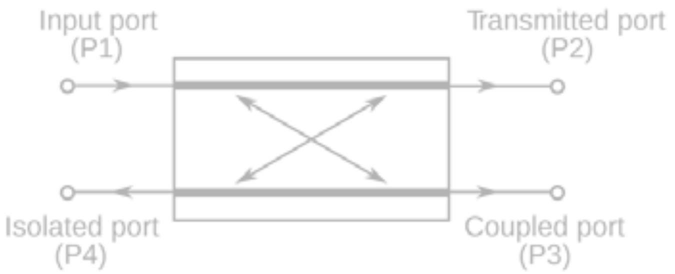
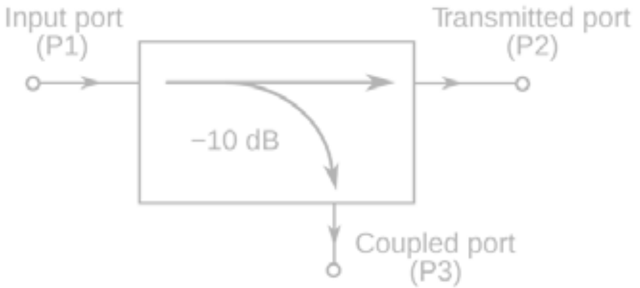
# Microwave Engineering MCC121, 7.5hec, 2014

## Lecture 8
## Passive devices





*State-of-the-art*
*Challenging*
*Stimulating*
*Rewarding*

# Outline

- Summary of lecture 7 (Ch5)
- Passive microwave devices
  - attenuators, loads
  - phase shifters
  - power dividers (7.1-7.4)

# Objectives

On completion of this course unit you should be able to:

- ☑ Analyse wave propagating properties of guided wave structures (TE, TM, TEM waves, microstrip, stripline, rectangular and circular waveguides, coupled lines)
- ☑ Apply N-port representations for analysing microwave circuits
- ☑ Apply the Smith chart to evaluate microwave networks
- ☑ Design and evaluate impedance matching networks
- ☑ Design, evaluate and characterise directional couplers and power dividers
- ☐ Design and analyse attenuators, phase shifters and resonators
- ☐ Explain basic properties of ferrite devices (circulators, isolators)

# Transformers

# Tapered transformer

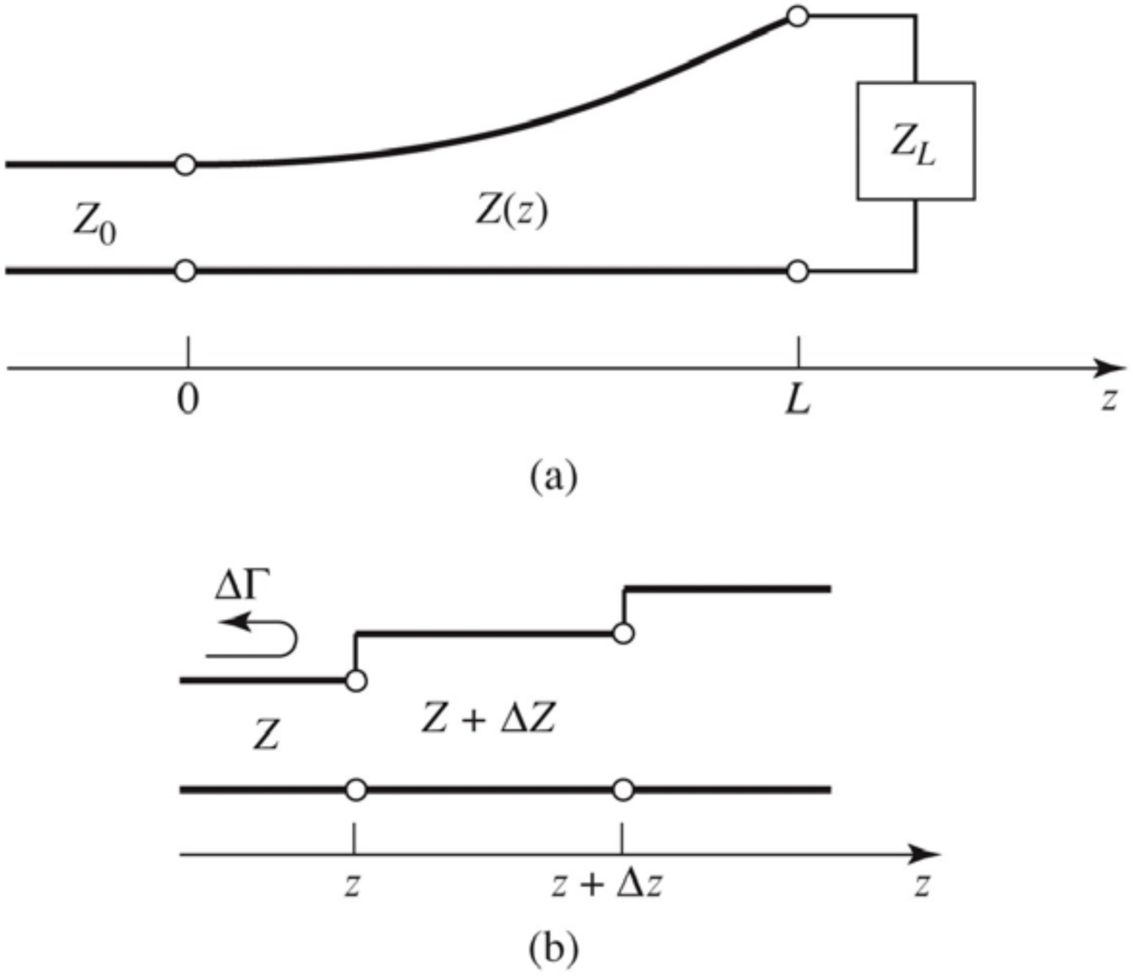
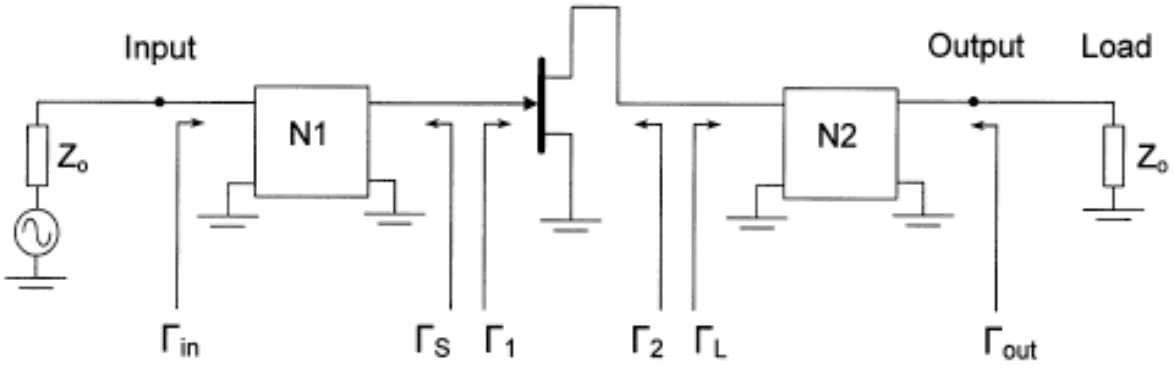


**Figure 5.18**
© John Wiley & Sons, Inc. All rights reserved.

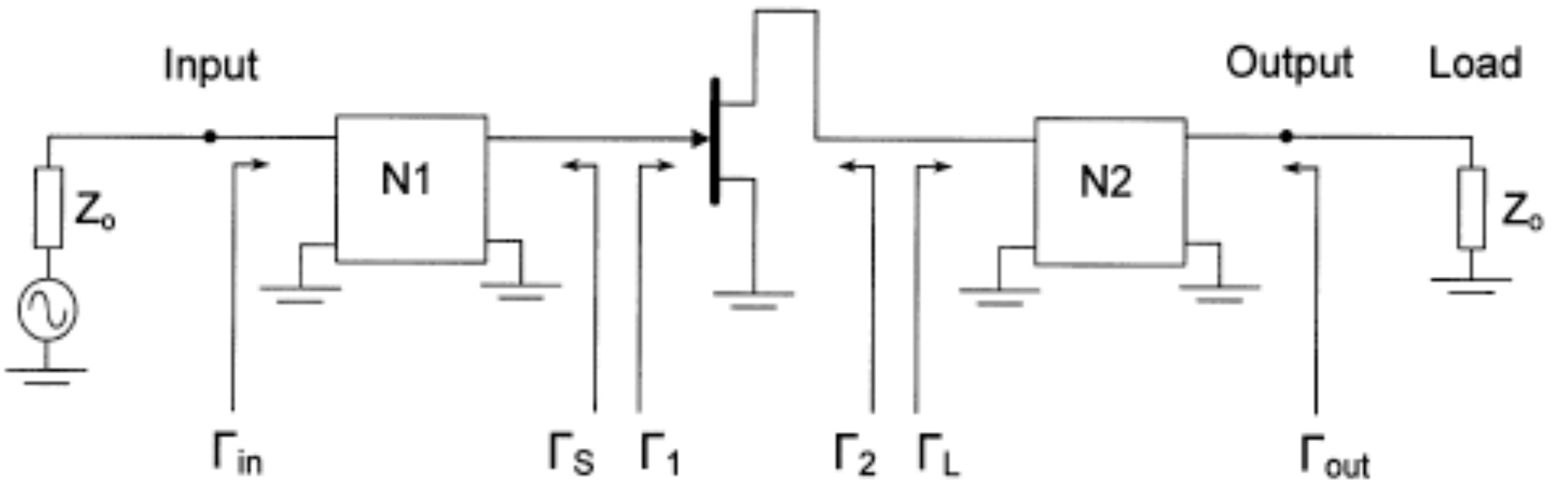
$$d\Gamma_{in} = e^{-2j\beta z}\frac{1}{2}\frac{d}{dz}\left(\ln Z\right)dz$$

$$\Gamma_{in} = \int_0^L d\Gamma_{in} = \frac{1}{2}\int_0^L e^{-2j\beta z}\frac{d}{dz}\left(\ln Z\right)dz \quad (1)$$

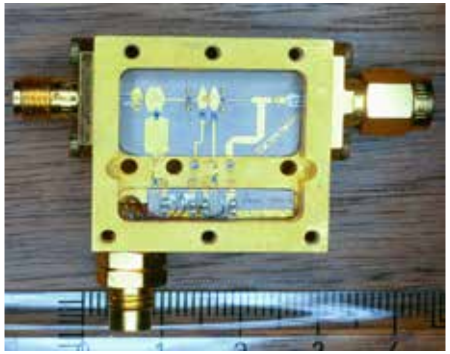


# Design of complex impedance terminations

# Ex) design of amplifier



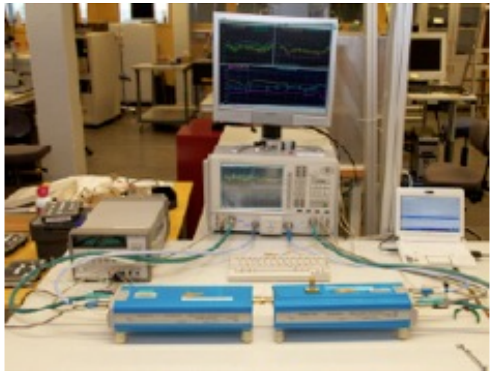
- Find Gamma-S &-L for a certain noise, gain, stability requirements... (more about this in active microwave circuits)
- Synthesise matching networks N1 and N2 to provide these complex impedances (This course MCC121)



