Lecture 14

FULL-WAVE ANALYSIS AND EQUIVALENT-CIRCUIT MODELING OF SIW COMPONENTS

OUTLINE

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- Introduction on Substrate Integrated Waveguide (SIW) components
- Basic concepts of the Boundary Integral-Resonant Mode Expansion (BI-RME) method
- BI-RME modeling of SIW interconnects
- BI-RME modeling of SIW components
- Effect of losses
- Equivalent circuit models of SIW discontinuities
- Conclusions

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SUBSTRATE INTEGRATED WAVEGUIDE

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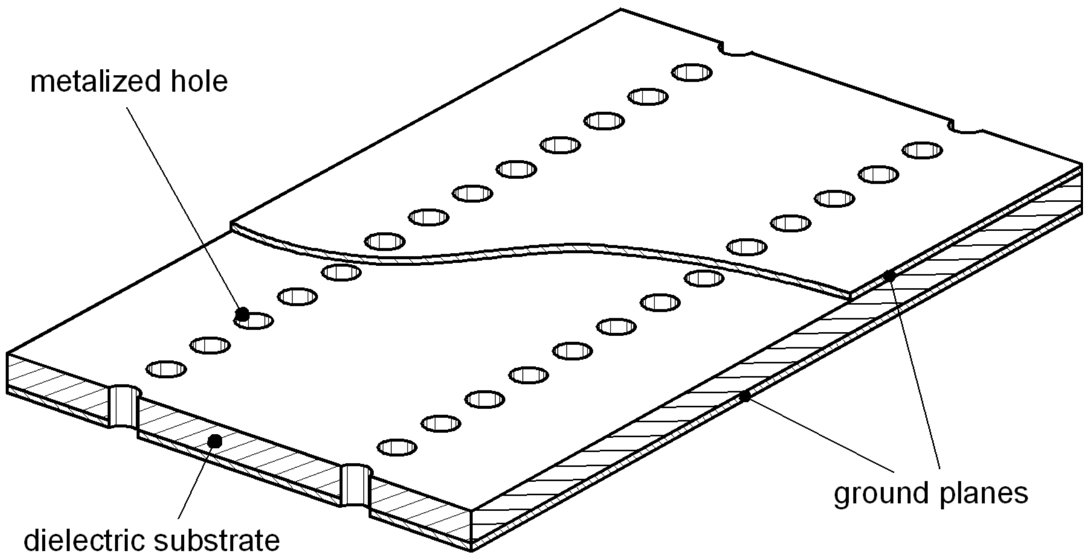
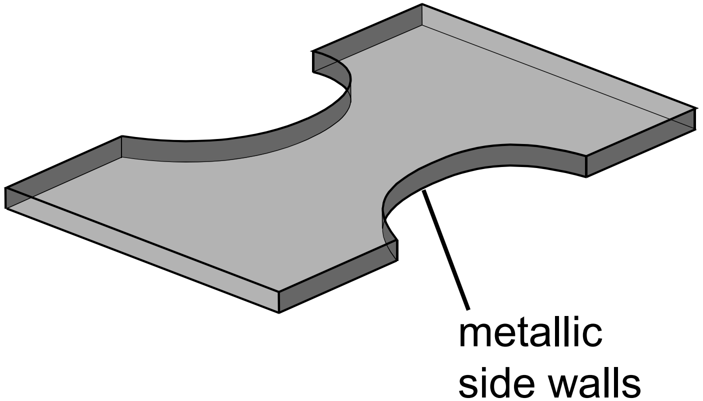
Substrate Integrated Waveguides (**SIW**) are novel transmission lines that implement rectangular waveguides in planar form.



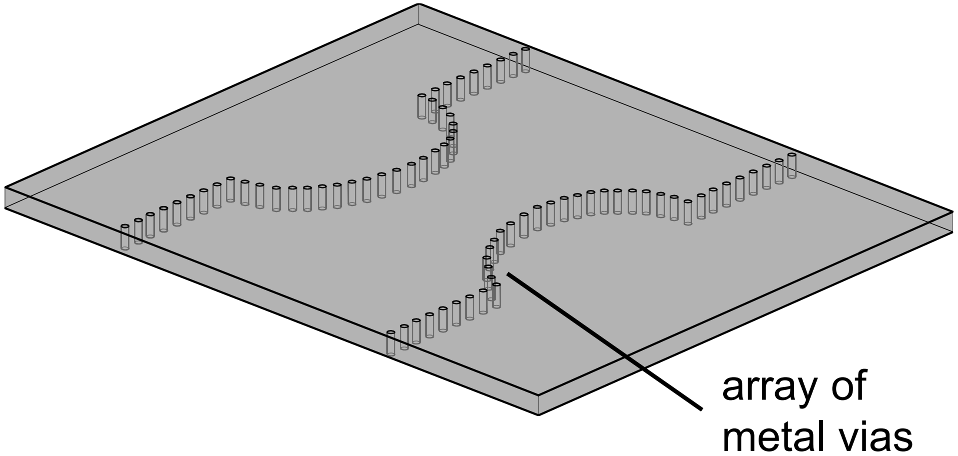
SIW consist of two rows of conducting cylinders embedded in a dielectric substrate that connect two parallel metal plates.

SIW COMPONENTS

SIW technology permits to realize waveguide components in a dielectric substrate by replacing the metallic side walls by arrays of metal vias.

