

Curs 6

2025/2026

Dispozitive și circuite de microunde pentru radiocomunicații

Disciplina 2025/2026

- 2C/1L (+1), **DCMR (CDM)**
- Minim 7 prezente (curs+laborator)
- Curs - **conf. Radu Damian**
 - Vineri 10-12/**Video (istoric)**, C1, corp C
 - E – **50%** din nota
 - probleme + (2p prez. curs) + (3 teste) + (bonus activitate)
 - primul test L1: ~01.10.2025 (t2 si t3 neanuntate la **curs**)
 - 3pz (C) $\approx$ +0.5p (**2p** max)
 - toate materialele permise

Disciplina 2025/2026

- 2C/1L, **DCMR (CDM)**
- Laborator – **conf. Radu Damian**
 - L – **25%** din nota
 - ADS, 4 sedinte aplicatii
 - prezenta + **rezultate personale!**
 - P – **25%** din nota
 - ADS, 3 sedinte aplicatii (-1? 21-22.12.2022)
 - tema personala

Documentatie

■ <https://rf-opto.etti.tuiasi.ro>



Microwave and Optoelectronics Laboratory
Faculty of Electronics, Telecommunications and Information Technology
Gheorghe Asachi Technical University of Iasi

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Microwave Devices and Circuits for Radiocommunicati

Course: DCMR (2024-2025)

Course Coordinator: Assoc.P. Dr. Radu-Florin Damian
Code: DOS412T
Discipline Type: DOS; Alternative, Specialty
Credits: 4
Enrollment Year: 4, **Sem.** 7

Activities

Course: Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:
Laboratory: Instructor: Assoc.P. Dr. Radu-Florin Damian, 1 Hours/Week, Group, Timetable:

Evaluation

Type: **Exam**

A: 50%, (Test/Colloquium)
B: 25%, (Seminary/Laboratory/Project Activity)
D: 25%, (Homework/Specialty papers)

Grades

[Aggregate Results](#)

Documentatie

- RF-OPTO
 - <https://rf-opto.etti.tuiasi.ro> ~~Moodle~~
- Fotografie
 - de trimis pe [rf-opto](#)
 - necesara la laborator/curs
 - bonus activitate 1p/0.5p (~~C4~~/C7)

Bibliografie

- <https://rf-opto.etti.tuiasi.ro>
- Irinel Casian-Botez: "Microunde vol. 1: Proiectarea de circuit", Ed. TEHNOPRES, 2008
- David Pozar, Microwave Engineering, Wiley; 4th edition , 2011, ISBN : 978-1-118-29813-8 (E), ISBN : 978-0-470-63155-3 (P)

Examen: Reprezentare logaritmică

$$\text{dB} = 10 \cdot \log_{10} (P_2 / P_1)$$

$$0 \text{ dB} = 1$$

$$+ 0.1 \text{ dB} = 1.023 (+2.3\%)$$

$$+ 3 \text{ dB} = 2$$

$$+ 5 \text{ dB} = 3$$

$$+ 10 \text{ dB} = 10$$

$$-3 \text{ dB} = 0.5$$

$$-10 \text{ dB} = 0.1$$

$$-20 \text{ dB} = 0.01$$

$$-30 \text{ dB} = 0.001$$

$$\text{dBm} = 10 \cdot \log_{10} (P / 1 \text{ mW})$$

$$0 \text{ dBm} = 1 \text{ mW}$$

$$3 \text{ dBm} = 2 \text{ mW}$$

$$5 \text{ dBm} = 3 \text{ mW}$$

$$10 \text{ dBm} = 10 \text{ mW}$$

$$20 \text{ dBm} = 100 \text{ mW}$$

$$-3 \text{ dBm} = 0.5 \text{ mW}$$

$$-10 \text{ dBm} = 100 \mu\text{W}$$

$$-30 \text{ dBm} = 1 \mu\text{W}$$

$$-60 \text{ dBm} = 1 \text{ nW}$$

$$[\text{dBm}] + [\text{dB}] = [\text{dBm}]$$

$$[\text{dBm/Hz}] + [\text{dB}] = [\text{dBm/Hz}]$$

$$[x] + [\text{dB}] = [x]$$

Examen

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

Linii de transmisie in mod TEM

Cuprins

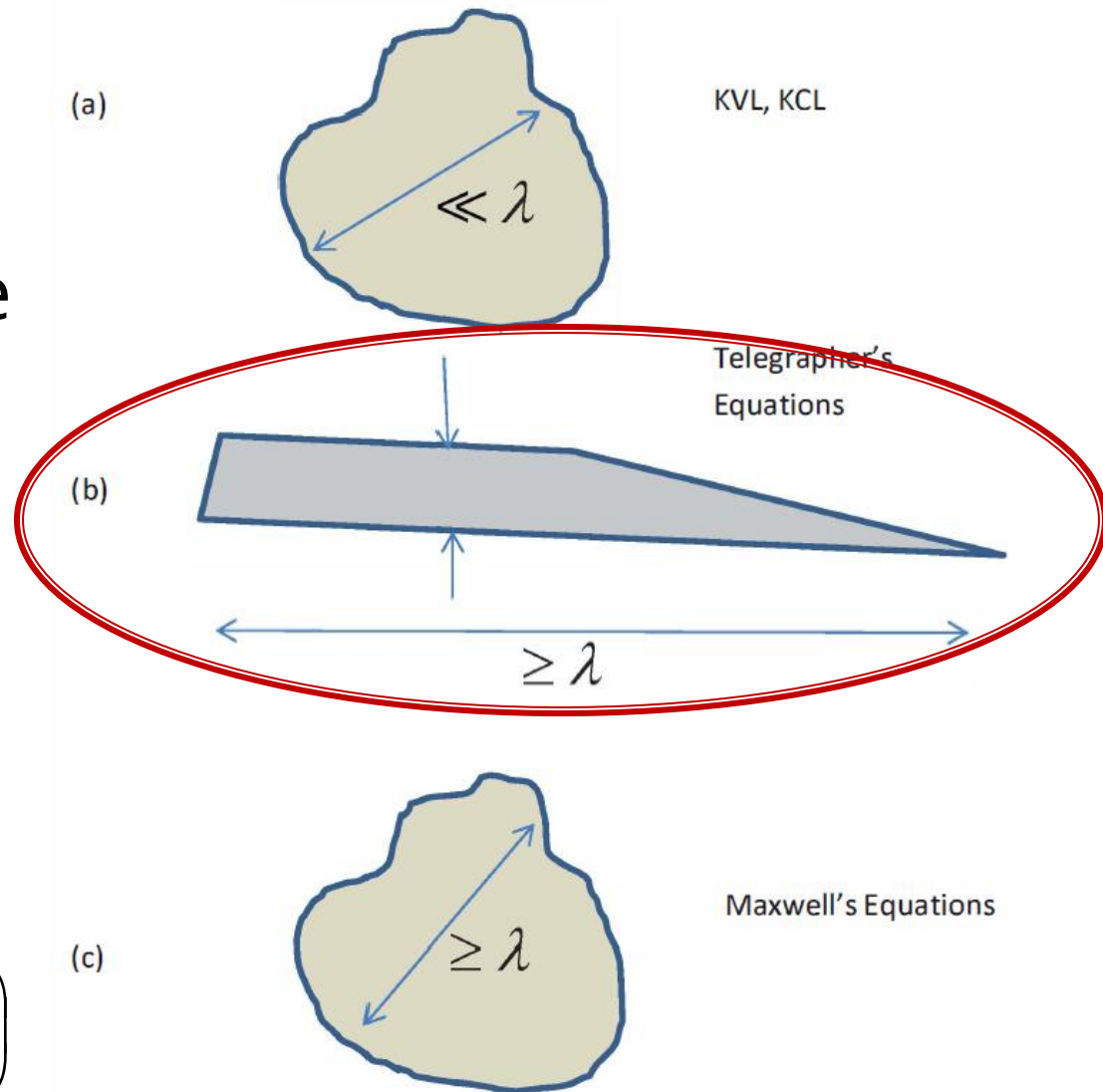
- **Linii de transmisie**
- **Adaptarea de impedanță**
- **Cuploare direcționale**
- **Divizoare de putere**
- **Amplificatoare de microunde**
- **Filtre de microunde**
- **Oscilatoare de microunde ?**

Lungime electrica

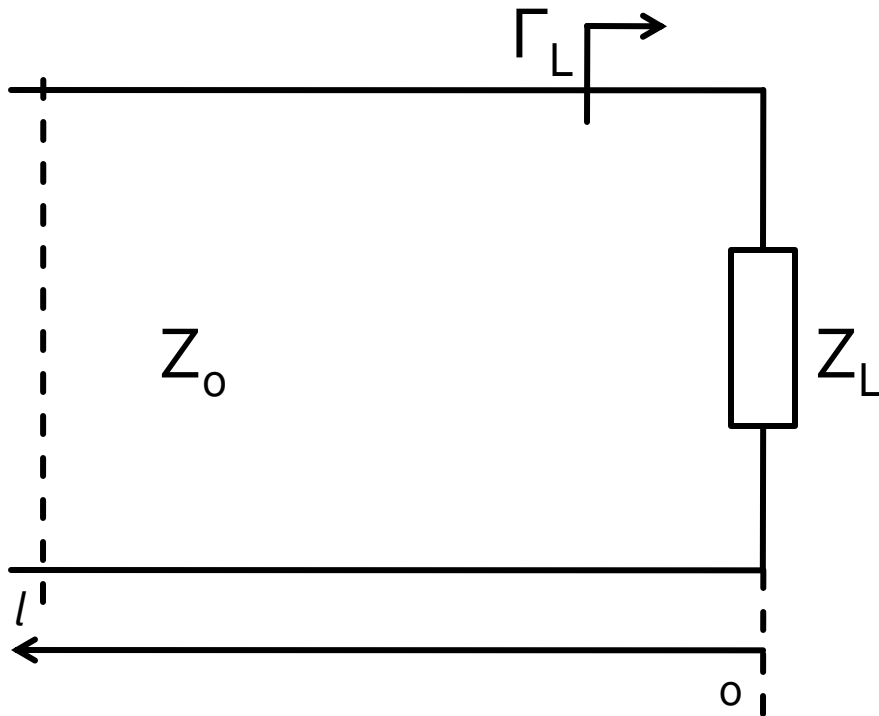
- Comportarea (descrierea) unui circuit depinde de lungimea sa electrica la frecventele de interes

- $E \approx 0 \rightarrow$ Kirchhoff
- $E > 0 \rightarrow$ propagare

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



Linie fara pierderi



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

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

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

- coeficient de reflexie in tensiune

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

- Z_0 real

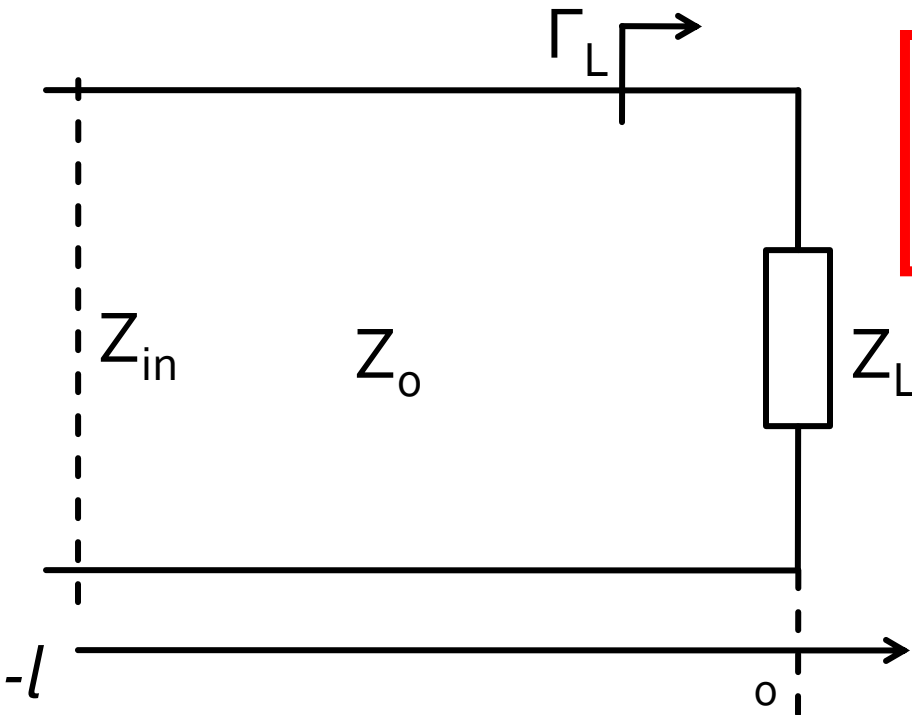
Linie fara pierderi

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

- Puterea medie e constanta in lungul liniei
 - (**fara** $P_{avg}(\mathbf{z})$)
 - 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_0 , de lungime l , terminata cu impedanta Z_L



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

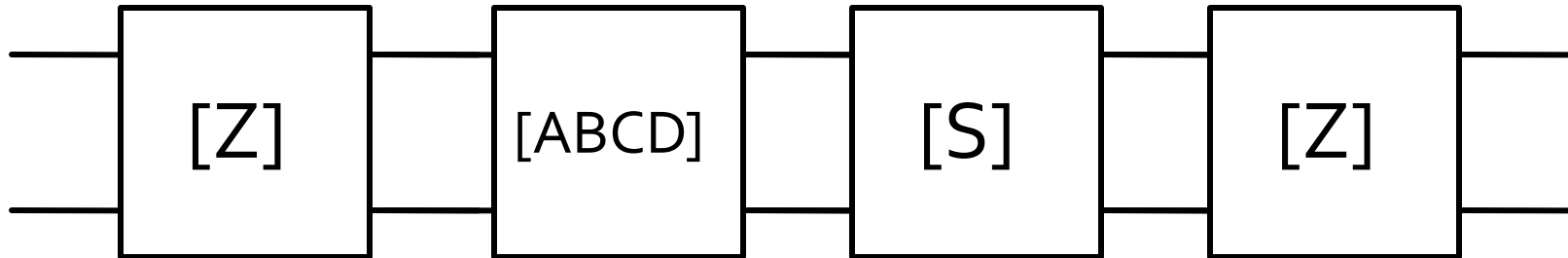
Tema C5

- Scrieți pe o foaie de hârtie (si scanați/foto) modalitatea de determinare a matricii ABCD pentru:
 - admitanță paralel
 - linie de transmisie
 - transformator
 - diport π
 - diport T

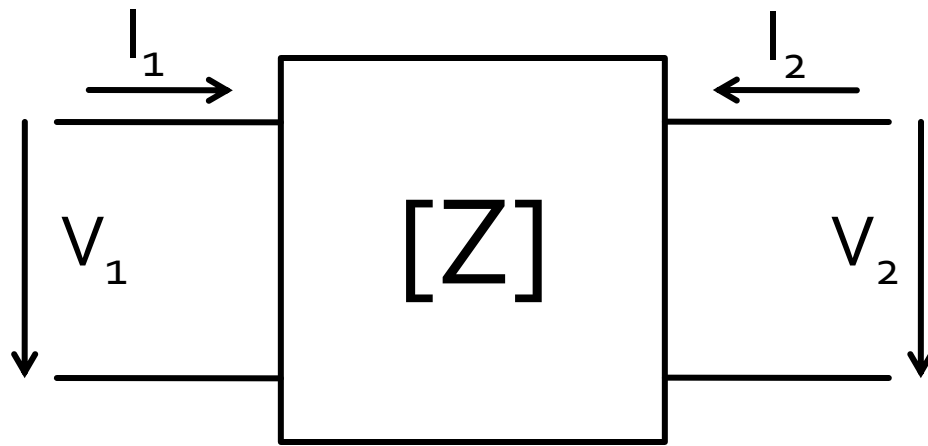
**Analiza la nivel de rețea a
circuitelor de microunde**

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



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

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

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

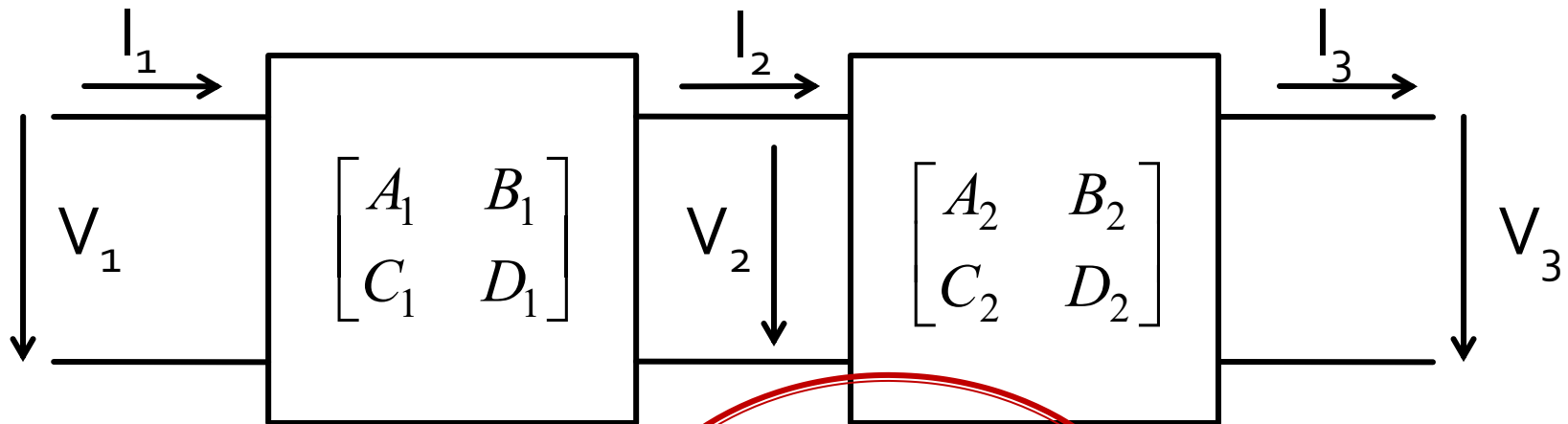
$$V_1 = Z_{11} \cdot I_1 \Big|_{I_2=0} \quad Z_{11} = \frac{V_1}{I_1} \Big|_{I_2=0}$$

- **Z₁₁** – impedanta de intrare cu iesirea in gol

$$Z_{11} = \frac{V_1}{I_1} \Big|_{I_2=0} \quad Z_{12} = \frac{V_1}{I_2} \Big|_{I_1=0} \quad Z_{21} = \frac{V_2}{I_1} \Big|_{I_2=0} \quad Z_{22} = \frac{V_2}{I_2} \Big|_{I_1=0}$$

Matricea ABCD – de transmisie

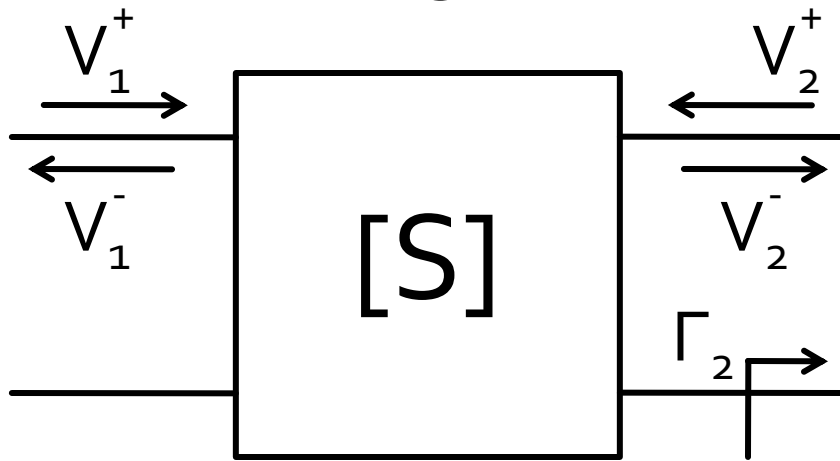
- introduce o legatura intre "intrare" si "iesire"
- permite inlantuirea usoara intre mai multe blocuri



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

Matricea S (repartitie)

- Scattering parameters



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

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

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

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

Proprietati [S]

- Daca portul i este conectat la o linie cu impedanta caracteristica Z_{0i}

■ Curs 3

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

In planul de
referinta al
portului, $z=0$

$$V_i = V_i^+ + V_i^-$$

$$I_i = \frac{V_i^+}{Z_{0i}} - \frac{V_i^-}{Z_{0i}}$$

$$[Z_0] = \begin{bmatrix} Z_{01} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Z_{0n} \end{bmatrix}$$

- Legatura cu matricea Z $[Z] \cdot [I] = [V]$

$$[Z] \cdot [I] = [Z_0]^{-1} \cdot [Z] \cdot [V^+] - [Z_0]^{-1} \cdot [Z] \cdot [V^-] \quad [V] = [V^+] + [V^-]$$

$$[Z_0]^{-1} \cdot [Z] \cdot [V^+] - [Z_0]^{-1} \cdot [Z] \cdot [V^-] = [V^+] + [V^-] \quad ([Z] - [Z_0]) \cdot [V^+] = ([Z] + [Z_0]) \cdot [V^-]$$

$$[V^-] = [S] \cdot [V^+]$$

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

Proprietati [S]

- Circuite reciproce (fara circuite active, ferite)

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

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

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

- Circuite fara pierderi

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

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

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

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

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

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

Matricea S generalizata

- Definim unde de putere

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

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

$Z_R = R_R + j \cdot X_R$
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

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

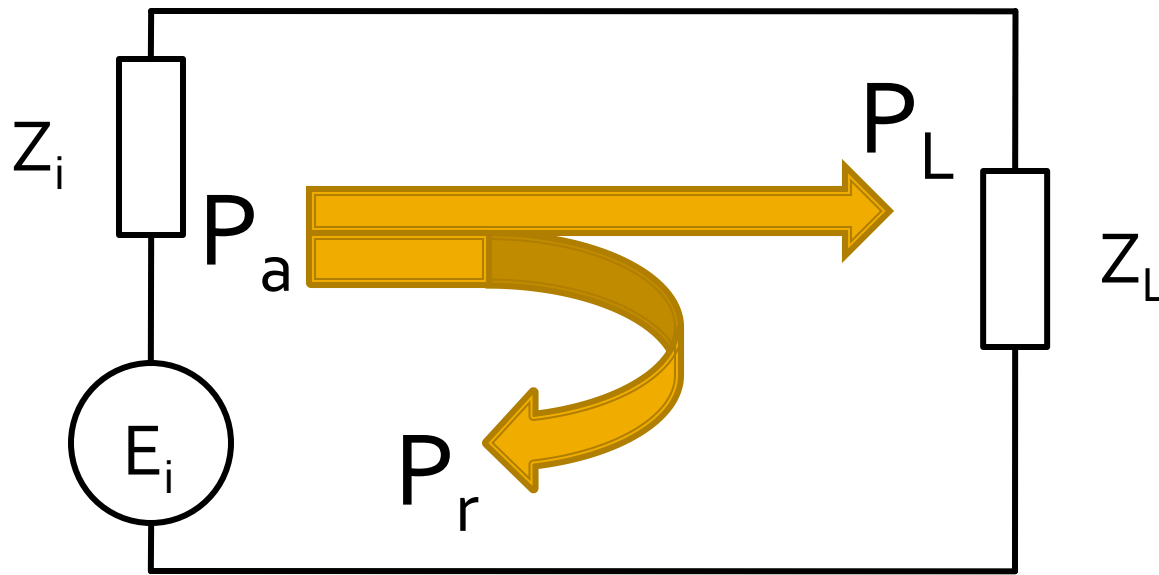
- Reflexie in putere C4

$$\begin{aligned} Z_L = Z_i^* \quad P_{L\max} &\equiv P_a & \Gamma &= \frac{Z - Z_0^*}{Z + Z_0} \\ Z_L \neq Z_i^* \quad P_r &= P_a \cdot |\Gamma|^2 & P_L &= P_a - P_r = P_a - P_a \cdot |\Gamma|^2 = P_a \cdot (1 - |\Gamma|^2) \end{aligned}$$

- Reflexie in putere C5

$$\begin{aligned} P_{L\max} &\equiv P_a = \frac{1}{2} \cdot |a|^2 & P_L &= \frac{1}{2} \cdot |a|^2 - \frac{1}{2} \cdot |b|^2 & \Gamma_p &= \frac{b}{a} = \frac{V - Z_R^* \cdot I}{V + Z_R \cdot I} = \frac{Z_L - Z_R^*}{Z_L + Z_R} \\ P_L &= \frac{1}{2} \cdot |a|^2 - \frac{1}{2} \cdot |a|^2 \cdot |\Gamma_p|^2 & P_L &= P_a \cdot (1 - |\Gamma_p|^2) & P_r &= P_a \cdot |\Gamma_p|^2 = \frac{1}{2} \cdot |b|^2 \end{aligned}$$

Reflexie de putere / Model / C4



$$P_a = \frac{|E_i|^2}{4R_i}$$

$$P_L = \frac{R_L \cdot |E_i|^2}{(R_i + R_L)^2 + (X_i + X_L)^2}$$

$$\Gamma_L = \frac{Z_L - Z_0^*}{Z_L + Z_0}$$

$$P_r = \frac{|E_i|^2}{4R_i} \cdot \left[\frac{(R_i - R_L)^2 + (X_i + X_L)^2}{(R_i + R_L)^2 + (X_i + X_L)^2} \right] = P_a \cdot |\Gamma|^2$$