Courtesy of Niklas Wadefalk
MC2, Chalmers and
Low Noise Factory

# Passive microwave devices

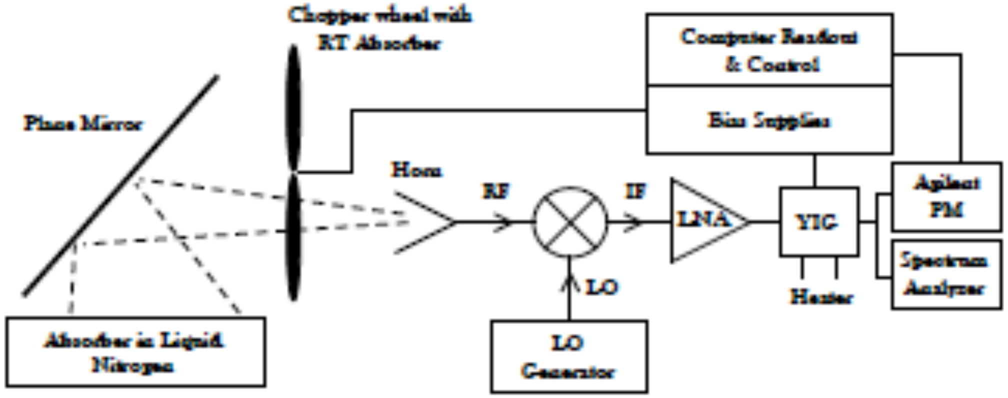
# Terminations

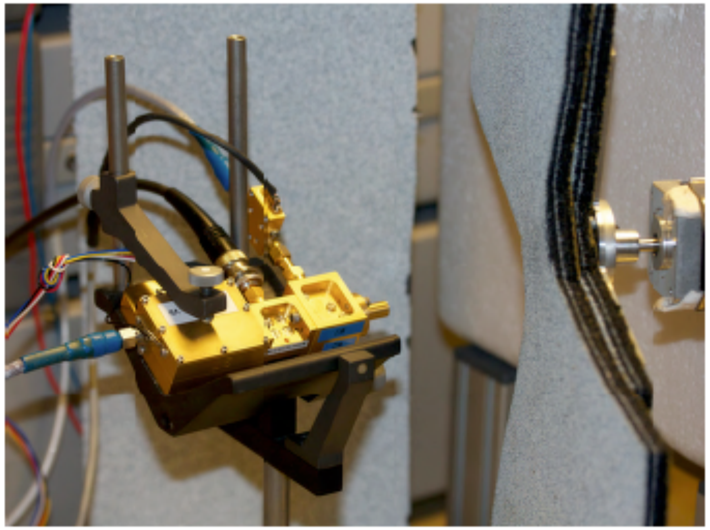


Common μ-wave lab utensils

- Matched load $\Gamma = 0$
- Variable short circuit $\Gamma = 1 \cdot e^{j\phi}$

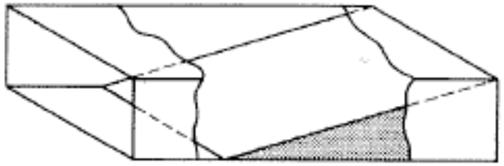
# Ex) Matched loads



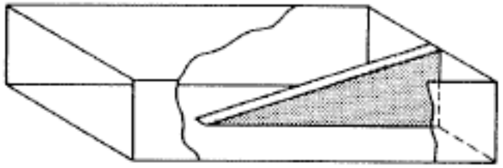


- Noise figure measurement (Y-factor measurement using two loads at two different temperatures)
- Termination to absorb all power (terminating the line in its characteristic impedance)

# matched load



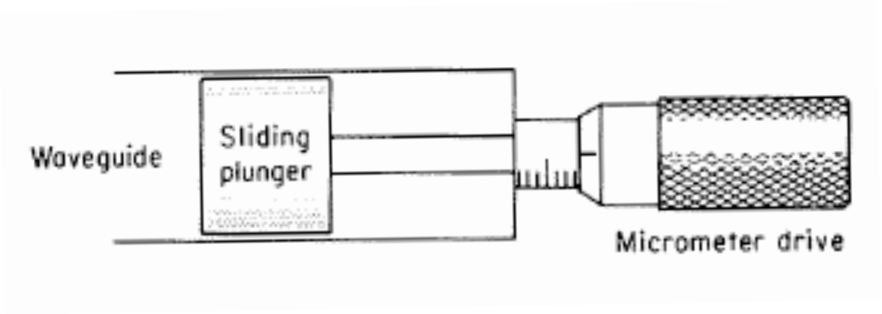
(a)



(b)

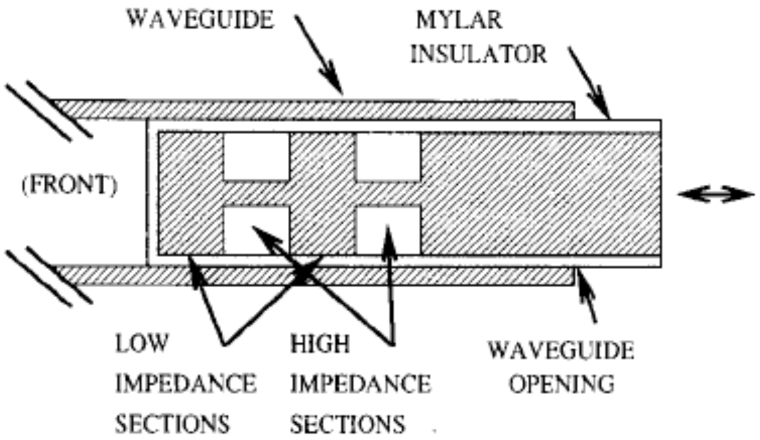
- ”lossy” transmission line
- Reflections are avoided by tapering the lossy material into a wedge

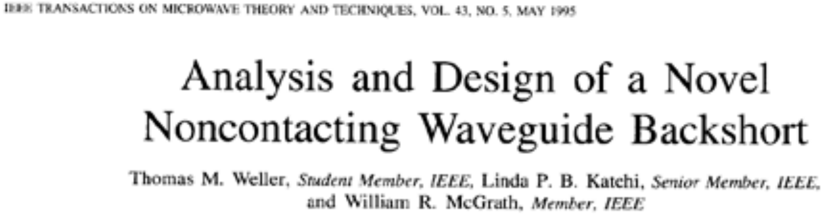
# Movable shorts



- Impedance tuning element (reactance)

# The art of making a movable waveguide short



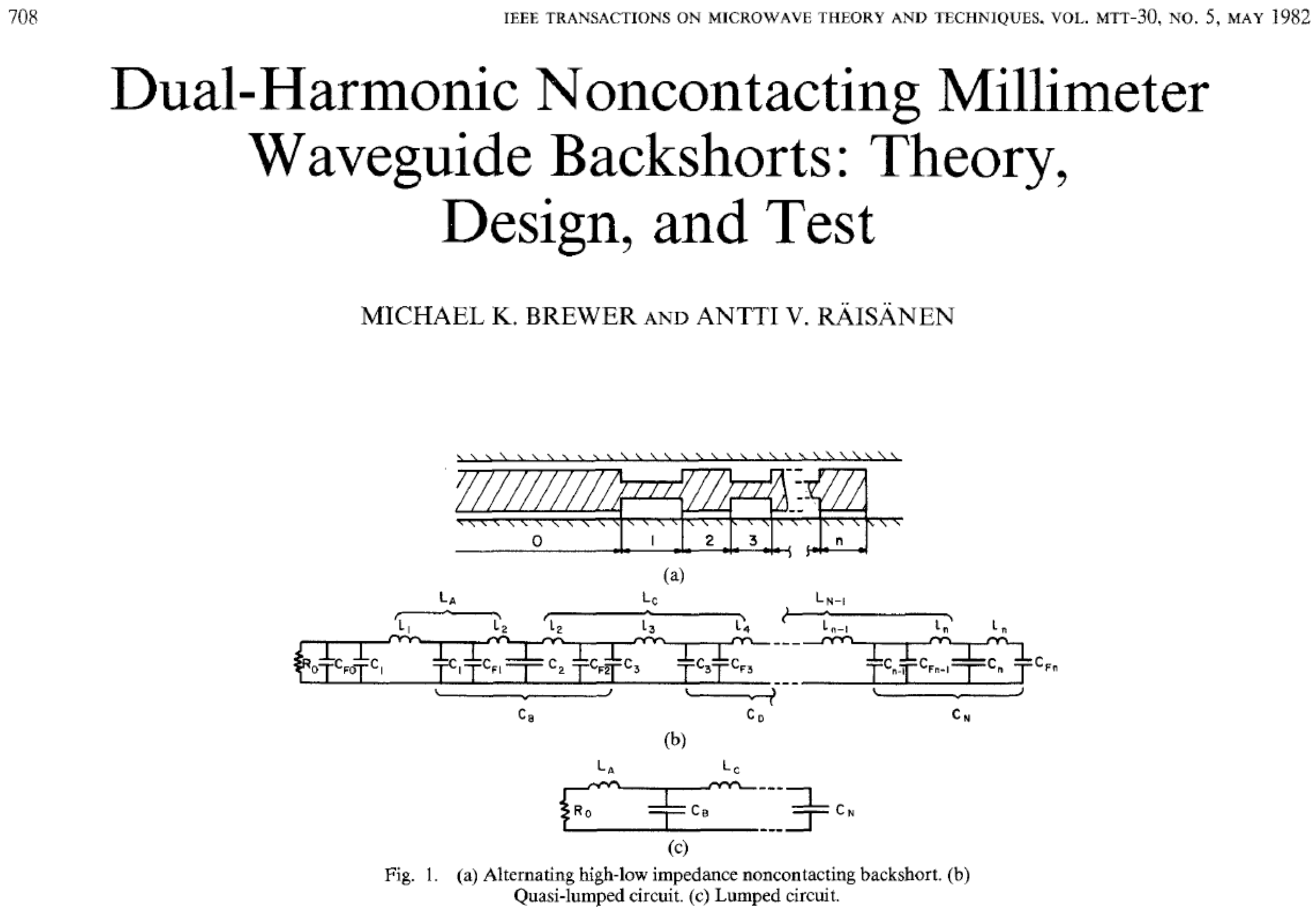

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 43, NO. 5, MAY 1995

Analysis and Design of a Novel Noncontacting Waveguide Backshort

Thomas M. Weller, *Student Member, IEEE*, Linda P. B. Katehi, *Senior Member, IEEE*, and William R. McGrath, *Member, IEEE*

$$Z_{\mathrm{RF}} = \left(\frac{Z_{\mathrm{low}}}{Z_{\mathrm{high}}}\right)^{n} Z_{\mathrm{low}}$$

- Contacting versus noncontacting shorts
  - Contacting wear out + hard to achieve perfect contact
- Solution: High and low impedance quarter wave sections (guided wave). Or apply filter theory...



