Curs 6

2022/2023

Dispozitive şi circuite de microunde pentru radiocomunicații

Disciplina 2022/2023

- 2C/1L, **DCMR (CDM)**
- **Minim 7 prezente (curs+laborator)**
- Curs - **conf. Radu Damian**
  - Marti 15-17, ~~Online~~/**Video (istoric)**, P2
  - E – **50%** din nota
  - **probleme** + (2p prez. curs) + (3 teste) + (bonus activitate)
    - primul test L1: 05.10.2022 (t2 si t3 neanuntate la **curs**)
    - 3pz (C) ≈ +0.5p (**2p** max)
  - **toate materialele permise**

Disciplina 2022/2023

- 2C/1L, **DCMR (CDM)**
- Laborator – **conf. Radu Damian**
  - Miercuri/Joi, 12/14 par/impar, **II.13**
  - 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

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

Documentatie

- RF-OPTO
  - http://rf-opto.etti.tuiasi.ro ~~Moodle~~
- Fotografie
  - de trimis pe rf-opto
  - necesara la laborator/curs
  - ~~bonus~~ activitate ~~0.5p~~/~~1p~~

Istoric

Alte informatii

Online Exam manual (pdf, 2.56 MB, en,)
Exam Simulation (video) (mp4, 41.96 MB, en,)
Important Agilent Application Notes (rar, 2.36 MB, ro,)

Ani anteriori

2020-2021 | 2019-2020 | 2018-2019 | 2017-2018 | 2016-2017 | Mai mult...

Dispozitive si circuite de microunde pentru radiocomunicatii

Disciplina: DCMR (2020-2021)

Coordonator Disciplina: conf. dr. Radu-Florin Damian
Cod: DOS412T
Tip Disciplina: DOS; Disciplina Optionala, Disciplina de Specialitate
Credite: 4
An de Studiu: 4, **Sem.** 7

Activitati

Curs: Cadru Didactic: conf. dr. Radu-Florin Damian, 2 Ore/Saptamana, Sectie Specializare, Orar:
Laborator: Cadru Didactic: conf. dr. Radu-Florin Damian, 1 Ore/Saptamana, Grupa, Orar:

Acces

- ~~Personalizat~~

Date:

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5184

Acceseaza ca acest student

Note obtinute

Disciplina	Tip	Data	Descriere	Nota	Puncte	Obs.
TW	Tehnologii Web					
	N	17/01/2014	Nota finala	10	-	
	A	17/01/2014	Colocviu Tehnologii Web 2013/2014	10	7.55	
	B	17/01/2014	Laborator Tehnologii Web 2013/2014	9	-	
	D	17/01/2014	Tema Tehnologii Web 2013/2014	9	-	

Nume

Email

Cod de verificare

344bd9f

Trimite

Online

- acces la **examene** necesita **parola** primita prin email

Online

- acces email/parola

Parola

- primita prin **email**

Important message from RF-OPTO Inbox ×

Radu-Florin Damian
to me, POPESCU

Romanian > English Translate message

Laboratorul de Microunde si Optoelectronica
Facultatea de Electronica, Telecomunicatii si Tehnologia Informatiei
Universitatea Tehnica "Gh. Asachi" Iasi

In atentia: POPESCU GOPO ION

Parola pentru a accesa examenele pe server-ul **rf-opto** este
Parola: [redacted]

Identificati-va pe server, cu parola, cat mai rapid, pentru confirmare.

Memorati acest mesaj intr-un loc sigur, pentru utilizare ulterioara

---

Attention: POPESCU GOPO ION

The password to access the exams on the **rf-opto** server is
Password: [redacted]

Login to the server, with this password, as soon as possible, for confirmation.

Save this message in a safe place for later use

Reply Reply all Forward

Subject	Correspondents
Important message from RF-OPTO	POPESCU GOPO ION
Validation of MDCR exam from 02/05/2020	[redacted]
[redacted]	[redacted]

From Me <rdamian@etti.tuiasi.ro>
Subject **Important message from RF-OPTO**
To [redacted]
Cc Me <rdamian@etti.tuiasi.ro>

Laboratorul de Microunde si Optoelectronica
Facultatea de Electronica, Telecomunicatii si Tehnologia Informatiei
Universitatea Tehnica "Gh. Asachi" Iasi

In atentia: POPESCU GOPO ION

Parola pentru a accesa examenele pe server-ul **rf-opto** este
Parola: [redacted]

Identificati-va pe server, cu parola, cat mai rapid, pentru confirmare.

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Attention: POPESCU GOPO ION

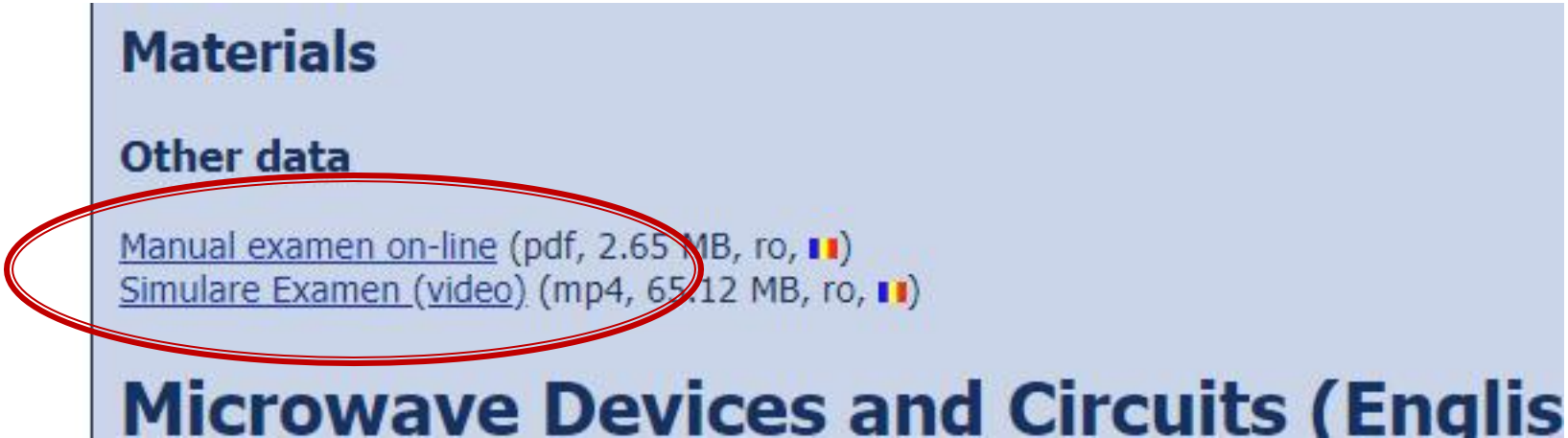
The password to access the exams on the **rf-opto** server is
Password: [redacted]

Login to the server, with this password, as soon as possible, for confirmation.

Save this message in a safe place for later use

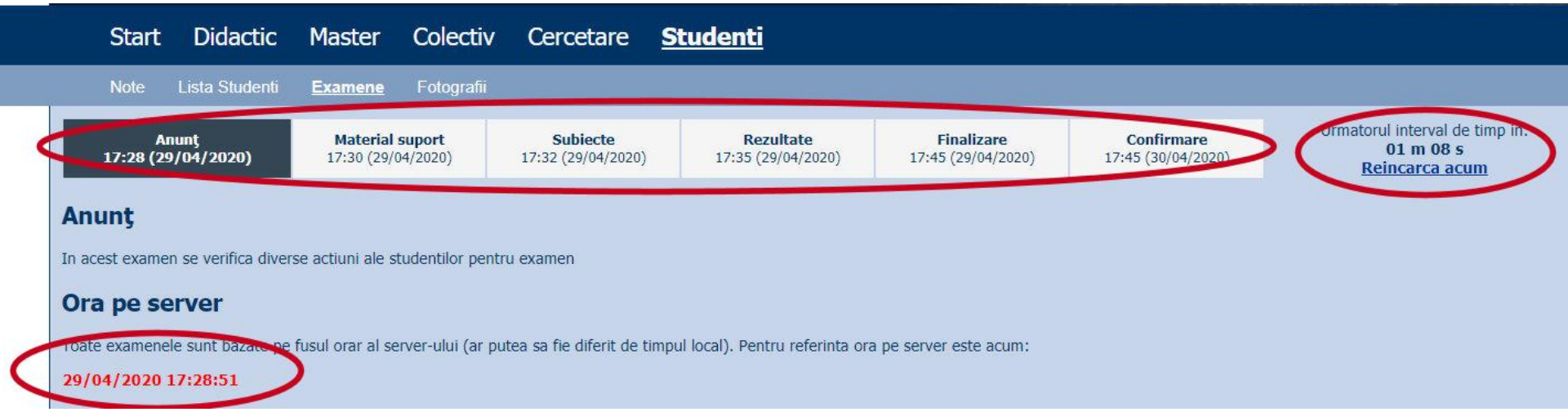
Manual examen online

- Aplicatia de examen online utilizata intens la:
  - ~~curs (prezenta)~~
  - **laborator (rezultate)**
  - **proiect (predare)**
  - ~~examen~~



Examen online

- intotdeauna **contratimp**
  - **perioada lunga** (rezultate laborator)
  - perioada scurta (teste: 15min, examen: 2h)



Examen online laborator 1

Examene online: 2022/2023

Disciplina: DCMR (Dispozitive si circuite de microunde pentru r

Pas 3

Nr.	Titlu	Start	Stop	Text
1	Laborator 1 (s3-5)	24/10/2022; 08:00	09/11/2022; 15:00	Temele individuale pent ...

Cuprins

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

Bibliografie

- http://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

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

0 dB	= 1
+ 0.1 dB	= 1.023 (+2.3%)
+ 3 dB	= 2
+ 5 dB	= 3
+ 10 dB	= 10
-3 dB	= 0.5
-10 dB	= 0.1
-20 dB	= 0.01
-30 dB	= 0.001

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

0 dBm	= 1 mW
3 dBm	= 2 mW
5 dBm	= 3 mW
10 dBm	= 10 mW
20 dBm	= 100 mW
-3 dBm	= 0.5 mW
-10 dBm	= 100 μW
-30 dBm	= 1 μW
-60 dBm	= 1 nW

[dBm] + [dB] = [dBm]

[dBm/Hz] + [dB] = [dBm/Hz]

[x] + [dB] = [x]

Examen

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

Linii de transmisie in mod TEM

Cuprins

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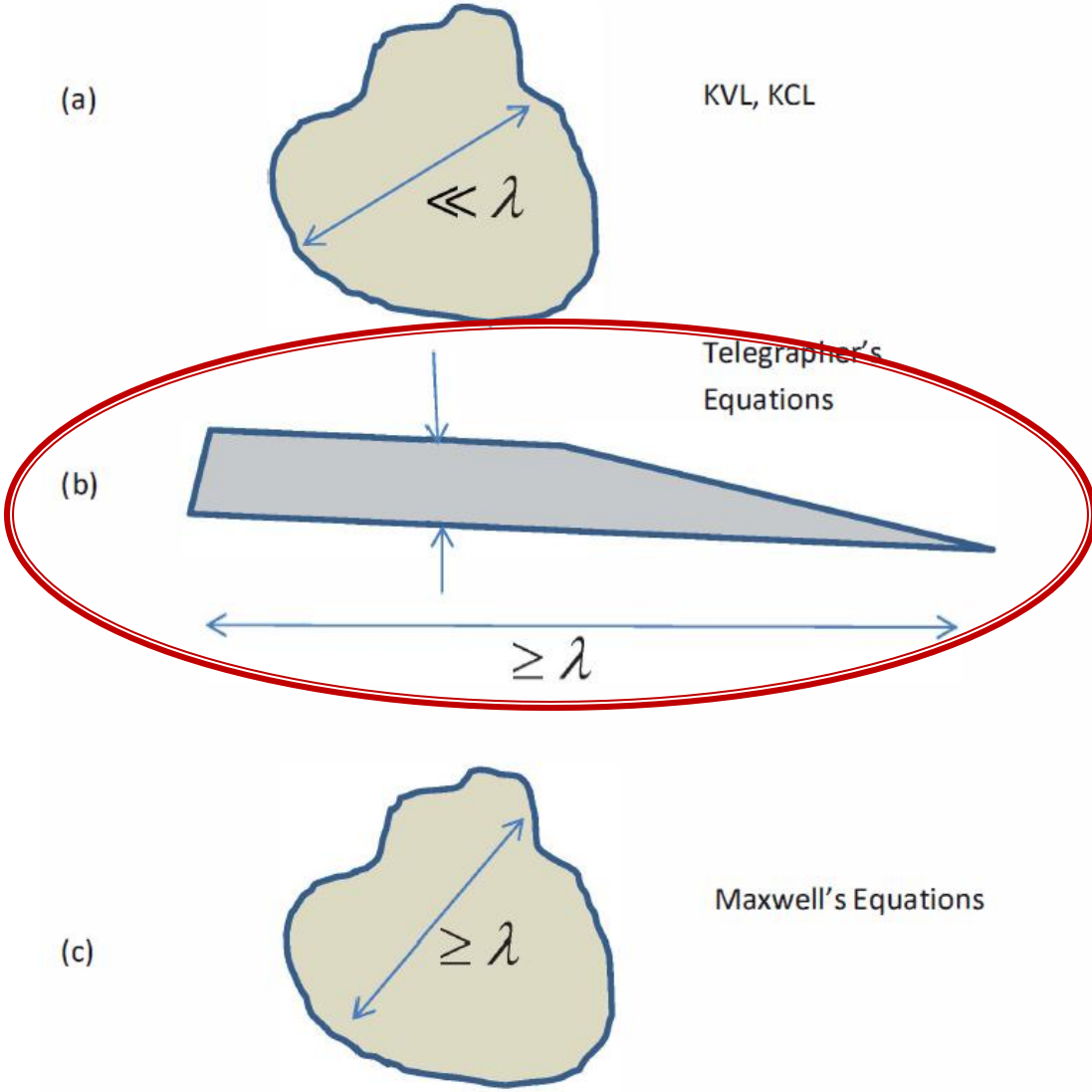
- Amplificatoare de microunde
- Filtre de microunde
- Oscilatoare de microunde ?

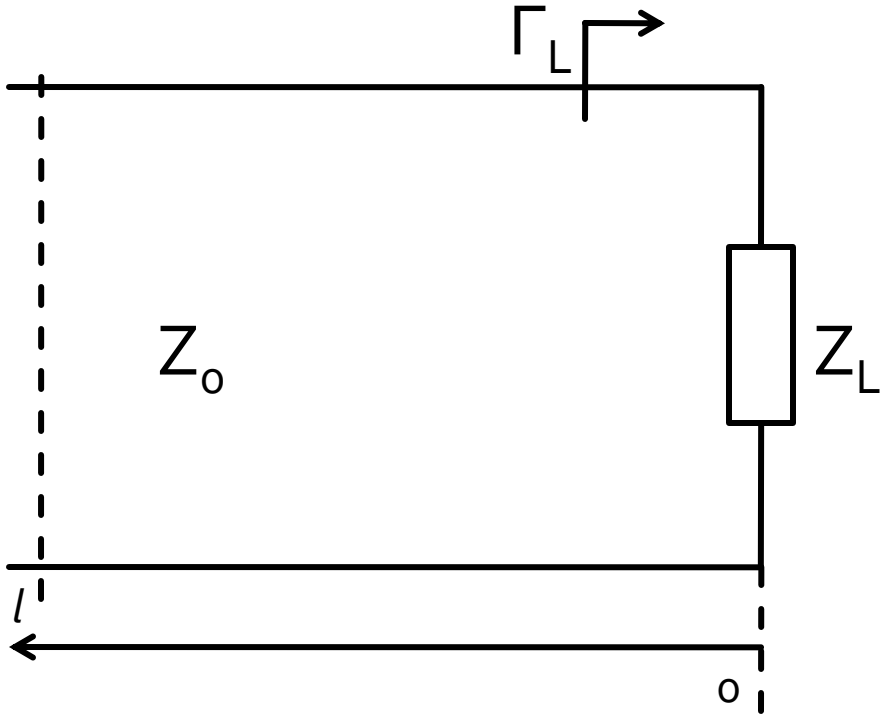
Lungime electrica

- Comportarea (descrierea) unui circuit depinde de lungimea sa electrica la frecventele de interes
  - E≈0 → Kirchhoff
  - E>0 → propagare

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



Linie fara pierderi



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

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

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

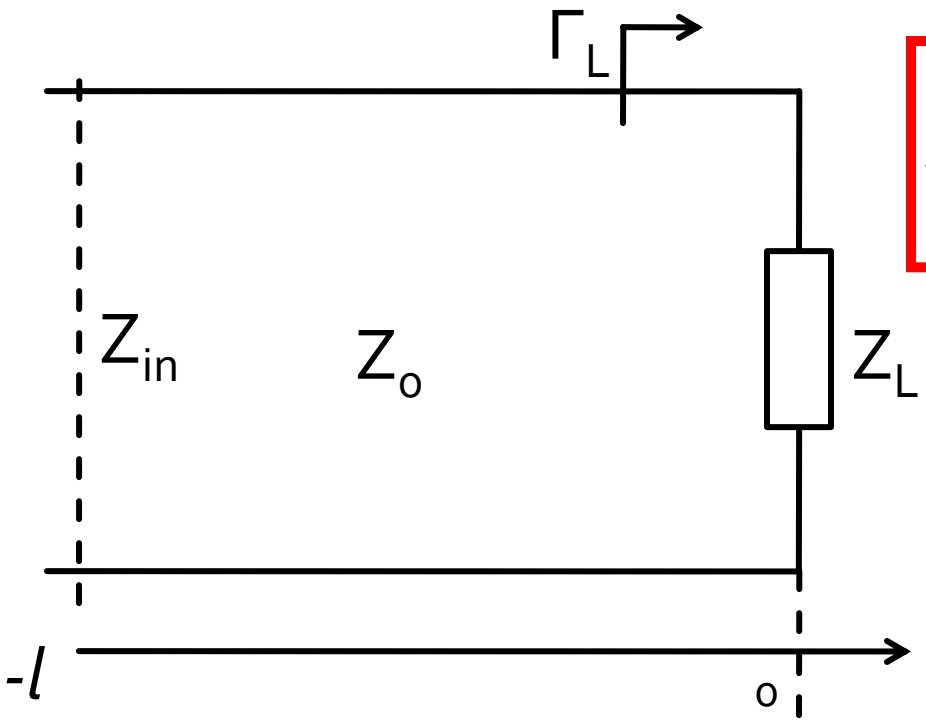
- coeficient de reflexie in tensiune

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

- Z_o real

Linie fara pierderi

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



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

Transfer de putere

Adaptarea de impedanța

Cuprins

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

Adaptare dpdv al puterii

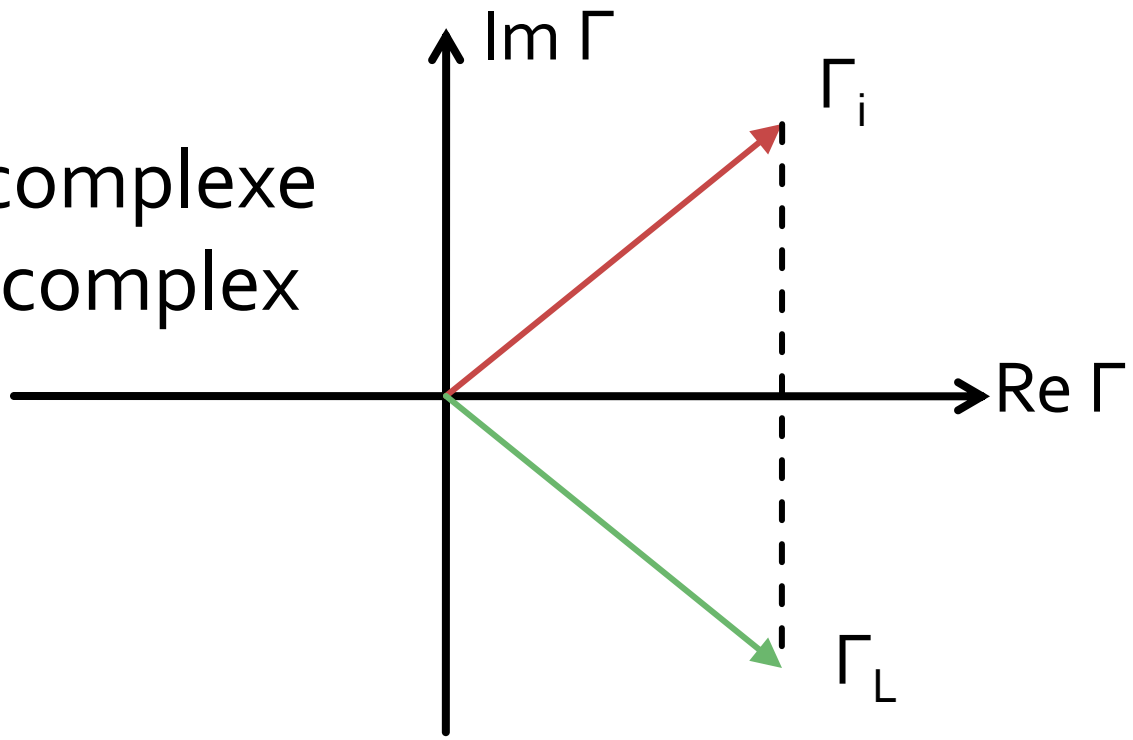
$$Z_L = Z_i^*$$

Daca se alege un Zo real

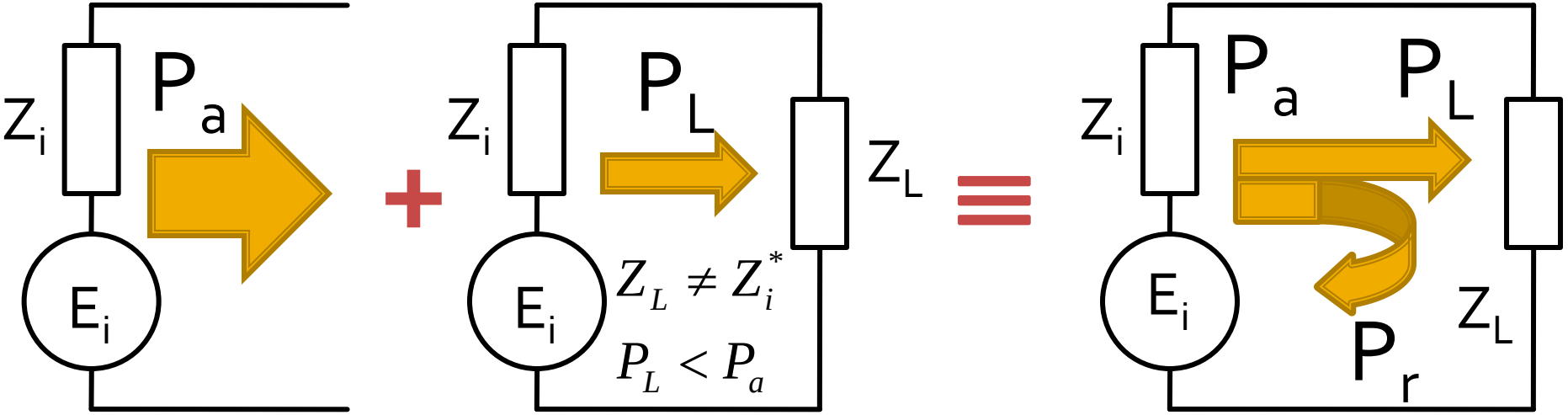
$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

$$\Gamma_L = \Gamma_i^*$$

- numere complexe
- in planul complex



Reflexie de putere / Model

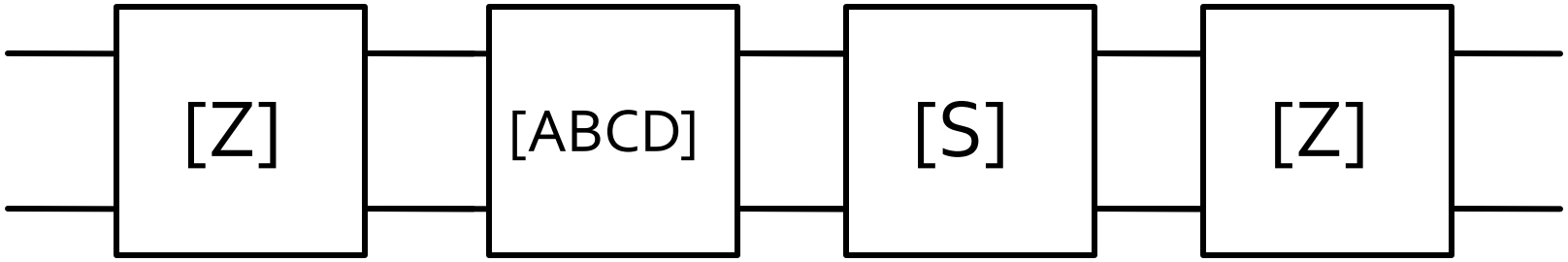


- Generatorul are posibilitatea de a oferi o anumita putere maxima de semnal P_a
- Pentru o sarcina oarecare, acesteia i se ofera o putere de semnal mai mica $P_L < P_a$
- Se intampla **"ca si cum"** (model) o parte din putere se reflecta $P_r = P_a - P_L$
- Puterea este o marime **scalara!**

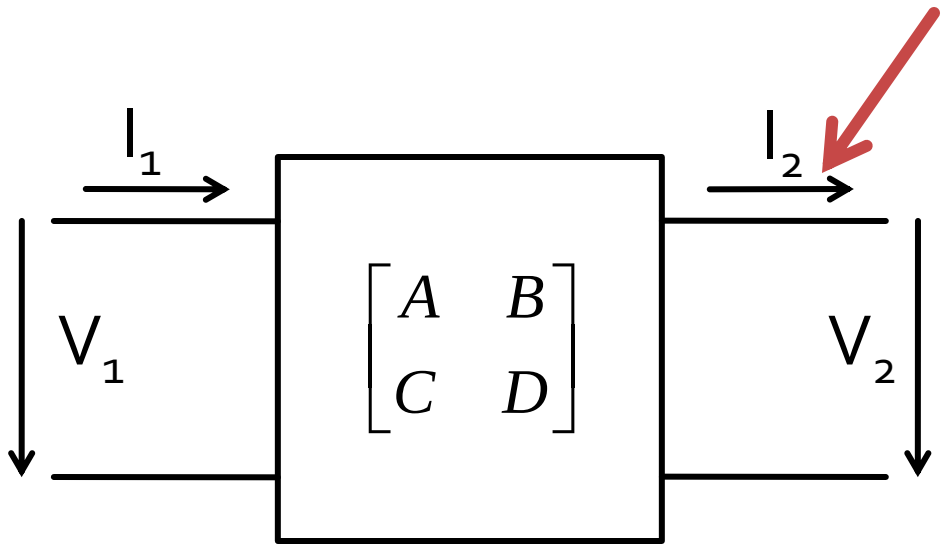
Analiza la nivel de rețea a circuitelor de microunde

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 ABCD – de transmisie



$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

$$V_1 = A \cdot V_2 + B \cdot I_2$$

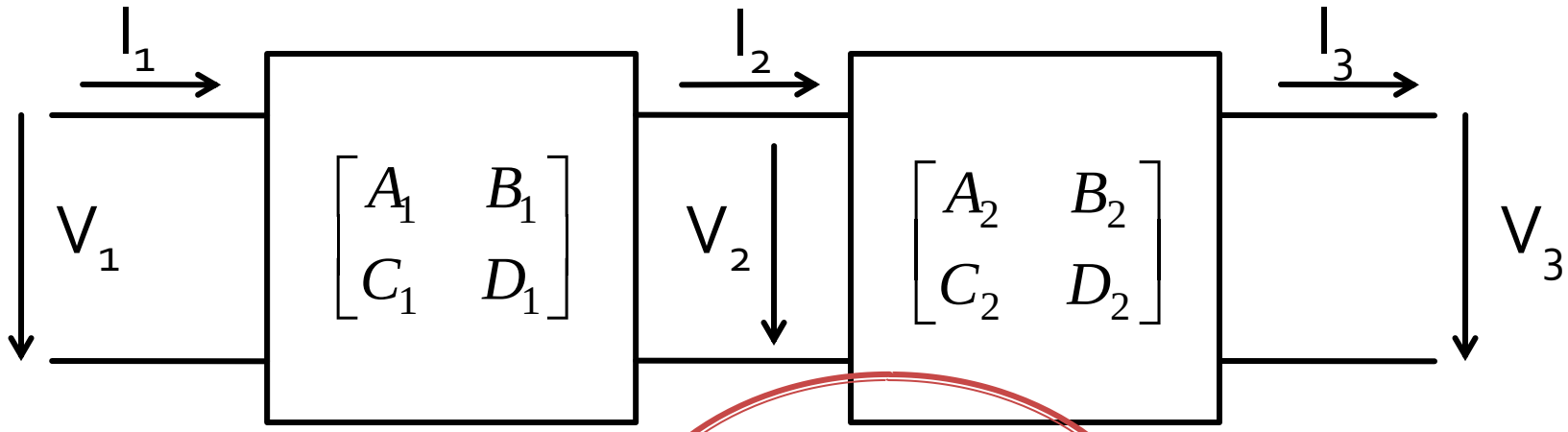
$$I_1 = C \cdot V_2 + D \cdot I_2$$

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \frac{1}{A \cdot D - B \cdot C} \cdot \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

$$A = \left.\frac{V_1}{V_2}\right|_{I_2=0} \qquad B = \left.\frac{V_1}{I_2}\right|_{V_2=0} \qquad C = \left.\frac{I_1}{V_2}\right|_{I_2=0} \qquad D = \left.\frac{I_1}{I_2}\right|_{V_2=0}$$

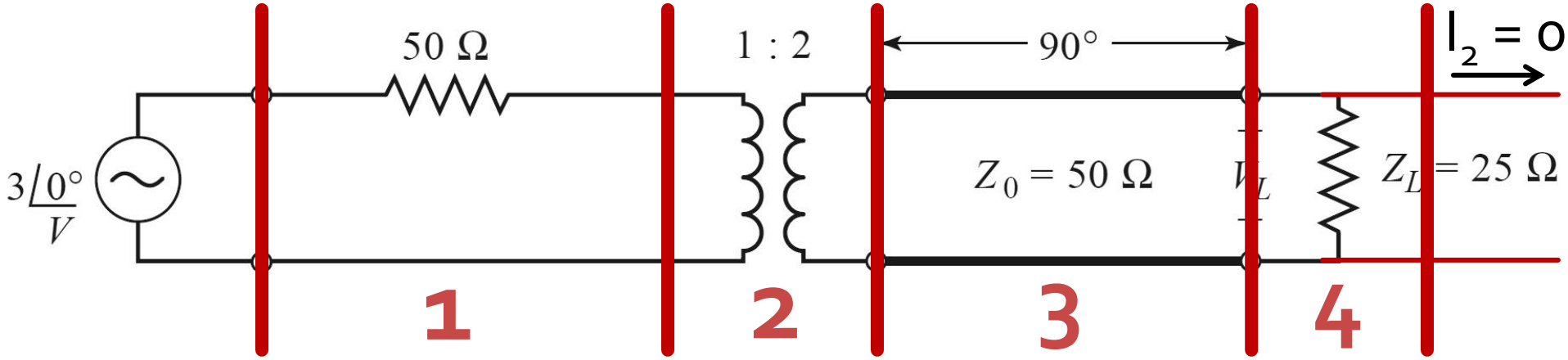
Matricea ABCD – de transmisie

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



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

Exemplu utilizare matrice ABCD



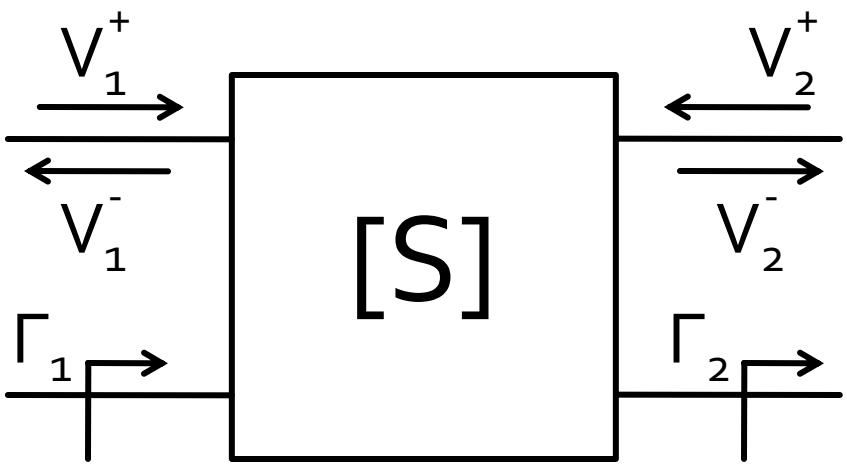
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 50 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{2} & 0 \\ 0 & 2 \end{bmatrix} \cdot \begin{bmatrix} 0 & 50 \cdot j \\ \frac{j}{50} & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{1}{25} & 1 \end{bmatrix} = \begin{bmatrix} 3 \cdot j & 25 \cdot j \\ \frac{j}{25} & 0 \end{bmatrix}$$

$$V_L = \frac{V}{A} = \frac{3\angle 0°}{3 \cdot j} = 1\angle -90°$$

Continuare

Analiza la nivel de rețea a circuitelor de microunde

Matricea S (repartitie)



