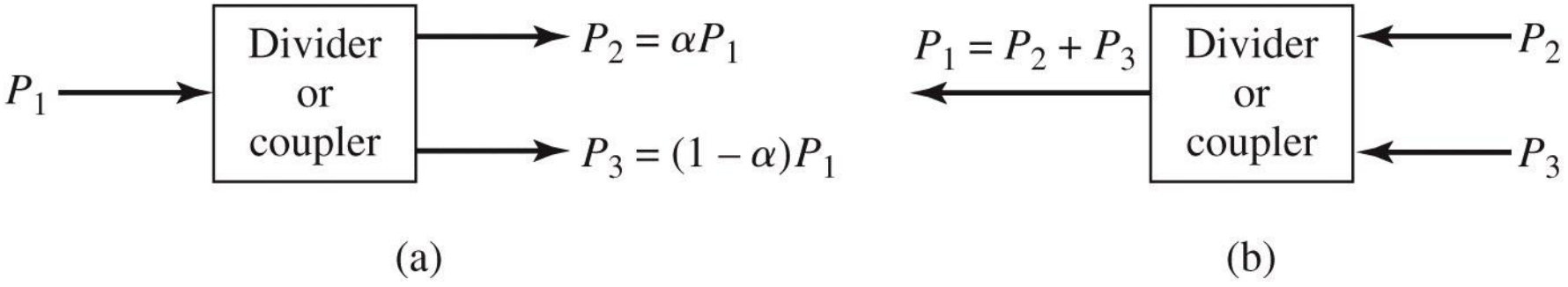
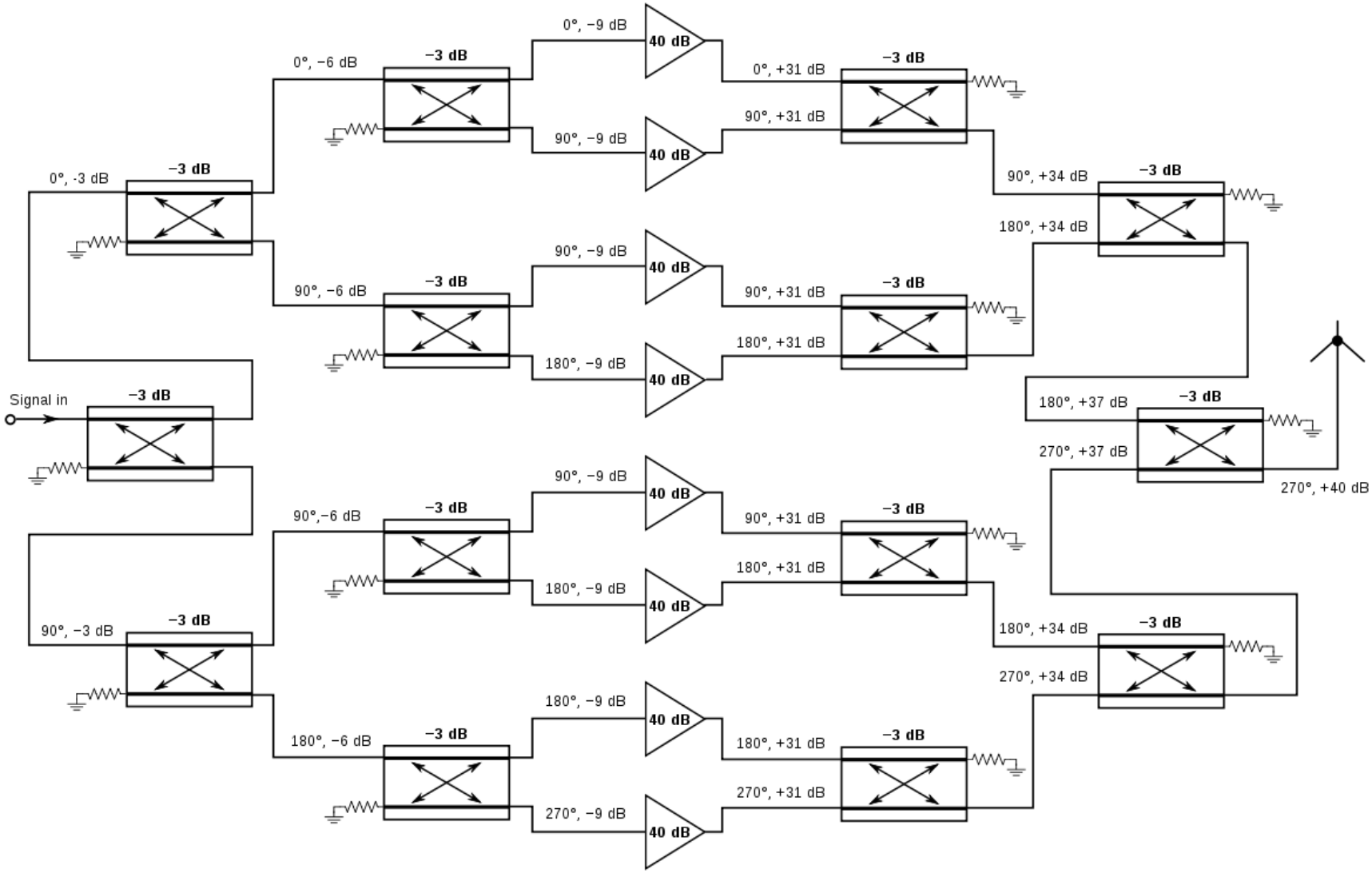



Figure 7.1

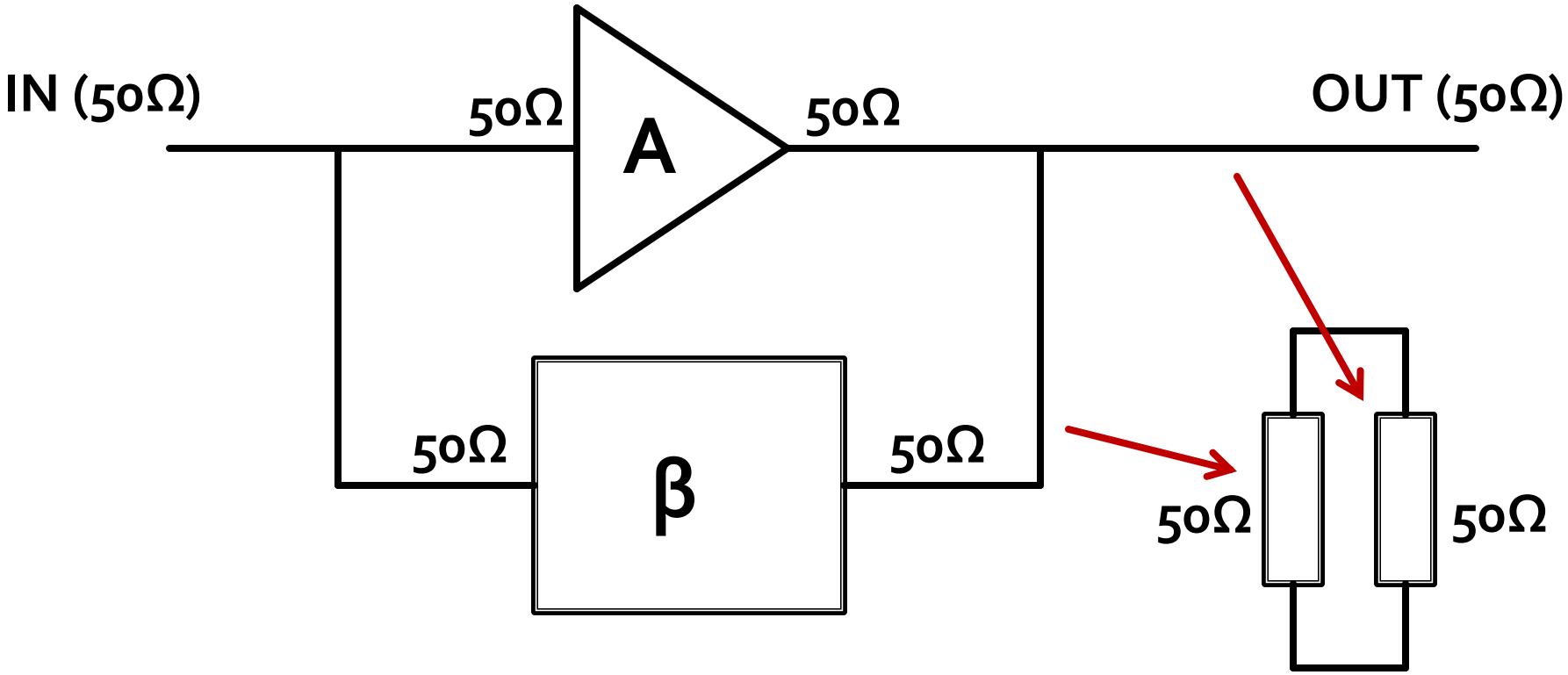
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# Amplificatoare echilibrate



# Amplificatoare

- amplificator cu reactie
- control automat al amplitudinii



# Circuite cu trei porți

- numite si joncțiune in T
- caracterizate de o matrice **S** 3x3

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

- circuitul este **reciproc** dacă **nu** conține:
  - materiale anizotrope (de obicei ferite)
  - circuite active
- e de dorit să obținem funcționalitatea dorită de divizare/combinare de putere **fără pierderi** interne
- e de dorit sa obținem circuitul **adaptat simultan la toate porțile**
  - evitarea unor pierderi externe de putere

# Circuite cu trei porți

- circuit reciproc

$$[S]=[S]^t \qquad S_{ij}=S_{ji}, \forall j \neq i$$

$$S_{12}=S_{21}, S_{13}=S_{31}, S_{23}=S_{32}$$

- adaptat simultan la toate portile

$$S_{ii}=0, \forall i \qquad S_{11}=0, S_{22}=0, S_{33}=0$$

- matricea S devine:

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

# Circuite cu trei porți

- reciproc, adaptat, matricea S:

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

- circuit unitar (fără pierderi)
  - toata puterea introdusa pe un port se regaseste la celelalte porturi

$$[S]^* \cdot [S]^t = [1] \qquad \sum_{k=1}^{N} S_{ki} \cdot S_{kj}^* = \delta_{ij}, \forall i, j$$

$$\sum_{k=1}^{N} S_{ki} \cdot S_{ki}^* = 1 \qquad \sum_{k=1}^{N} S_{ki} \cdot S_{kj}^* = 0, \forall i \neq j$$

# Circuite cu trei porți

- circuit unitar (fără pierderi)

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

$$\sum_{k=1}^{N} S_{ki}\cdot S_{ki}^{*}=1$$

$$\sum_{k=1}^{N} S_{ki}\cdot S_{kj}^{*}=0,\forall i\neq j$$

- 6 ecuatii / 3 necunoscute

$$|S_{12}|^2+|S_{13}|^2=1 \qquad S_{13}^{*}S_{23}=0$$

$$|S_{12}|^2+|S_{23}|^2=1 \qquad S_{12}^{*}S_{13}=0$$

$$|S_{13}|^2+|S_{23}|^2=1 \qquad S_{23}^{*}S_{12}=0$$

- nici o solutie posibila

$$S_{12}=0 \rightarrow \begin{cases} |S_{13}|=1 \\ |S_{23}|=1 \end{cases} \rightarrow S_{13}^{*}S_{23}=\pm 1/j\neq 0$$

# Circuite cu trei porți

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

- 6 ecuații / 3 necunoscute
  - nici o soluție posibila
- Un circuit cu 3 porți **NU** poate fi simultan:
  - reciproc
  - fara pierderi
  - adaptat simultan la toate cele 3 porți
- Renunțarea la una din cele 3 condiții conduce la circuite realizabile (**~divizoare de putere**)

# Circuit cu trei porți nereciproc

- de obicei cu materiale anizotrope, ferite
- **nereciproc**, dar adaptat simultan si fara pierderi $S_{ij} \neq S_{ji}$
- matricea S

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix}$$

- 6 ecuatii / 6 necunoscute

$$|S_{21}|^2 + |S_{31}|^2 = 1 \qquad S_{31}^* S_{32} = 0$$
$$|S_{12}|^2 + |S_{32}|^2 = 1 \qquad S_{21}^* S_{23} = 0$$
$$|S_{13}|^2 + |S_{23}|^2 = 1 \qquad S_{12}^* S_{13} = 0$$

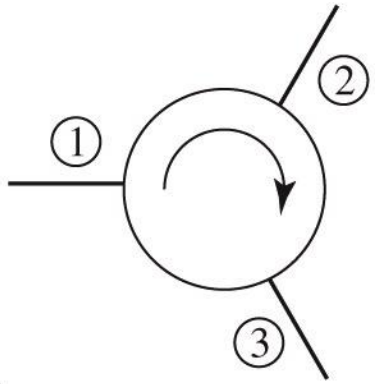
# Circuit cu trei porți nereciproc

- doua solutii posibile
- **circulatoare**
  - in sens orar direct

$$S_{12} = S_{23} = S_{31} = 0$$

$$|S_{21}| = |S_{32}| = |S_{13}| = 1$$

$$[S] = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$



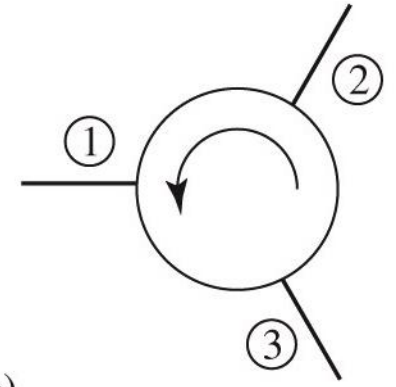

(a)

  - in sens orar invers

$$S_{21} = S_{32} = S_{13} = 0$$

$$|S_{12}| = |S_{23}| = |S_{31}| = 1$$

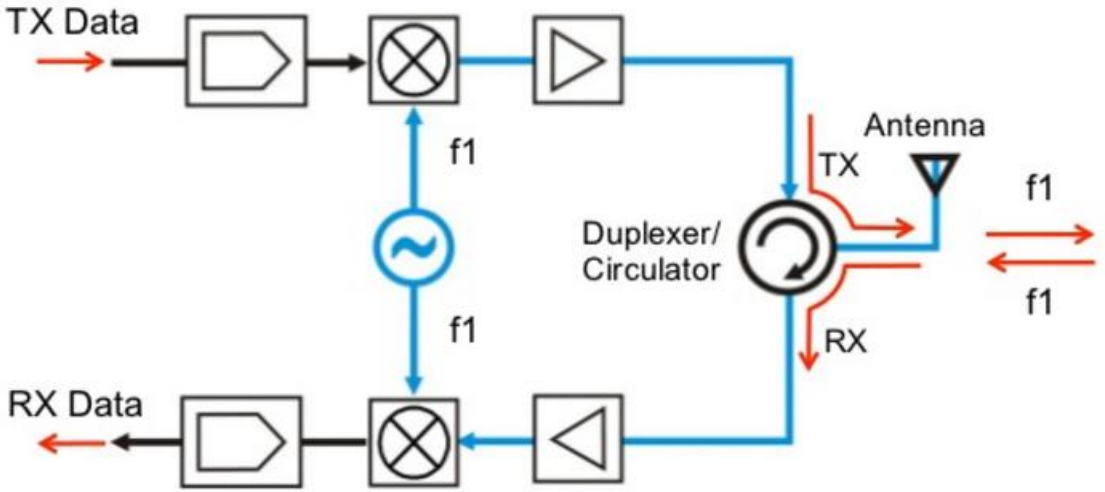
$$[S] = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

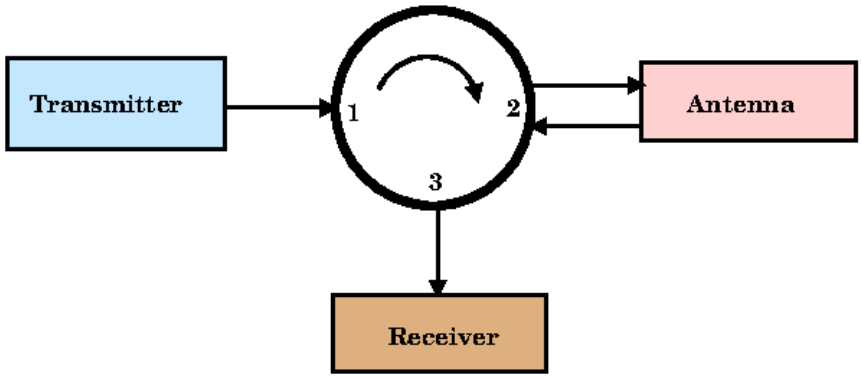



(b)

# Circuit cu trei porți nereciproc

- circulator deseori in duplexer



# Circuit cu trei porți neadaptat

- Un circuit cu 3 porți reciproc si fara pierderi poate fi adaptat numai la 2 porți

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix}$$

$$S_{13}^{*}S_{23}=0$$

$$S_{12}^{*}S_{13}+S_{23}^{*}S_{33}=0$$

$$S_{23}^{*}S_{12}+S_{33}^{*}S_{13}=0$$

$$S_{13}=S_{23}=0$$

$$|S_{12}|^{2}+|S_{13}|^{2}=1$$

$$|S_{12}|^{2}+|S_{23}|^{2}=1$$

$$|S_{13}|=|S_{23}|$$

$$|S_{13}|^{2}+|S_{23}|^{2}+|S_{33}|^{2}=1$$

$$|S_{12}|=|S_{33}|=1$$

# Circuit cu trei porți neadaptat

- Un circuit cu 3 porți reciproc si fara pierderi

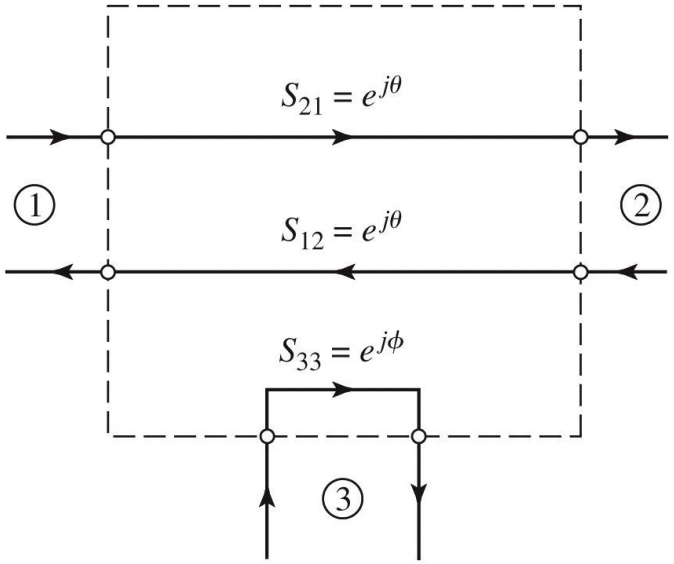
$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix}$$

$$S_{13}=S_{23}=0 \qquad |S_{12}|=|S_{33}|=1$$

$$S_{12}=e^{j\theta}$$

$$S_{33}=e^{j\varphi}$$

$$[S]=\begin{bmatrix} 0 & e^{j\theta} & 0 \\ e^{j\theta} & 0 & 0 \\ 0 & 0 & e^{j\phi} \end{bmatrix}$$




- Un circuit cu 3 porți reciproc si fara pierderi **degenereaza** in doua componente separate:
  - **o linie** fara pierderi, adaptata, intre doua dintre porturi
  - al treilea **port** e **separat** si **dezadaptat**

# Circuite cu patru porți

- caracterizate de o matrice **S** 4x4

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

- circuitul este **reciproc** dacă nu conține:
  - materiale anizotrope (de obicei ferite)
  - circuite active
- e de dorit să obținem funcționalitatea dorită de divizare/combinare de putere **fără pierderi** interne
- e de dorit sa obținem circuitul **adaptat simultan la toate porțile**
  - evitarea unor pierderi externe de putere

# Circuite cu patru porți

- circuit reciproc

$$[S]=[S]^t \qquad S_{ij}=S_{ji}, \forall j \neq i$$

$$S_{12}=S_{21}, S_{13}=S_{31}, S_{23}=S_{32}$$

- adaptat simultan la toate portile

$$S_{ii}=0, \forall i \qquad S_{11}=0, S_{22}=0, S_{33}=0, S_{44}=0$$

- matricea S devine:

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

# Circuite cu patru porți

- reciproc, adaptat, matricea S:

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

- circuit unitar (fără pierderi)
  - toata puterea introdusa pe un port se regaseste la celelalte porturi

$$[S]^* \cdot [S]^t = [1] \qquad \sum_{k=1}^{N} S_{ki} \cdot S_{kj}^* = \delta_{ij}, \forall i, j$$

$$\sum_{k=1}^{N} S_{ki} \cdot S_{ki}^* = 1 \qquad \sum_{k=1}^{N} S_{ki} \cdot S_{kj}^* = 0, \forall i \neq j$$

# Circuite cu patru porți

$$S_{13}^* \cdot S_{23} + S_{14}^* \cdot S_{24} = 0 \quad /\cdot S_{24}^*$$
$$S_{14}^* \cdot S_{13} + S_{24}^* \cdot S_{23} = 0 \quad /\cdot S_{13}^*$$
$$S_{14}^* \cdot \left( |S_{13}|^2 - |S_{24}|^2 \right) = 0$$

$$S_{12}^* \cdot S_{23} + S_{14}^* \cdot S_{34} = 0 \quad /\cdot S_{12}$$
$$S_{14}^* \cdot S_{12} + S_{34}^* \cdot S_{23} = 0 \quad /\cdot S_{34}^*$$
$$S_{23} \cdot \left( |S_{12}|^2 - |S_{34}|^2 \right) = 0$$

- o solutie: $S_{14} = S_{23} = 0$
- cuplorul rezulta **directional**

$$|S_{12}|^2 + |S_{13}|^2 = 1$$
$$|S_{12}|^2 + |S_{24}|^2 = 1 \Rightarrow |S_{13}| = |S_{24}|$$
$$|S_{13}|^2 + |S_{34}|^2 = 1$$
$$|S_{24}|^2 + |S_{34}|^2 = 1 \Rightarrow |S_{12}| = |S_{34}|$$

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & 0 \\ S_{12} & 0 & 0 & S_{24} \\ S_{13} & 0 & 0 & S_{34} \\ 0 & S_{24} & S_{34} & 0 \end{bmatrix}$$

# Circuite cu patru porți

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} & 0 \\ S_{12} & 0 & 0 & S_{24} \\ S_{13} & 0 & 0 & S_{34} \\ 0 & S_{24} & S_{34} & 0 \end{bmatrix}$$

$$|S_{12}|=|S_{34}|=\alpha \qquad |S_{13}|=|S_{24}|=\beta$$

β – coeficientul de cuplaj în tensiune

- Alegem referintele de faza

$$S_{12}=S_{34}=\alpha \qquad S_{13}=\beta\cdot e^{j\theta} \qquad S_{24}=\beta\cdot e^{j\phi}$$

$$S_{12}^{*}\cdot S_{13}+S_{24}^{*}\cdot S_{34}=0 \quad \rightarrow \quad \theta+\phi=\pi\pm 2\cdot n\cdot\pi$$

$$|S_{12}|^{2}+|S_{24}|^{2}=1 \quad \rightarrow \quad \alpha^{2}+\beta^{2}=1$$

- Cealalta solutie posibila pentru ecuatiile anterioare ofera fie aceeasi solutie (cu alta referinta de faza) fie un caz degenerat

$$S_{14}^{*}\cdot\left(|S_{13}|^{2}-|S_{24}|^{2}\right)=0 \qquad S_{23}\cdot\left(|S_{12}|^{2}-|S_{34}|^{2}\right)=0$$

# Circuite cu patru porți

- Un circuit cu 4 porti care este simultan:
  - adaptat la toate portile
  - reciproc
  - fara pierderi
- este **intotdeauna directional**
  - puterea de semnal introdusa pe un port este trimisa **numai spre doua** din celelalte trei porturi

$$[S]=\begin{bmatrix} 0 & \alpha & \beta\cdot e^{j\theta} & 0 \\ \alpha & 0 & 0 & \beta\cdot e^{j\phi} \\ \beta\cdot e^{j\theta} & 0 & 0 & \alpha \\ 0 & \beta\cdot e^{j\phi} & \alpha & 0 \end{bmatrix}$$

# Divizoare de putere

# Circuite cu trei porți

- circuit **nereciproc**:
  - de obicei ferite
  - **circulatoare**
- circuit **neadaptat** la o poartă
  - **degenerat**

# Divizarea de putere a jonctiunii in T

- consta in separarea unei linii incidente in doua linii separate
- se poate implementa in diverse tehnologii

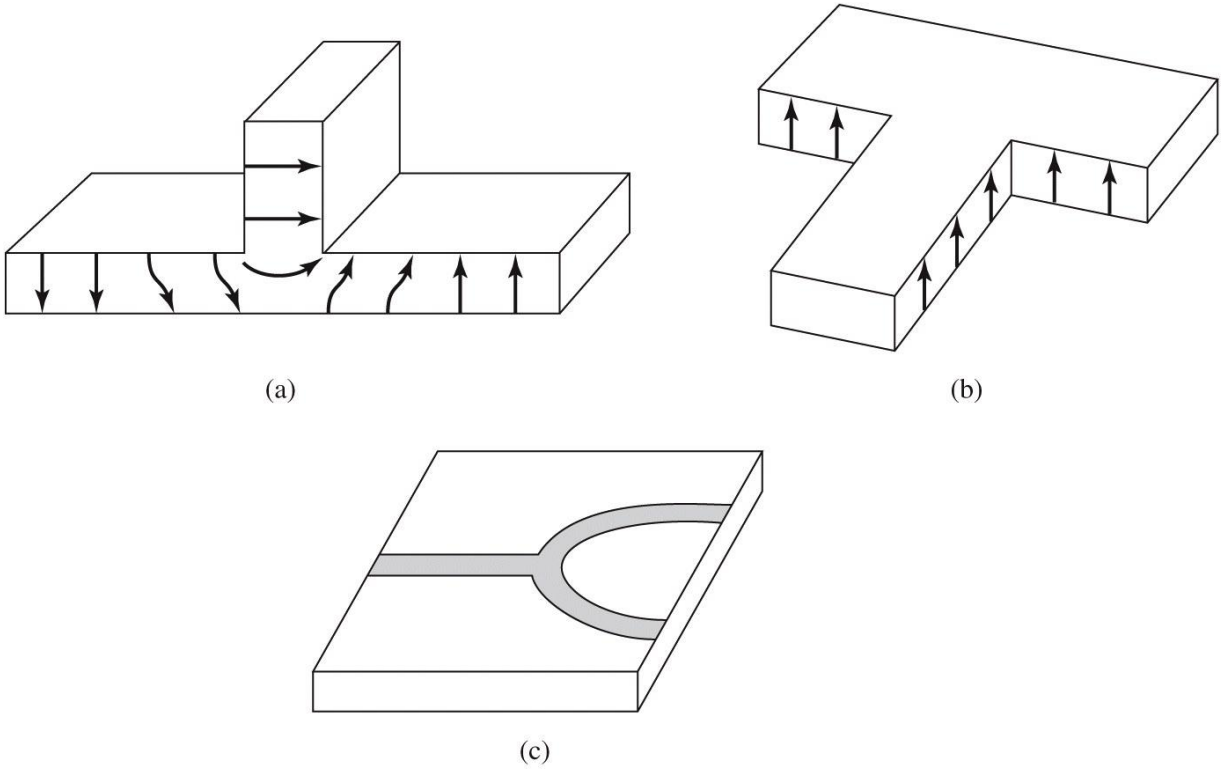



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# Divizarea de putere a jonctiunii in T

- daca liniile sunt fără pierderi, diportul este reciproc, deci nu poate fi adaptat la toate porțile simultan