708 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-30, NO. 5, MAY 1982

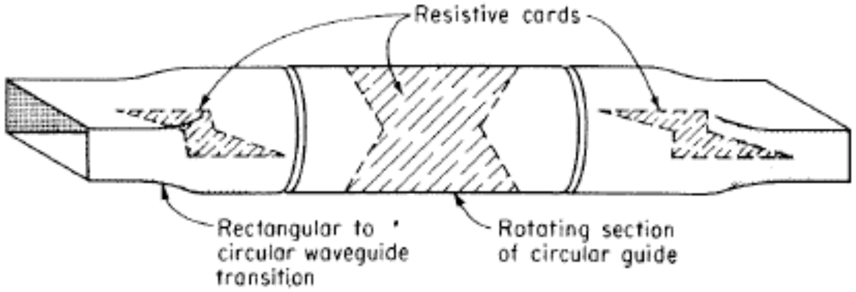
# Dual-Harmonic Noncontacting Millimeter Waveguide Backshorts: Theory, Design, and Test

MICHAEL K. BREWER AND ANTTI V. RÄISÄNEN

Fig. 1. (a) Alternating high-low impedance noncontacting backshort. (b) Quasi-lumped circuit. (c) Lumped circuit.

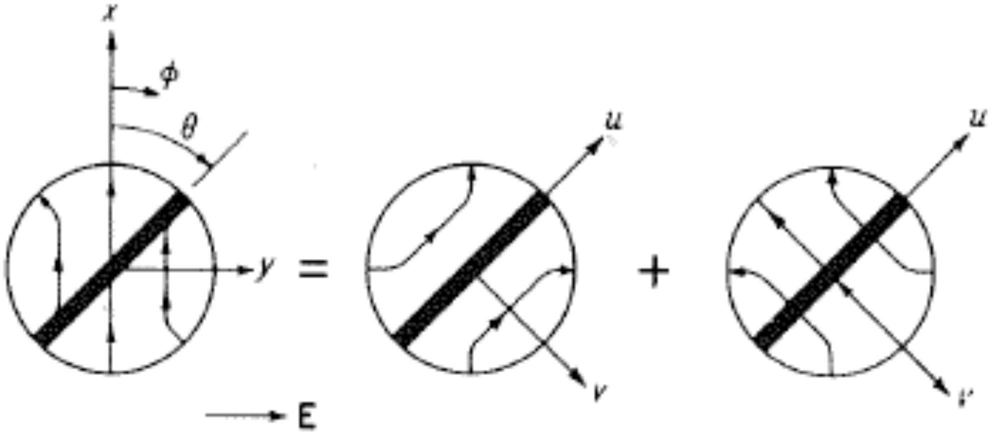
filter theory -> synthesise a band stop filter (high VSWR)

# Rotary attenuator

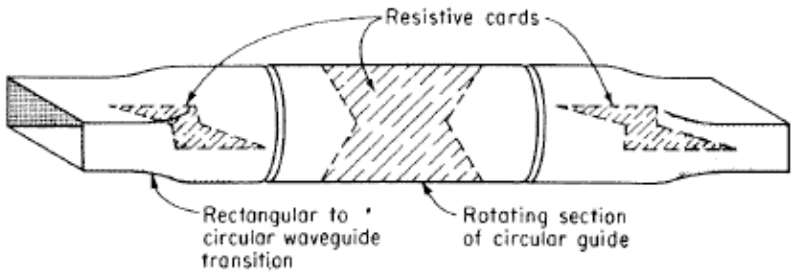


- Precision attenuator with low VSWR. The attenuation is insensitive to frequency; variations of phase with attenuation are negligible.
- Lab equipment rather than employed in systems.

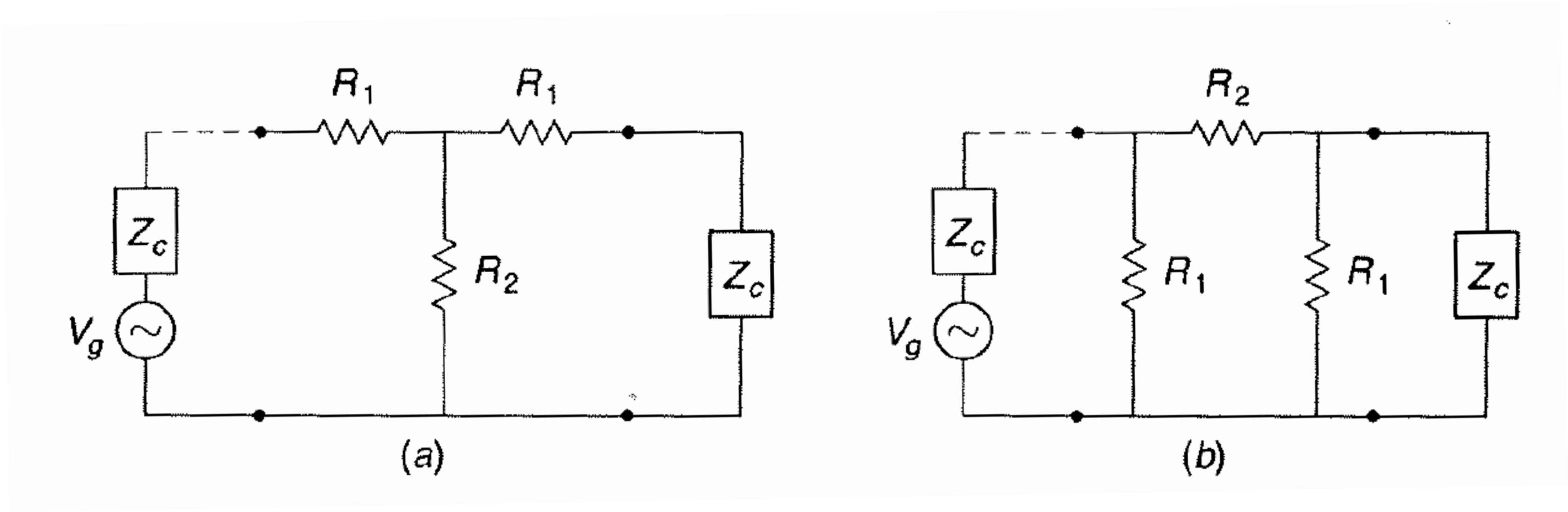
# Decomposition of TE$_{11}$ mode



Sum of two orthogonally polarized modes



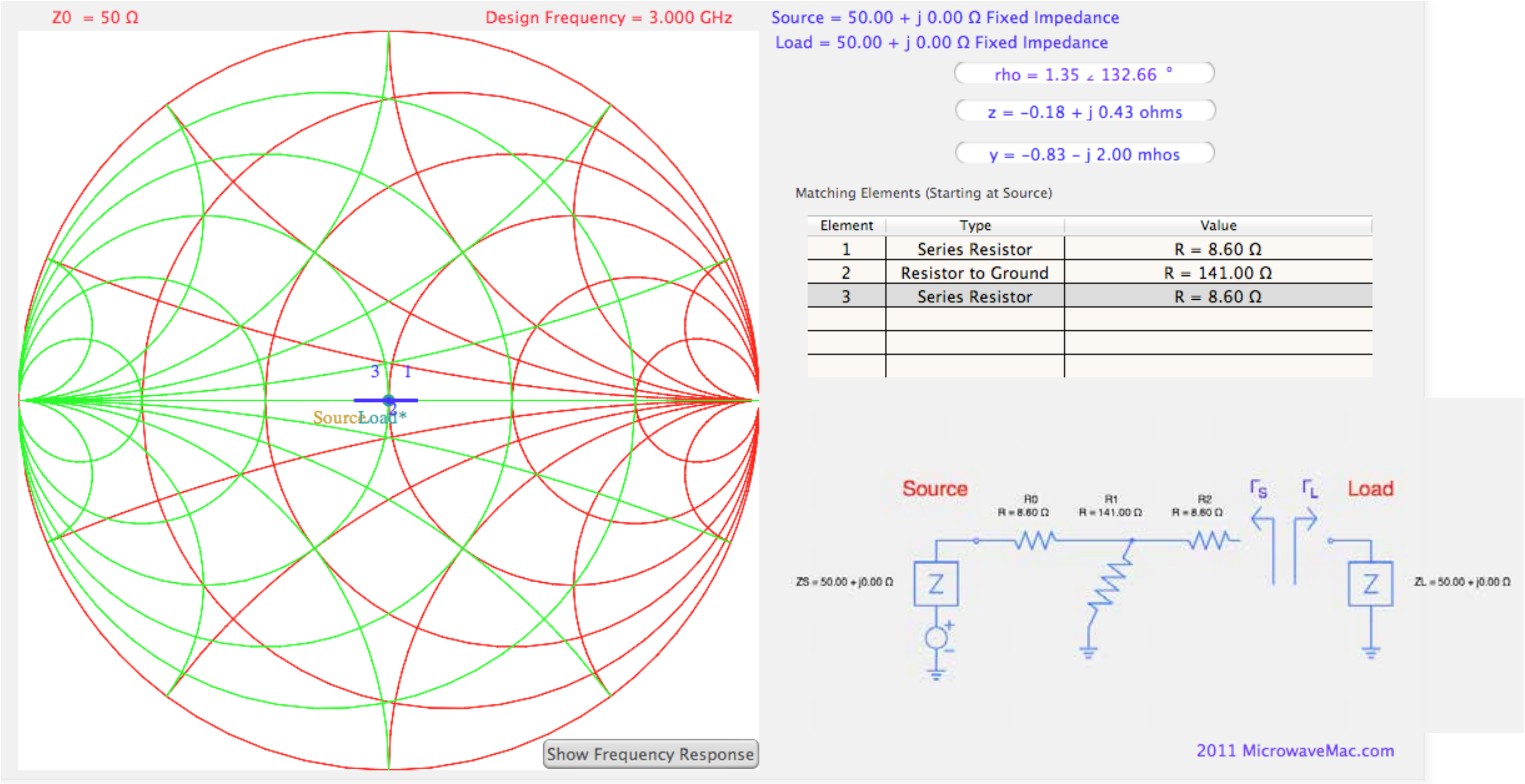
# Resistive T or Pi -attenuator



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

- *On white board: Derive a set of design equations for a resistive attenuator (T).*