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

$$S_{11} = \left.\frac{V_1^-}{V_1^+}\right|_{V_2^+=0} = \Gamma_1\big|_{\Gamma_2=0}$$

$$S_{21} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0} = T_{21}\big|_{\Gamma_2=0}$$

- S11 este coeficientul de reflexie la portul ***1*** cand cand portul ***2*** este terminat pe impedanta care realizeaza adaptarea
- S21 este coeficientul de transmisie de la portul ***1*** (**al doilea** indice**!**) la portul ***2*** (**primul** indice**!**) cand se depune semnal la portul ***1*** portul ***2*** este terminat pe impedanta care realizeaza adaptarea

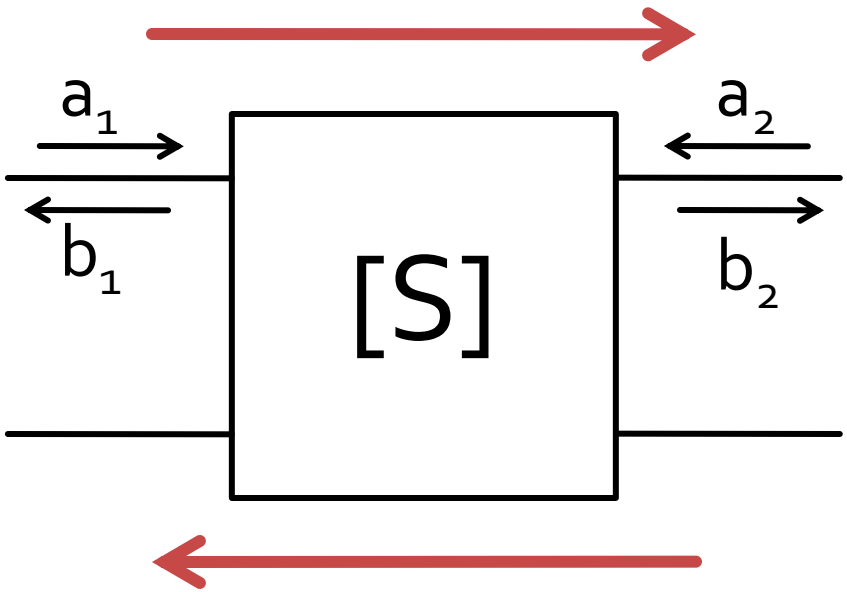
Matricea S (repartitie)

- Matricea S poate fi extinsa (generalizata) pentru multiporti (n-porturi)

$$S_{ii} = \left.\frac{V_i^-}{V_i^+}\right|_{V_k^+=0,\forall k\neq i} \qquad S_{ij} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+=0,\forall k\neq j}$$

- S_{ii} este coeficientul de reflexie la portul ***i*** cand toate celelalte porturi sunt conectate la impedanta care realizeaza adaptarea
- S_{ij} este coeficientul de transmisie de la portul ***j*** (**al doilea** indice**!**) la portul ***i*** (**primul** indice**!**) cand se depune semnal la portul ***j*** si toate celelalte porturi sunt conectate la impedanta care realizeaza adaptarea

Matricea S (repartitie)



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

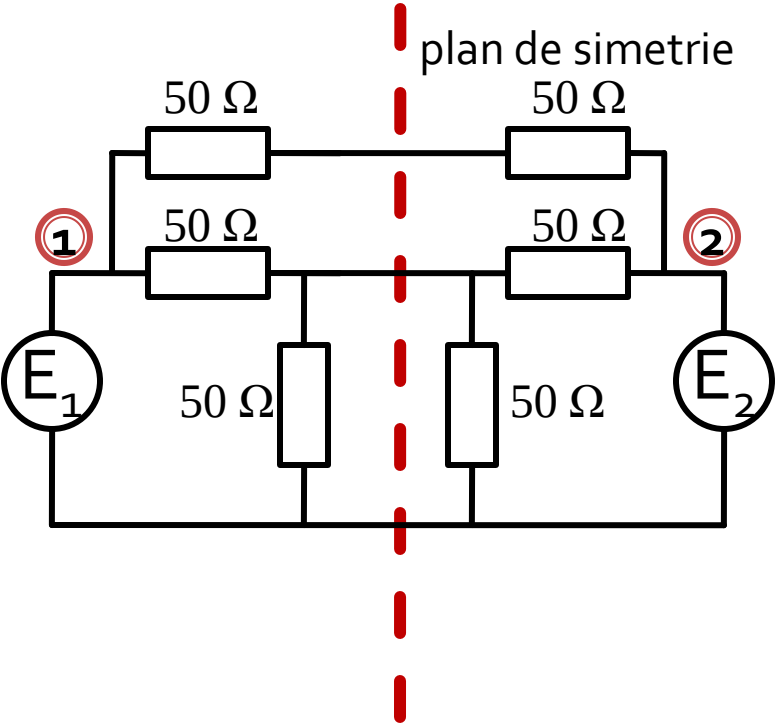
$$|S_{21}|^2 = \frac{Putere\ sarcina\ Z_0}{Putere\ sursa\ Z_0}$$

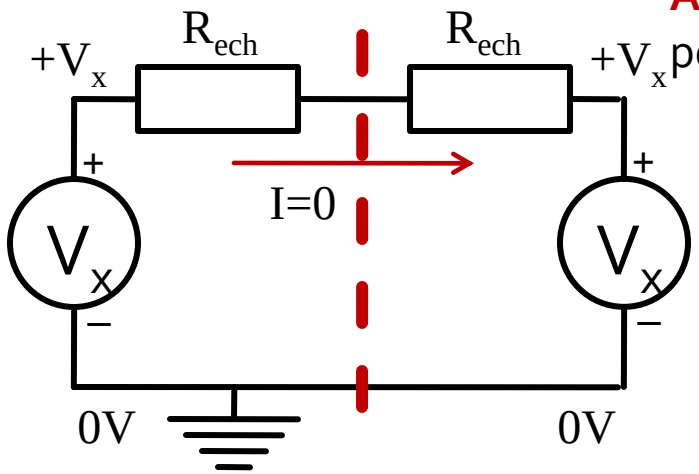
- a,b
  - informatia despre putere **SI** faza
- S_{ij}
  - influenta circuitului asupra puterii semnalului incluzand informatiile relativ la faza

Analiza pe mod par/impar

Analiza pe mod par/impar (even/odd)

- la atacul porturilor cu surse simetrice/antisimetrice planele de simetrie se transforma in
  - gol virtual
  - masa virtuala

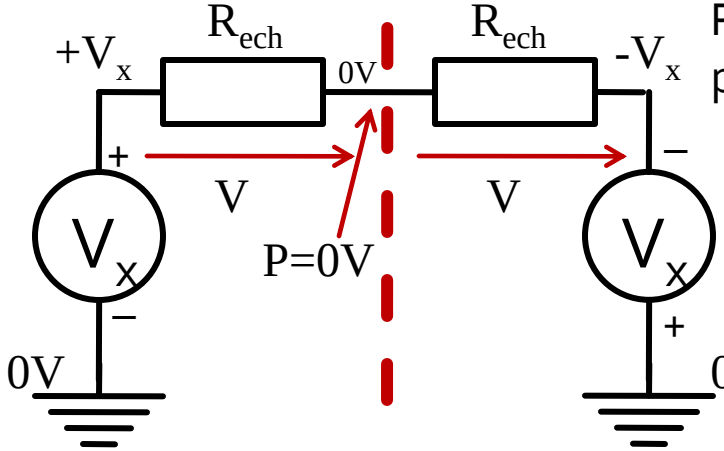




Aceeasi polaritate pentru surse

$$I = 0, \forall V_x$$

plan de simetrie **gol**



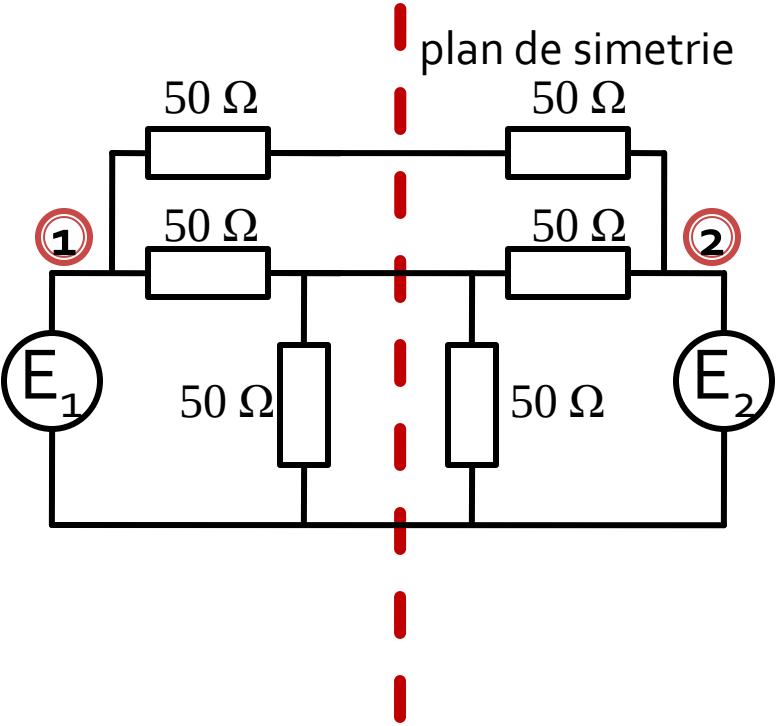
Polaritate **diferita** pentru surse

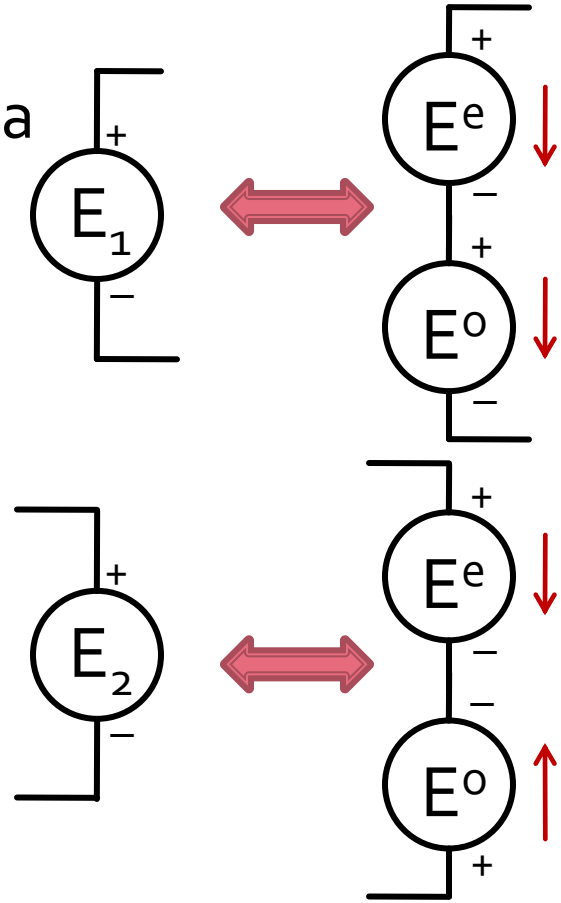
$$P = 0, \forall V_x$$

plan de simetrie **masa**

Analiza pe mod par/impar (even/odd)

- orice combinatie de 2 surse poate fi echivalata pentru circuitele liniare cu o suprapunere:
  - o sursa simetrica
  - o sursa antisimetrica





$$E_1 = E^e + E^o$$

$$E_2 = E^e - E^o$$

$$E^e = \frac{E_1 + E_2}{2}$$

$$E^o = \frac{E_1 - E_2}{2}$$

Analiza pe mod par/impar (even/odd)

- In circuite liniare putem aplica suprapunerea efectelor

Efect (Sursa1 + Sursa2) = Efect (Sursa1) + Efect (Sursa2)

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

OARECARE

Putem beneficia de avantajele simetriilor!!

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

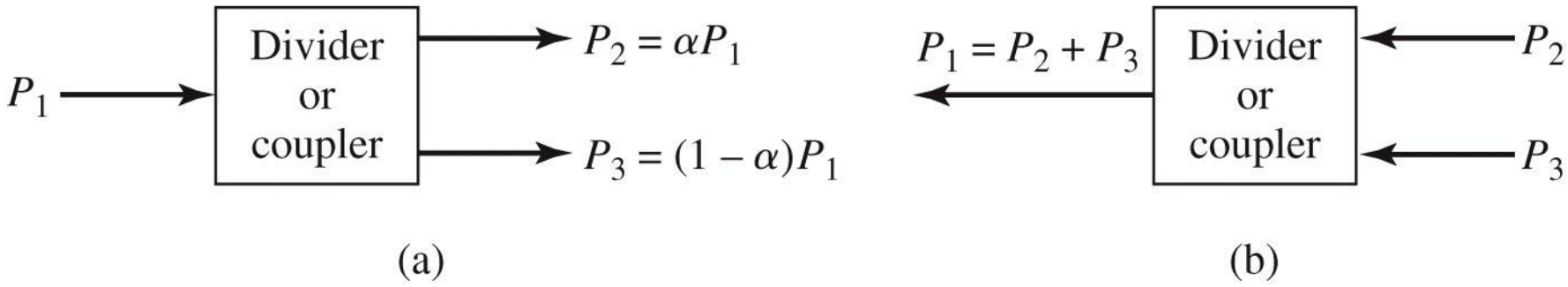


Figure 7.1
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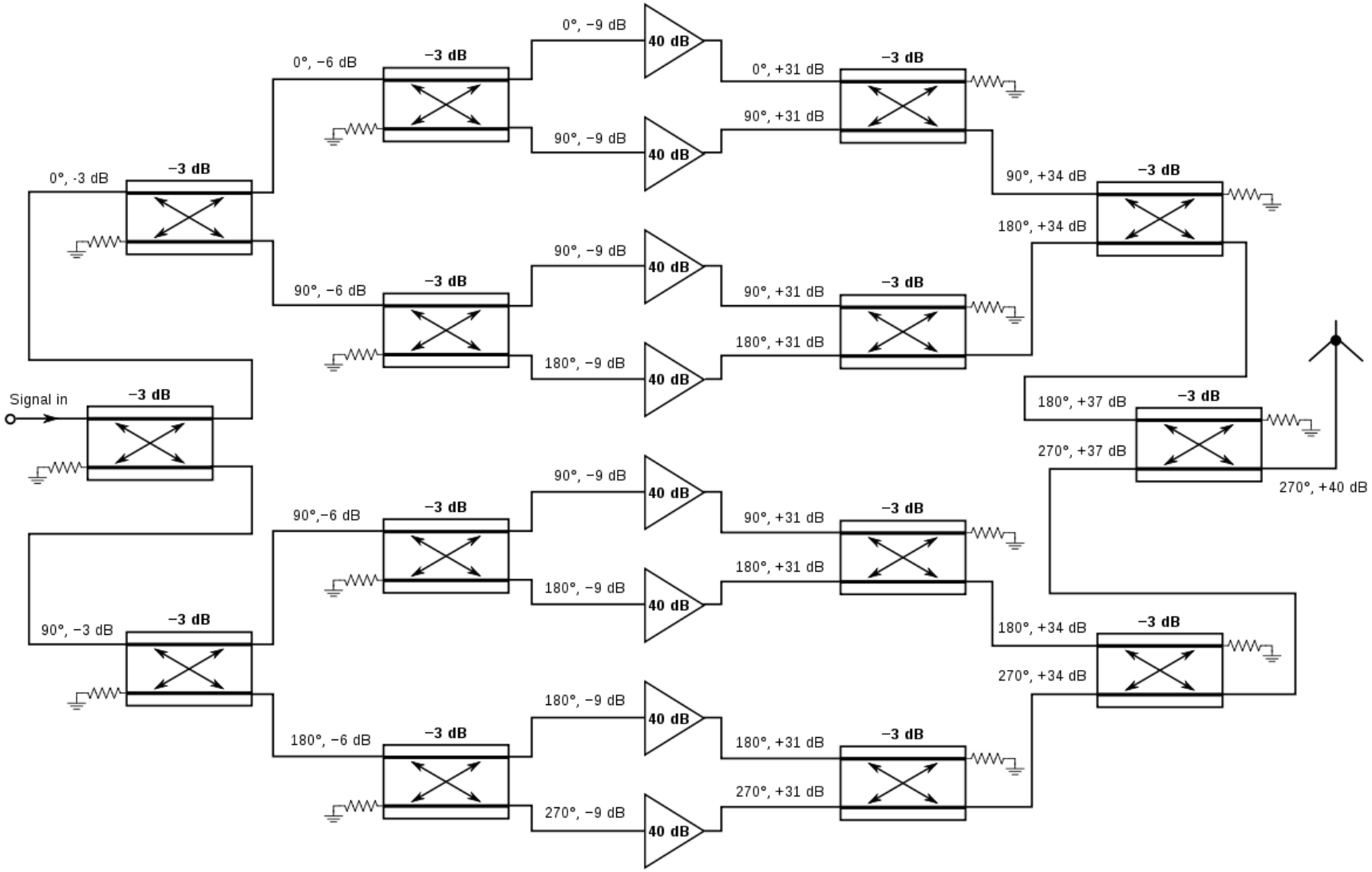
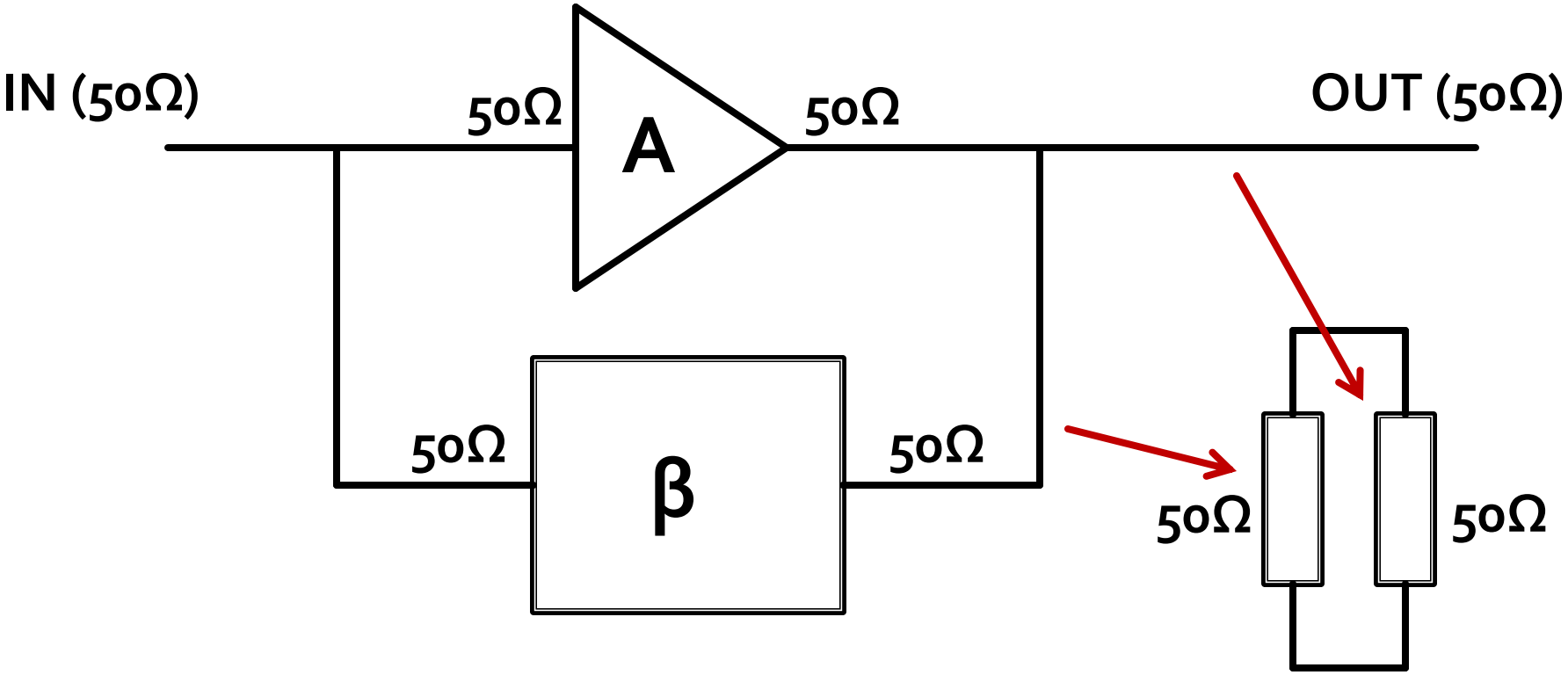
Amplificatoare echilibrate



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)

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \qquad \sum_{k=1}^{N} S_{ki}\cdot S_{ki}^{*}=1$$

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

- 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

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

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

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

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

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

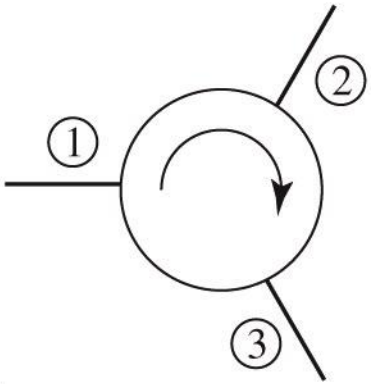
Circuit cu trei porți nereciproc

- doua solutii posibile
- circulatoare
  - in sens orar direct

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

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

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



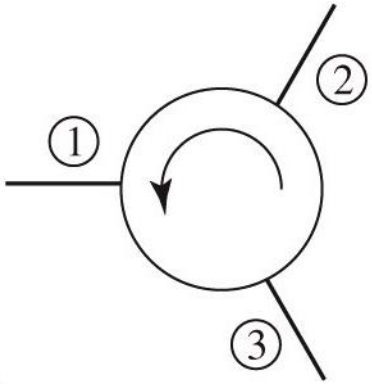
(a)

  - in sens orar invers

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

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

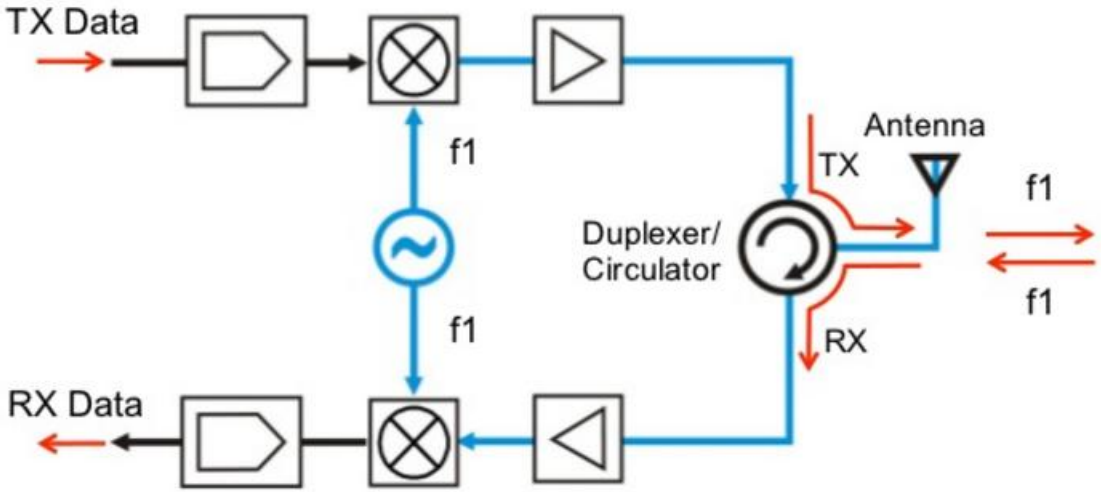
$$[S] = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

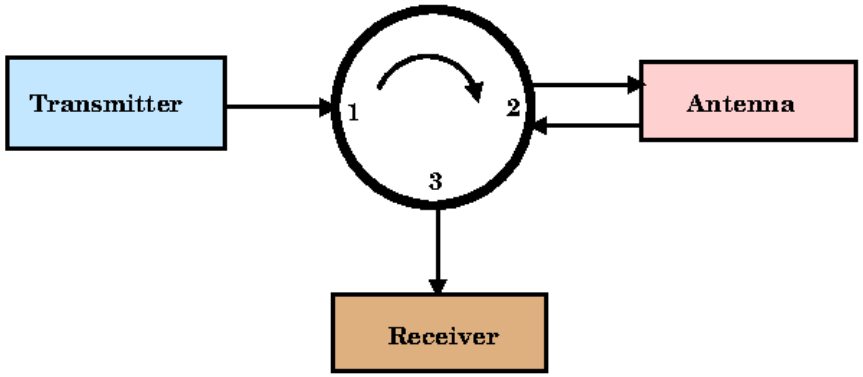


(b)

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

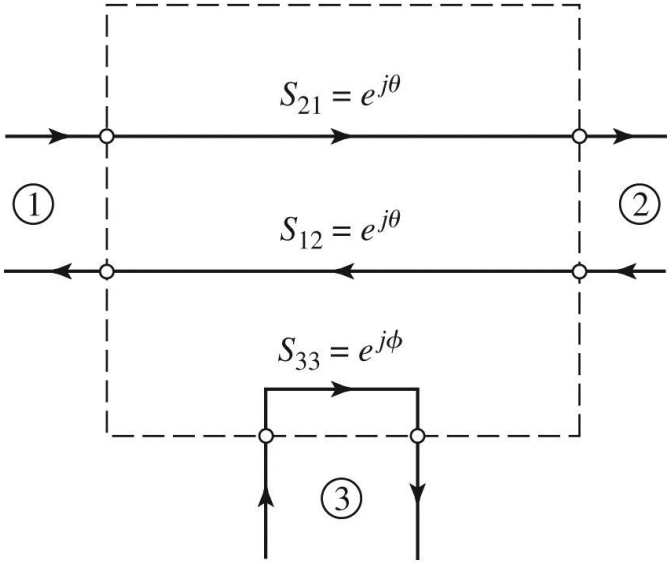
$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix}$$

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

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

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

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



- 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**

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

$$|S_{13}| = |S_{24}|$$

$$|S_{12}| = |S_{34}|$$

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

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

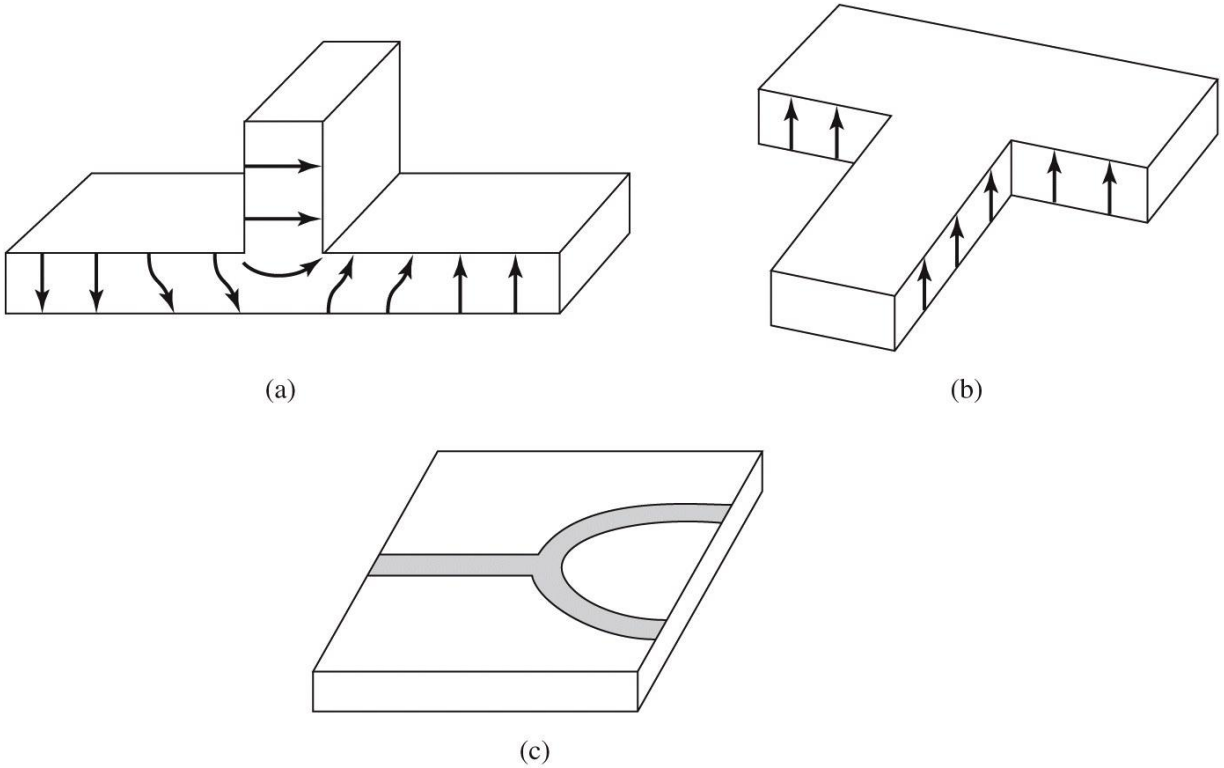
- Un circuit cu 4 porti care este simultan:
  - adaptat la toate portile
  - reciproc
  - fara pierderi
- este **intotdeauna directional**
  - puterea de semnal introdusa pe un port este trimisa **numai spre doua** din celelalte trei porturi