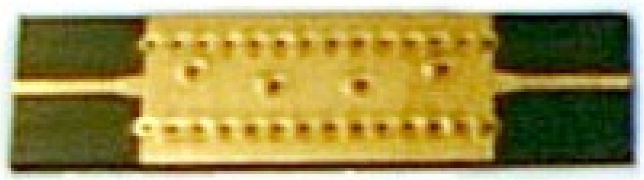


planar waveguide component

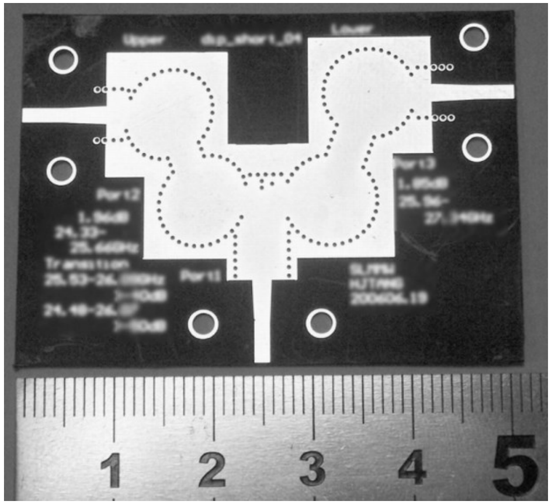


corresponding SIW component

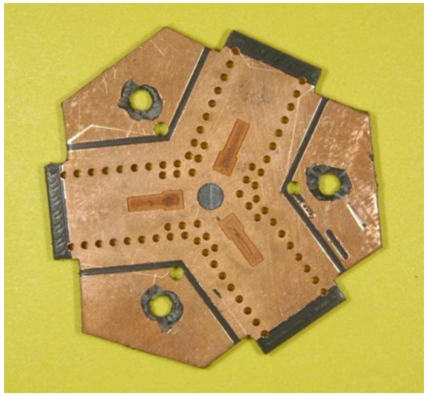
EXAMPLES OF SIW COMPONENTS



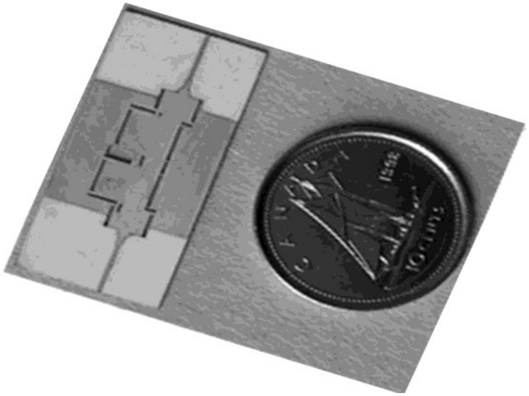
SIW post filter at 27 GHZ



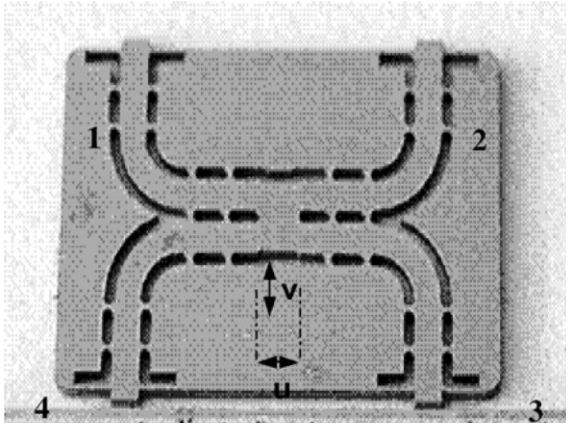
SIW diplexer at 26 GHz



SIW circulator at 24 GHz



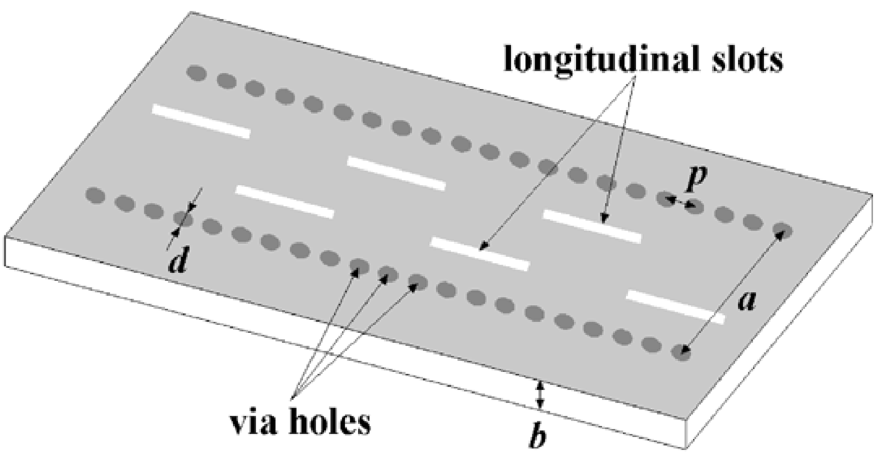
SIW dual-mode filter

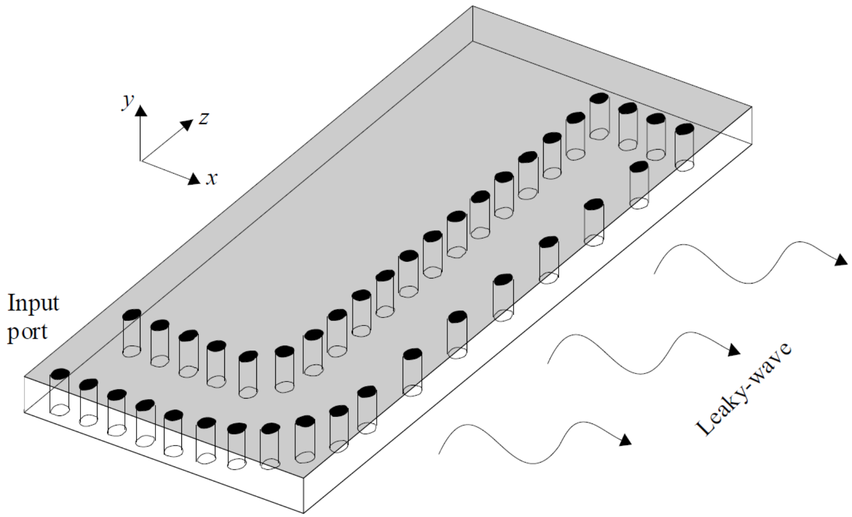


SIW hybrid coupler at 94 GHz

There are two major topologies of SIW antennas:

- slotted waveguide antennas are based on longitudinal slots;
- leaky-wave SIW antennas, obtained by properly spacing the metal vias in order to create radiation leakage.





SYSTEMS-ON-SUBSTRATE (SOS)

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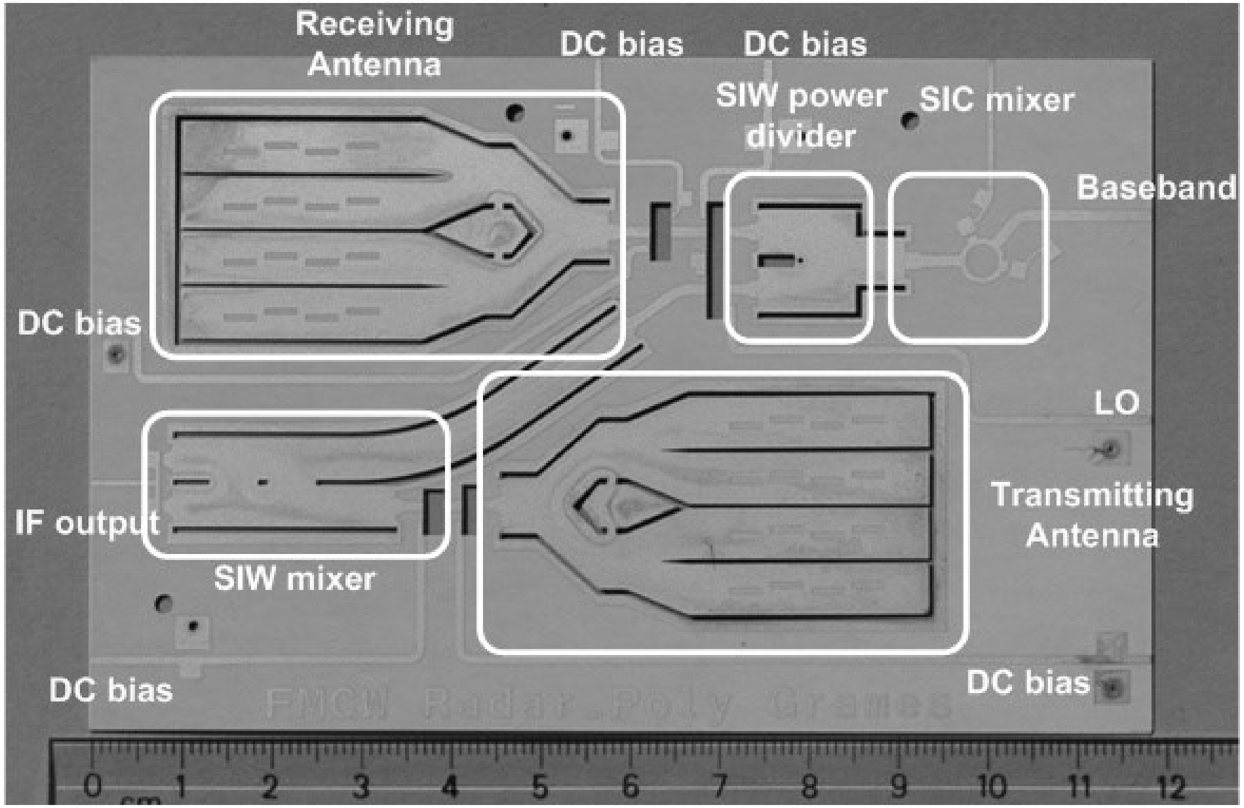
Replacing the current System-in-Package (SiP) approach with the System-on-Substrate (SoS) concept for mm-wave systems.



Z. Li and K. Wu, “24-GHz Frequency-Modulation Continuous-Wave Radar Front-End System-on-Substrate,” *IEEE Trans. on Microwave Theory and Techniques*, Vol. 56, No. 2, pp. 278-285, Feb. 2008.

ADVANTAGES OF SIW TECHNOLOGY

complete circuit in planar form (including passive components, active elements and antennas)