# 3-dB attenuator



Z0 = 50 Ω

Design Frequency = 3.000 GHz

Source = 50.00 + j 0.00 Ω Fixed Impedance

Load = 50.00 + j 0.00 Ω Fixed Impedance

rho = 1.35 ∠ 132.66 °

z = −0.18 + j 0.43 ohms

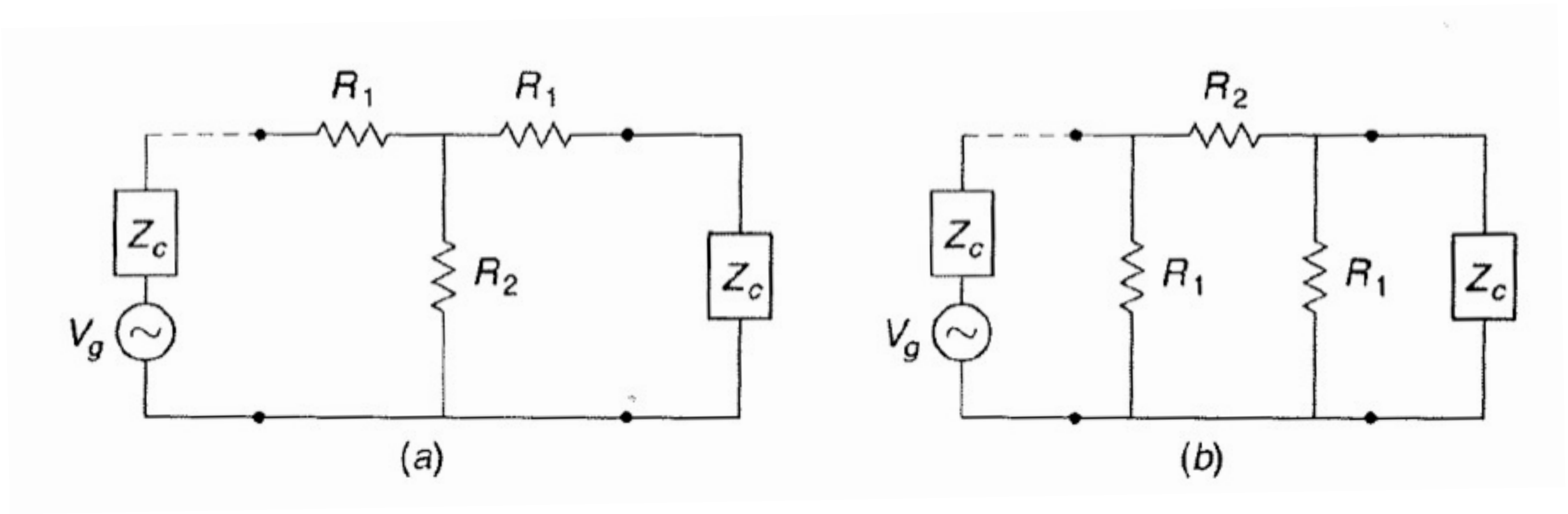
y = −0.83 − j 2.00 mhos

Matching Elements (Starting at Source)

| Element | Type | Value |
|---|---|---|
| 1 | Series Resistor | R = 8.60 Ω |
| 2 | Resistor to Ground | R = 141.00 Ω |
| 3 | Series Resistor | R = 8.60 Ω |

Explain the different ”moves” in the Smith Chart. Can we replace the shunt resistor? to avoid via-hole to ground.

# Resistive T or Pi -attenuator

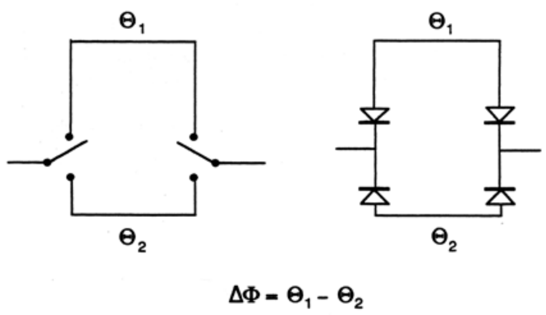


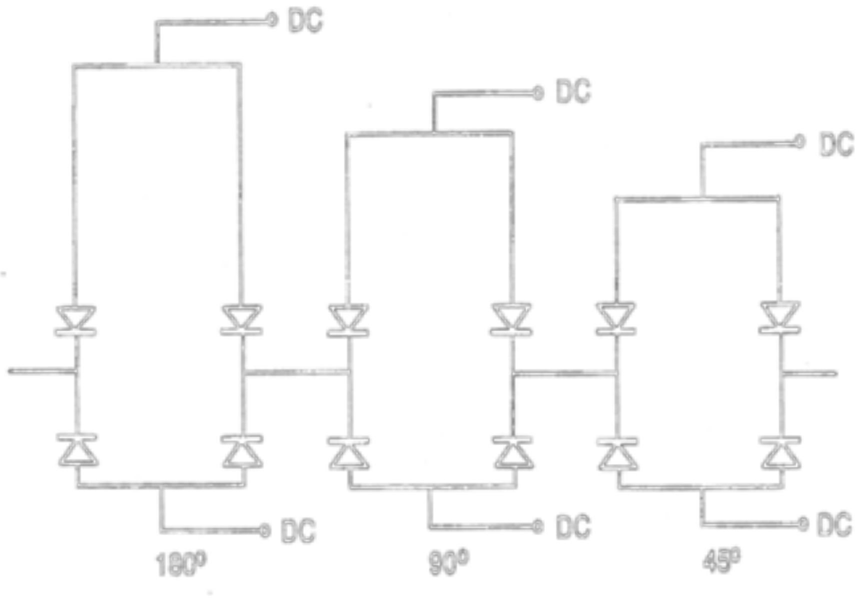
$$[S] = \begin{bmatrix} 0 & k \\ k & 0 \end{bmatrix}$$

# Phase shifter

- Phase shifters are components used to control the phase of a signal with lowest possible influence on the amplitude.
- There are many different types of phase shifters depending on the used technology.

# Switched line phase shifter





$$\Delta\phi(f) = \theta_1(f) - \theta_2(f) = \theta_1\big|_{f=f_0}\frac{f}{f_0} - \theta_2\big|_{f=f_0}\frac{f}{f_0} =$$

$$= \beta\left(l_1\frac{f}{f_0} - l_2\frac{f}{f_0}\right)$$

- The losses are constant at all states
- The circuit is very simple
- The circuit is small

- Each bit needs at least 4 diodes, high power consumption
- Complicated DC supply

© J. Piotr Starski

# Differential phase shifters

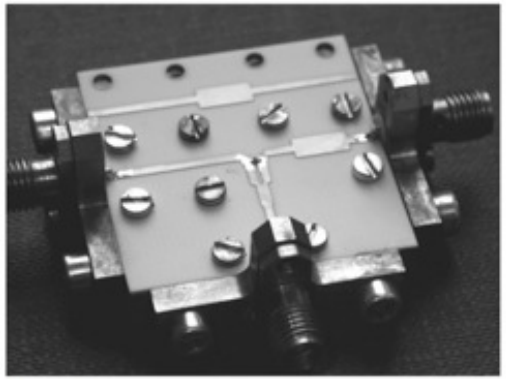


**Fig. 10** *Photograph of the coaxial test fixture with an assembled phase shifter circuit. A 100 Ω 0402-thinfilm resistor chip was used for the Wilkinson divider odd mode termination*

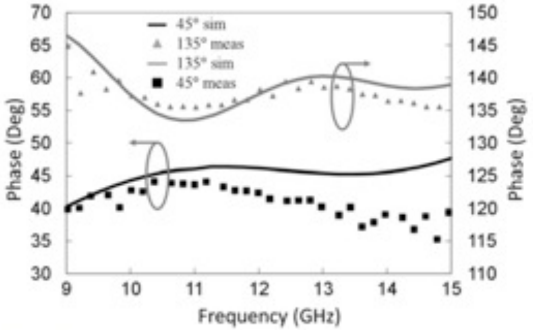


**Fig. 11** *Simulated (line) and measured (dot) differential phase of the 45° (black) and 135° (grey) differential phase shifter circuits*

from P. Sobis, J. Stake, and A. Emrich, “High/low-impedance transmission-line and coupled-line filter networks for differential phase shifters,” *IET Microwaves, Antennas & Propagation*, vol. 5, no. 4, pp. 386–392, 2011.

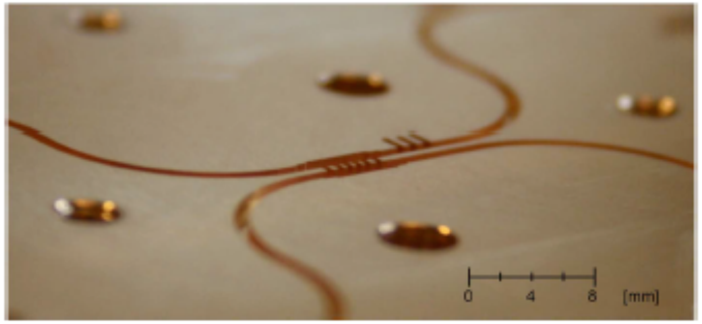


Fig. 2. Photograph of the WR-05 waveguide phase shifter hybrid manufactured in an E-plane split block.