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

Divizoare de putere

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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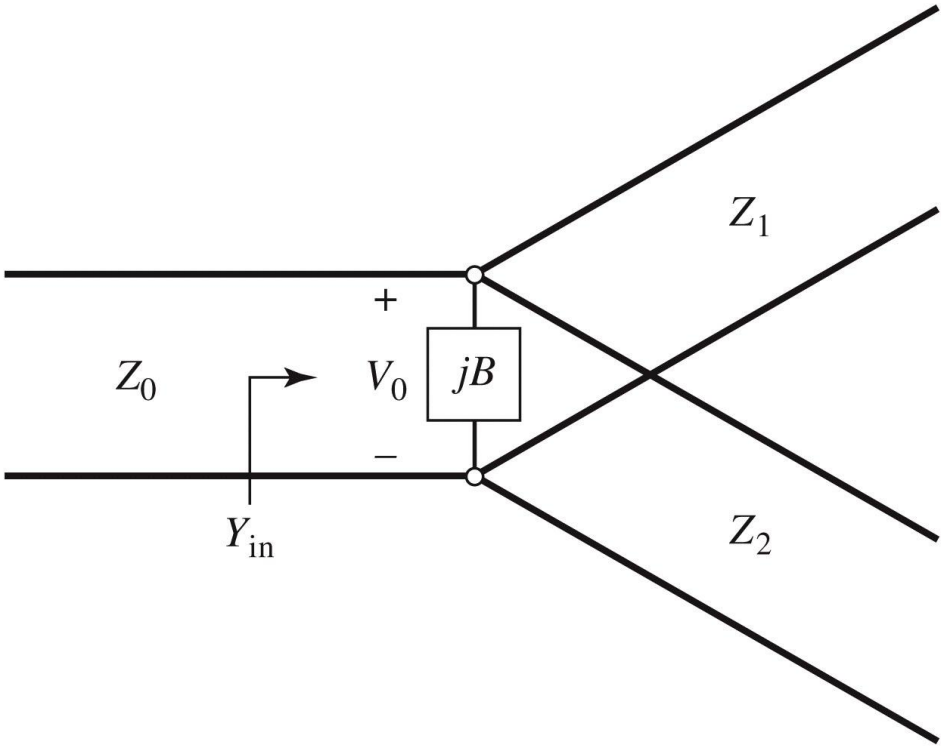
Divizarea de putere a jonctiunii in T

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



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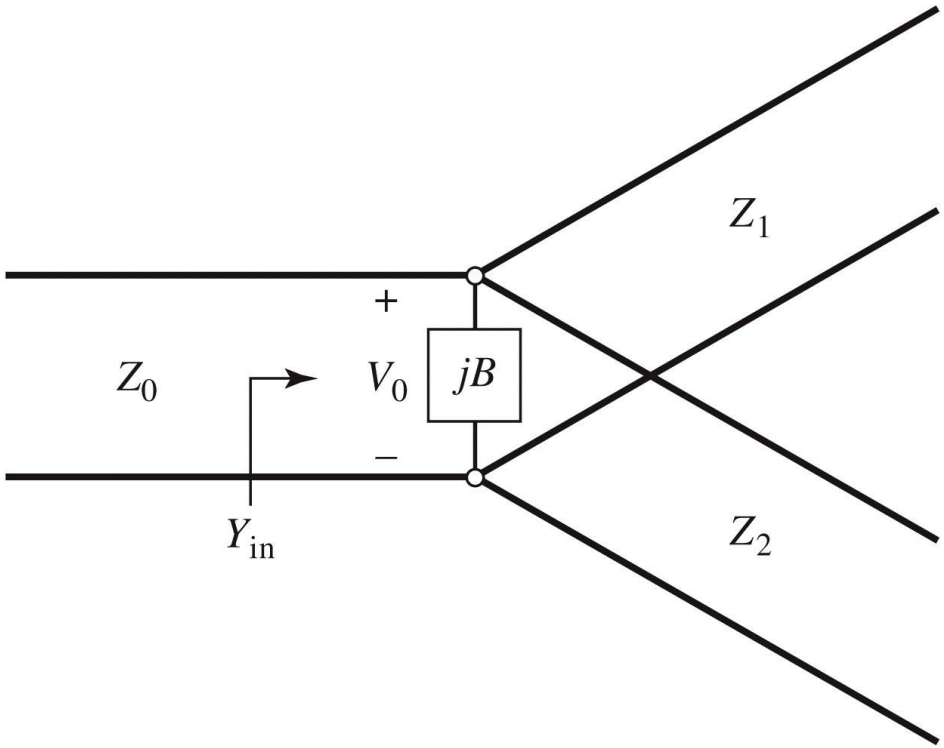
- la nivelul joncțiunii câmpurile sunt neuniforme, generând moduri de ordin superior localizate
- aceasta energie localizata poate fi modelata cu o reactanța concentrata la nivelul joncțiunii: **B**
- Proiectarea divizorului presupune adaptarea la linia de intrare cu Z_0
  - ieșirile pot fi adaptate 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 ≅ 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_o e amplitudinea semnalului la jonctiune

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

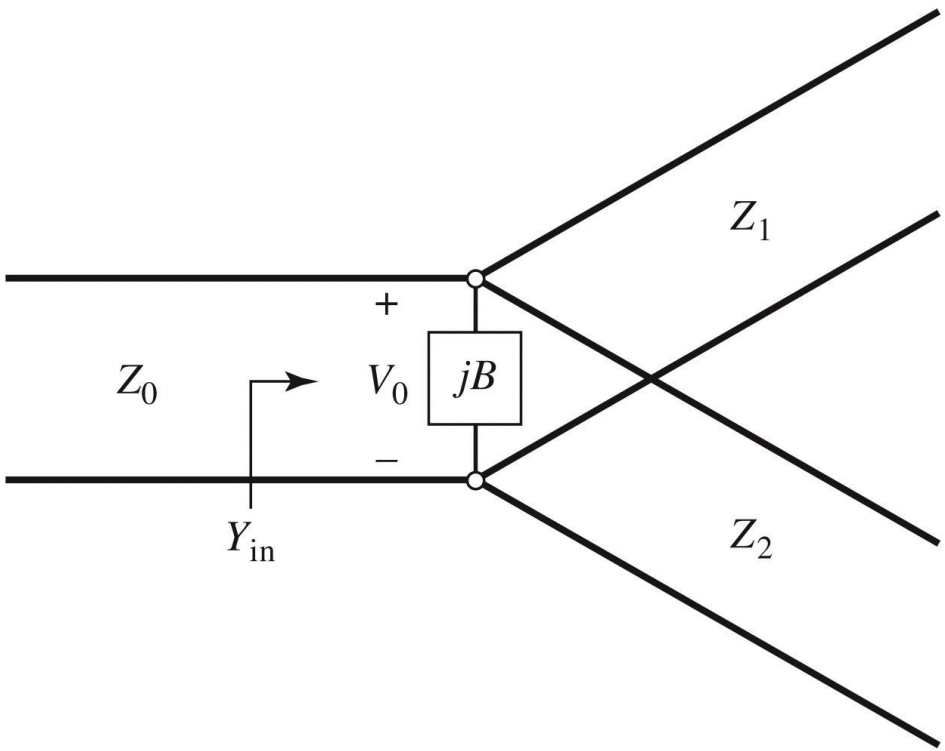
$$P_1 = \frac{1}{2} \cdot \frac{V_0^2}{Z_1}$$

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

deci:

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

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



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

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

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

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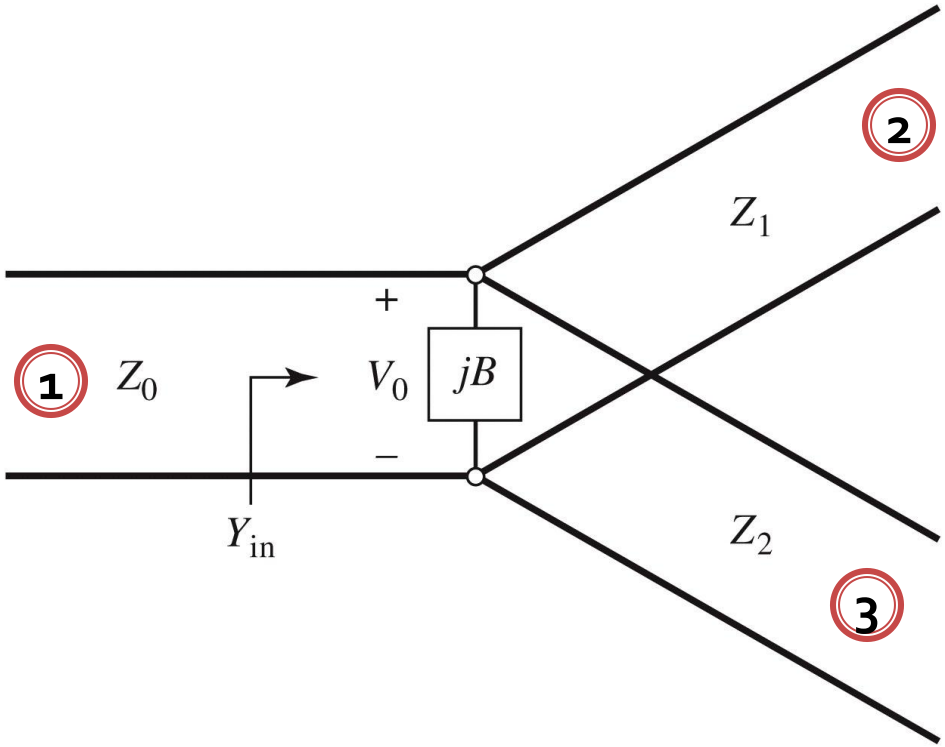
Divizarea de putere a jonctiunii in T

- 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

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

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

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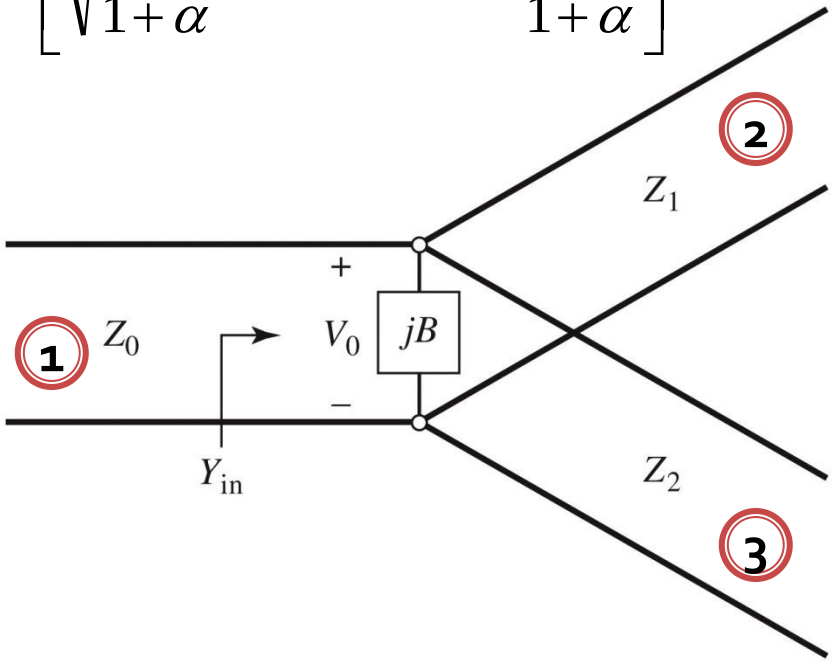
Divizarea de putere a jonctiunii in T

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

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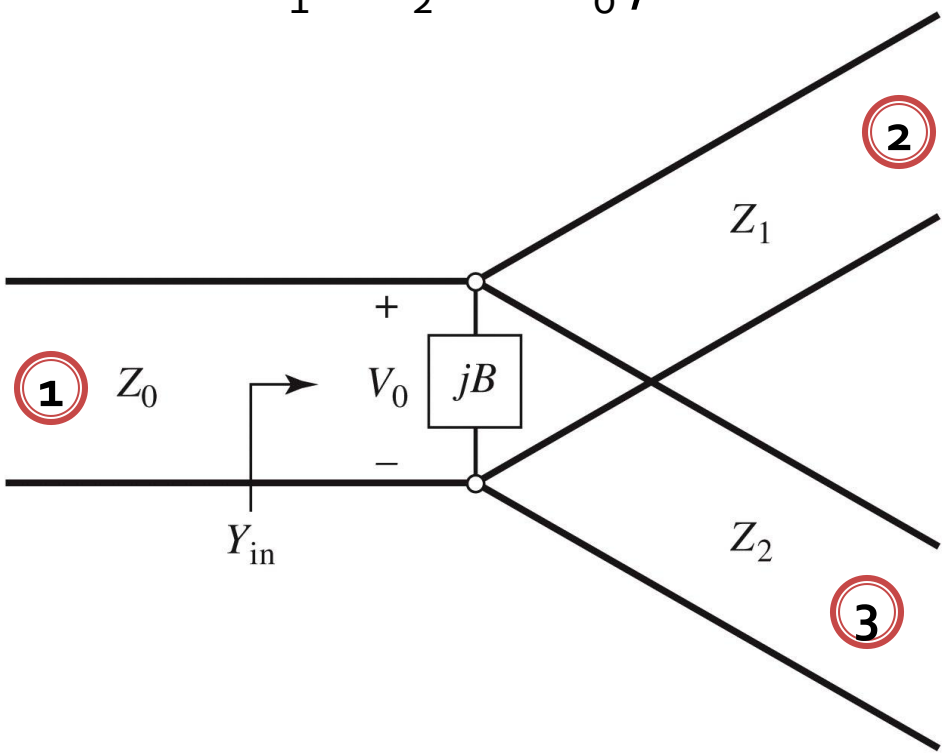
$$[S]=\begin{bmatrix} 0 & \sqrt{\frac{\alpha}{1+\alpha}} & \sqrt{\frac{1}{1+\alpha}} \\ \sqrt{\frac{\alpha}{1+\alpha}} & -\frac{1}{1+\alpha} & \frac{\sqrt{\alpha}}{1+\alpha} \\ \sqrt{\frac{1}{1+\alpha}} & \frac{\sqrt{\alpha}}{1+\alpha} & -\frac{\alpha}{1+\alpha} \end{bmatrix}$$

Divizarea de putere a jonctiunii in T

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

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



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

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

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

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

Verificare

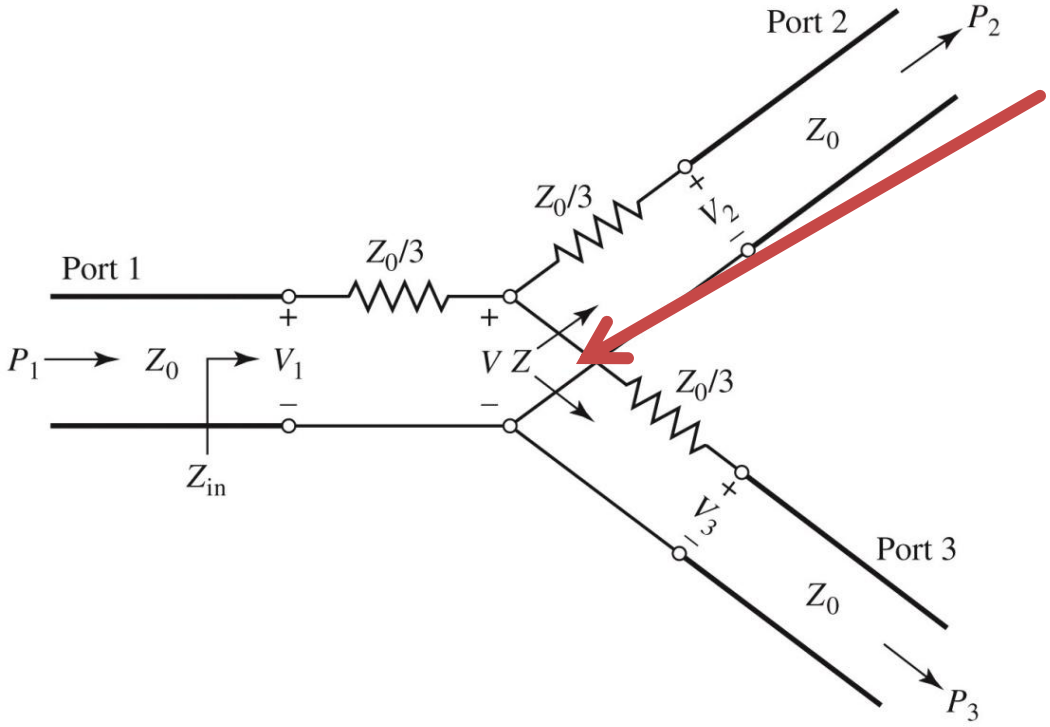
$$Z_{in} = 40\,\Omega \,\|\, 120\,\Omega = 30\,\Omega$$

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

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

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

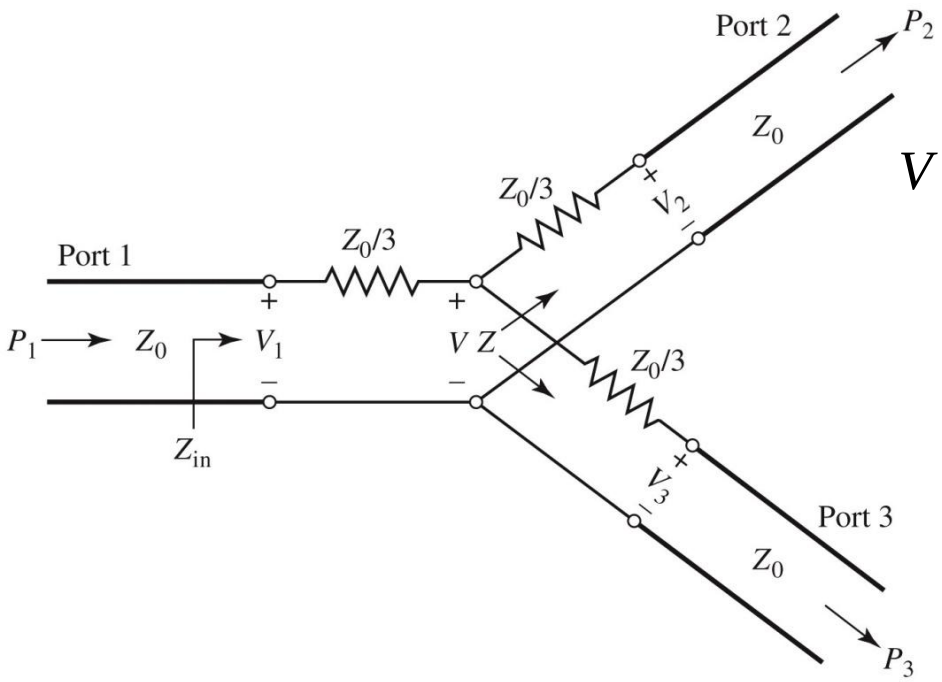

Figure 7.7
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V_1 e tensiunea la intrarea in portul 1, calculam tensiunea la nivelul jonctiunii V

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

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

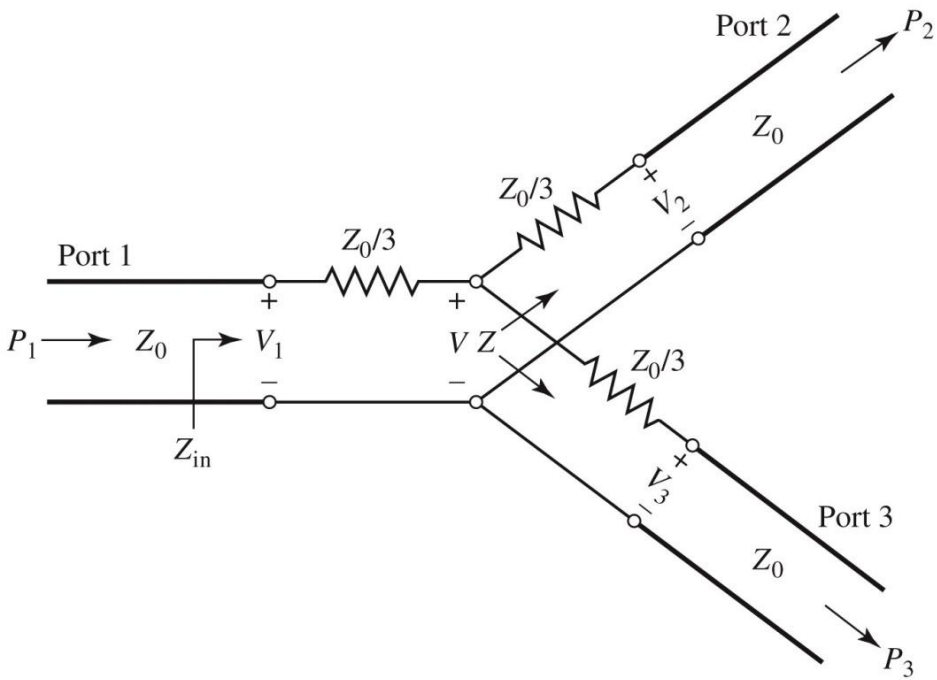

Figure 7.7
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Matricea S $$[S] = \frac{1}{2} \cdot \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

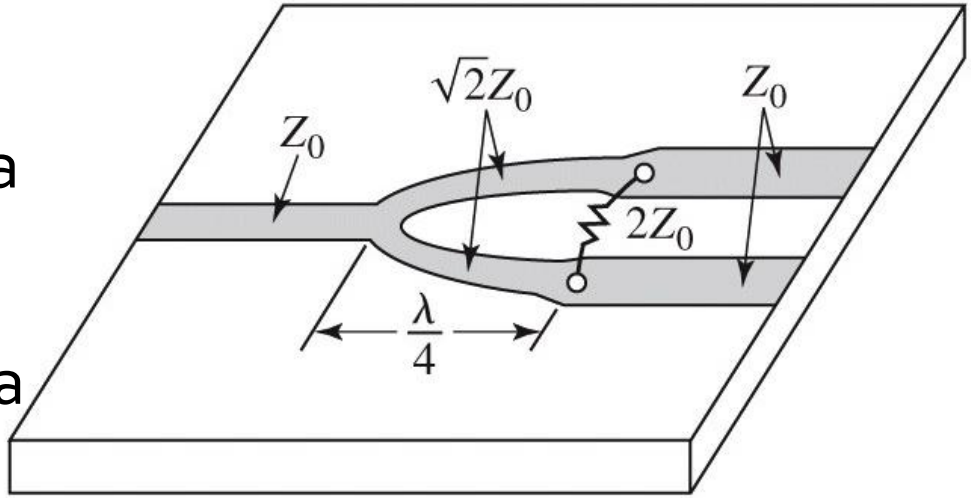
Puteri: $$P_{in} = \frac{1}{2} \cdot \frac{V_1^2}{Z_0}$$

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

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

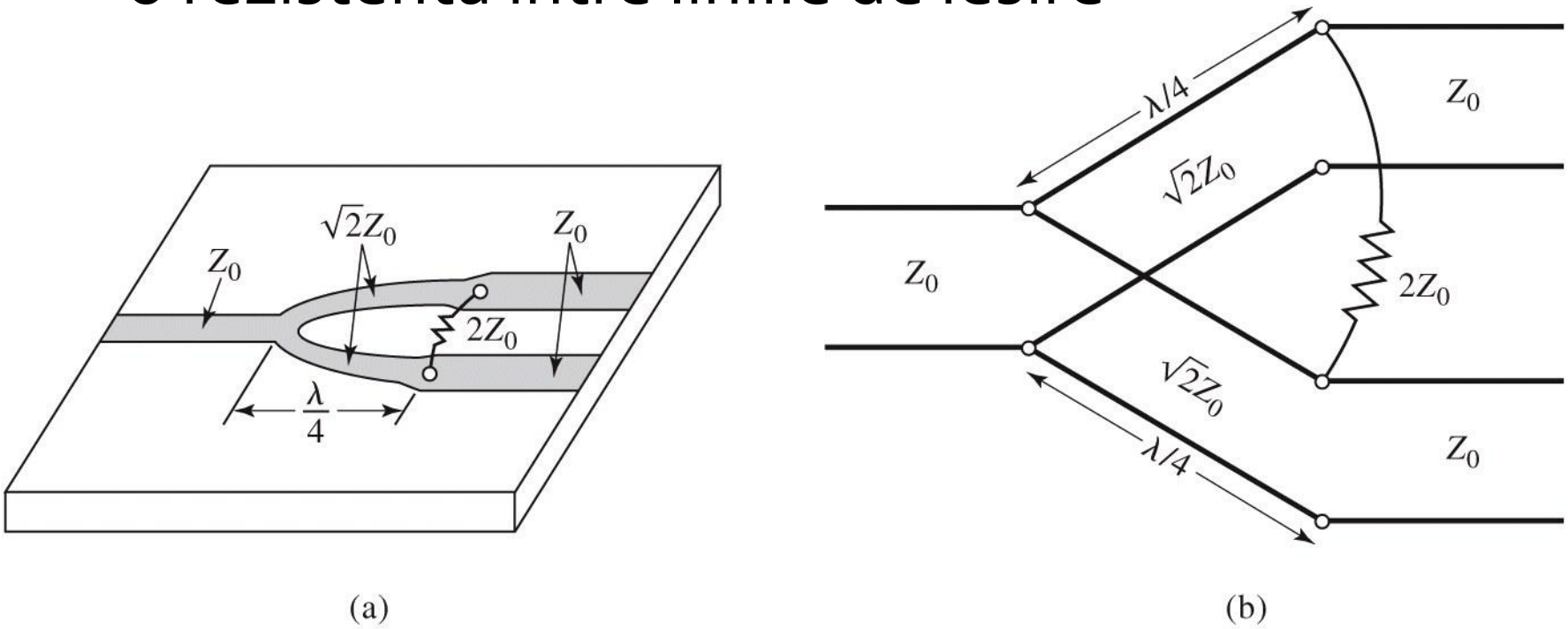


Figure 7.8

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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!!

Divizorul de putere Wilkinson

- schema normalizata si “simetrizata”

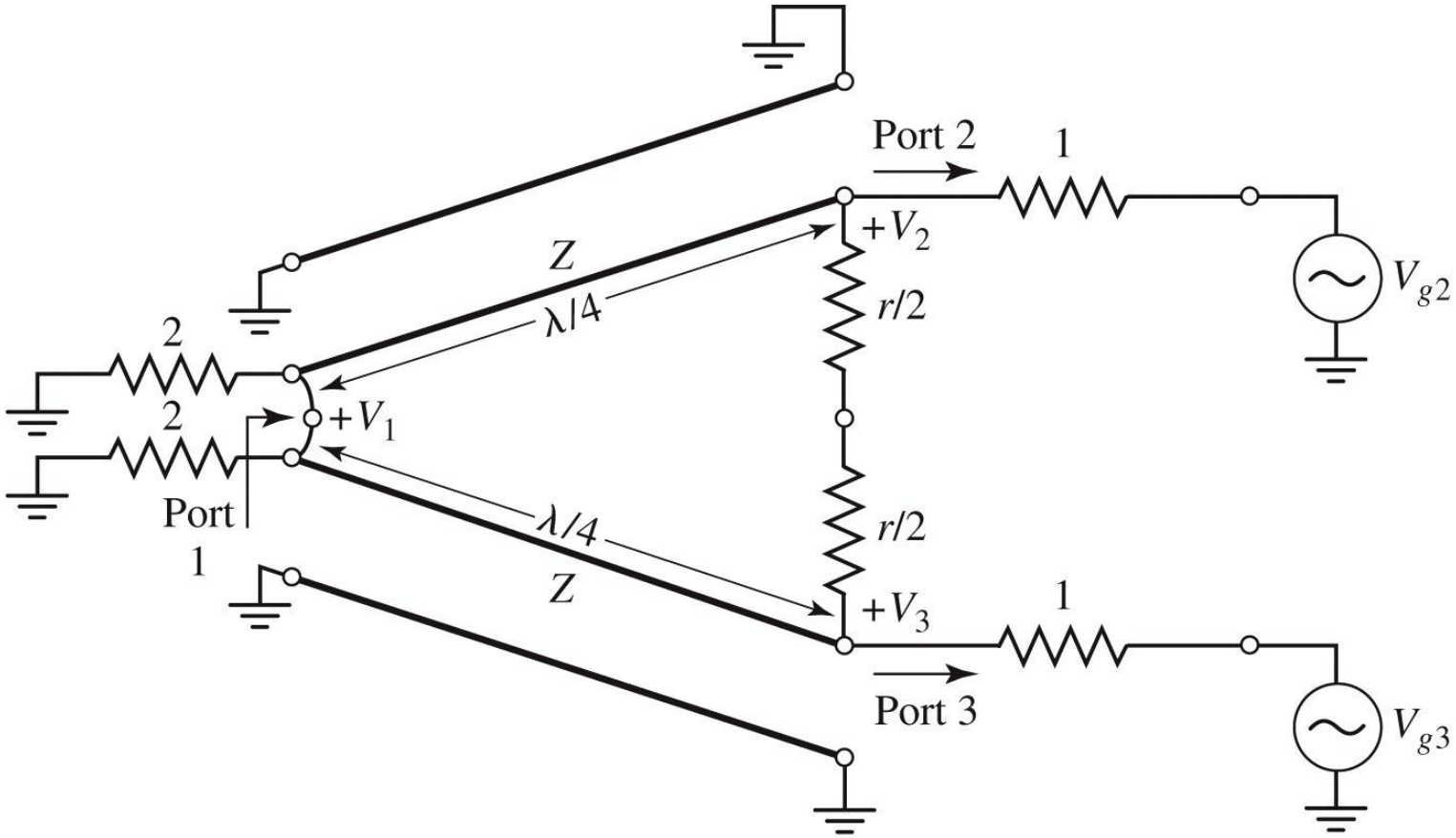

Figure 7.9
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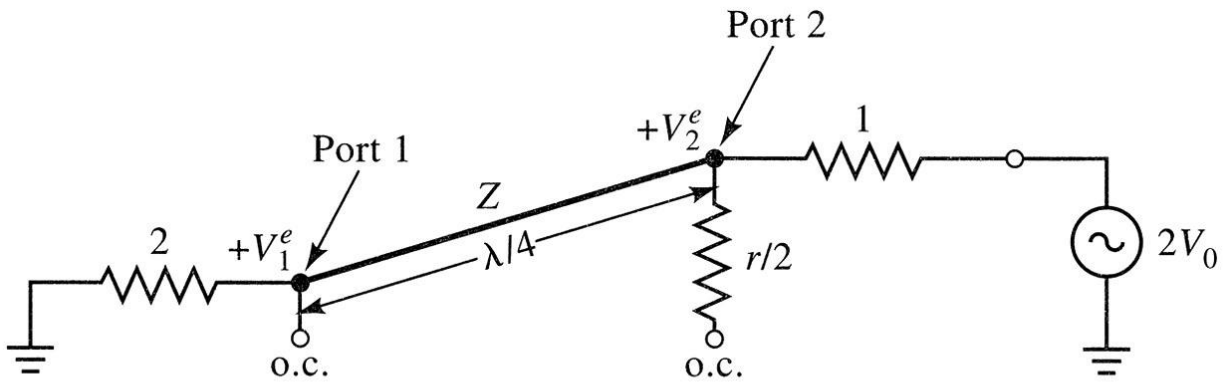
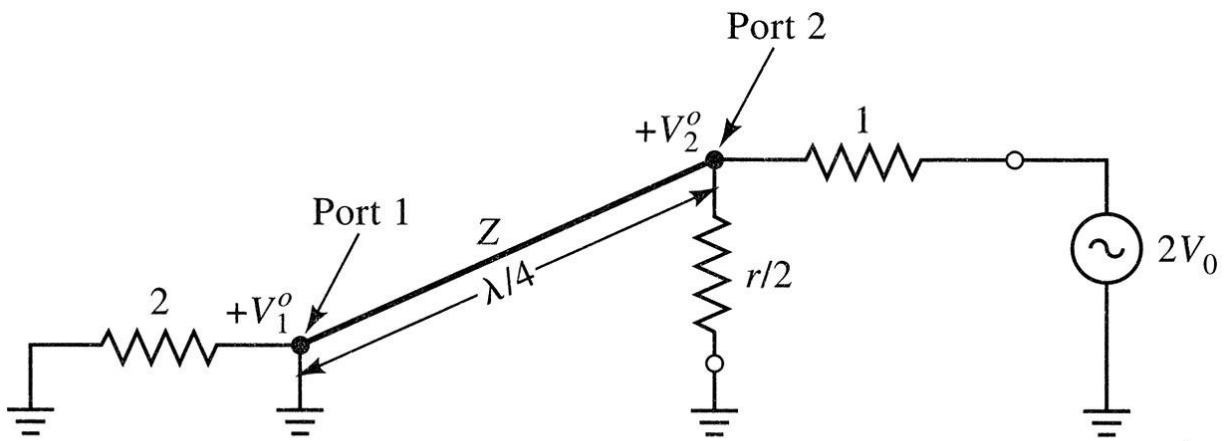
Divizorul de putere Wilkinson