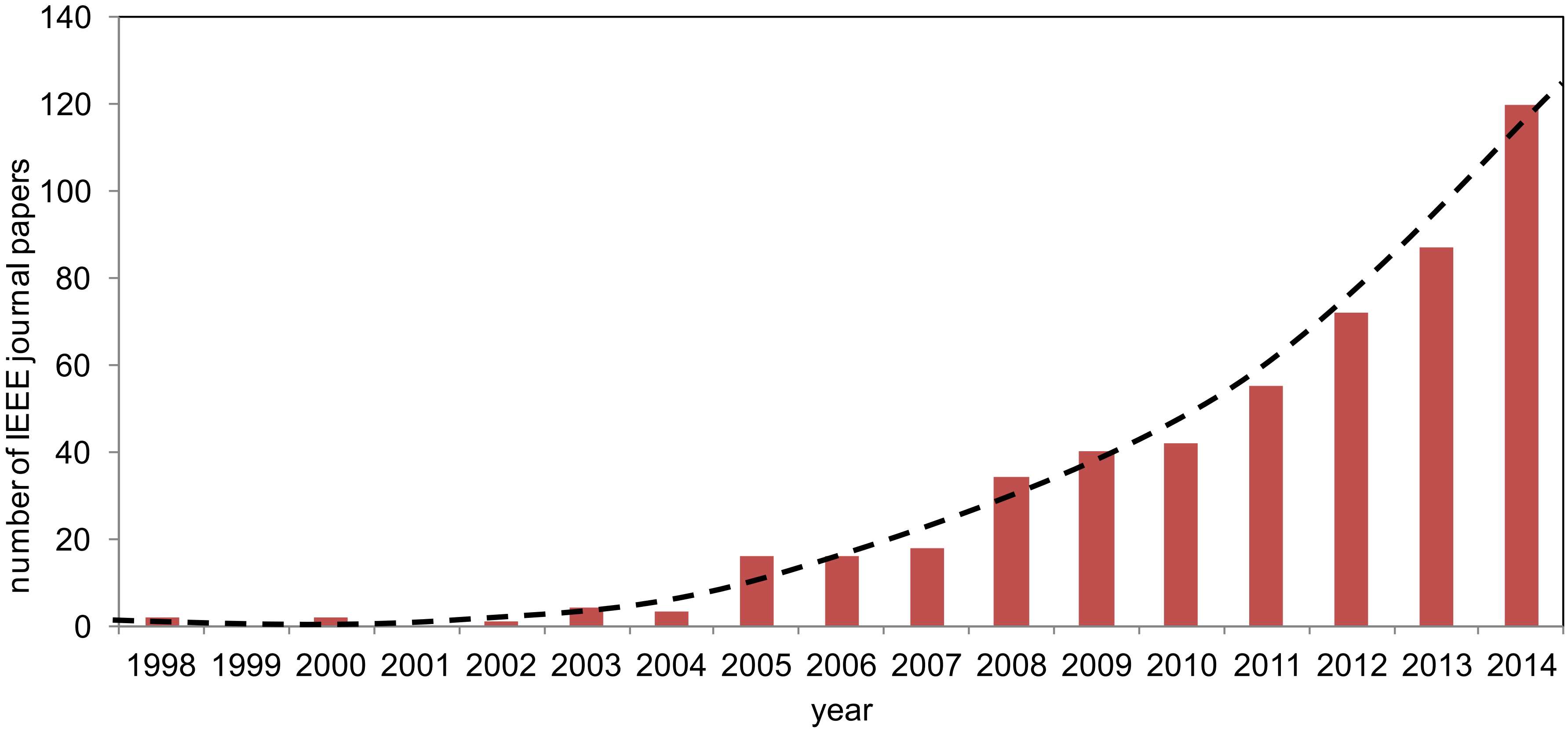
low-cost and well–developed manufacturing process (PCB, LTCC, …)

high-density integration of mm-wave components & systems

complete shielding (no interference) and **low losses** (energy saving!)

EVOLUTION OF RESEARCH ON SIW

There is a growing interest for SIW technology worldwide.



Number of publications on the SIW in IEEE journals (source: ieeexplore.ieee.org)

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THE BI-RME METHOD

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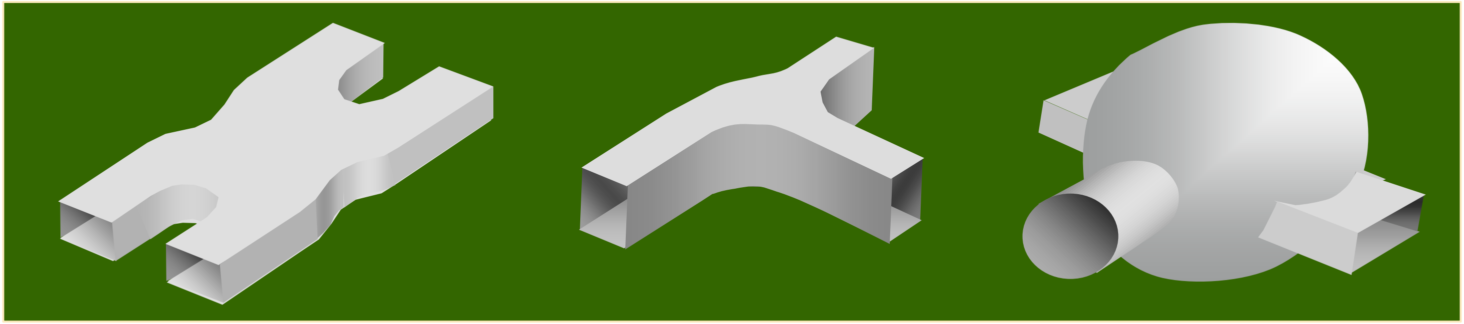
BI-RME = Boundary Integral-Resonant Mode Expansion

Originally **developed at the University of Pavia** for the modeling of waveguide circuits:



H-plane circuit E-plane circuit 3D circuit

G. Conciauro, "The BI-RME method," Chap. 5 in: G. Conciauro, M. Guglielmi, and R. Sorrentino, *Advanced Modal Analysis*, New York, Wiley, 2000.

THE BI-RME METHOD

The BI-RME method yields the admittance matrix ***Y*** of a **lossless** and **shielded** waveguide component in the form of a pole expansion in the frequency domain:

$$Y_{ij} = \boxed{\frac{1}{j\omega}A_{ij} + j\omega B_{ij}} + j\omega^3 \sum_{\boxed{m}=1}^{M} \frac{C_{im}C_{jm}}{\omega_m^2(\omega_m^2 - \omega^2)}$$

low-frequency terms — modes of the cavity

where ***A***, ***B***, ***C***, **ω** are frequency-independent matrices obtained by solving a single real eigenvalue problem.

THE BI-RME METHOD

Advantages of the BI-RME method:

- Modeling of components with arbitrarily shaped geometry
- Mathematical model of the component in the form of the pole expansion of the Y-parameters
- Very fast!

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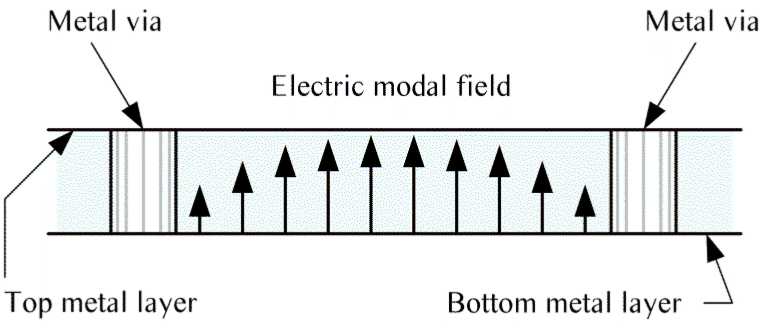
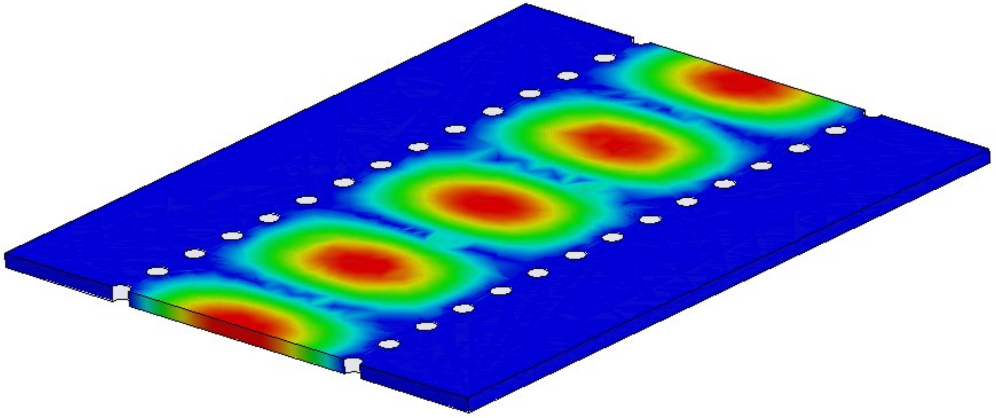
SIW INTERCONNECTS

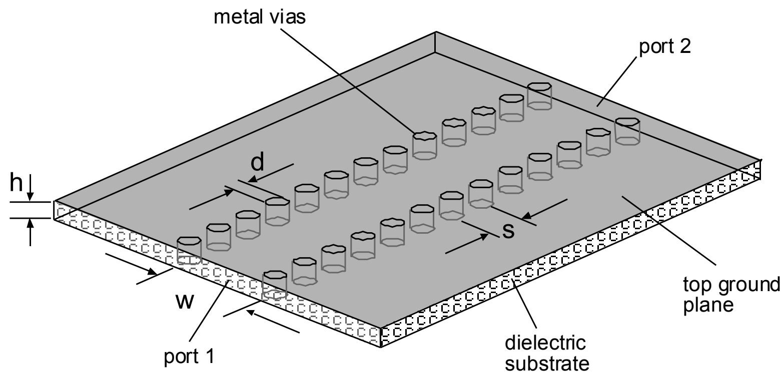
The **modal field propagation** in SIW interconnects is similar to classical rectangular waveguides (TE_{n0} modes, n=1, 2, …).