- coeficient de reflexie in putere

Unde de putere pentru multiporti

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

- legatura intre undele de putere incidenta si reflectata

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

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

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

- tipic

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

$$R_0 = 50\Omega$$

$$[S_p] \equiv [S]$$

■ **coincid!!!**

Continuare

Cuploare directionale si divizoare de putere

Cuprins

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

Cuploare/Divizoare

- Funcționalitatea dorită:
 - divizarea
 - combinarea
- puterii semnalului

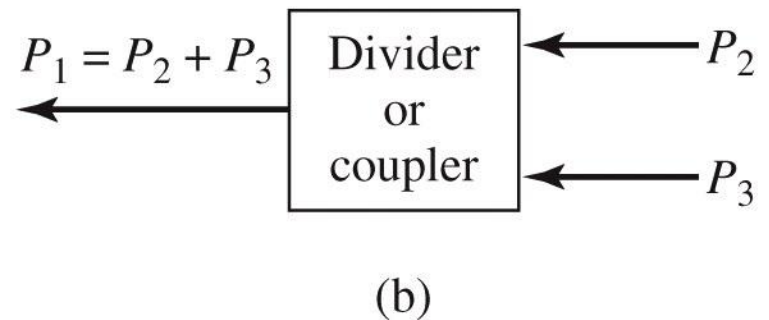
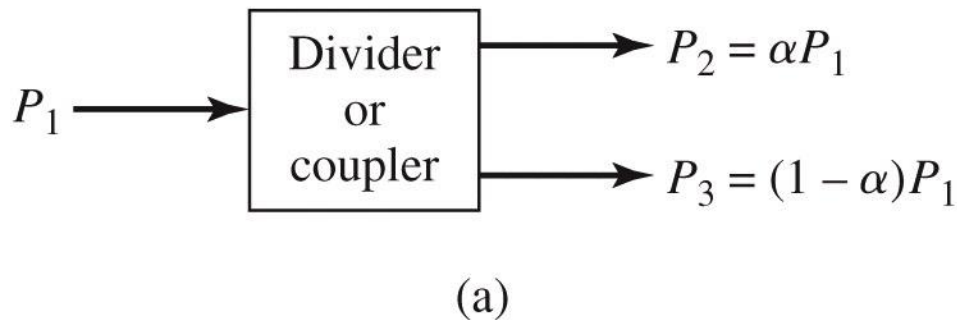
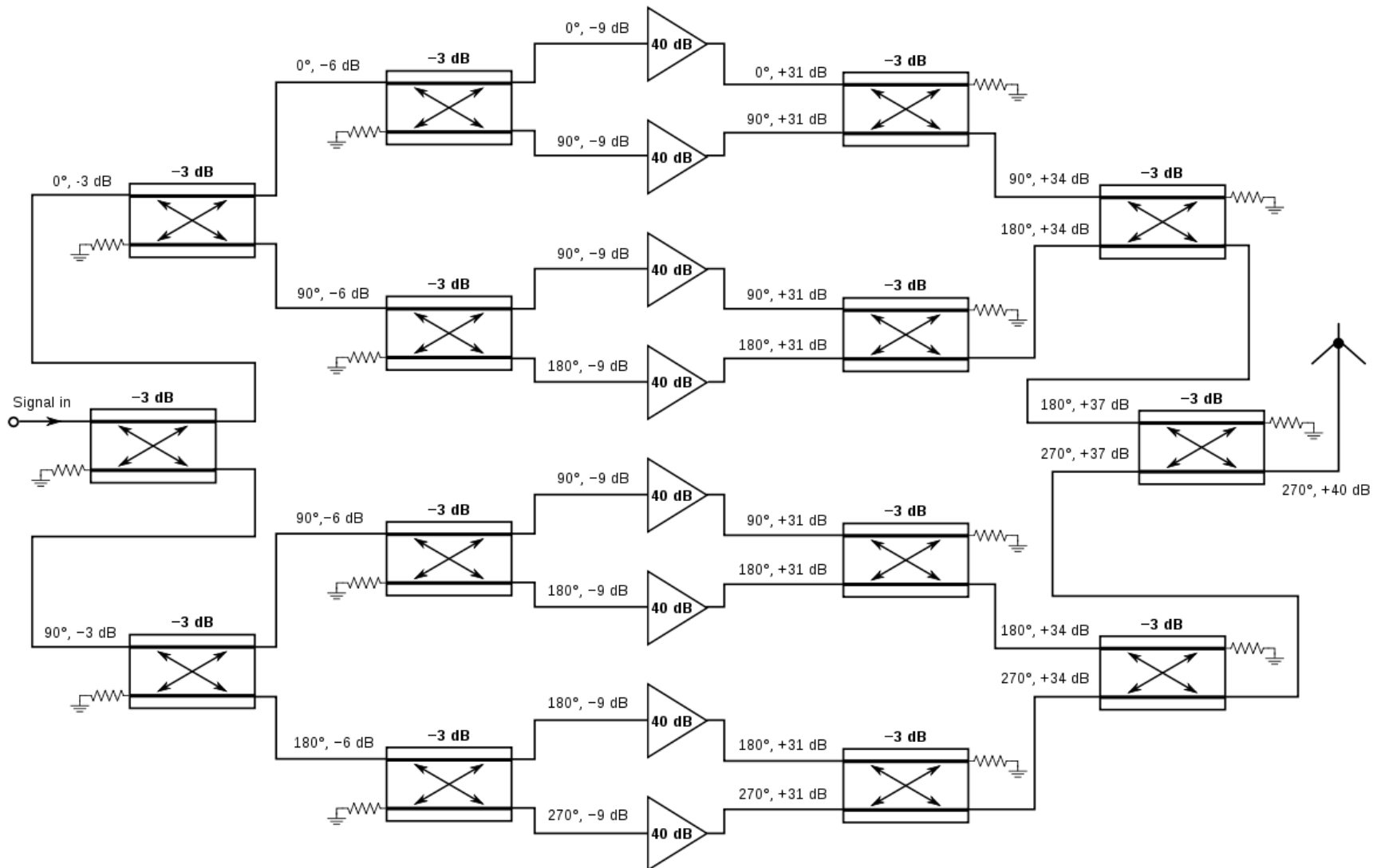


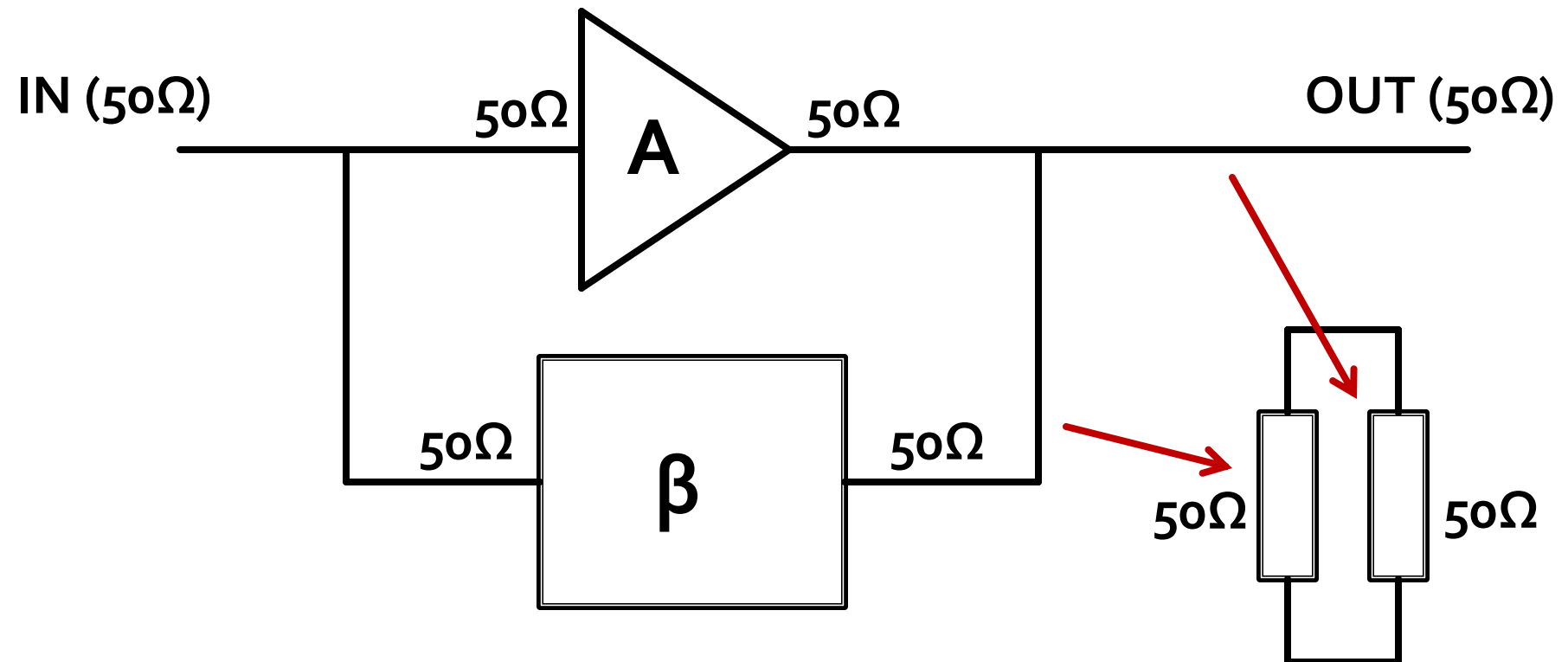
Figure 7.1
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Amplificatoare echilibrate



Amplificatoare

- amplificator cu reactie
- control automat al amplitudinii



Circuite cu trei porți

- numite si joncțiune in T
- caracterizate de o matrice $\mathbf{S}$ 3x3

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

- 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

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

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

- adaptat simultan la toate portile

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

- 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)
 - toată puterea introdusă pe un port se regăsește la celelalte porturi

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

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

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

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

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

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

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

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

$$S_{12}^* S_{13} = 0$$

$$S_{23}^* S_{12} = 0$$

- 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 posibilă
- Un circuit cu 3 porți **NU** poate fi simultan:
 - reciproc
 - fără 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 nereciproce

- de obicei cu materiale anizotrope, ferite
- **nereciproce**, dar adaptat simultan și fără 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 ecuații / 6 necunoscute

$$|S_{21}|^2 + |S_{31}|^2 = 1 \quad S_{31}^* S_{32} = 0$$

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

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

Circuit cu trei porți neregiproce

- doua solutii posibile
- circulatoare

- in sens orar direct

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

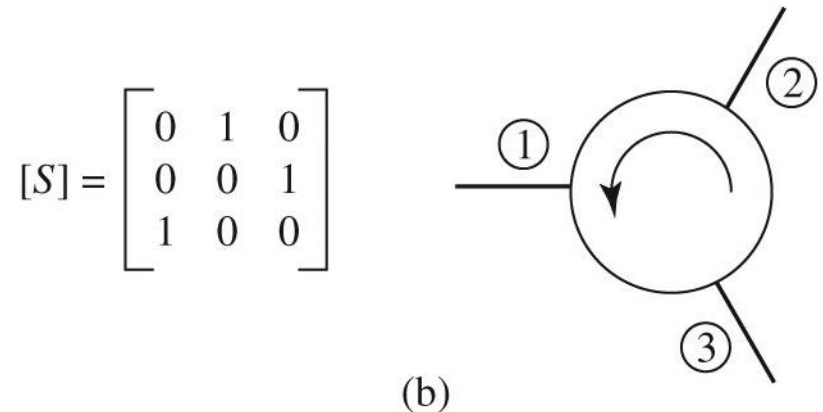
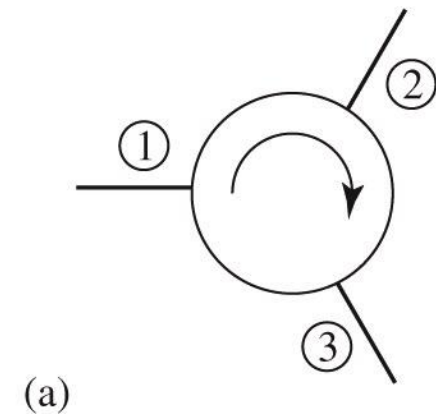
$$|S_{21}| = |S_{32}| = |S_{13}| = 1$$

- in sens orar invers

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

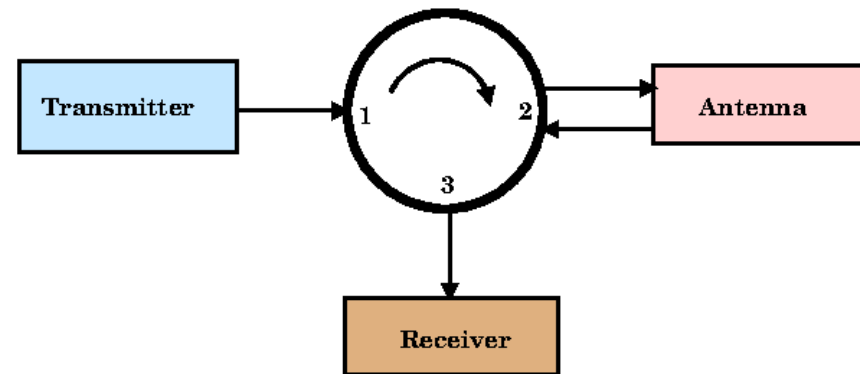
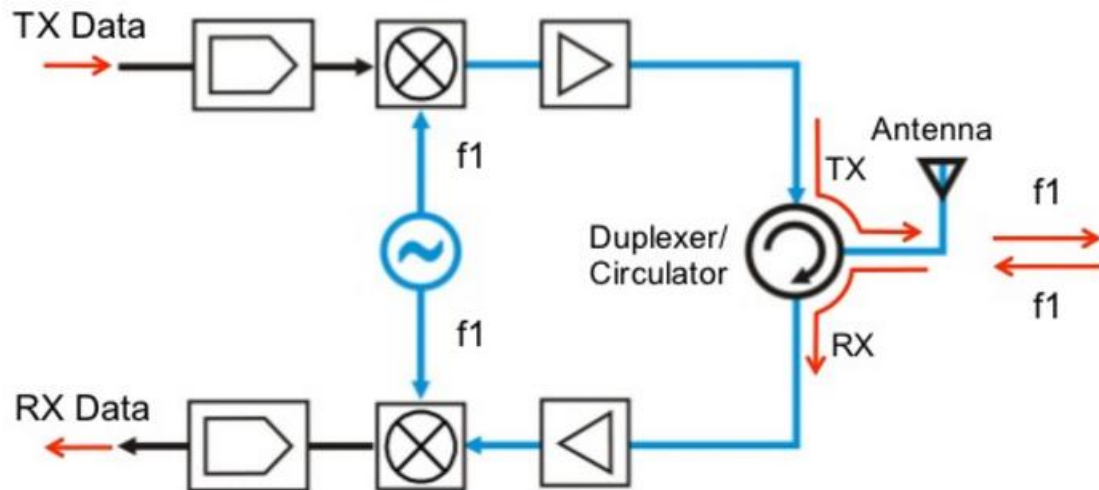
$$|S_{12}| = |S_{23}| = |S_{31}| = 1$$

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



Circuit cu trei porți neregiproce

- circulator deseori în duplexer



Circuit cu trei porți neadaptat

- Un circuit cu 3 porți reciproc și fără pierderi poate fi adaptat numai la 2 porți

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

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

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

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

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

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

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

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

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

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

Circuit cu trei porți neadaptat

- Un circuit cu 3 porți reciproc și fără pierderi

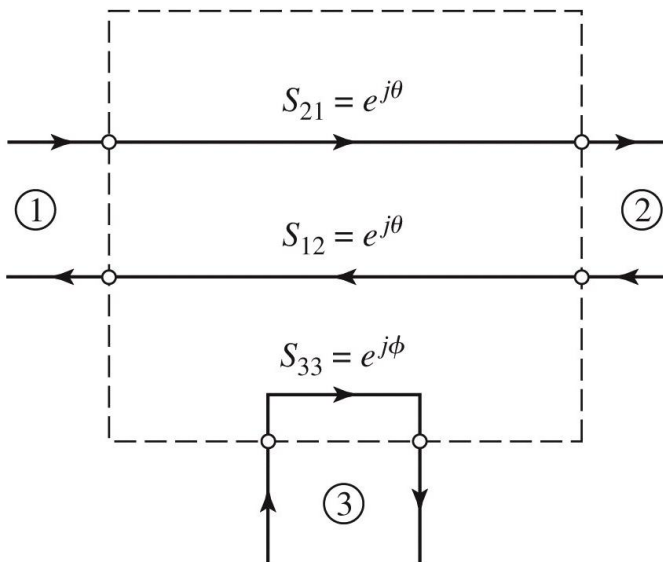
$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix}$$

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

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

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

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



- Un circuit cu 3 porți reciproc și fără pierderi **degenerează** în două componente separate:

- o linie** fără pierderi, adaptată, între două dintre porturi
- al treilea **port** e **separat** și **dezadaptat**

Circuite cu patru porți

- caracterizate de o matrice $S_{4 \times 4}$

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

- 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 să obținem circuitul **adaptat simultan la toate porțile**
 - evitarea unor pierderi externe de putere

Circuite cu patru porți

- circuit reciproc

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

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

- adaptat simultan la toate portile

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

- 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)
 - toată puterea introdusă pe un port se regăsește la celelalte porturi

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

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

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

Circuite cu patru porți

$$S_{13}^* \cdot S_{23} + S_{14}^* \cdot S_{24} = 0 \quad / \cdot S_{24}^*$$

$$S_{14}^* \cdot S_{13} + S_{24}^* \cdot S_{23} = 0 \quad / \cdot S_{13}^*$$

$$S_{14}^* \cdot (|S_{13}|^2 - |S_{24}|^2) = 0$$

$$S_{12}^* \cdot S_{23} + S_{14}^* \cdot S_{34} = 0 \quad / \cdot S_{12}^*$$

$$S_{14}^* \cdot S_{12} + S_{34}^* \cdot S_{23} = 0 \quad / \cdot S_{34}^*$$

$$S_{23} \cdot (|S_{12}|^2 - |S_{34}|^2) = 0$$

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

$$|S_{12}|^2 + |S_{13}|^2 = 1 \quad \rightarrow \quad |S_{13}| = |S_{24}|$$

$$|S_{12}|^2 + |S_{24}|^2 = 1 \quad \rightarrow \quad |S_{13}| = |S_{24}|$$

$$|S_{13}|^2 + |S_{34}|^2 = 1 \quad \rightarrow \quad |S_{12}| = |S_{34}|$$

$$|S_{24}|^2 + |S_{34}|^2 = 1 \quad \rightarrow \quad |S_{12}| = |S_{34}|$$

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

Circuite cu patru porți

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & 0 \\ S_{12} & 0 & 0 & S_{24} \\ S_{13} & 0 & 0 & S_{34} \\ 0 & S_{24} & S_{34} & 0 \end{bmatrix} \quad \begin{array}{l} |S_{12}| = |S_{34}| = \alpha \quad |S_{13}| = |S_{24}| = \beta \\ \beta - \text{coeficientul de cuplaj în tensiune} \end{array}$$

■ Alegem referintele de faza

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

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

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

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

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

Circuite cu patru porți

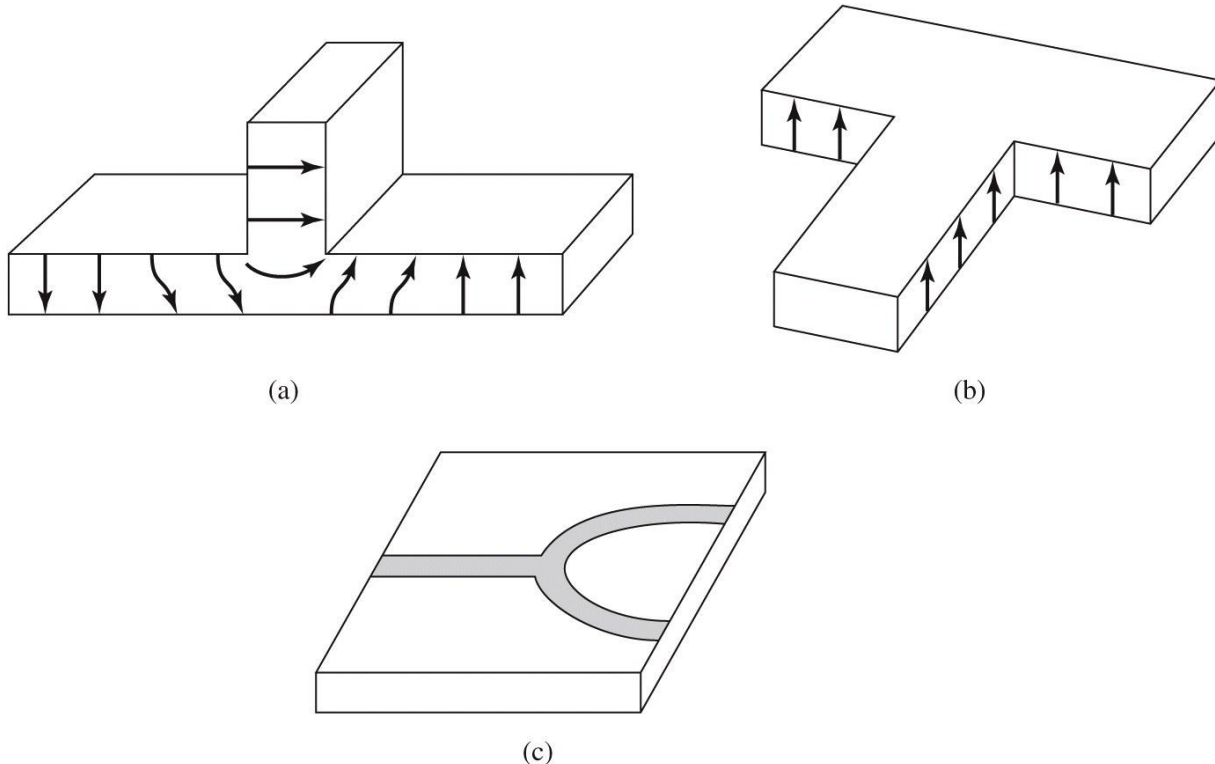
- Un circuit cu 4 porți care este simultan:
 - adaptat la toate portile
 - reciproc
 - fara pierderi
- este **intotdeauna** **directional**
 - puterea de semnal introdusa pe un port este trimisa **numai spre doua** din celelalte trei porturi

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

Divizoare de putere

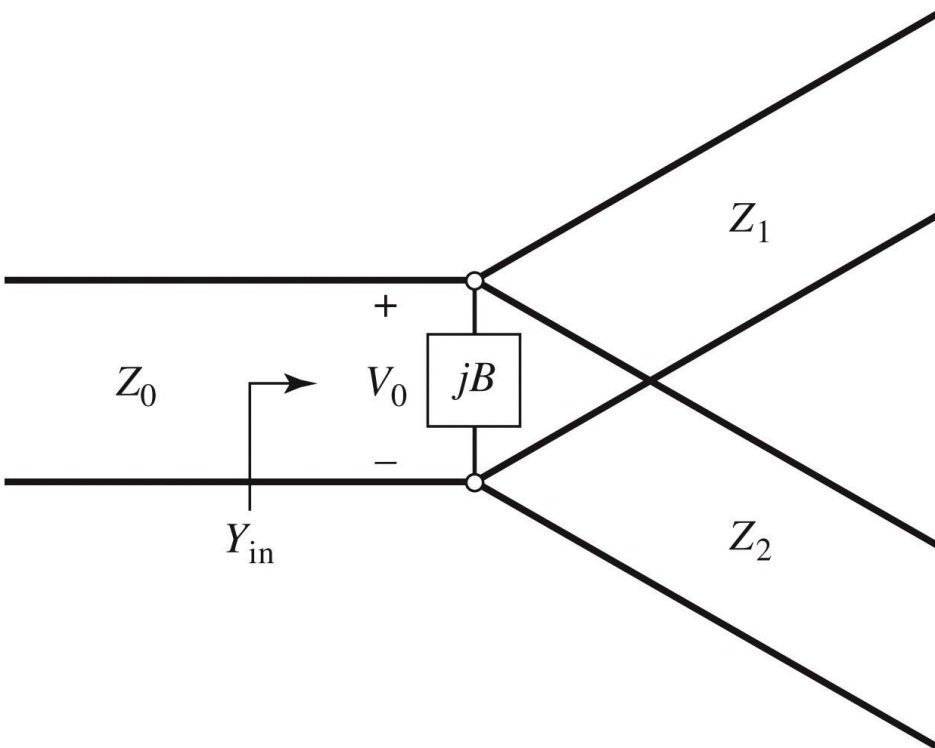
Divizarea de putere a jonctiunii in T

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



Divizarea de putere a jonctiunii in T

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



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

Divizarea de putere a jonctiunii in T

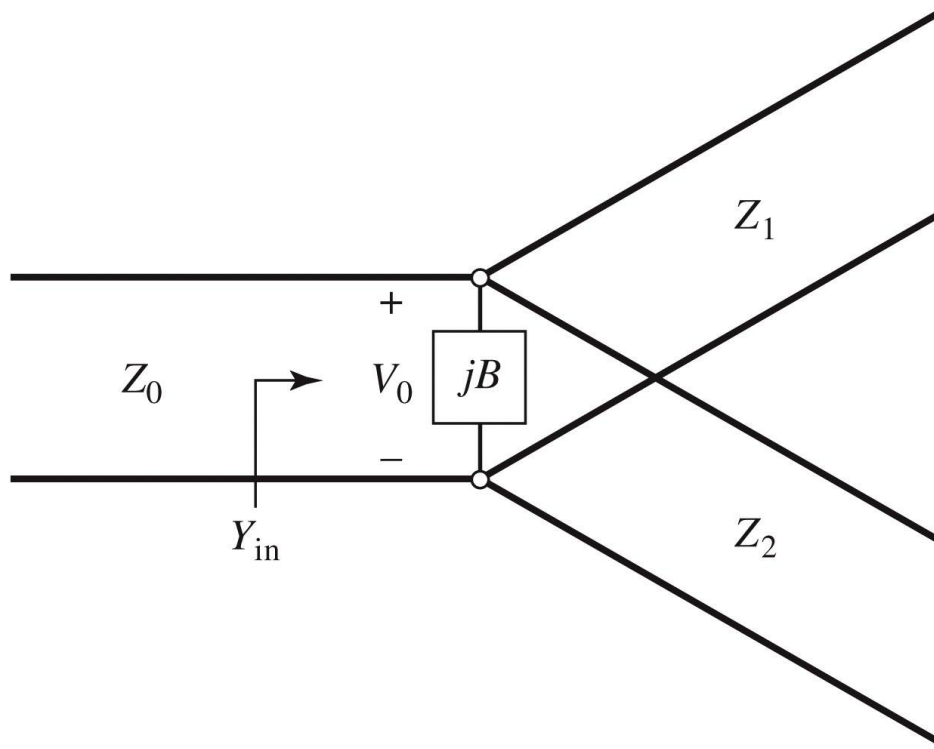


Figure 7.6
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$$Y_{in} = j \cdot B + \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0}$$

- daca liniile sunt fără pierderi, impedantele caracteristice sunt reale
- conditia de adaptare poate fi indeplinita doar daca **$B \cong 0$** 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

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

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

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

deci:

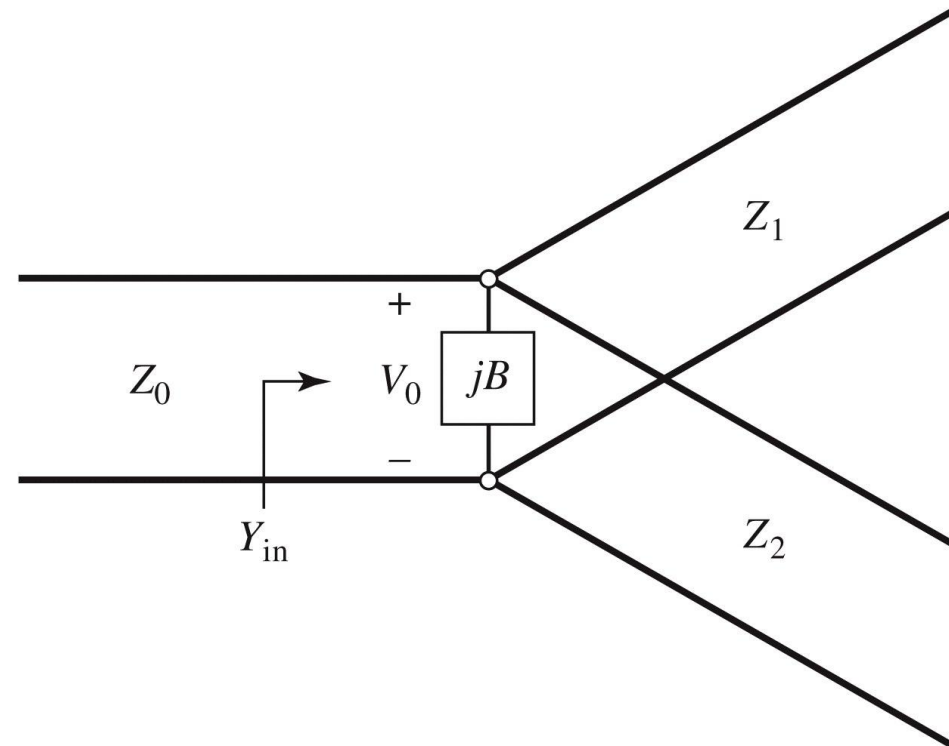
$$P_{in} = P_1 + P_2 \quad (\text{fara pierderi})$$

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

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

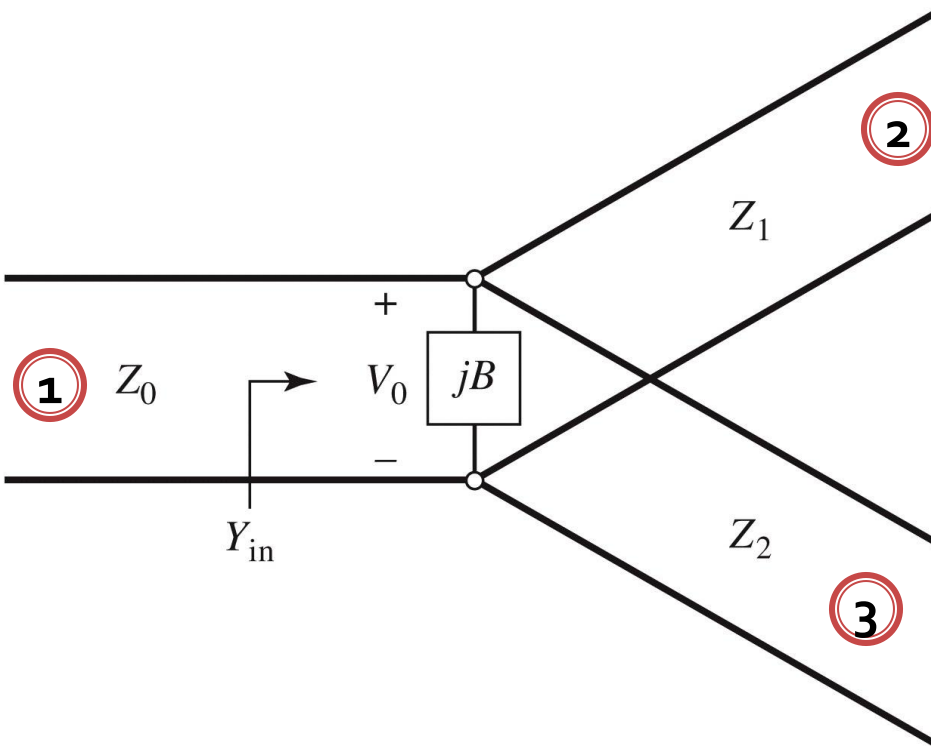
$$P_1 = P_{in} \cdot \frac{\alpha}{1 + \alpha} \quad P_2 = P_{in} \cdot \frac{1}{1 + \alpha}$$

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



Divizarea de putere a jonctiunii in T

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



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

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

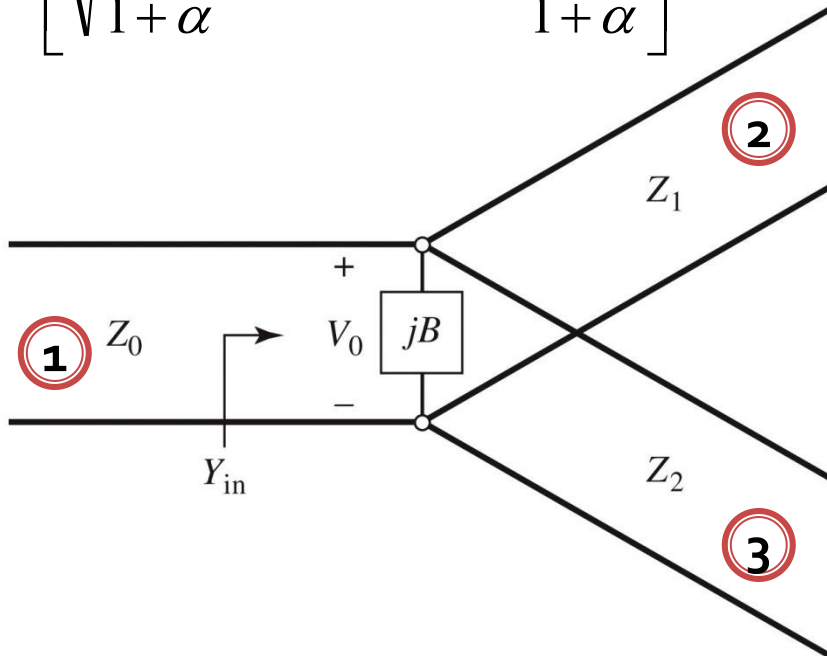
Coeficienti de reflexie la iesiri

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

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

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

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

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

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

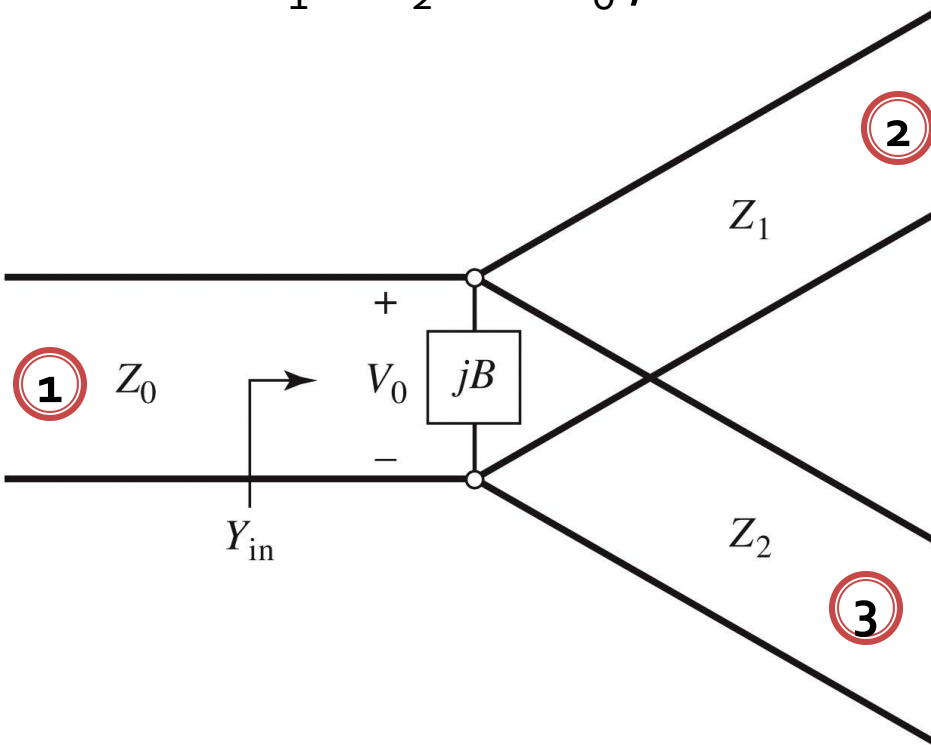
Divizarea de putere a jonctiunii in T

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

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

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 ieșire de 1:3. Proiectați transformatoare în sfert de lungime de undă care să convertească impedanța liniilor de ieșire la 30Ω .

$$P_{in} = \frac{1}{2} \cdot \frac{V_0^2}{Z_0} \quad \begin{cases} P_1 + P_2 = P_{in} \\ P_1 : P_2 = 1 : 3 \end{cases} \Rightarrow \begin{cases} P_1 = \frac{1}{4} \cdot P_{in} \\ P_2 = \frac{3}{4} \cdot P_{in} \end{cases}$$

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

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

Verificare

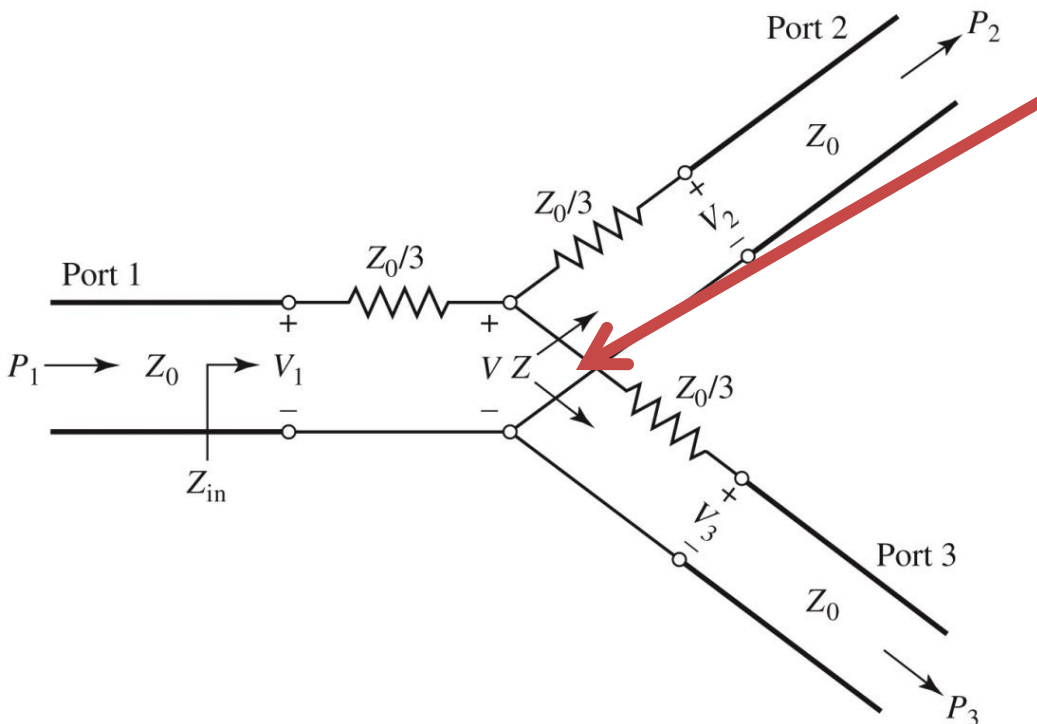
$$Z_{in} = 40\Omega || 120\Omega = 30\Omega$$

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

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

Divizorul de putere rezistiv

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



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

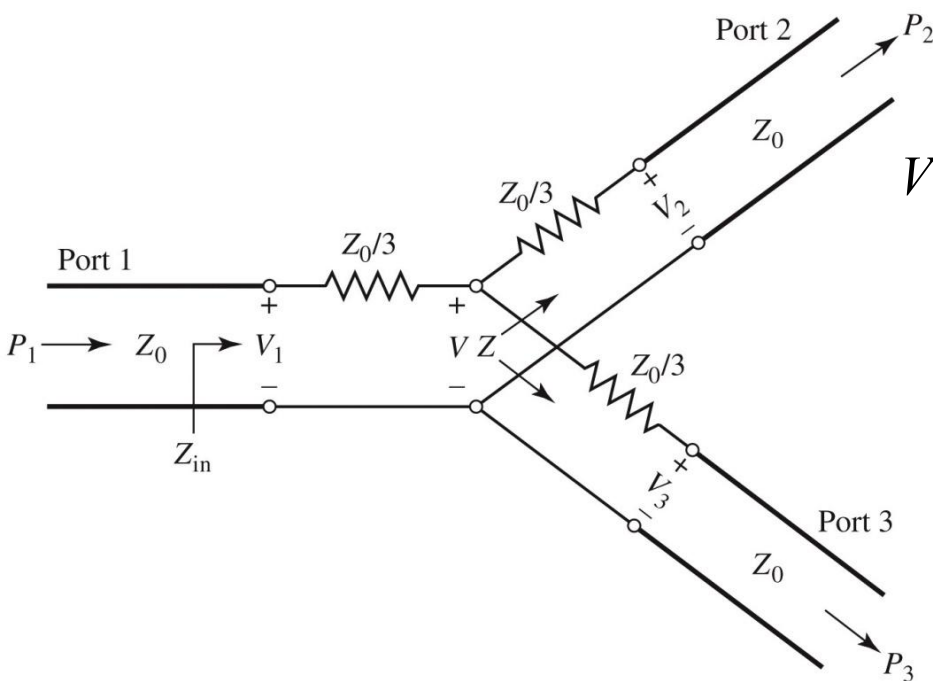
$$Z_{in} = \frac{Z_0}{3} + \frac{1}{2} \cdot \frac{4Z_0}{3} = Z_0$$

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 porti $S_{11} = S_{22} = S_{33} = 0$



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:

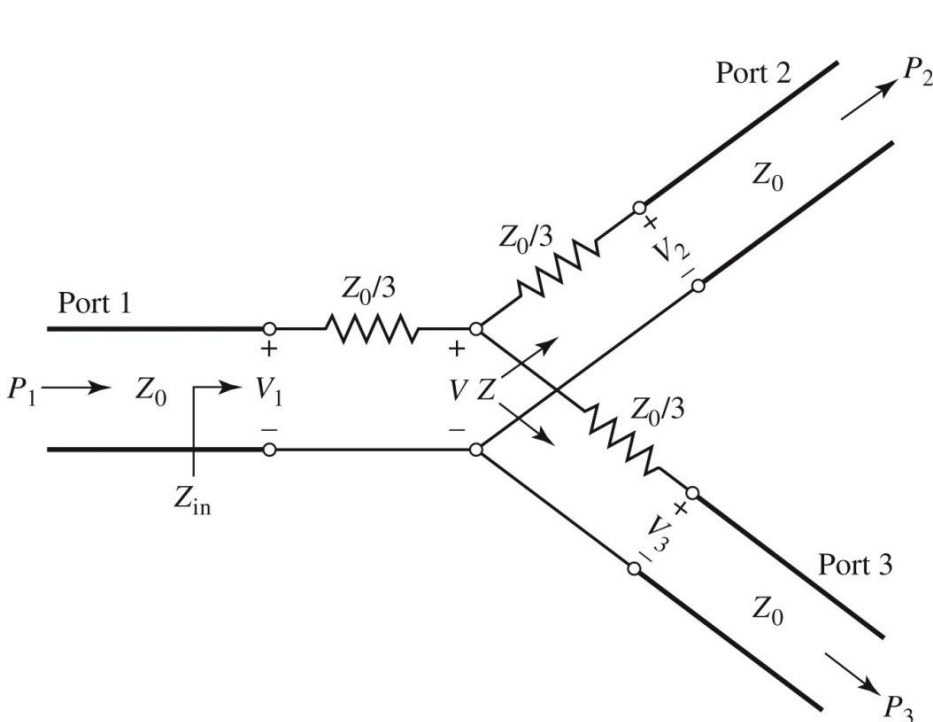
$$V_2 = V_3 = V \cdot \frac{Z_0}{Z_0 + Z_0/3} = \frac{3}{4} \cdot V = \frac{1}{2} \cdot V_1$$

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

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 $S_{11} = S_{22} = S_{33} = 0$



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

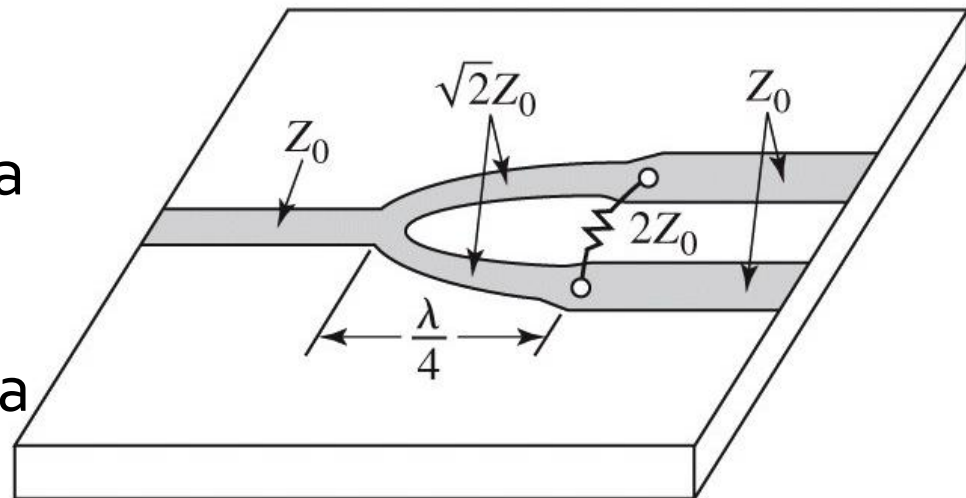
Puteri: $P_{in} = \frac{1}{2} \cdot \frac{V_1^2}{Z_0}$

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

Jumatate din putere se disipa pe cei 3 rezistori

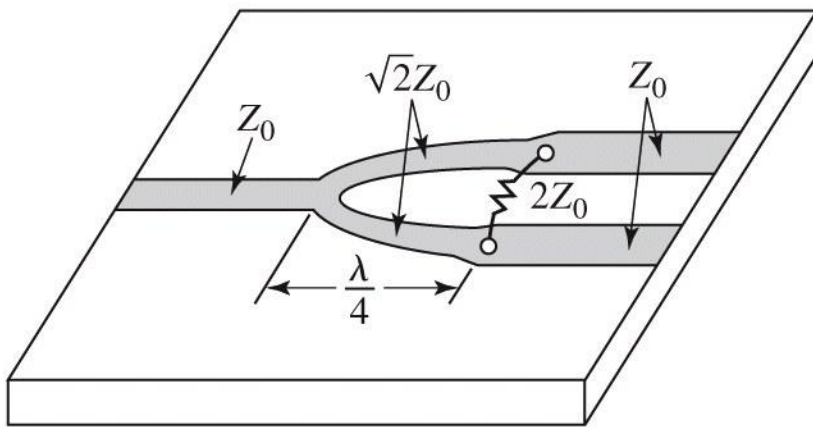
Divizorul de putere Wilkinson

- 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

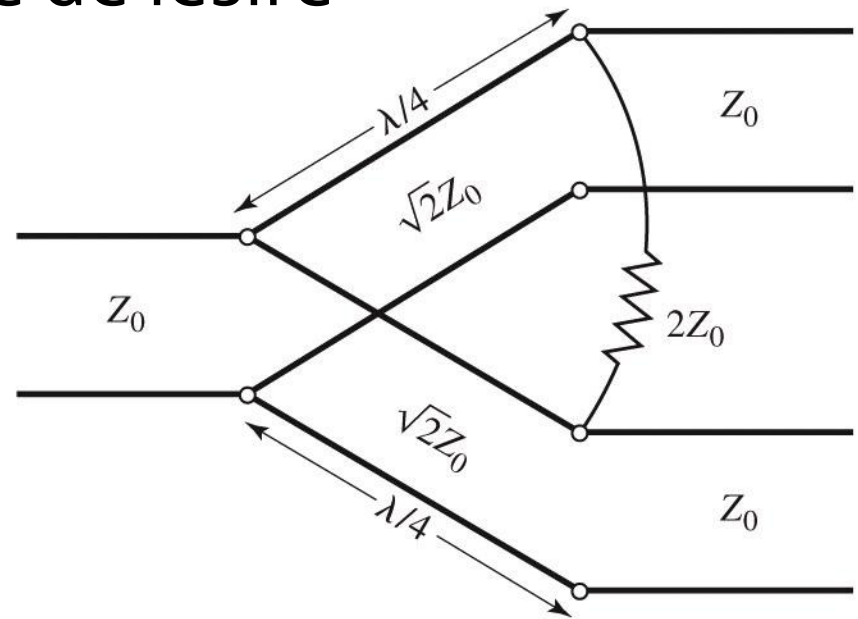


Divizorul de putere Wilkinson

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



(a)



(b)

Analiza pe mod par/impar (even/odd)

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

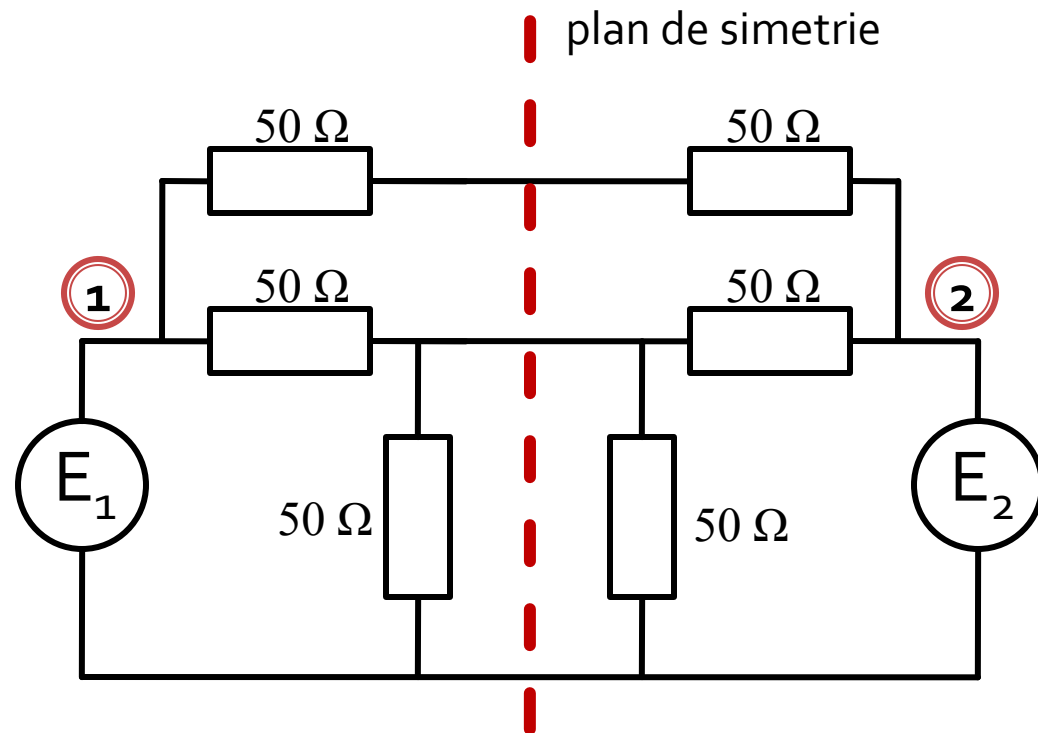
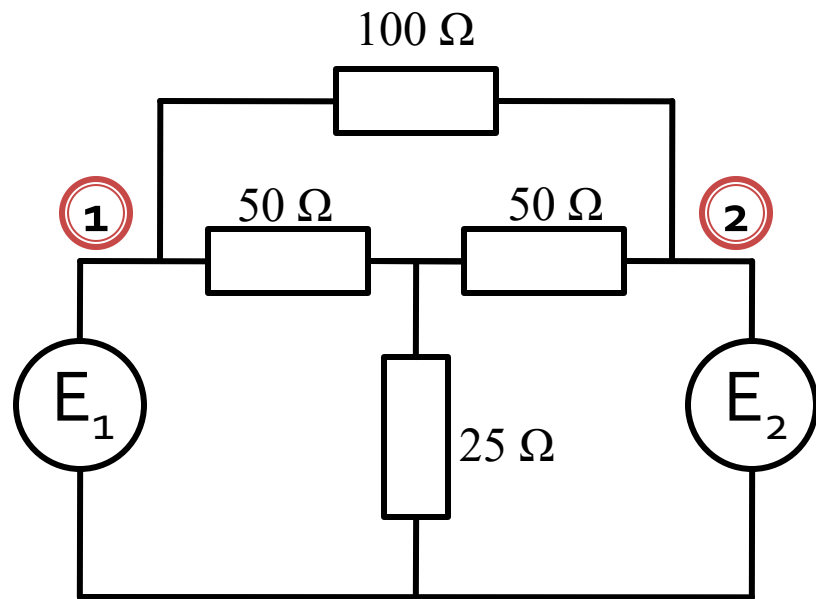
$$\text{Efect} (\text{PAR} + \text{IMPAR}) = \text{Efect} (\text{PAR}) + \text{Efect} (\text{IMPAR})$$



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"