- analiza pe mod par si impar



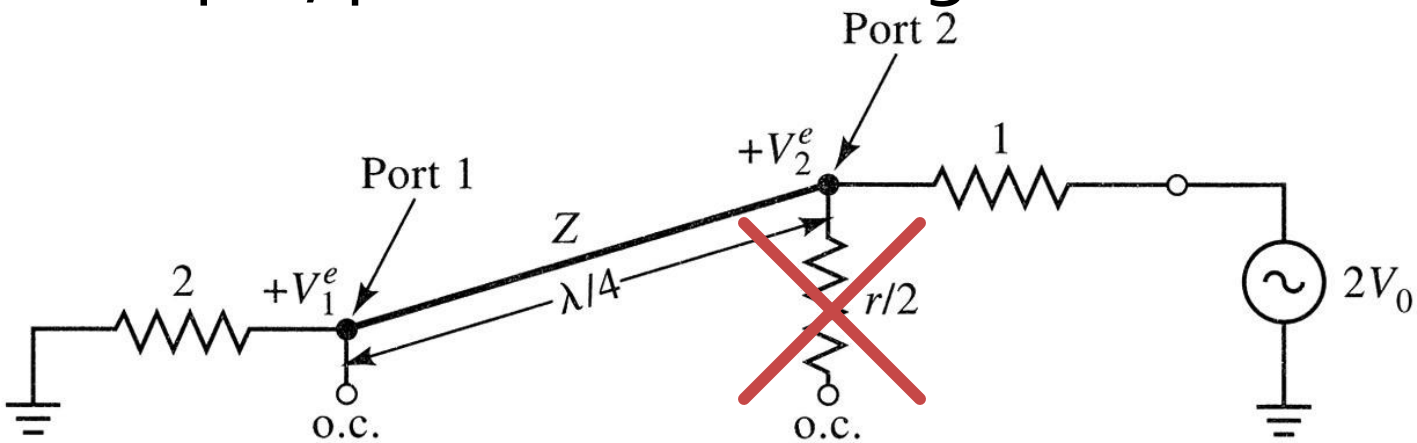
(a)



(b)

Divizorul de putere Wilkinson

- mod par, plan de simetrie gol



privind din portul 2, transformator λ/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=-λ/4 la portul 2

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

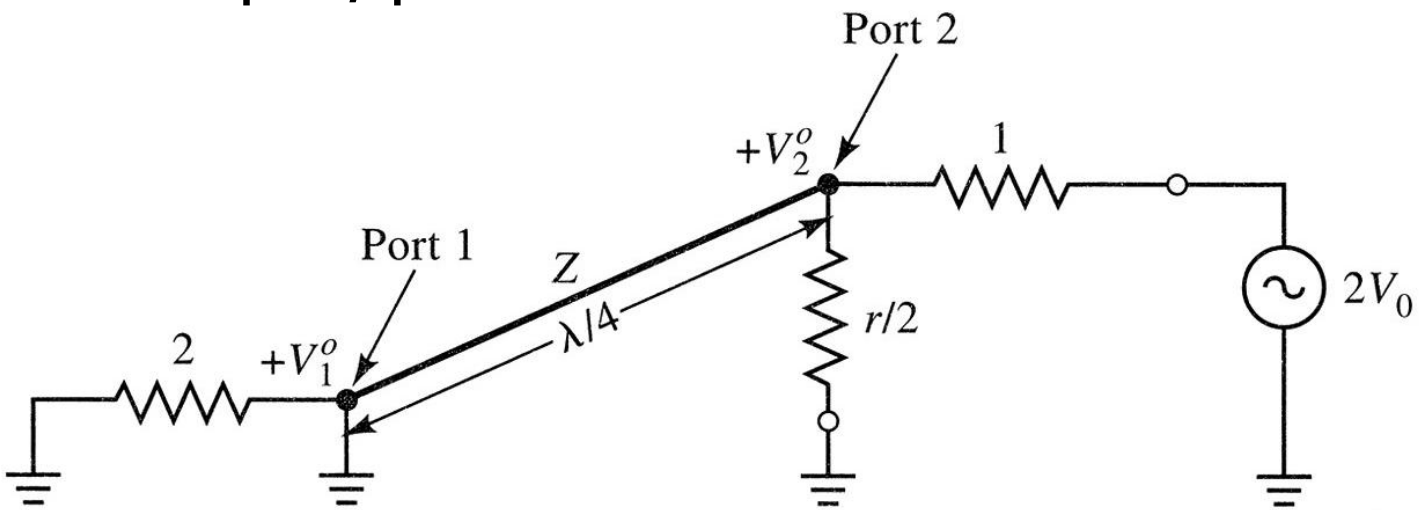
$$Z_{in2}^e = 1$$

Γ: 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



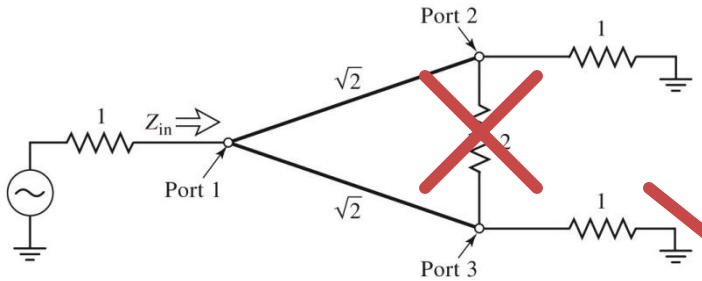
linia in λ/4 este scurtcircuitata la capat
impedanta vazuta dinspre portul 2 este ∞ $Z_{in2}^o = r/2$ daca $r = 2$ portul 2 este adaptat

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

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

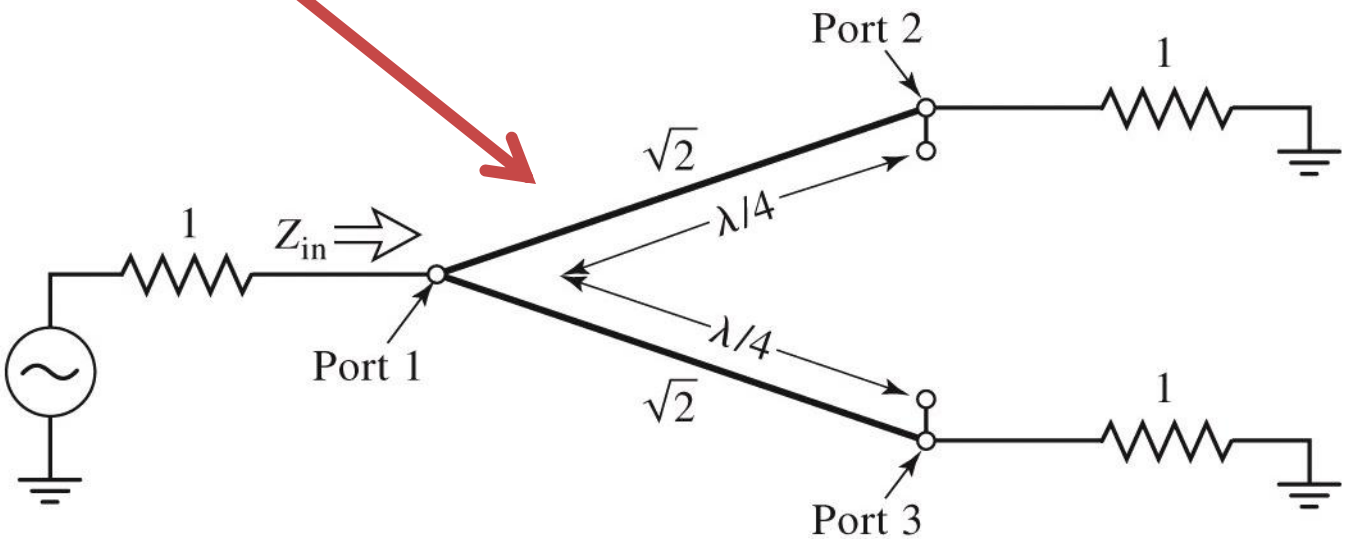
Divizorul de putere Wilkinson

- impedanta de intrare in portul 1



doua transformatoare λ/4 in paralel

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



Divizorul de putere Wilkinson

- parametrii S

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

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

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

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 $\lambda_o/4$) avem izolare intre cele doua linii de iesire

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

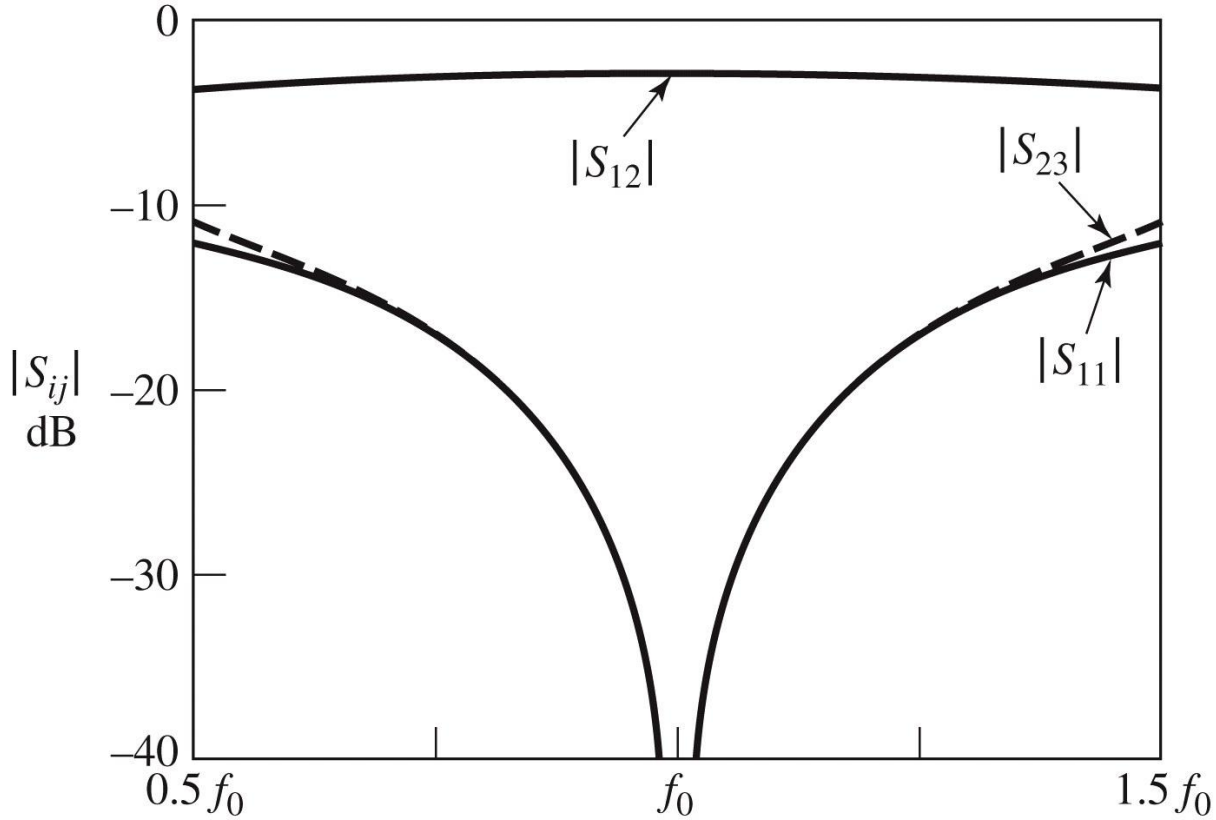


Figure 7.12
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Divizorul de putere Wilkinson

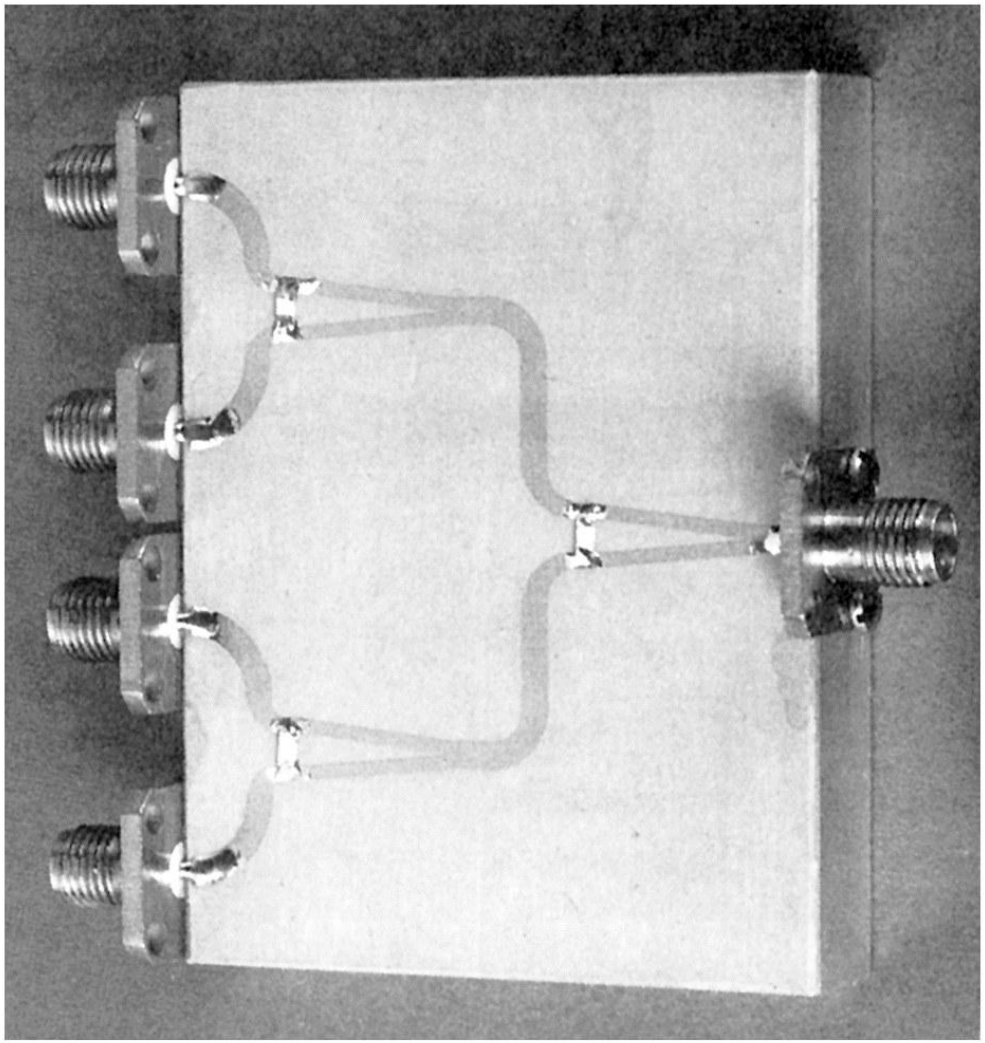
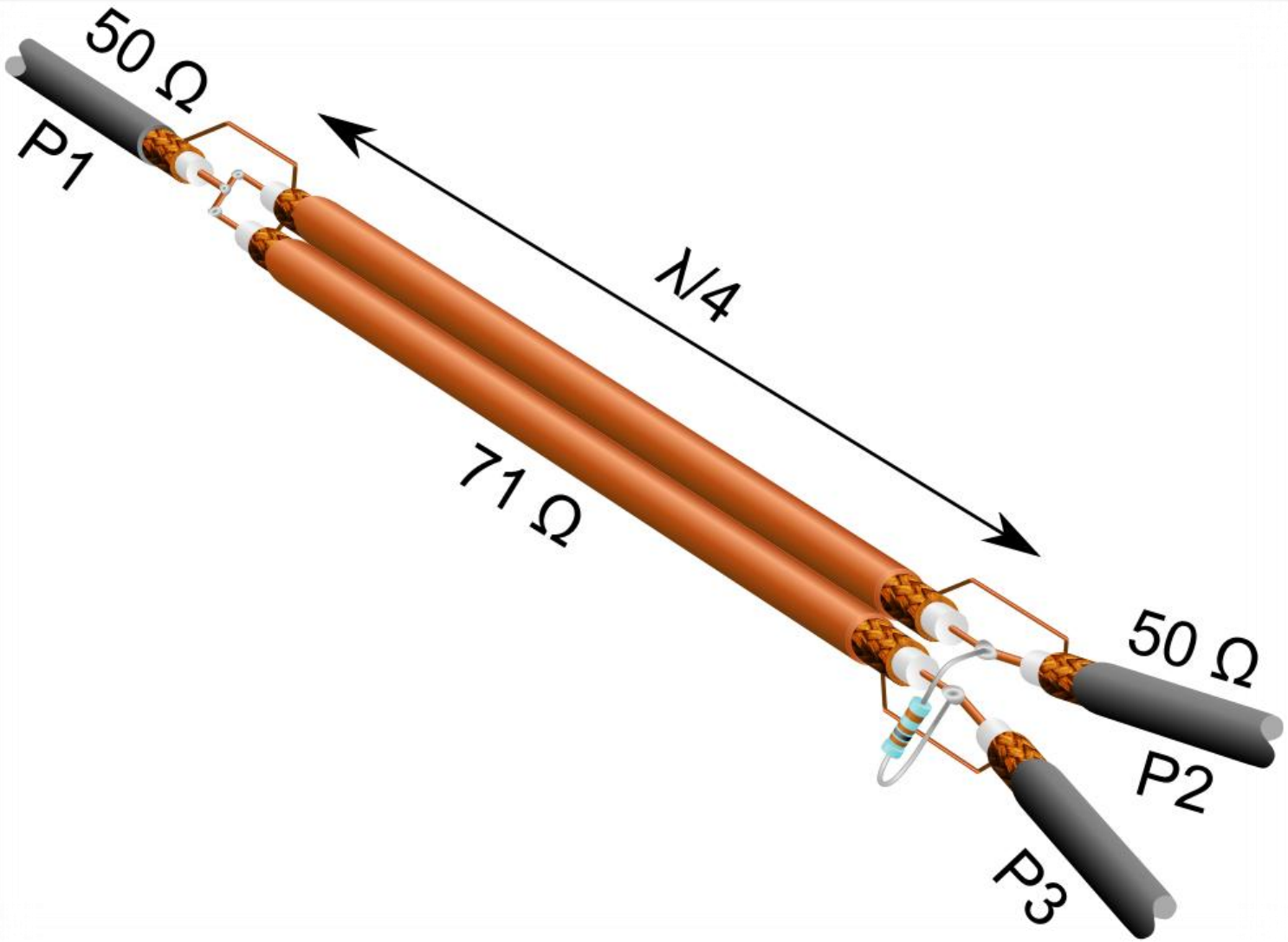


Figure 7.15
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

- 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 $\theta = \phi = \pi/2$

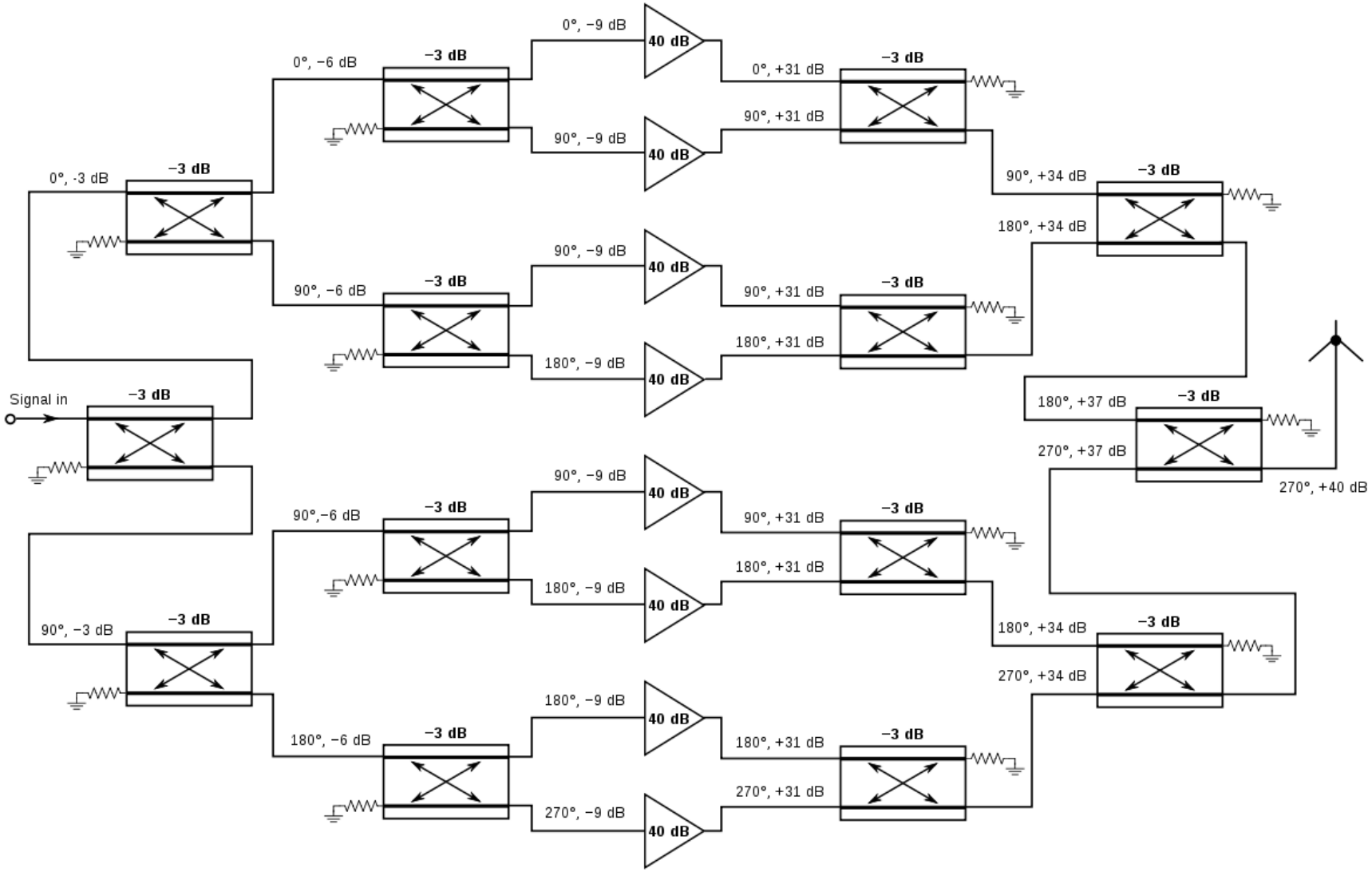
$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

  - 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

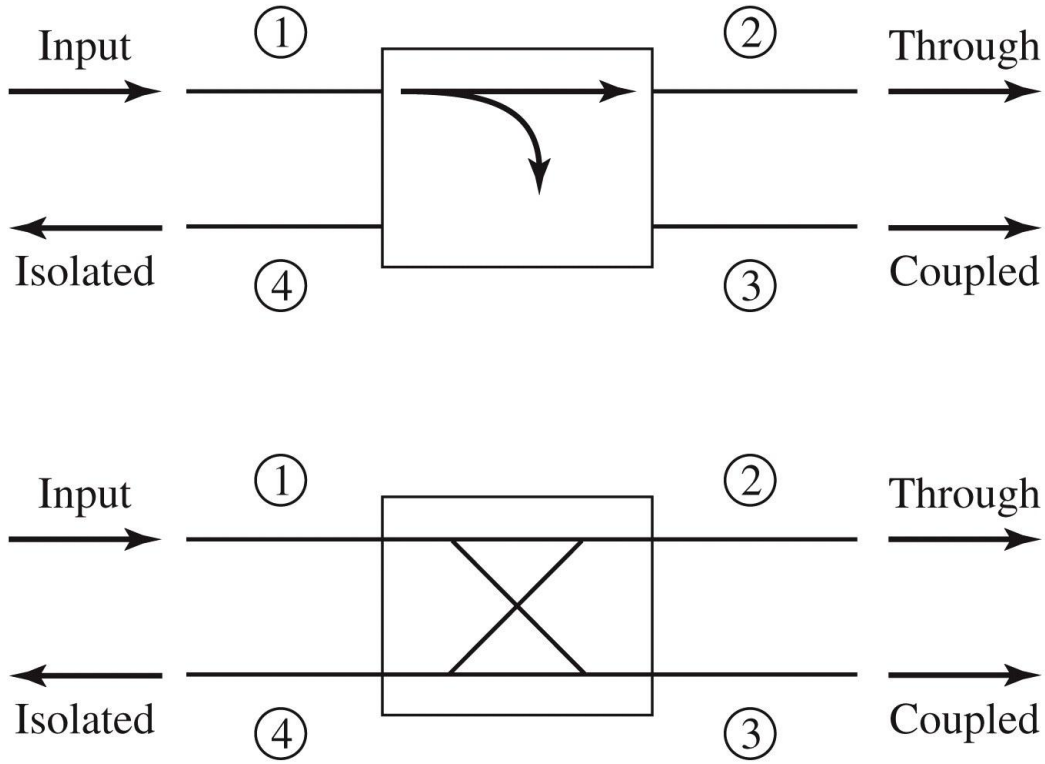


Figure 7.4
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$$\left|S_{12}\right|^2 = \alpha^2 = 1 - \beta^2$$

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

Cuplaj

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

Directivitate

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

Izolare

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

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

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°)

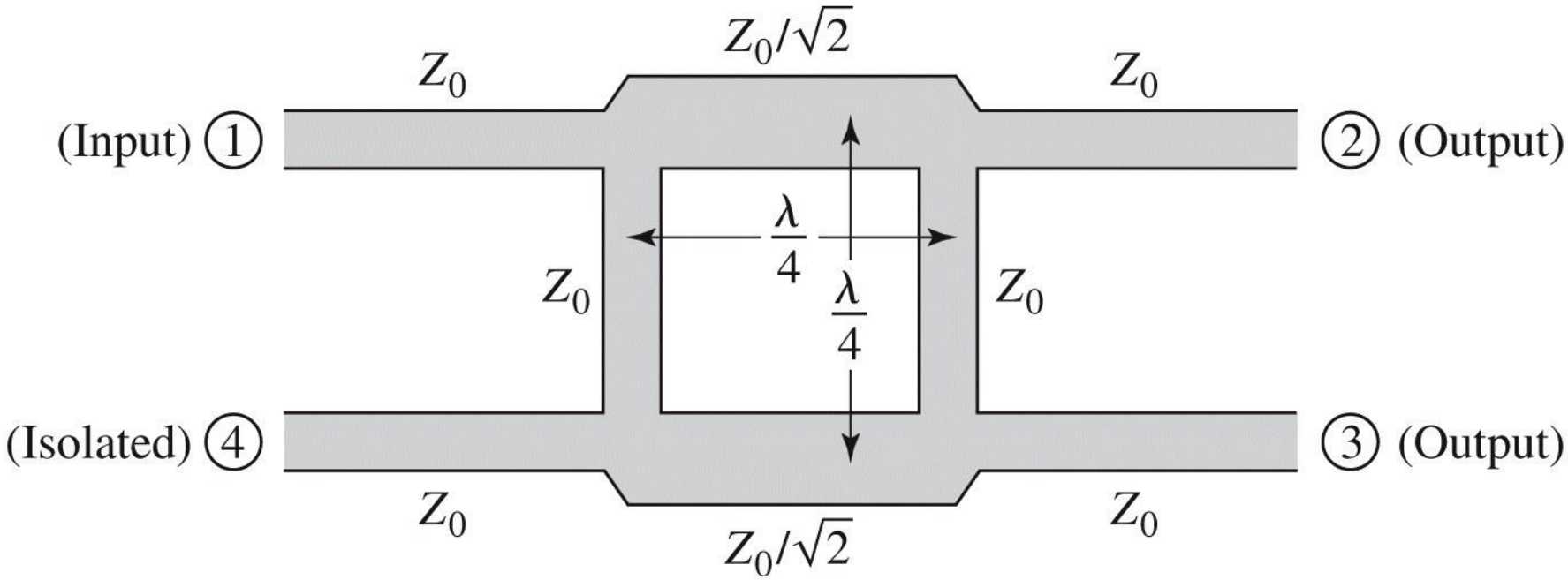

Figure 7.21
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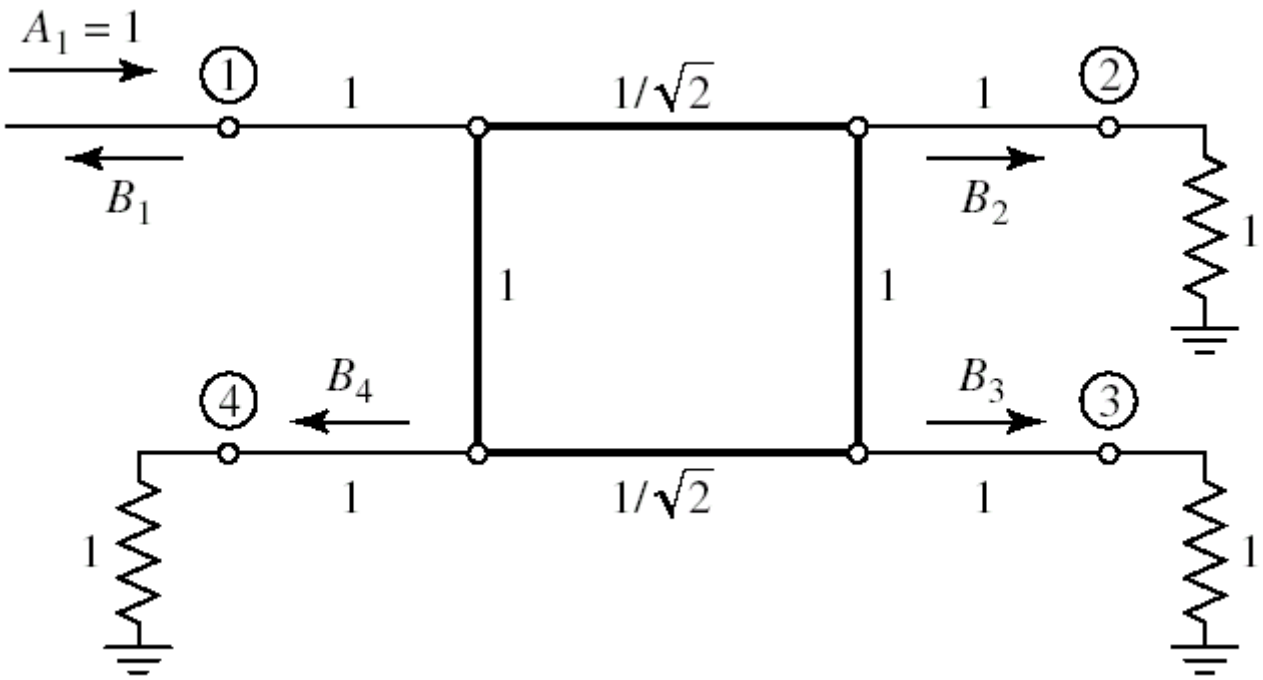
$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