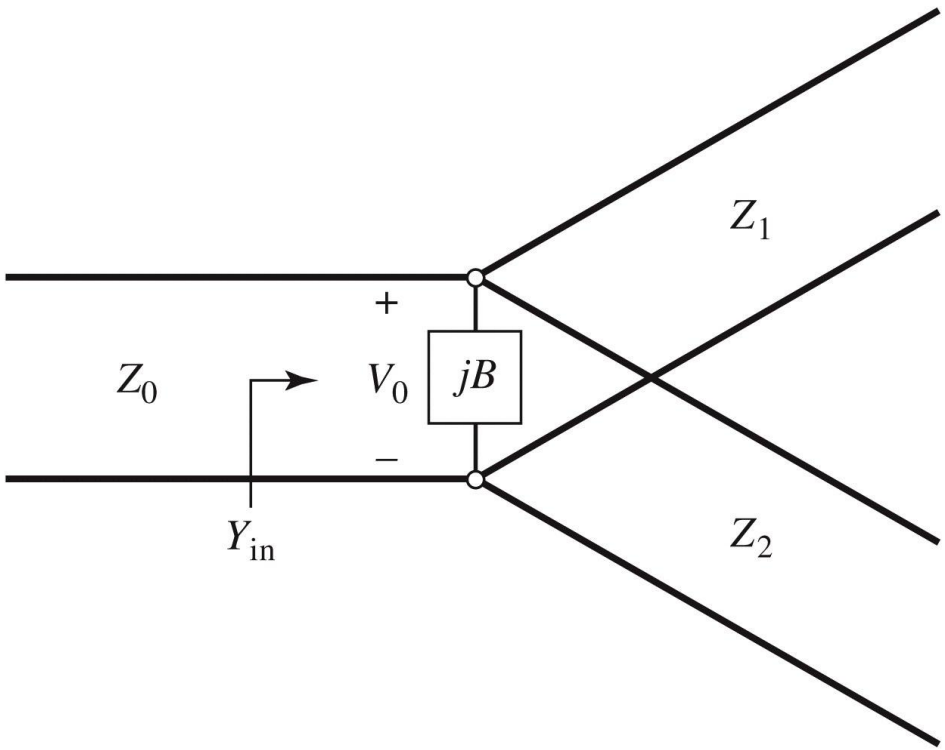



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- la nivelul joncțiunii câmpurile sunt neuniforme, generând moduri de ordin superior localizate
- aceasta energie localizata poate fi modelata cu o reactanța concentrata la nivelul joncțiunii: **B**
- Proiectarea divizorului presupune adaptarea la linia de intrare cu $Z_0$
  - ieșirile pot fi adaptate mai departe cu circuite suplimentare ($\lambda/4$, binomial, Cebișev)

# Divizarea de putere a jonctiunii in T

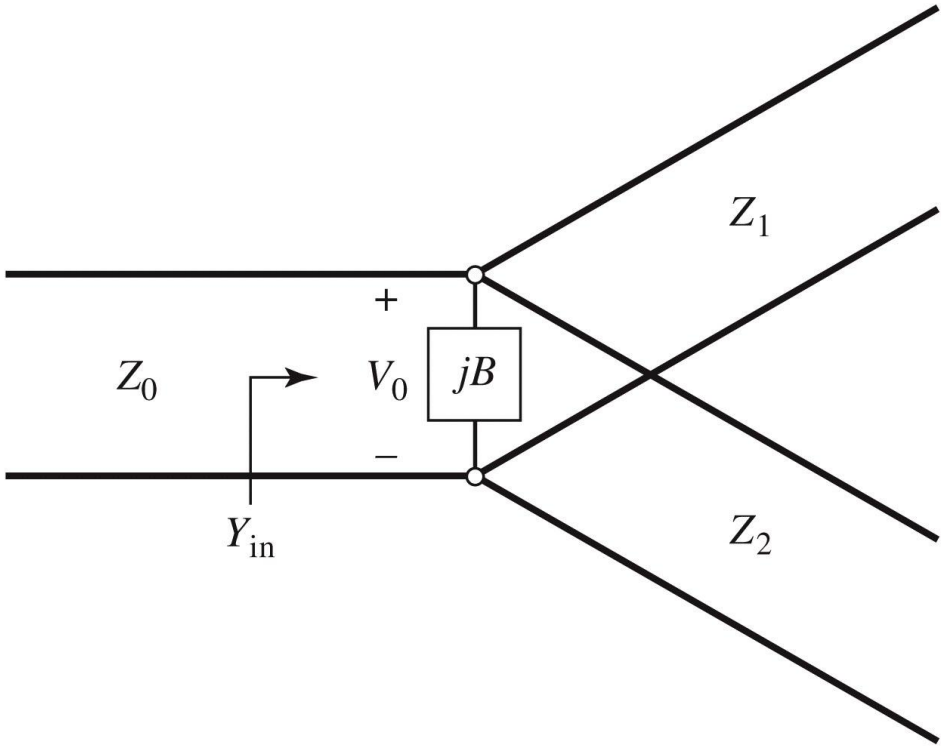



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$$Y_{in} = j \cdot B + \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0}$$

- daca liniile sunt fără pierderi, impedantele caracteristice sunt reale
- conditia de adaptare poate fi indeplinita doar daca **B ≅ o** caz in care conditia de adaptare este:

$$\frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0}$$

In practica daca B nu poate fi neglijat, se introduce o reactanta externa de compensare, reglabila, cu efect macar intr-o banda ingusta de frecventa.

# Divizarea de putere a jonctiunii in T

- daca $V_0$ e amplitudinea semnalului la jonctiune

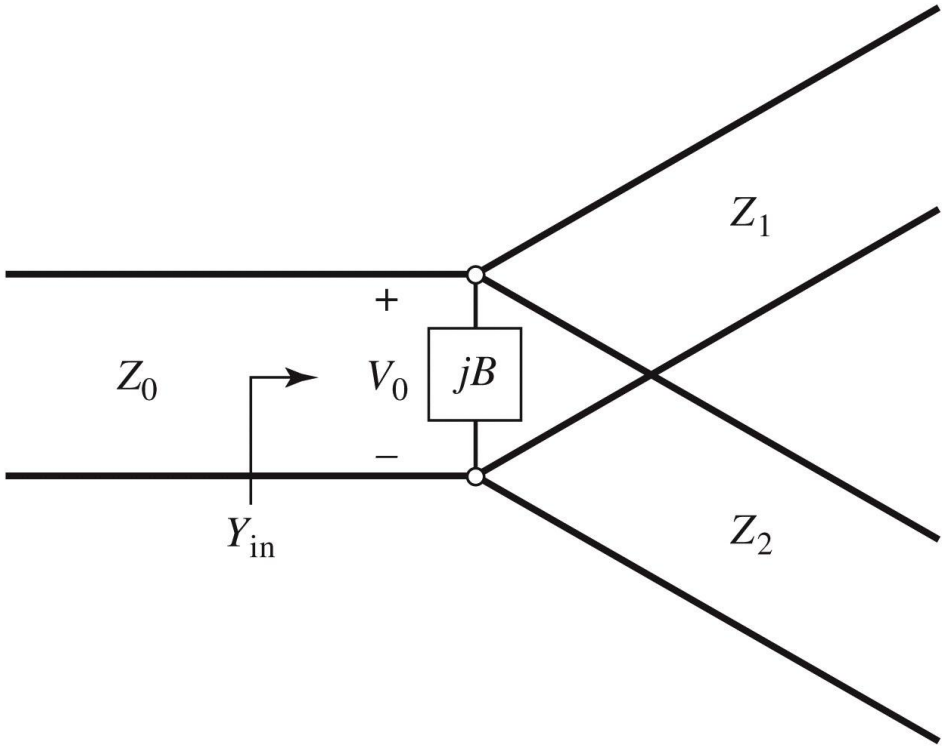



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$$P_{in} = \frac{1}{2} \cdot \frac{V_0^2}{Z_0}$$

$$P_1 = \frac{1}{2} \cdot \frac{V_0^2}{Z_1}$$

$$P_2 = \frac{1}{2} \cdot \frac{V_0^2}{Z_2}$$

deci:

$$P_{in} = P_1 + P_2$$ (fara pierderi)

$$\frac{P_1}{P_2} = \frac{Z_2}{Z_1} = \alpha$$ (impartirea puterii pe cele doua linii de iesire)

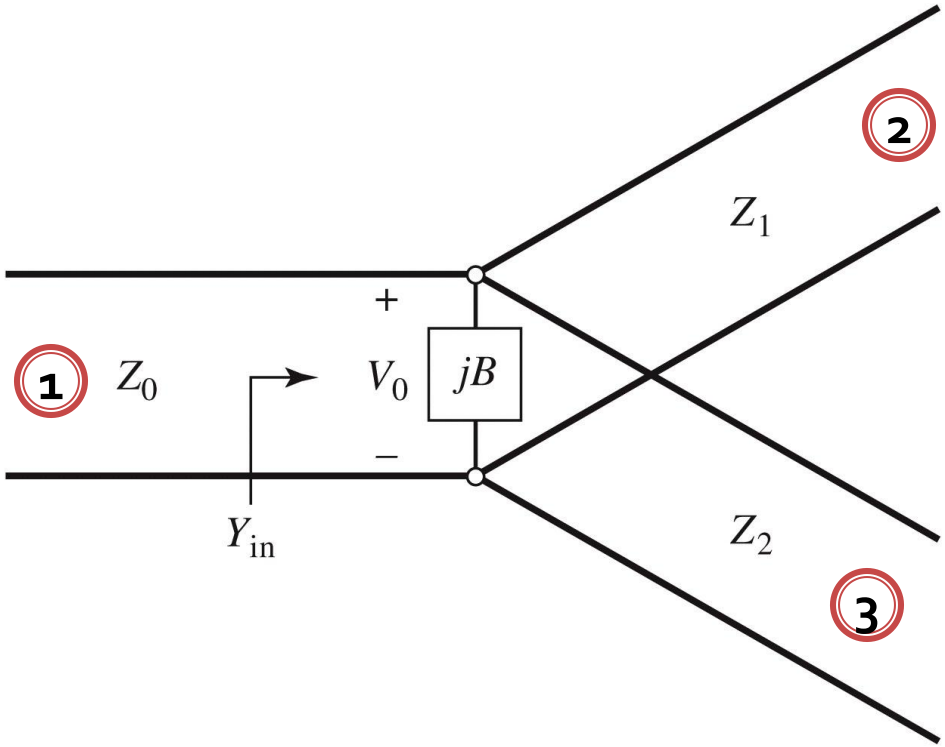
$$P_1 = P_{in} \cdot \frac{Z_2}{Z_1 + Z_2} \qquad P_2 = P_{in} \cdot \frac{Z_1}{Z_1 + Z_2}$$

$$P_1 = P_{in} \cdot \frac{\alpha}{1+\alpha} \qquad P_2 = P_{in} \cdot \frac{1}{1+\alpha}$$

$$Z_1 = Z_0 \cdot \left(1 + \frac{1}{\alpha}\right) \qquad Z_2 = Z_0 \cdot (1+\alpha)$$

# Divizarea de putere a jonctiunii in T

- matricea S
  - fara pierderi (matrice unitara)
  - reciproc (matrice simetrica)
  - portul de intrare este adaptat $S_{11} = 0$




$$P_2 = P_1 \cdot \frac{\alpha}{1+\alpha} \qquad S_{21} = S_{12} = \sqrt{\frac{\alpha}{1+\alpha}}$$

$$P_3 = P_1 \cdot \frac{1}{1+\alpha} \qquad S_{31} = S_{13} = \sqrt{\frac{1}{1+\alpha}}$$

Coeficienti de reflexie la iesiri

$$S_{22} = \Gamma_1 = \frac{Z_0 \,||\, Z_2 - Z_1}{Z_0 \,||\, Z_2 + Z_1} = -\frac{1}{1+\alpha}$$

$$S_{33} = \Gamma_2 = \frac{Z_0 \,||\, Z_1 - Z_2}{Z_0 \,||\, Z_1 + Z_2} = -\frac{\alpha}{1+\alpha}$$

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# Divizarea de putere a jonctiunii in T

$$[S]=\begin{bmatrix} 0 & \sqrt{\frac{\alpha}{1+\alpha}} & \sqrt{\frac{1}{1+\alpha}} \\ \sqrt{\frac{\alpha}{1+\alpha}} & -\frac{1}{1+\alpha} & x \\ \sqrt{\frac{1}{1+\alpha}} & x & -\frac{\alpha}{1+\alpha} \end{bmatrix}$$

Matrice unitara, coloanele 1 si 2

$$0-\frac{1}{1+\alpha}\cdot\sqrt{\frac{\alpha}{1+\alpha}}+x\cdot\sqrt{\frac{1}{1+\alpha}}=0$$

$$S_{23}=S_{32}=\frac{\sqrt{\alpha}}{1+\alpha}$$

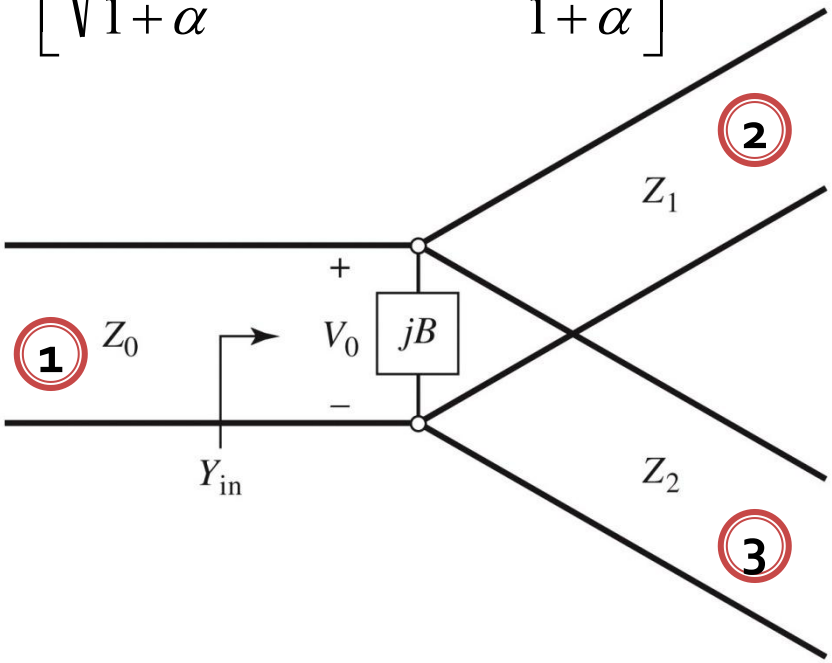



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$$[S]=\begin{bmatrix} 0 & \sqrt{\frac{\alpha}{1+\alpha}} & \sqrt{\frac{1}{1+\alpha}} \\ \sqrt{\frac{\alpha}{1+\alpha}} & -\frac{1}{1+\alpha} & \frac{\sqrt{\alpha}}{1+\alpha} \\ \sqrt{\frac{1}{1+\alpha}} & \frac{\sqrt{\alpha}}{1+\alpha} & -\frac{\alpha}{1+\alpha} \end{bmatrix}$$

# Divizarea de putere a jonctiunii in T

- divizor de 3dB
  - impartire egala a puterii intre cele doua iesiri
  - $Z_1 = Z_2 = 2 \cdot Z_0$ , $\alpha = 1$

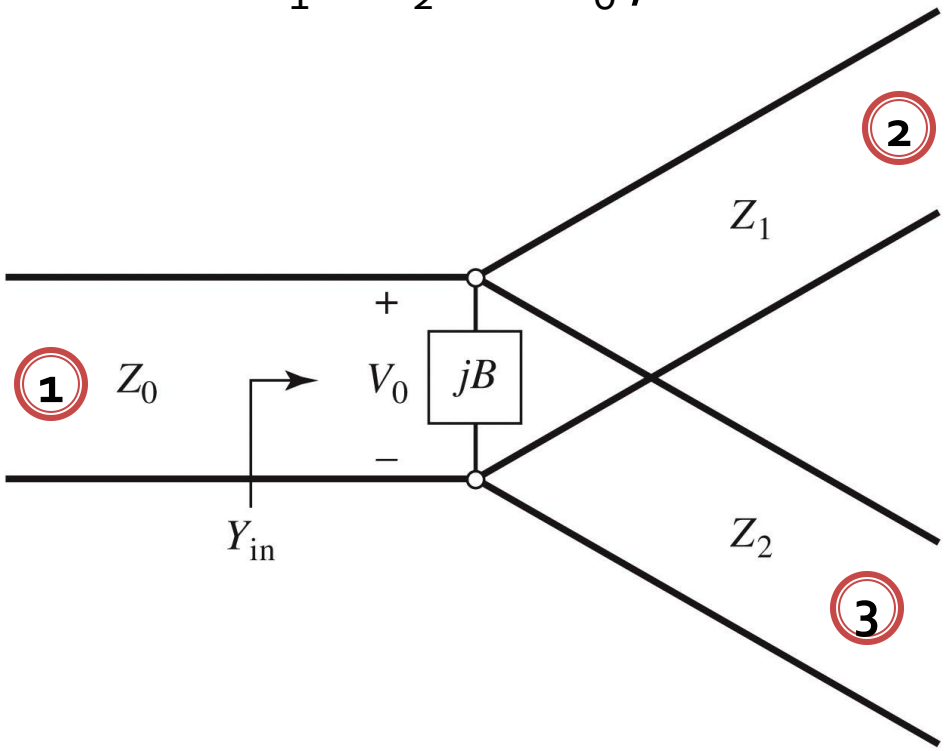



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$$[S] = \begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2} \end{bmatrix}$$

Daca se adauga transformatoare in $\lambda/4$ pentru a adapta iesirile la $Z_0$ matricea S devine:

$$[S] = \begin{bmatrix} 0 & -\frac{j}{\sqrt{2}} & -\frac{j}{\sqrt{2}} \\ -\frac{j}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2} \\ -\frac{j}{\sqrt{2}} & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

# Exemplu

- Proiectați un divizor cu joncțiune în T care are o impedanță a sursei de 30Ω, pentru a obține un raport de puteri la ieşire de 1:3. Proiectați transformatoare in sfert de lungime de undă care să convertească impedanța liniilor de ieşire la 30Ω.

$$P_{in} = \frac{1}{2} \cdot \frac{V_0^2}{Z_0}$$

$$\begin{cases} P_1 + P_2 = P_{in} \\ P_1 : P_2 = 1:3 \end{cases} \Rightarrow \begin{cases} P_1 = \frac{1}{4} \cdot P_{in} \\ P_2 = \frac{3}{4} \cdot P_{in} \end{cases}$$

$$P_1 = \frac{1}{2} \cdot \frac{V_0^2}{Z_1} = \frac{1}{4} \cdot P_{in} \qquad Z_1 = 4 \cdot Z_0 = 120\Omega$$

$$P_2 = \frac{1}{2} \cdot \frac{V_0^2}{Z_2} = \frac{3}{4} \cdot P_{in} \qquad Z_2 = 4 \cdot Z_0/3 = 40\Omega$$

Verificare

$$Z_{in} = 40\Omega || 120\Omega = 30\Omega$$

Transformatoare $Z_c^i = \sqrt{Z_i \cdot Z_L}$

$$Z_c^1 = \sqrt{Z_1 \cdot Z_L} = \sqrt{120\Omega \cdot 30\Omega} = 60\Omega \qquad Z_c^2 = \sqrt{Z_2 \cdot Z_L} = \sqrt{40\Omega \cdot 30\Omega} = 34.64\Omega$$

# Divizorul de putere rezistiv

- Introducerea elementelor disipative (pierderi) permite realizarea divizorului:
  - reciproc
  - adaptat la toate cele porti

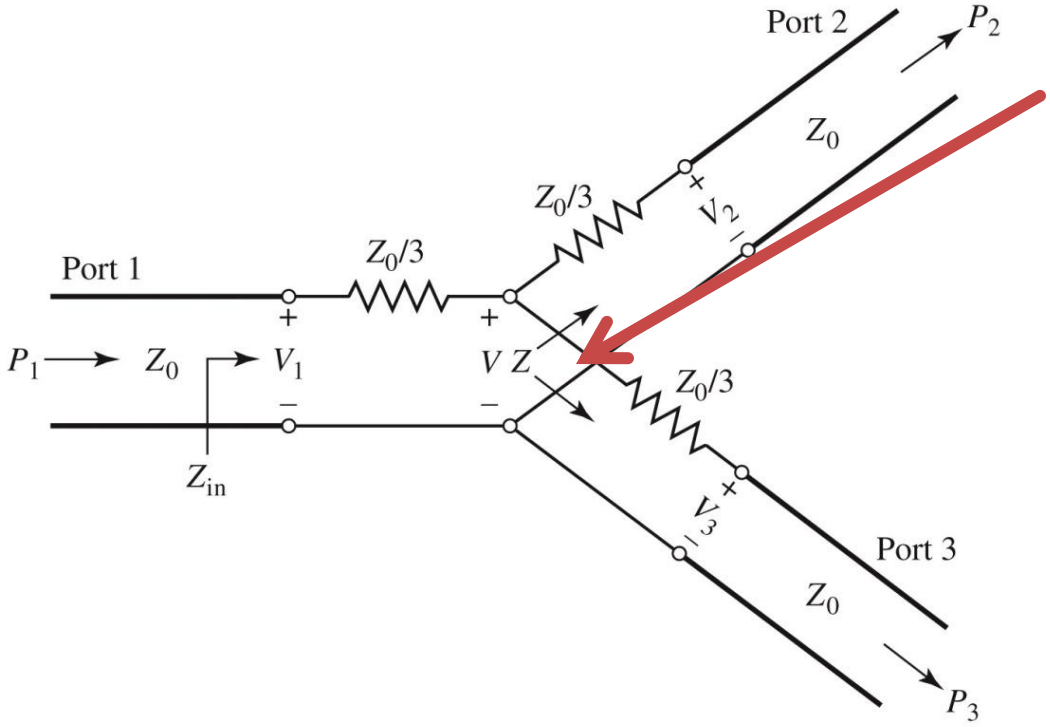



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Impedanta Z vazuta de la nivelul jonctiunii spre una din linii:

$$Z = \frac{Z_0}{3} + Z_0 = \frac{4Z_0}{3}$$

Linia de intrare va vedea la capat o rezistenta in serie cu doua astfel de linii in paralel

$$Z_{in} = \frac{Z_0}{3} + \frac{1}{2} \cdot \frac{4Z_0}{3} = Z_0$$

deci va fi adaptata: $S_{11} = 0$

din simetrie: $S_{11} = S_{22} = S_{33} = 0$

# Divizorul de putere rezistiv

- Introducerea elementelor disipative (**pierderi**) permite realizarea divizorului:
  - **reciproc** (matricea S e simetrica)
  - **adaptat** la toate cele 3 porti $S_{11} = S_{22} = S_{33} = 0$

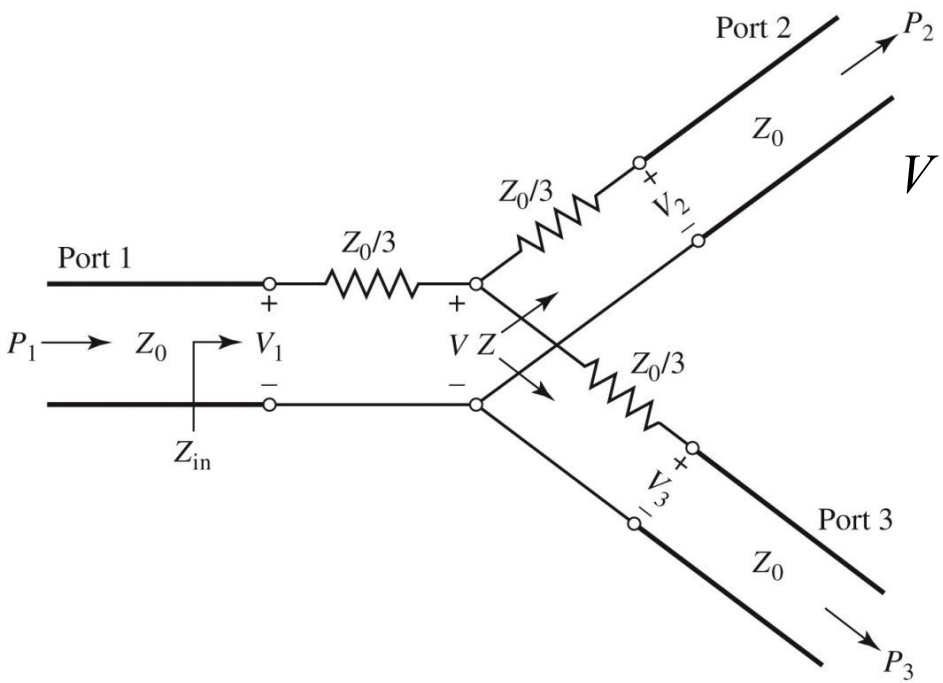



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$V_1$ e tensiunea la intrarea in portul 1, calculam tensiunea la nivelul jonctiunii V

$$V = V_1 \cdot \frac{Z/2}{Z/2 + Z_0/3} = V_1 \cdot \frac{2Z_0/3}{2Z_0/3 + Z_0/3} = \frac{2}{3} \cdot V_1$$

Tensiunile de iesire se obtin tot prin divizare:

$$V_2 = V_3 = V \cdot \frac{Z_0}{Z_0 + Z_0/3} = \frac{3}{4} \cdot V = \frac{1}{2} \cdot V_1$$

$$S_{21} = S_{31} = \frac{1}{2}$$

din simetrie: $S_{21} = S_{31} = S_{23} = \frac{1}{2}$

# Divizorul de putere rezistiv

- Introducerea elementelor disipative (pierderi) permite realizarea divizorului:
  - reciproc (matricea S e simetrica) $S_{21} = S_{31} = S_{23} = \frac{1}{2}$
  - adaptat la toate cele porti $S_{11} = S_{22} = S_{33} = 0$

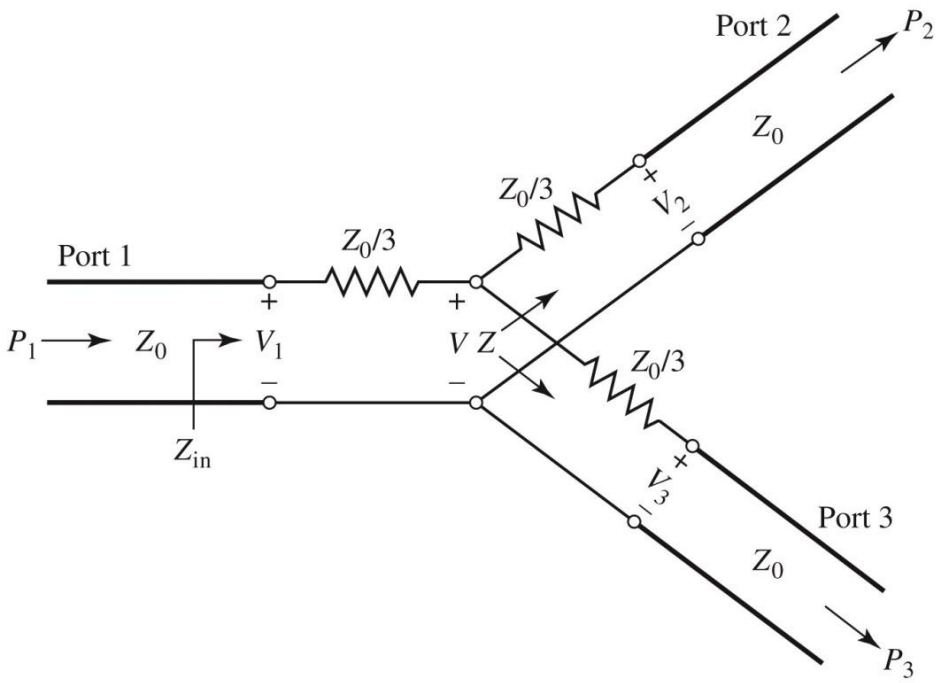



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Matricea S $$[S] = \frac{1}{2} \cdot \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

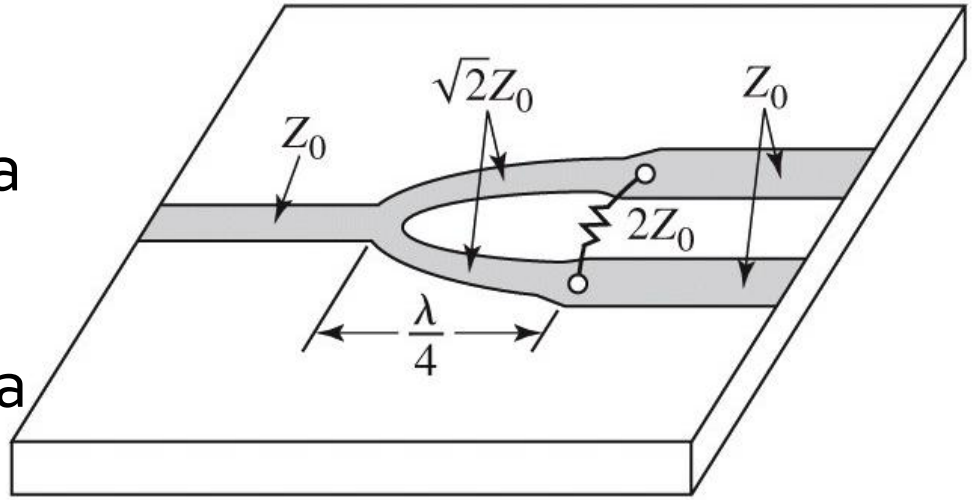
Puteri: $$P_{in} = \frac{1}{2} \cdot \frac{V_1^2}{Z_0}$$

$$P_2 = P_3 = \frac{1}{2} \cdot \frac{(1/2\,V_1)^2}{Z_0} = \frac{1}{8} \cdot \frac{V_1^2}{Z_0} = \frac{1}{4} \cdot P_{in}$$