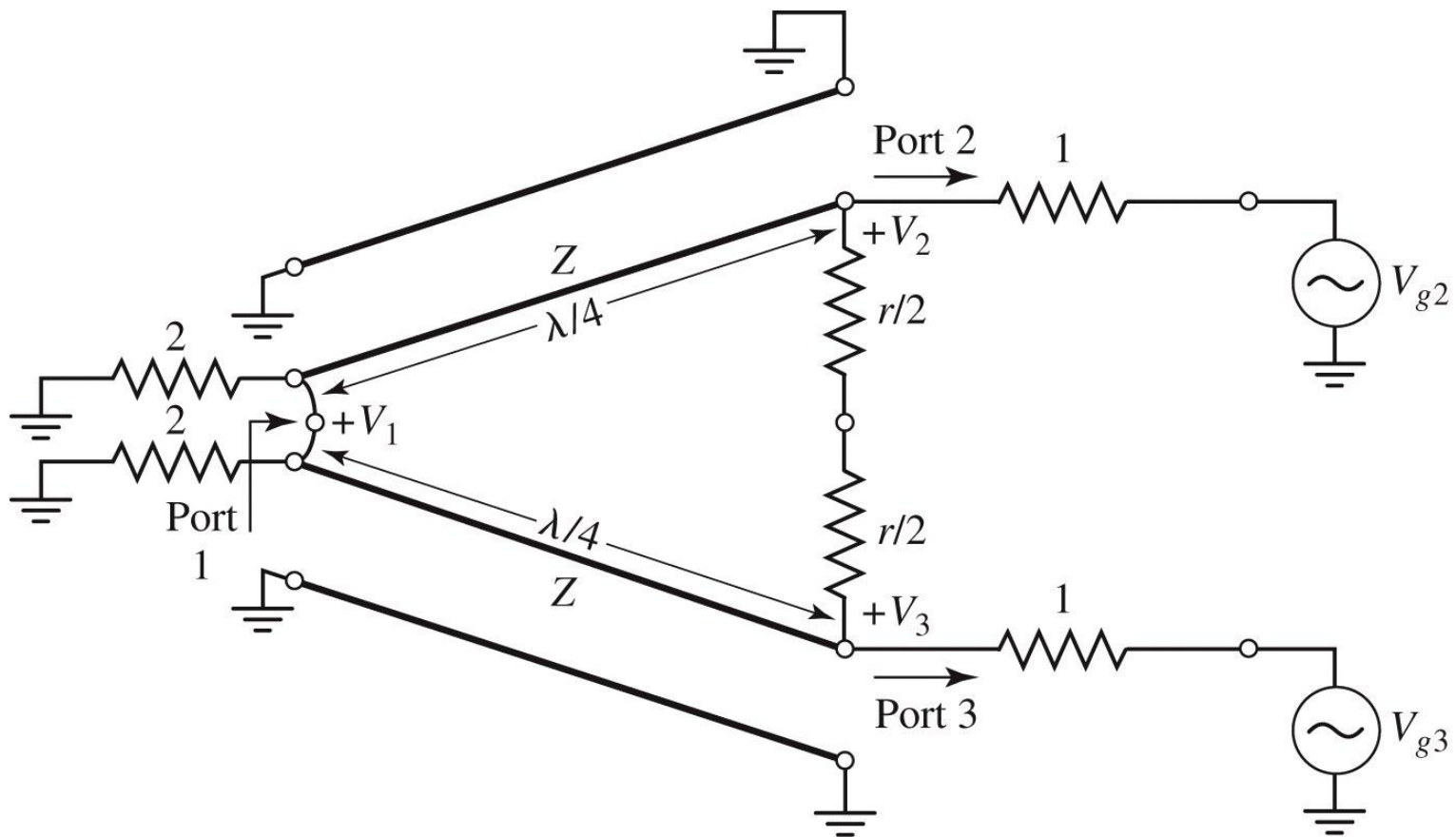
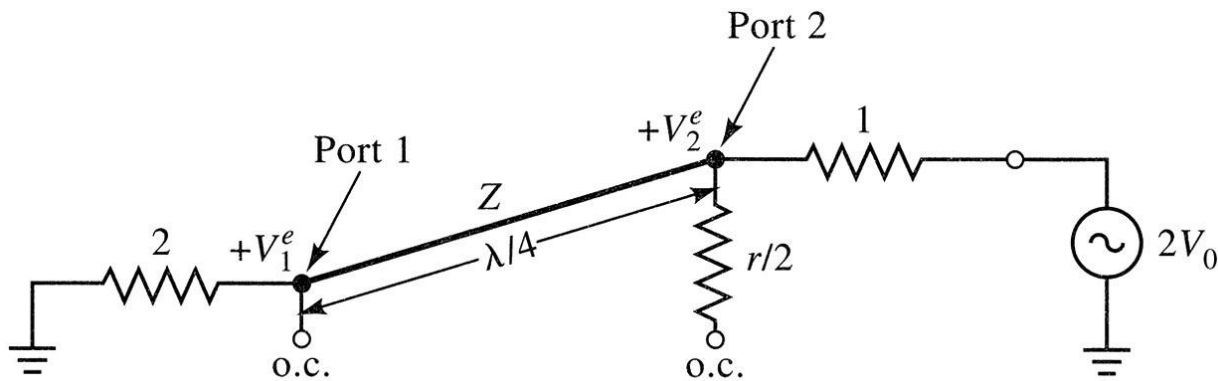


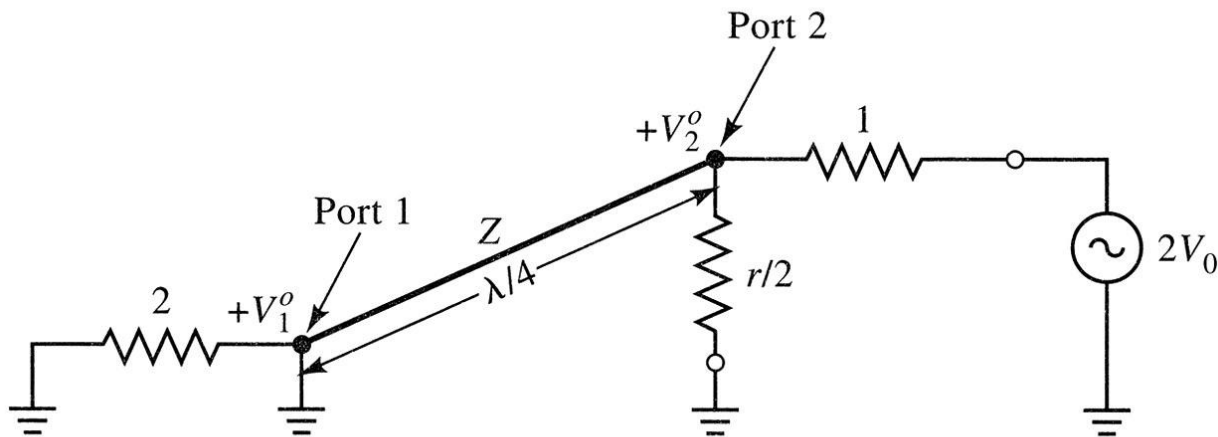
Figure 7.9

Divizorul de putere Wilkinson

- analiza pe mod par si impar



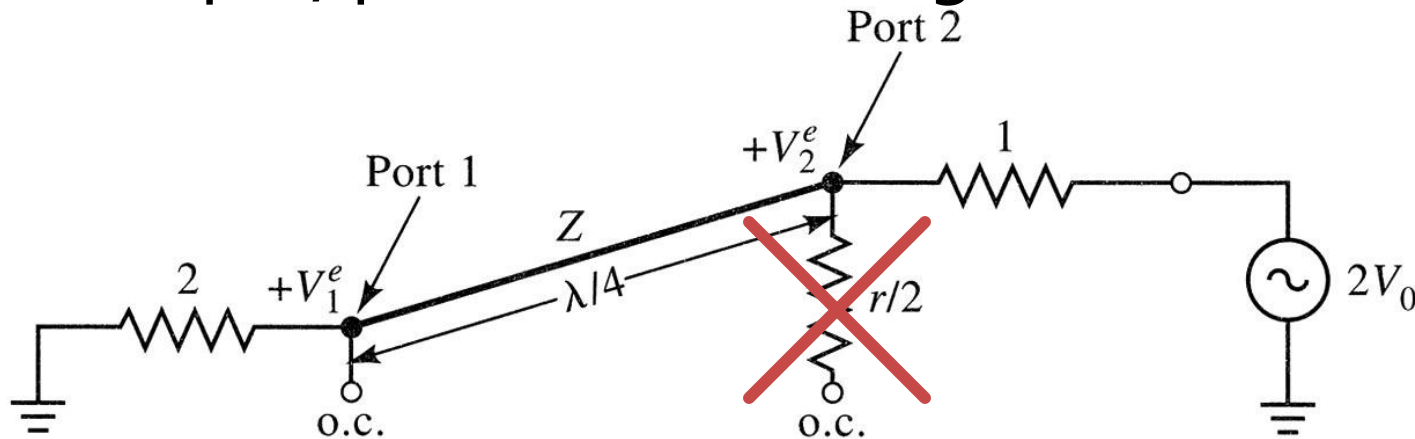
(a)



(b)

Divizorul de putere Wilkinson

- mod par, plan de simetrie gol



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

$$V(x) = V^+ \cdot (e^{-j\beta \cdot x} + \Gamma \cdot e^{j\beta \cdot x}) \quad \begin{array}{l} x=0 \text{ la portul 1} \\ x=-\lambda/4 \text{ la portul 2} \end{array}$$

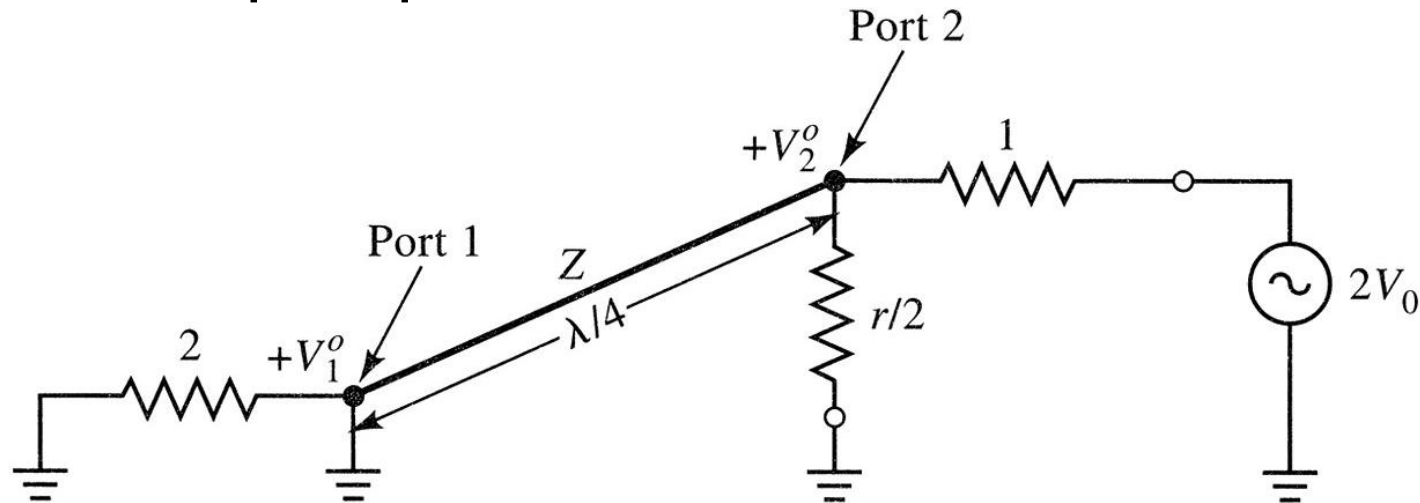
$$V_2^e = V(-\lambda/4) = jV^+ \cdot (1 - \Gamma) = V_0 \quad V_1^e = V(0) = V^+ \cdot (1 + \Gamma) = jV_0 \cdot \frac{\Gamma + 1}{\Gamma - 1}$$

$Z_{in2}^e = 1$

Γ : coeficientul de reflexie vazut dinspre transformatorul cu $Z = \sqrt{2}$ spre impedanta normalizata 2 $\Gamma = \frac{2 - \sqrt{2}}{2 + \sqrt{2}}$ $V_1^e = -jV_0\sqrt{2}$

Divizorul de putere Wilkinson

- mod impar, plan de simetrie masa



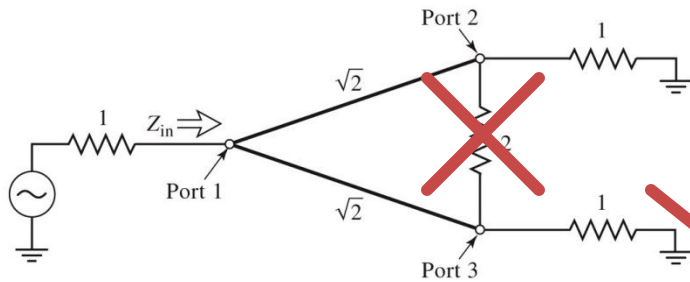
linia in $\lambda/4$ este scurtcircuitata la capat
 impedanta vazuta dinspre portul 2 este ∞ $Z_{in2}^o = r/2$ daca $r = 2$ portul 2 este adaptat

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

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

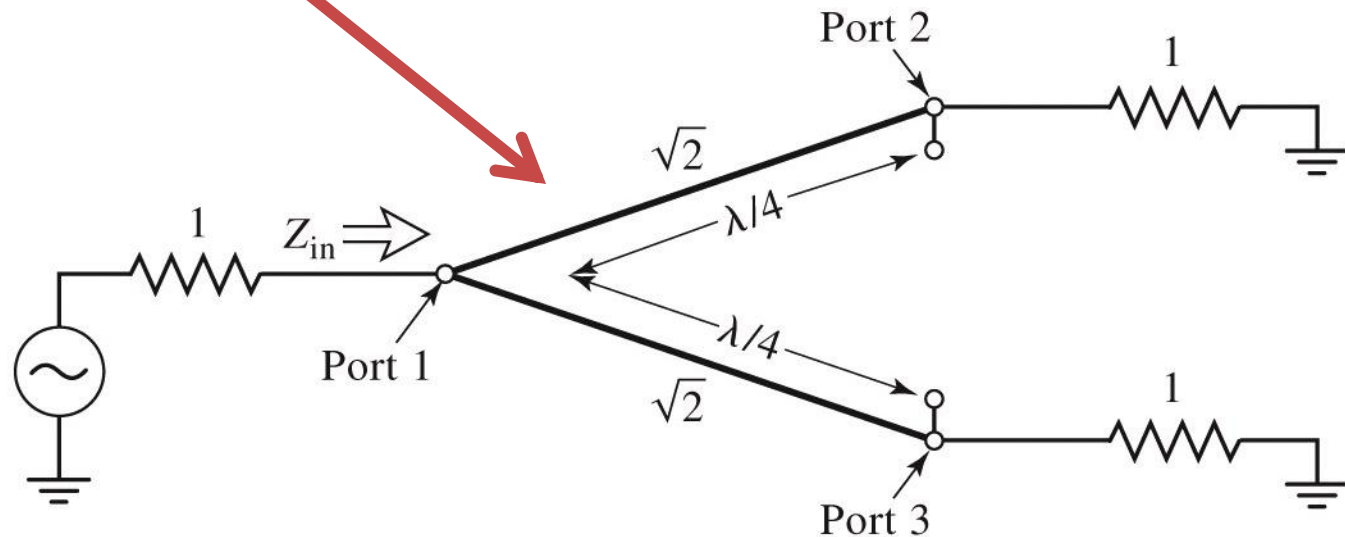
Divizorul de putere Wilkinson

- impedanta de intrare in portul 1



doua transformatoare $\lambda/4$ in paralel

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



Divizorul de putere Wilkinson

■ parametrii S

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

$$Z_{in2}^e = 1 \quad Z_{in2}^o = 1 \quad \text{si similar} \quad Z_{in3}^e = 1 \quad Z_{in3}^o = 1 \quad S_{22} = S_{33} = 0$$

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

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

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

Divizorul de putere Wilkinson

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

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

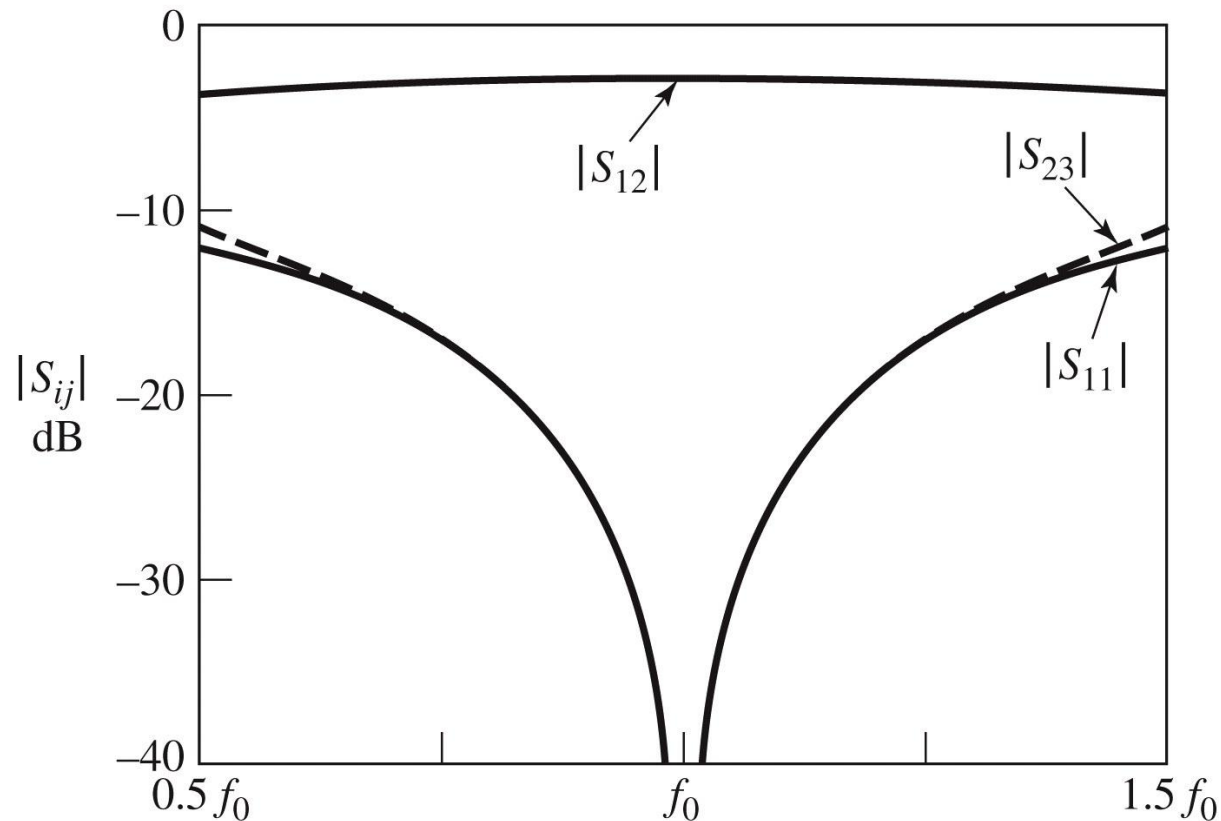
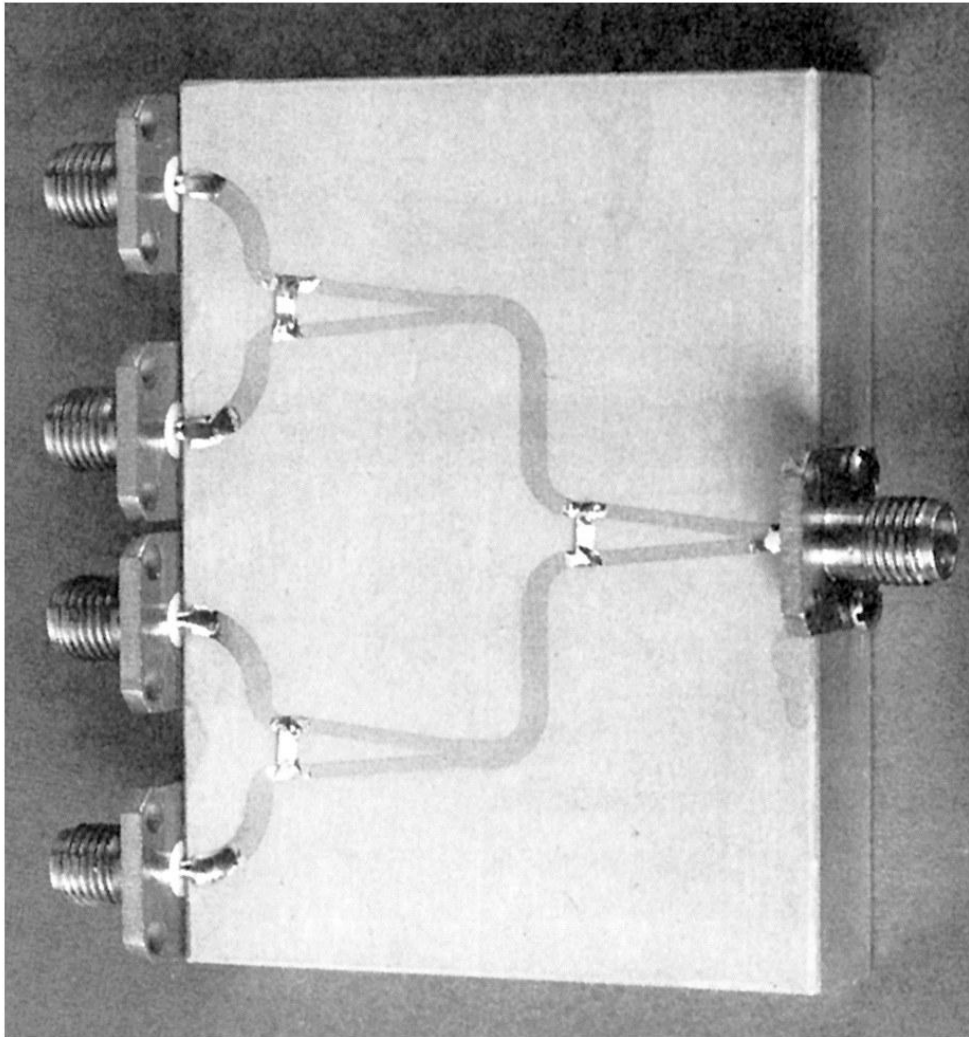


Figure 7.12
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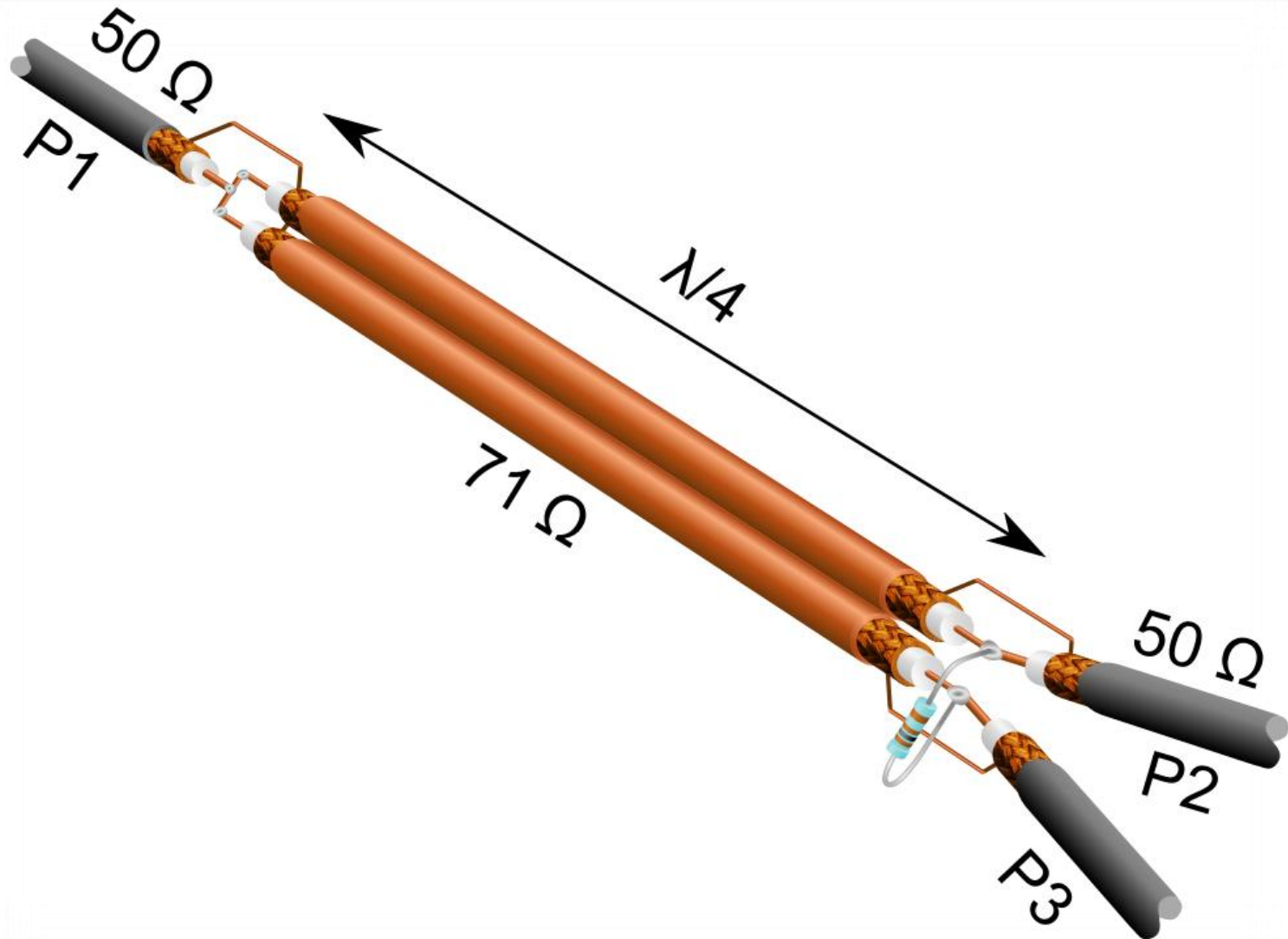
Divizorul de putere Wilkinson



- 3 X Wilkinson = divizor de putere pe 4 porturi

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

Divizorul de putere Wilkinson



Cuploare directionale

Circuite cu patru porți

- Un circuit cu 4 porți 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 $\theta = \phi = \pi/2$