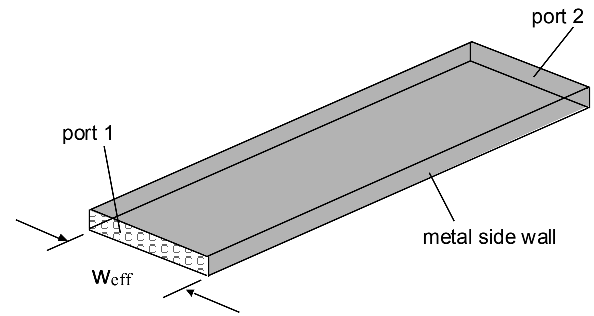


Equivalent Waveguide

It is possible to define an **equivalent rectangular waveguide**, whose mode spectrum coincides with the SIW mode spectrum.



SIW STRUCTURE



EQUIVALENT RECTANGULAR WAVEGUIDE

$$w_{\mathrm{eff}} = w - \frac{d^2}{0.95\, s}$$

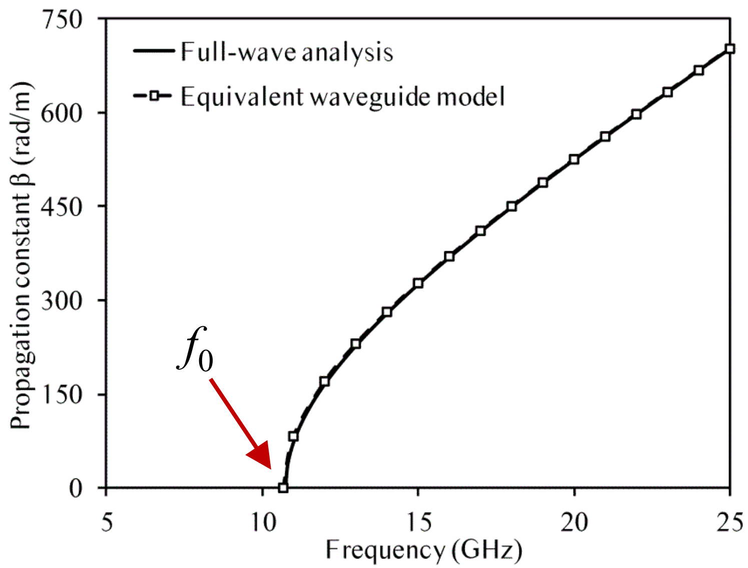
EQUIVALENT WIDTH

EQUIVALENT WAVEGUIDE

Once the equivalent width w_{eff} has been determined:

$$f_0 = \frac{c}{2\,w_{\text{eff}}\sqrt{\varepsilon_r}}$$

$$\beta(f) = \sqrt{\left(\frac{2\pi f\sqrt{\varepsilon_r}}{c}\right)^2 - \left(\frac{\pi}{w_{\text{eff}}}\right)^2}$$

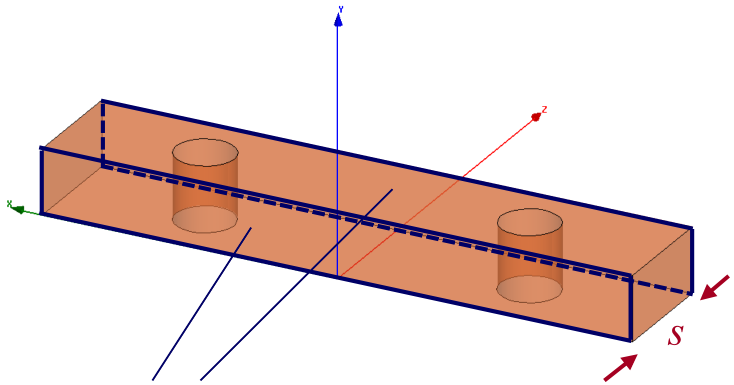


Example – Propagation constant versus frequency for the fundamental mode of an SIW (w = 10 mm, d = 1 mm, s = 2 mm, h = 1 mm, ε_r = 2.2).

MODELING OF SIW INTERCONNECTS

Full-wave modeling by using **commercial software** (e.g. HFSS)

The analysis of the unit cell provides, for each phase shift φ, the eigen-frequencies f and the quality factors Q.



propagation constant $$\beta = \frac{\varphi}{S}$$

attenuation constant $$\alpha = \frac{\pi f}{v_g Q}$$ where $$v_g = 2\pi \frac{\partial f}{\partial \beta}$$

MODELING OF SIW INTERCONNECTS

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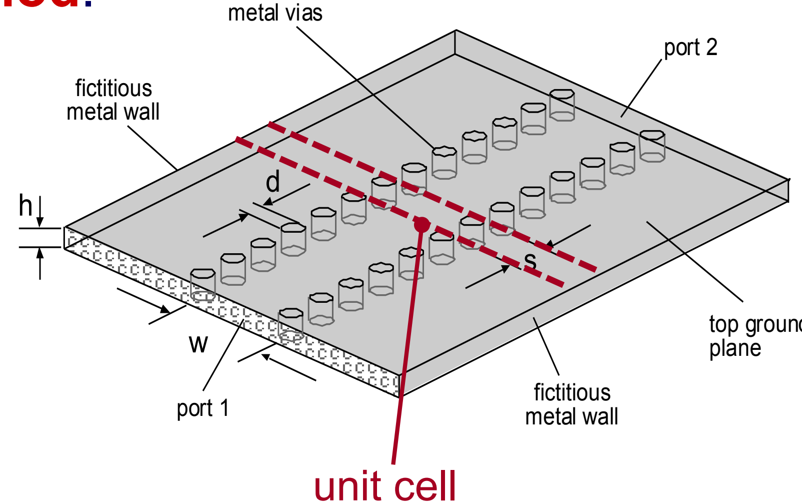
Full-wave modeling by the **BI-RME method**.



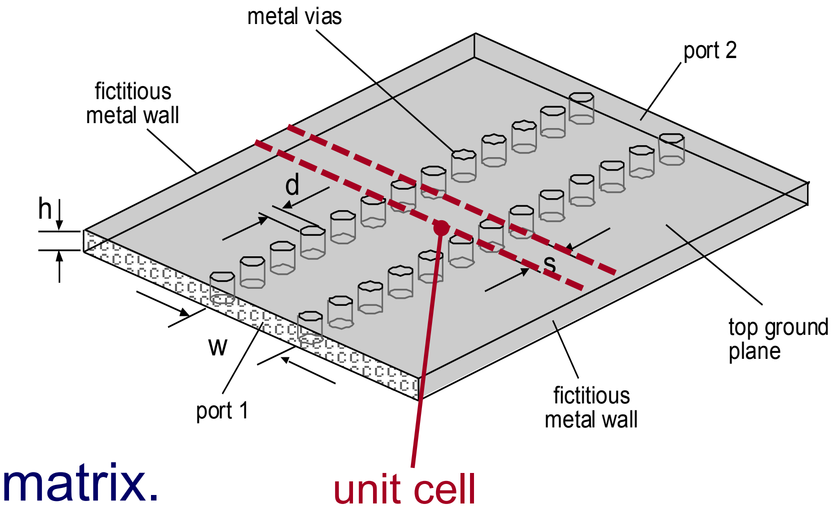
The unit cell of a 1D periodic structure is considered.

Preliminary hypotheses are needed to apply the BI-RME method:

- lossless dielectric material and perfect conductor
- no radiation (addition of fictitious metallic side walls)
- embedding rectangular ports with modal vector $\mathbf{E}_{WG}$.

MODELING OF SIW INTERCONNECTS

The modal propagation constants can be obtained by formulating an **eigenvalue problem** for the unit cell.



The $ABCD$ matrix is derived from the $\boldsymbol{Y}$ matrix.

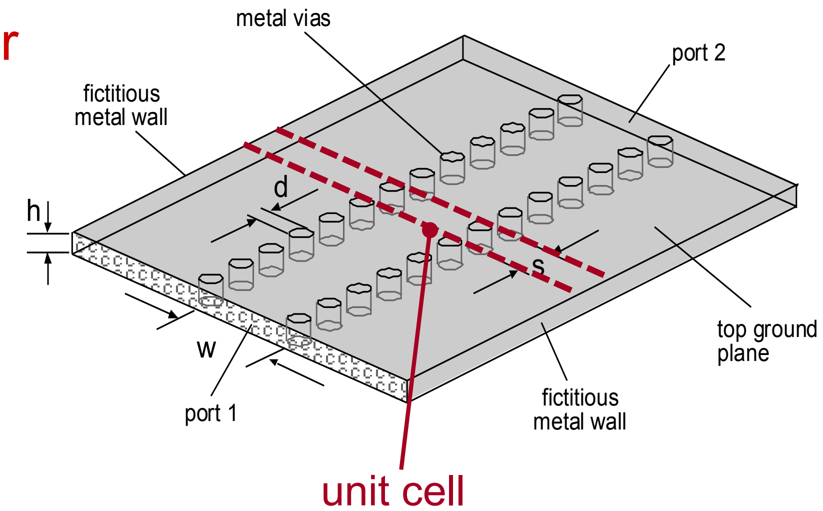
$$\begin{bmatrix} ABCD_{11} & ABCD_{12} \\ ABCD_{21} & ABCD_{22} \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} = e^{j\beta s} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

The eigenvalues at each frequency permit to determine the **propagation constant** of the modes.