Jumatate din putere se disipa pe cei 3 rezistori

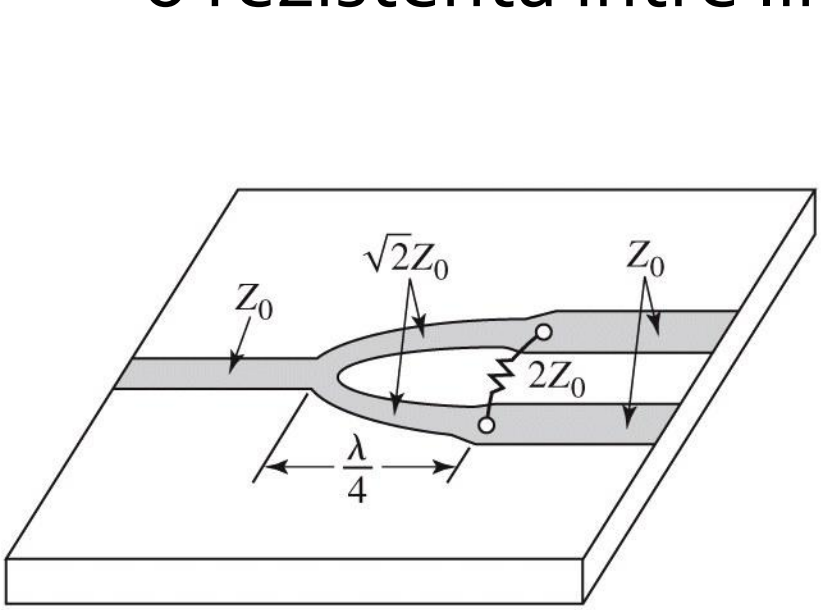
# Divizorul de putere Wilkinson

- Divizoarele de putere anterioare au un dezavantaj major, nu exista **izolare** intre cele doua porturi de iesire $S_{23} = S_{32} \neq 0$
  - acest deziderat e important in anumite aplicatii
- Divizorul Wilkinson este introdus pentru rezolvarea acestui impediment
  - o proprietate utila suplimentara este ca "pare" fara pierderi daca porturile de iesire sunt adaptate
  - numai energia reflectata din iesiri este disipata

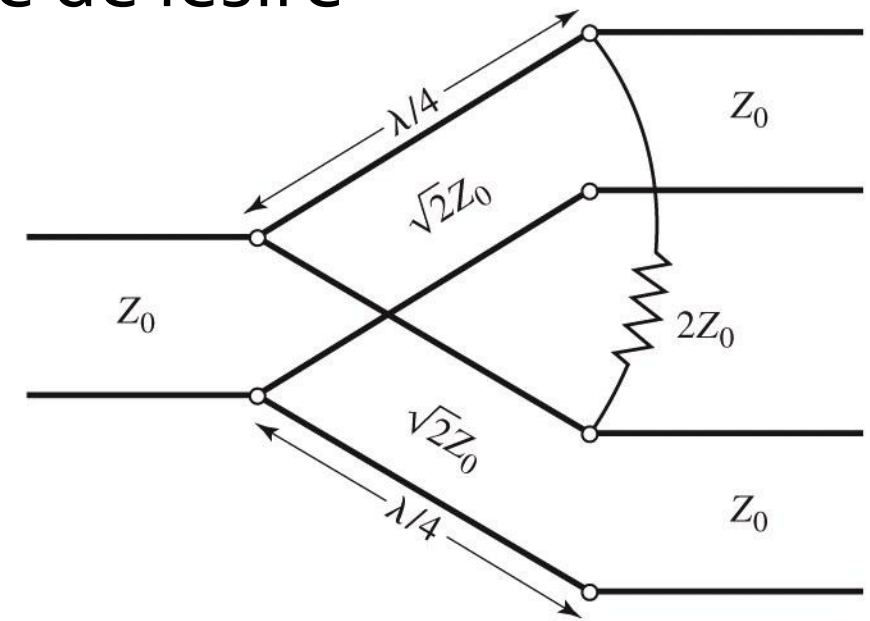


# Divizorul de putere Wilkinson

- o linie de intrare
- doua transformatoare $\lambda/4$
- o rezistenta intre liniile de iesire




(a)




(b)

Figure 7.8

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# Analiza pe mod par/impar (even/odd)

- In circuite liniare putem aplica suprapunerea efectelor
- avantaje
  - reducerea complexitatii circuitului
  - reducerea numarului de porturi (**principalul** avantaj)

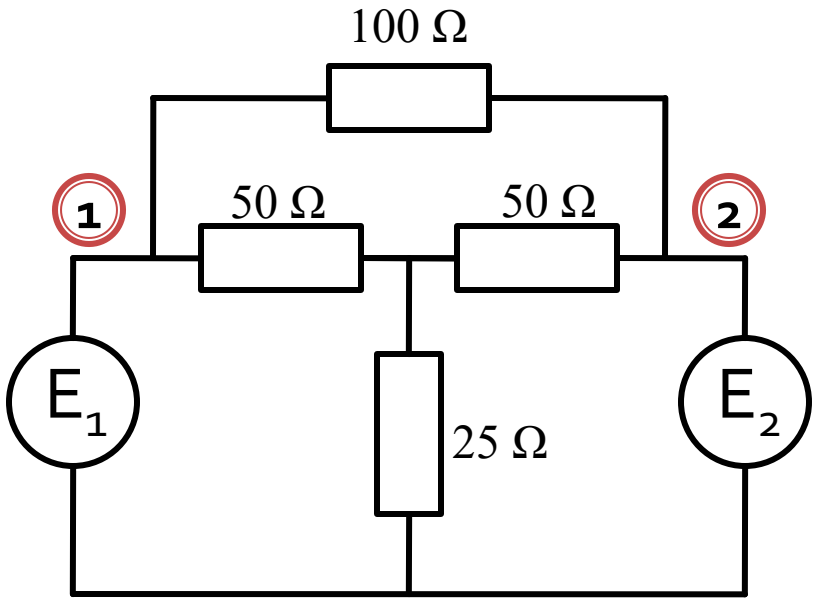
**Efect ( PAR+ IMPAR ) = Efect ( PAR ) + Efect ( IMPAR )**

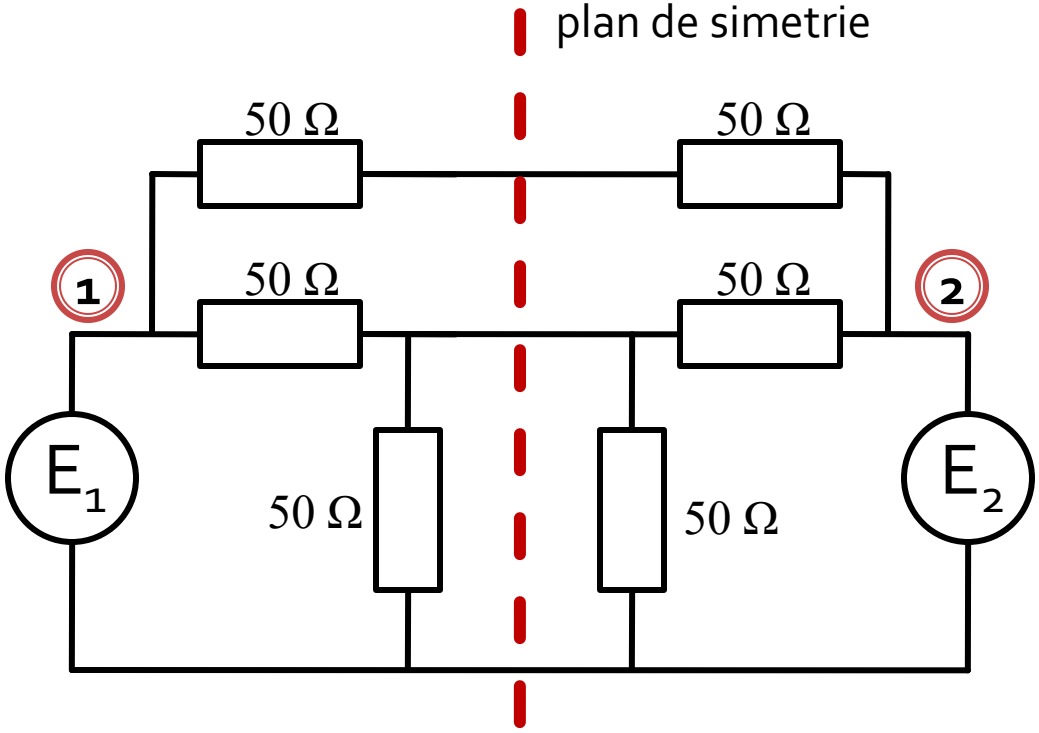


**Putem beneficia de avantajele simetriilor!!**

# Analiza pe mod par/impar (even/odd)

- analiza pe mod par/impar beneficiaza de existenta in circuit a unor plane de simetrie
  - initiale
  - create



# Divizorul de putere Wilkinson

- schema normalizata si “simetrizata”

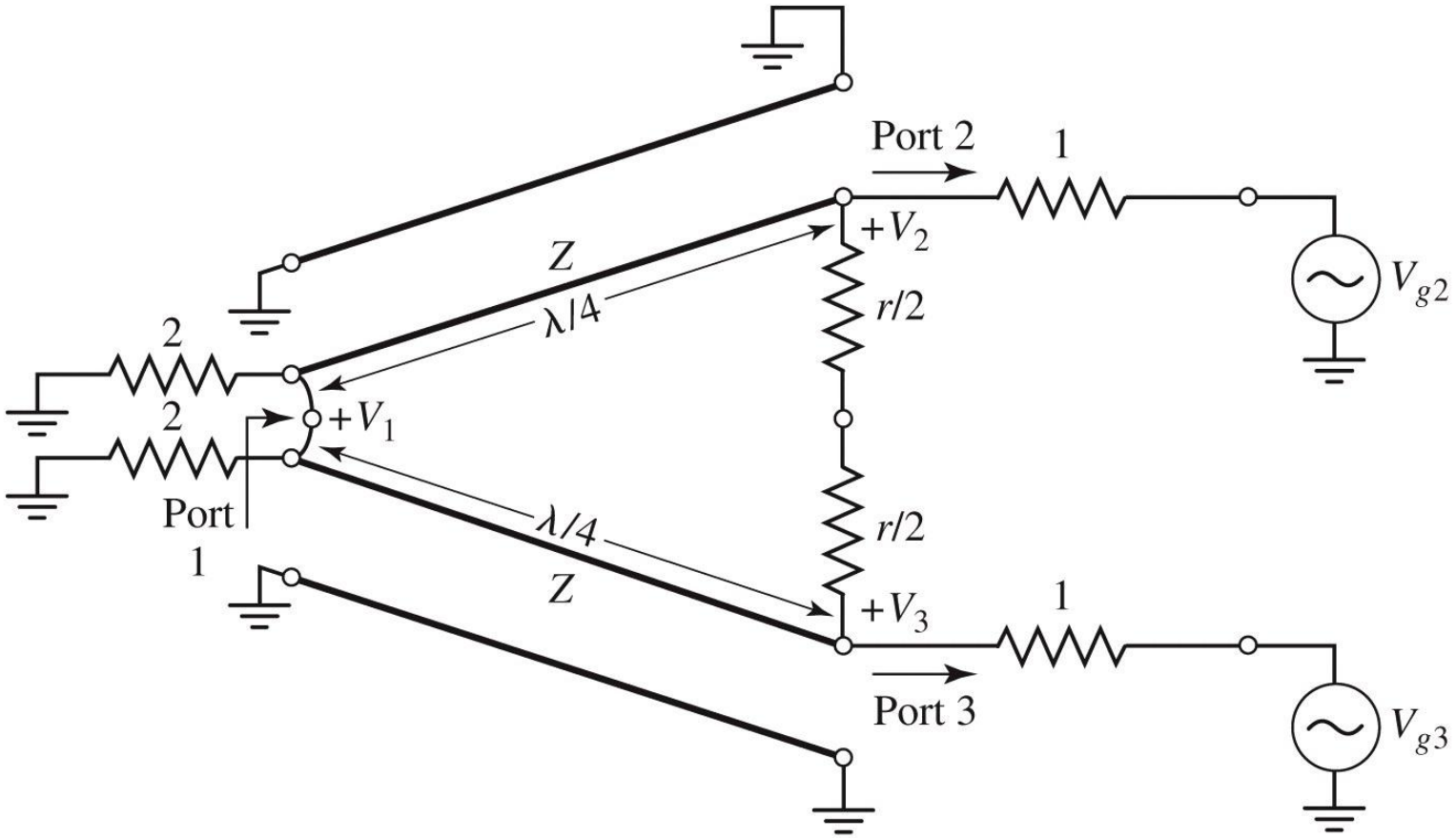
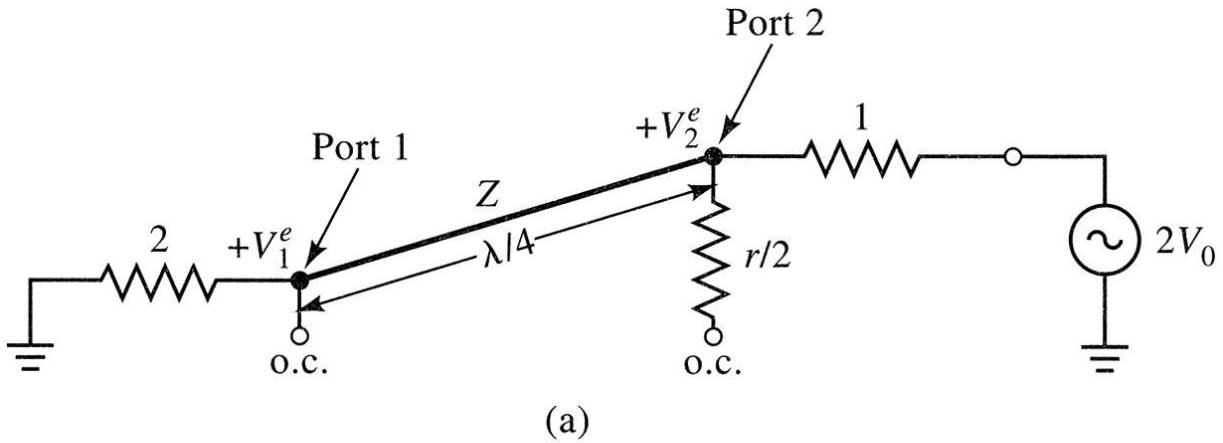



Figure 7.9

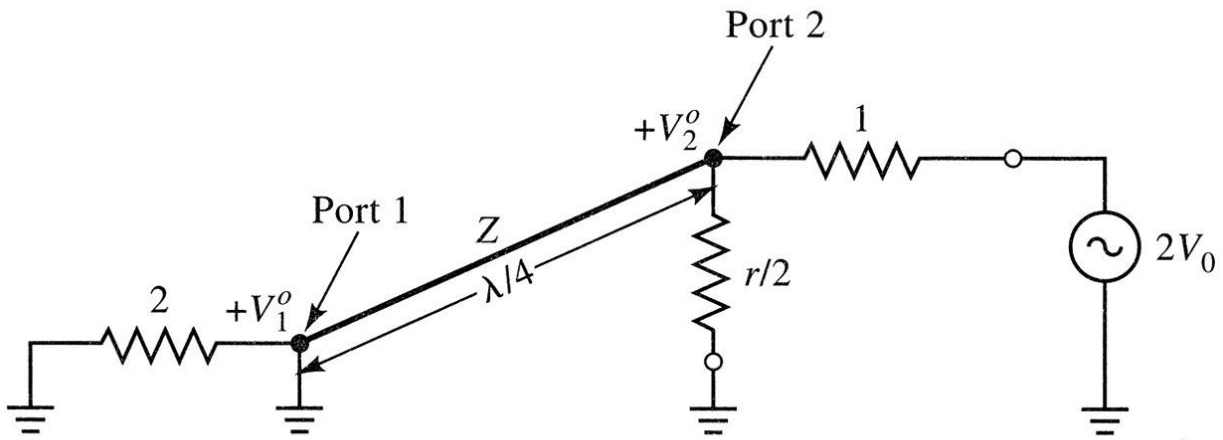
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# Divizorul de putere Wilkinson

- analiza pe mod par si impar



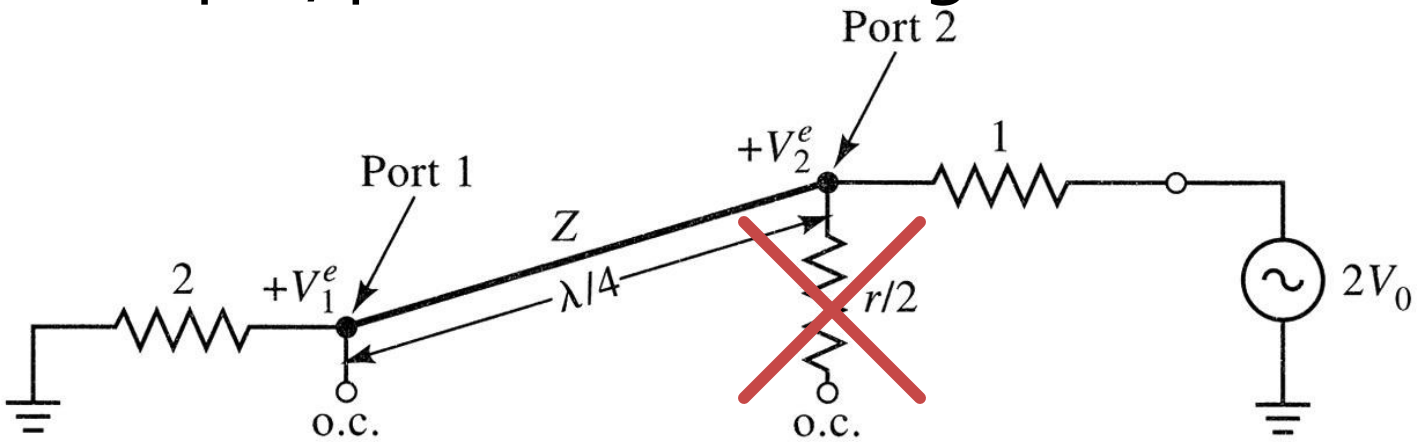

(a)




(b)

# Divizorul de putere Wilkinson

- mod par, plan de simetrie gol




privind din portul 2, transformator $\lambda/4$ $Z_{in2}^e = \frac{Z^2}{2}$ daca $Z = \sqrt{2}$ portul 2 este adaptat $Z_{in2}^e = 1$

$$V(x) = V^+ \cdot \left(e^{-j\beta \cdot x} + \Gamma \cdot e^{j\beta \cdot x}\right)$$

x=0 la portul 1

x=-$\lambda/4$ la portul 2

$$V_2^e = V(-\lambda/4) = jV^+ \cdot (1-\Gamma) = V_0 \qquad V_1^e = V(0) = V^+ \cdot (1+\Gamma) = jV_0 \cdot \frac{\Gamma+1}{\Gamma-1}$$

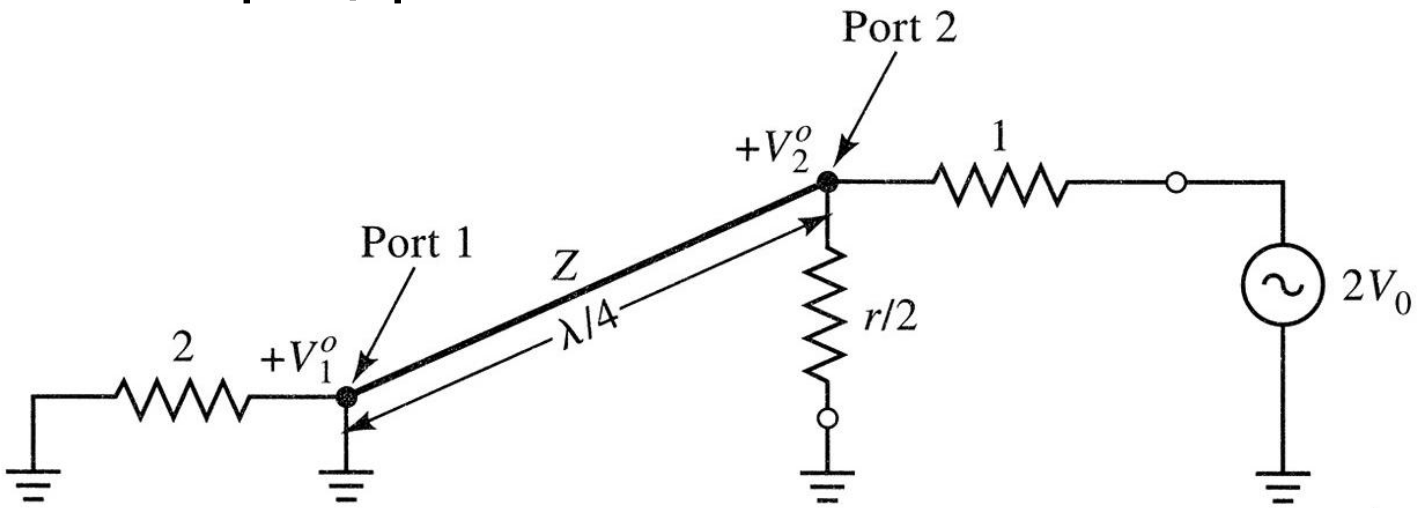
$$Z_{in2}^e = 1$$

$\Gamma$: coeficientul de reflexie vazut dinspre transformatorul cu $Z = \sqrt{2}$ spre impedanta normalizata 2

$$\Gamma = \frac{2-\sqrt{2}}{2+\sqrt{2}} \qquad V_1^e = -jV_0\sqrt{2}$$

# Divizorul de putere Wilkinson

- mod impar, plan de simetrie masa



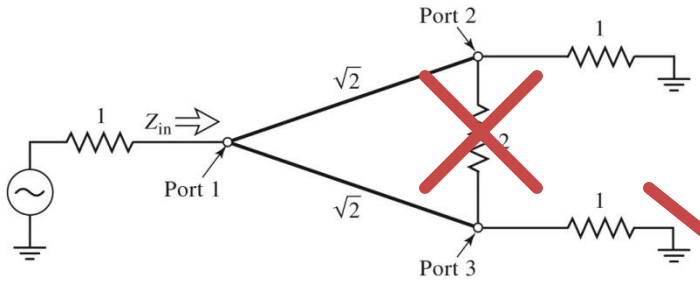

linia in $\lambda/4$ este scurtcircuitata la capat
impedanta vazuta dinspre portul 2 este $\infty$ $Z_{in2}^o = r/2$ daca $r = 2$ portul 2 este adaptat

$Z_{in2}^o = 1 \rightarrow V_2^o = V_0$

$V_1^o = 0$ in modul impar toata puterea se disipa in rezistorul *r*/2

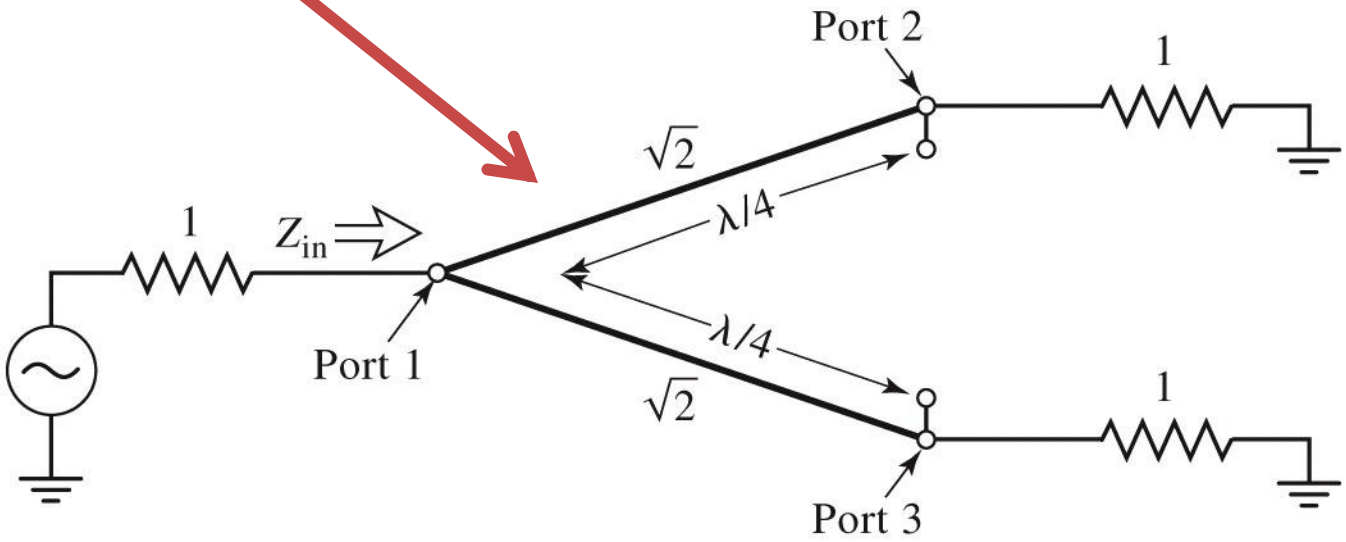
# Divizorul de putere Wilkinson

- impedanta de intrare in portul 1




doua transformatoare λ/4 in paralel

$$Z_{in1} = \frac{1}{2}\left(\sqrt{2}\right)^2 = 1$$



# Divizorul de putere Wilkinson

- parametrii S

$$Z_{in1} = \frac{1}{2}\left(\sqrt{2}\right)^2 = 1 \qquad S_{11} = 0$$

$$Z^e_{in2} = 1 \quad Z^o_{in2} = 1 \qquad \text{si similar} \quad Z^e_{in3} = 1 \quad Z^o_{in3} = 1 \qquad S_{22} = S_{33} = 0$$

$$S_{12} = S_{21} = \frac{V_1^e + V_1^o}{V_2^e + V_2^o} = -\frac{j}{\sqrt{2}}$$

si similar $S_{13} = S_{31} = -\frac{j}{\sqrt{2}}$

$S_{23} = S_{32} = 0$ scurt sau gol intre porturile 2 si 3 elimina orice transfer de putere + circuit reciproc

# Divizorul de putere Wilkinson

- la frecventa de proiectare (lungimile transformatoarelor egale cu $\lambda_0/4$) avem izolare intre cele doua linii de iesire

$$[S] = \begin{bmatrix} 0 & -\frac{j}{\sqrt{2}} & -\frac{j}{\sqrt{2}} \\ -\frac{j}{\sqrt{2}} & 0 & 0 \\ -\frac{j}{\sqrt{2}} & 0 & 0 \end{bmatrix}$$