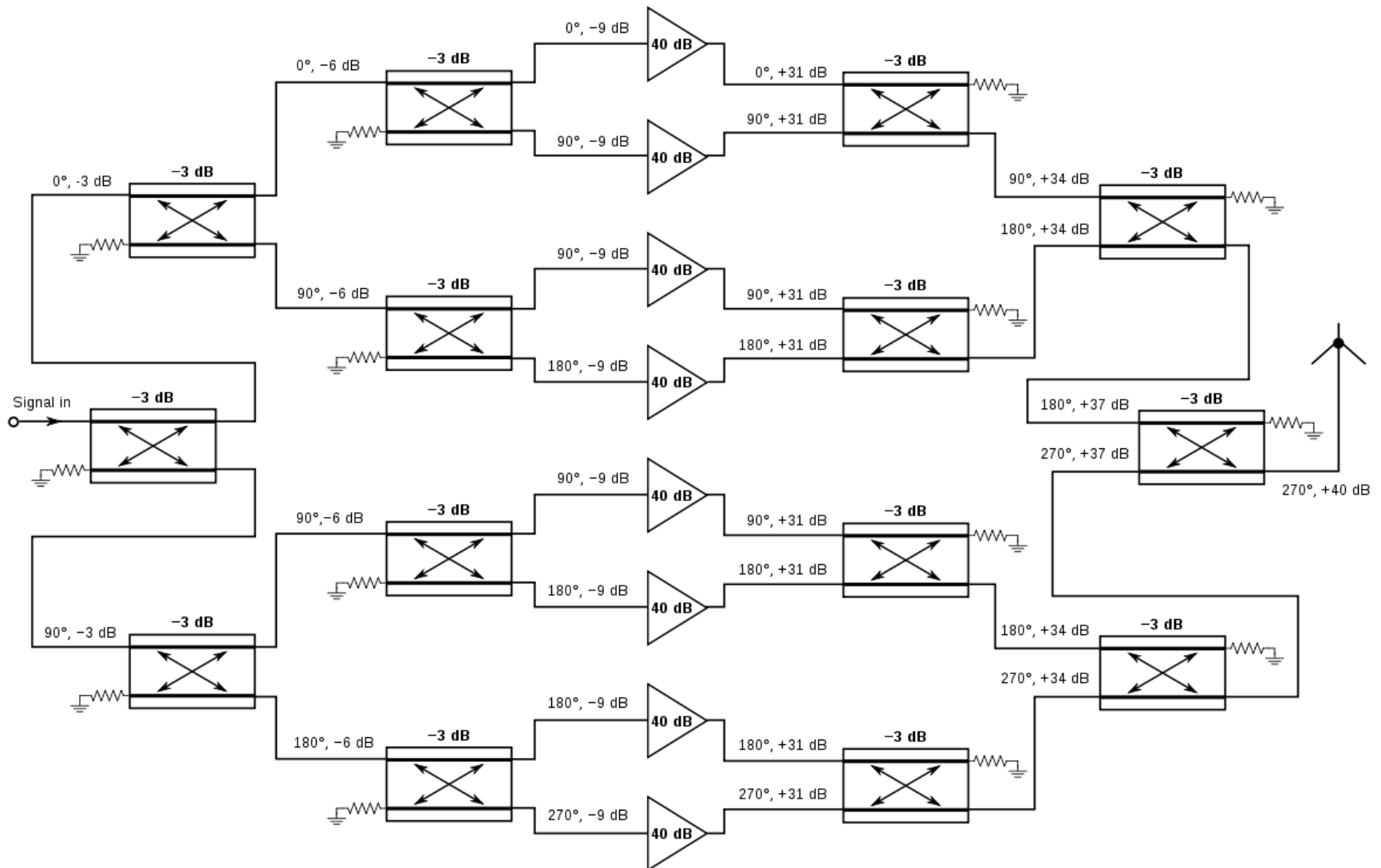
$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

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

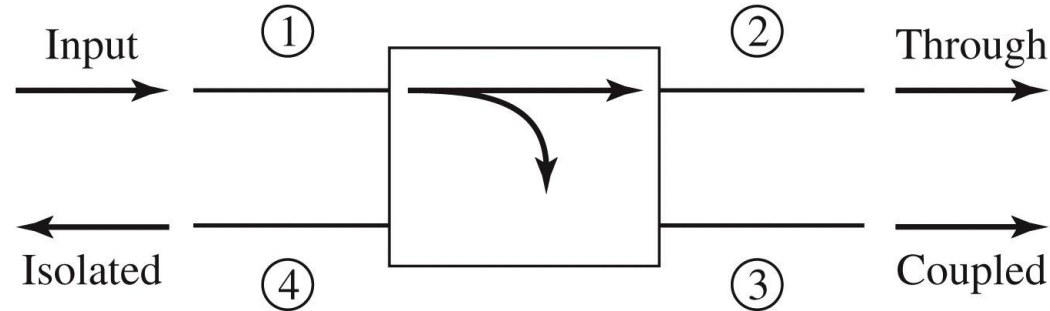
$$[S] = \begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

β – coeficientul de
cuplaj în tensiune

Amplificatoare echilibrate



Cuplor directional



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

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

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

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

$$I = D + C, \text{ dB}$$

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°)

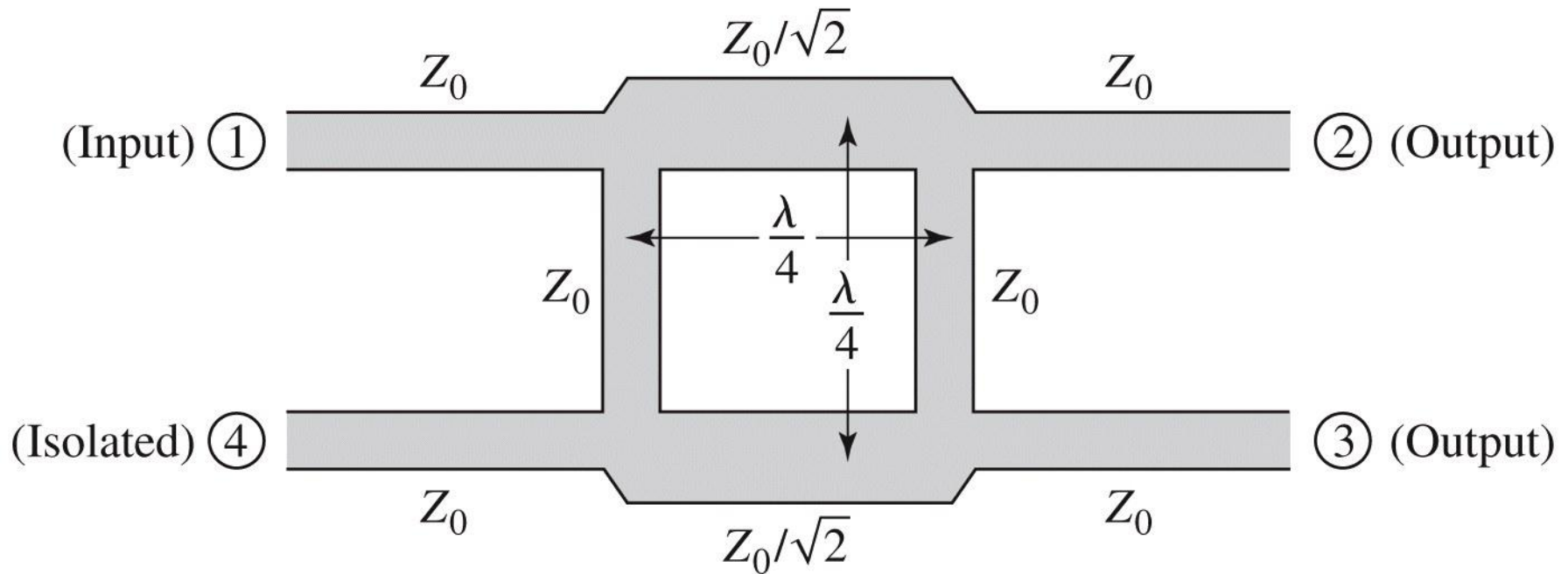
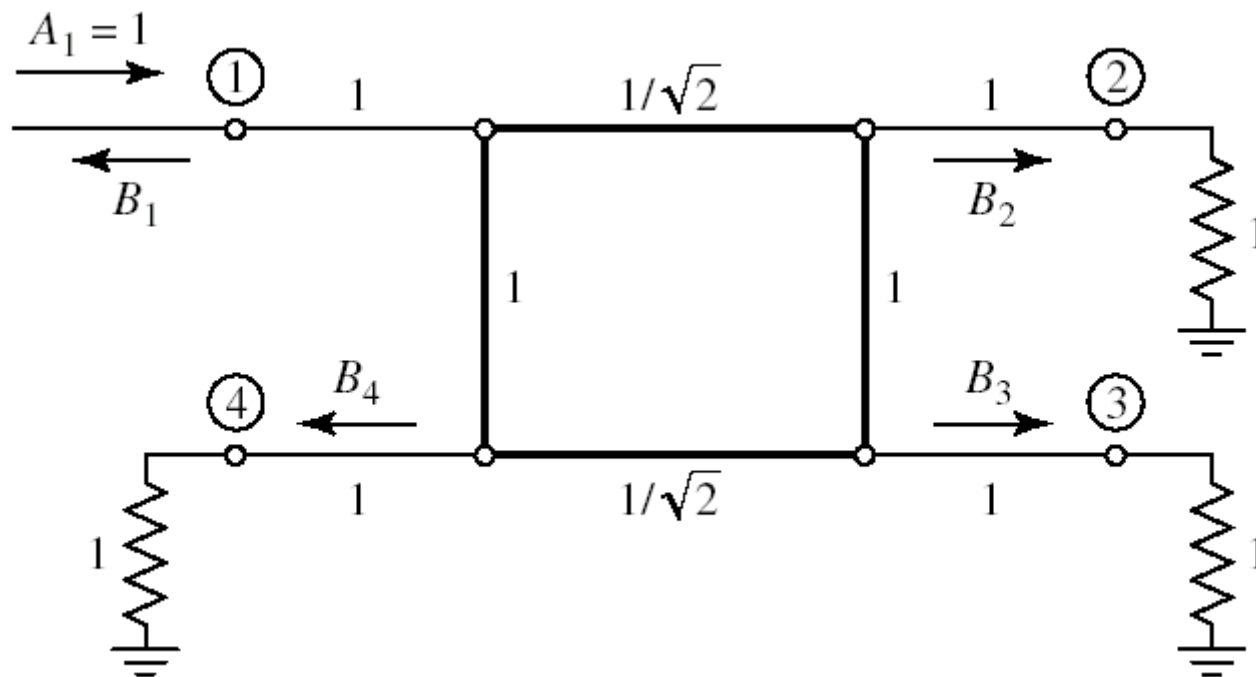


Figure 7.21
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$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

Analiza pe modul par-impair



Analiza pe modul par-impair

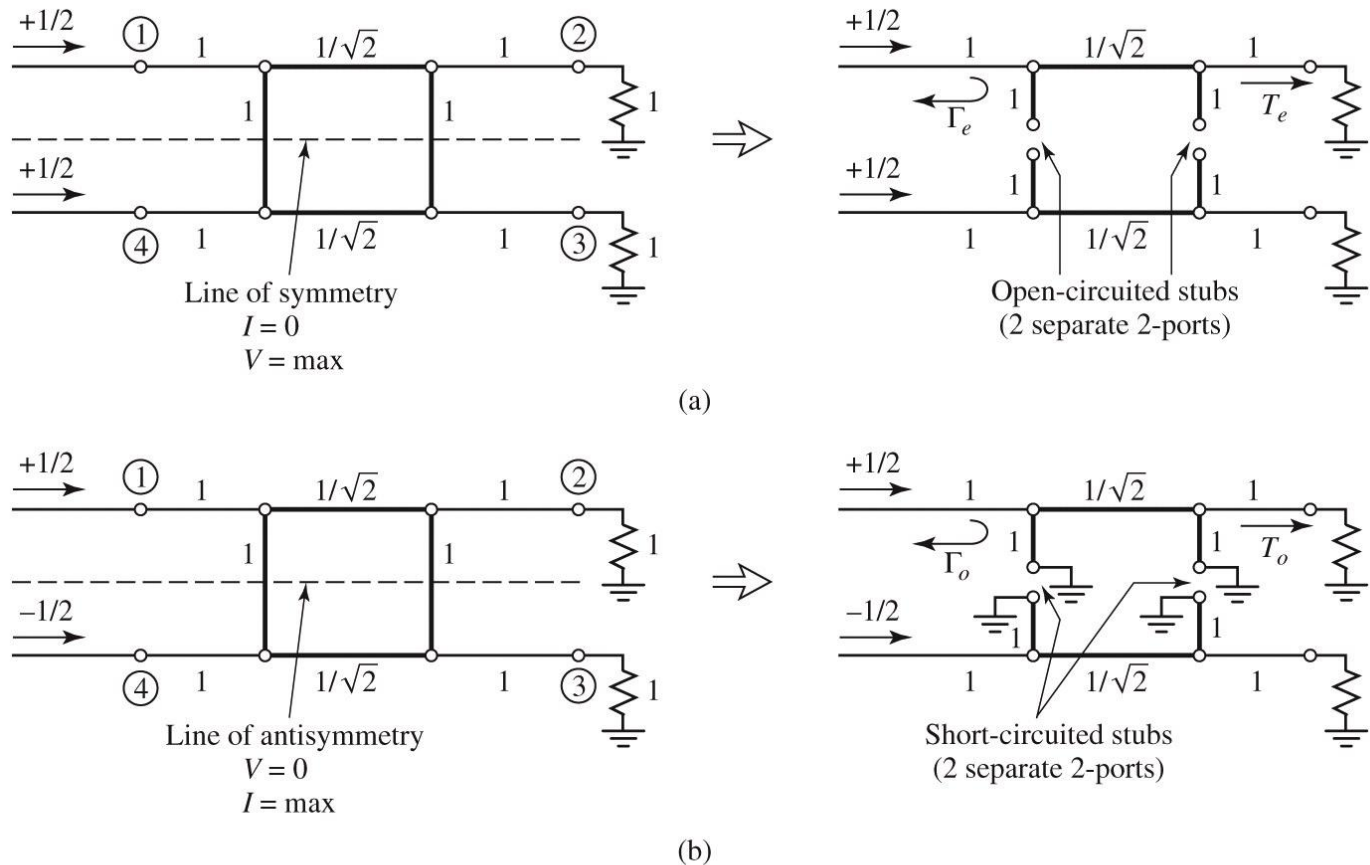


Figure 7.23
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$$b_1 = \frac{1}{2} \Gamma_e + \frac{1}{2} \Gamma_o$$

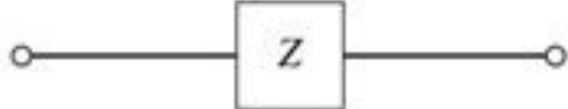
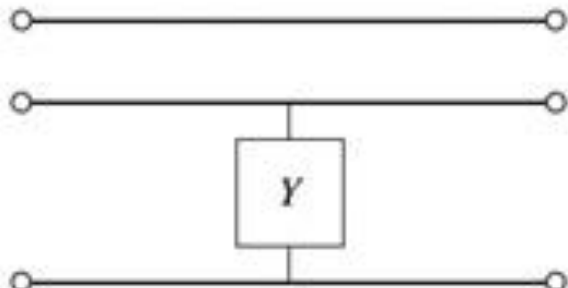
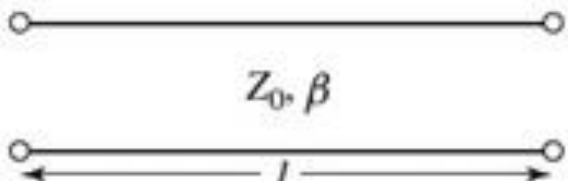
$$b_2 = \frac{1}{2} T_e + \frac{1}{2} T_o$$

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

$$b_4 = \frac{1}{2} \Gamma_e - \frac{1}{2} \Gamma_o$$

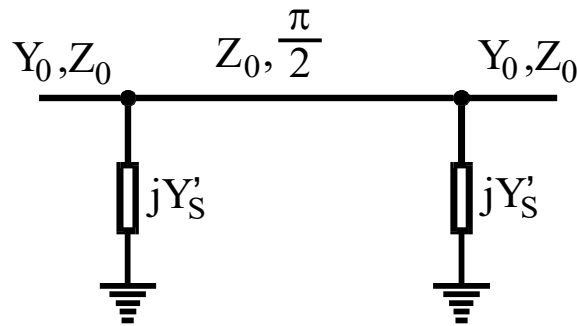
Bibliotece de matrici ABCD

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

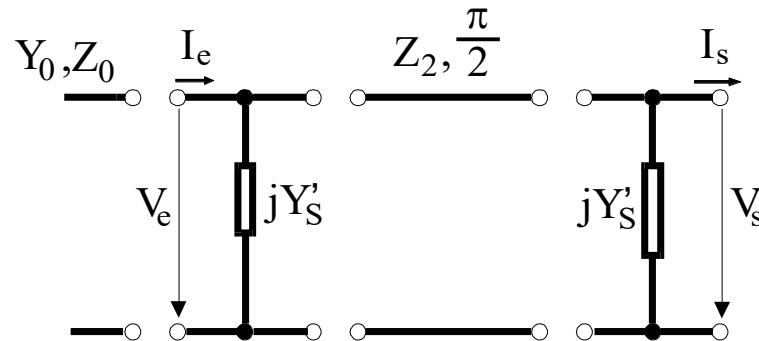
Circuit	<i>ABCD</i> Parameters	
	$A = 1$ $C = 0$	$B = Z$ $D = 1$
	$A = 1$ $C = Y$	$B = 0$ $D = 1$
	$A = \cos \beta \ell$ $C = jY_0 \sin \beta \ell$	$B = jZ_0 \sin \beta \ell$ $D = \cos \beta \ell$

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)

$$\begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY'_s & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 & jZ_2 \\ jY_2 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ jY'_s & 1 \end{bmatrix} \cdot \begin{bmatrix} V_s \\ I_s \end{bmatrix}$$

$$\begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} -Y'_s Z_2 & jZ_2 \\ -jY'^2_s Z_2 + jY_2 & -Y'_s Z_2 \end{bmatrix} \cdot \begin{bmatrix} V_s \\ I_s \end{bmatrix}$$

$$S_{11} = \frac{j\frac{Z_2}{Z_0} - Z_0(-jY'^2_s Z_2 + jY_2)}{-2Y'_s Z_2 + j\frac{Z_2}{Z_0} + Z_0(-jY'^2_s Z_2 + jY_2)}$$

$$S_{12} = \frac{2|(-Y'_s Z_2)^2 - jZ_2(-jY'^2_s Z_2 + jY_2)|}{-2Y'_s Z_2 + j\frac{Z_2}{Z_0} + Z_0(-jY'^2_s Z_2 + jY_2)}$$

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

$$S_{21} = \frac{2}{-2Y'_s Z_2 + j\frac{Z_2}{Z_0} + Z_0(-jY'^2_s Z_2 + jY_2)} \quad S_{22} = \frac{j\frac{Z_2}{Z_0} - Z_0(-jY'^2_s Z_2 + jY_2)}{-2Y'_s Z_2 + j\frac{Z_2}{Z_0} + Z_0(-jY'^2_s Z_2 + jY_2)}$$

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

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

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

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

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

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

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

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

$$b_1 = 0 \quad b_4 = 0 \quad b_3 = -y_1 z_2 \quad b_2 = -j z_2$$

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

$$b_3 = -C$$

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

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

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

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

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

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

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

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

Cuplorul in cuadratura

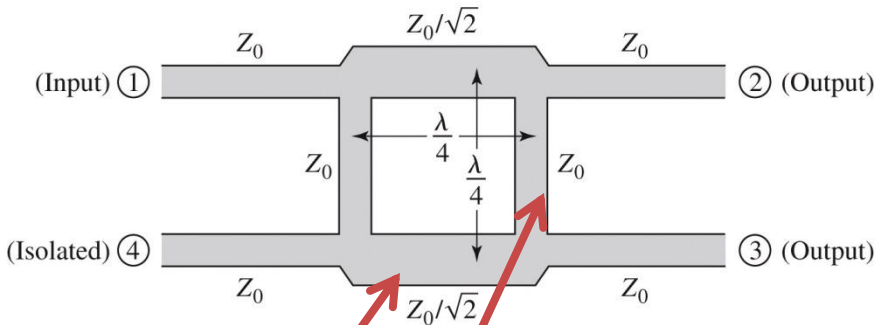


Figure 7.21
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$$y_2^2 = 1 + y_1^2$$

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

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

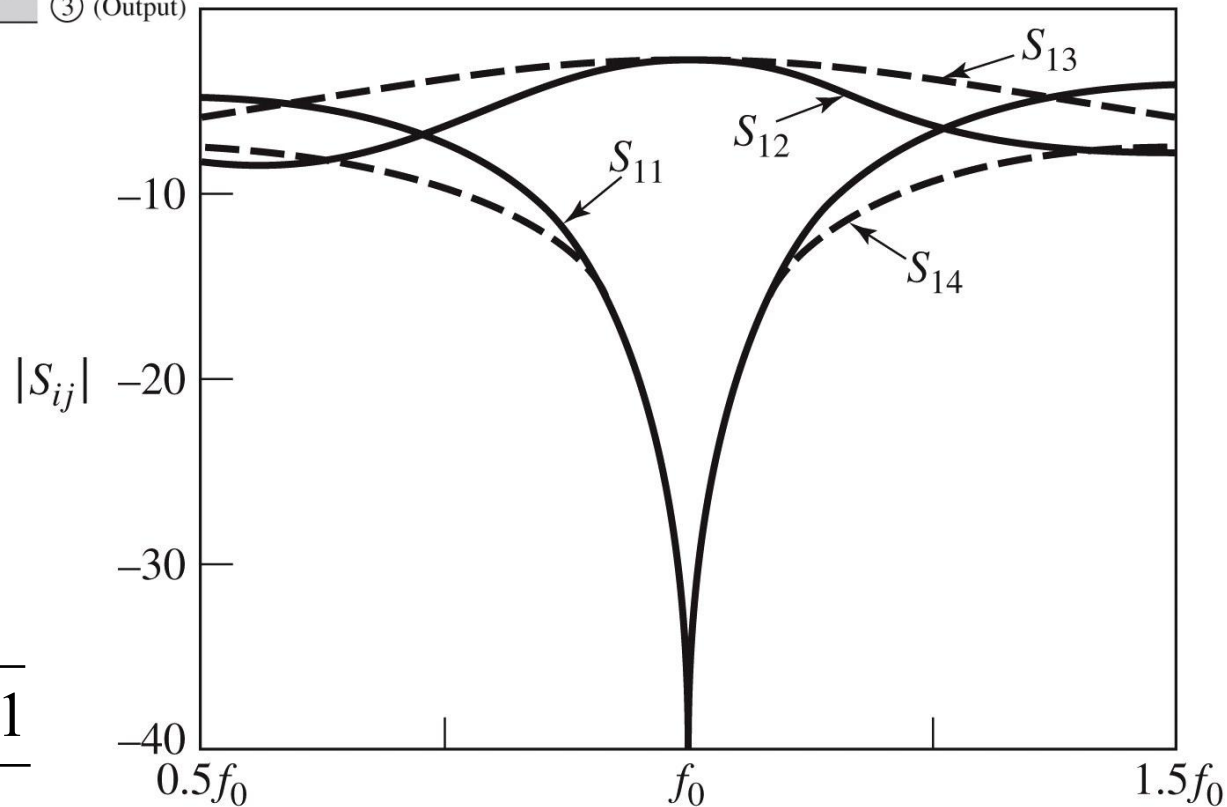


Figure 7.25
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Exemplu

Proiectați un cuplor în scară pe impedanța caracteristică de 50Ω , și reprezentați mărimea parametrilor S între

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

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

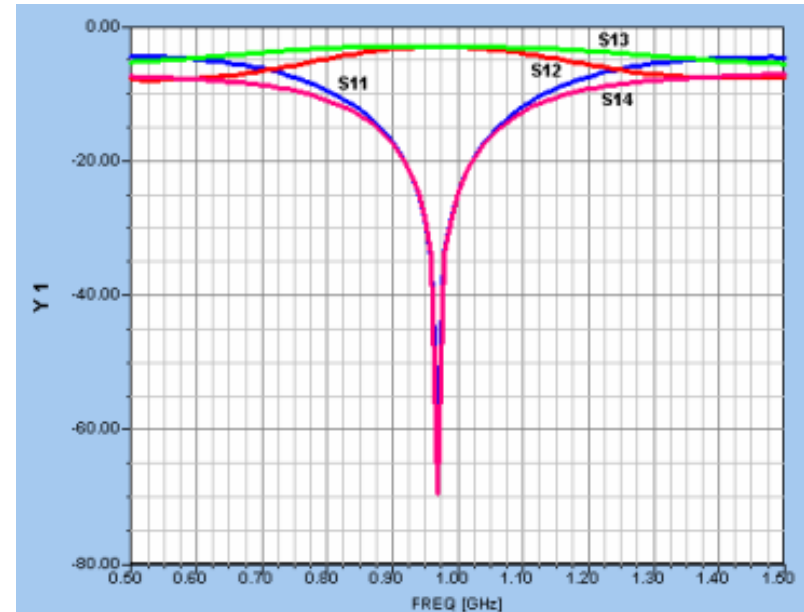
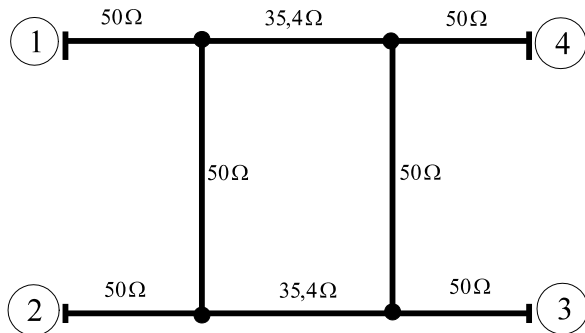
Solutie

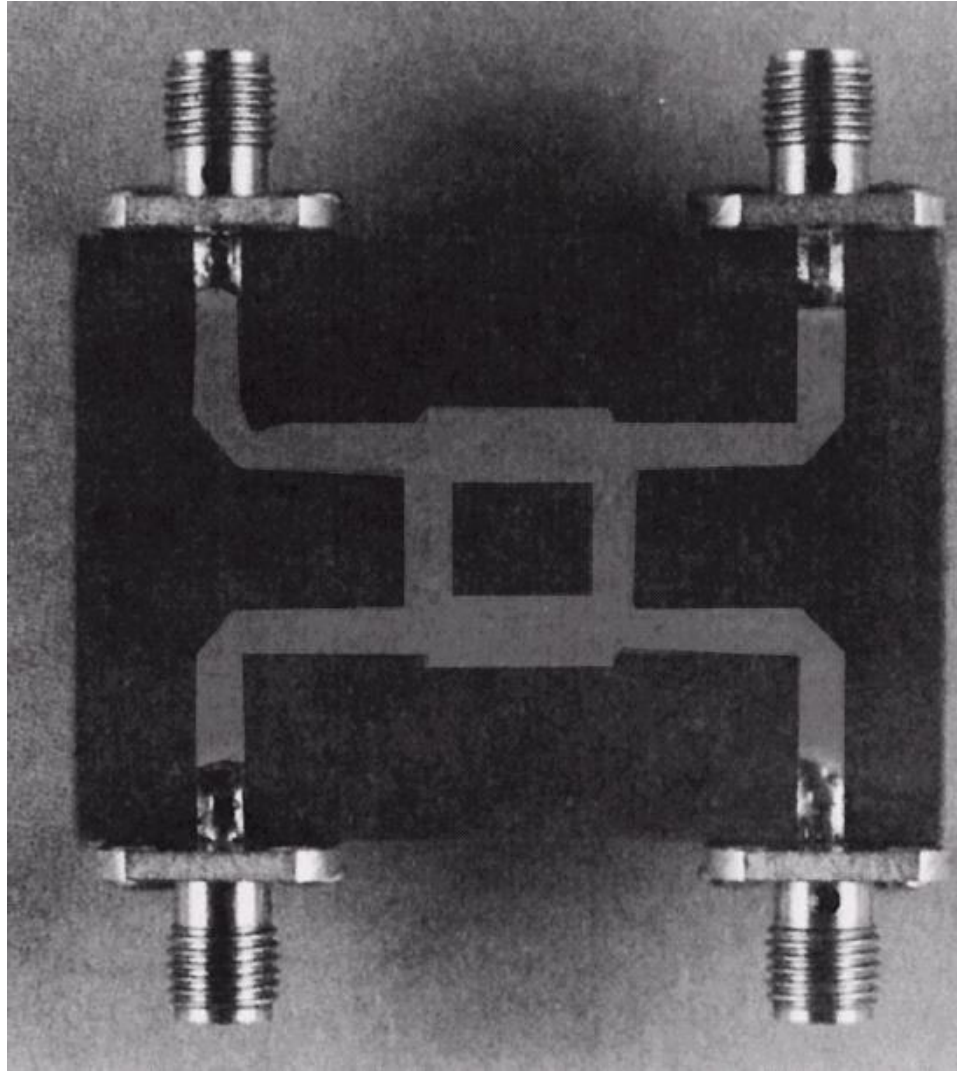
Un cuplor în cuadratură (scară) cu $C = 3\text{dB}$, are $C = 1/\sqrt{2}$. Atunci