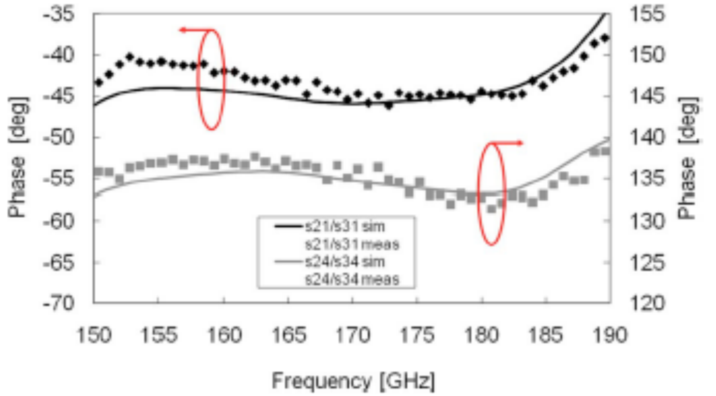
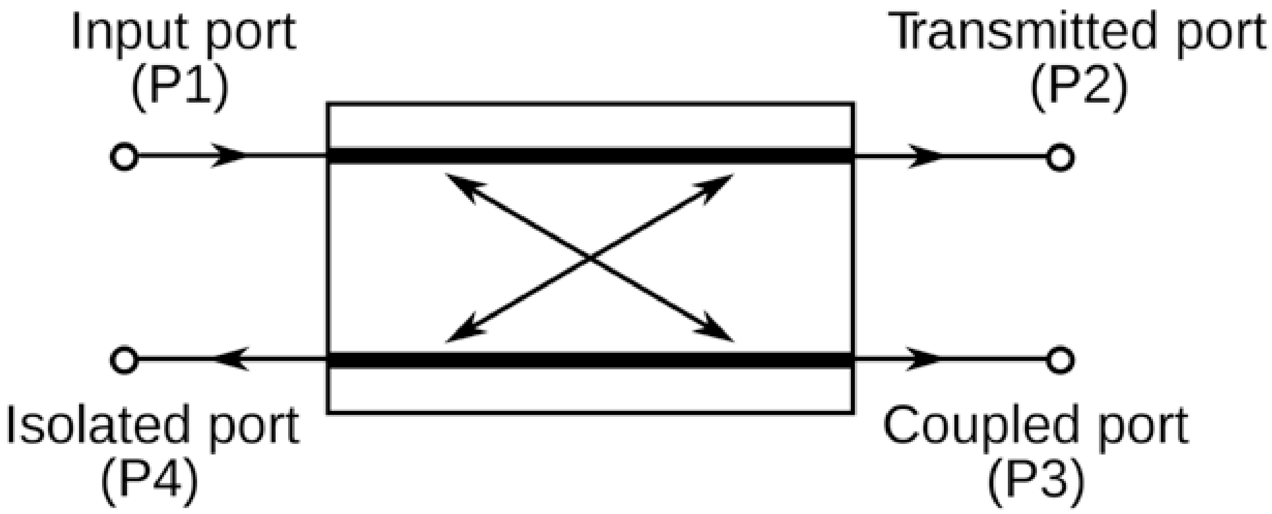


Fig. 3. Simulated (solid) and measured (dot) phase imbalance.

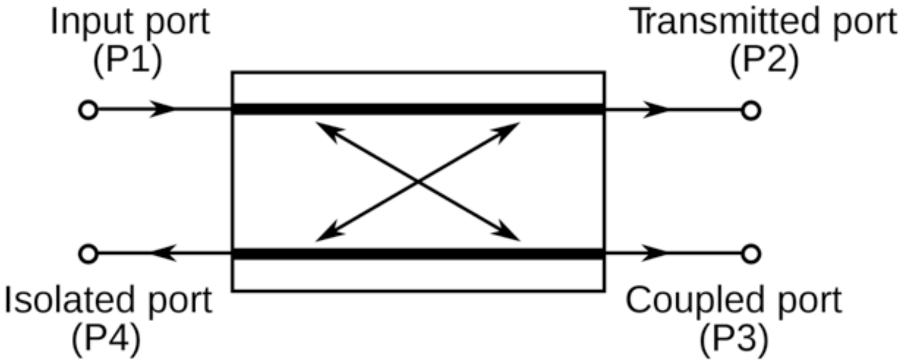
from P. Sobis, J. Stake, and A. Emrich, “A 170 GHz 45° Hybrid for Submillimeter Wave Sideband Separating Subharmonic Mixers,” *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 10, pp. 680–682, Oct. 2008.

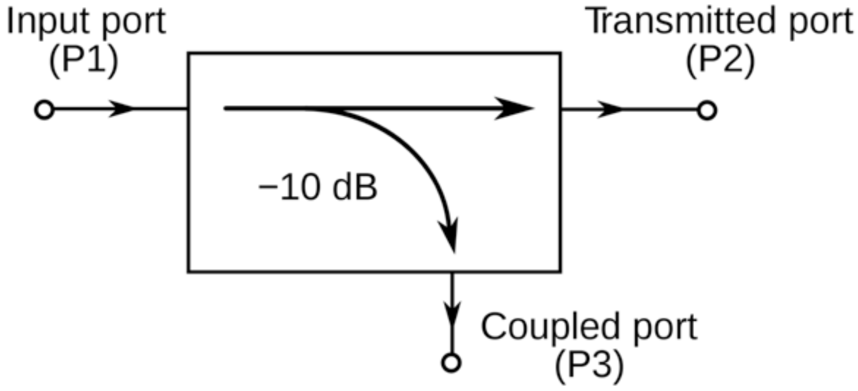


# Directional couplers

# Properties

- All ports matched
- Ex) Incident power at port 1 couples to port 2 and 3, but not into port 4. Hence, ports 1 & 4 are uncoupled





# Applications

- Power monitoring
- Impedance measurement (reflectivity)
- Power dividers (distributing networks)

# S-parameter test set-up

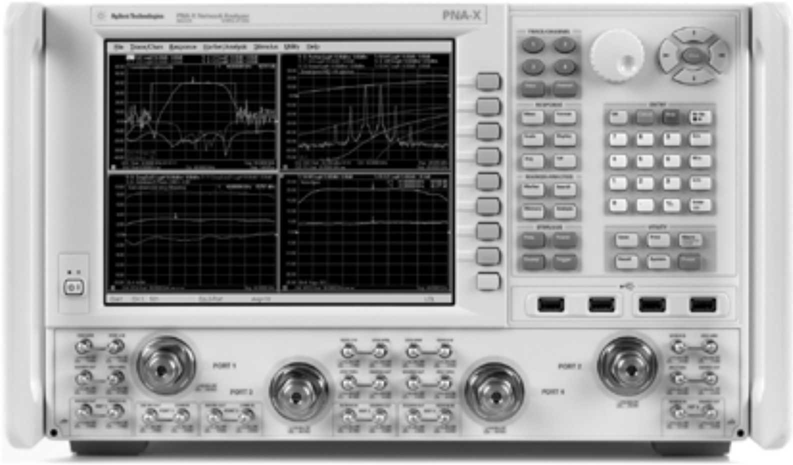
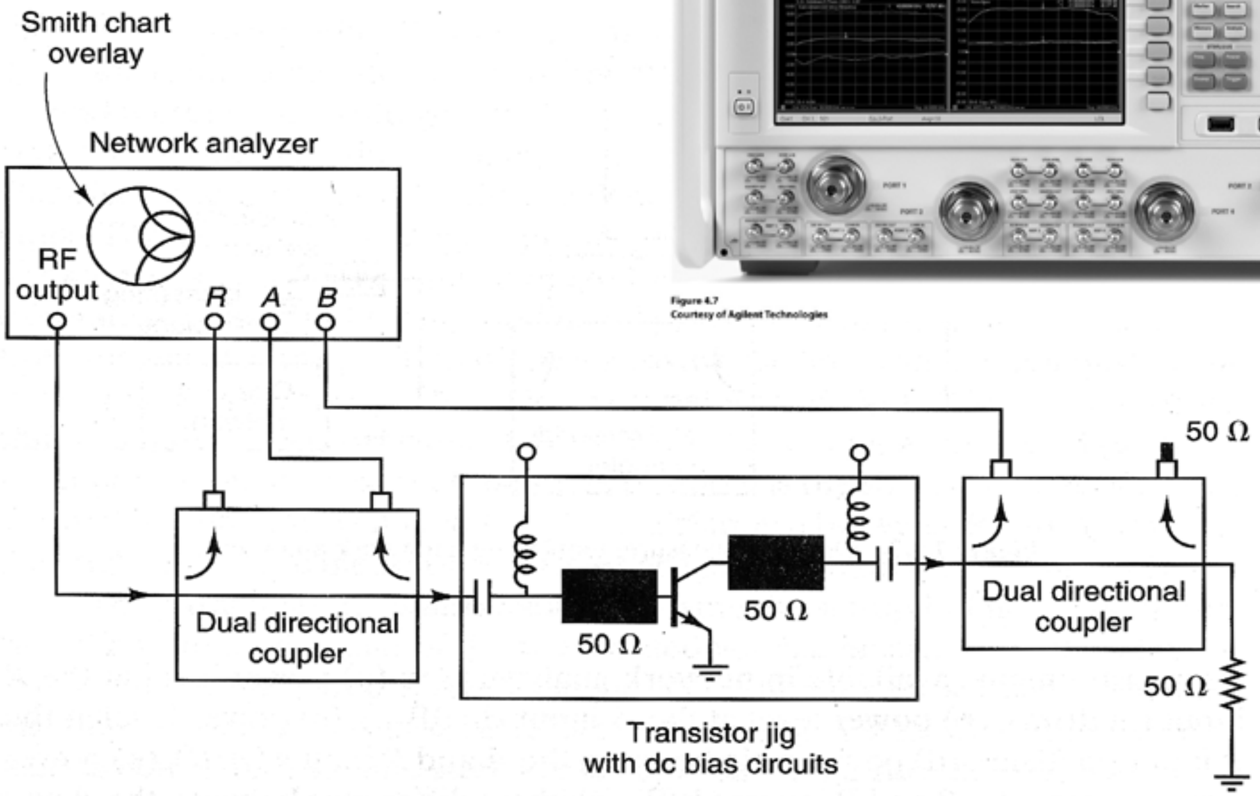
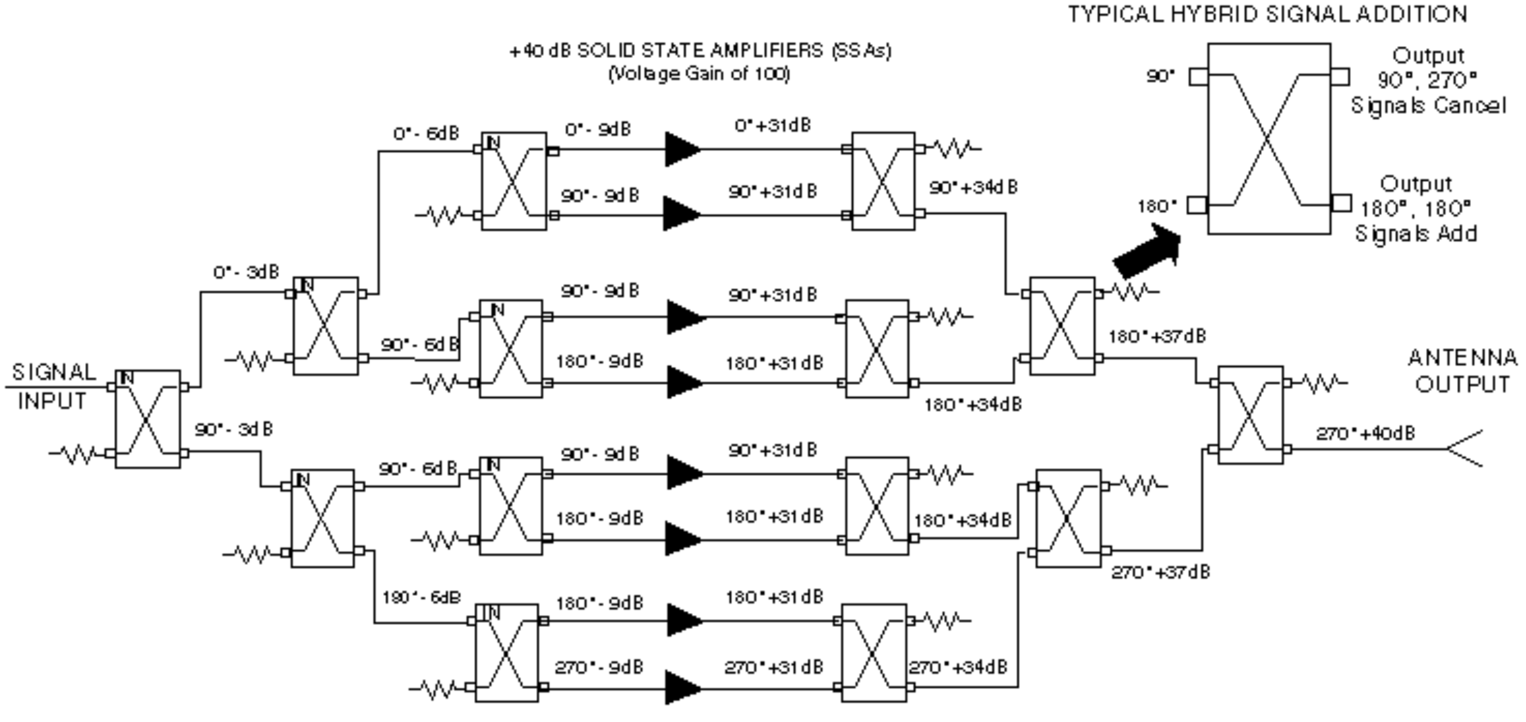