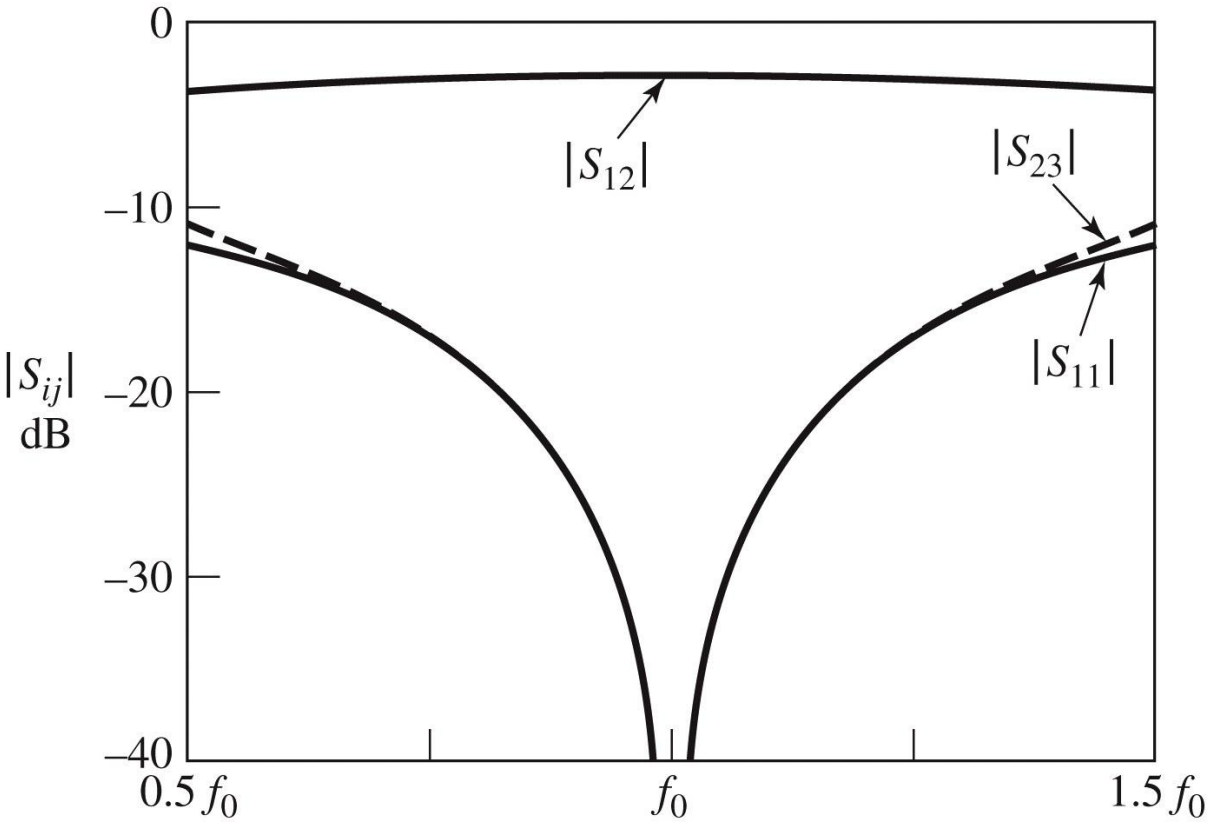



Figure 7.12
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# Divizorul de putere Wilkinson

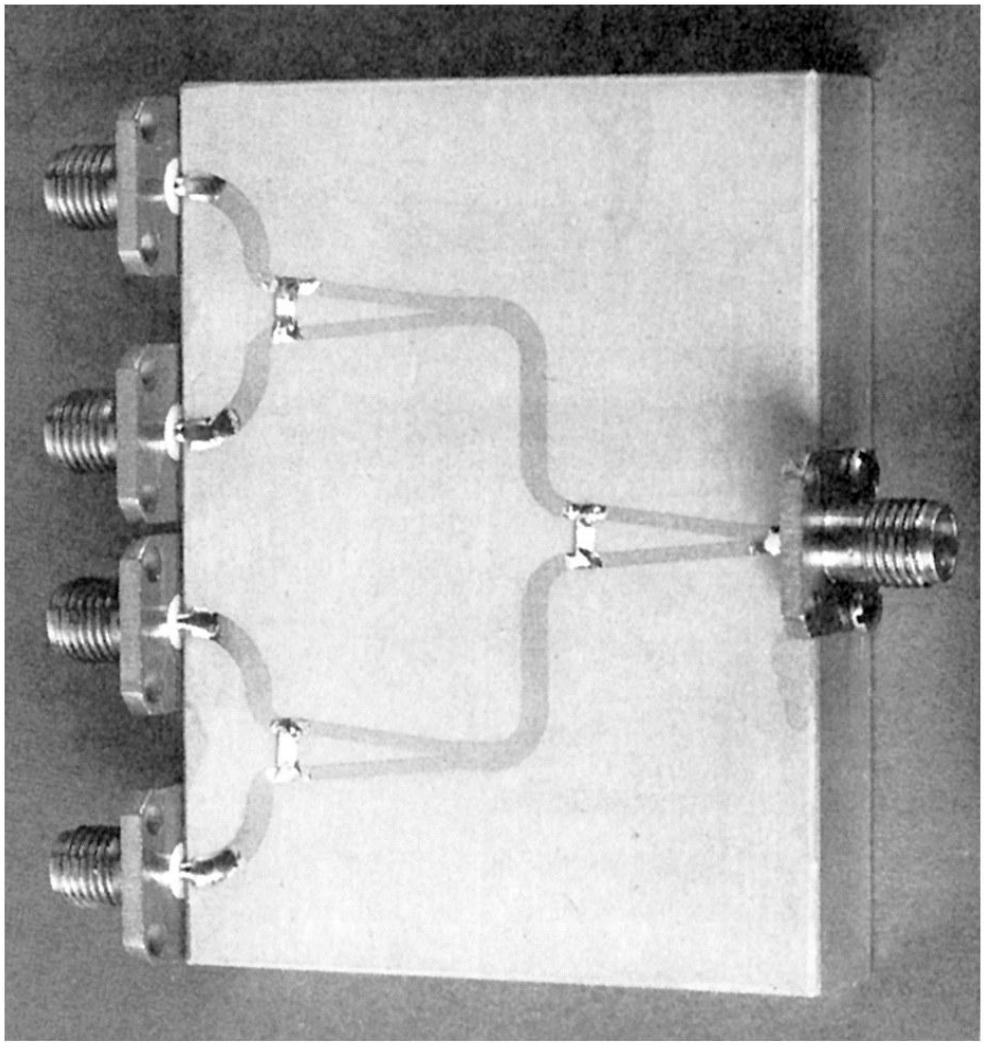
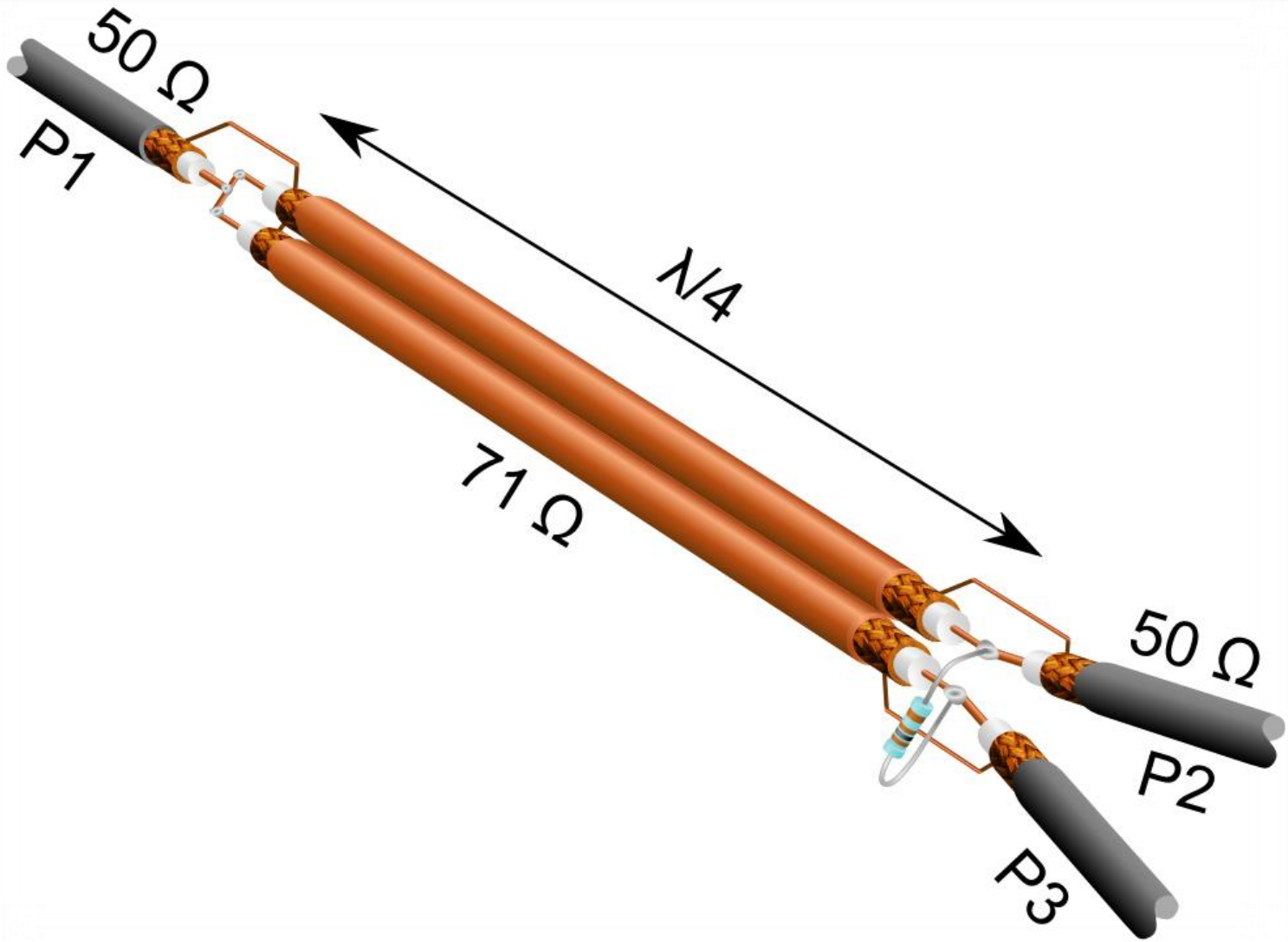


Figure 7.15
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

- 3 X Wilkinson = divizor de putere pe 4 porturi

# Divizorul de putere Wilkinson



# Cuploare directionale

# Circuite cu patru porți

- Un circuit cu 4 porti care este simultan:
  - adaptat la toate portile
  - reciproc
  - fara pierderi
- este **intotdeauna directional**
  - puterea de semnal introdusa pe un port este trimisa **numai spre doua** din celelalte trei porturi

$$[S]=\begin{bmatrix} 0 & \alpha & \beta\cdot e^{j\theta} & 0 \\ \alpha & 0 & 0 & \beta\cdot e^{j\phi} \\ \beta\cdot e^{j\theta} & 0 & 0 & \alpha \\ 0 & \beta\cdot e^{j\phi} & \alpha & 0 \end{bmatrix}$$

# Circuite cu patru porți

- 2 cazuri mai des intalnite in practica
  - cuplor simetric $\theta = \phi = \pi/2$

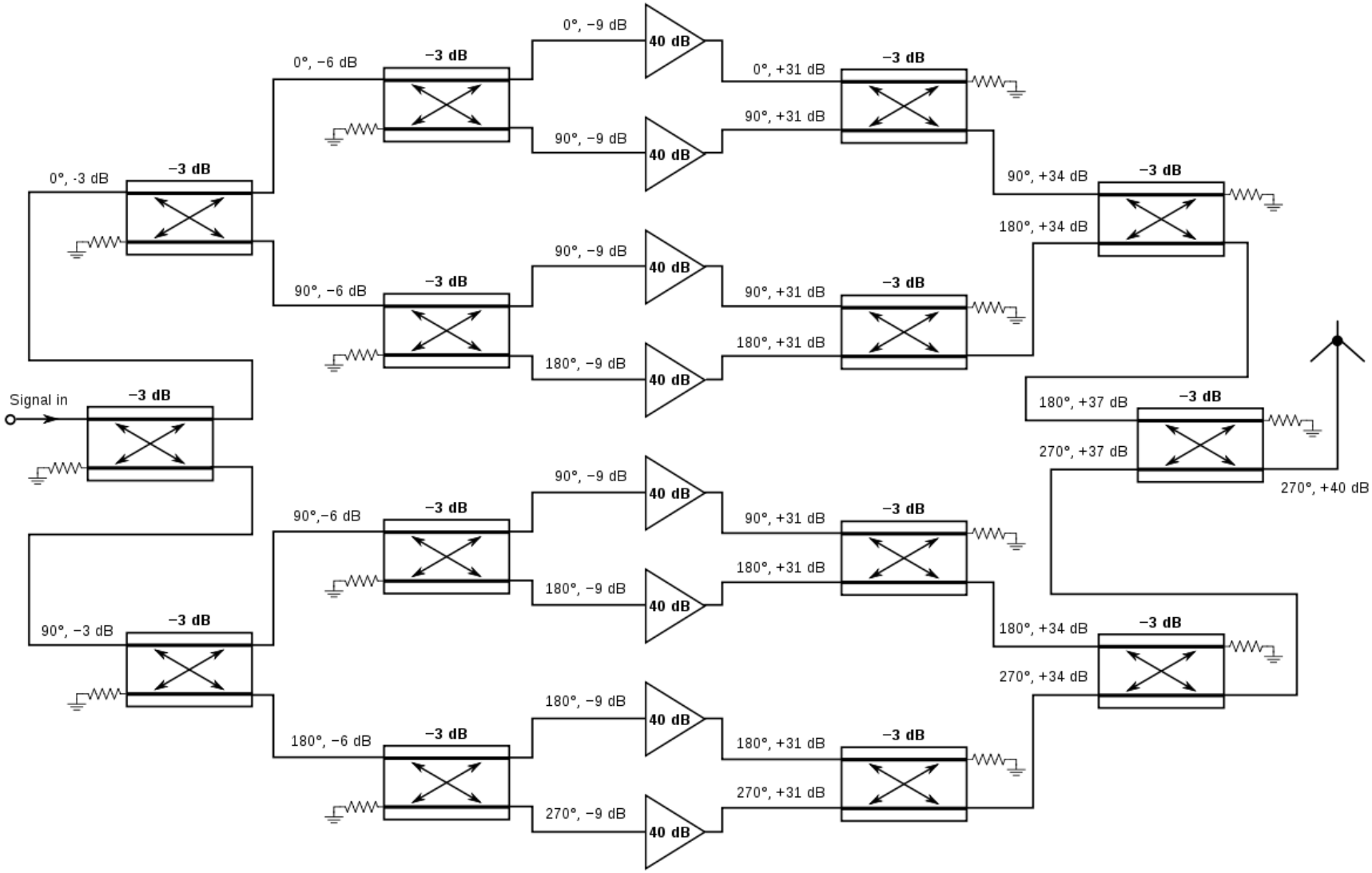
$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

  - cuplor asimetric $\theta = 0, \phi = \pi$

$$[S] = \begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

β – coeficientul de cuplaj în tensiune

# Amplificatoare echilibrate



# Cuplor directional

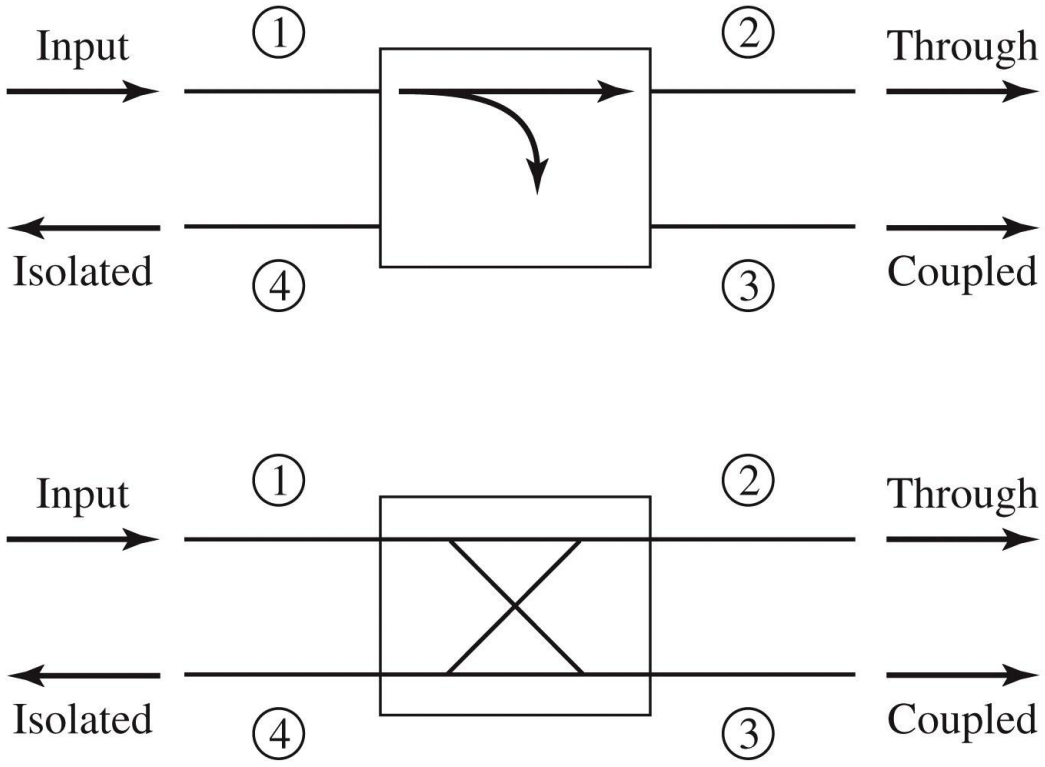



Figure 7.4
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$$|S_{12}|^2 = \alpha^2 = 1 - \beta^2$$

$$|S_{13}|^2 = \beta^2$$

**Cuplaj**

$$C = 10\log\frac{P_1}{P_3} = -20\cdot\log(\beta)\,[\text{dB}]$$

**Directivitate**

$$D = 10\log\frac{P_3}{P_4} = 20\cdot\log\left(\frac{\beta}{|S_{14}|}\right)[\text{dB}]$$

**Izolare**

$$I = 10\log\frac{P_1}{P_4} = -20\cdot\log|S_{14}|\,[\text{dB}]$$

$$I = D + C\ ,\ \ dB$$

# Cuplor hibrid

Cuplorul hibrid este cuplorul directional de 3 dB

$$\alpha = \beta = 1/\sqrt{2}$$

**Cuplor hibrid in cuadratura**

$$(\theta = \phi = \pi/2)$$

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

**Cuplor hibrid in inel**

$$(\theta = 0\,, \phi = \pi)$$

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

# Cuplorul hibrid în cuadratură (90°)

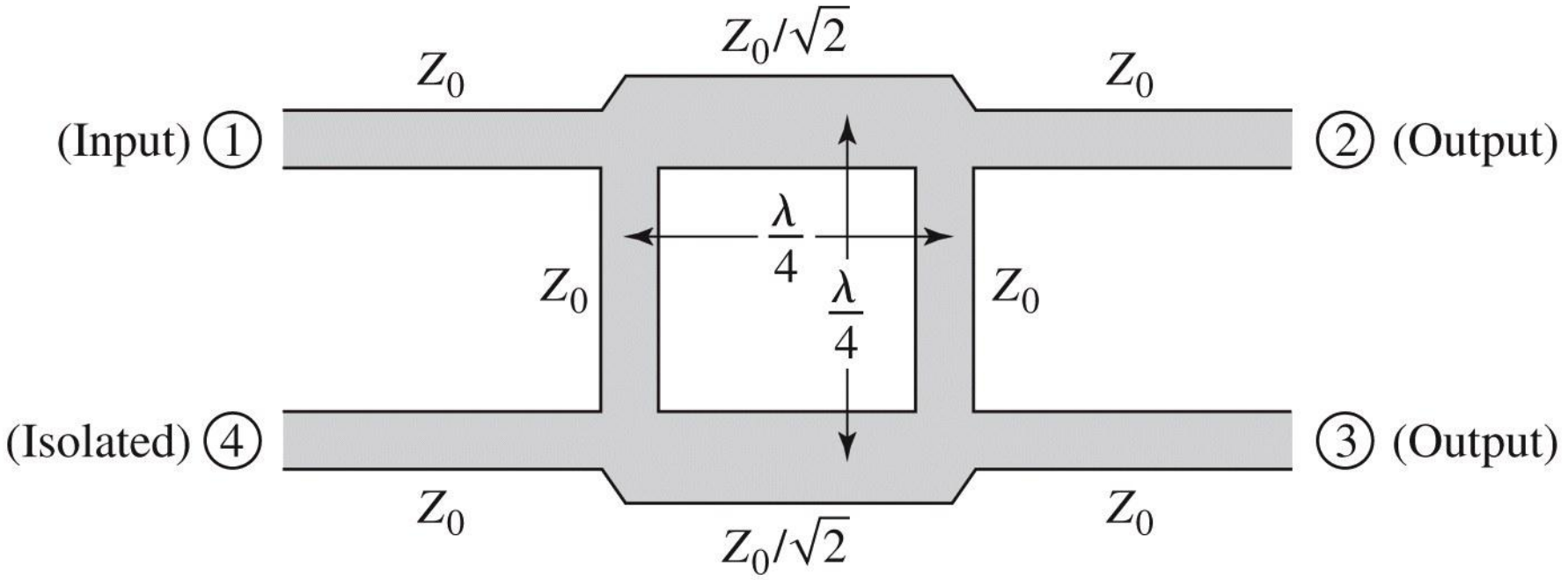
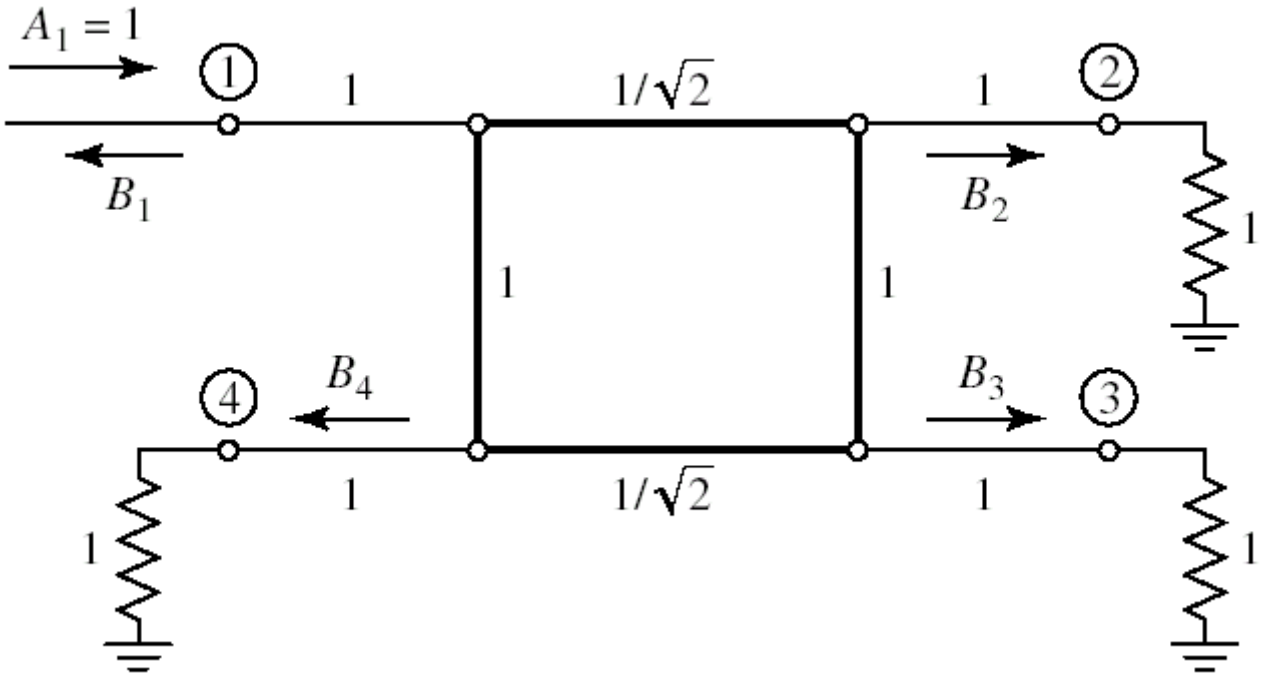



Figure 7.21
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$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

# Analiza pe modul par-impar



# Analiza pe modul par-impar

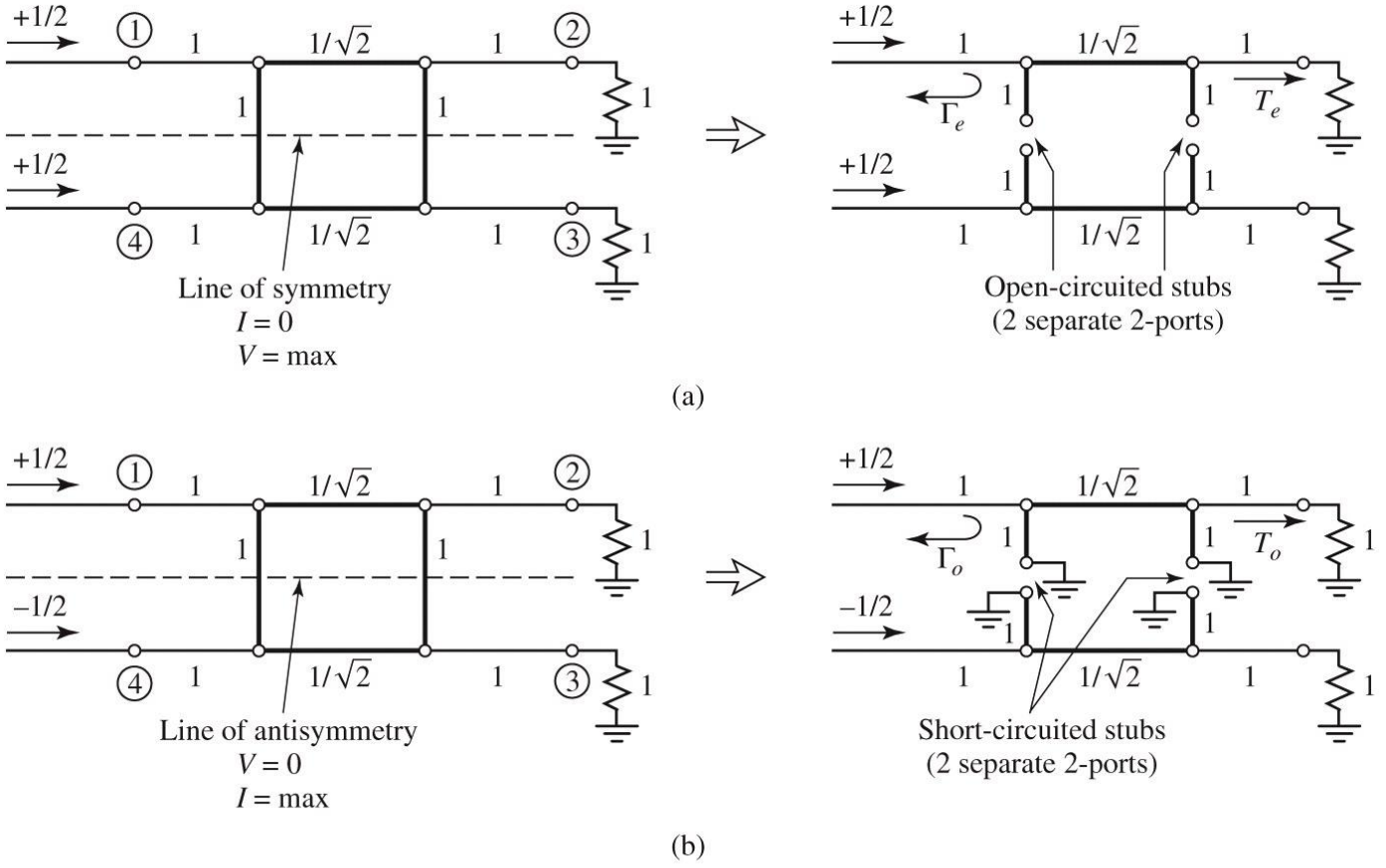


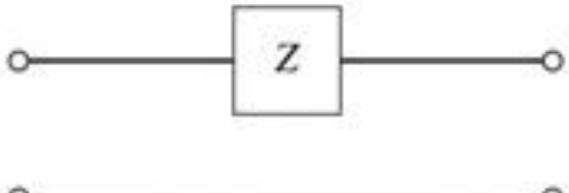
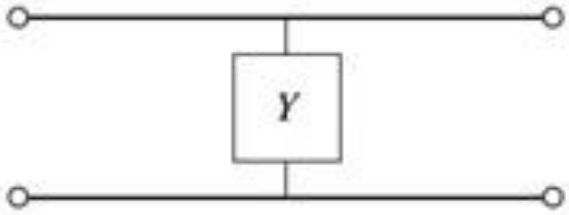
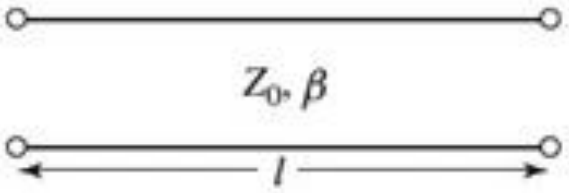

Figure 7.23

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$$b_1 = \frac{1}{2}\Gamma_e + \frac{1}{2}\Gamma_o \qquad b_2 = \frac{1}{2}T_e + \frac{1}{2}T_o \qquad b_3 = \frac{1}{2}T_e - \frac{1}{2}T_o \qquad b_4 = \frac{1}{2}\Gamma_e - \frac{1}{2}\Gamma_o$$