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

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

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





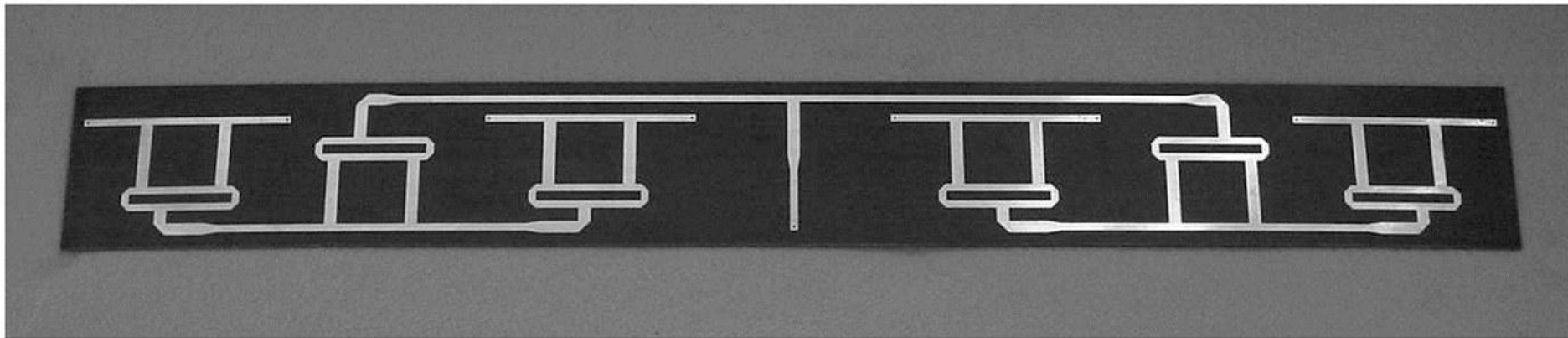
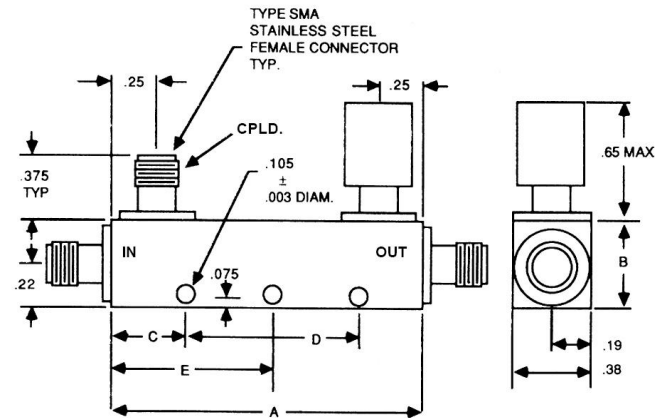


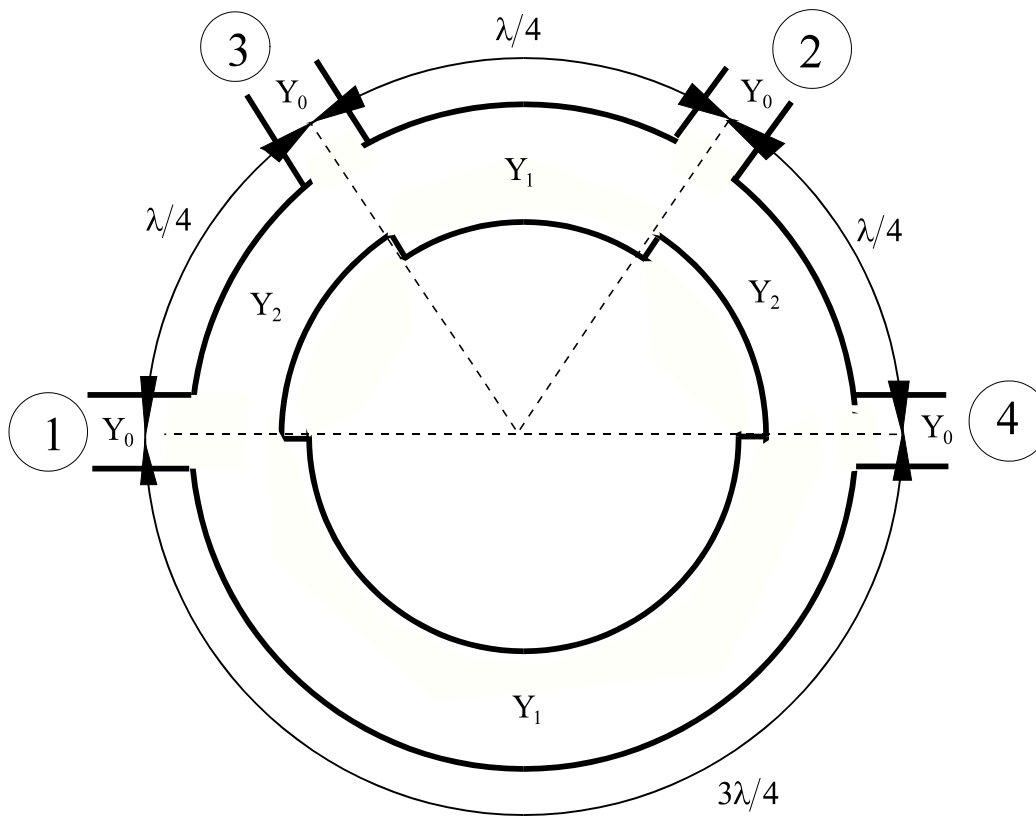
Figure 7.24
Courtesy of ProSensing, Inc., Amherst, Mass.

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
MDC6227-30	7.0-12.4	30 ±1.00	±0.50	0.30	0.20	17	1.30	1.30

Cuplorul in inel



Cuplorul in inel

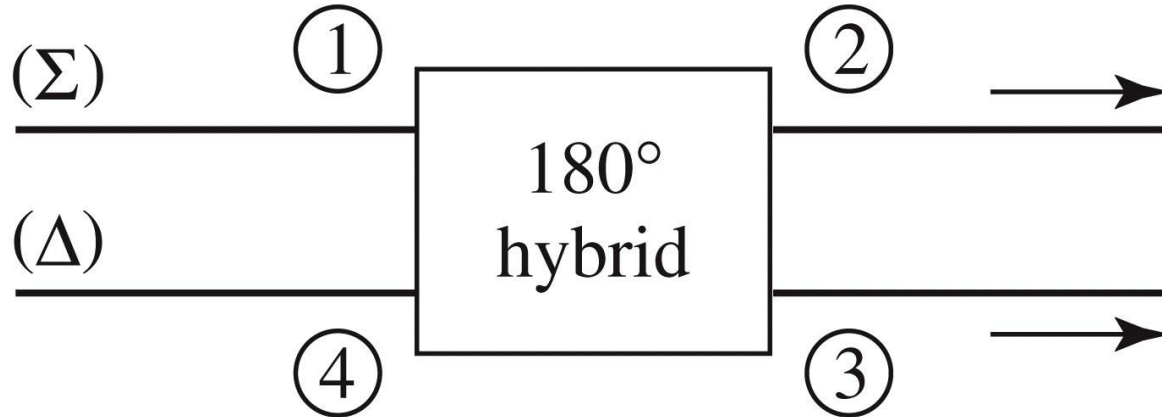
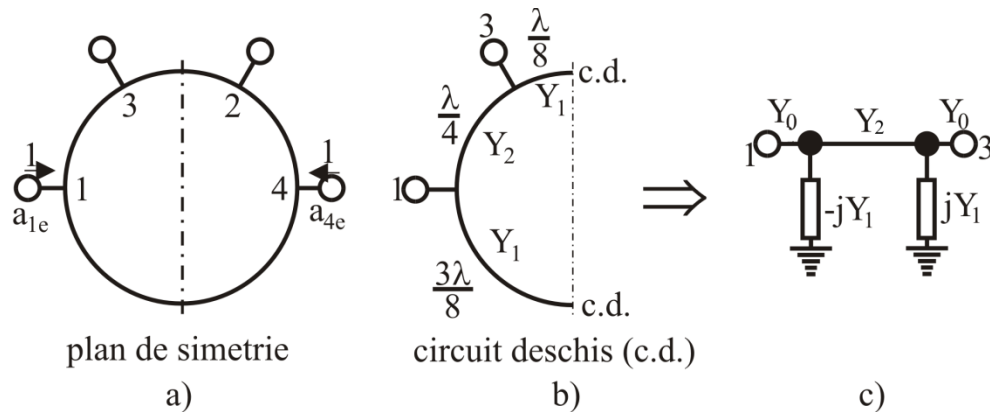


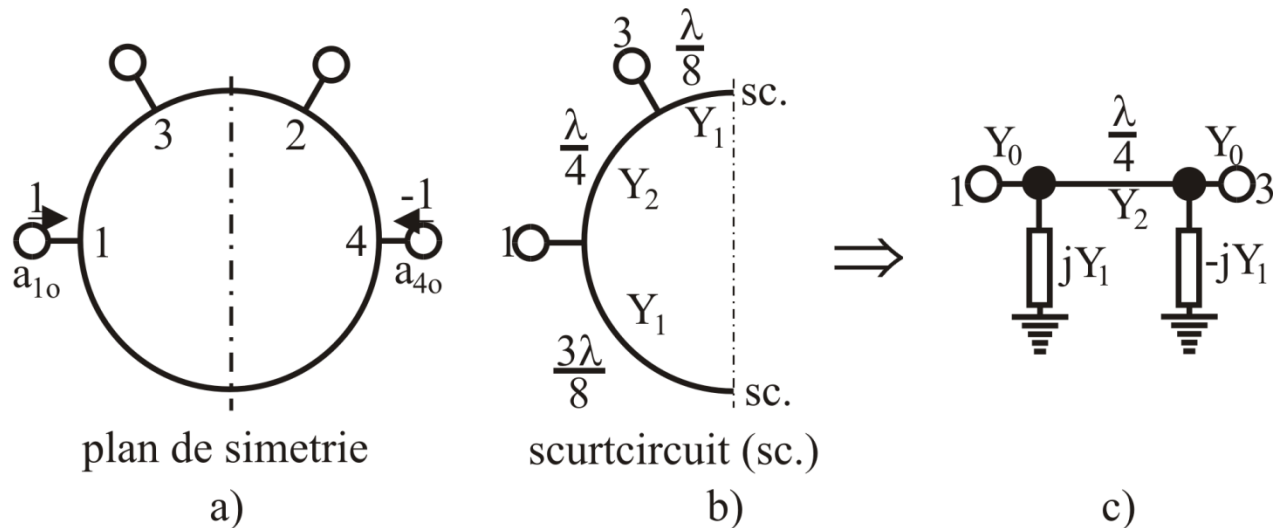
Figure 7.41
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- cuplorul de 3dB (hibrid) poate fi folosit in mai multe moduri
 - intrare pe port 1, iesiri egale pe 2 si 3, in faza
 - intrare pe port 4, iesiri egale pe 2 si 3, in opozitie de faza
 - intrari pe porturi 2 si 3, suma semnalelor pe portul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

Analiza cuplorului in inel



Modul par



Modul impar

Analiza cuplorului in inel

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

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

Pentru modul par:

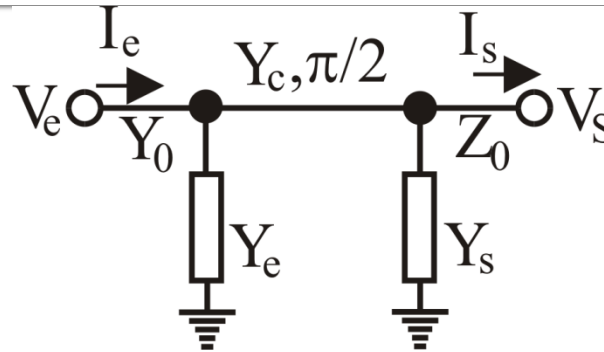
$$y_e = -jy_1$$

$$y_s = jy_1$$

$$S_{11e} = \frac{z_2 - y_2 - y_1^2 z_2 + 2jz_2 y_1}{z_2 + y_2 + y_1^2 z_2}$$

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

$$S_{22e} = \frac{z_2 - y_2 - y_1^2 z_2 - 2jz_2 y_1}{z_2 + y_2 + y_1^2 z_2}$$



Conditia de adaptare

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

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

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

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

Pe modul impar:

$$y_e = jy_1$$

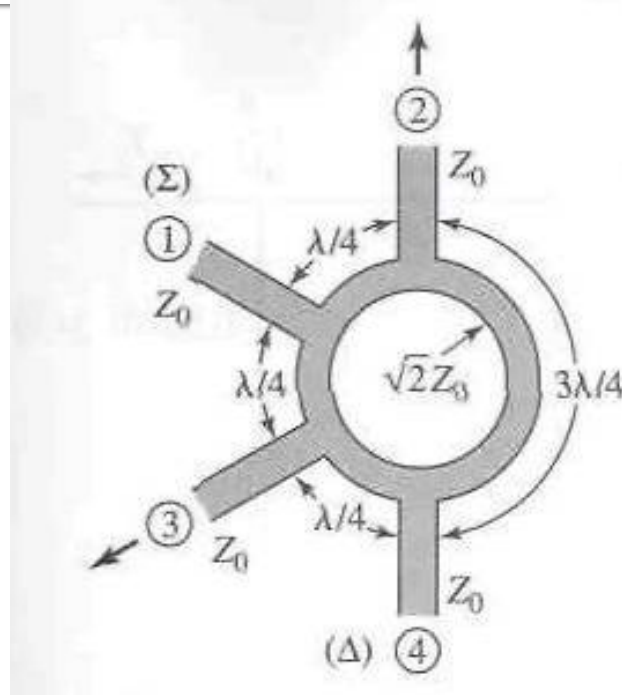
$$y_s = -jy_1$$

$$S_{11o} = \frac{z_2 - y_2 - y_1^2 z_2 - 2jz_2 y_1}{z_2 + y_2 + y_1^2 z_2}$$

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

$$S_{22o} = \frac{z_2 - y_2 - y_1^2 z_2 + 2jz_2 y_1}{z_2 + y_2 + y_1^2 z_2}$$

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 și performanța unui cuplor în inel

Proiectați un cuplor în inel hibrid (3dB) pe impedanța de $50\ \Omega$ și reprezentați mărimea parametrilor S între 0.5 și 1.5 din frecvența centrală.

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

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

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

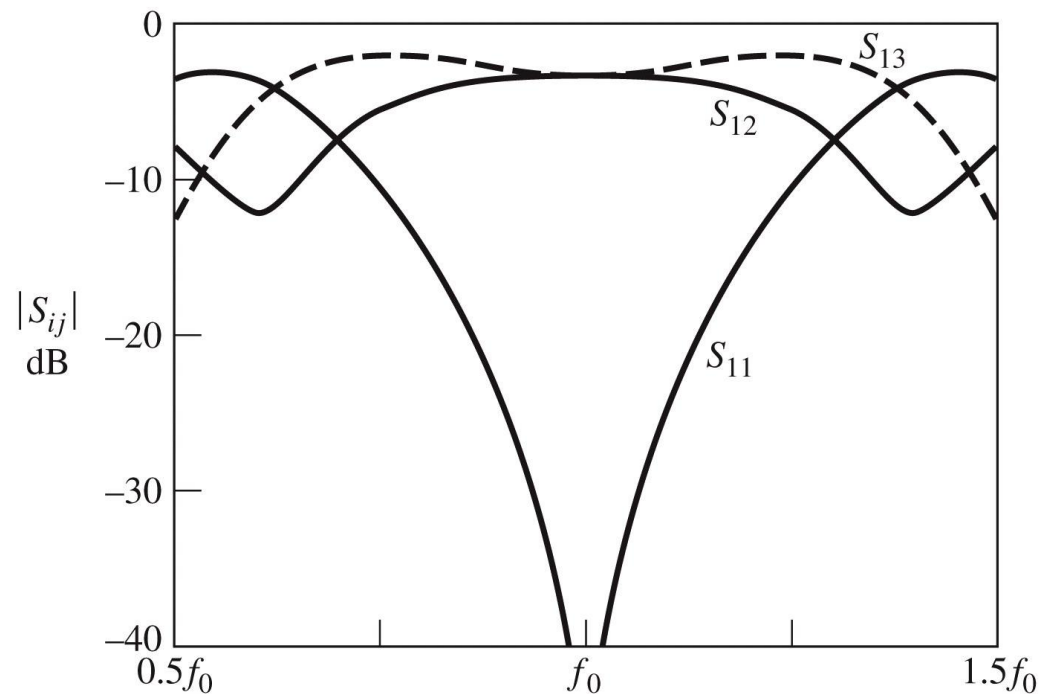
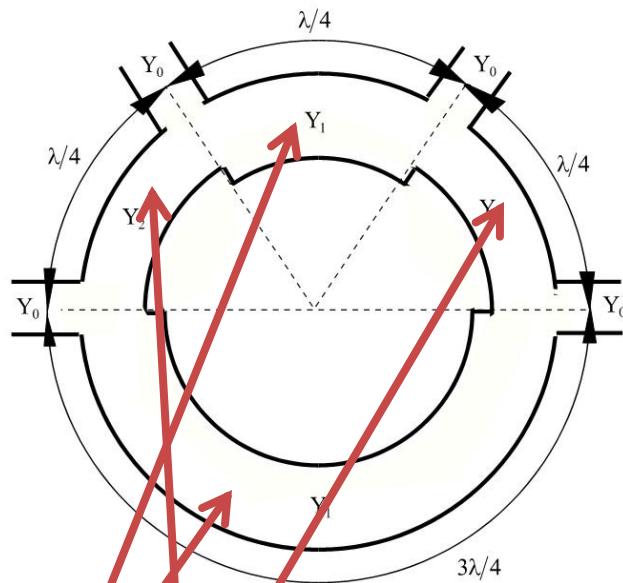


Figure 7.46
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Cuplorul în inel



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

$$|\beta| = y_1$$

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

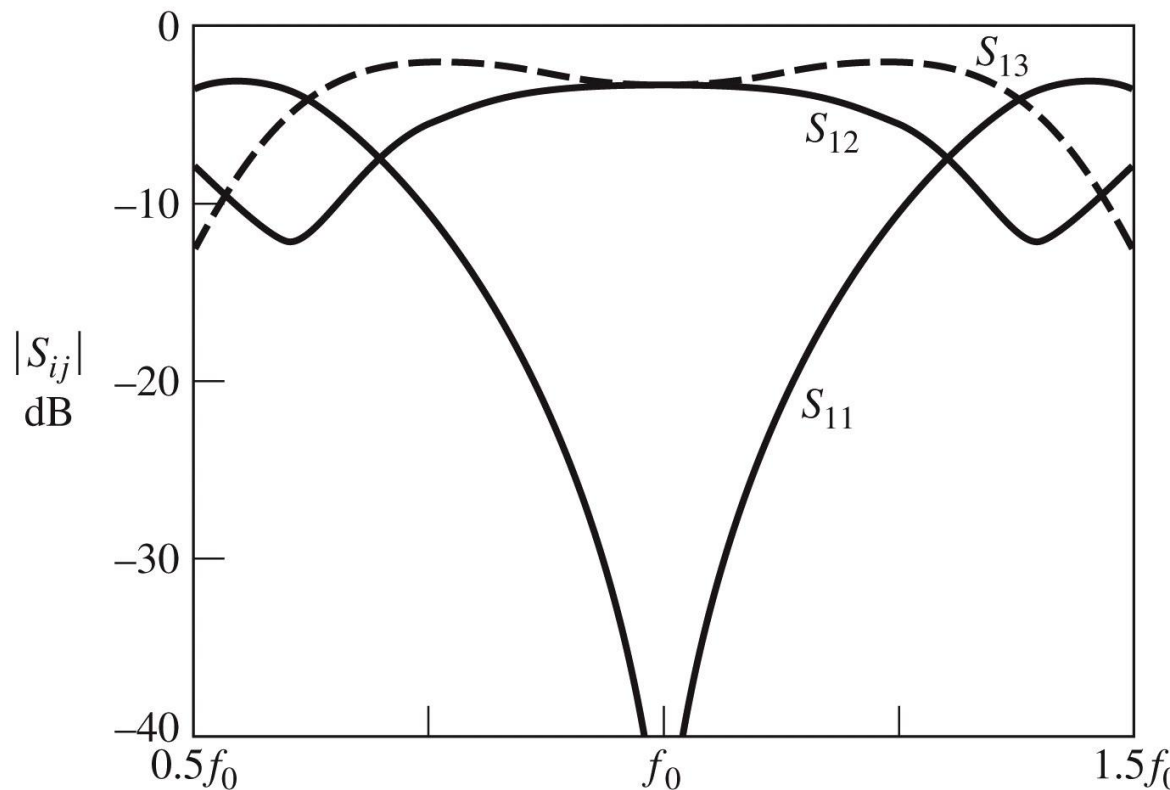


Figure 7.46
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Cuplor în inel

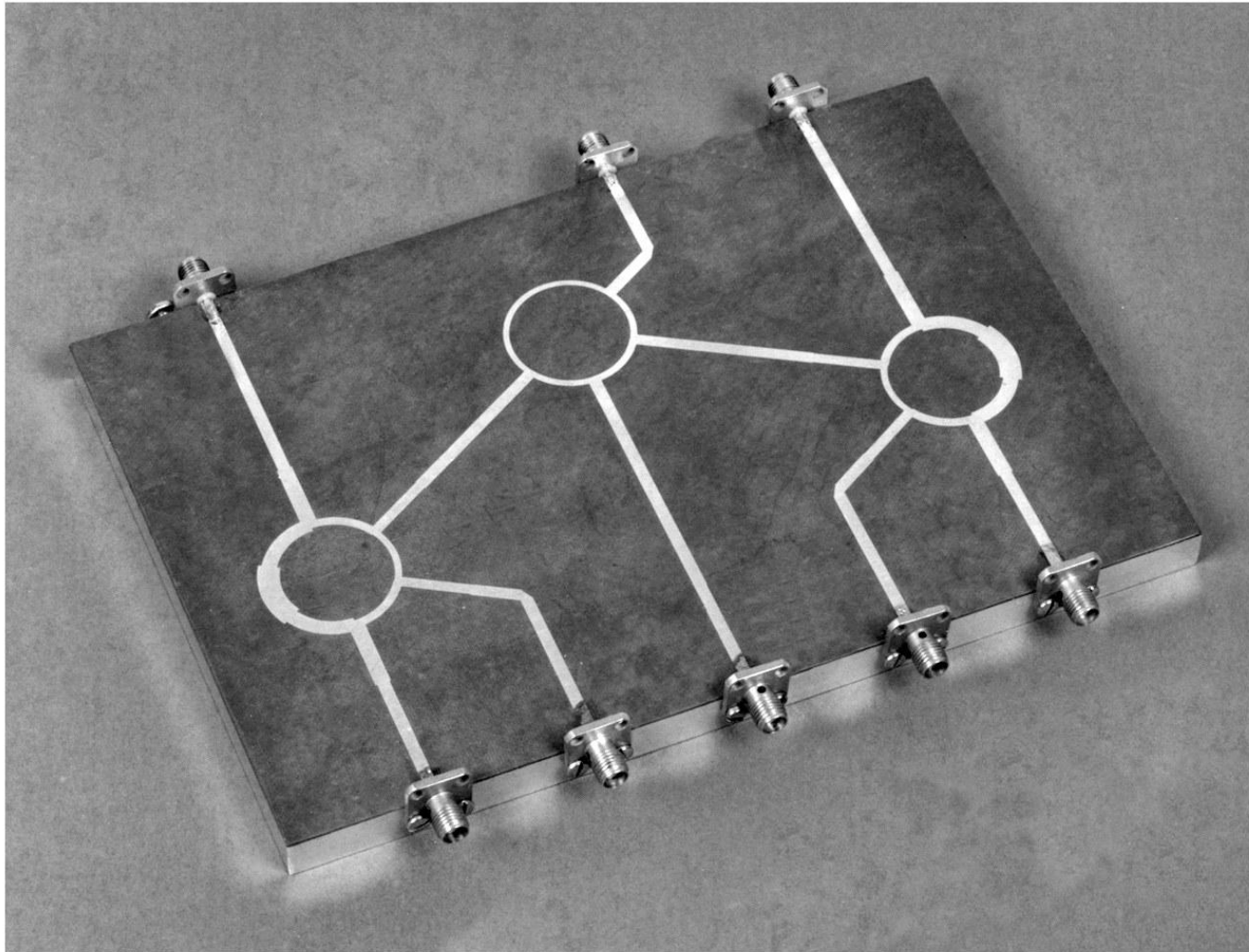
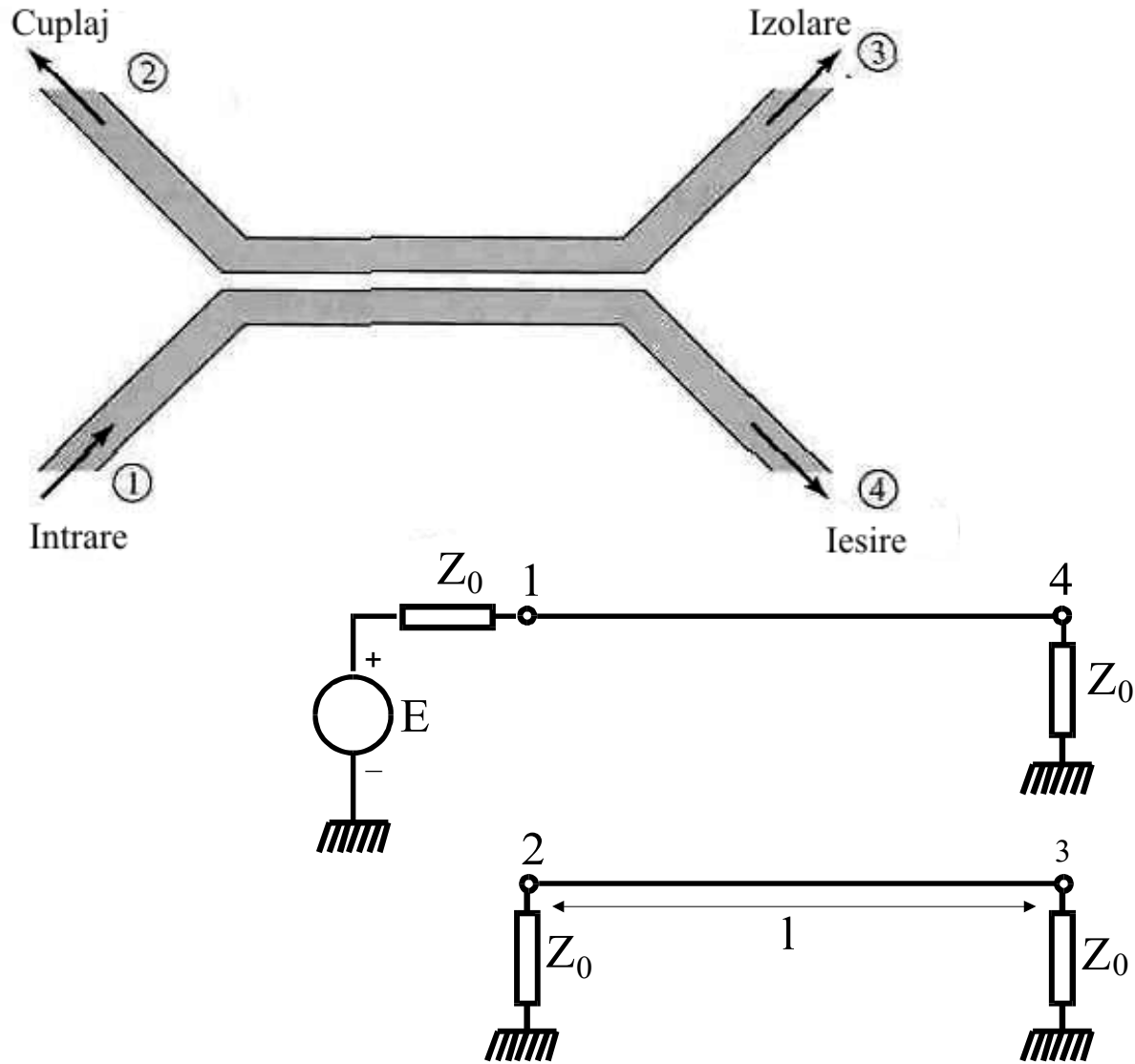