Modeling of SIW Interconnects

The SIW modal vectors $\mathbf{E}_{\mathrm{SIW}}$ are a linear combination of the rectangular waveguide modal vectors $\mathbf{E}_{\mathrm{WG}}$:

$$\mathbf{E}_{\mathrm{SIW}} = \mathbf{T}\,\mathbf{E}_{\mathrm{WG}}$$



$$\mathbf{T} = \left(\begin{array}{ccc|ccc} V_{11} & \dots & V_{1P} & 0 & \dots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ V_{N1} & \dots & V_{NP} & 0 & \dots & 0 \\ \hline 0 & \dots & 0 & V_{11} & \dots & V_{1P} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & V_{N1} & \dots & V_{NP} \end{array}\right)$$

P-th eigenvector

EXAMPLE: SIW INTERCONNECT

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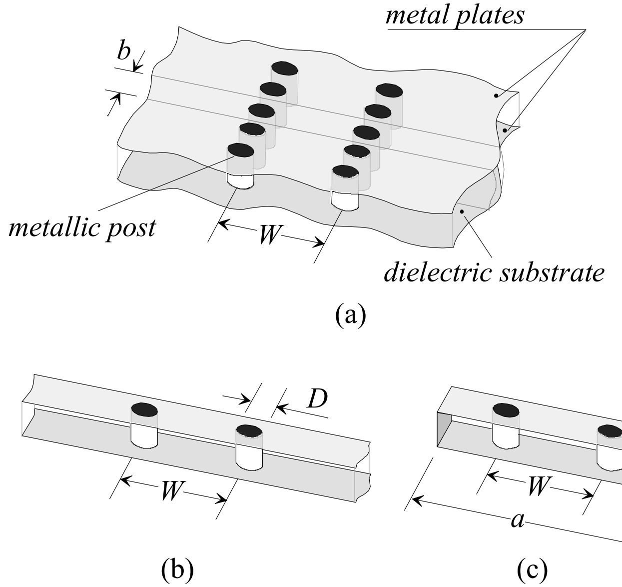

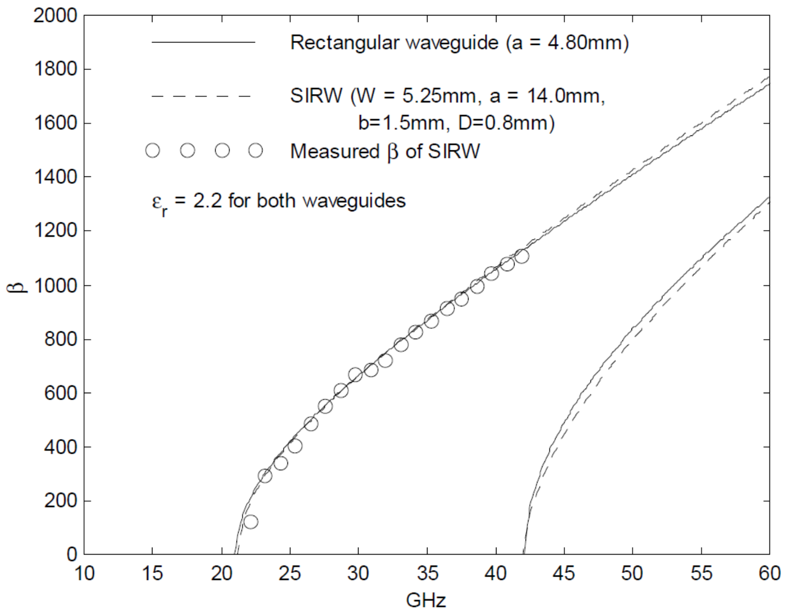

Y. Cassivi, L. Perregrini, P. Arcioni, M. Bressan, K. Wu, G. Conciauro, "Dispersion Characteristics of Substrate Integrated Rectangular Waveguide," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 9, pp. 333-335, Sept. 2002.

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MODELING OF SIW COMPONENTS

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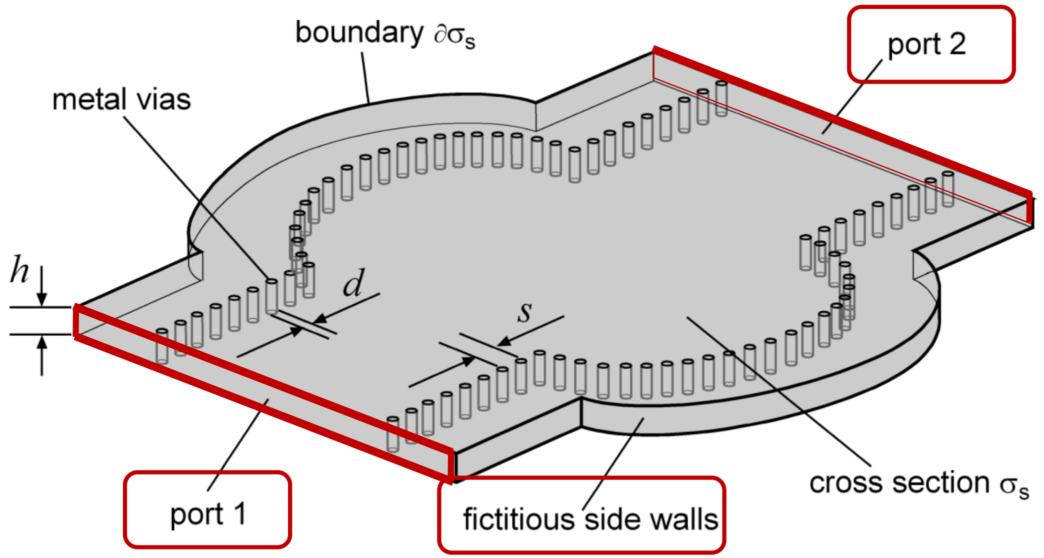
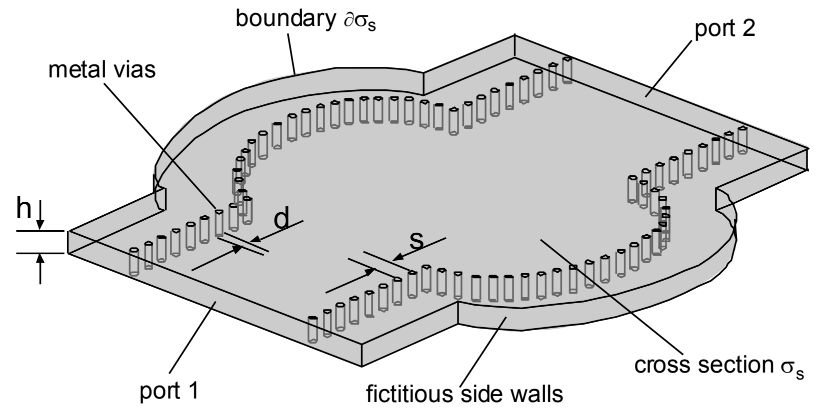
The BI-RME modeling of SIW components requires the calculation of the generalized admittance matrix $\mathbf{Y}$ (lossless case, rectangular ports).



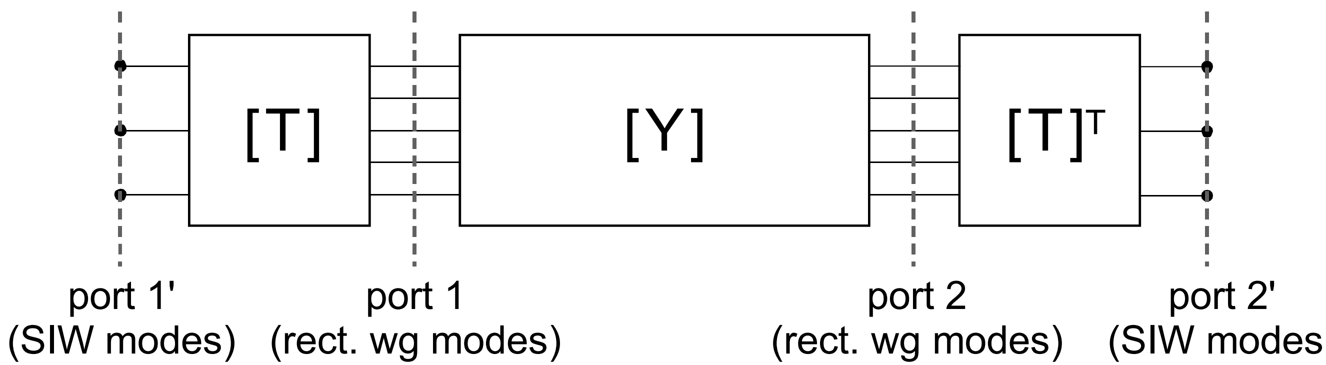
SIW circuits are **H-plane waveguide components.**

The BI-RME method provides the $\mathbf{Y}$ matrix of SIW components referred to rectangular ports.