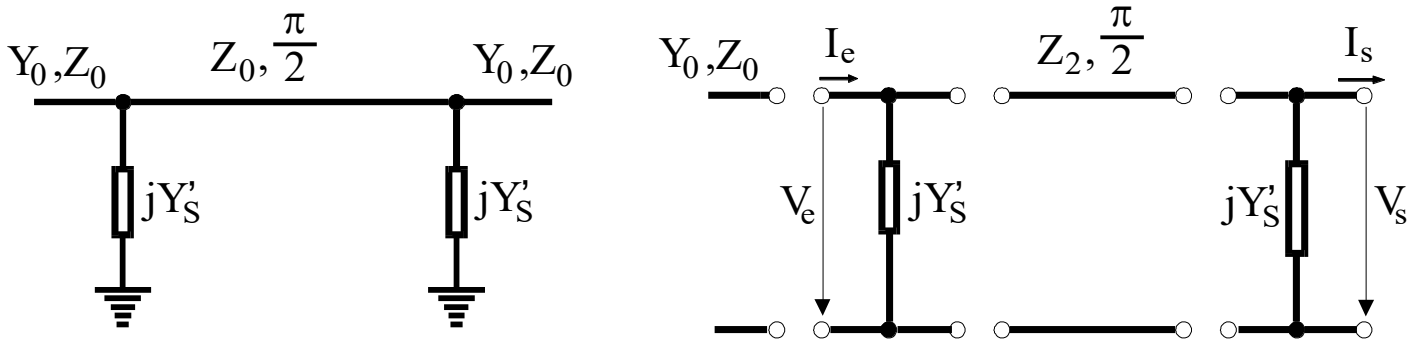
# Biblioteci de matrici ABCD

**TABLE 4.1** *ABCD* Parameters of Some Useful Two-Port Circuits

| Circuit | *ABCD* Parameters | |
|---|---|---|
|  | $A = 1$<br>$C = 0$ | $B = Z$<br>$D = 1$ |
|  | $A = 1$<br>$C = Y$ | $B = 0$<br>$D = 1$ |
|  | $A = \cos \beta\ell$<br>$C = jY_0 \sin \beta\ell$ | $B = jZ_0 \sin \beta\ell$<br>$D = \cos \beta\ell$ |

# Calculul cuploarelor cu două trepte

$$Y'_S = \begin{cases} Y_1 & \text{pentru modul par} \\ -Y_1 & \text{pentru modul impar} \end{cases}$$




a) b)

$$\begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY'_S & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 & jZ_2 \\ jY_2 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ jY'_S & 1 \end{bmatrix} \cdot \begin{bmatrix} V_S \\ I_S \end{bmatrix} \qquad \begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} -Y'_S Z_2 & jZ_2 \\ -jY'^2_S Z_2 + jY_2 & -Y'_S Z_2 \end{bmatrix} \cdot \begin{bmatrix} V_S \\ I_S \end{bmatrix}$$

$$S_{11} = \frac{j\frac{Z_2}{Z_0} - Z_0\left(-jY'^2_S Z_2 + jY_2\right)}{-2Y'_S Z_2 + j\frac{Z_2}{Z_0} + Z_0\left(-jY'^2_S + jY_2\right)} \qquad S_{12} = \frac{2\left[(-Y'_S Z_2)^2 - jZ_2\left(-jY'^2_S Z_2 + jY_2\right)\right]}{-2Y'_S Z_2 + j\frac{Z_2}{Z_0} + Z_0\left(-jY'^2_S Z_2 + jY_2\right)}$$

$$\Gamma = S_{11} = \frac{j\left(z_2 - y_2 + y'^2_S z_2\right)}{-2y'_S z_2 + j\left(z_2 + y_2 - y'^2_S z_2\right)} = S_{22}$$

$$S_{21} = \frac{2}{-2Y'_S Z_2 + j\frac{Z_2}{Z_0} + Z_0\left(-jY'^2_S Z_2 + jY_2\right)} \qquad S_{22} = \frac{j\frac{Z_2}{Z_0} - Z_0\left(-jY'^2_S Z_2 + jY_2\right)}{-2Y'_S Z_2 + j\frac{Z_2}{Z_0} + Z_0\left(-jY'^2_S Z_2 + jY_2\right)}$$

$$T = S_{21} = \frac{2}{-2y'_S z_2 + j\left(z_2 + y_2 - y'^2_S z_2\right)} = S_{12}$$

# Legatura dintre parametrii S si parametrii ABCD

$$A = \sqrt{\frac{Z_{01}}{Z_{02}}}\,\frac{(1+S_{11}-S_{22}-\Delta S)}{2S_{21}}$$

$$B = \sqrt{Z_{01}Z_{02}}\,\frac{(1+S_{11}+S_{22}+\Delta S)}{2S_{21}}$$

$$C = \frac{1}{\sqrt{Z_{01}Z_{02}}}\,\frac{1-S_{11}-S_{22}+\Delta S}{2S_{21}}$$

$$D = \sqrt{\frac{Z_{02}}{Z_{01}}}\,\frac{1-S_{11}+S_{22}-\Delta S}{2S_{21}}$$

$$\Delta S = S_{11}S_{22} - S_{12}S_{21}$$

$$S_{11} = \frac{AZ_{02}+B-CZ_{01}Z_{02}-DZ_{01}}{AZ_{02}+B+CZ_{01}Z_{02}+DZ_{01}}$$

$$S_{12} = \frac{2(AD-BC)\sqrt{Z_{01}Z_{02}}}{AZ_{02}+B+CZ_{01}Z_{02}+DZ_{01}}$$

$$S_{21} = \frac{2\sqrt{Z_{01}Z_{02}}}{AZ_{02}+B+CZ_{01}Z_{02}+DZ_{01}}$$

$$S_{22} = \frac{-AZ_{02}+B-CZ_{01}Z_{02}+DZ_{01}}{AZ_{02}+B+CZ_{01}Z_{02}+DZ_{01}}$$

# Adaptarea cuplorului si coeficientul de cuplaj

$$\Gamma_e = \frac{j\cdot\left(z_2 - y_2 + y_1^2 z_2\right)}{-2y_1 z_2 + j\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$\Gamma_o = \frac{j\cdot\left(z_2 - y_2 + y_1^2 z_2\right)}{2y_1 z_2 + j\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$T_e = \frac{2}{-2y_1 z_2 + j\cdot\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$T_o = \frac{2}{2y_1 z_2 + j\cdot\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$b_1 = \frac{\Gamma_e + \Gamma_o}{2} = \frac{z_2^2 - \left(y_2 - y_1^2 z_2\right)^2}{(2y_1 z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_2 = \frac{T_e + T_o}{2} = \frac{-2j\left(z_2 + y_2 - y_1^2 z_2\right)}{(2y_1 z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_3 = \frac{T_e - T_o}{2} = \frac{-4y_1 z_2}{(2y_1 z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_4 = \frac{\Gamma_e - \Gamma_o}{2} = \frac{-2jy_1 z_2\left(z_2 - y_2 + y_1^2 z_2\right)}{(2y_1 z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_1 = 0 \Rightarrow z_2 - y_2 + y_1^2 z_2 = 0 \Rightarrow z_2^2 = \frac{1}{1 + y_1^2}$$

$$\boxed{y_2^2 = 1 + y_1^2}$$

$$C = 10\log\frac{P_1}{P_3} = -20\log|b_3|\ ,dB$$

$$b_1 = 0\ b_4 = 0\ b_3 = -y_1 z_2\ \ b_2 = -jz_2$$

$$b_3 = -\frac{\sqrt{y_2^2 - 1}}{y_2}\ ,\ b_2 = -\frac{j}{y_2}$$

$$\boxed{\beta = \frac{\sqrt{y_2^2 - 1}}{y_2}}$$

$$b_3 = -C$$

$$b_2 = -j\sqrt{1 - C^2}$$

$$[S] = \begin{bmatrix} 0 & -j\sqrt{1-C^2} & -C & 0 \\ -j\sqrt{1-C^2} & 0 & 0 & -C \\ -C & 0 & 0 & -j\sqrt{1-C^2} \\ 0 & -C & -j\sqrt{1-C^2} & 0 \end{bmatrix}$$

# Cuplorul in cuadratura

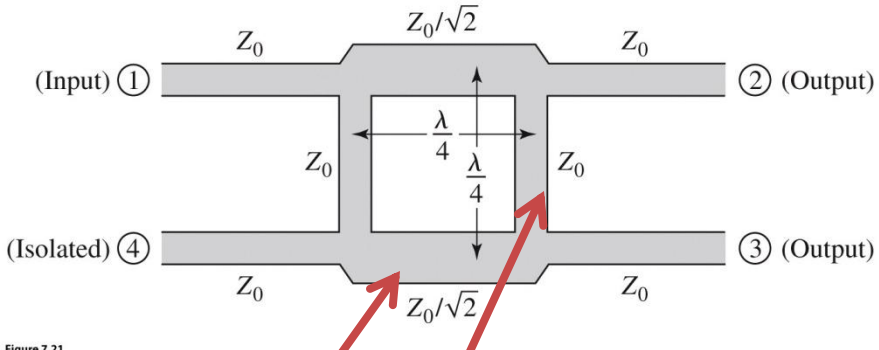



Figure 7.21
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$$y_2^2 = 1 + y_1^2$$

$$|\beta| = \frac{\sqrt{y_2^2 - 1}}{y_2}$$

$$C[\text{dB}] = -20 \cdot \log_{10} \frac{\sqrt{y_2^2 - 1}}{y_2}$$

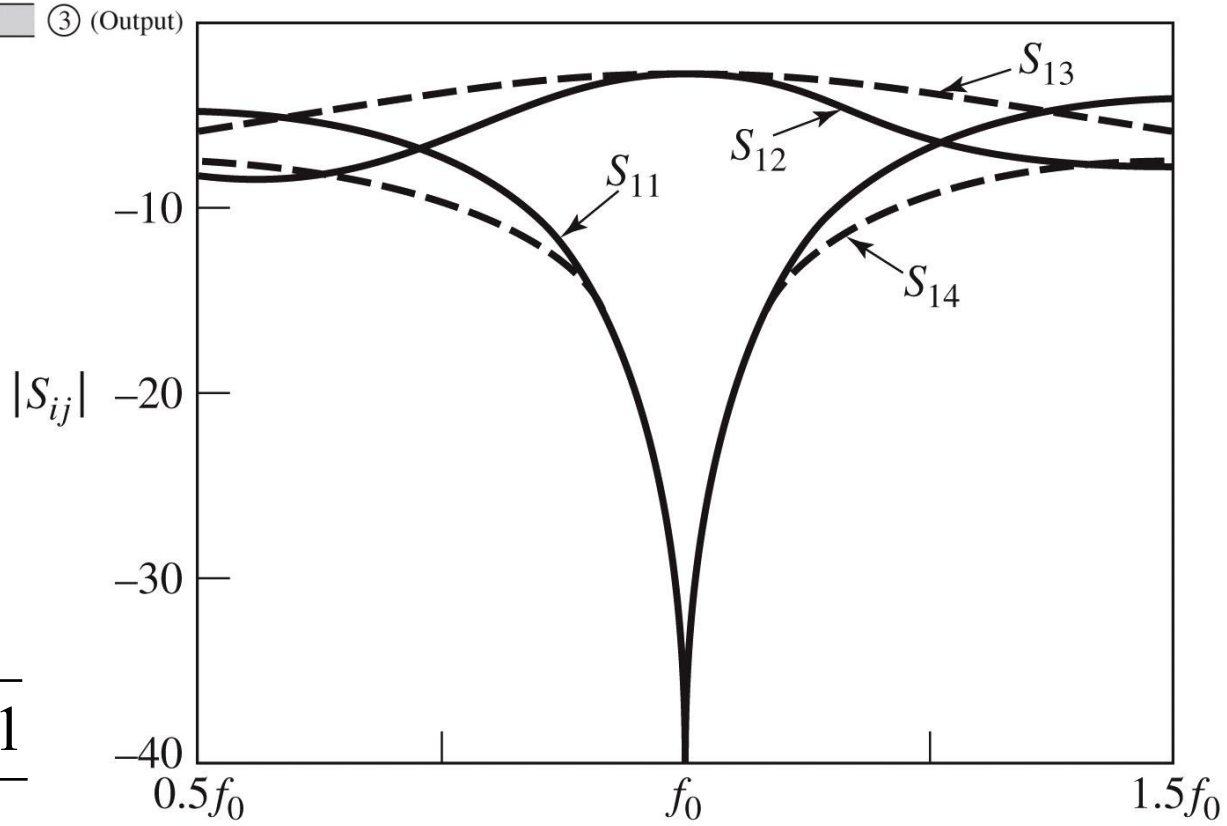



Figure 7.25
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# Exemplu

Proiectaţi un cuplor în scară pe impedanţa caracteristică de 50 Ω, şi reprezentati mărimea parametrilor S între

$$0.5 f_0 \text{ şi } 1.5 f_0 \text{ , unde } f_0$$

este frecvenţa de proiectare la care liniile cuplorului sunt de lungime $\lambda/4$

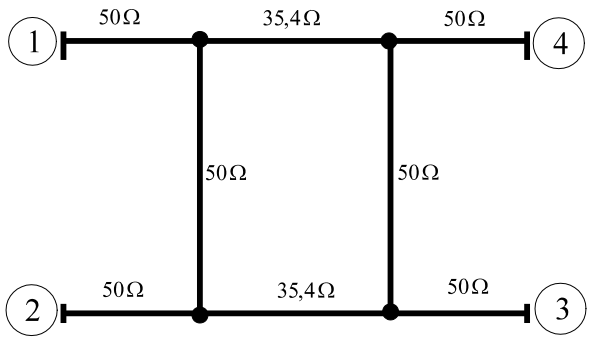
# Solutie

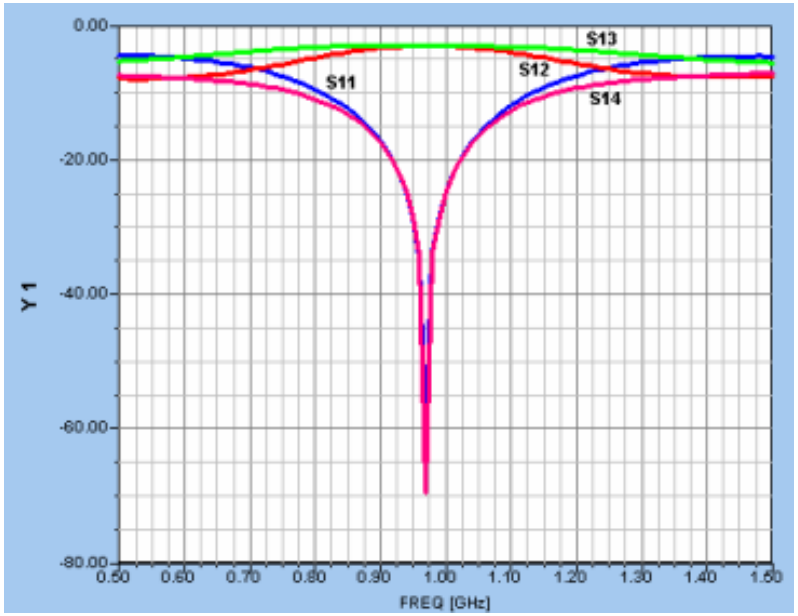
Un cuplor în cuadratură (scară) cu C = 3dB, are $C = 1/\sqrt{2}$ . Atunci

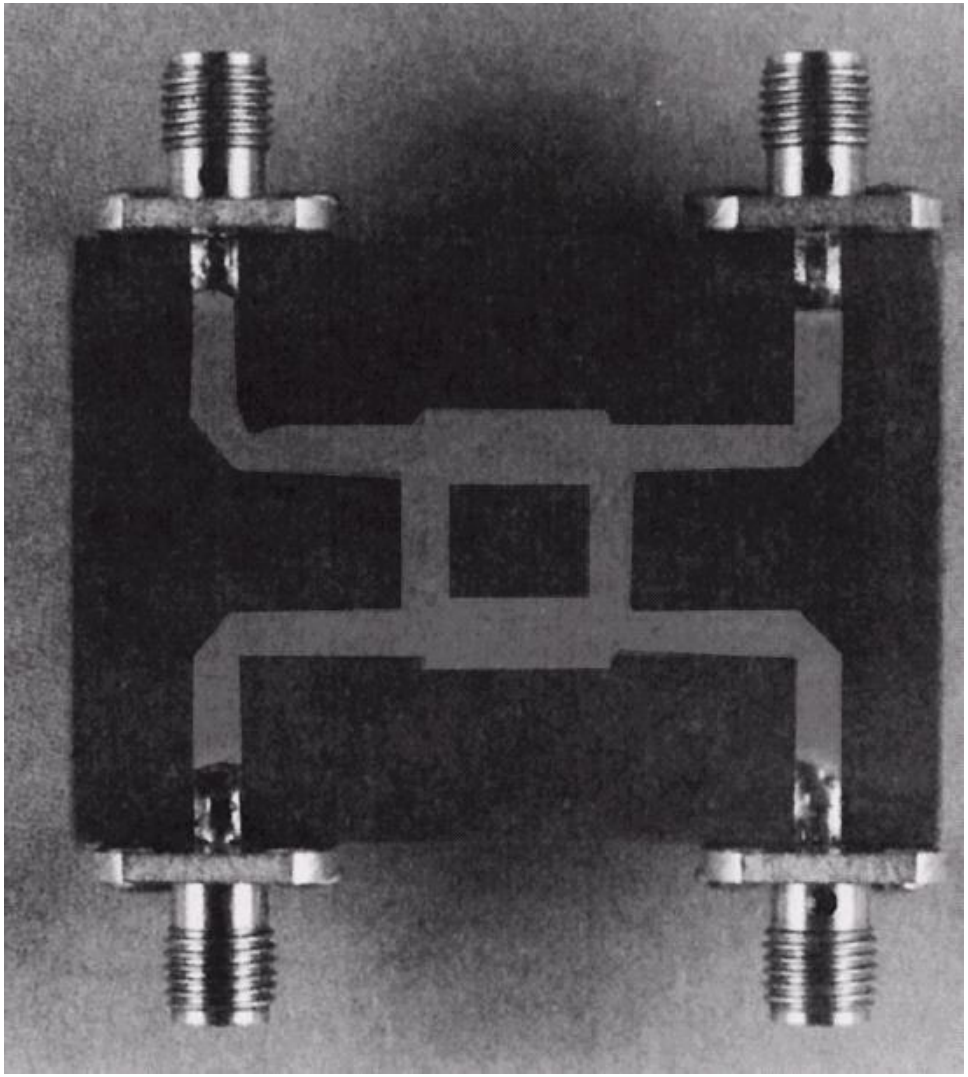
$$y_2 = \sqrt{2} \quad \text{şi} \quad y_1 = 1$$

Pentru $Z_0 = 50\Omega$ impedanţele caracteristice ale liniilor cuplorului vor fi:

$$Z_1 = Z_0 = 50\Omega \qquad Z_2 = \frac{Z_0}{\sqrt{2}} = 35.4\Omega$$





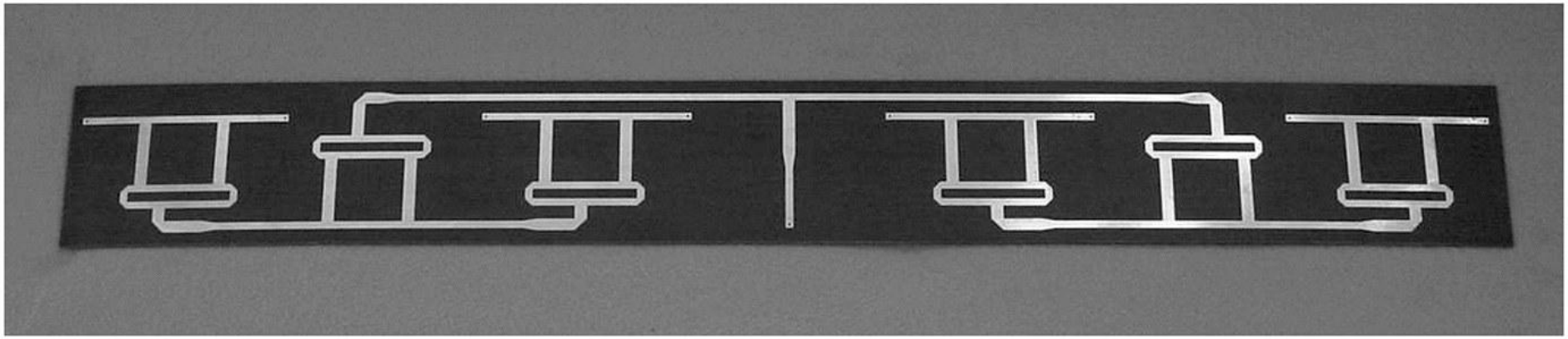
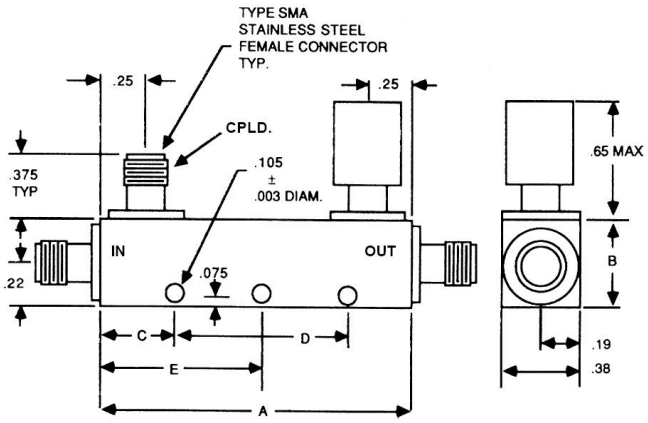


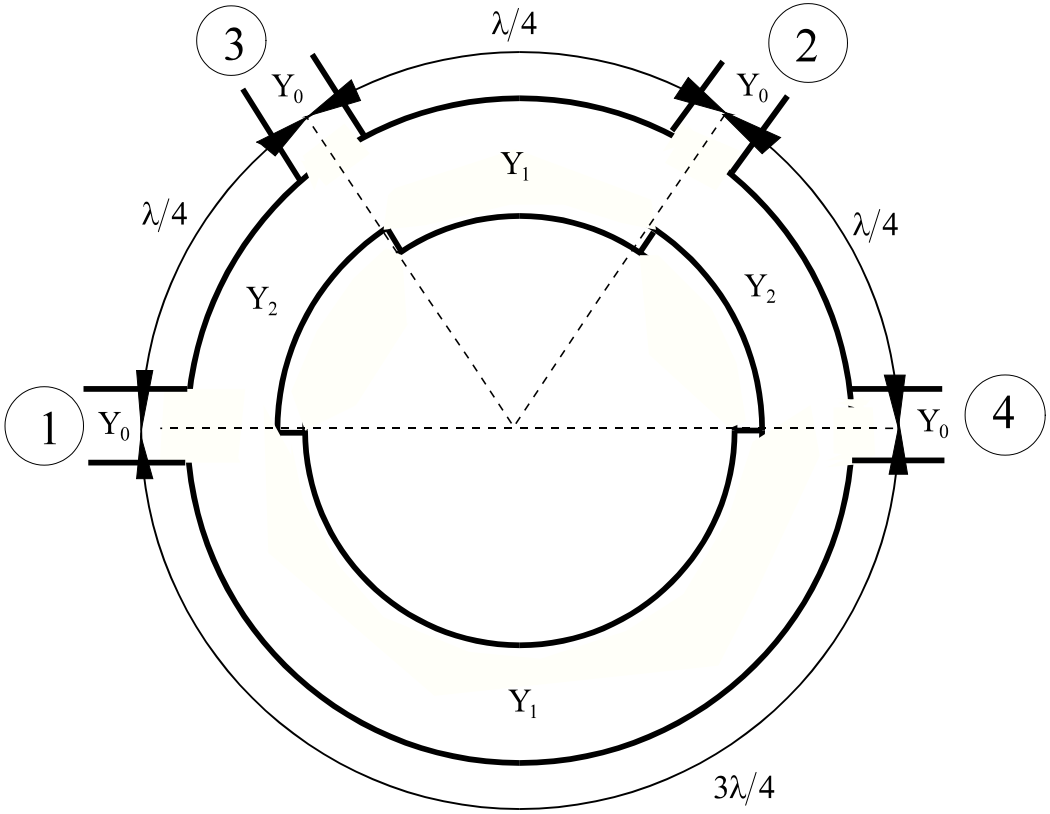
**Figure 7.24**
**Courtesy of ProSensing, Inc., Amherst, Mass.**

# Catalog




| Model No. | Frequency Range (Ghz) | Coupling † (dB) | Freq. Sens. (dB) | Insertion Loss (dB) | | Directivity (dB min.) | VSWR max. | |
|---|---|---|---|---|---|---|---|---|
| | | | | Excl. Cpld Pwr | True | | Primary Line | Secondary Line |
| MDC6223-6 | 0.5-1.0 | 6 ±1.00 | ±0.60 | 0.20 | 1.80 | 25 | 1.15 | 1.15 |
| MDC6223-10 | 0.5-1.0 | 10 ±1.25 | ±0.75 | 0.20 | 0.80 | 25 | 1.10 | 1.10 |
| MDC6223-20 | 0.5-1.0 | 20 ±1.25 | ±0.75 | 0.15 | 0.20 | 25 | 1.10 | 1.10 |
| MDC6223-30 | 0.5-1.0 | 30 ±1.25 | ±0.75 | 0.15 | 0.20 | 25 | 1.10 | 1.10 |
| MDC6224-6 | 1.0-2.0 | 6 ±1.00 | ±0.60 | 0.20 | 1.80 | 25 | 1.15 | 1.15 |
| MDC6224-10 | 1.0-2.0 | 10 ±1.25 | ±0.75 | 0.20 | 0.80 | 25 | 1.10 | 1.10 |
| MDC6224-20 | 1.0-2.0 | 20 ±1.25 | ±0.75 | 0.15 | 0.20 | 25 | 1.10 | 1.10 |
| MDC6224-30 | 1.0-2.0 | 30 ±1.25 | ±0.75 | 0.15 | 0.20 | 25 | 1.10 | 1.10 |
| MDC6225-6 | 2.0-4.0 | 6 ±1.00 | ±0.60 | 0.20 | 1.80 | 22 | 1.15 | 1.15 |
| MDC6225-10 | 2.0-4.0 | 10 ±1.25 | ±0.75 | 0.20 | 0.80 | 22 | 1.15 | 1.15 |
| MDC6225-20 | 2.0-4.0 | 20 ±1.25 | ±0.75 | 0.15 | 0.20 | 22 | 1.15 | 1.15 |
| MDC6225-30 | 2.0-4.0 | 30 ±1.25 | ±0.75 | 0.15 | 0.20 | 22 | 1.15 | 1.15 |
| MDC6266-6 | 2.6-5.2 | 6 ±1.00 | ±0.60 | 0.20 | 1.80 | 20 | 1.25 | 1.25 |
| MDC6266-10 | 2.6-5.2 | 10 ±1.25 | ±0.75 | 0.20 | 0.80 | 20 | 1.25 | 1.25 |
| MDC6266-20 | 2.6-5.2 | 20 ±1.25 | ±0.75 | 0.20 | 0.25 | 20 | 1.25 | 1.25 |
| MDC6266-30 | 2.6-5.2 | 30 ±1.25 | ±0.75 | 0.20 | 0.20 | 20 | 1.25 | 1.25 |
| MDC6226-6 | 4.0-8.0 | 6 ±1.00 | ±0.60 | 0.25 | 1.90 | 20 | 1.25 | 1.25 |
| MDC6226-10 | 4.0-8.0 | 10 ±1.25 | ±0.75 | 0.25 | 0.90 | 20 | 1.25 | 1.25 |
| MDC6226-20 | 4.0-8.0 | 20 ±1.25 | ±0.75 | 0.25 | 0.30 | 20 | 1.25 | 1.25 |
| MDC6226-30 | 4.0-8.0 | 30 ±1.25 | ±0.75 | 0.25 | 0.25 | 20 | 1.25 | 1.25 |
| MDC6227-6 | 7.0-12.4 | 6 ±1.00 | ±0.50 | 0.30 | 2.00 | 17 | 1.30 | 1.30 |
| MDC6227-10 | 7.0-12.4 | 10 ±1.00 | ±0.50 | 0.30 | 1.00 | 17 | 1.30 | 1.30 |
| MDC6227-20 | 7.0-12.4 | 20 ±1.00 | ±0.50 | 0.30 | 0.35 | 17 | 1.30 | 1.30 |