Figure 7.43
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

Cuplorul prin proximitate



Linii cuplate

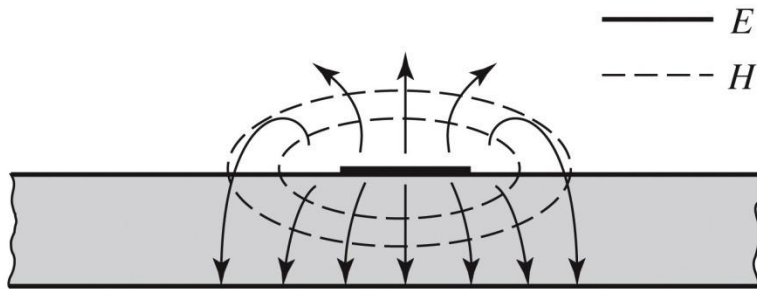
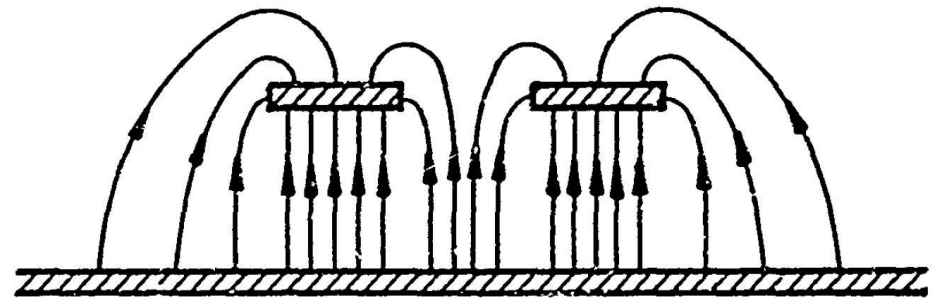
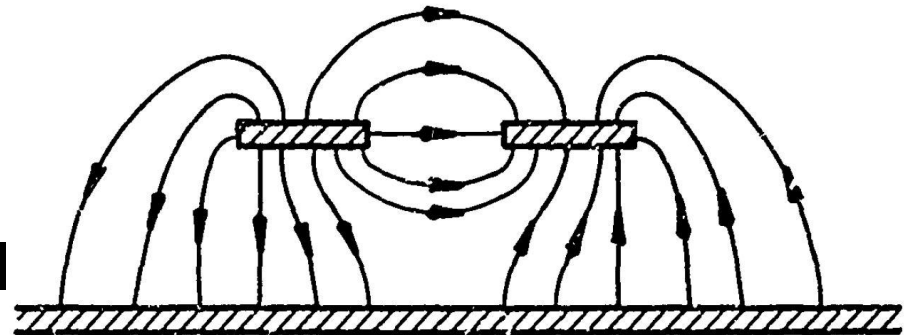


Figure 3.25b
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b) EVEN MODE ELECTRIC FIELD PATTERN (SCHEMATIC)



c) ODD 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**

Linii cuplate

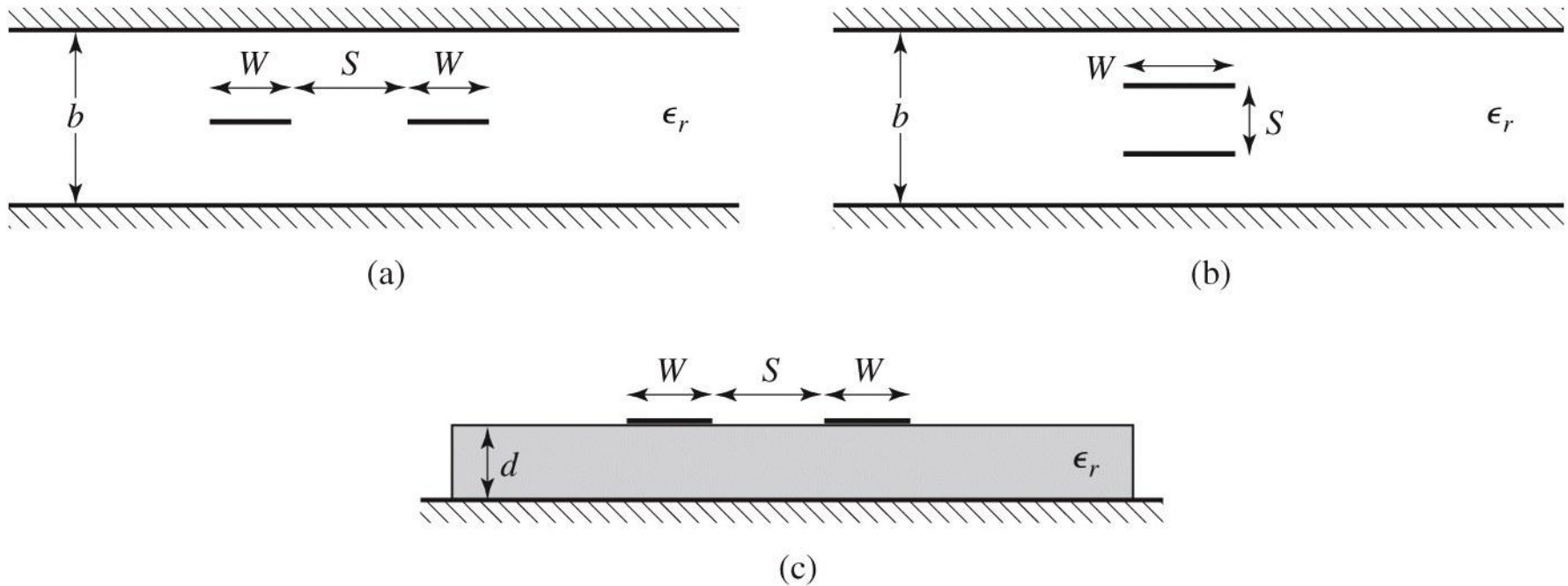


Figure 7.26
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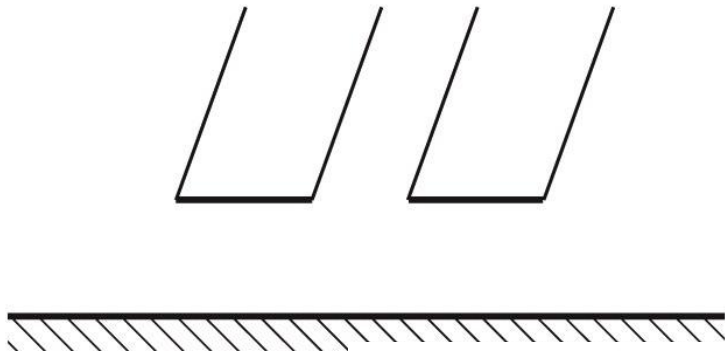
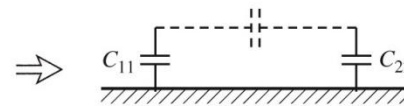
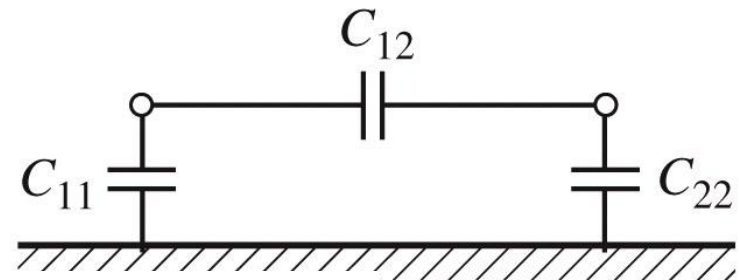
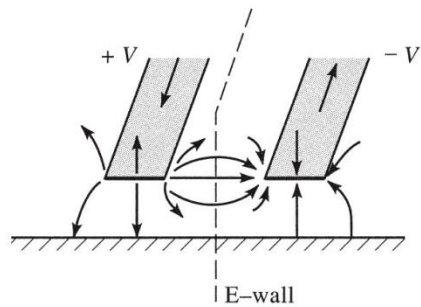
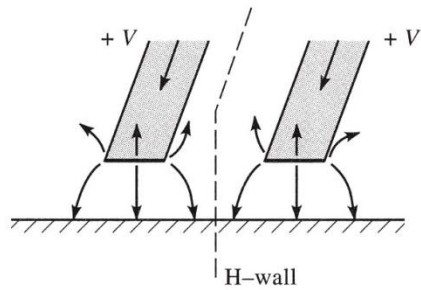
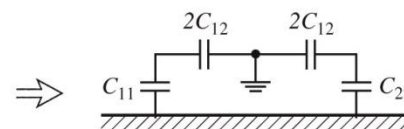


Figure 7.27
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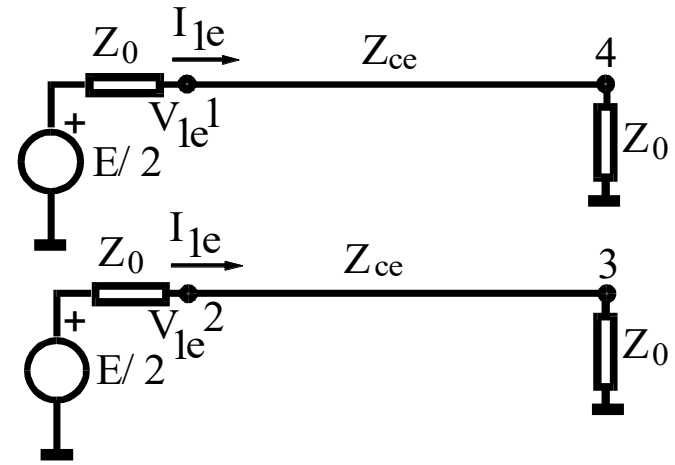
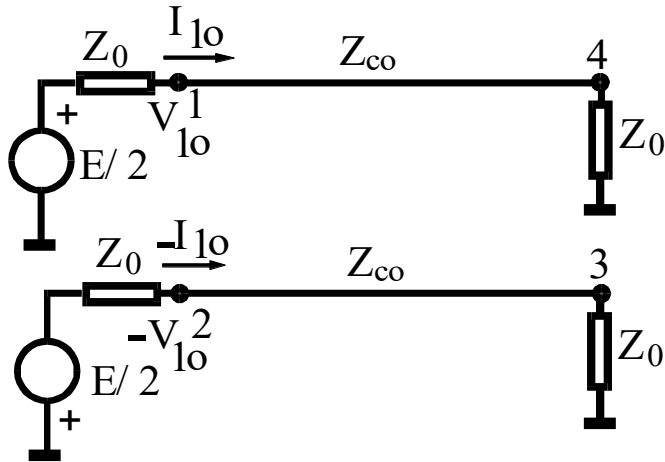


(a)



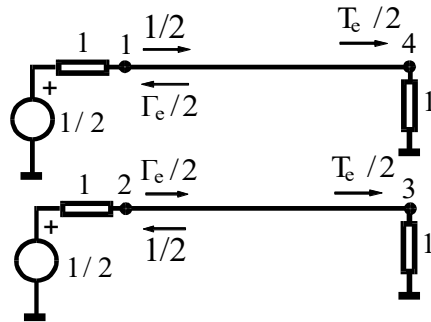
(b)

Adaptarea cuplorului prin proximitate

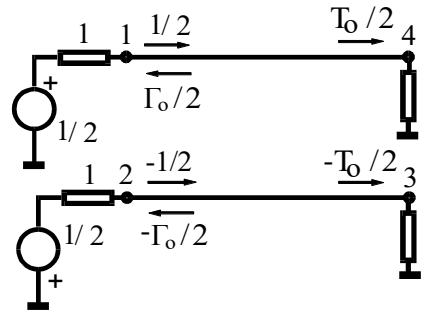


$$\begin{cases} Z_{ce}Z_{co} = Z_0^2 \\ \theta_e = \theta_o \end{cases}$$

Directivitatea și coeficientul de cuplaj ale cuplorului prin proximitate



modul par



modul impar

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

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

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

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

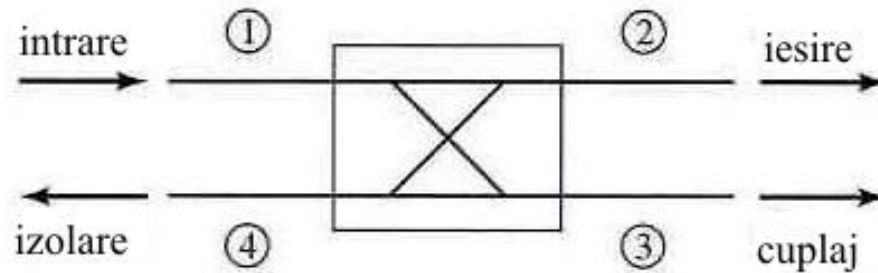
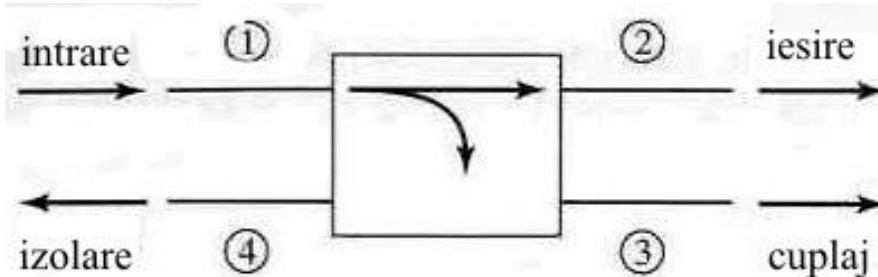
$$b_4 = \frac{1}{2}(T_e + T_o) = \frac{\sqrt{1-C^2}}{\cos(\theta)\sqrt{1-C^2} + j \sin(\theta)}$$

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

$$\theta = \pi/2$$

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

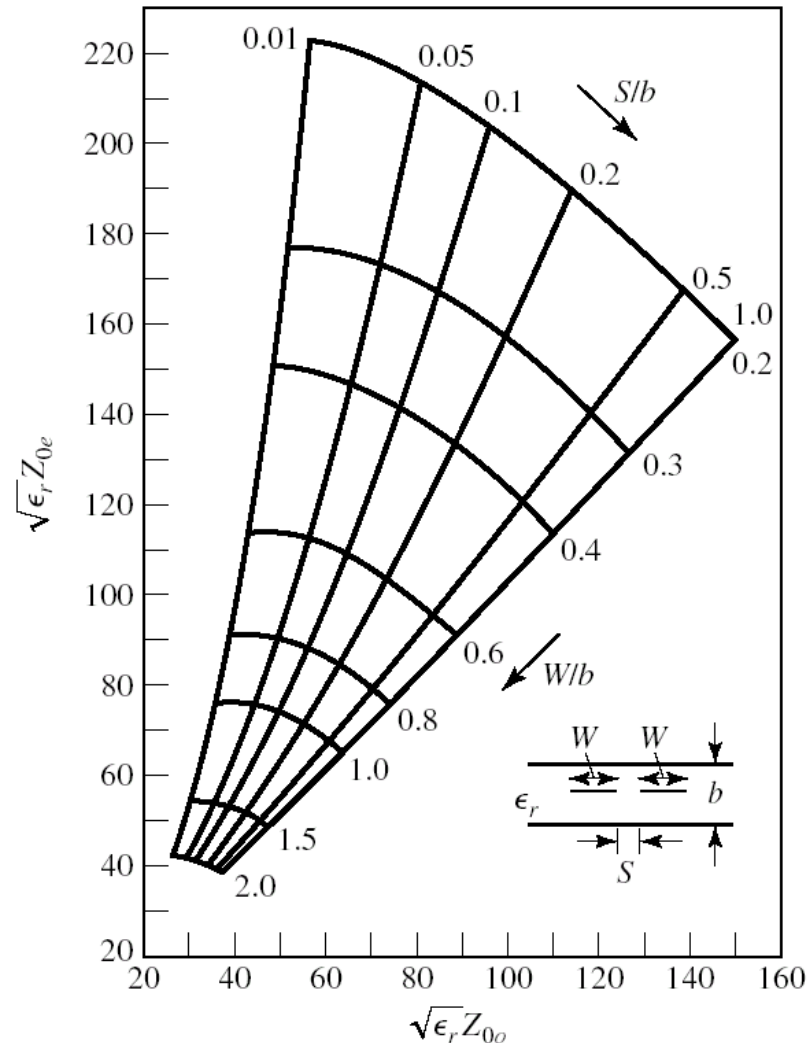
Cuplor prin proximitate



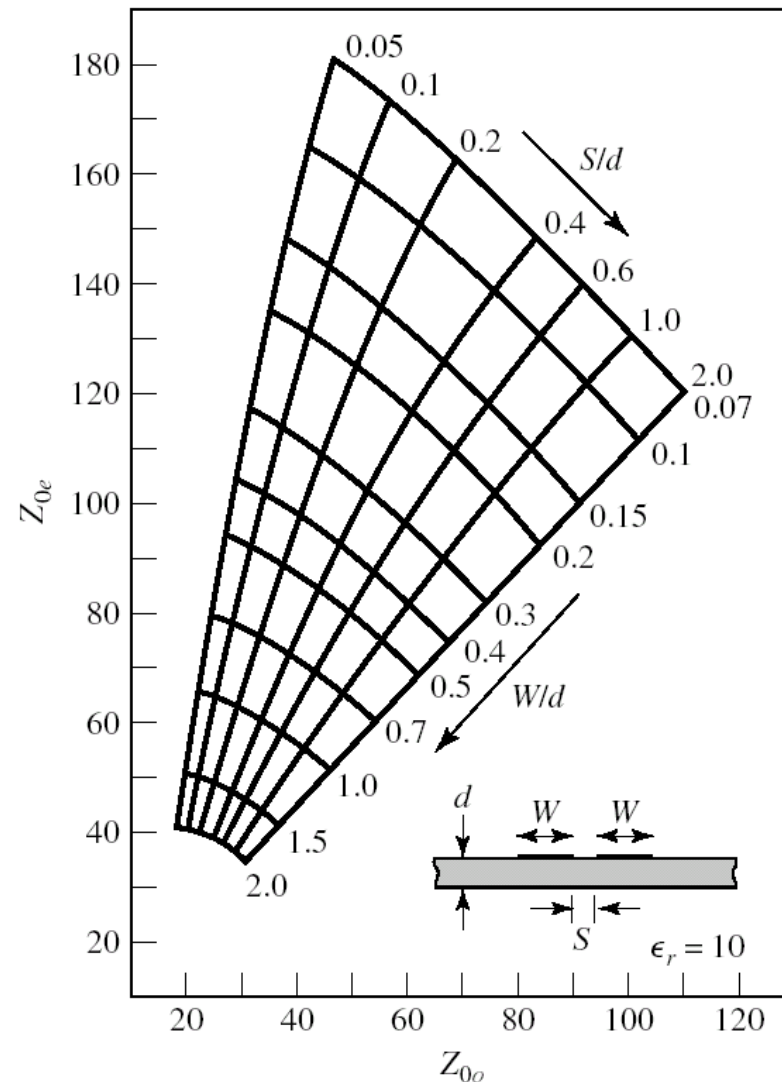
$$[S] = -j \cdot \begin{bmatrix} 0 & \sqrt{1-C^2} & jC & 0 \\ \sqrt{1-C^2} & 0 & 0 & jC \\ jC & 0 & 0 & \sqrt{1-C^2} \\ 0 & jC & \sqrt{1-C^2} & 0 \end{bmatrix}$$

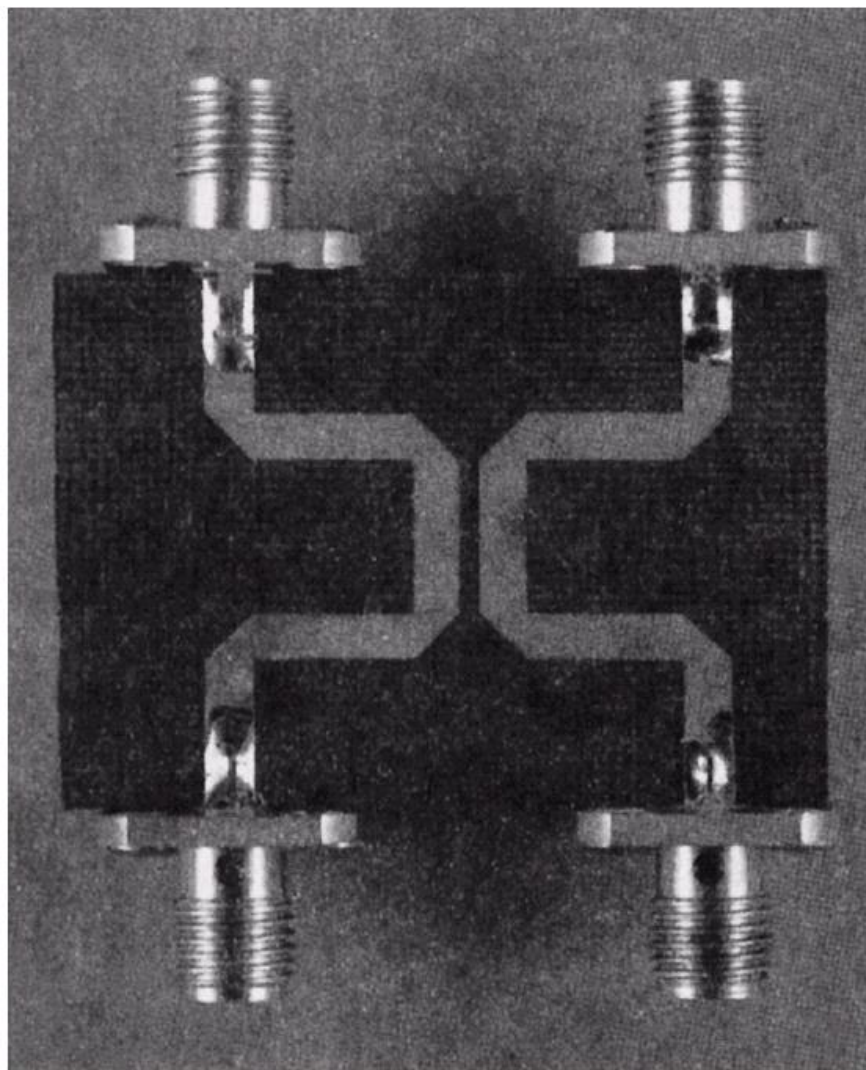
$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

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

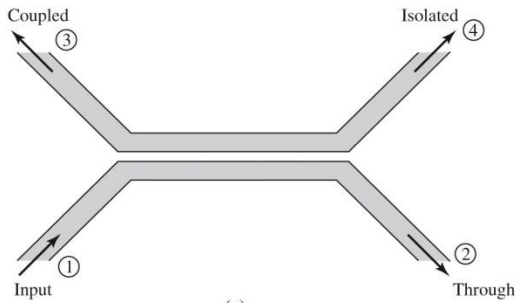


Even- and odd-mode characteristic impedance design data for coupled microstrip lines on a substrate with $\epsilon_r = 10$.