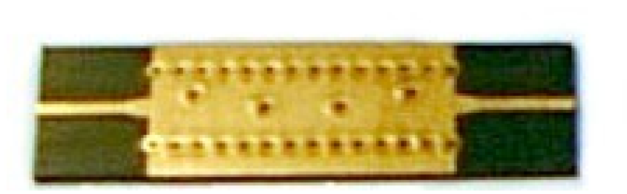
The **$\mathbf{Y}'$ matrix referred to the SIW modes** can be obtained as:

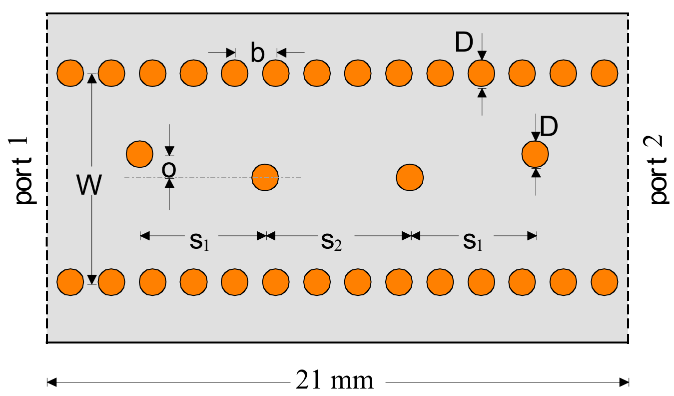
$$\mathbf{Y}' = \mathbf{T}\mathbf{Y}\mathbf{T}^T$$

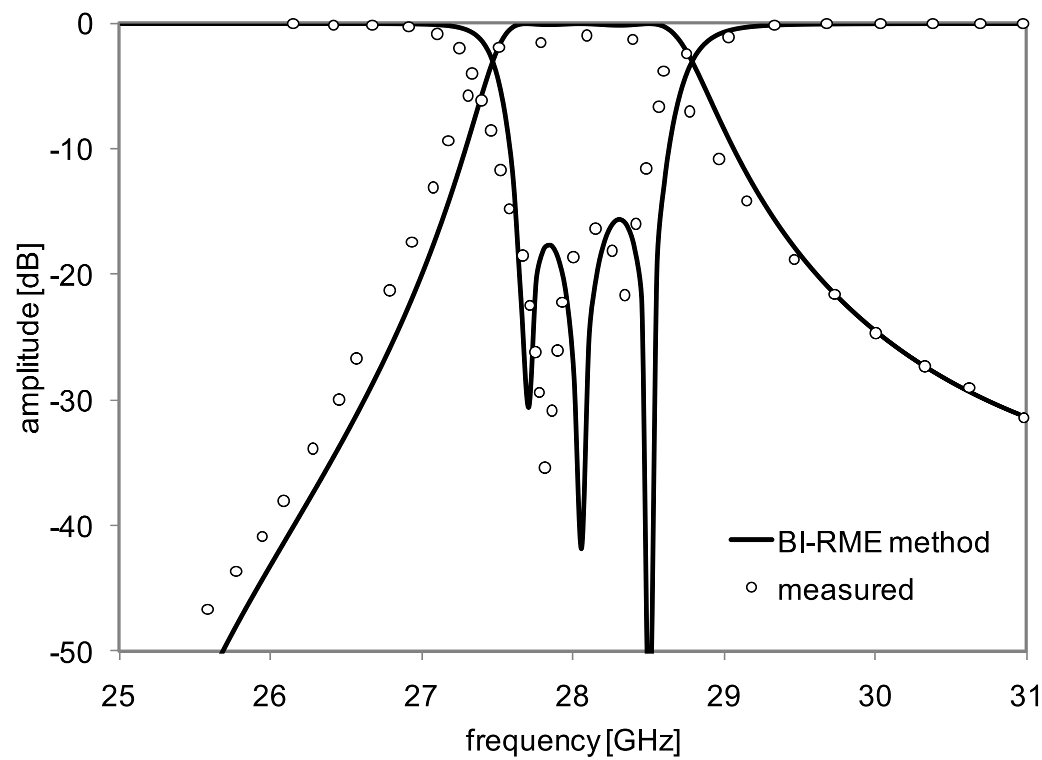


The resulting $\mathbf{Y}'$ matrix is still in the form of a pole expansion.

EXAMPLE: SIW FILTER







W=5.563 mm, b=1.525 mm, D=0.775 mm,
o=1.01 mm, s_1=4.71 mm, s_2=5.11 mm, ε_r=2.2

D. Deslandes and Ke Wu, "Single-Substrate Integration Technique of Planar Circuits and Waveguide Filters," *IEEE Trans. on Microwave Theory and Techniques*, Vol. MTT-51, No. 2, pp. 593-596, Feb. 2003.

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LOSSES IN SIW STRUCTURES

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conductor loss

σ_c= metal conductivity

dielectric loss

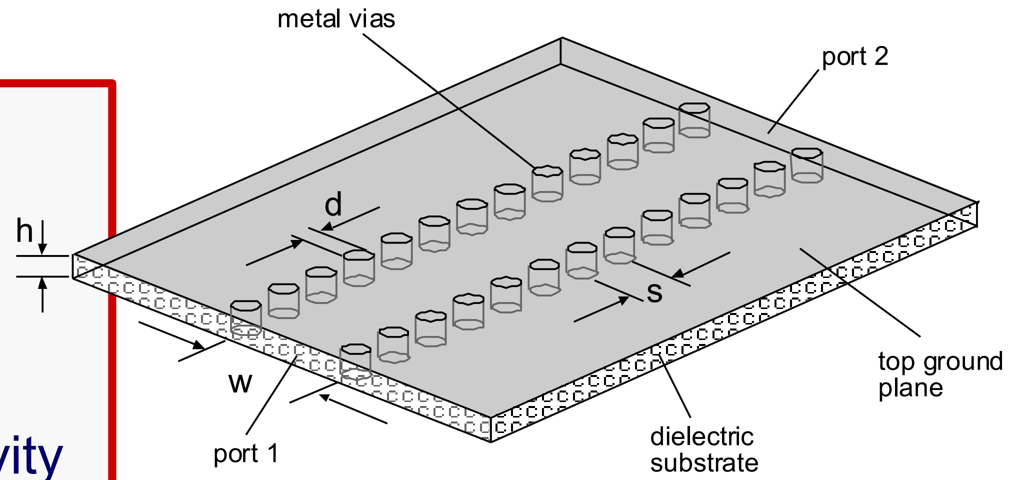
ε_r= relative dielectric permittivity

σ_d= dielectric conductivity

radiation leakage

leakage thought the gaps

(small if *s*/*d*<2.5)



M. Bozzi, M. Pasian, L. Perregrini, and K. Wu, “On the Losses in Substrate Integrated Waveguides and Cavities,” *International Journal Microwave and Wireless Technologies*, 2009.

CONDUCTOR & DIELECTRIC LOSSES

The BI-RME method can be modified to include **conductor** and **dielectric losses** by using a perturbation approach.