Analiza pe modul par-impar



Analiza pe modul par-impar

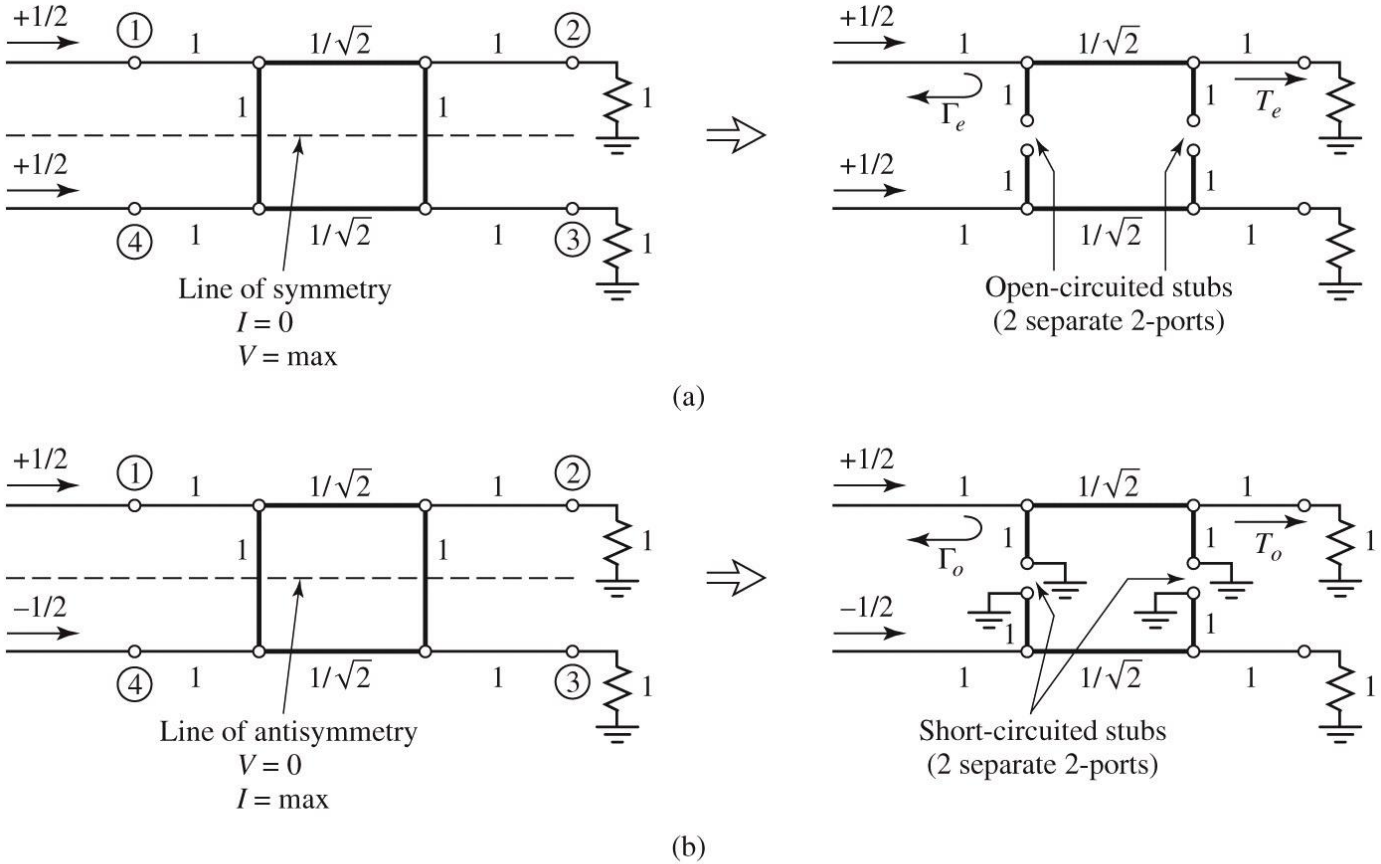


Figure 7.23

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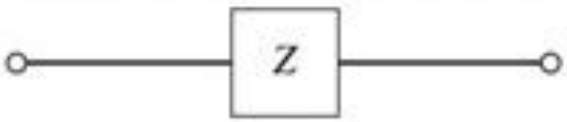
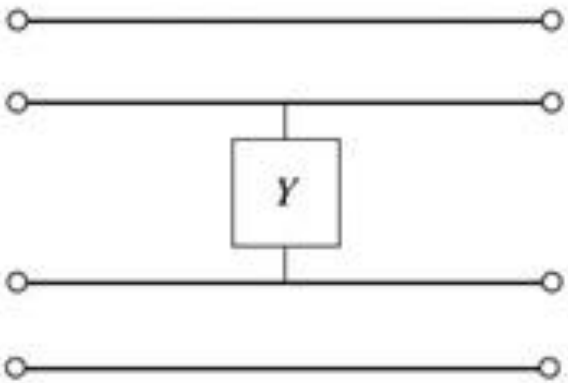
$$b_1 = \frac{1}{2}\Gamma_e + \frac{1}{2}\Gamma_o \qquad b_2 = \frac{1}{2}T_e + \frac{1}{2}T_o \qquad b_3 = \frac{1}{2}T_e - \frac{1}{2}T_o \qquad b_4 = \frac{1}{2}\Gamma_e - \frac{1}{2}\Gamma_o$$

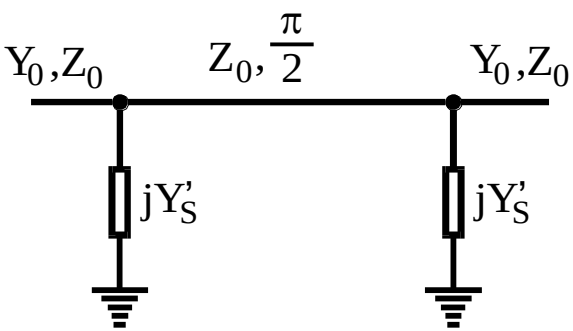
Biblioteci de matrici ABCD

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

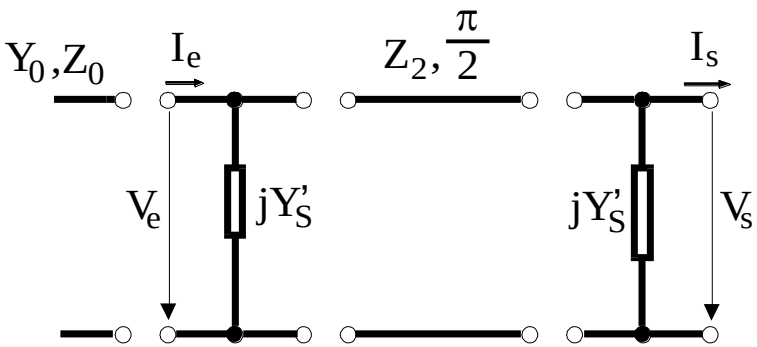
Circuit	*ABCD* Parameters	
	$A = 1$ $C = 0$	$B = Z$ $D = 1$
	$A = 1$ $C = Y$	$B = 0$ $D = 1$
	$A = \cos \beta\ell$ $C = jY_0 \sin \beta\ell$	$B = jZ_0 \sin \beta\ell$ $D = \cos \beta\ell$

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)

$$\begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jY'_S & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 & jZ_2 \\ jY_2 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ jY'_S & 1 \end{bmatrix} \cdot \begin{bmatrix} V_S \\ I_S \end{bmatrix}$$

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

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

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

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

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

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

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

Legatura dintre parametrii S si parametrii ABCD

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

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

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

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

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

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

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

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

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

Adaptarea cuplorului si coeficientul de cuplaj

$$\Gamma_e = \frac{j\cdot\left(z_2 - y_2 + y_1^2 z_2\right)}{-2y_1z_2 + j\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$\Gamma_o = \frac{j\cdot\left(z_2 - y_2 + y_1^2 z_2\right)}{2y_1z_2 + j\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$T_e = \frac{2}{-2y_1z_2 + j\cdot\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$T_o = \frac{2}{2y_1z_2 + j\cdot\left(z_2 + y_2 - y_1^2 z_2\right)}$$

$$b_1 = \frac{\Gamma_e + \Gamma_o}{2} = \frac{z_2^2 - \left(y_2 - y_1^2 z_2\right)^2}{(2y_1z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_2 = \frac{T_e + T_o}{2} = \frac{-2j\left(z_2 + y_2 - y_1^2 z_2\right)}{(2y_1z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_3 = \frac{T_e - T_o}{2} = \frac{-4y_1z_2}{(2y_1z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

$$b_4 = \frac{\Gamma_e - \Gamma_o}{2} = \frac{-2jy_1z_2\left(z_2 - y_2 + y_1^2 z_2\right)}{(2y_1z_2)^2 + \left(z_2 + y_2 - y_1^2 z_2\right)^2}$$

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

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

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

$$b_1 = 0 \;\; b_4 = 0 \;\; b_3 = -y_1z_2 \;\; b_2 = -jz_2$$

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

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

$$b_3 = -C$$

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

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

Cuplorul in cuadratura

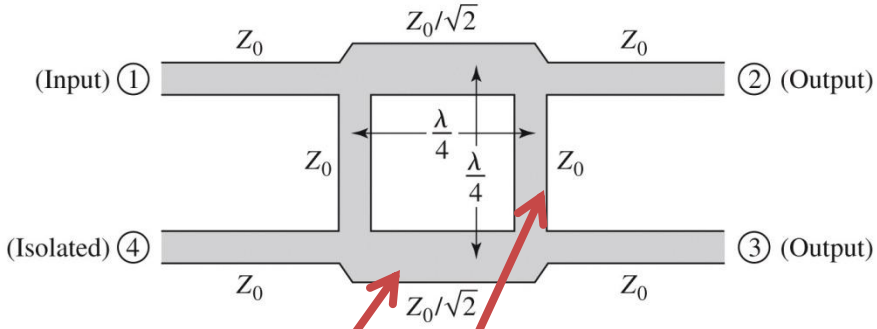


Figure 7.21
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$$y_2^2 = 1 + y_1^2$$

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

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

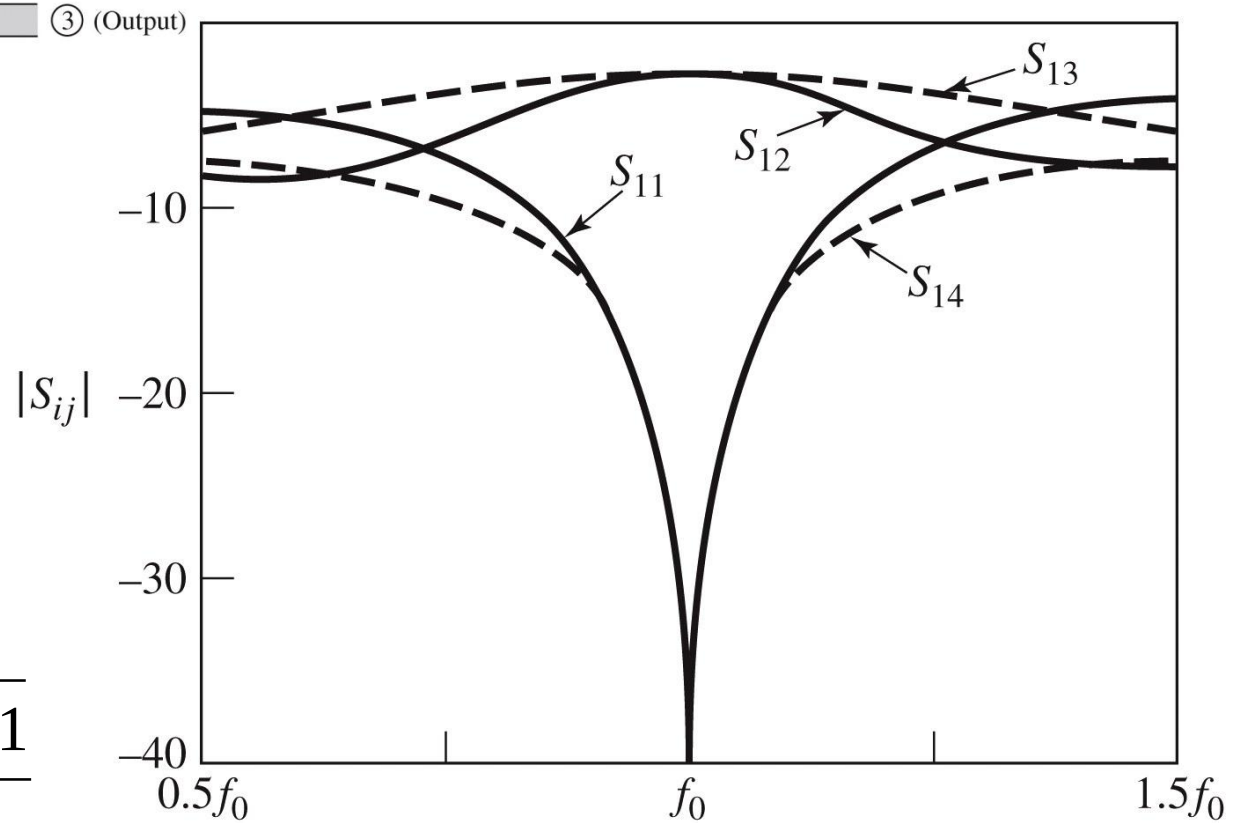

Figure 7.25
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Exemplu

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

$0.5 f_0$ şi $1.5 f_0$, unde f_0

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

Solutie

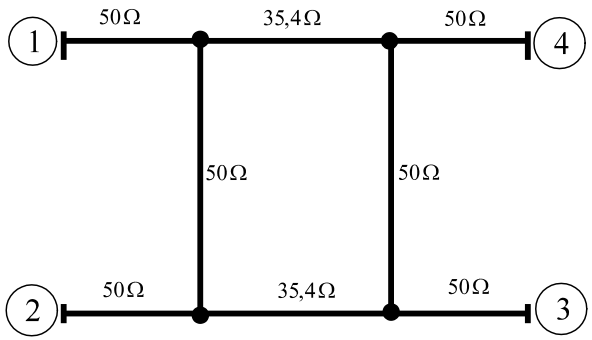
Un cuplor în scară cu C = 3dB, are $C = 1/\sqrt{2}$. Atunci

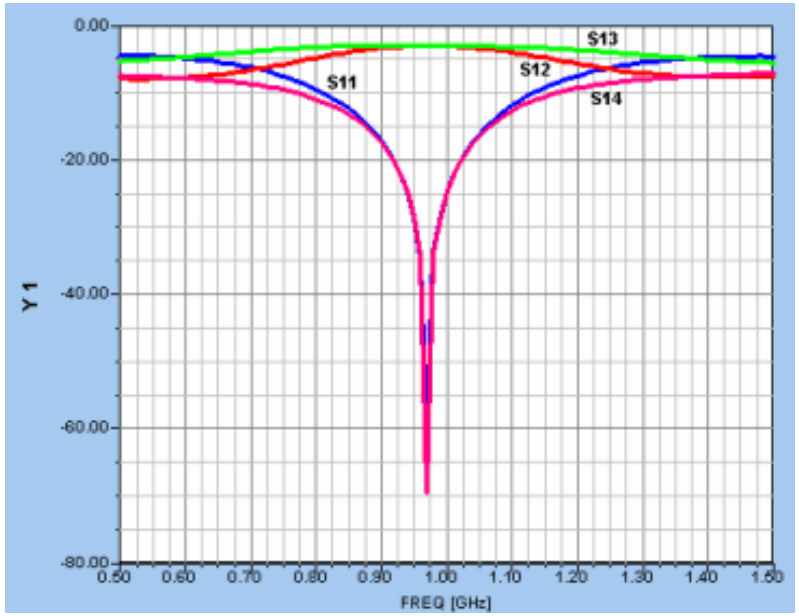
$$y_2 = \sqrt{2} \quad \text{şi} \quad y_1 = 1$$

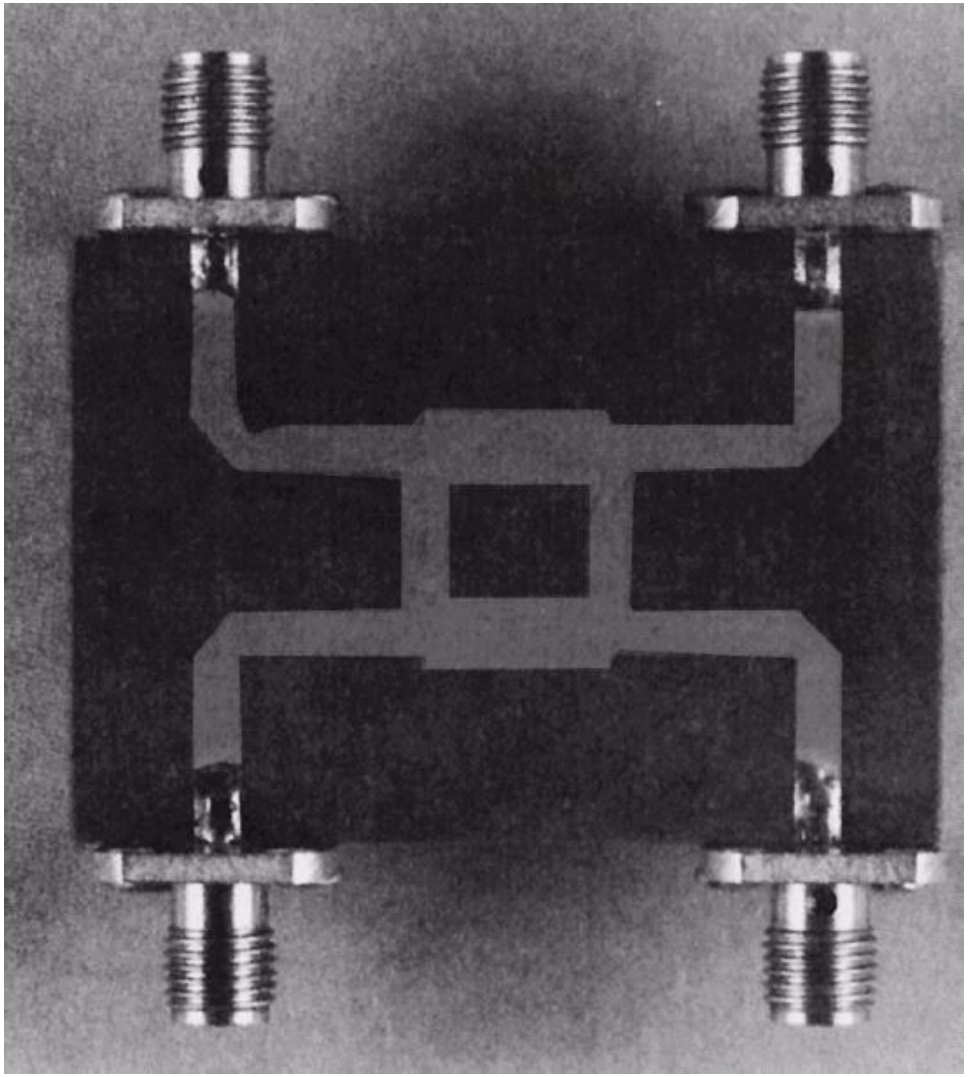
Astfel matricea S din relaţia (&.47) devine cea din relaţia (&.38). În plus, pentru $Z_0 = 50\Omega$

, impedanţele caracteristice ale liniilor cuplorului vor fi:

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







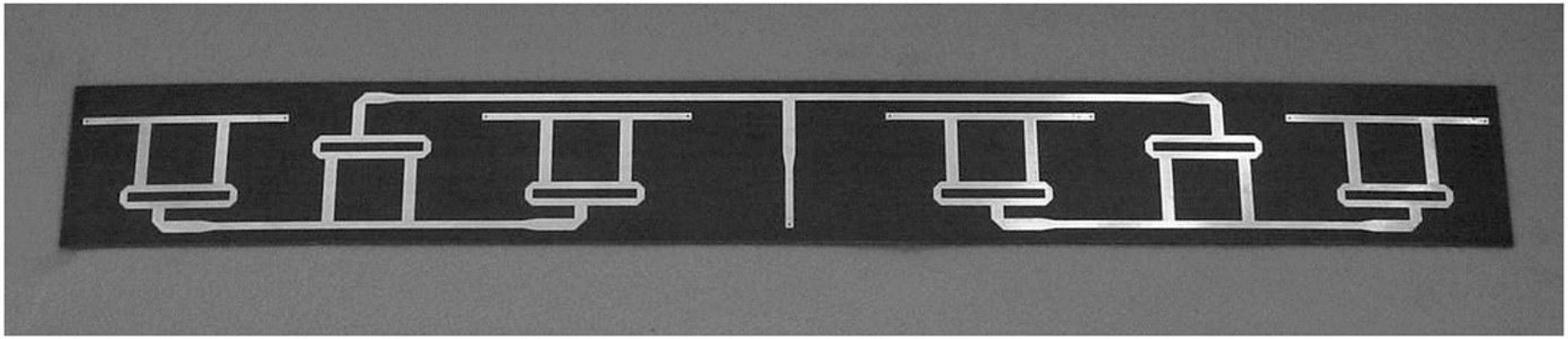
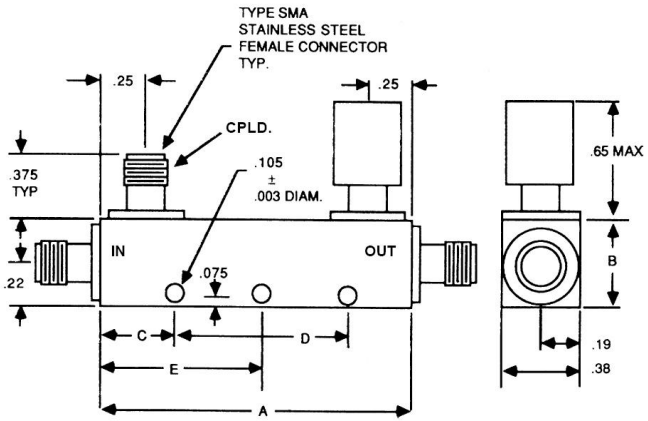


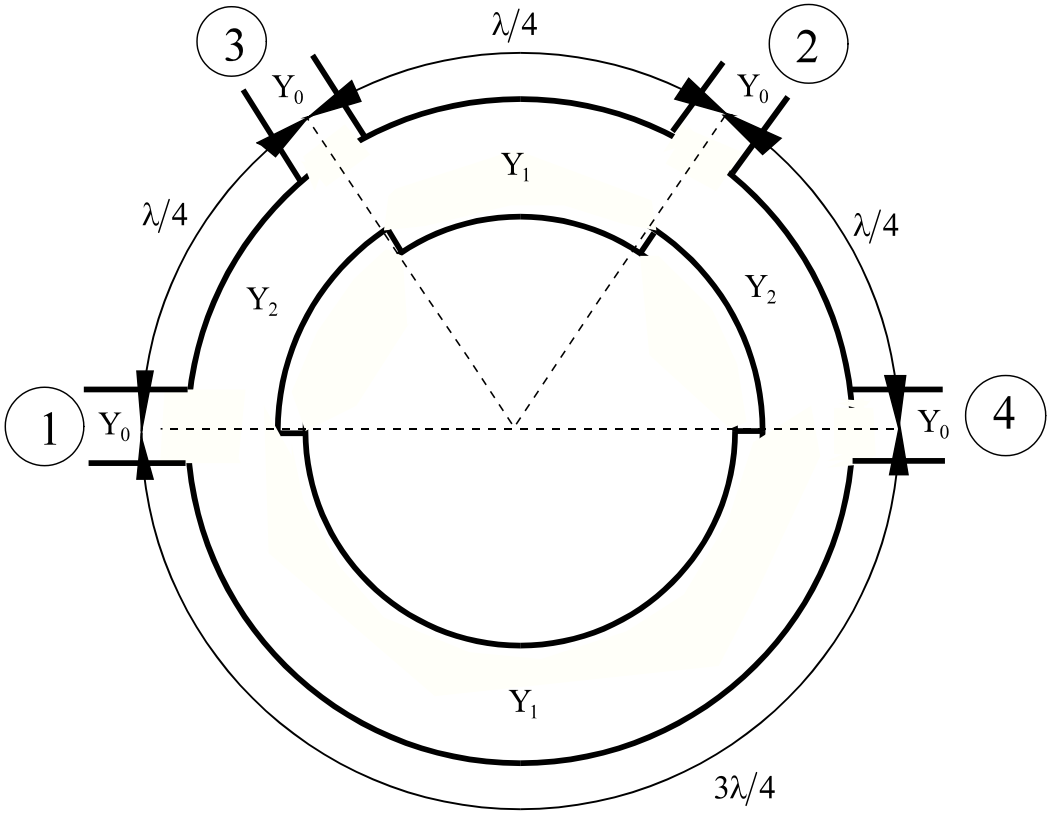
Figure 7.24
Courtesy of ProSensing, Inc., Amherst, Mass.

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

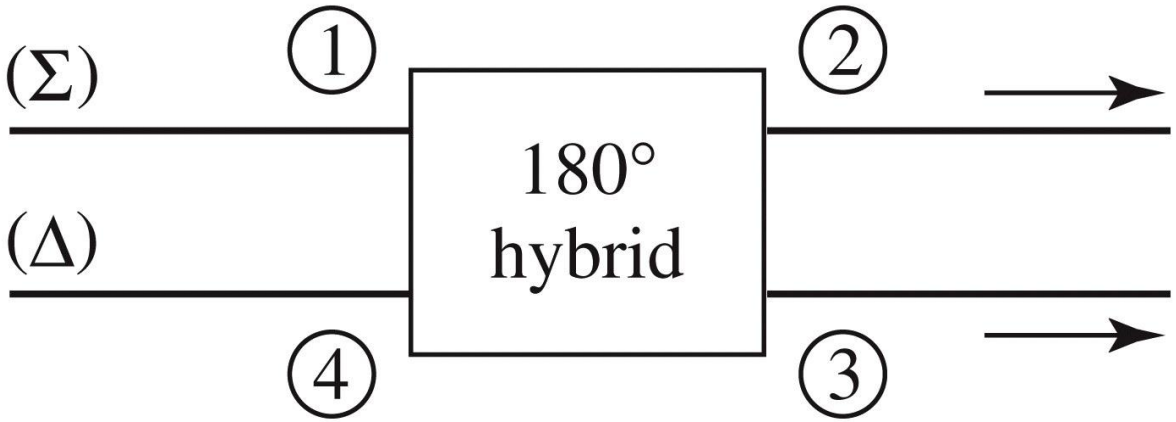


Figure 7.41
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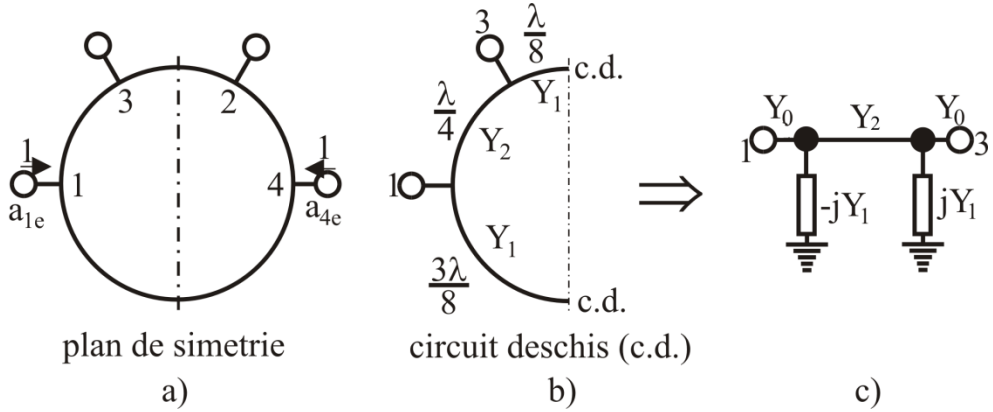
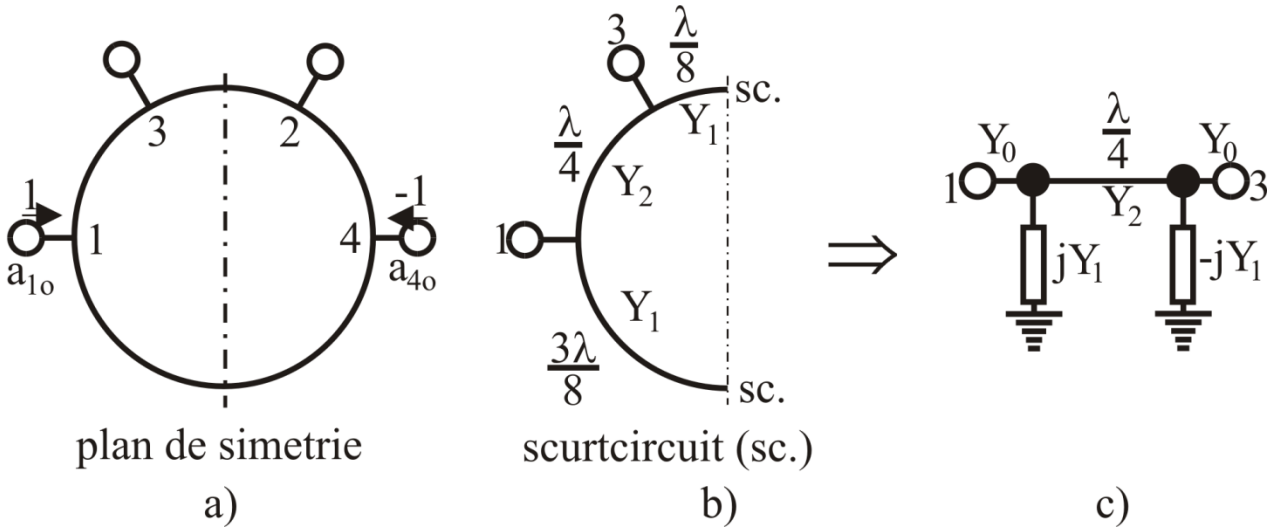
- cuplorul de 3dB (hibrid) poate fi folosit in mai multe moduri
  - intrare pe port 1, iesiri egale pe 2 si 3, in faza
  - intrare pe port 4, iesiri egale pe 2 si 3, in opozitie de faza
  - intrari pe porturi 2 si 3, suma semnalelor pe portul 1, diferenta pe portul 4

Analiza cuplorului in inel



Modul par

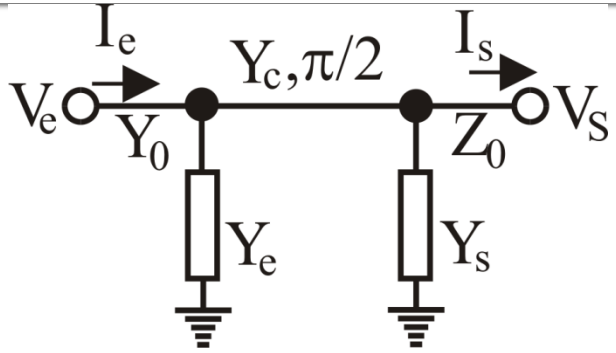


Modul impar

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:

$$y_e = jy_1$$

$$y_s = -jy_1$$

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

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

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

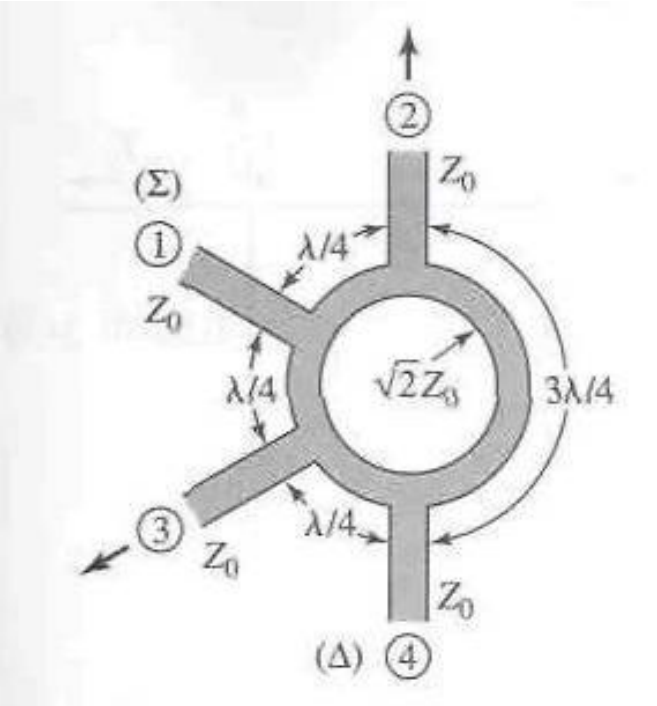
$$[S] = \begin{bmatrix} 0 & 0 & -jy_2 & jy_1 \\ 0 & 0 & -jy_1 & -jy_2 \\ -jy_2 & -jy_1 & 0 & 0 \\ jy_1 & -jy_2 & 0 & 0 \end{bmatrix}$$

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

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

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

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 performanţa 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.