# Cuplorul in inel



# Cuplorul in inel

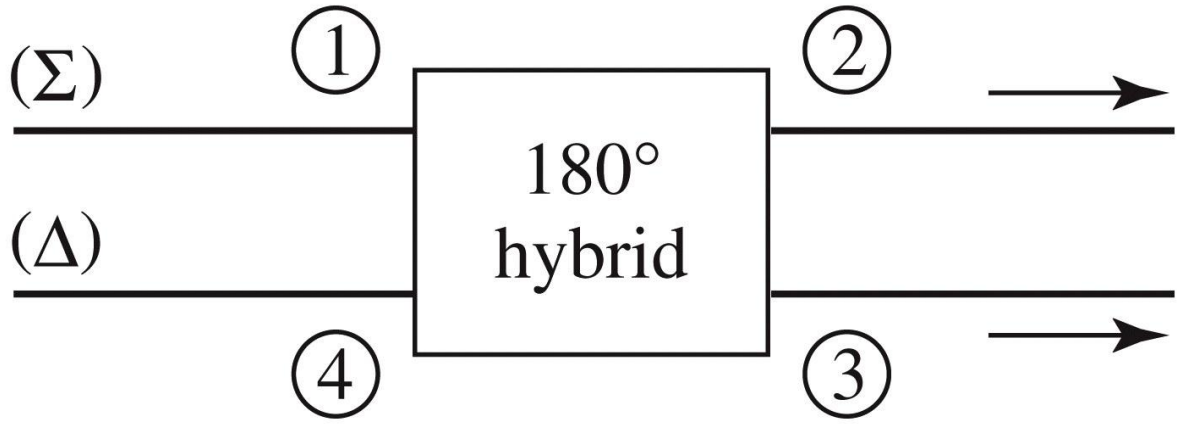
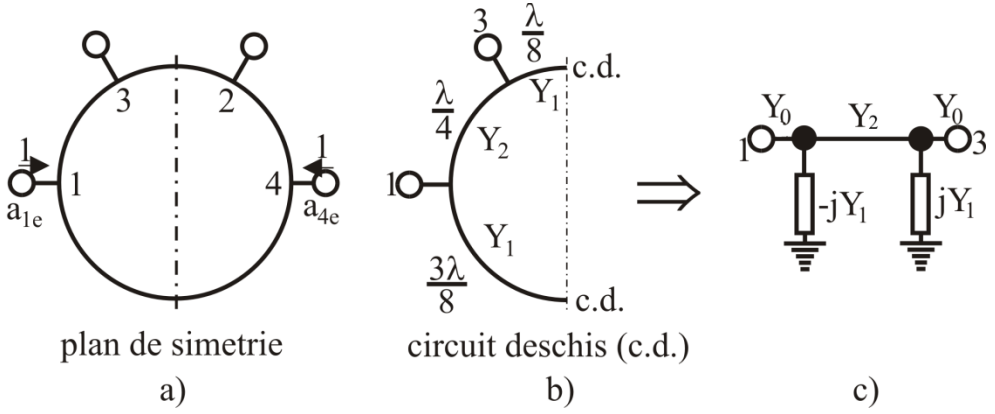


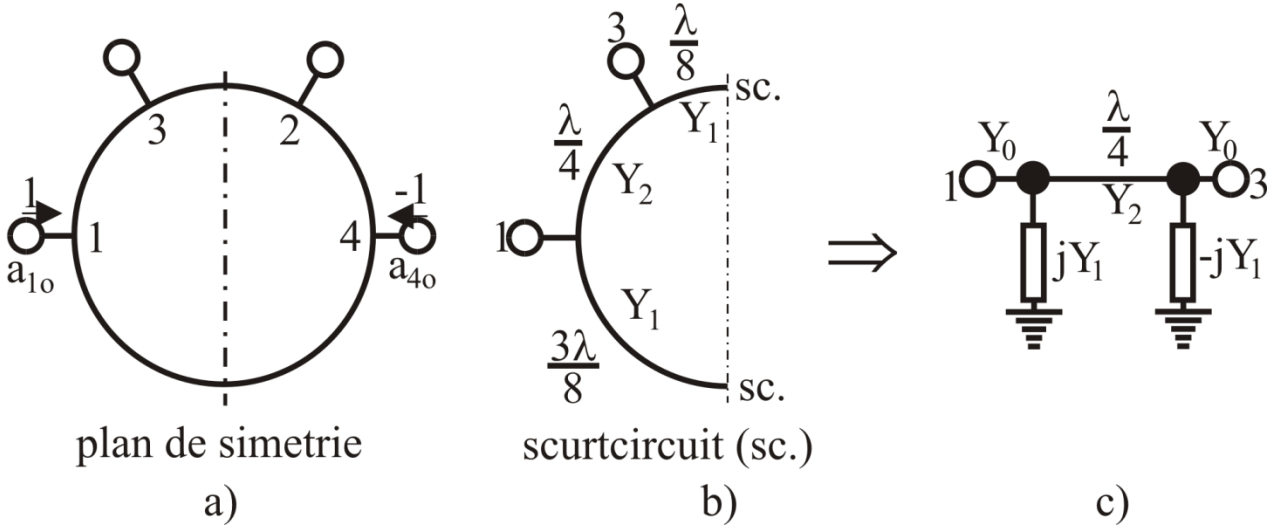

Figure 7.41
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- cuplorul de 3dB (hibrid) poate fi folosit in mai multe moduri
  - intrare pe port 1, iesiri egale pe 2 si 3, in faza
  - intrare pe port 4, iesiri egale pe 2 si 3, in opozitie de faza
  - intrari pe porturi 2 si 3, suma semnalelor pe portul 1, diferenta pe portul 4

# Analiza cuplorului in inel




Modul par

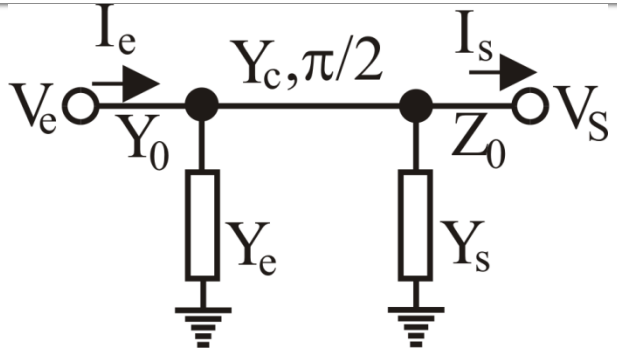



Modul impar

# Analiza cuplorului in inel

$$S_{11} = \frac{jz_2y_s + jz_2 - j(y_2 + y_e y_s z_2) - jy_e z_2}{jz_2y_s + jz_2 + j(y_2 + y_e y_s z_2) + jy_e z_2}$$

$$S_{12} = \frac{2}{jz_2y_s + jz_2 + j(y_2 + y_e y_s z_2) + jy_e z_2}$$




$$S_{21} = \frac{2}{jz_2y_s + jz_2 + j(y_2 + y_e y_s z_2) + jy_e z_2}$$

$$S_{22} = \frac{-jz_2y_s + jz_2 - j(y_2 + y_e y_s z_2) + jy_e z_2}{jz_2y_s + jz_2 + j(y_2 + y_e y_s z_2) + jy_e z_2}$$

**Pentru modul par:**

$y_e = -jy_1$

$y_s = jy_1$

**Conditia de adaptare**

$$y_1^2 + y_2^2 = 1$$

**Pe modul impar:**

$y_e = jy_1$

$y_s = -jy_1$

$$S_{11e} = \frac{z_2 - y_2 - y_1^2 z_2 + 2jz_2y_1}{z_2 + y_2 + y_1^2 z_2}$$

$$S_{12e} = S_{21e} = \frac{-2j}{z_2 + y_2 + y_1^2 z_2}$$

$$S_{22e} = \frac{z_2 - y_2 - y_1^2 z_2 - 2jz_2y_1}{z_2 + y_2 + y_1^2 z_2}$$

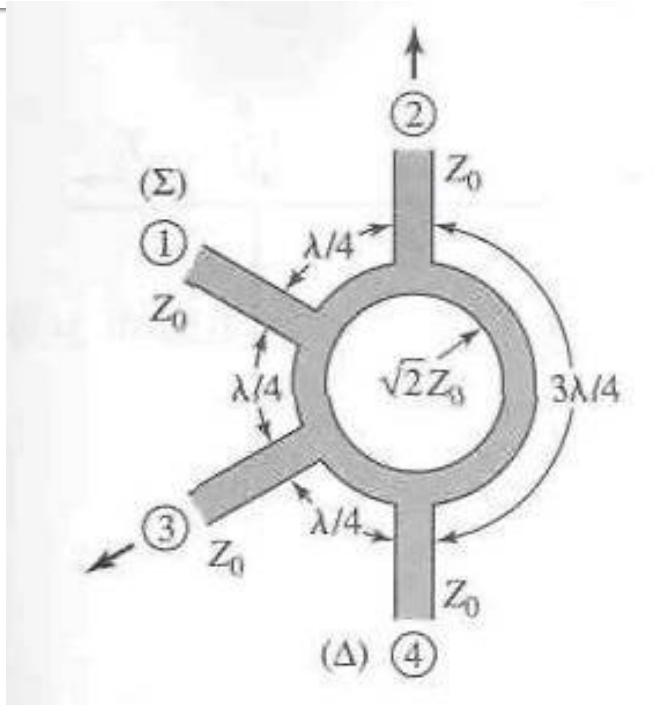
$$[S] = \begin{bmatrix} 0 & 0 & -jy_2 & jy_1 \\ 0 & 0 & -jy_1 & -jy_2 \\ -jy_2 & -jy_1 & 0 & 0 \\ jy_1 & -jy_2 & 0 & 0 \end{bmatrix}$$

$$S_{11o} = \frac{z_2 - y_2 - y_1^2 z_2 - 2jz_2y_1}{z_2 + y_2 + y_1^2 z_2}$$

$$S_{12o} = S_{21o} = \frac{-2j}{z_2 + y_2 + y_1^2 z_2}$$

$$S_{22o} = \frac{z_2 - y_2 - y_1^2 z_2 + 2jz_2y_1}{z_2 + y_2 + y_1^2 z_2}$$

# Cuplorul in inel




$$[S]=\begin{bmatrix} 0 & -jy_2 & -jy_1 & 0 \\ -jy_2 & 0 & 0 & jy_1 \\ -jy_1 & 0 & 0 & -jy_2 \\ 0 & jy_1 & -jy_2 & 0 \end{bmatrix} = -j\begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

$$C(dB) = -20\log(\beta) = -20\log(y_1)$$

# Proiectarea şi performanța unui cuplor în inel

Proiectaţi un cuplor în inel hibrid (3dB) pe impedanţa de 50 Ω şi reprezentati mărimea parametrilor S între 0.5 si 1.5 din frecventa centrala.

$$C[\text{dB}] = -20\log(y_1)$$

$$y_1 = y_2 = \frac{1}{\sqrt{2}}$$

$$Z_1 = Z_2 = \sqrt{2}Z_0 = 70.7\Omega$$

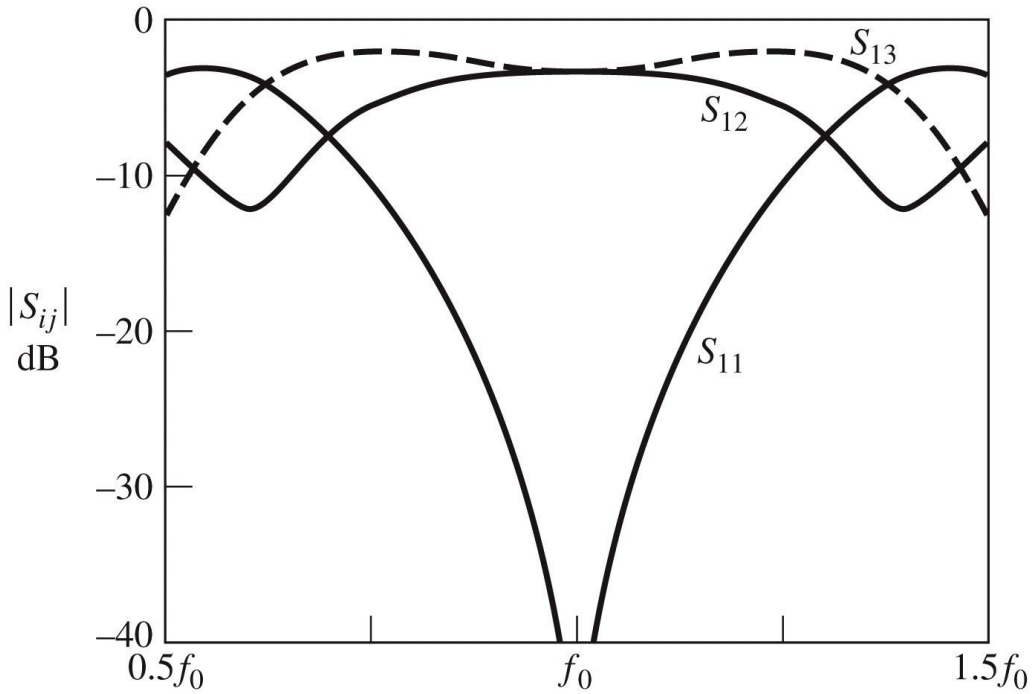
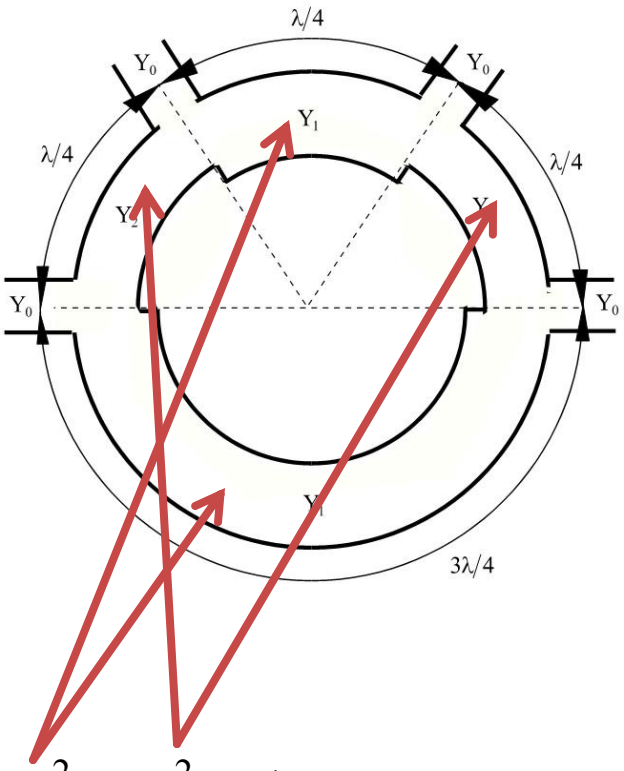



Figure 7.46
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# Cuplorul în inel




$$y_1^2 + y_2^2 = 1$$

$$|\beta| = y_1$$

$$C\,[\mathrm{dB}] = -20 \cdot \log_{10}(y_1)$$

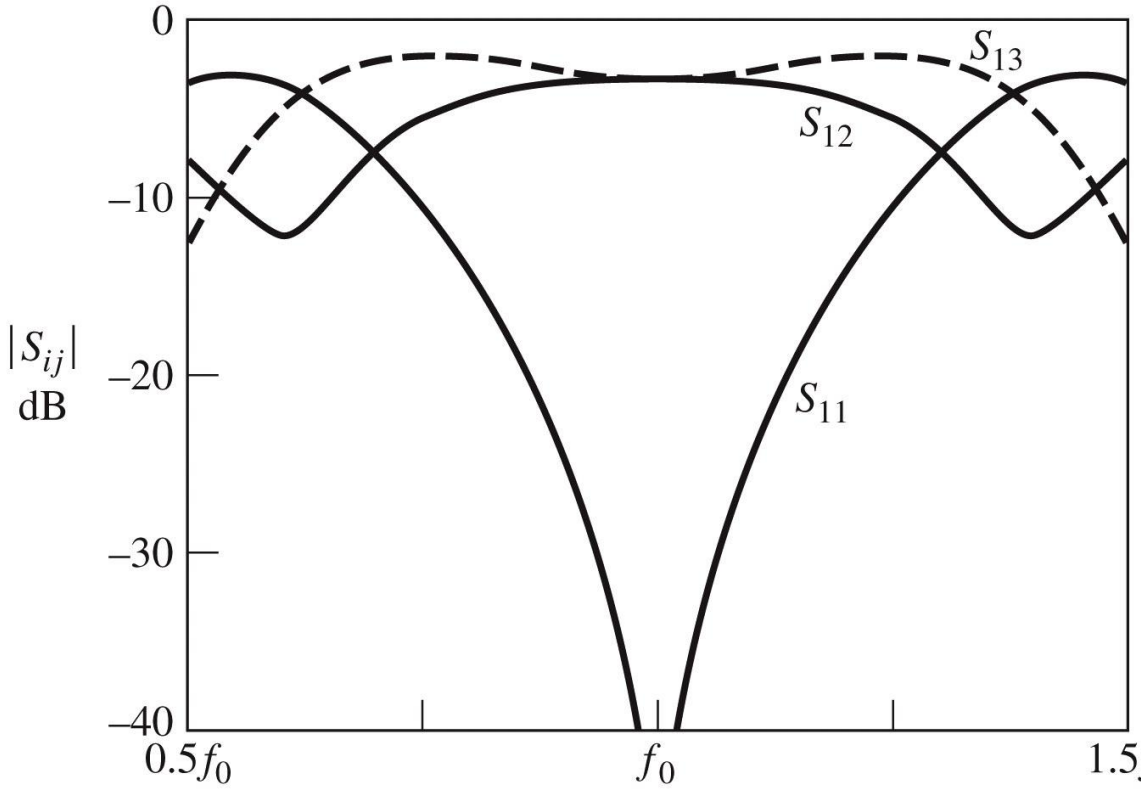



Figure 7.46
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# Cuplor în inel

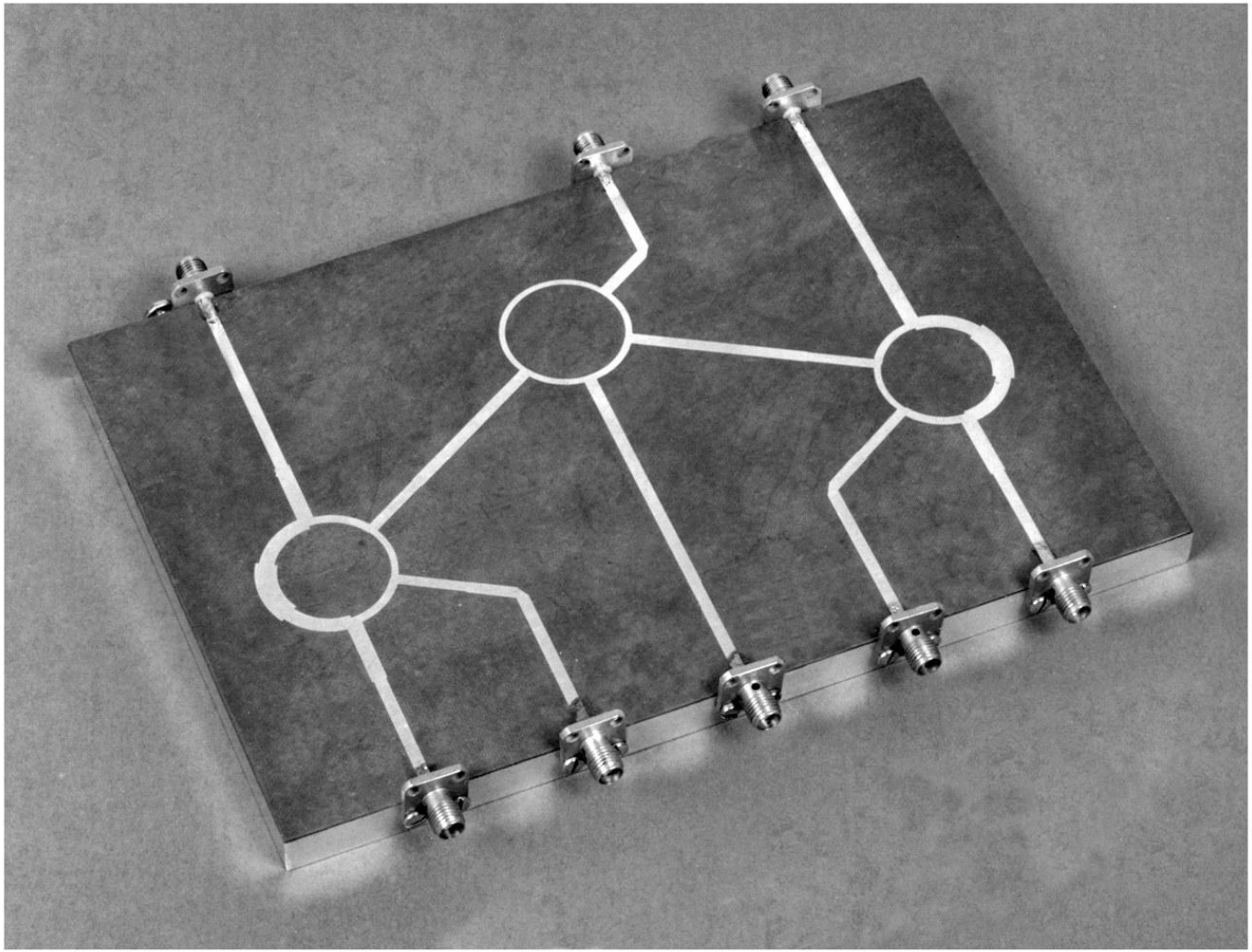
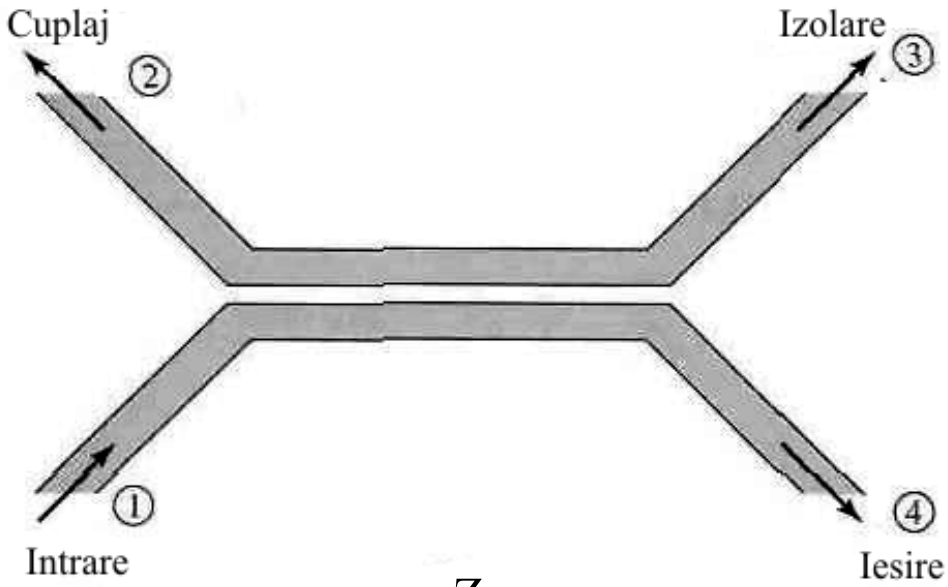
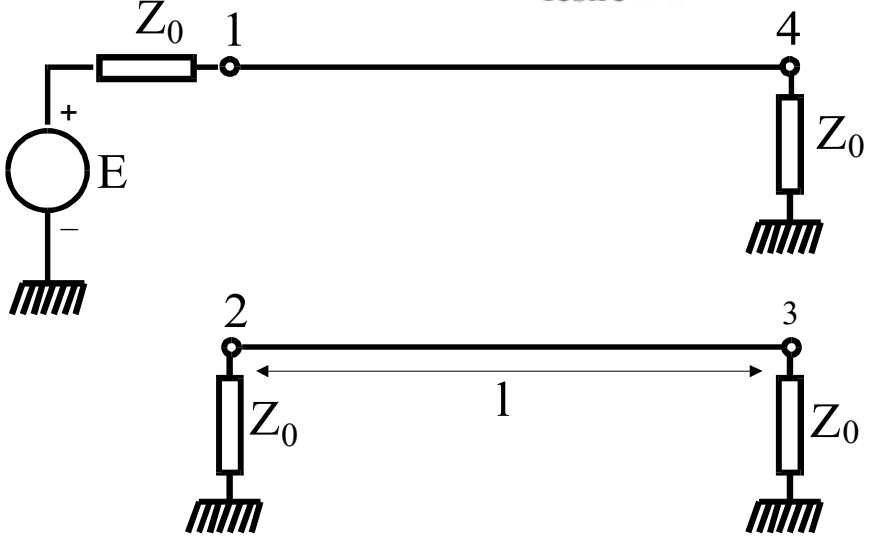


Figure 7.43
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

# Cuplorul prin proximitate



# Linii cuplate

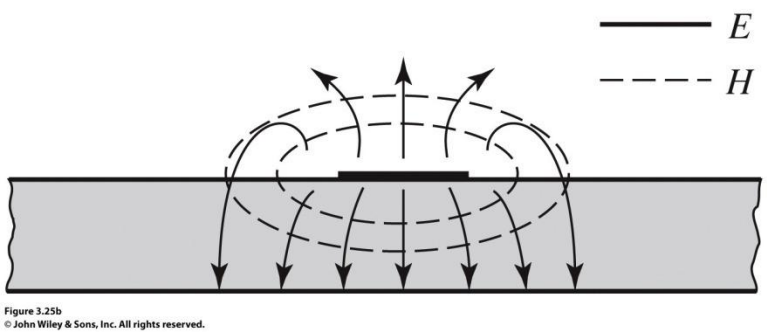
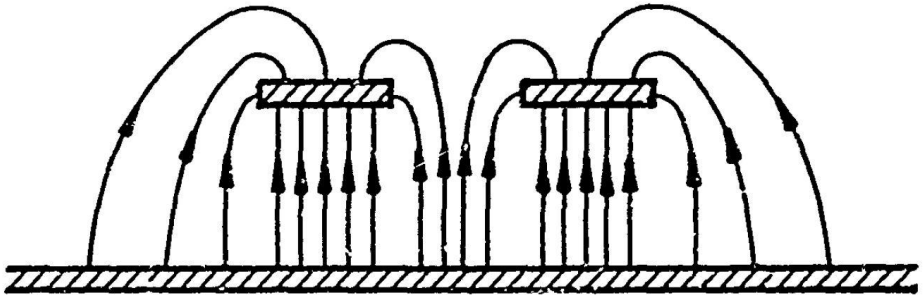
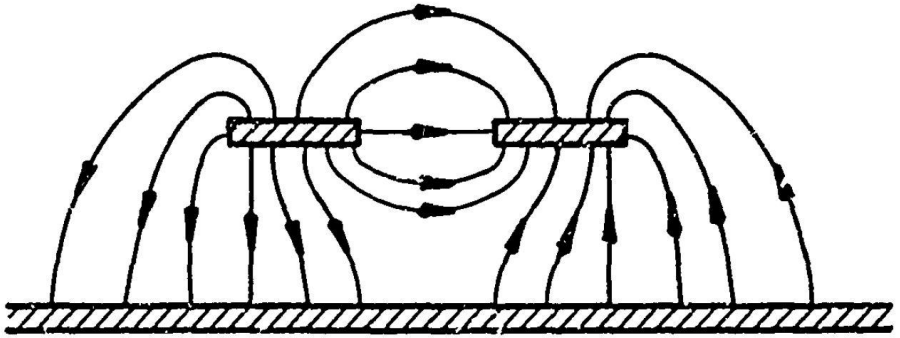



Figure 3.25b
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b) EVEN MODE ELECTRIC FIELD PATTERN (SCHEMATIC)

- Mod par – caracterizeaza semnalul de mod comun de pe cele doua linii
- Mod impar – caracterizeaza semnalul de mod diferential dintre cele doua linii
- Fiecare din cele doua moduri e caracterizat de impedante caracteristice **diferite**



c) ODD MODE ELECTRIC FIELD PATTERN (SCHEMATIC)