The Y matrix is written as a pole expansion in the frequency domain:

$$Y_{ij}(k) = \frac{A_{ij}}{j\eta k} + \frac{jk}{\eta}\sum_{p=1}^{P}\frac{C_{ip}C_{ip}}{k_p^2 + jkk_p/Q_p - k^2}$$

low-frequency term — modes of the cavity — quality factor

where the quality factor is defined as:

$$\frac{1}{Q_p} = \frac{1}{Q_p^{(c)}} + \frac{1}{Q_p^{(d)}} = \frac{1}{\sqrt{2\omega_p\mu_0\sigma_c}}\int_S |\mathbf{H}_p|^2 dS + \frac{\sigma_d}{\omega_p\varepsilon_0\varepsilon_r}$$

conductor loss — dielectric loss

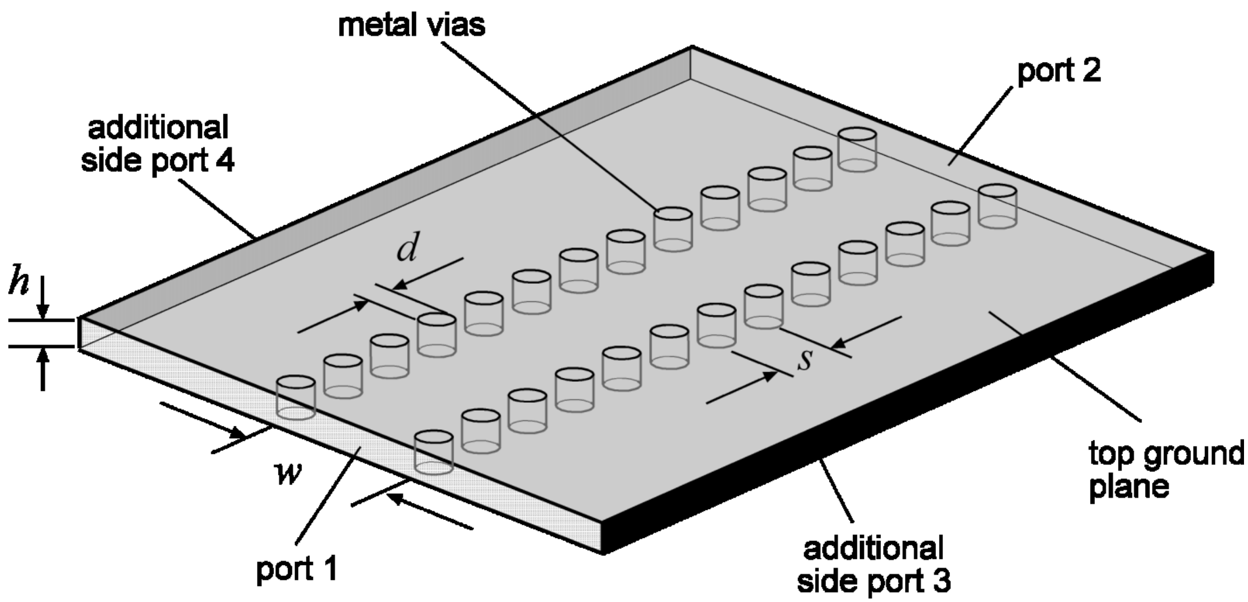
After some algebraic manipulations, the final expression results:

$$Y_{ij}(k_0) = \frac{A_{ij}}{j\eta_0 k_0} + \sigma_d B_{ij} + \frac{jk_0\varepsilon_r}{\eta_0} B_{ij} + \frac{k_0^2 \varepsilon_r^{3/2}}{\eta_0} \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{k_p Q_p \left(k_p^2 + jk_0 k_p \varepsilon_r^{1/2} / Q_p - k_0^2 \varepsilon_r\right)} +$$
$$+ \frac{jk_0^3 \varepsilon_r^2}{\eta_0} \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{k_p^2 \left(k_p^2 + jk_0 k_p \varepsilon_r^{1/2} / Q_p - k_0^2 \varepsilon_r\right)}$$

M. Bozzi, L. Perregrini, and K. Wu, "Modeling of Conductor, Dielectric and Radiation Losses in Substrate Integrated Waveguide by the Boundary Integral-Resonant Mode Expansion Method," *IEEE Trans. Microwave Theory & Techniques*, Vol. MTT-56, No. 12, pp. 3153-3161, Dec. 2008.

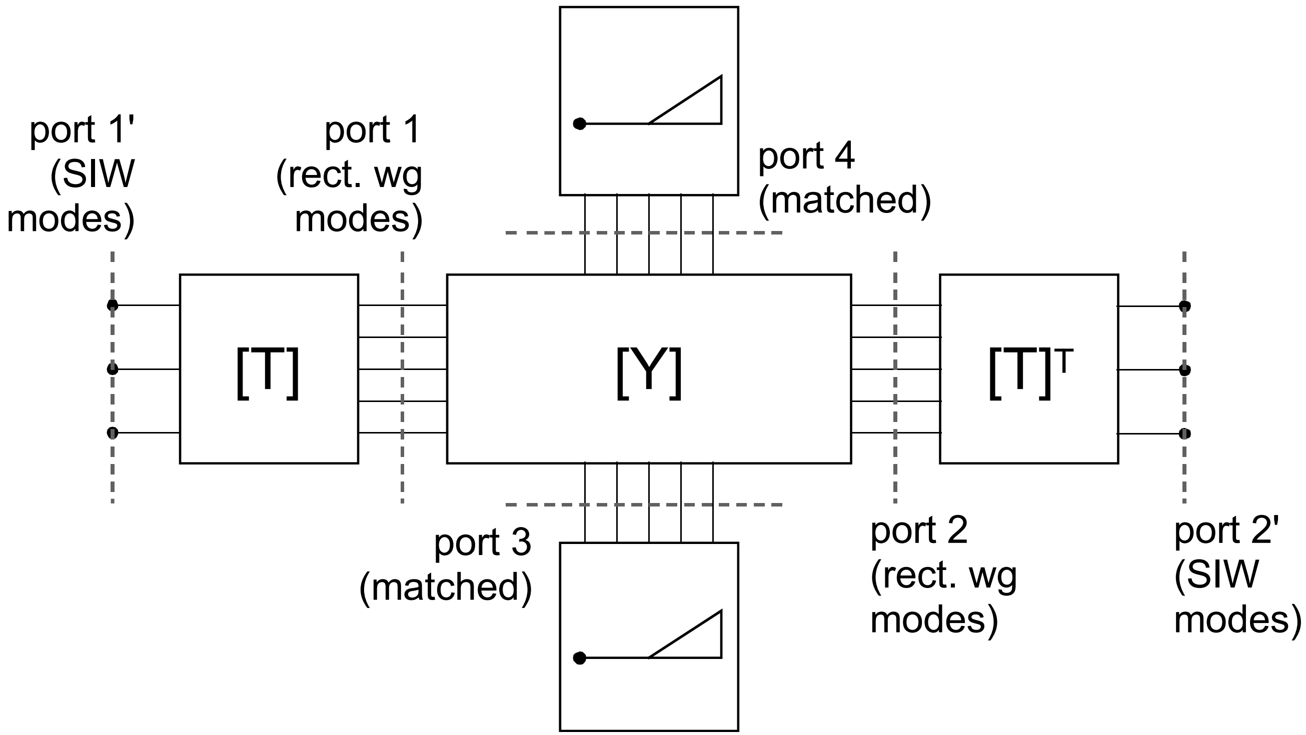
RADIATION LEAKAGE

The **radiation leakage** is accounted for by considering additional side ports, terminated with matched loads.



RADIATION LEAKAGE

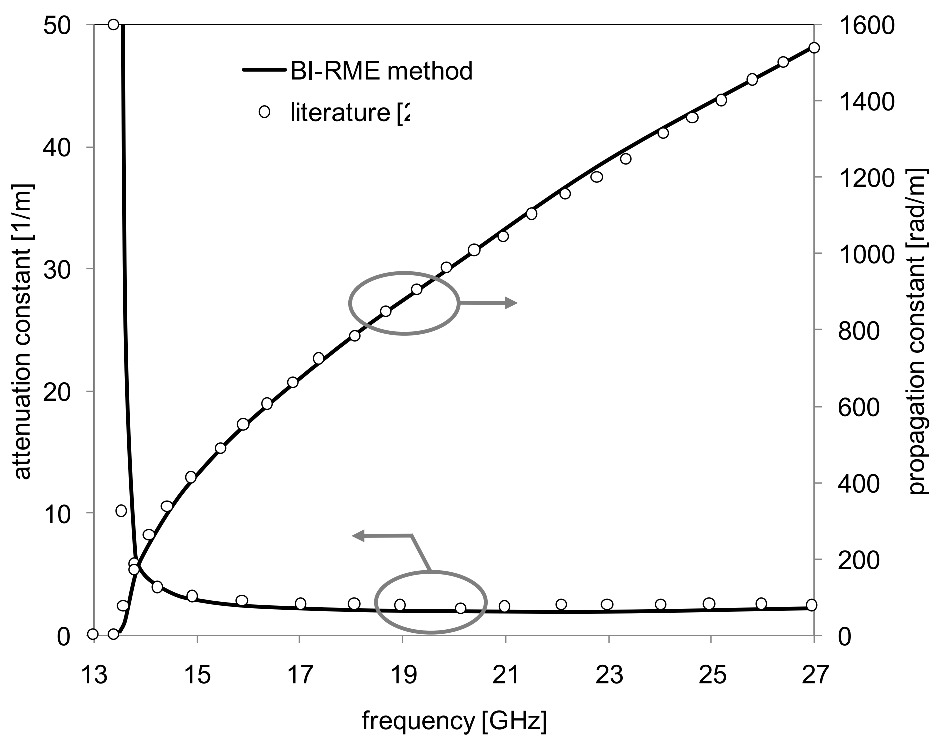
Schematic of the circuit, with definition of the ports.