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

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

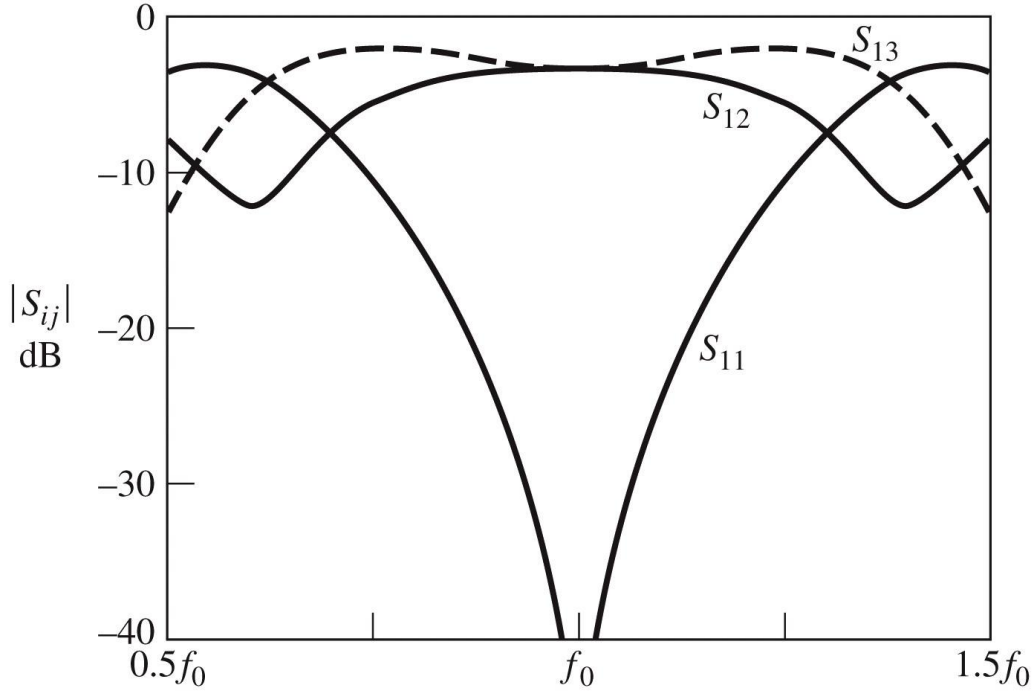


Figure 7.46
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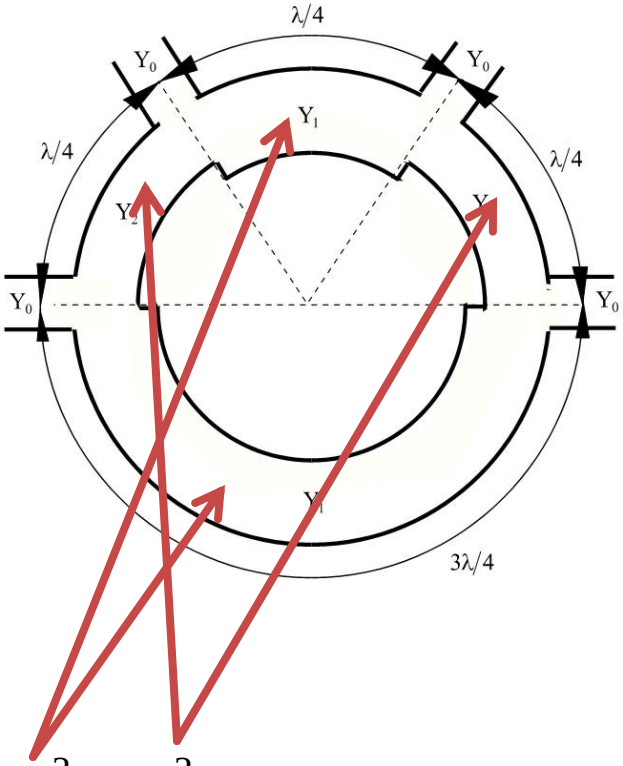
Cuplorul în inel



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

$$|\beta| = y_1$$

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

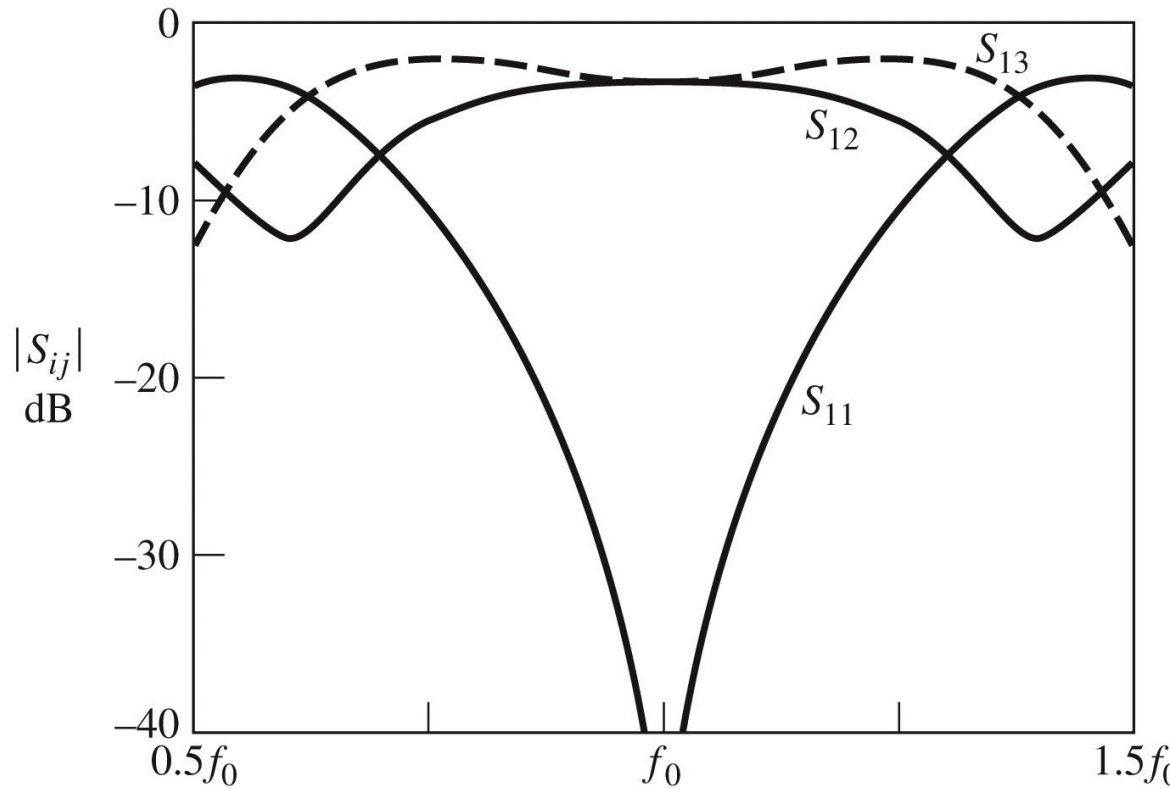


Figure 7.46
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Cuplor în inel

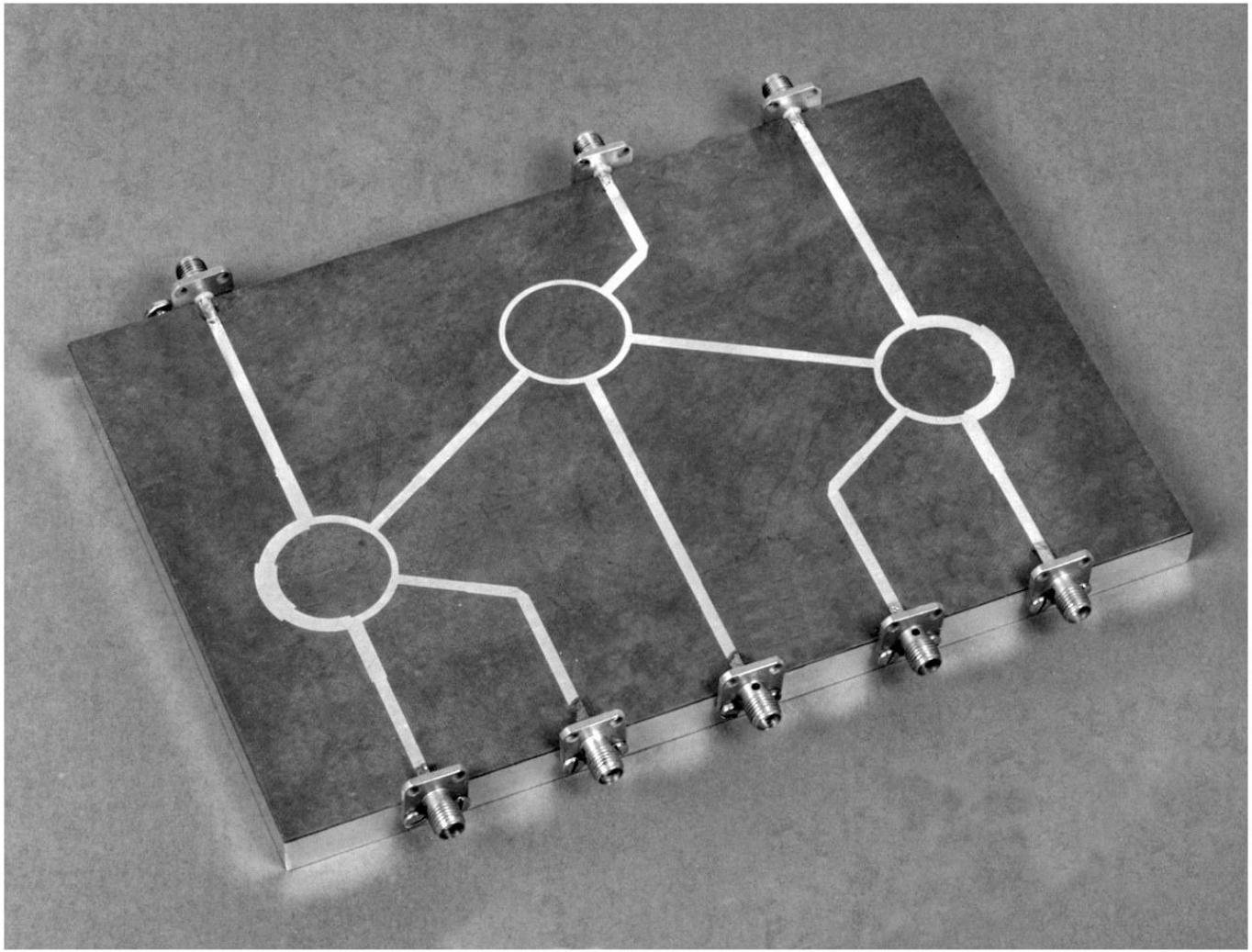
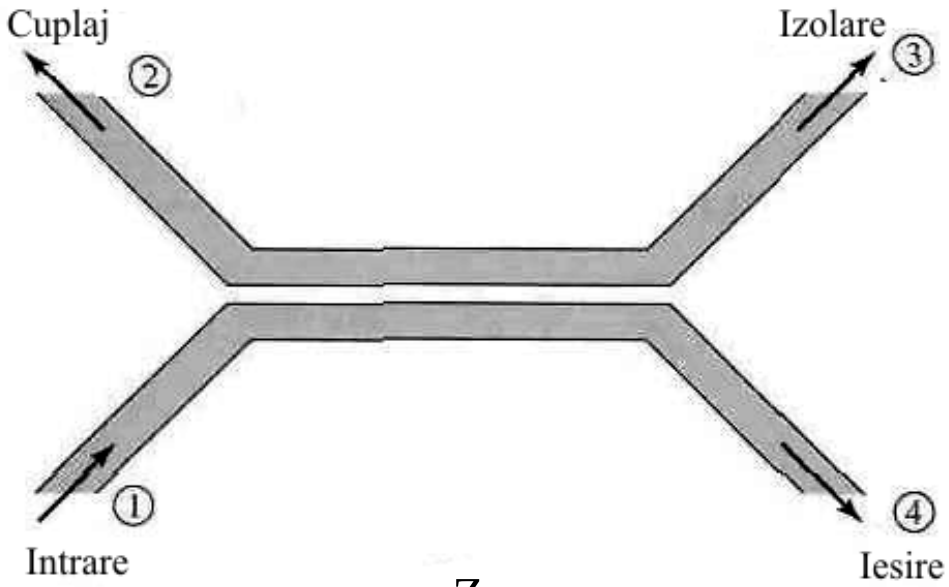
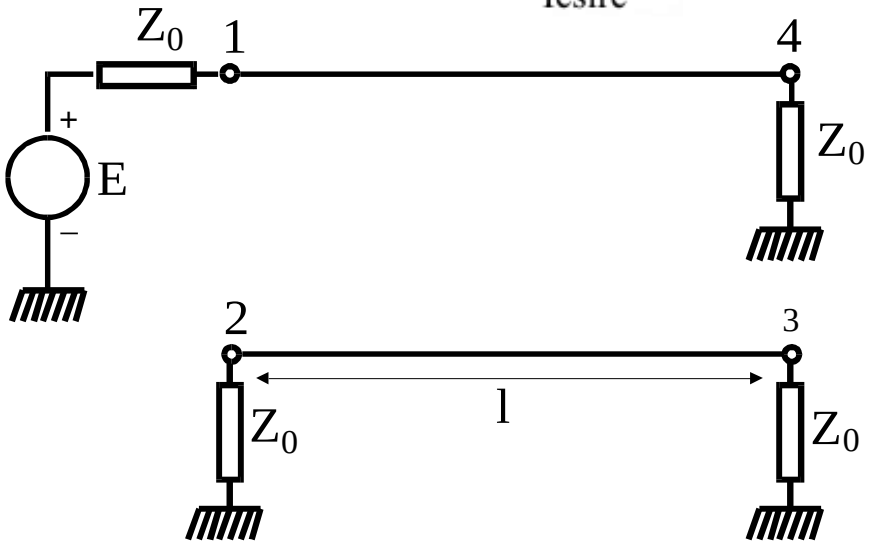


Figure 7.43
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

Cuplorul prin proximitate





Linii cuplate

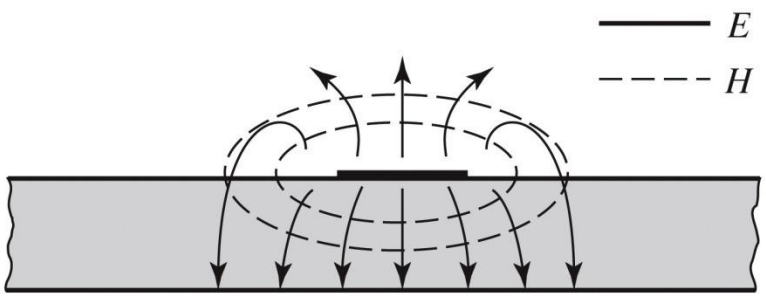


Figure 3.25b
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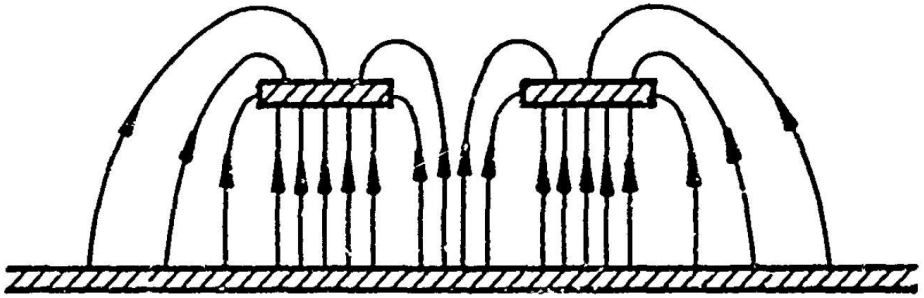
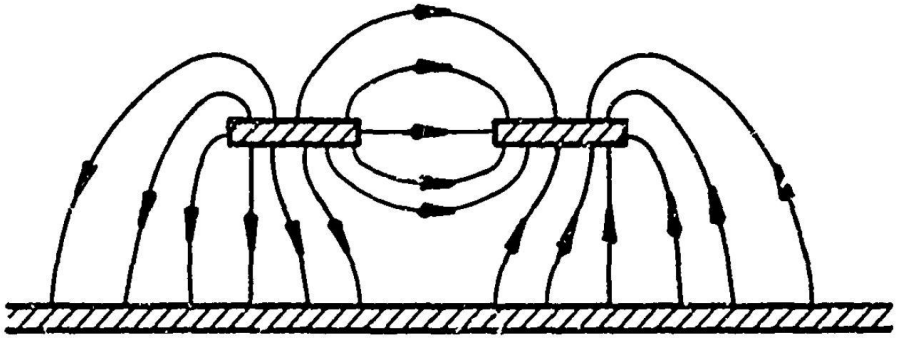


b) EVEN MODE ELECTRIC FIELD PATTERN (SCHEMATIC)



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

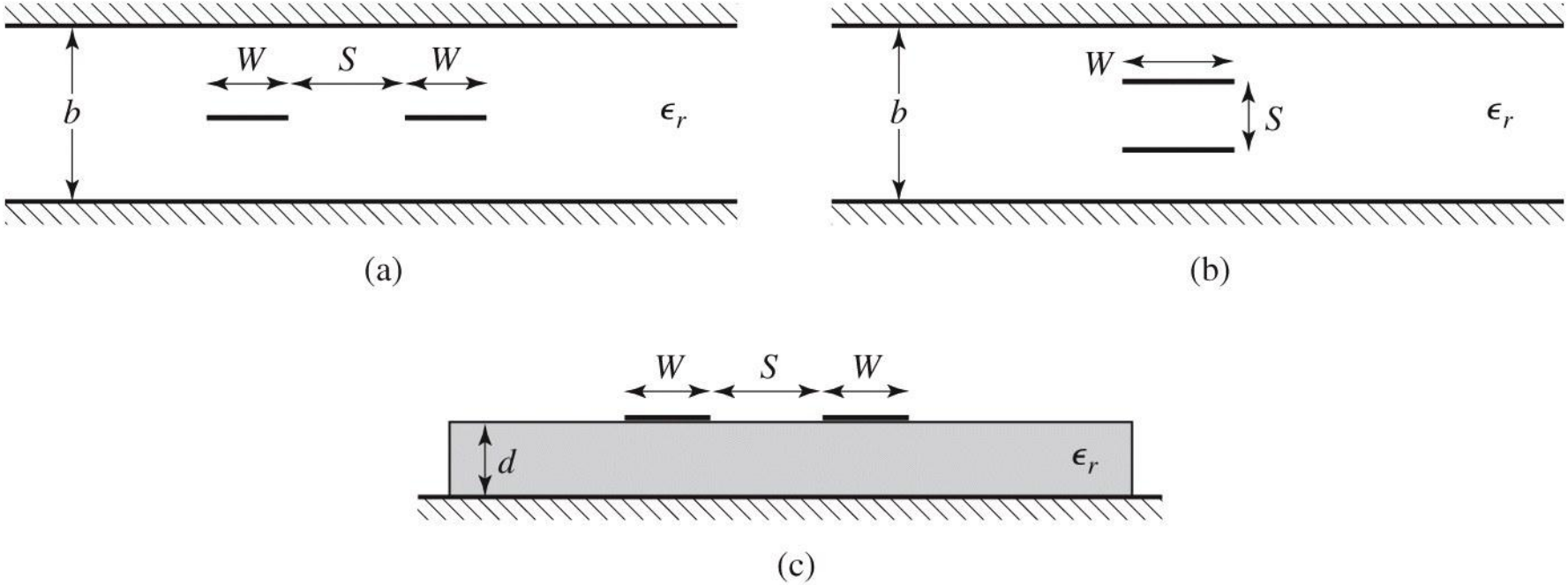


Figure 7.26

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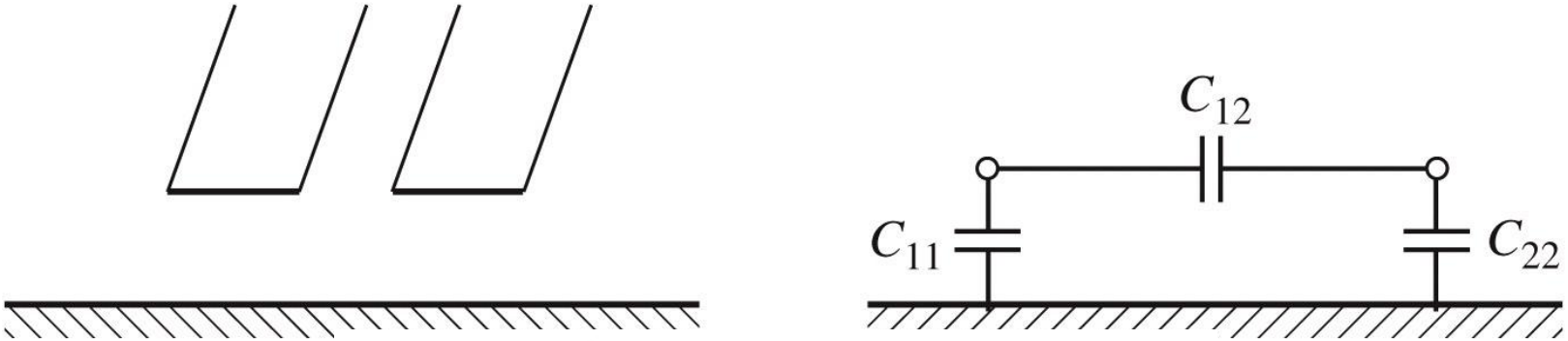

Figure 7.27
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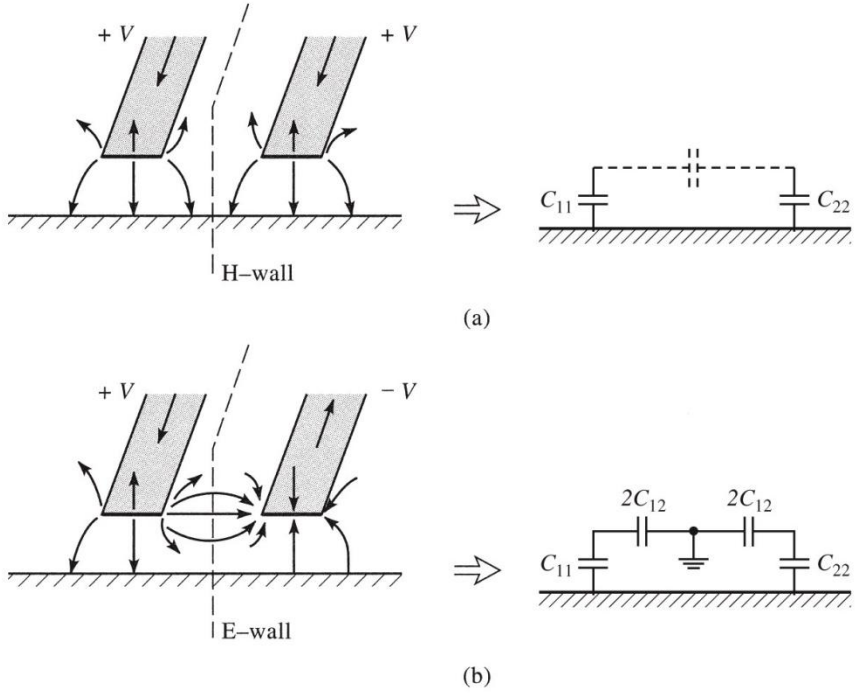

Figure 7.28
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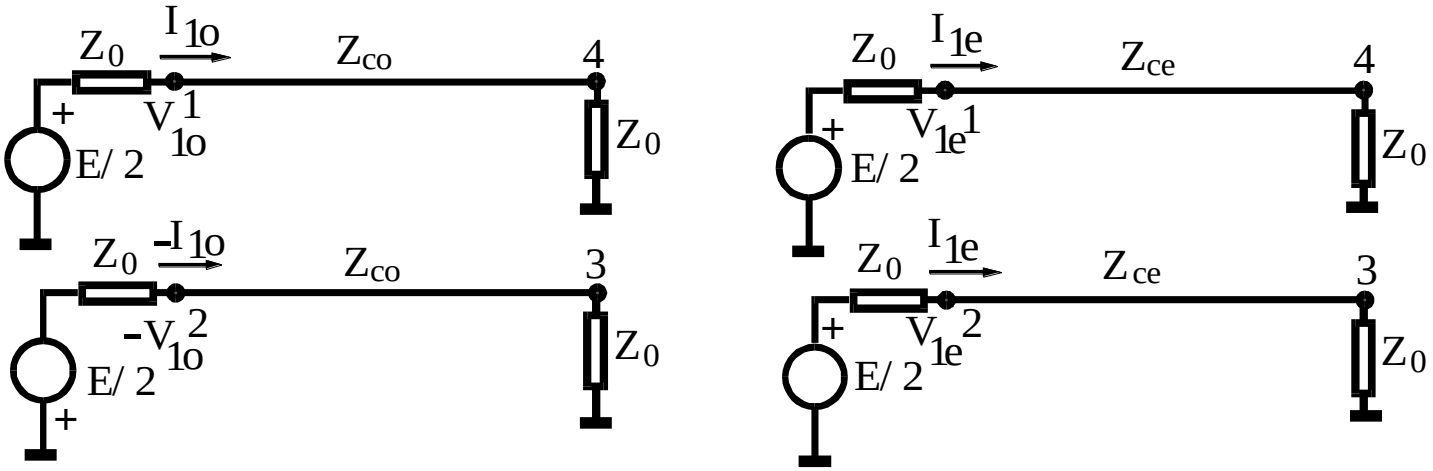
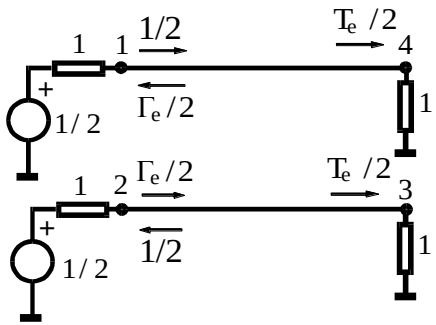
Adaptarea cuplorului prin proximitate

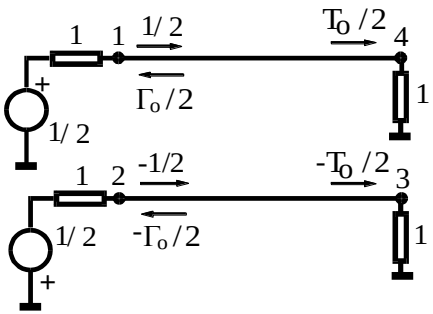


$$\begin{cases} Z_{ce} Z_{co} = Z_0^2 \\ \theta_e = \theta_o \end{cases}$$

Directivitatea şi coeficientul de cuplaj ale cuplorului prin proximitate



modul par



modul impar

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

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

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

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

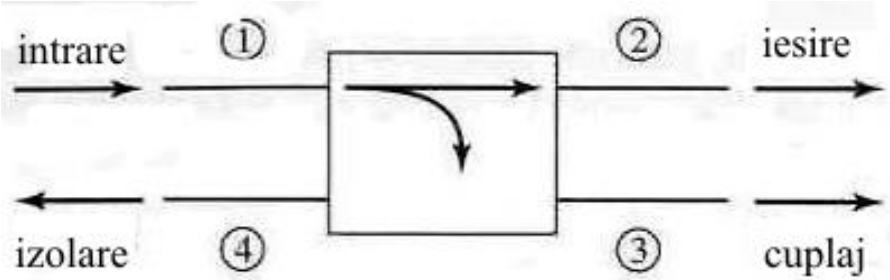
$$b_4 = \frac{1}{2}(T_e + T_o) = \frac{\sqrt{1-C^2}}{\cos(\theta)\sqrt{1-C^2} + j\sin(\theta)}$$

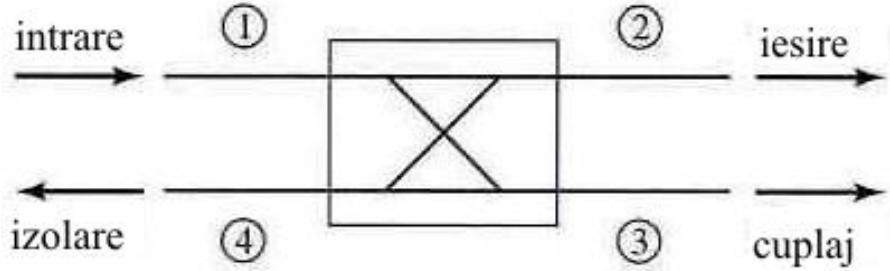
$$\boxed{C = \frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}}}$$

$$\boxed{\theta = \pi/2}$$

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

Cuplor prin proximitate

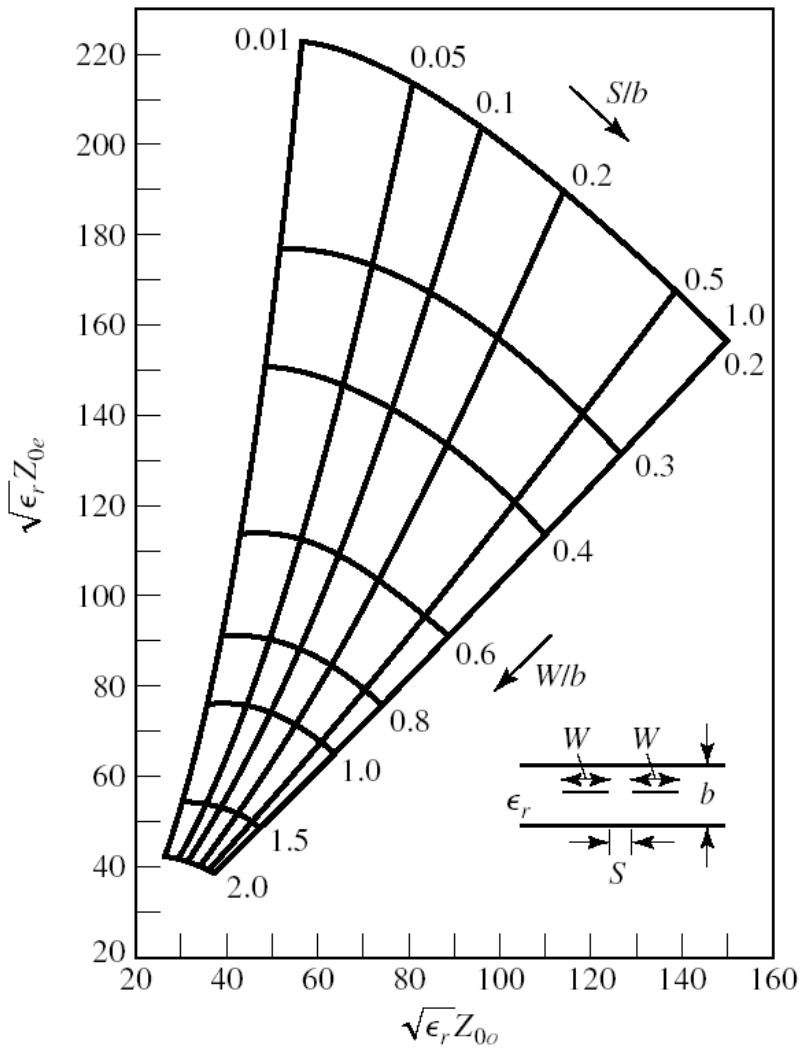




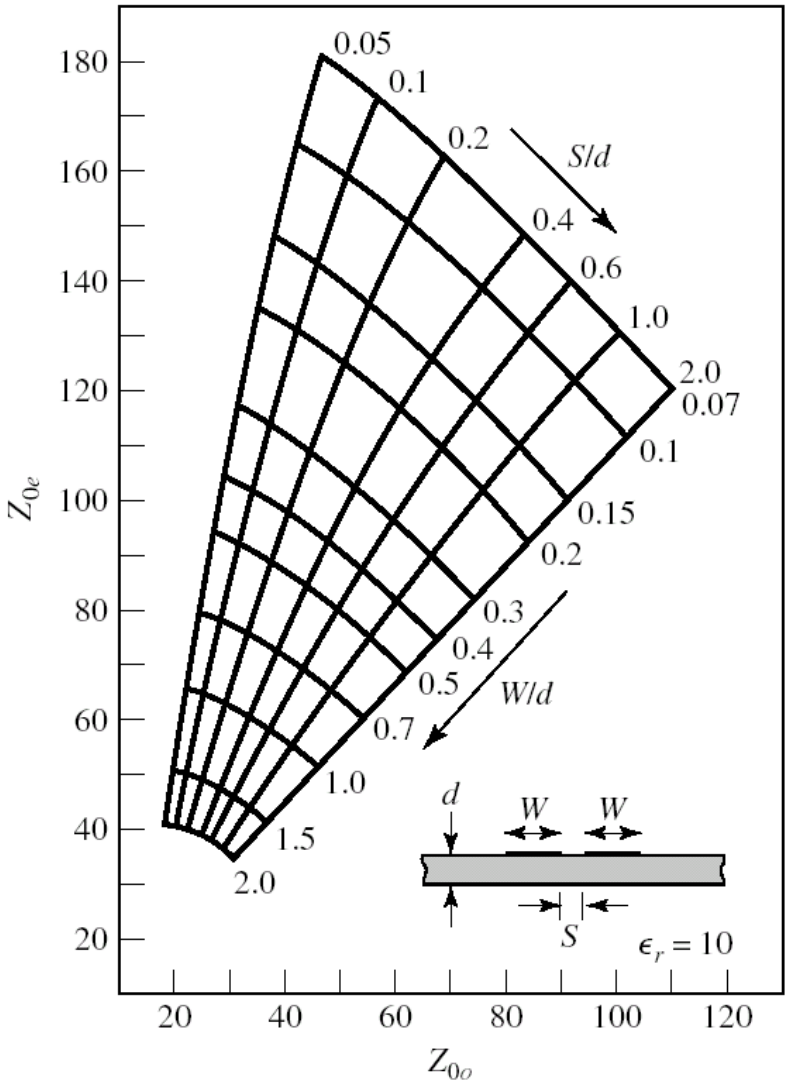
$$[S] = -j \cdot \begin{bmatrix} 0 & \sqrt{1-C^2} & jC & 0 \\ \sqrt{1-C^2} & 0 & 0 & jC \\ jC & 0 & 0 & \sqrt{1-C^2} \\ 0 & jC & \sqrt{1-C^2} & 0 \end{bmatrix}$$