# Linii cuplate

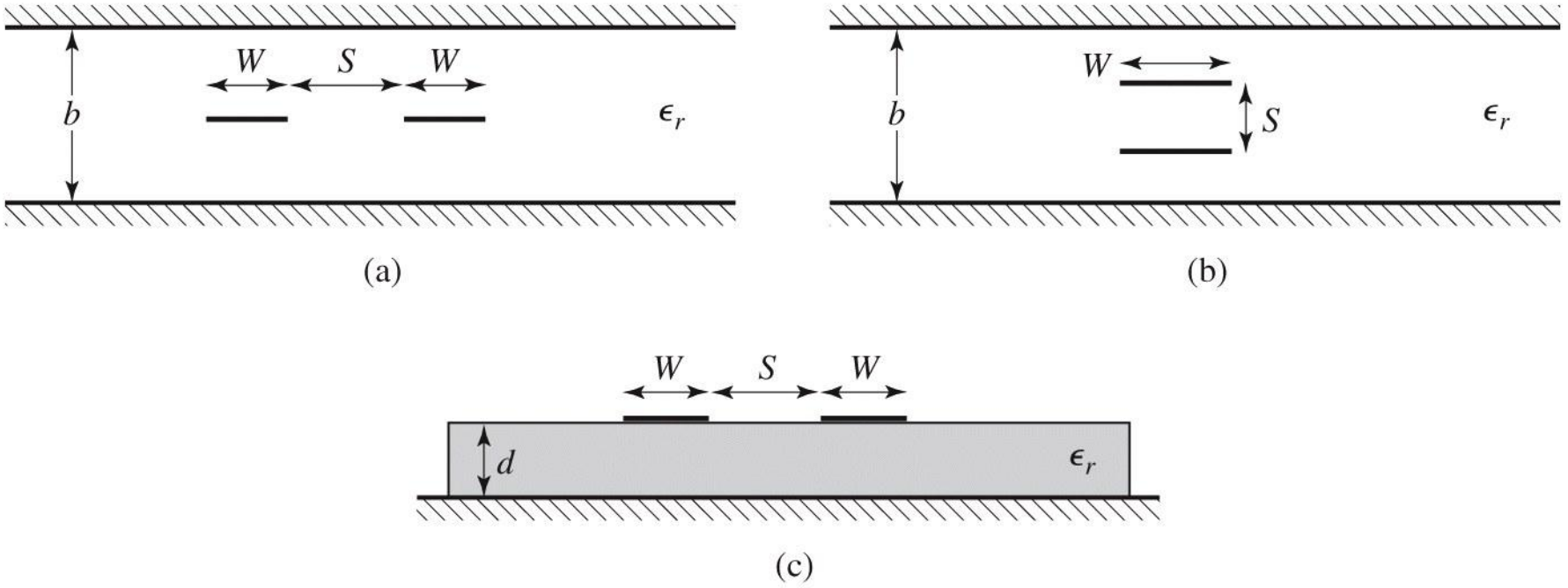



Figure 7.26

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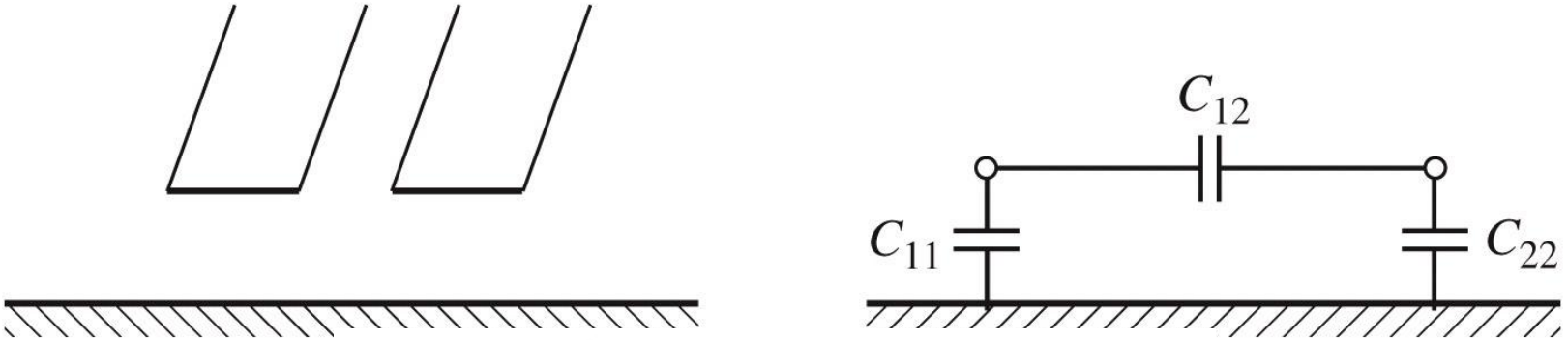
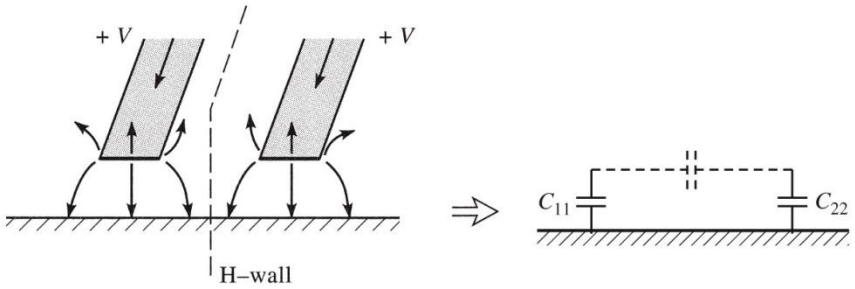
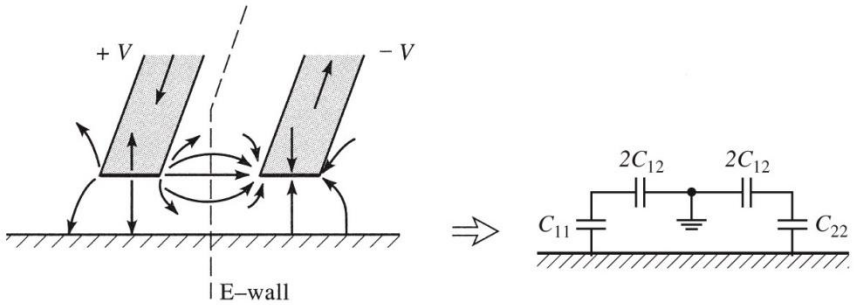



Figure 7.27
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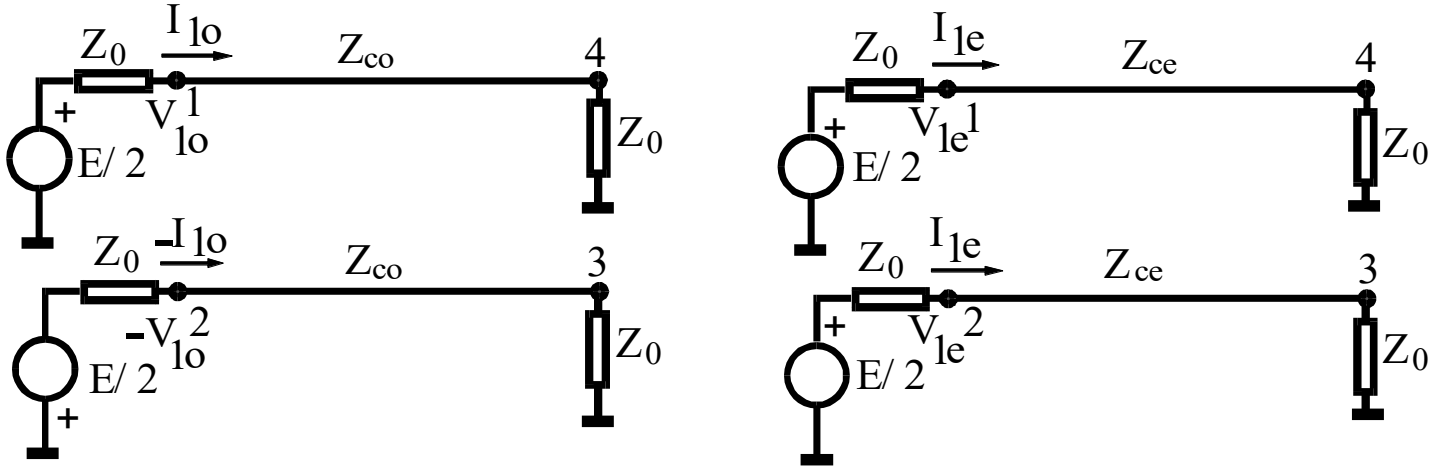

(a)




(b)

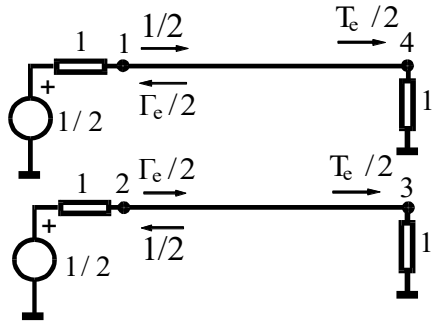
Figure 7.28
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# Adaptarea cuplorului prin proximitate

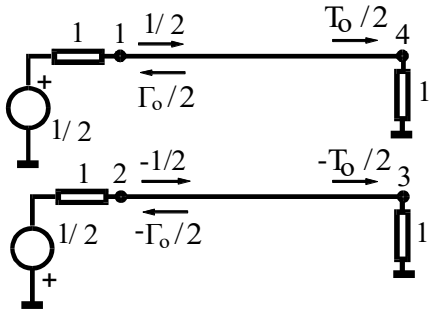



$$\begin{cases} Z_{ce}Z_{co} = Z_0^2 \\ \theta_e = \theta_o \end{cases}$$

# Directivitatea şi coeficientul de cuplaj ale cuplorului prin proximitate




modul par




modul impar

$$a_1 = a_{1e} + a_{1o} = 1\,,\; a_2 = a_3 = a_4 = 0$$

$$b_1 = \frac{1}{2}(\Gamma_e + \Gamma_o) = 0 \Leftrightarrow$$

$$\theta = \pi/2$$

$$b_2 = \frac{1}{2}(\Gamma_e - \Gamma_o) = \frac{jC\sin(\theta)}{\cos(\theta)\sqrt{1-C^2} + j\sin(\theta)}$$

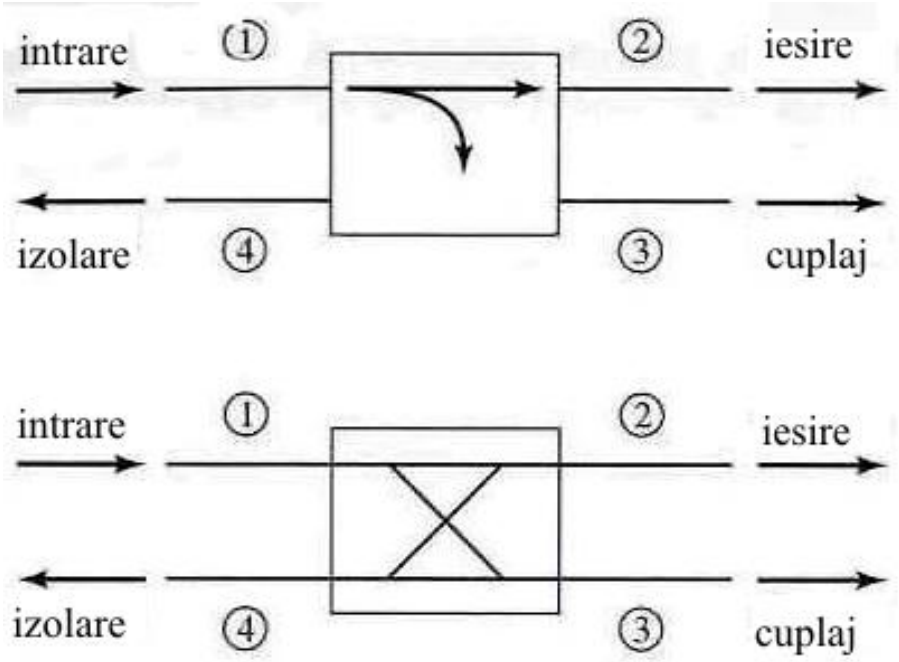
$$b_3 = \frac{1}{2}(T_e - T_o) = 0$$

$$b_4 = \frac{1}{2}(T_e + T_o) = \frac{\sqrt{1-C^2}}{\cos(\theta)\sqrt{1-C^2} + j\sin(\theta)}$$

$$C = \frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}}$$

$$[S] = \begin{bmatrix} 0 & C & 0 & -j\sqrt{1-C^2} \\ C & 0 & -j\sqrt{1-C^2} & 0 \\ 0 & -j\sqrt{1-C^2} & 0 & C \\ -j\sqrt{1-C^2} & 0 & C & 0 \end{bmatrix}$$

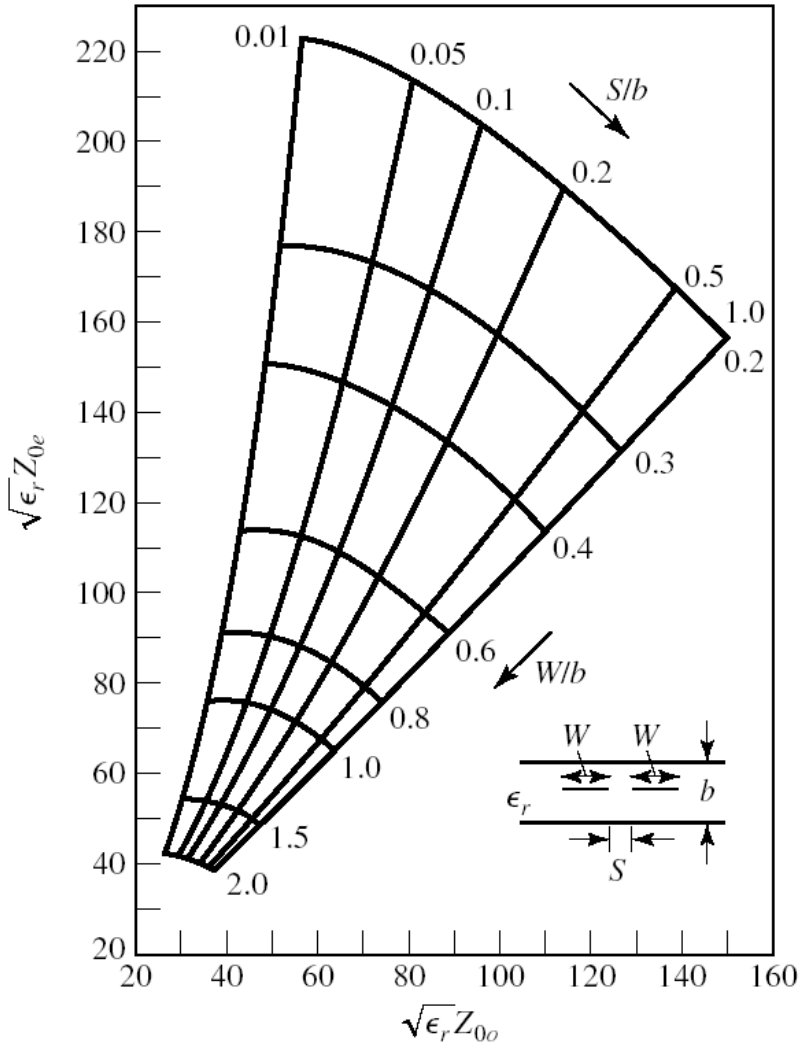
# Cuplor prin proximitate



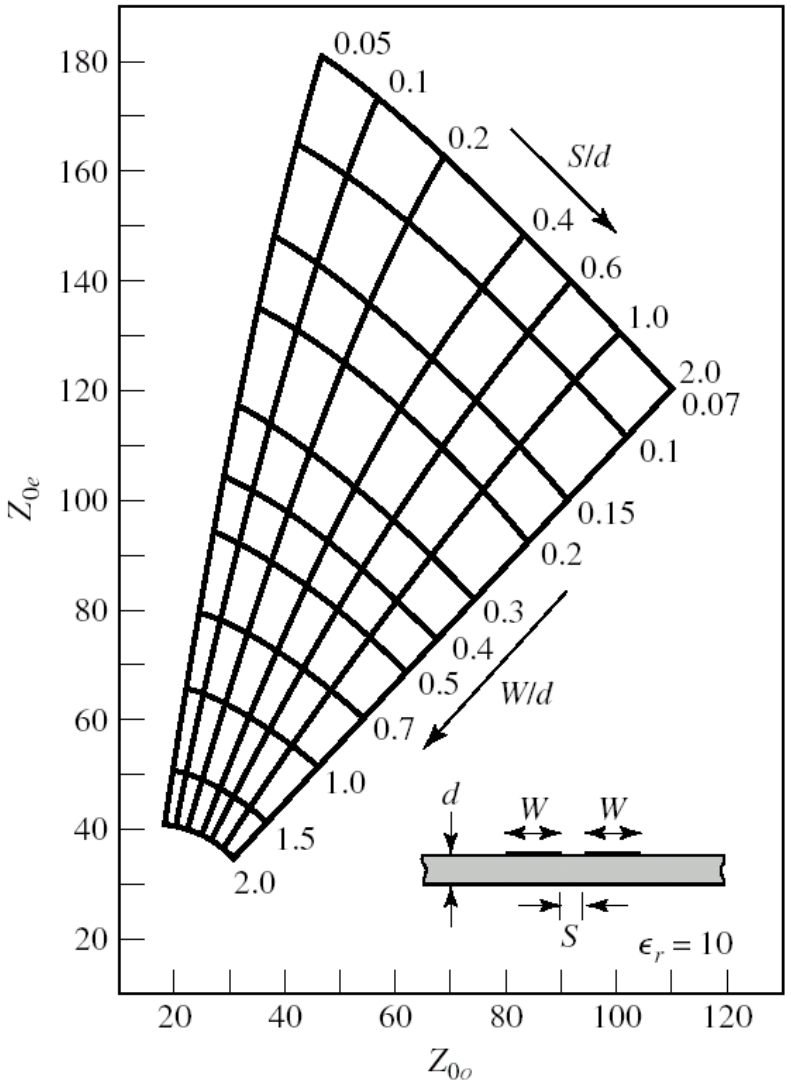

$$[S] = -j \cdot \begin{bmatrix} 0 & \sqrt{1-C^2} & jC & 0 \\ \sqrt{1-C^2} & 0 & 0 & jC \\ jC & 0 & 0 & \sqrt{1-C^2} \\ 0 & jC & \sqrt{1-C^2} & 0 \end{bmatrix}$$

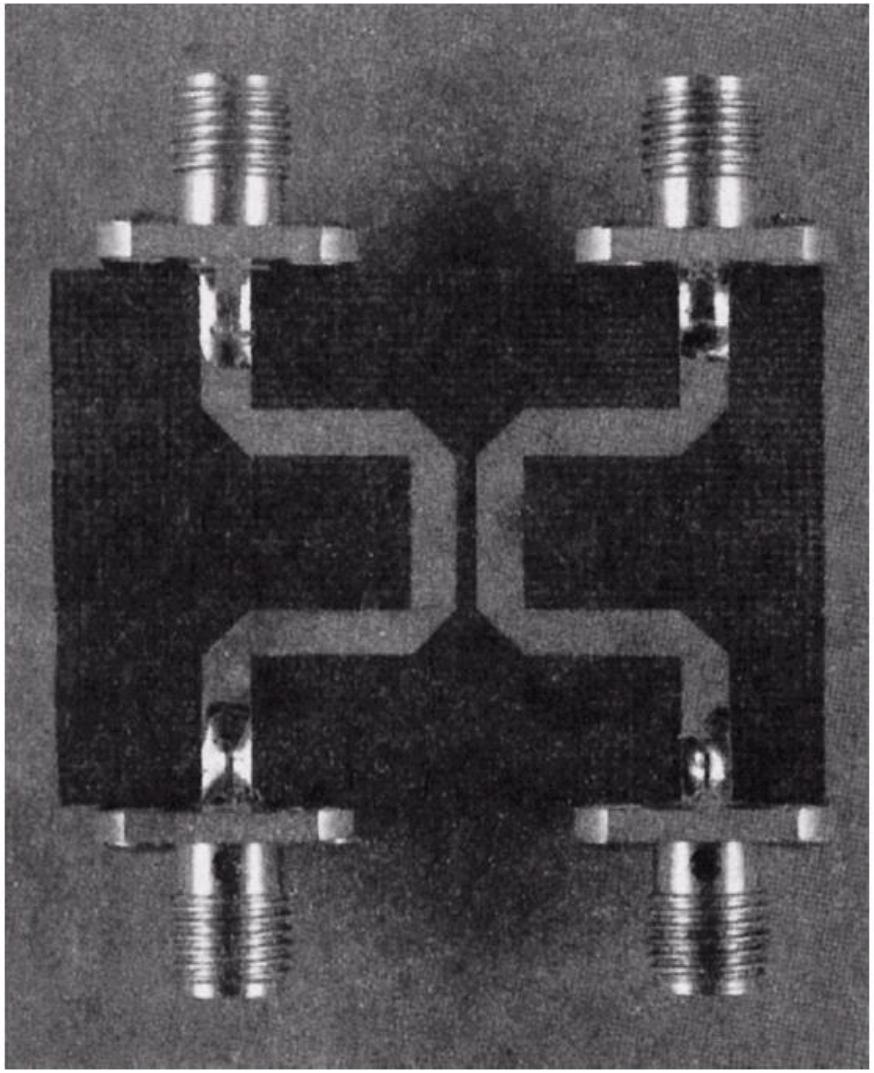
$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

# Normalized even- and odd-mode characteristic impedance design data for edge-coupled striplines.

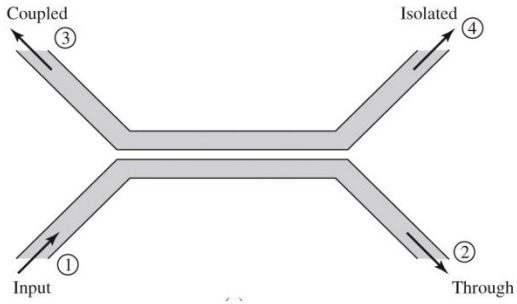


# Even- and odd-mode characteristic impedance design data for coupled microstrip lines on a substrate with $\varepsilon_r = 10$.





# Cuplor prin proximitate




$$Z_{ce}Z_{co} = Z_0^2$$

$$|\beta| = \frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}}$$

$$C\,[\text{dB}] = -20 \cdot \log_{10}\left(\frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}}\right)$$

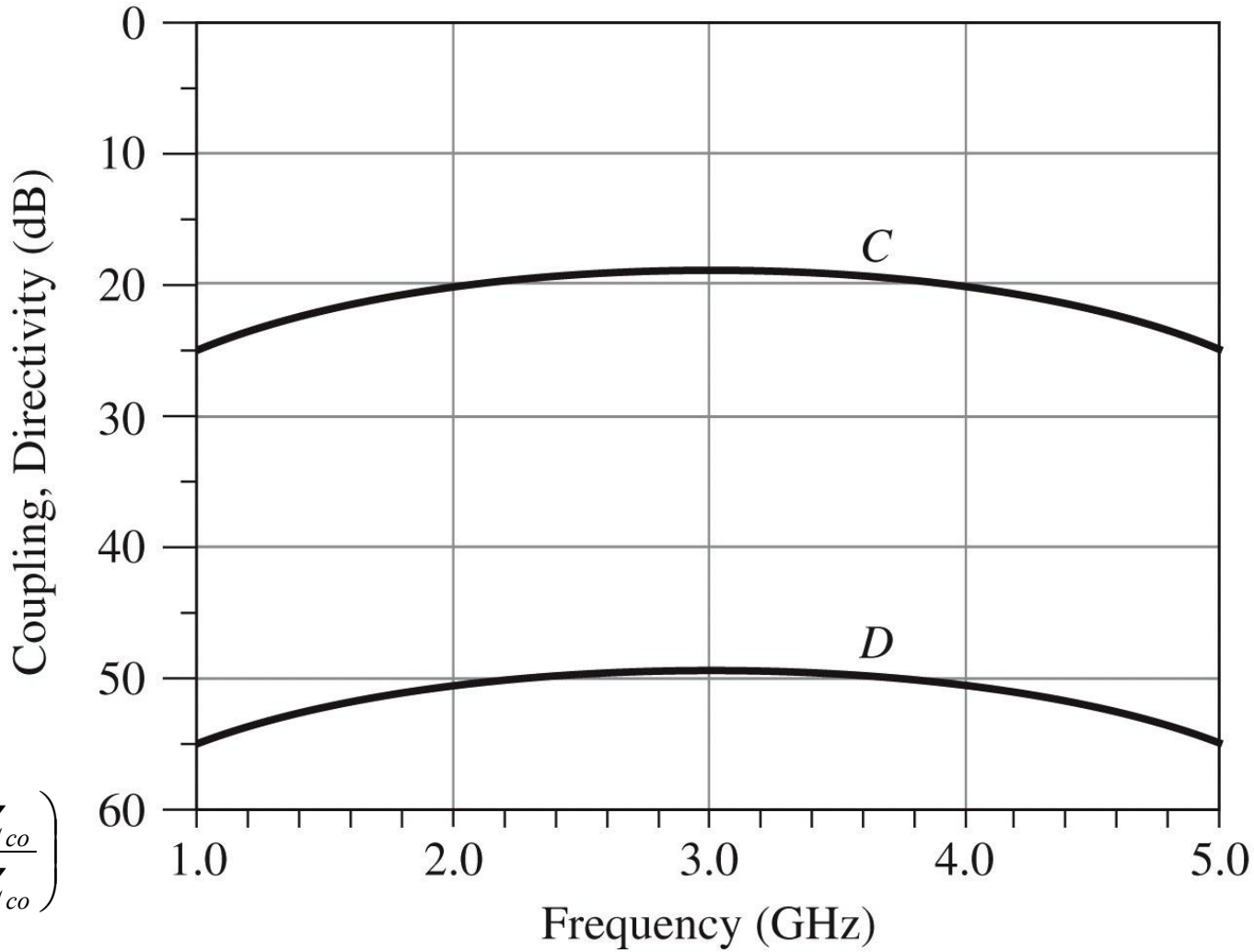



Figure 7.34

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# Exemplu

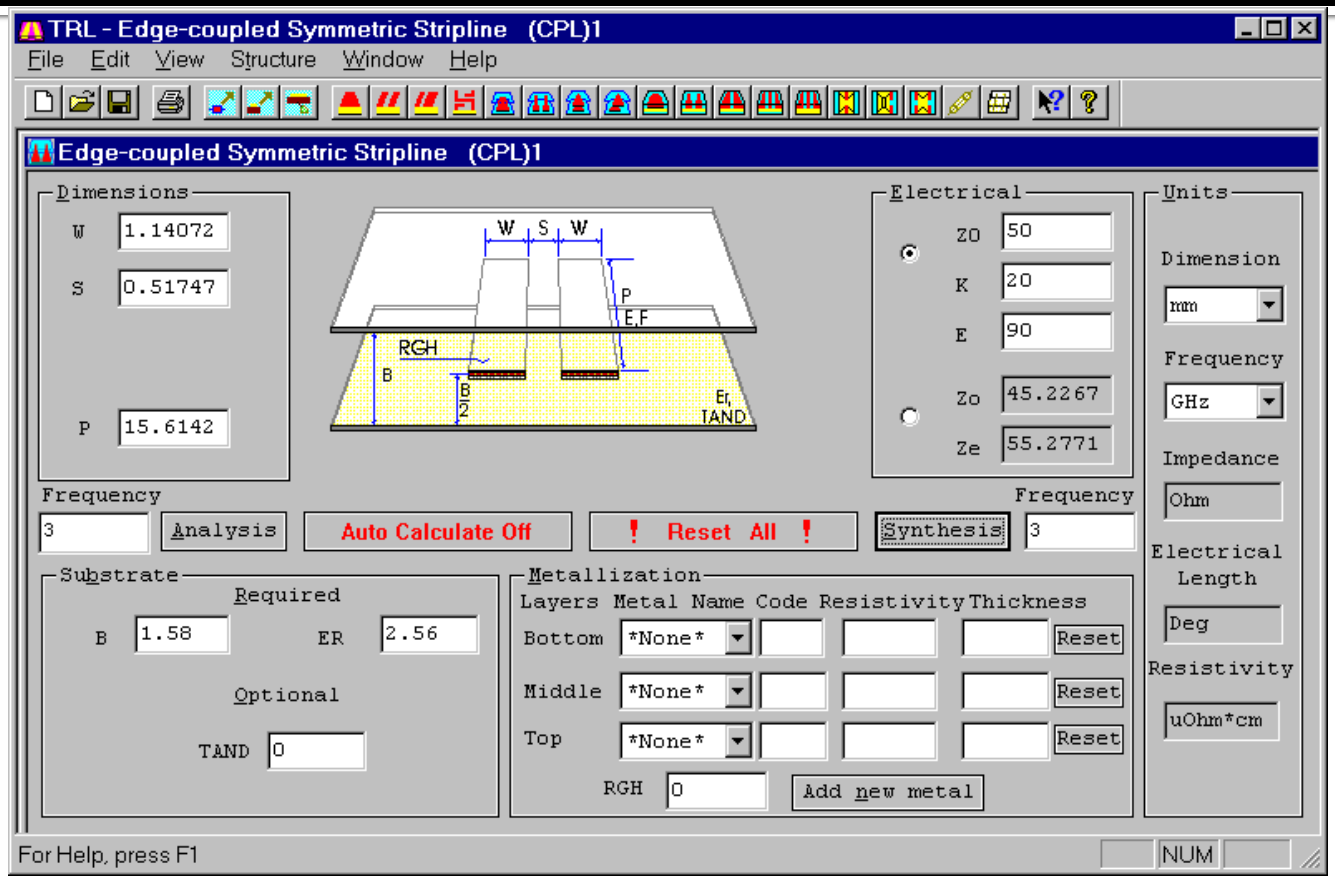
Proiectaţi un cuplor prin proximitate de 20 dB, în tehnologie stripline, folosind o distanta între planele de masă de 0.158 cm şi cu o permitivitate electrică relativa de 2.56, pe o impedanţa de 50 Ω, la frecvenţa de 3 GHz. Reprezentaţi cuplajul şi directivitatea între 1 si 5 GHz.