Cuplor prin proximitate



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

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

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

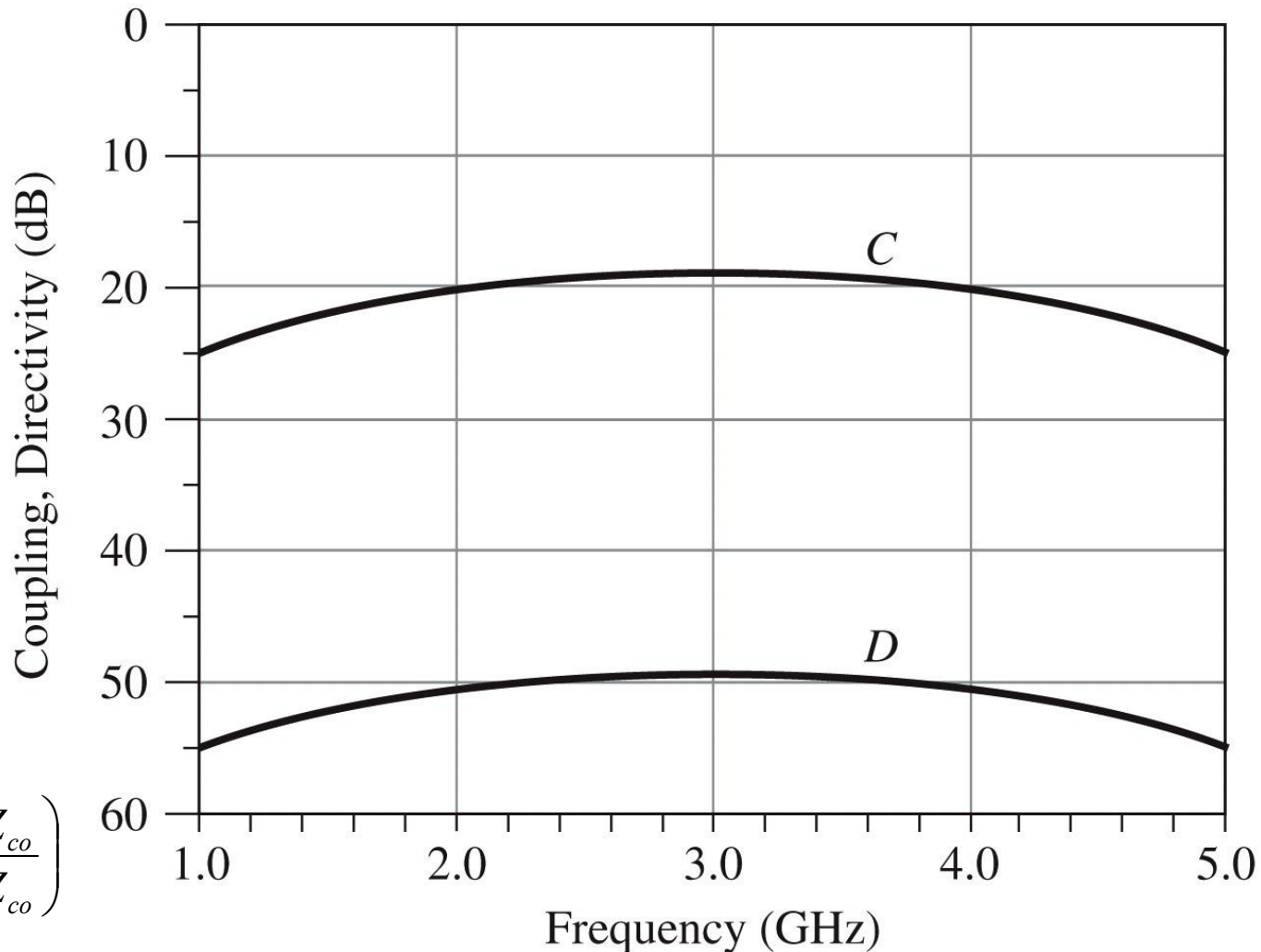


Figure 7.34

Exemplu

Proiectați un cuplor prin proximitate de 20 dB, în tehnologie stripline, folosind o distanță între planele de masă de 0.158 cm și cu o permitivitate electrică relativă de 2.56, pe o impedanță de $50\ \Omega$, la frecvența de 3 GHz. Reprezentați cuplajul și directivitatea între 1 și 5 GHz.

Soluție

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

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

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

TRL - Edge-coupled Symmetric Stripline (CPL)1

File Edit View Structure Window Help

Edge-coupled Symmetric Stripline (CPL)1

Dimensions

W 1.14072

S 0.51747

P 15.6142

Electrical

Z0 50

K 20

E 90

Zo 45.2267

Ze 55.2771

Units

Dimension mm

Frequency GHz

Impedance Ohm

Electrical Length Deg

Resistivity uOhm*cm

Frequency 3 Analysis Auto Calculate Off ! Reset All ! Synthesis 3

Substrate

Required

B 1.58 ER 2.56

Optional

TAND 0

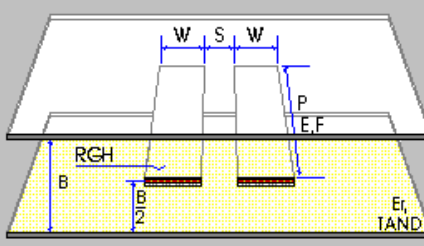
Metallization

Layers	Metal Name	Code	Resistivity	Thickness	
Bottom	*None*				Reset
Middle	*None*				Reset
Top	*None*				Reset

RGH 0 Add new metal

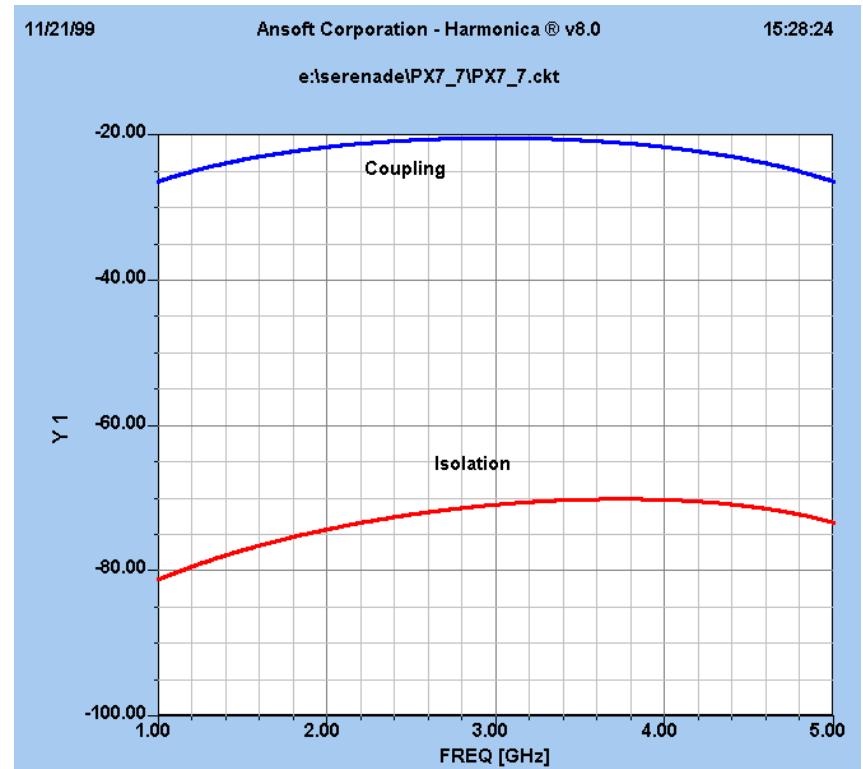
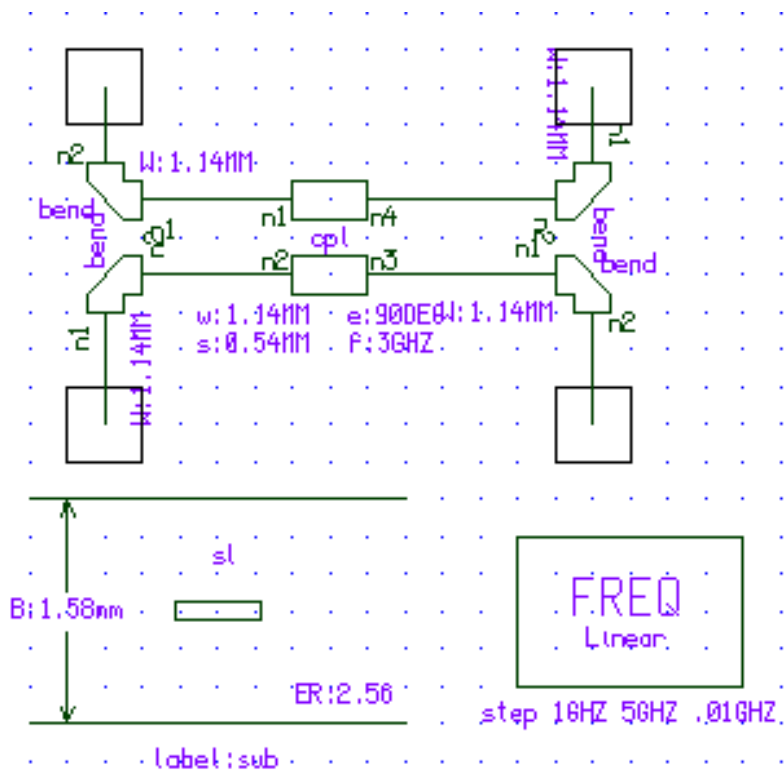
For Help, press F1

NUM



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

Simulare



Cuplor prin proximitate cu mai multe secțiuni

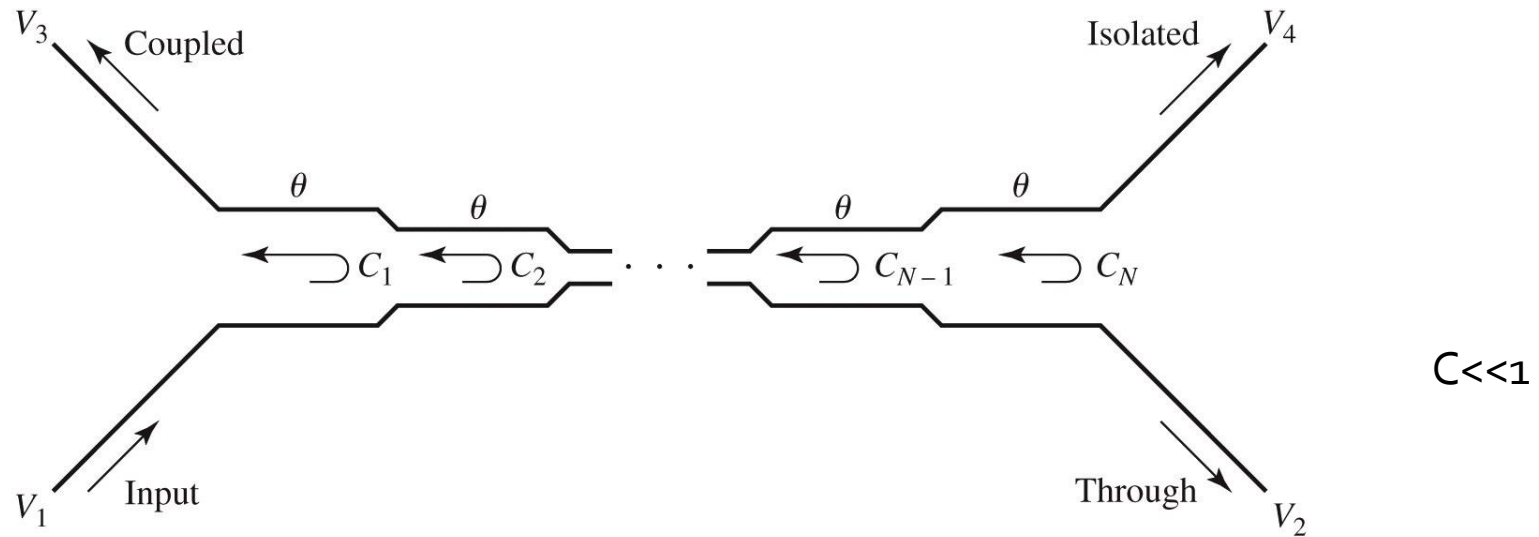


Figure 7.35

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

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

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

Exemplu

Să se proiecteze un cuplor cu trei secțiuni, avînd un cuplaj de 20 dB, cu caracteristică binomială (maxim plat), pe o impedanță de $50\ \Omega$, la frecvența centrală de 3 GHz. Să se reprezinte grafic cuplajul și directivitatea între 1 și 5 GHz.

Solutie

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

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

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

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

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

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

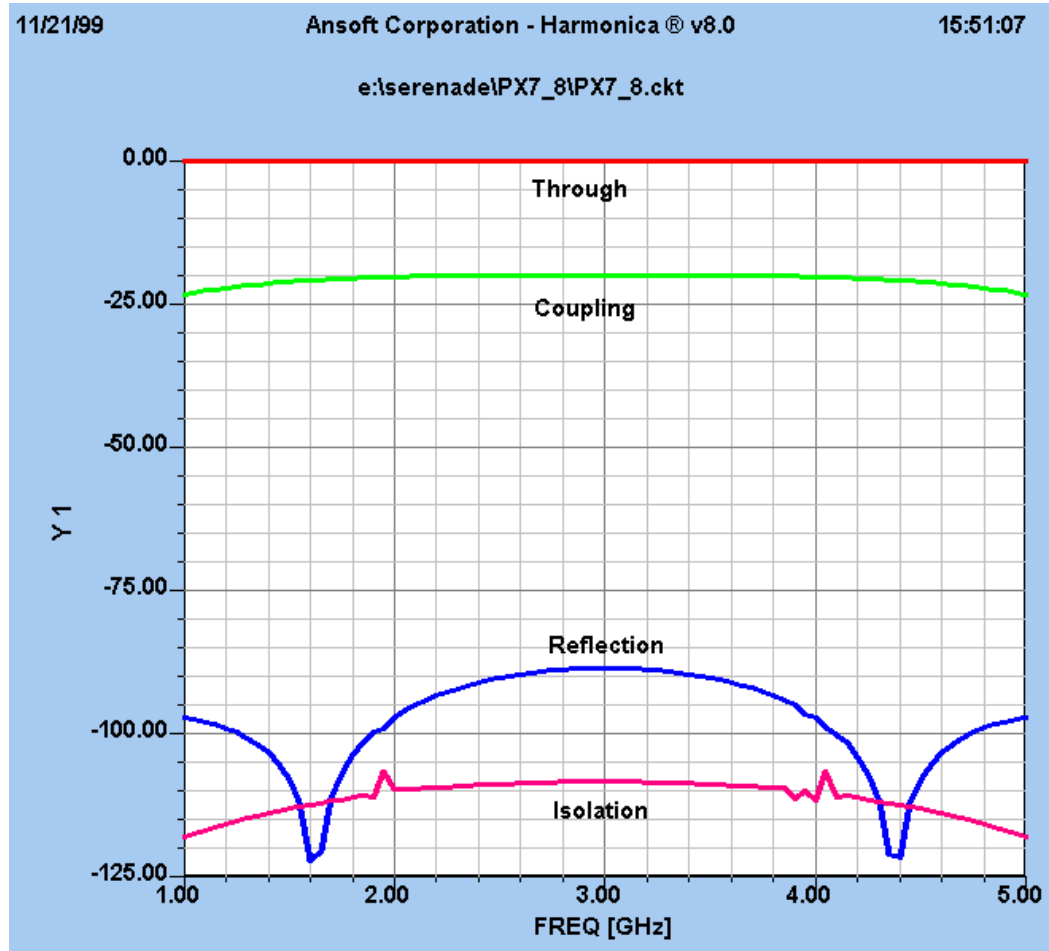
$$Z_{0e}^1 = Z_{0e}^3 = 50 \sqrt{\frac{1.0125}{0.9875}} = 50.63 \Omega$$

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

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

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

Simulare



Cuplorul Lange

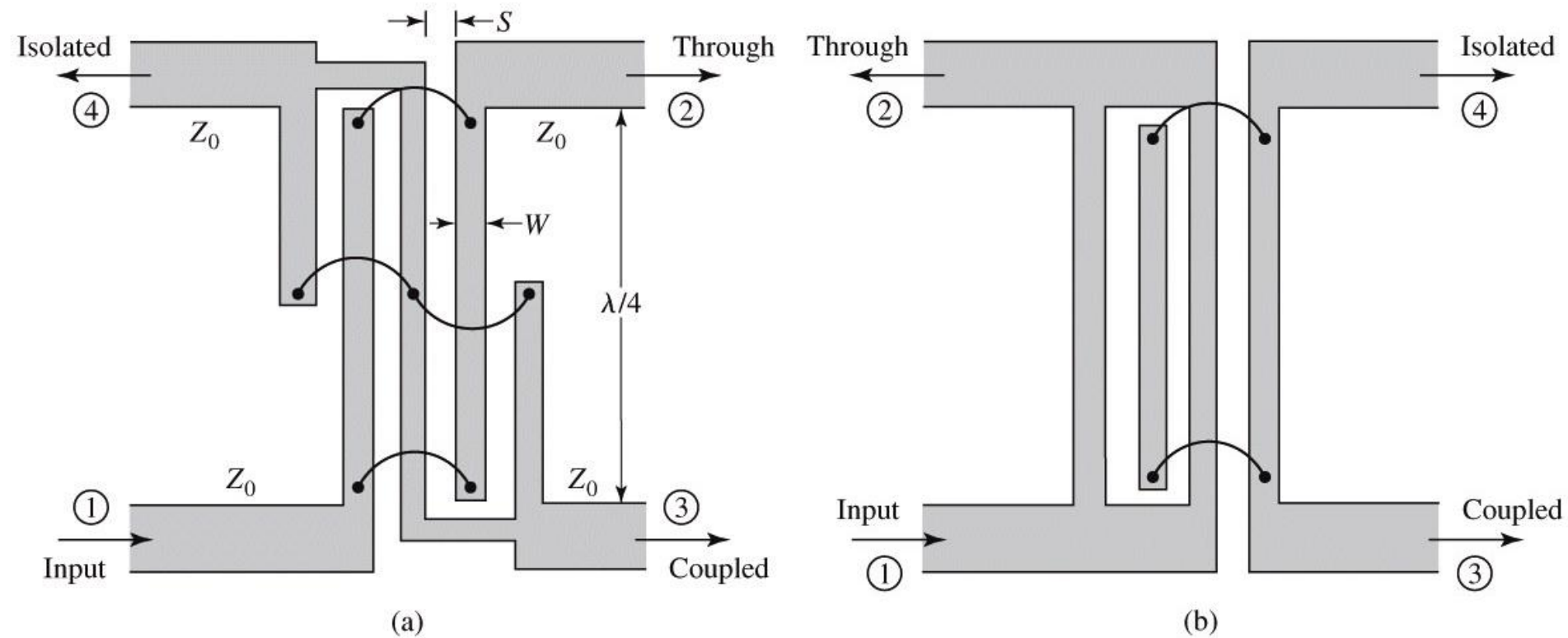
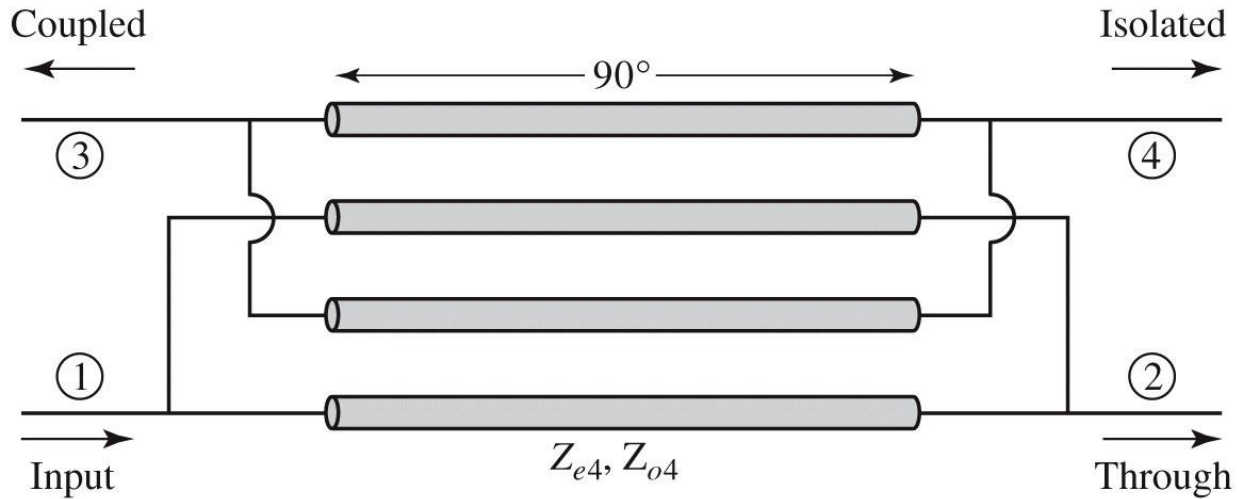


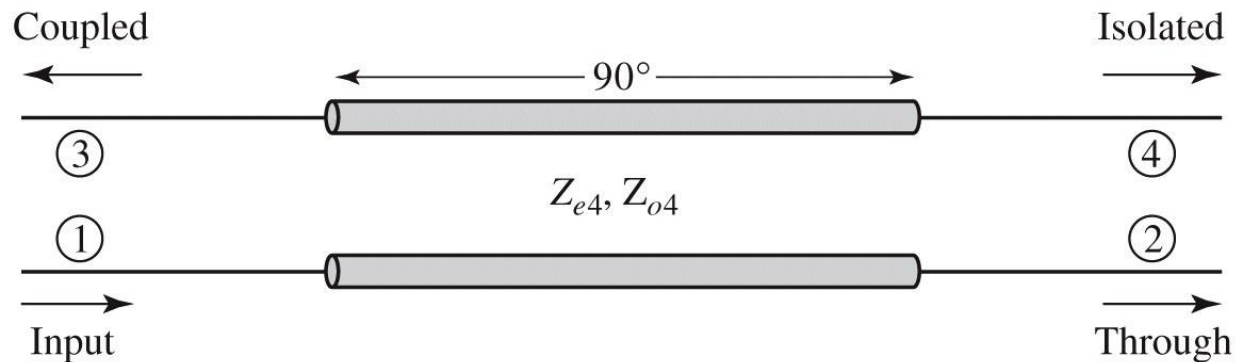
Figure 7.38

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Cuplor Lange

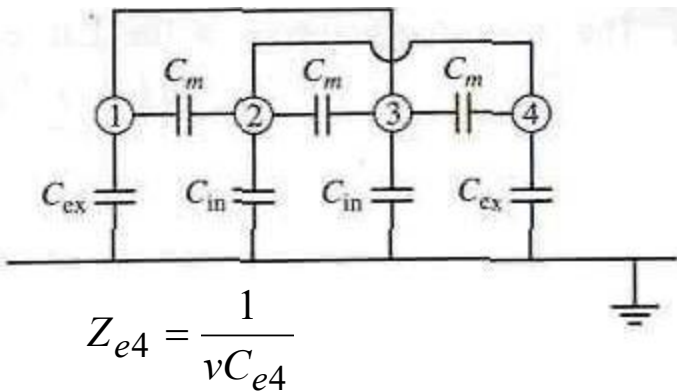


(a)



(b)

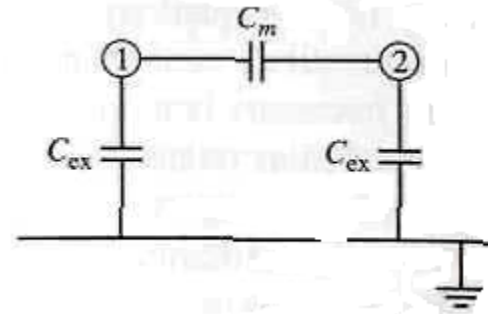
Modelul de circuit



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

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

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



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

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

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

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

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

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

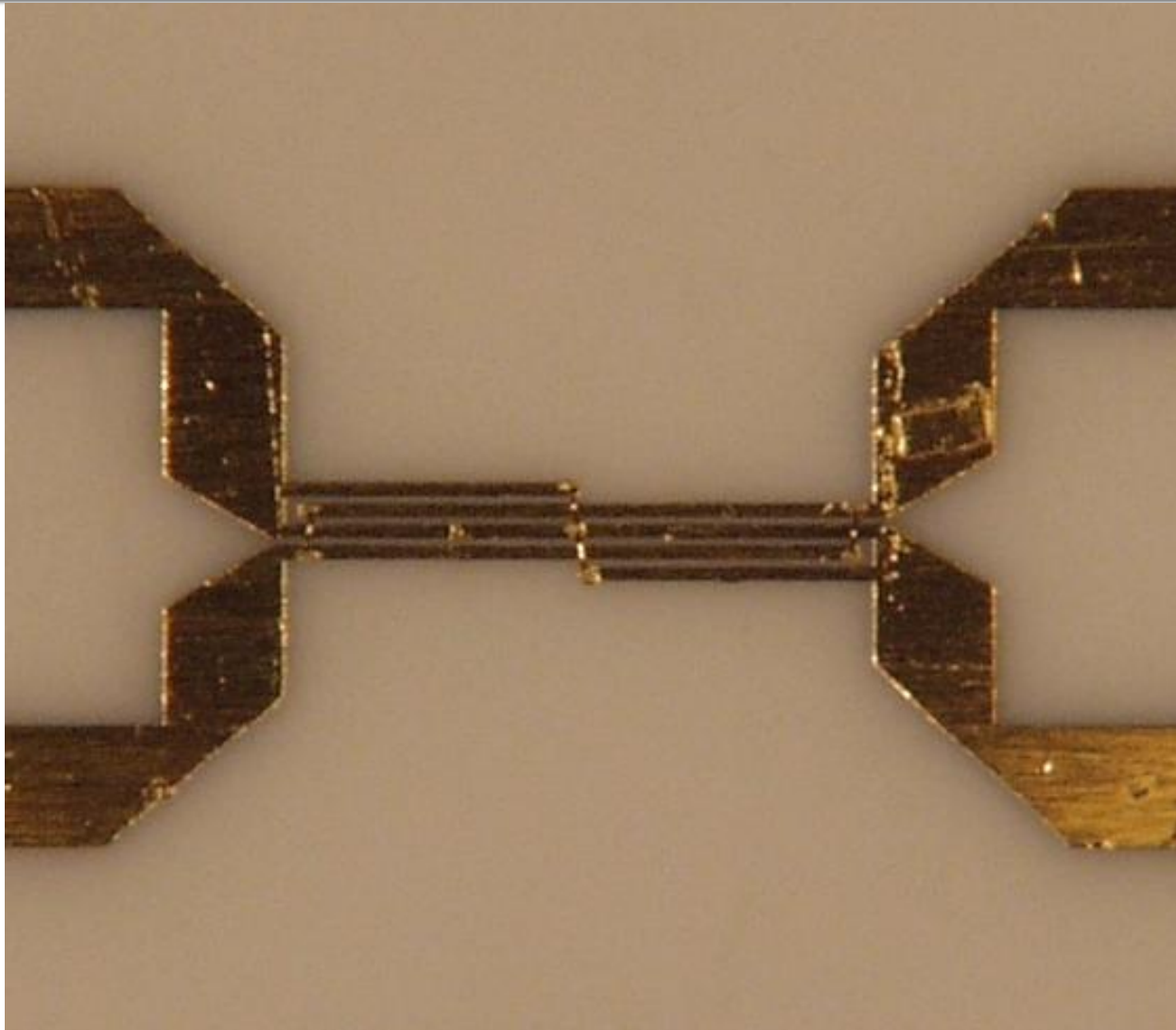
$$C_{o4} = \frac{C_o(3C_o + C_e)}{C_e + C_o}$$

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

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

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

Cuplor Lange



Contact

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- <https://rf-opto.etti.tuiasi.ro>
- rdamian@etti.tuiasi.ro