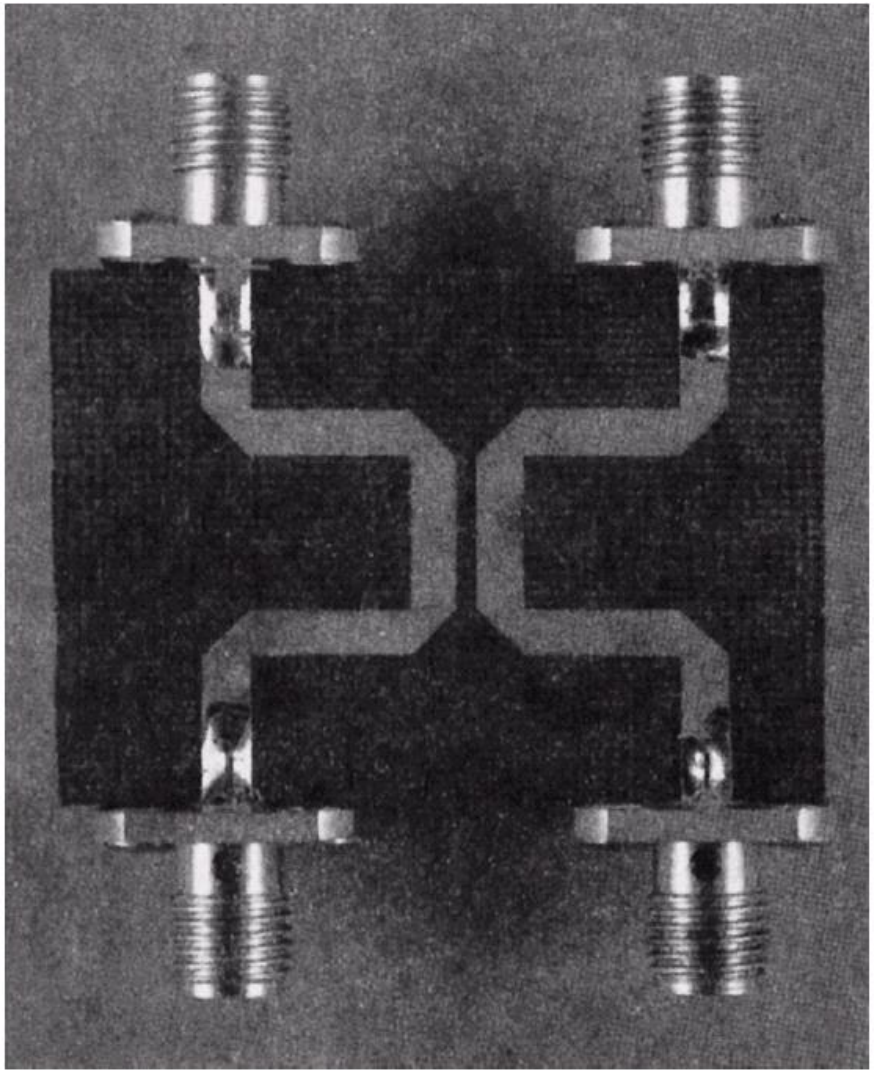
$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

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

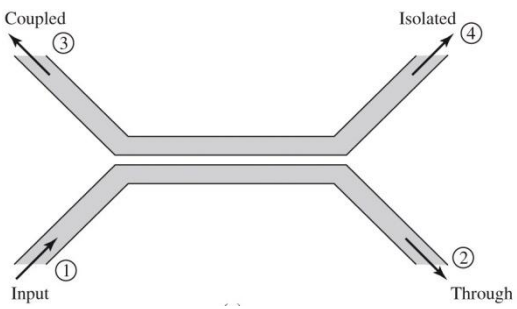


Even- and odd-mode characteristic impedance design data for coupled microstrip lines on a substrate with $\varepsilon_r = 10$.





Cuplor prin proximitate



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

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

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

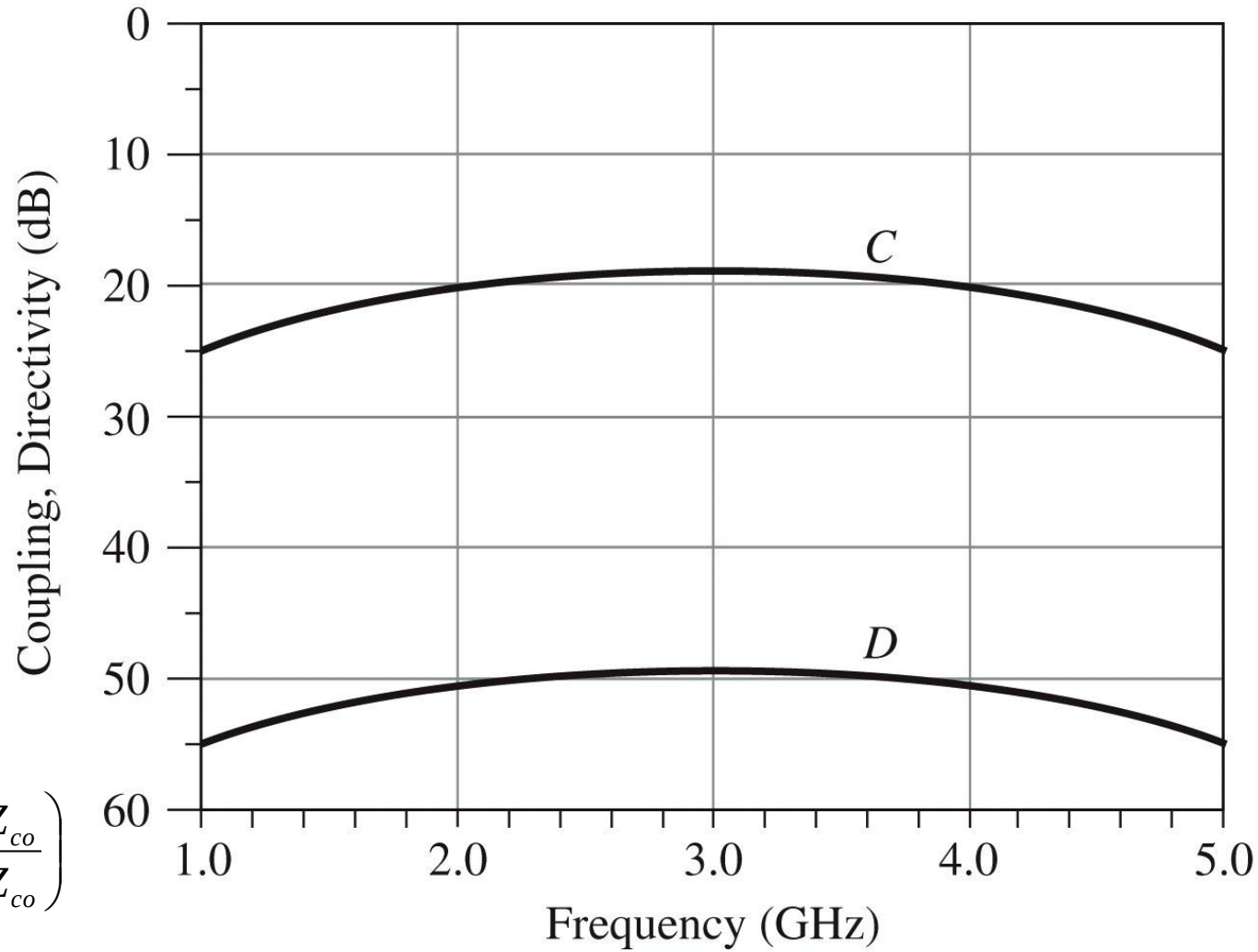


Figure 7.34
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Exemplu

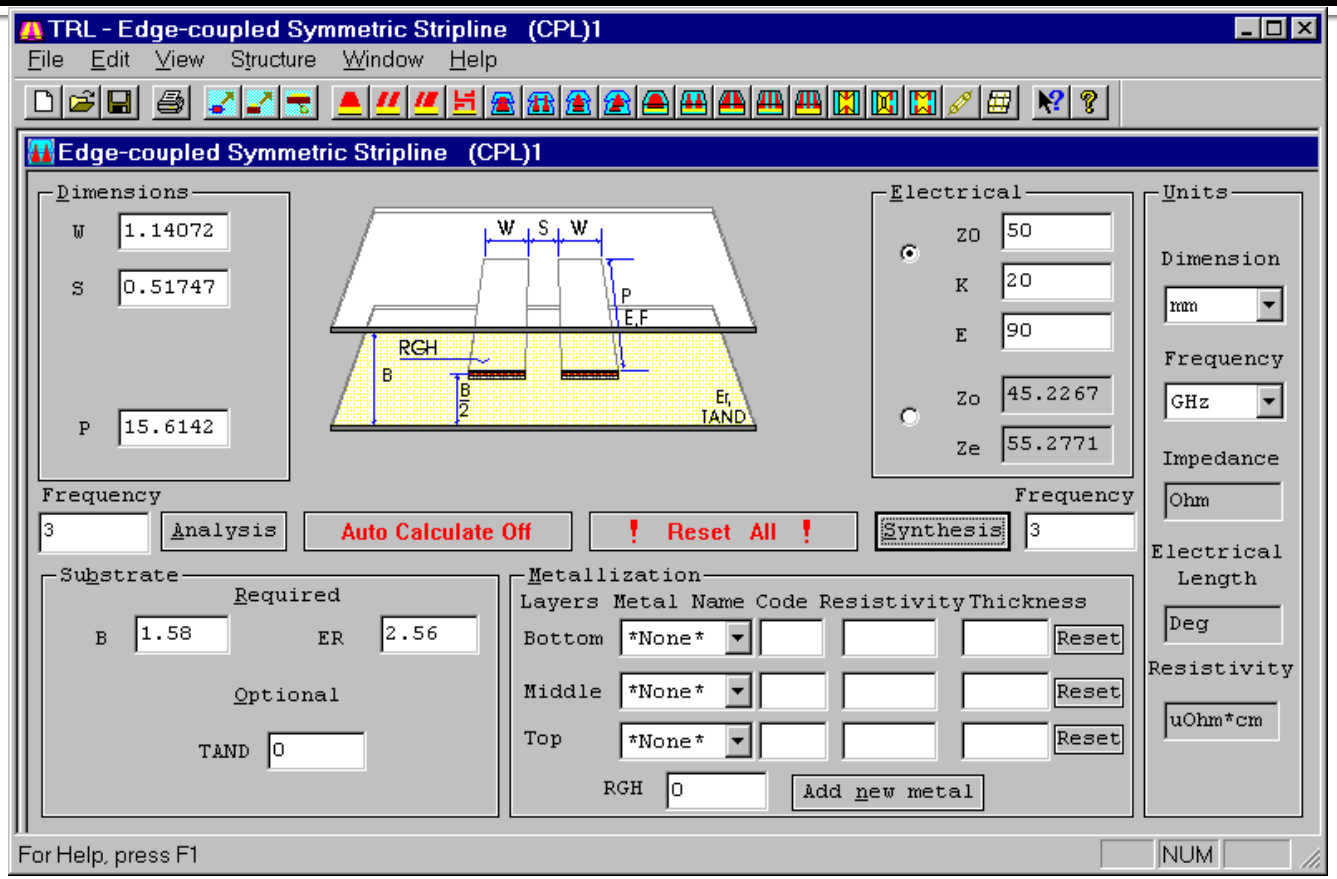
Proiectaţi un cuplor prin proximitate de 20 dB, în tehnologie stripline, folosind o distanta între planele de masă de 0.158 cm şi cu o permitivitate electrică relativa de 2.56, pe o impedanţa de 50 Ω, la frecvenţa de 3 GHz. Reprezentaţi cuplajul şi directivitatea între 1 si 5 GHz.

Soluție

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

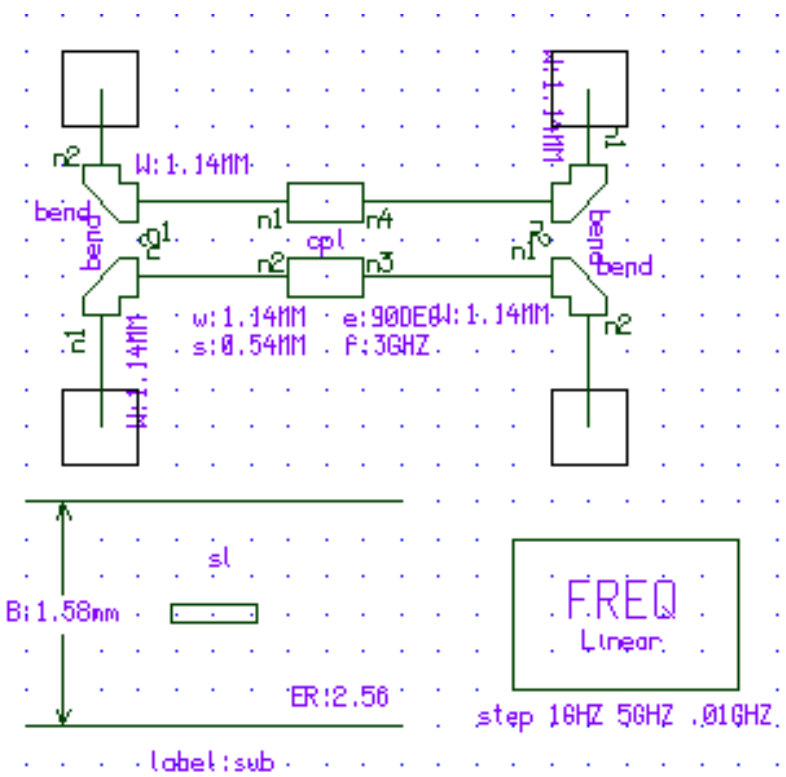
$$Z_{co} = 50\sqrt{\frac{0.9}{1.1}} = 45.23\Omega$$

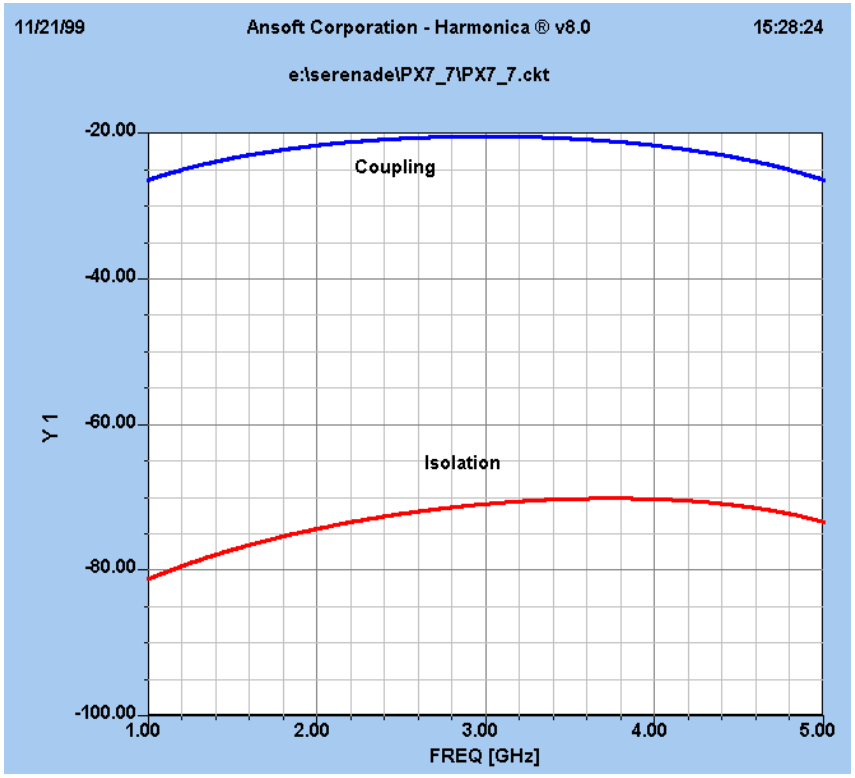
$$Z_{ce} = 50\sqrt{\frac{1.1}{0.9}} = 55.28\Omega$$



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

Simulare


W:1.14MM
bend
n1
n2
n3
n4
cpl
w:1.14MM
s:0.54MM
e:90DEG
f:3GHZ
sl
B:1.58mm
ER:2.56
FREQ
Linear
step 1GHZ 5GHZ .01GHZ
label:sub


11/21/99
Ansoft Corporation - Harmonica ® v8.0
15:28:24
e:\serenade\PX7_7\PX7_7.ckt
Coupling
Isolation
Y1
-20.00
-40.00
-60.00
-80.00
-100.00
1.00
2.00
3.00
4.00
5.00
FREQ [GHz]

Cuplor prin proximitate cu mai multe secțiuni

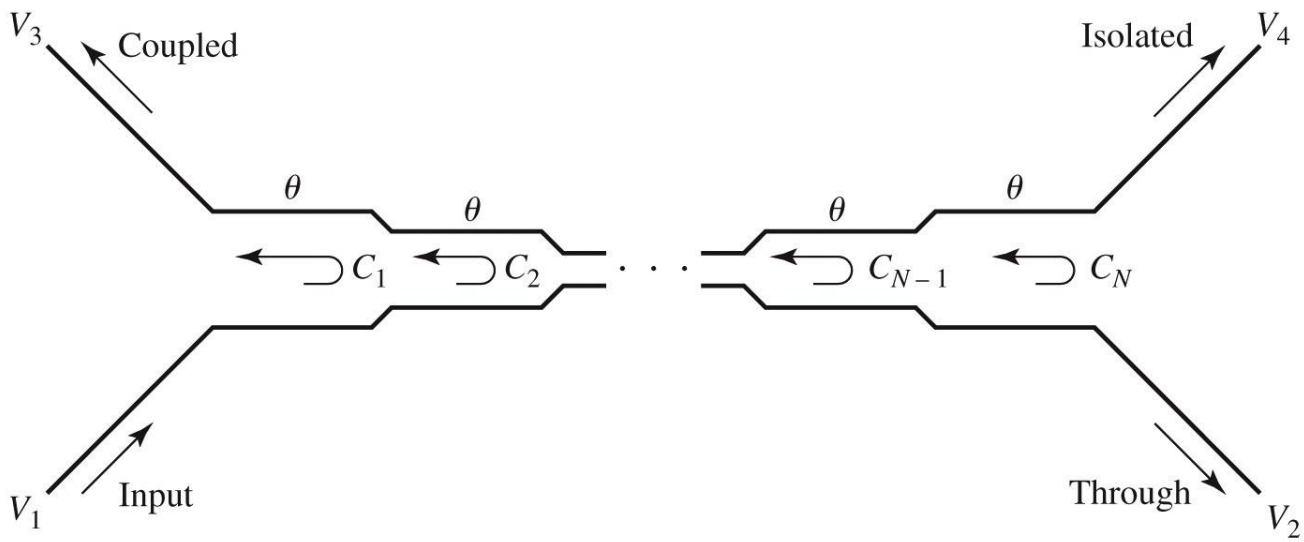


Figure 7.35
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C<<1

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

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

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

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

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

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

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

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

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

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

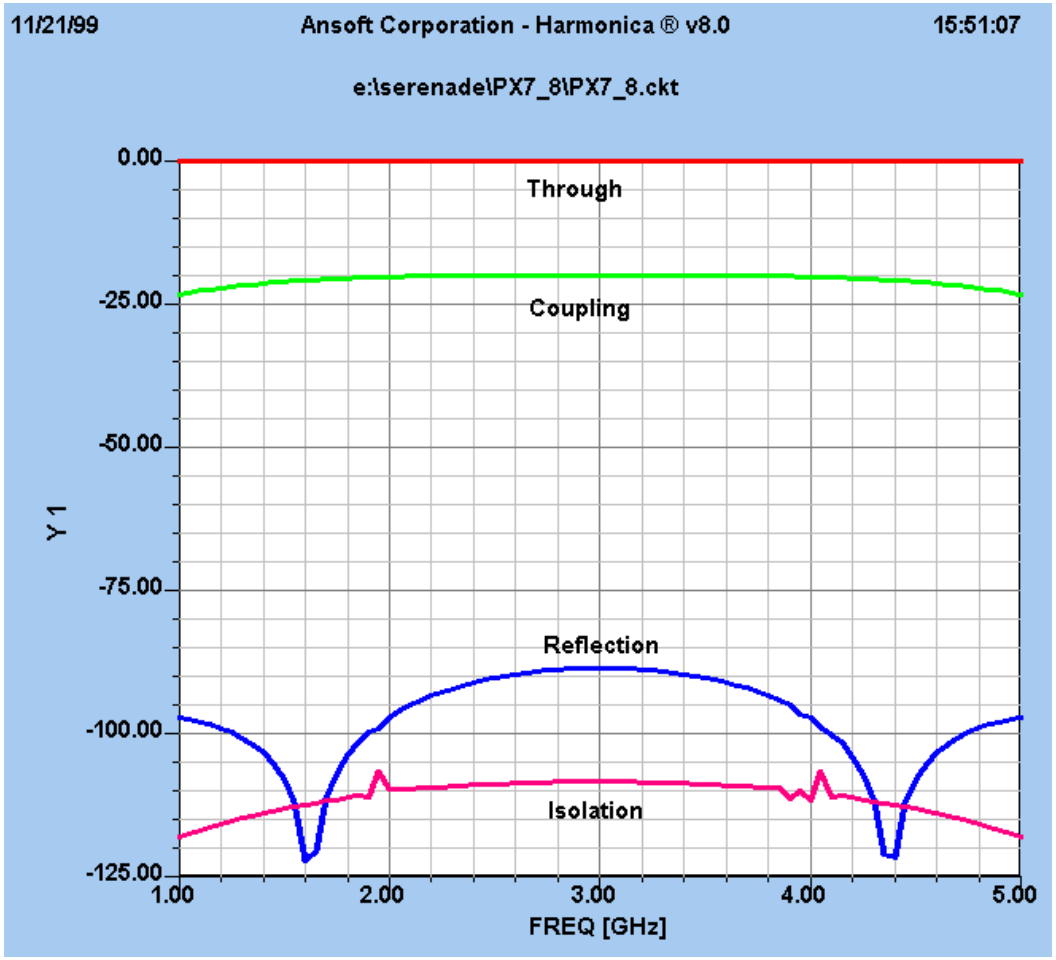
$$Z_{0e}^1 = Z_{0e}^3 = 50\sqrt{\frac{1.0125}{0.9875}} = 50.63\,\Omega$$

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

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

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

Simulare


11/21/99
Ansoft Corporation - Harmonica ® v8.0
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

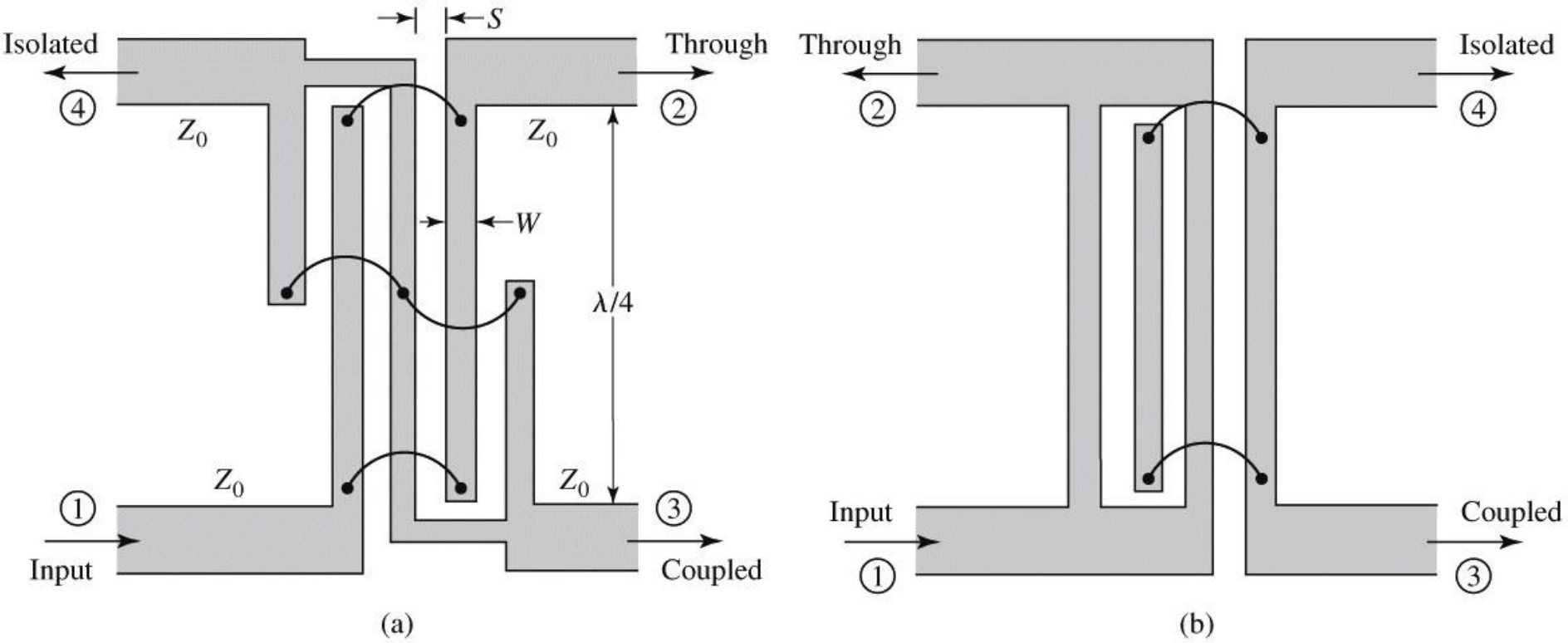


Figure 7.38

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Cuplor Lange

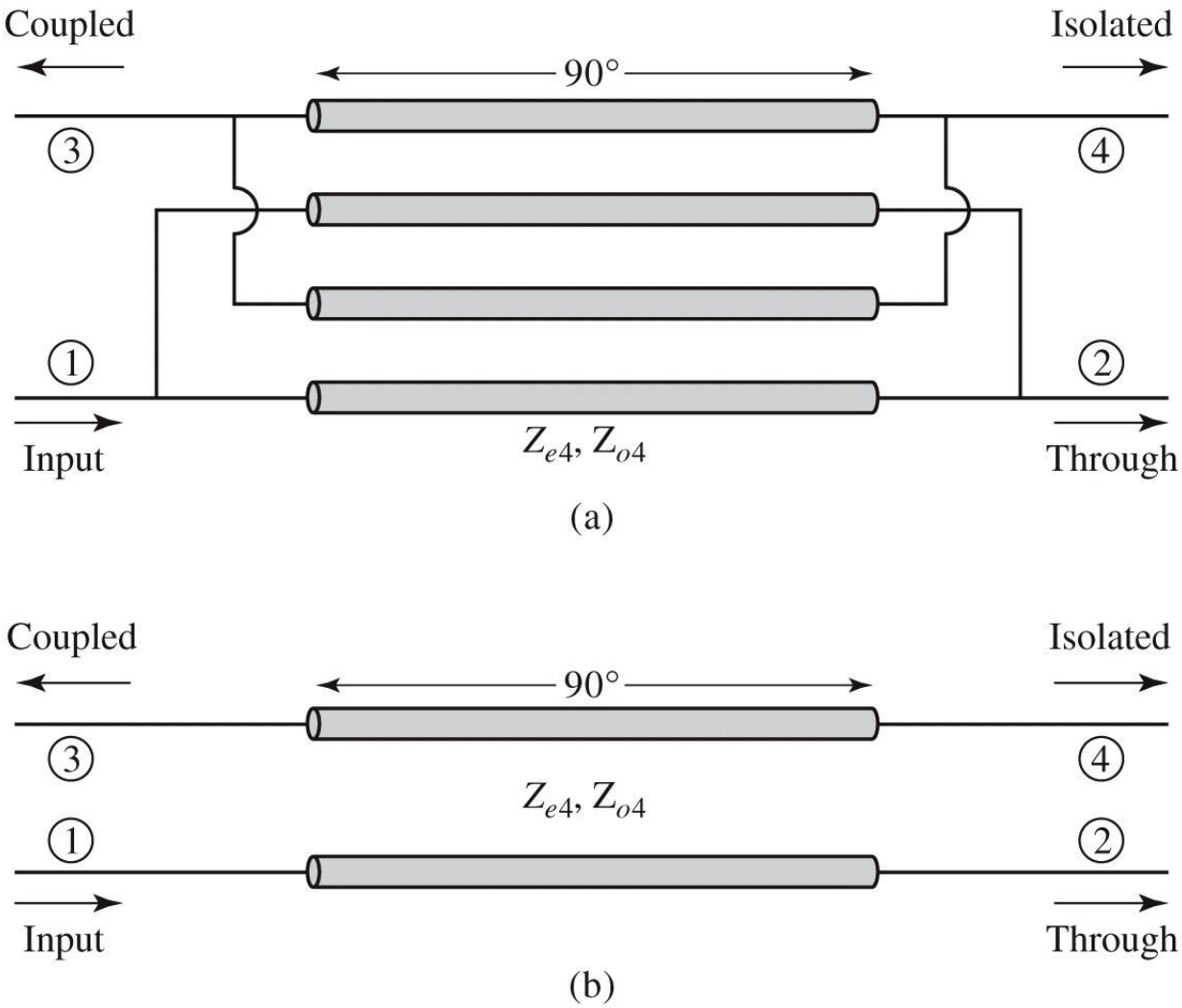

Figure 7.39

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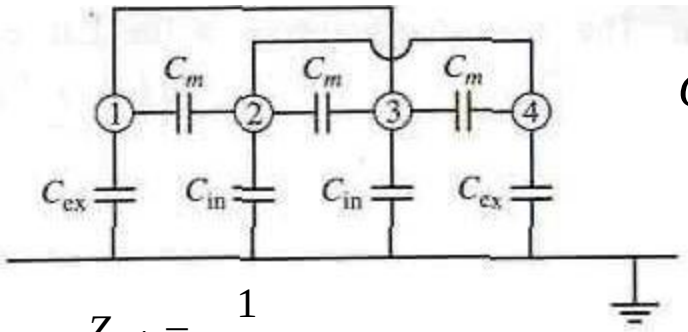
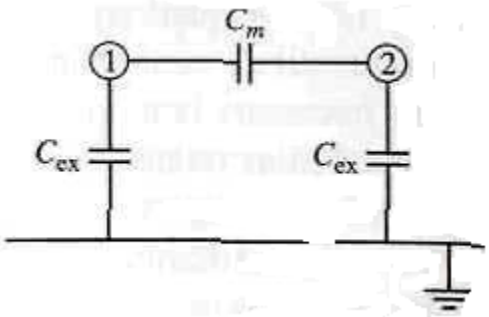
Modelul de circuit