Figure 4.7
Courtesy of Agilent Technologies

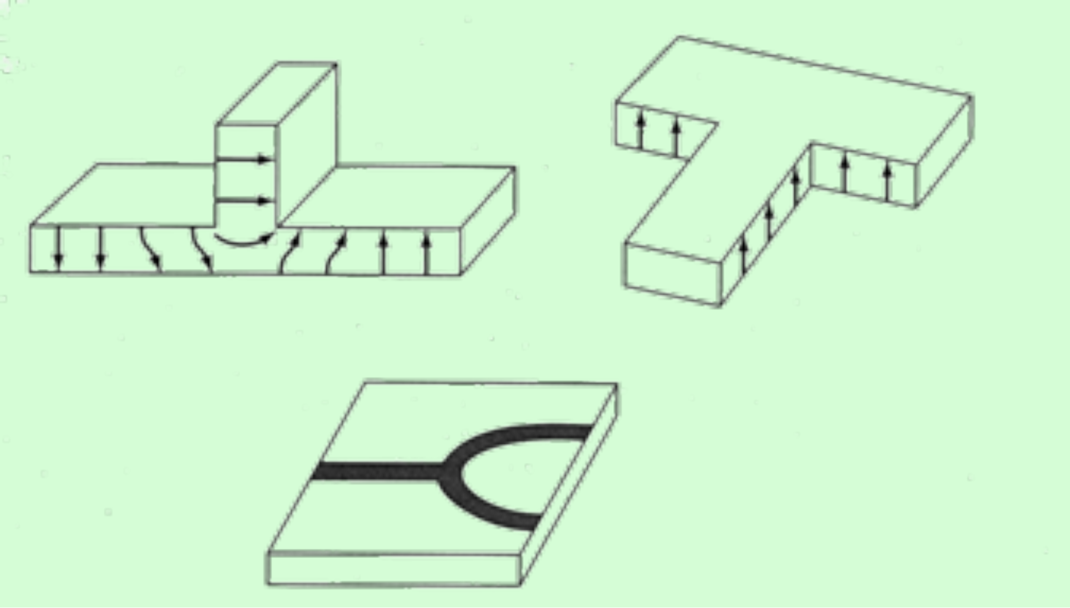


# Power combining networks



NOTE: All isolated ports of the hybrids have matched terminations. They have signals which are out of phase and cancel

**Figure 6.** Combiner Network



# Power dividers

# Power dividers or combiners

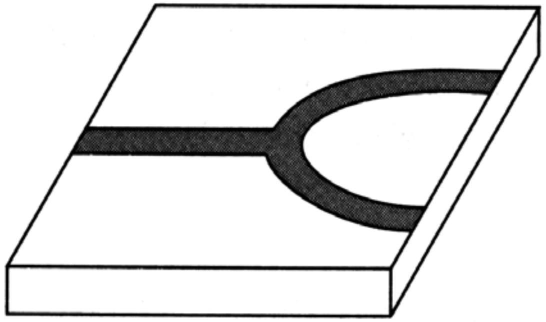
- Power divider is used to divide input power among several outputs
- We want:
  - reciprocal
  - lossless
  - matched

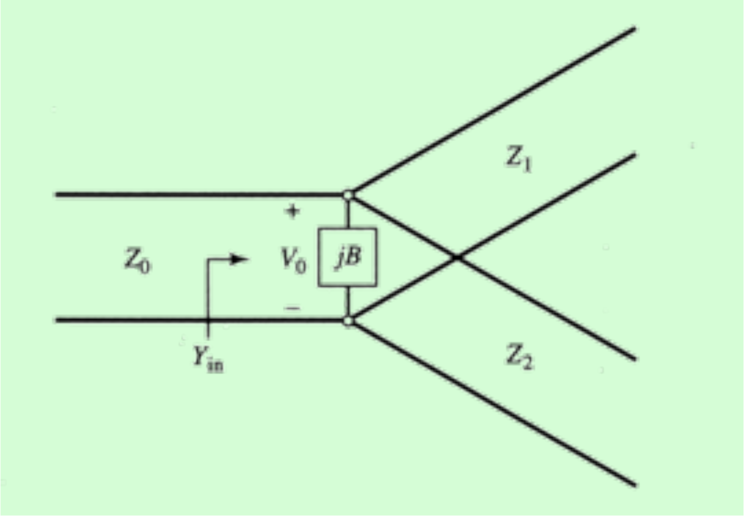
$$[s] = \begin{bmatrix} 0 & s_{12} & s_{13} \\ s_{12} & 0 & s_{23} \\ s_{13} & s_{23} & 0 \end{bmatrix}$$

*Impossible!*
*must relax one of the conditions*

- *On white board: Derive properties for a passive reciprocal 3-port*

# Lossless divider

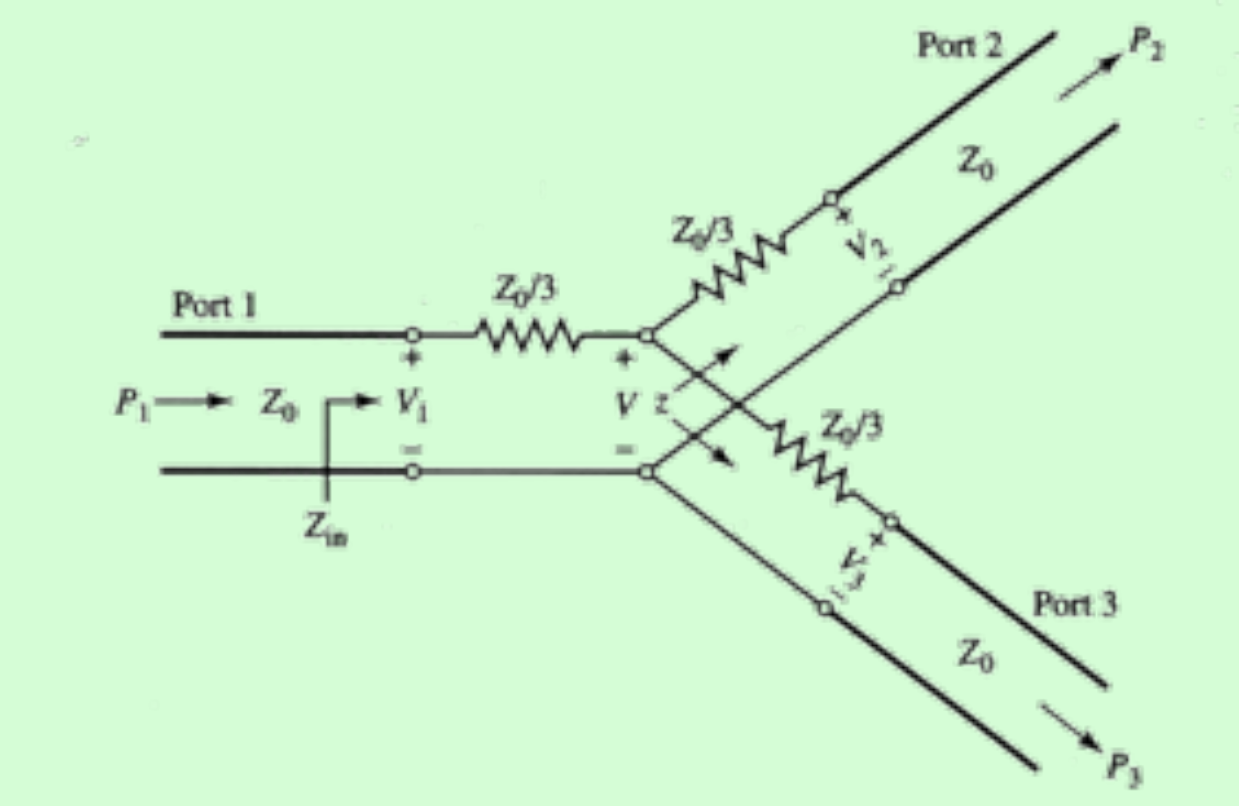




Can not be matched at all ports, and no isolation!

- *On white board: Show that a 2-way lossless divider (three-port junction) can not be simultaneously matched.*

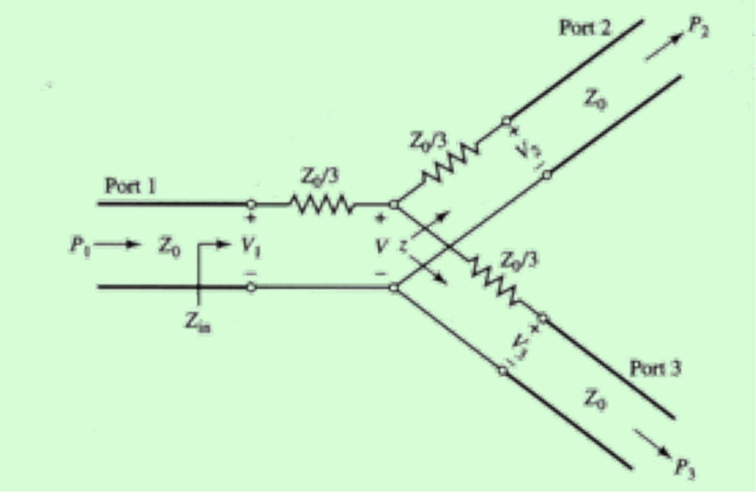
# Resistive divider



Lossy and reciprocal, thus can be matched at all ports

No isolation!