# Soluție

$$C = 10^{-20/20} = 0.1$$

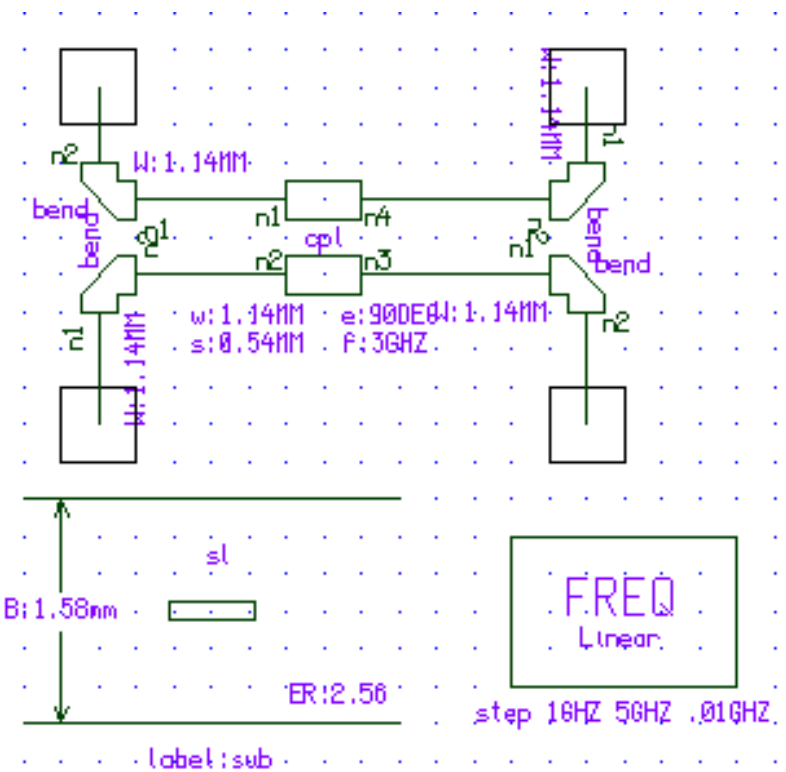
$$Z_{co} = 50\sqrt{\frac{0.9}{1.1}} = 45.23\Omega$$

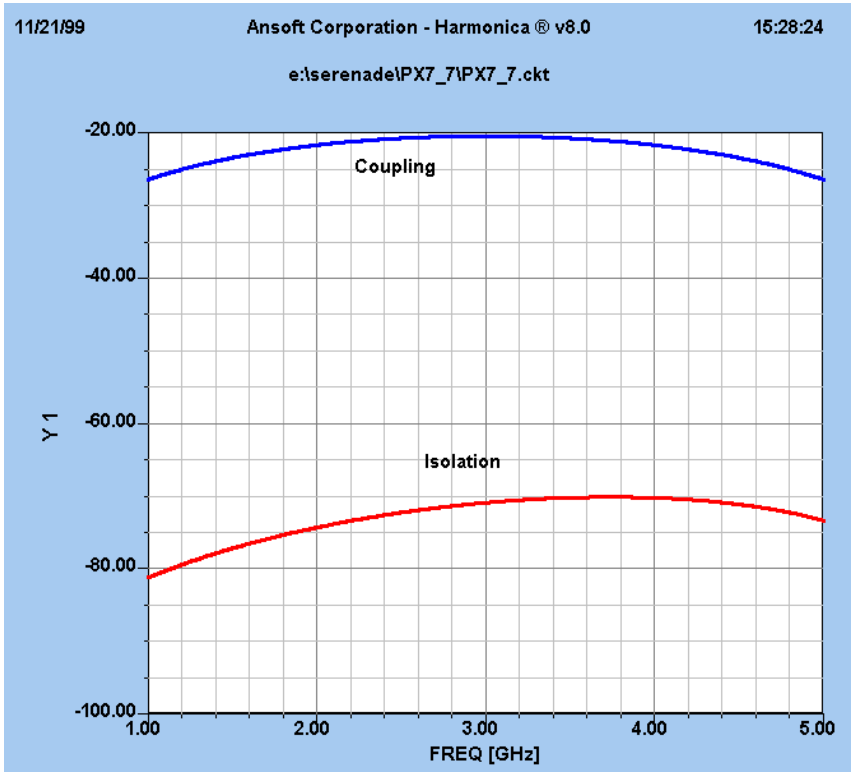
$$Z_{ce} = 50\sqrt{\frac{1.1}{0.9}} = 55.28\Omega$$




$$Z_{ce} = Z_0\sqrt{\frac{1+C}{1-C}}\,,\; Z_{co} = Z_0\sqrt{\frac{1-C}{1+C}}$$

# Simulare


W:1.14MM
bend
cpl
w:1.14MM
s:0.54MM
e:90DEG
W:1.14MM
F:3GHZ
sl
B:1.58mm
ER:2.56
FREQ
Linear
step 1GHZ 5GHZ .01GHZ
label:sub


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Ansoft Corporation - Harmonica ® v8.0
15:28:24
e:\serenade\PX7_7\PX7_7.ckt
Coupling
Isolation
-20.00
-40.00
-60.00
-80.00
-100.00
Y1
1.00
2.00
3.00
4.00
5.00
FREQ [GHz]

# Cuplor prin proximitate cu mai multe secțiuni

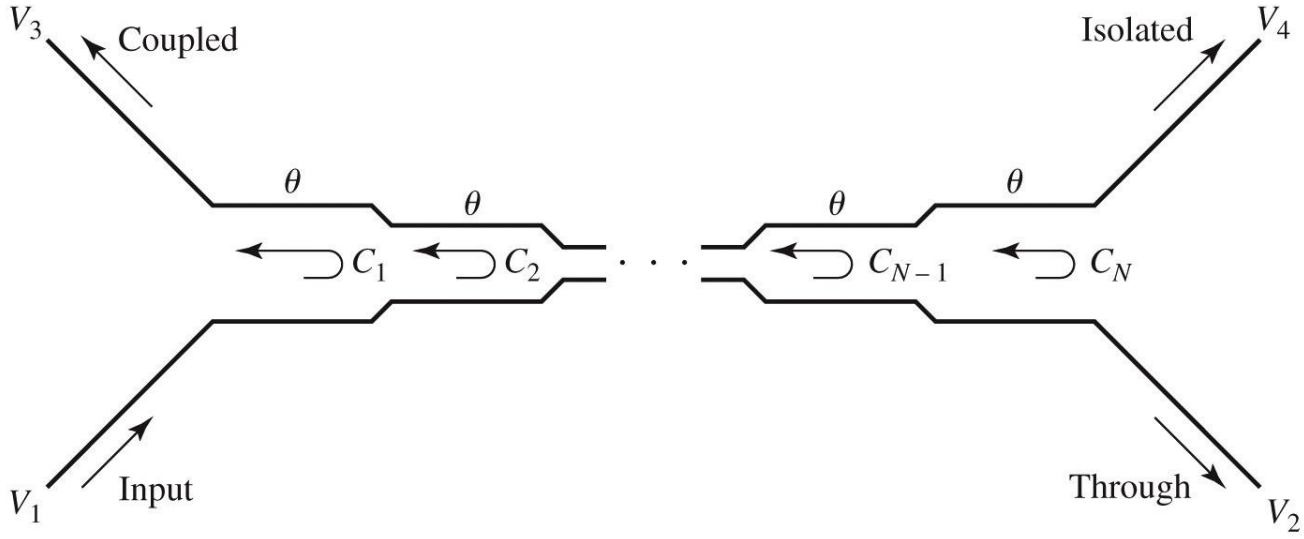



Figure 7.35
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C<<1

$$\frac{V_3}{V_1} = b_3 = \frac{jC\sin\theta}{\cos\theta\sqrt{1-C^2} + j\sin\theta} = \frac{jCtg\theta}{\sqrt{1-C^2} + jtg\theta} \approx \frac{jCtg\theta}{1+jtg\theta} = jC\sin\theta e^{-j\theta}$$

$$\frac{V_2}{V_1} = b_2 = \frac{\sqrt{1-C^2}}{\cos\theta\sqrt{1-C^2} + j\sin\theta} \approx \frac{1}{\cos\theta + j\sin} = e^{-j\theta}$$

$$C = \frac{V_3}{V_1} = 2j\sin\theta e^{-j\theta} e^{-j(N-1)\theta}\left[C_1\cos(N-1)\theta + C_2\cos(N-3)\theta + \ldots + \frac{1}{2}C_{\frac{N+1}{2}}\right]$$

# Exemplu

Să se proiecteze un cuplor cu trei secţiuni, avînd un cuplaj de 20 dB, cu caracteristică binomiala (maxim plat), pe o impedanţă de 50 Ω, la frecvenţa centrală de 3 GHz. Să se reprezinte grafic cuplajul şi directivitatea între 1 şi 5 GHz.

# Solutie

$$\left.\frac{d^n}{d\theta^n}C(\theta)\right|_{\theta=\pi/2}=0,\ n=1,2$$

$$C=\left|\frac{V_3}{V_1}\right|=2\sin\theta\left[C_1\cos 2\theta+\frac{1}{2}C_2\right]=C_1(\sin 3\theta-\sin\theta)+C_2\sin\theta$$

$$\frac{dC}{d\theta}=\left[3C_1\cos 3\theta+(C_2-C_1)\cos\theta\right]|_{\theta=\pi/2}=0$$

$$\frac{d^2C}{d\theta^2}=\left[-9C_1\sin 3\theta-(C_2-C_1)\sin\theta\right]|_{\theta=\pi/2}=10C_1-C_2=0$$

$$\begin{cases}C_2-2C_1=0.1\\10C_1-C_2=0\end{cases}$$

$$\begin{cases}C_1=C_3=0.0125\\C_2=0.125\end{cases}$$

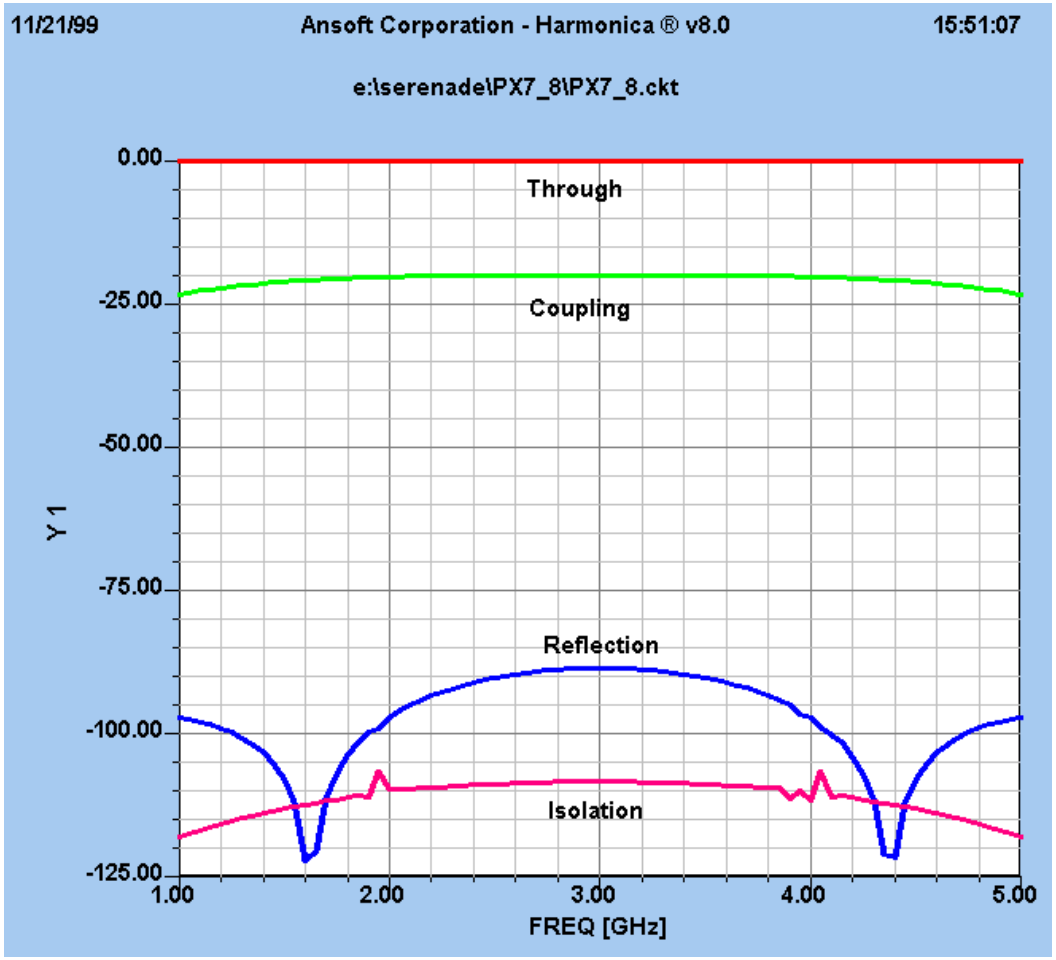
$$Z_{0e}^1=Z_{0e}^3=50\sqrt{\frac{1.0125}{0.9875}}=50.63\,\Omega$$

$$Z_{0o}^1=Z_{0o}^3=50\sqrt{\frac{0.9875}{1.0125}}=49.38\,\Omega$$

$$Z_{0e}^2=50\sqrt{\frac{1.125}{0.875}}=56.69\,\Omega$$

$$Z_{0o}^2=50\sqrt{\frac{0.875}{1.125}}=44.10\,\Omega$$

# Simulare


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15:51:07
e:\serenade\PX7_8\PX7_8.ckt
0.00
-25.00
-50.00
-75.00
-100.00
-125.00
Y 1
Through
Coupling
Reflection
Isolation
1.00
2.00
3.00
4.00
5.00
FREQ [GHz]

# Cuplorul Lange

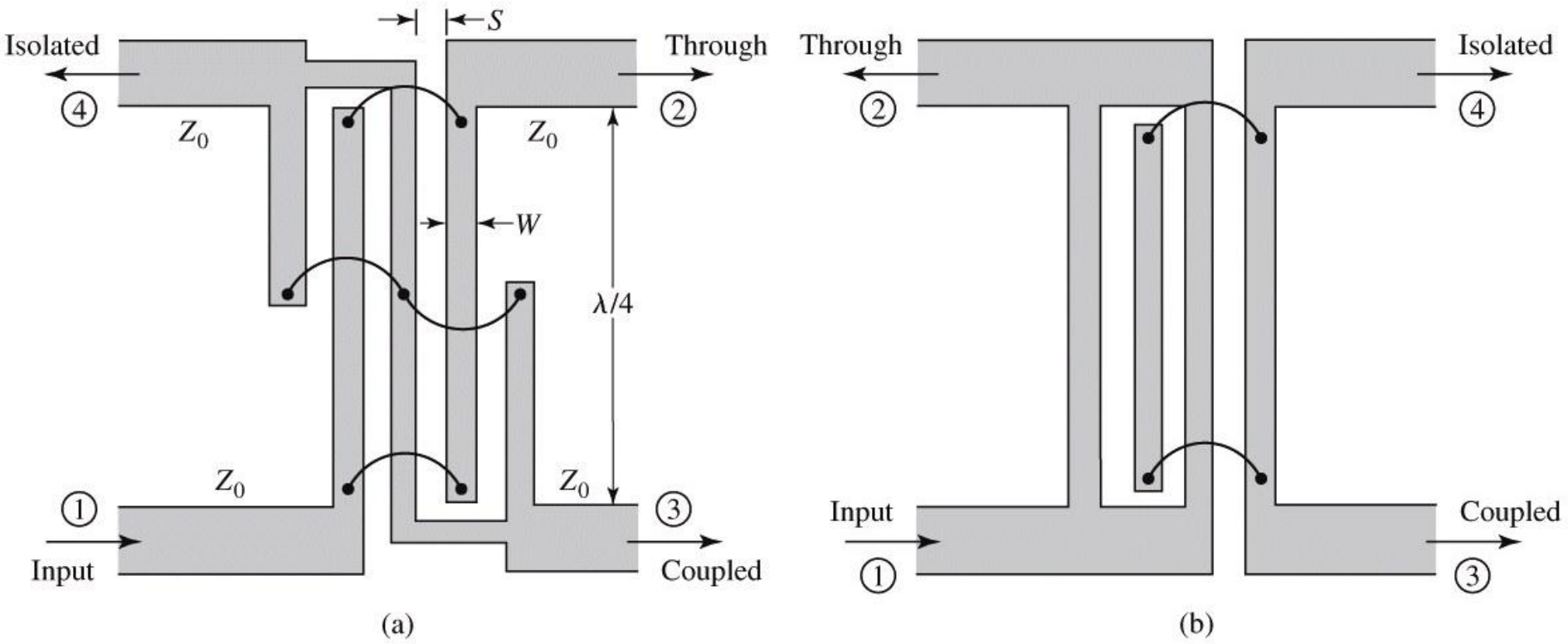



**Figure 7.38**

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# Cuplor Lange

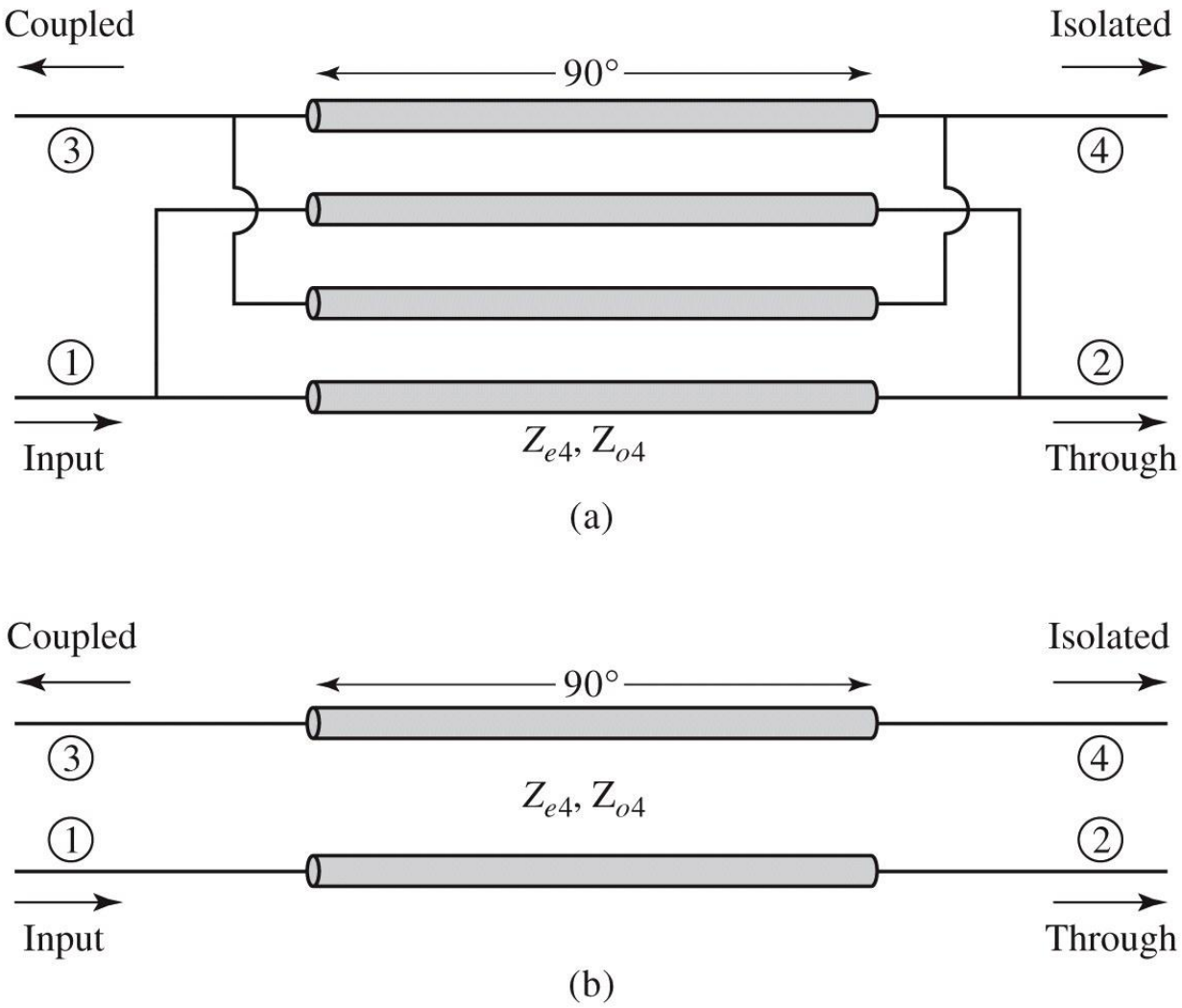
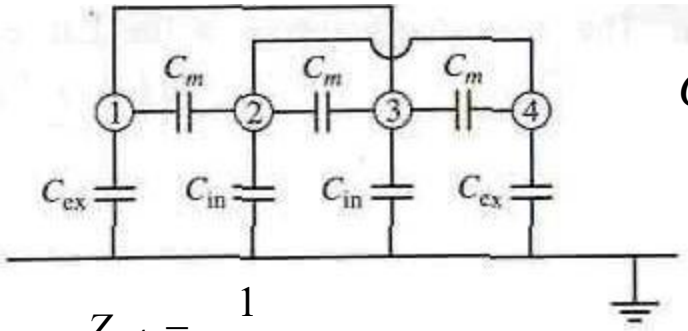



Figure 7.39

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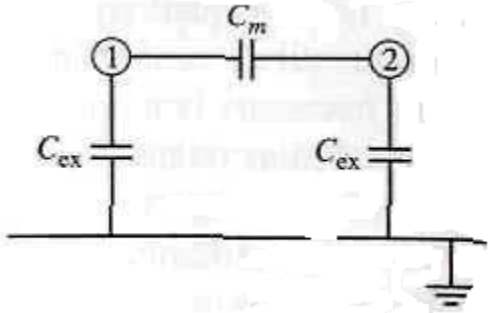
# Modelul de circuit




$$C_{in} = C_{ex} - \frac{C_{ex}C_m}{C_{ex} + C_m}$$

$$C_{e4} = C_{ex} + C_{in}$$

$$C_{o4} = C_{ex} + C_{in} + 6C_m$$




$$C_o = C_{ex} + 2C_m$$

$$Z_{e4} = \frac{1}{vC_{e4}}$$

$$Z_{o4} = \frac{1}{vC_{o4}}$$

$$Z_0 = \sqrt{Z_{e4}Z_{o4}} = \sqrt{\frac{Z_{0e}Z_{0o}(Z_{0o} + Z_{0e})^2}{(3Z_{0o} + Z_{0e})(3Z_{0e} + Z_{0o})}}$$

$$C_{e4} = \frac{C_e(3C_e + C_o)}{C_e + C_o}$$

$$Z_{e4} = Z_{0e}\frac{Z_{0e} + Z_{0o}}{3Z_{0o} + Z_{0e}}$$

$$C = \frac{Z_{e4} - Z_{o4}}{Z_{e4} + Z_{o4}} = \frac{3\left(Z_{0e}^2 - Z_{0o}^2\right)}{3\left(Z_{0e}^2 + Z_{0o}^2\right) + 2Z_{0e}Z_{0o}}$$

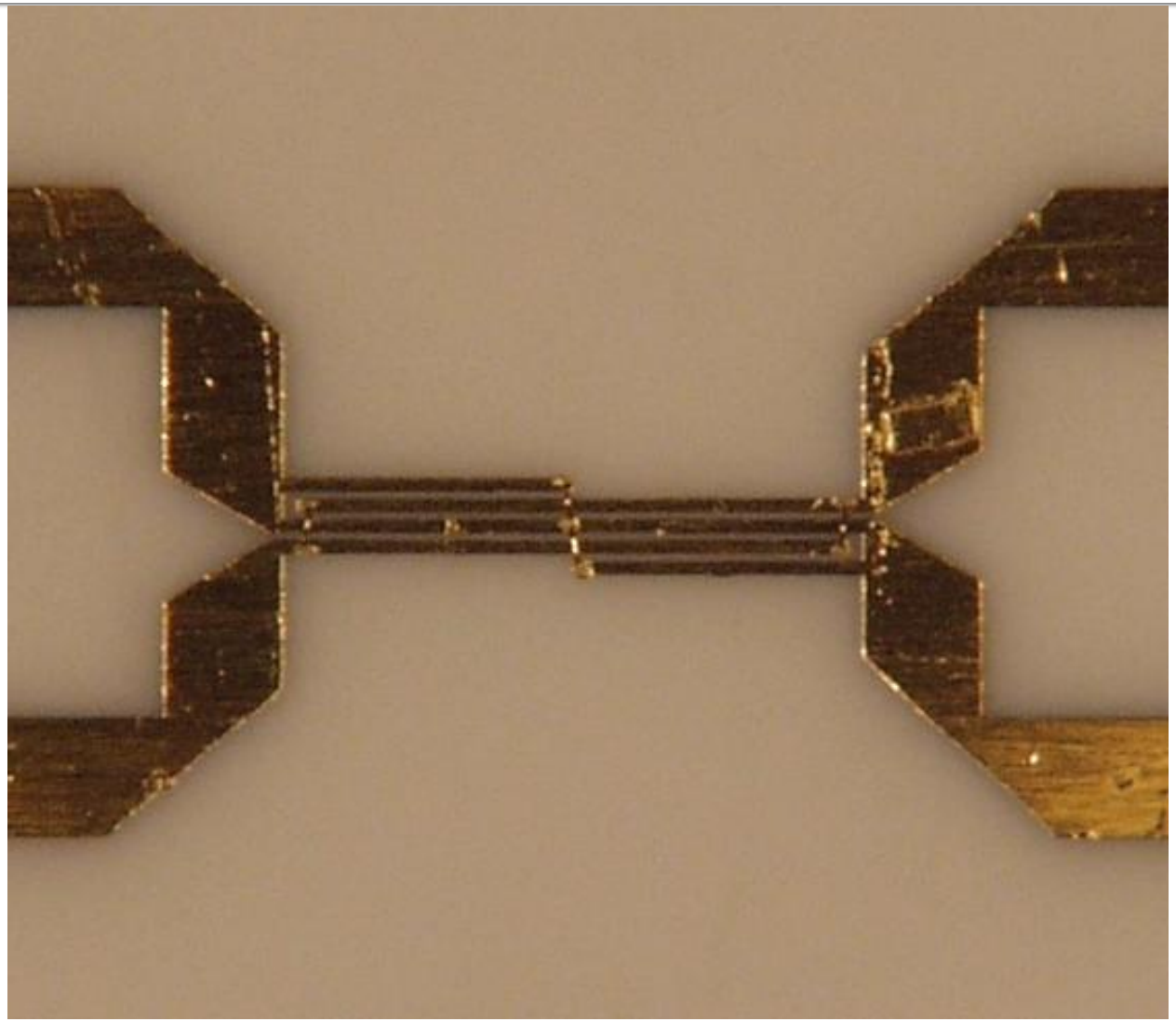
$$C_{o4} = \frac{C_o(3C_o + C_e)}{C_e + C_o}$$

$$Z_{o4} = Z_{0o}\frac{Z_{0e} + Z_{0o}}{3Z_{0e} + Z_{0o}}$$

$$Z_{0e} = \frac{4C - 3 + \sqrt{9 - 8C^2}}{2C\sqrt{(1-C)/(1+C)}}Z_0$$

$$Z_{0o} = \frac{4C + 3 - \sqrt{9 - 8C^2}}{2C\sqrt{(1+C)/(1-C)}}Z_0$$

# Cuplor Lange



# Contact

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