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

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

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



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

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

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

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

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

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

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

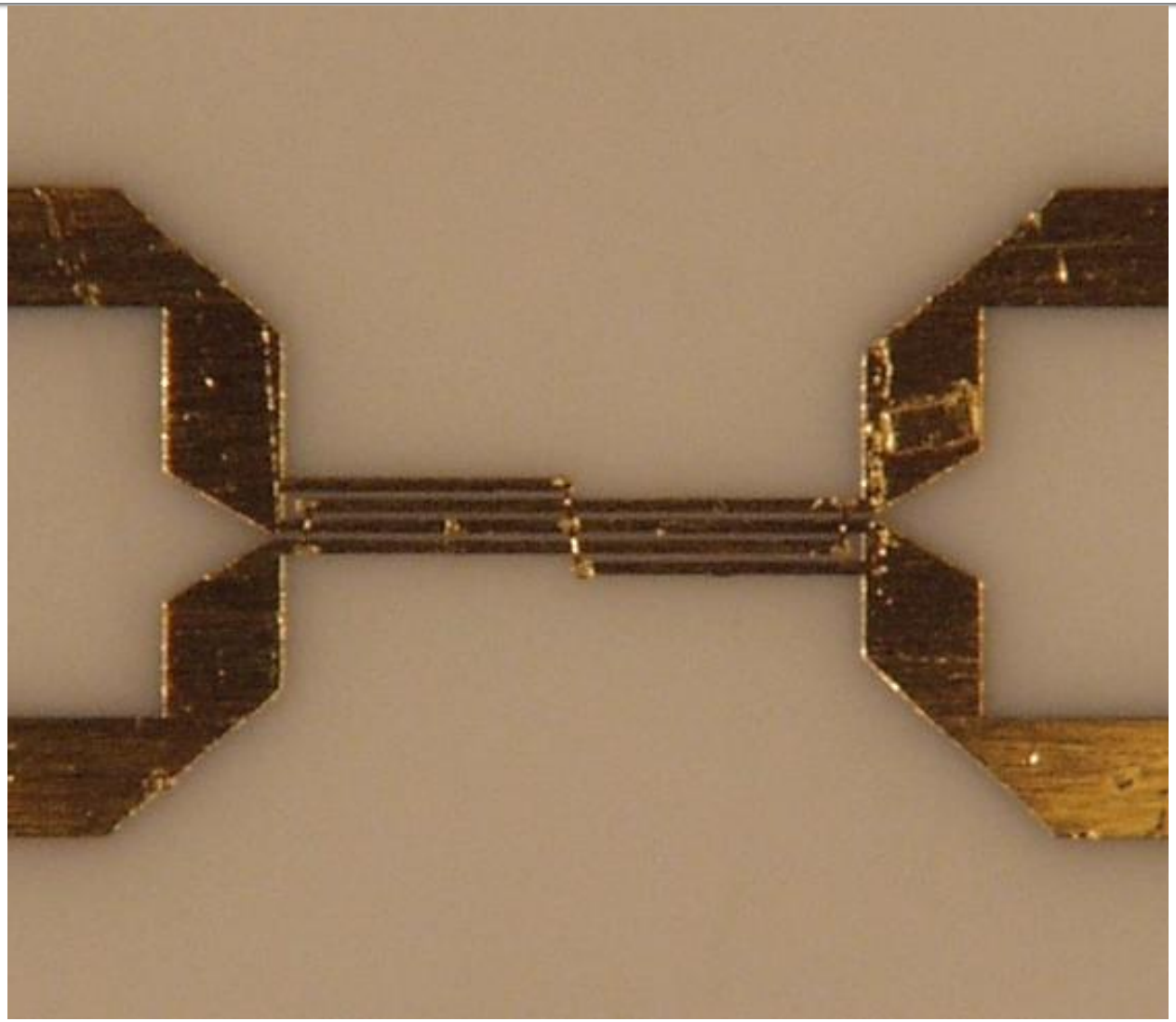
$$Z_{o4} = Z_{0o}\frac{Z_{0e} + Z_{0o}}{3Z_{0e} + Z_{0o}}$$

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

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

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

Cuplor Lange



Cuploare directionale

Laborator 2

Cuplor directional

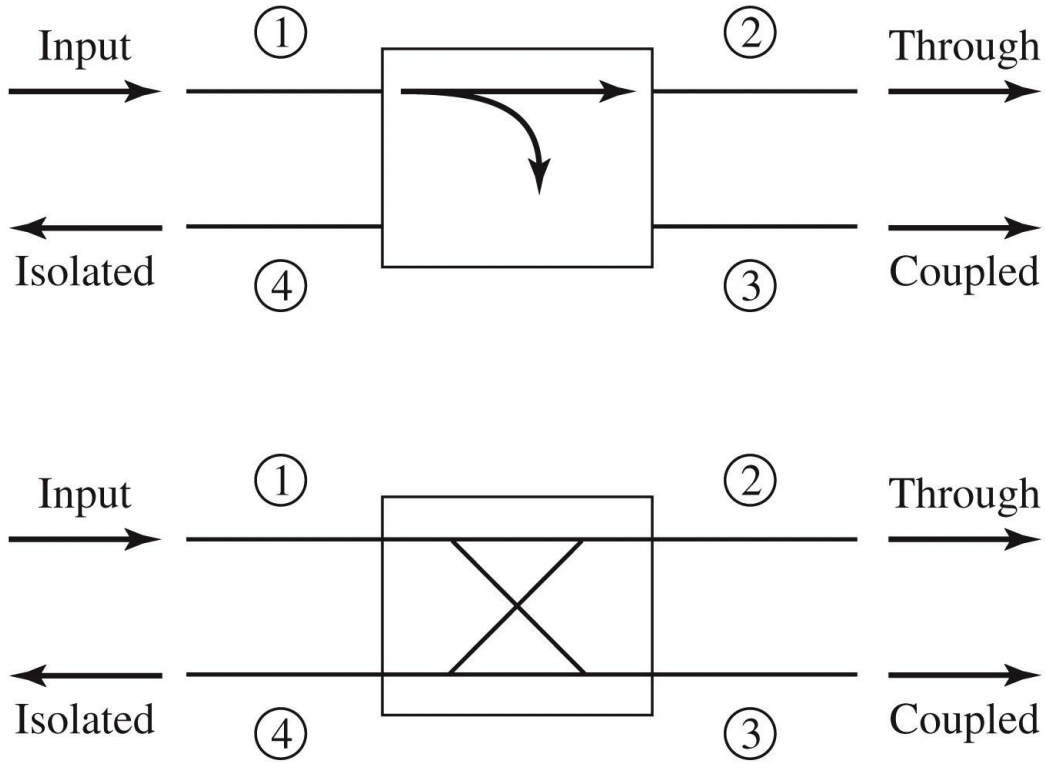


Figure 7.4
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$$\left|S_{12}\right|^2 = \alpha^2 = 1 - \beta^2$$

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

Cuplaj

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

Directivitate

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

Izolare

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

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

Cuplorul in cuadratura

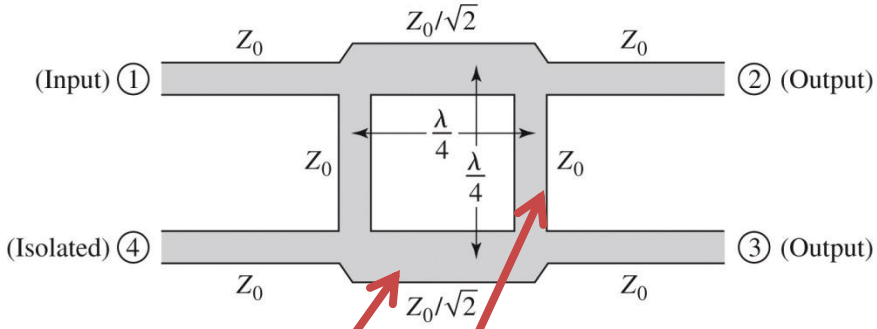

Figure 7.21
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$$y_2^2 = 1 + y_1^2$$

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

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

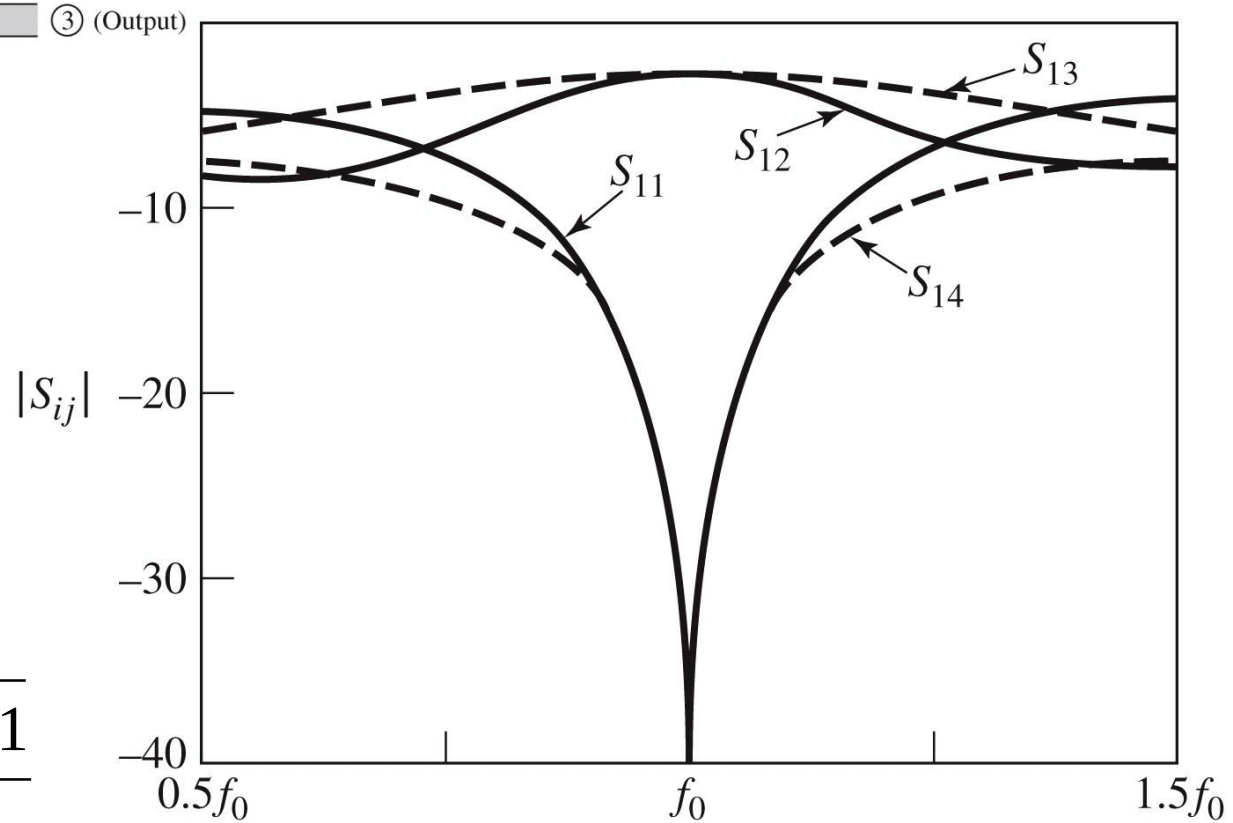

Figure 7.25
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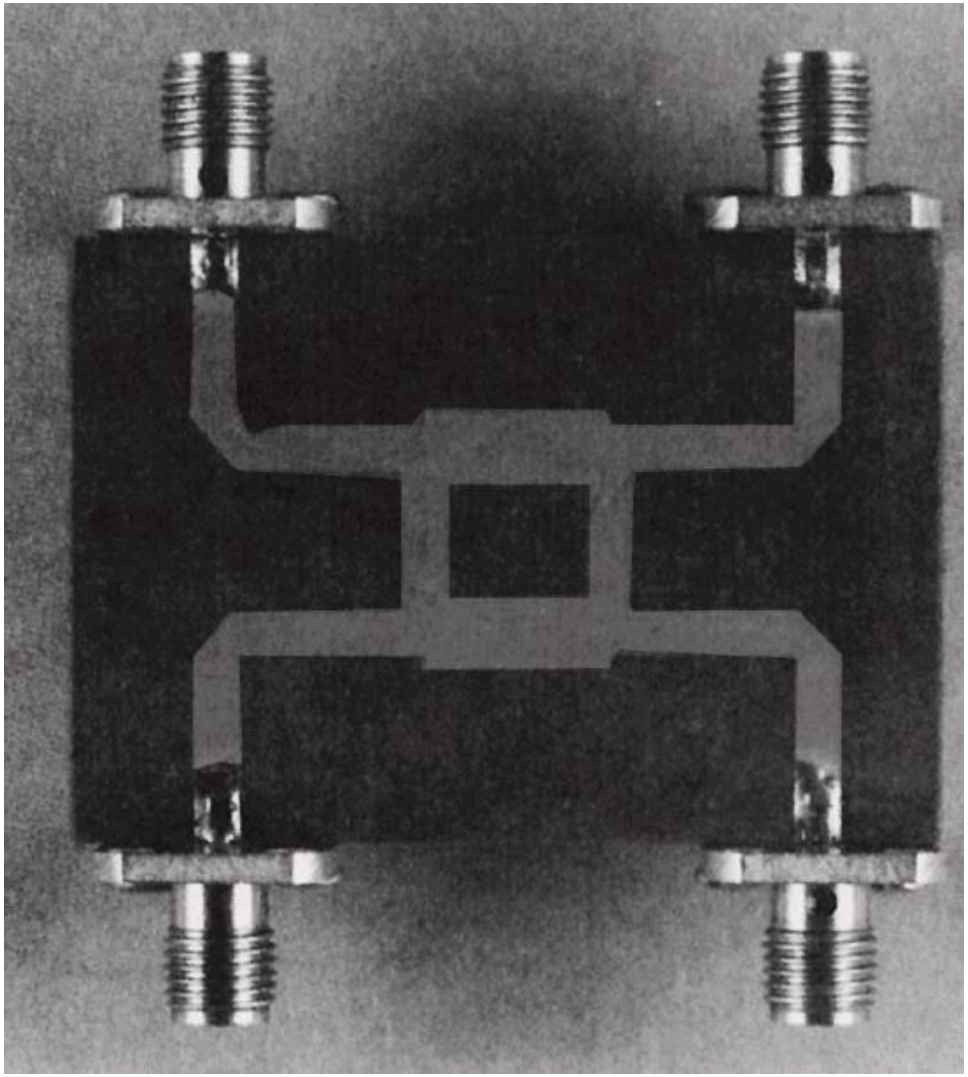
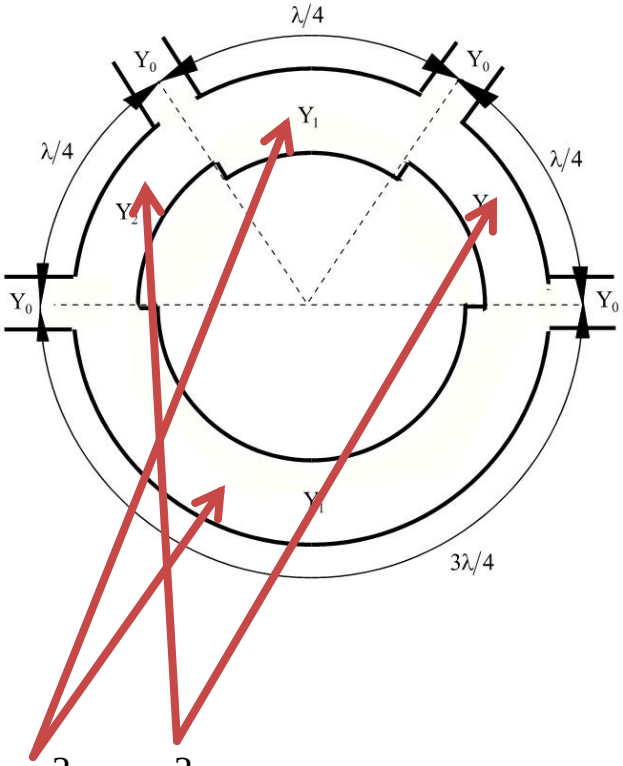


Cuplorul în inel



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

$$|\beta| = y_1$$

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

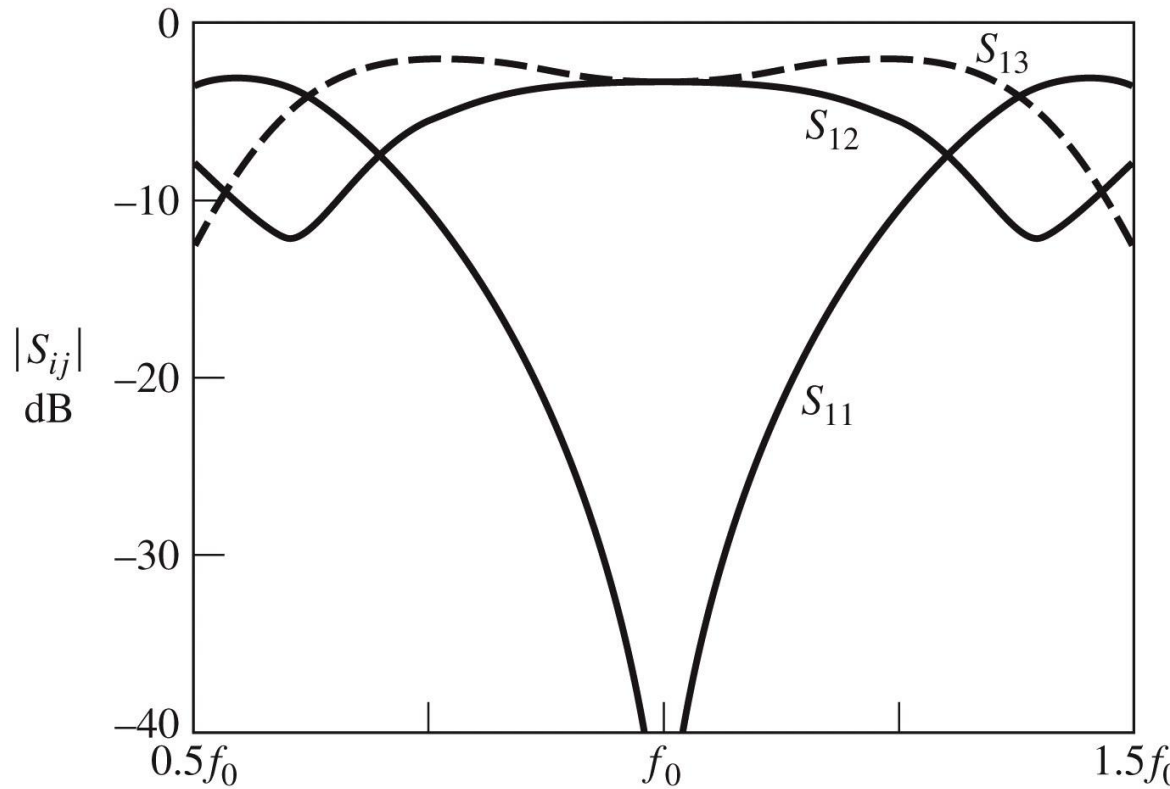


Figure 7.46
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Cuplor în inel

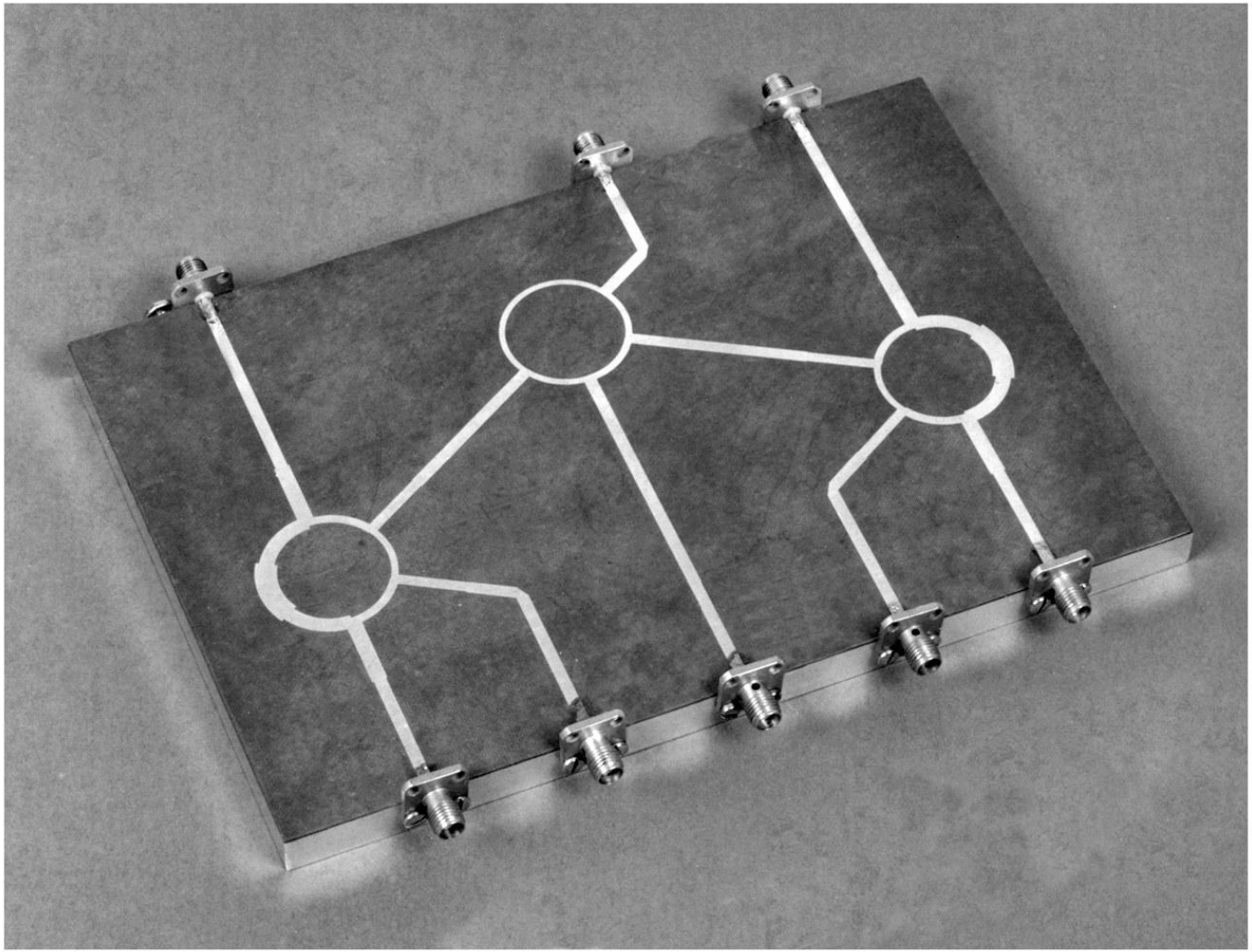
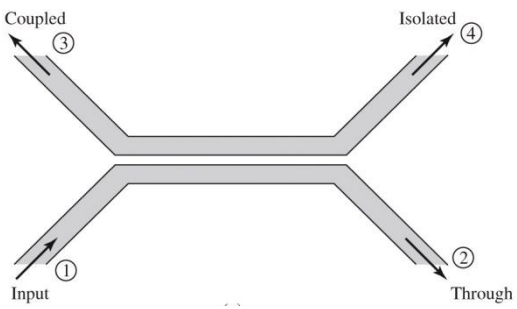


Figure 7.43
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

Cuplor prin proximitate



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

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

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

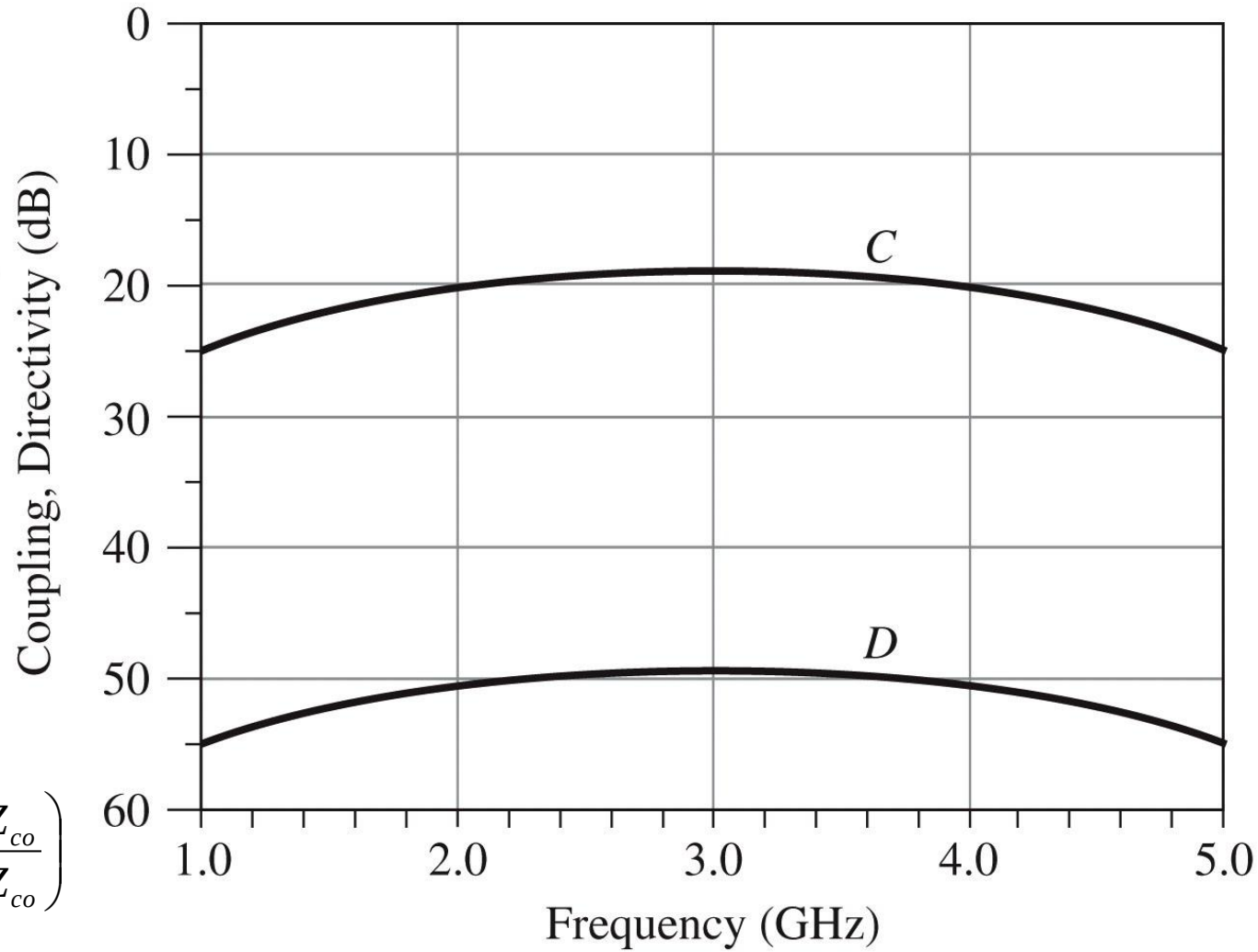


Figure 7.34
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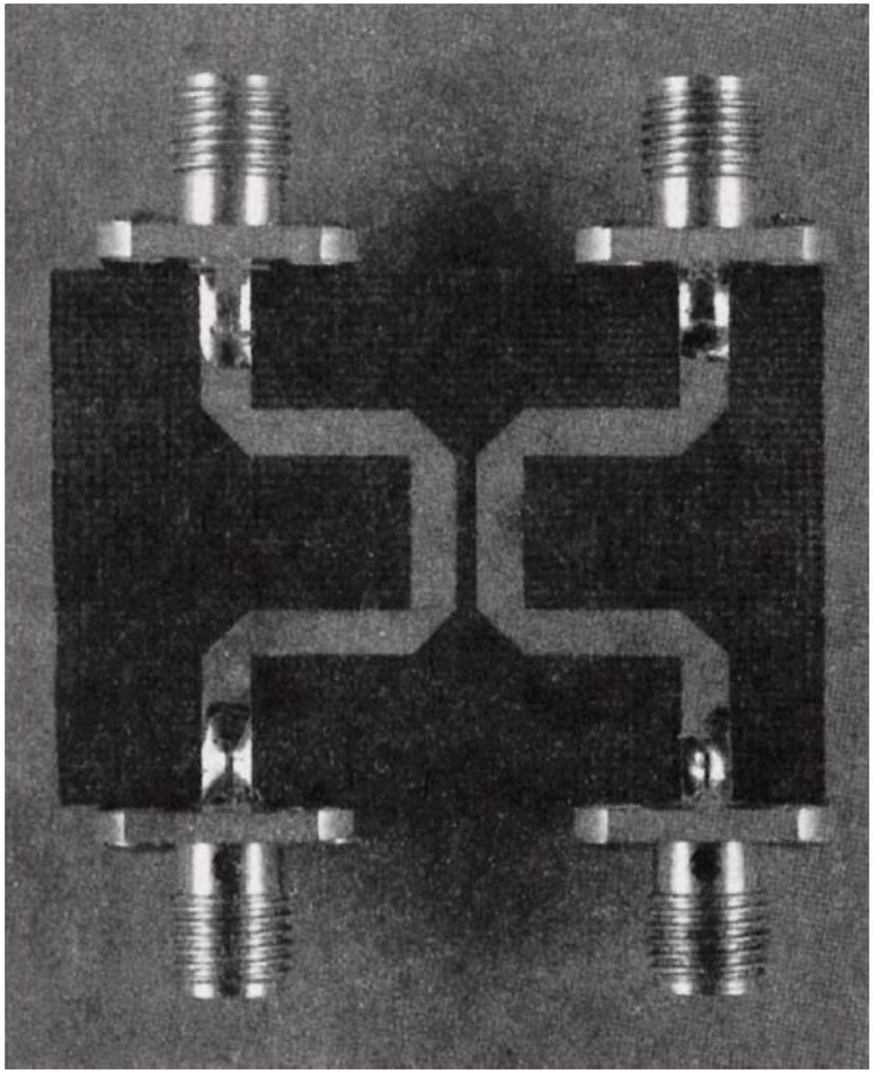

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