- *On white board: Derive properties for a 3-port resistive divider.*



$$[s]=\frac{1}{2}\begin{bmatrix}0 & 1 & 1\\ 1 & 0 & \textcircled{1}\\ 1 & \textcircled{1} & 0\end{bmatrix}$$

No isolation

The matrix is not unitary!!!!!

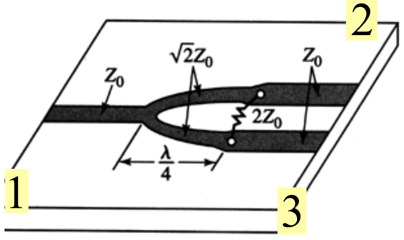
$$[s]^{*}\neq\left\{[s]^{T}\right\}^{-1}$$

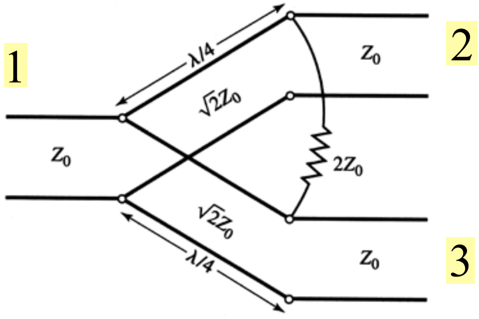
$$P_{in}=\frac{1}{2}\frac{V_1^2}{Z_0};\ P_2=P_3=\frac{1}{2}\frac{\left(\frac{1}{2}V_1\right)^2}{Z_0}=\frac{1}{8}\frac{V_1^2}{Z_0}=\frac{1}{4}P_{in}$$

Half of the incident power is lost in the power divider

# The Wilkinson power divider

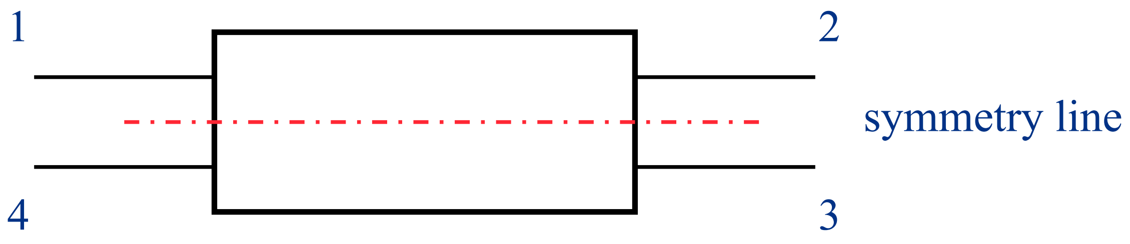
- The Wilkinson power divider is lossless, when the output ports are matched, and has isolation between the output ports.





# Even and odd mode method

Consider a **linear**, **reciprocal** 4-port with a **symmetry** line as marked

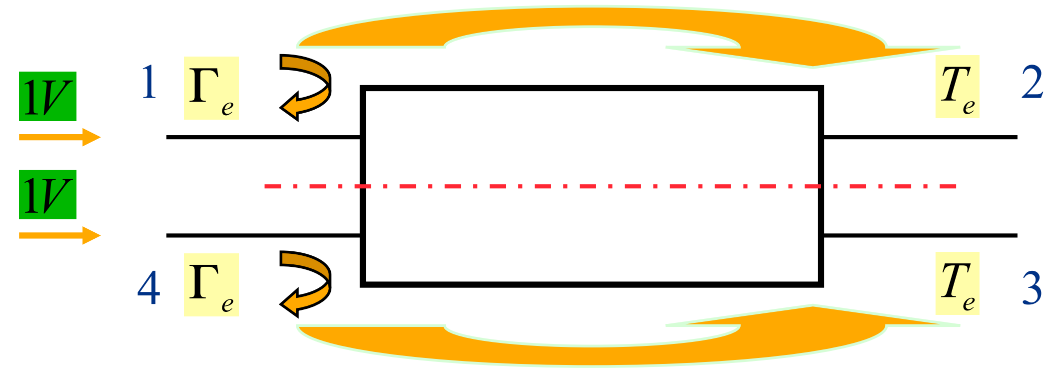


We will analyze this circuit by using the *even* and *odd mode* method. The method is based on two excitations: even and odd, applied to the ports on opposite sides of the symmetry line (in our case port 1 and 4). The even excitation corresponds to two voltages equal in amplitude and phase, e.g. +1V. The odd excitation corresponds to two voltages equal in amplitude but with 180° phase difference (+1V, and –1 V).

By applying the **even excitation** to the ports 1(+1 V), and 4(+1 V) the symmetry line will act as an **open circuit** or as we say **magnetic wall**.

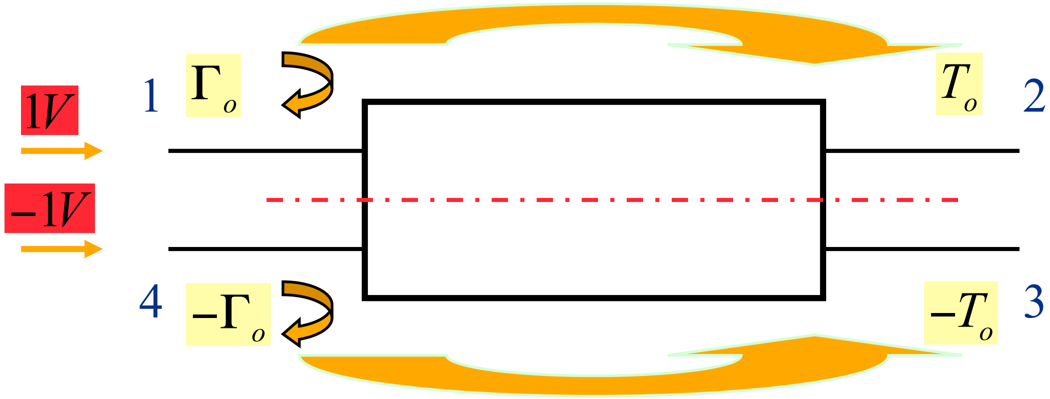
By applying the **odd excitation** to the ports 1(+1V), and 4(-1V) the symmetry line will act as a **short circuit** or as we say **electric wall**.

## Even mode



symmetry line
⇩
open circuit
⇩
*magnetic* wall

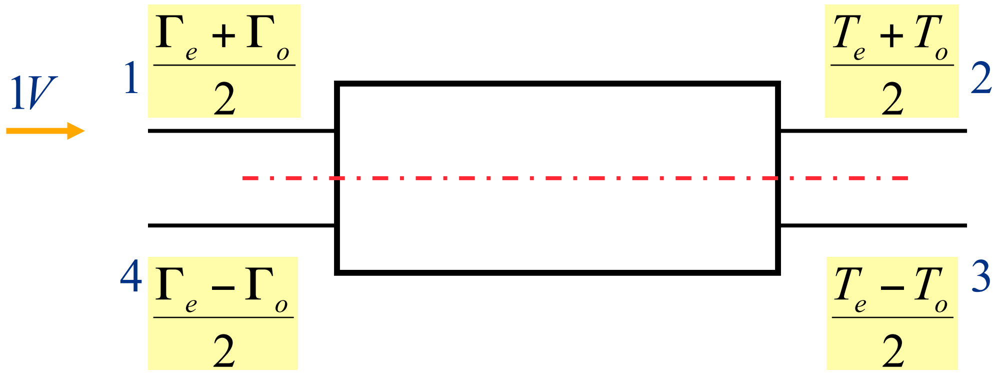
## Odd mode



symmetry line
⇩
short circuit
⇩
*electric* wall

© J. Piotr Starski

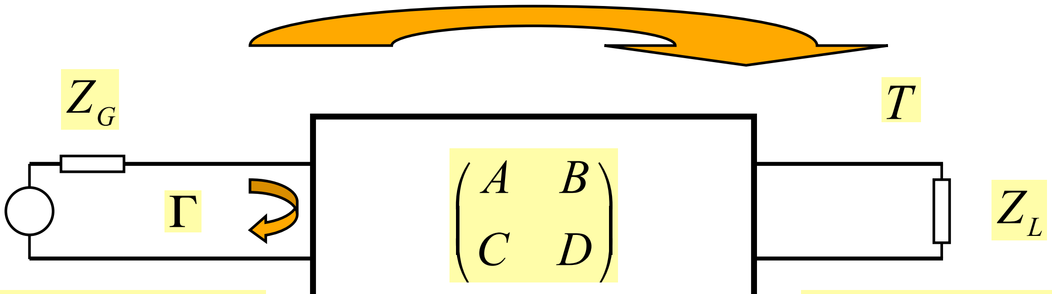
We superimpose now both excitations:



We have only excitation in port 1 and can calculate the reflected and transmitted waves in all ports.

This means that the analysis of a reciprocal, linear 4-port with a symmetry property can be performed by analyzing two 2-ports in two excitation modes and superposition of the results.

$\Gamma$ and $T$ for the 2-ports can be easily calculated from the cascade matrix analysis



$$\Gamma = \frac{AZ_L + B - CZ_GZ_L - DZ_G}{AZ_L + B + CZ_GZ_L + DZ_G}$$

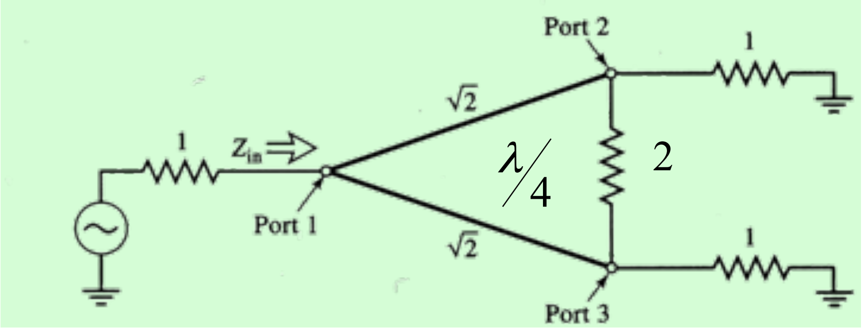
$$T = \frac{Z_G + Z_L}{AZ_L + B + CZ_GZ_L + DZ_G}$$

© J. Piotr Starski

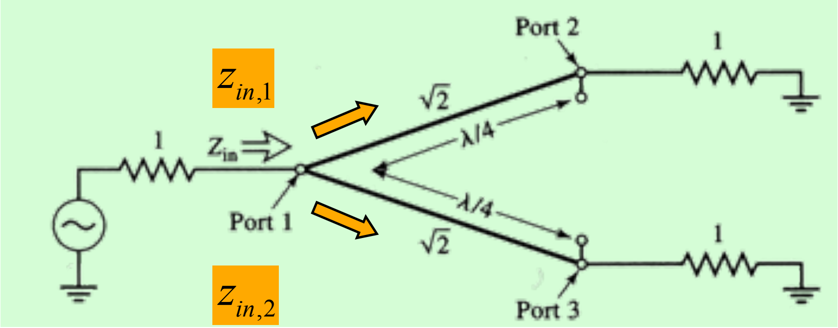
- *On white board: analyse the Wilkinson divider (3-dB case, three port)*

# Wilkinson divider: S matrix

$s_{11}$



The circuit is excited from port 1-
no current through isolating resistor



$$z_{in,1,2} = \frac{\left(\sqrt{2}\right)^2}{1} = 2; \quad z_{in} = \frac{2\bullet 2}{2+2} = 1$$

$$s_{11} = 0, \text{since } \Gamma = \frac{z_{in}-1}{z_{in}+1}$$

© J. Piotr Starski

# Wilkinson divider: S matrix

From previous calculations we have $s_{22} = s_{33}$

$$s_{12} = \frac{V_{1,e} + V_{1,o}}{V_{2,e} + V_{2,o}} = \frac{-j\sqrt{2} \bullet V + 0}{V + V} = -j\frac{1}{\sqrt{2}}$$

$$s_{12} = s_{21}$$

$$s_{13} = s_{31} = s_{12} = -\frac{j}{\sqrt{2}}$$ because the circuit is symmetric

$$s_{23} = s_{32} = 0$$ depending on the open or short circuit at the symmetry line

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

# ex) 4 way power divider

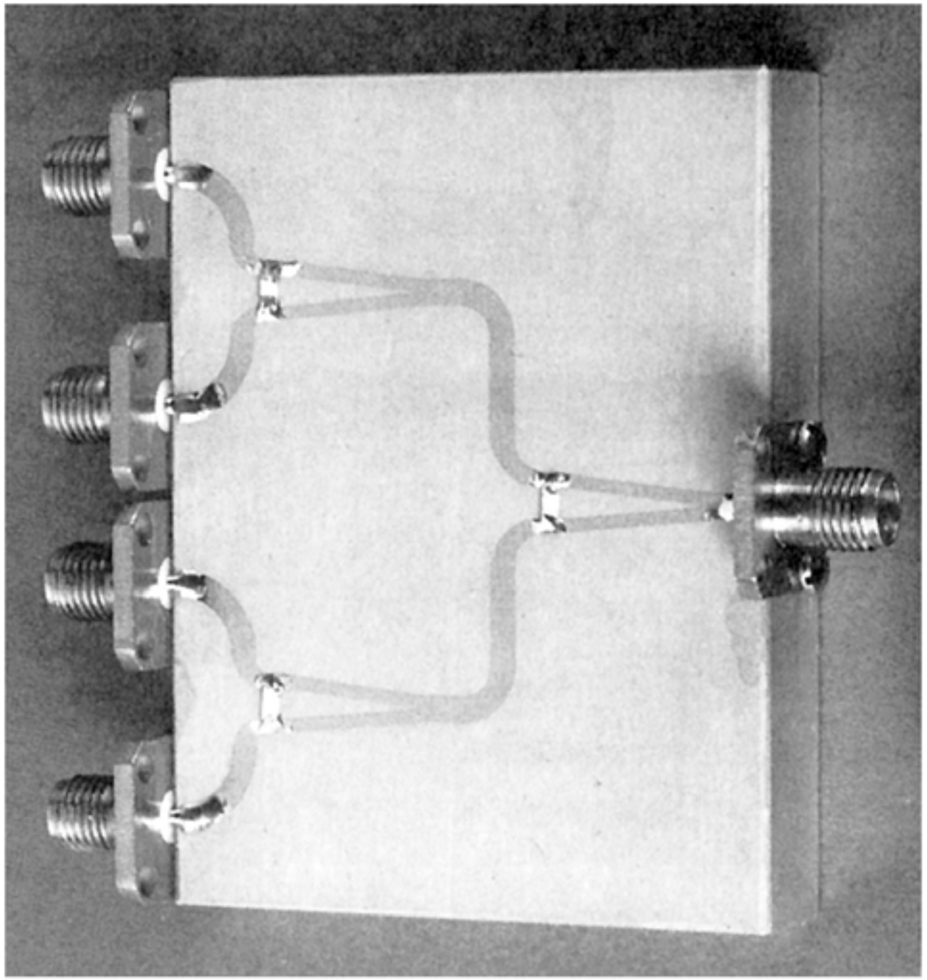
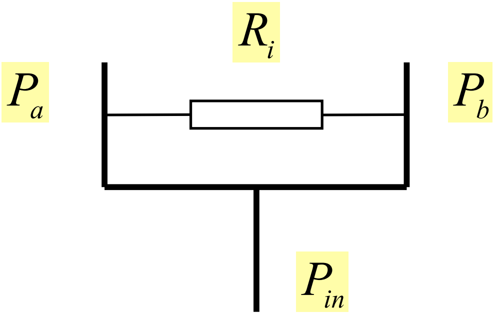


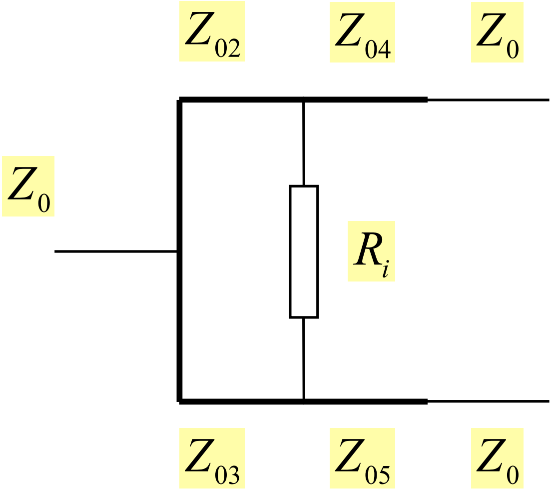
**Figure 7.15**
**Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.**

# Wilkinson unequal power divider



$$\frac{P_b}{P_a} = k^2 \Rightarrow k = \sqrt{\frac{P_b}{P_a}}$$

$$\left.\begin{aligned} P_a &= P_{in}\frac{1}{1+k^2} \\ P_b &= P_{in}\frac{k^2}{1+k^2} \end{aligned}\right\} P_a + P_b = P_{in}$$



$$Z_{02} = Z_0\sqrt{k(1+k^2)}$$

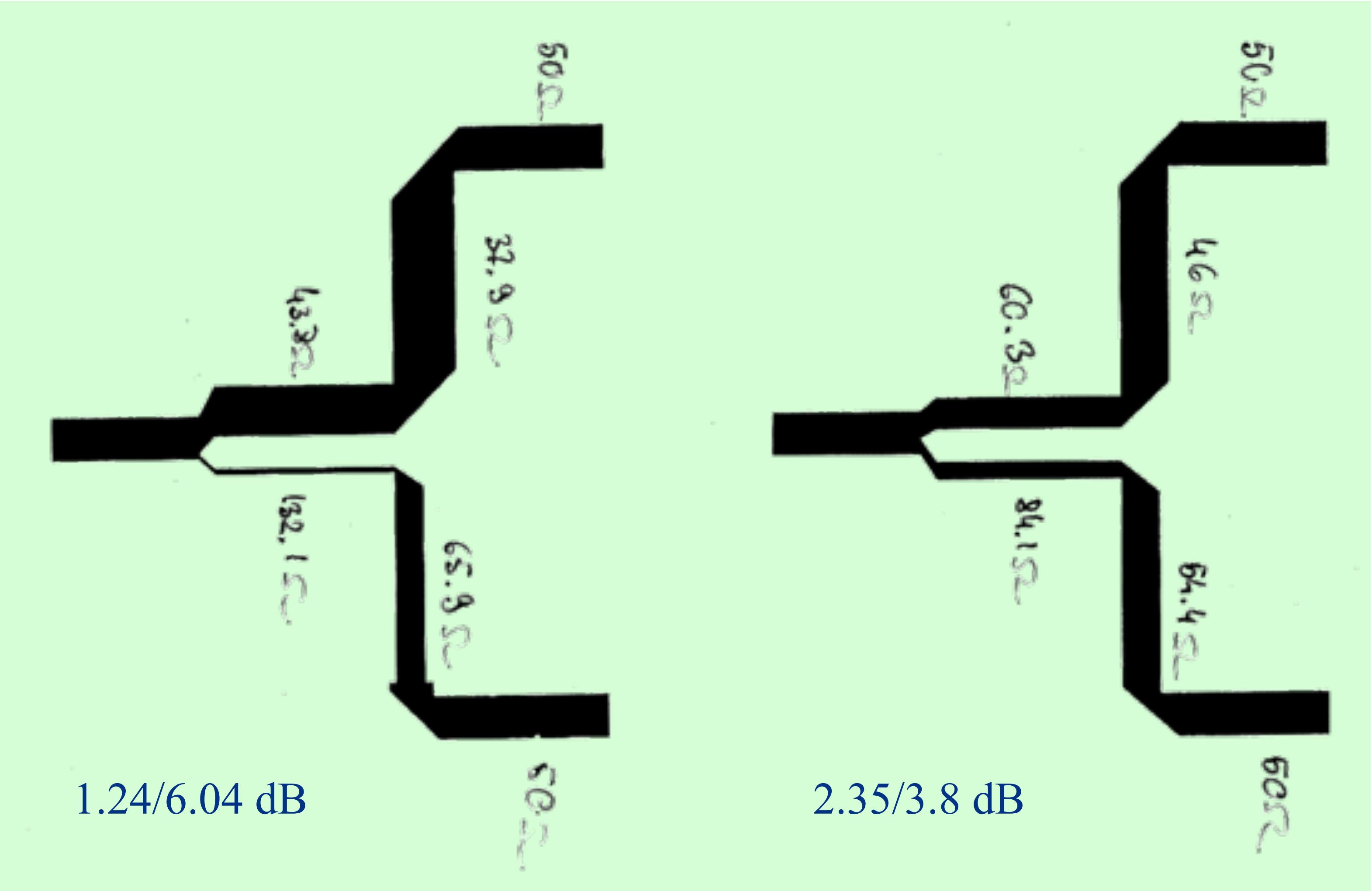
$$Z_{03} = \frac{Z_0}{k}\sqrt{\frac{1+k^2}{k}}$$

$$Z_{04} = Z_0\sqrt{k}$$

$$Z_{05} = \frac{Z_0}{\sqrt{k}}$$

$$R_i = Z_0\frac{1+k^2}{k}$$

# Typical examples of Wilkinson power dividers with unequal power split



1.24/6.04 dB

2.35/3.8 dB

© J. Piotr Starski

# Summary of lecture 8

- Read chapter 7.1-7.4 (dividers).
  - Attenuators, phase shifters
  - Directional couplers

# Further reading

- Ernest J. Wilkinson, "An N-Way Hybrid Power Divider," IRE Transactions on Microwave Theory and Techniques, vol. 8, no. 1, pp. 116–118, 1960.
- S. Cohn and R. Levy, "History of Microwave Passive Components with Particular Attention to Directional Couplers," IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 9, pp. 1046–1054, 1984.