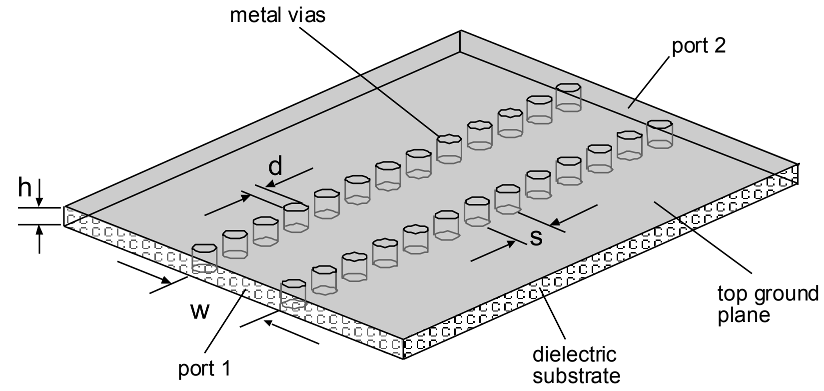


M. Bozzi, L. Perregrini, and K. Wu, "Modeling of Conductor, Dielectric and Radiation Losses in Substrate Integrated Waveguide by the Boundary Integral-Resonant Mode Expansion Method," *IEEE Trans. Microwave Theory & Techniques*, Vol. MTT-56, No. 12, pp. 3153-3161, Dec. 2008.

EXAMPLE: SIW INTERCONNECT

Structure with negligible radiation loss





w = 3.97 mm

d = 0.635 mm

s = 1.016 mm

h = 0.254 mm

ε_r = 9.9

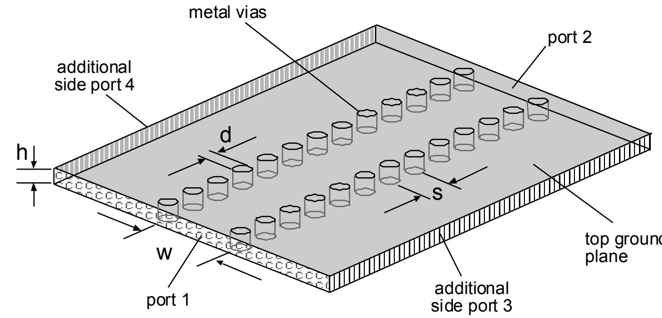
tan δ = 0.0002

$\sigma_c = 5 \cdot 10^7$ S/m

D. Deslandes and K. Wu, “Accurate Modeling, Wave Mechanisms, and Design Considerations of a Substrate Integrated Waveguide,” *IEEE Trans. on Microwave Theory and Techniques*, Vol. 54, No. 6, pp. 2516–2526, June 2006.

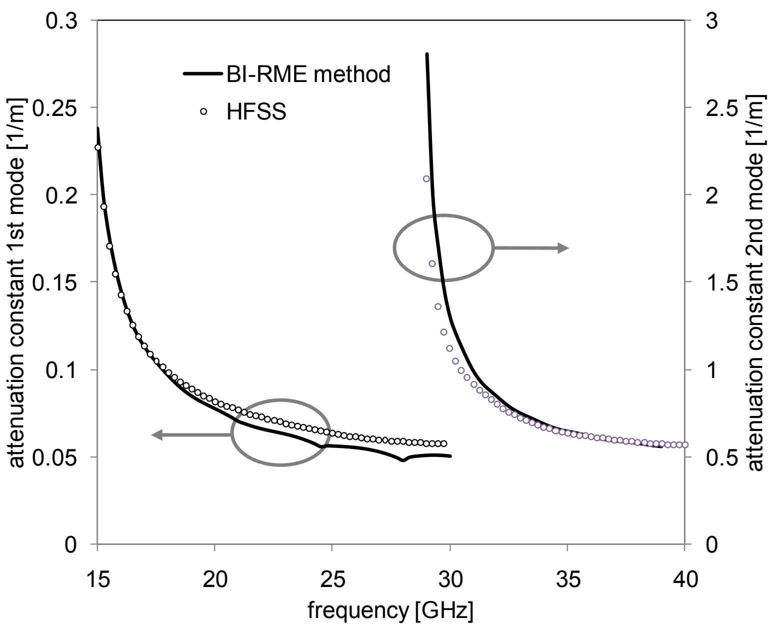
EXAMPLE: SIW WITH RADIATION

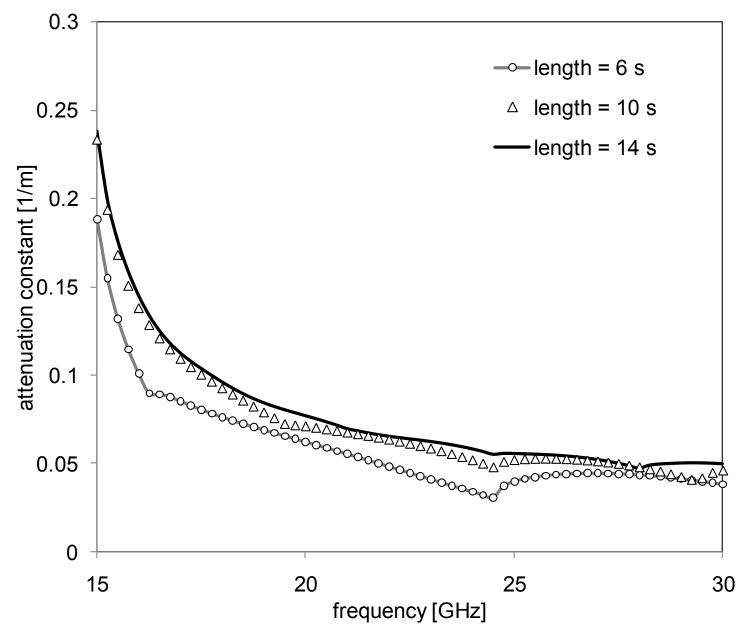
Structure with significant radiation loss



w=7.2 mm, d=0.8 mm, s=2 mm

h=0.508 mm, ε_r=2.33

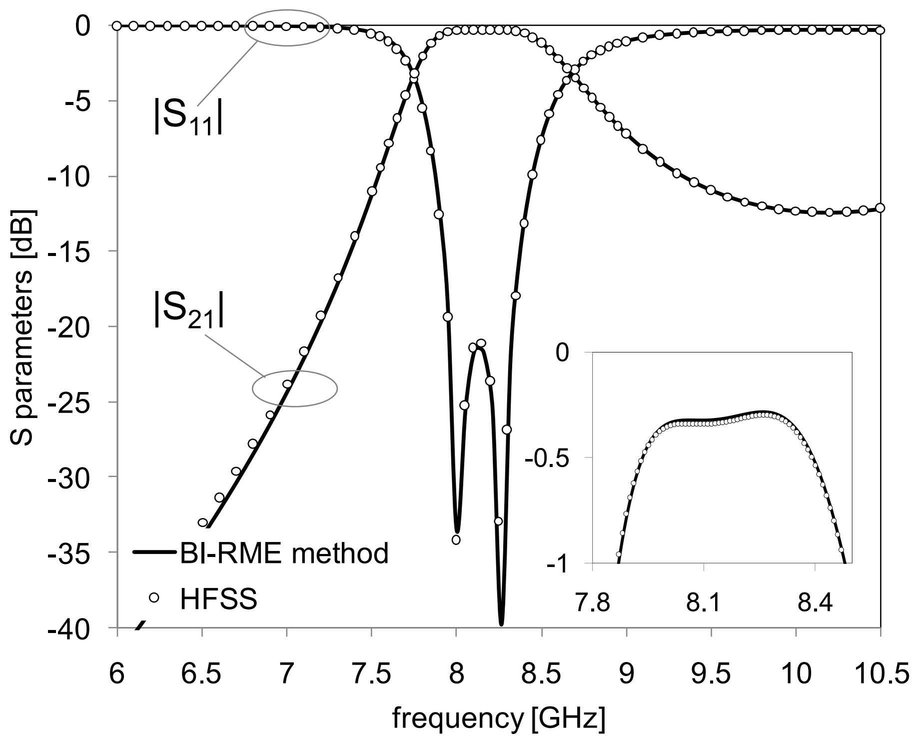


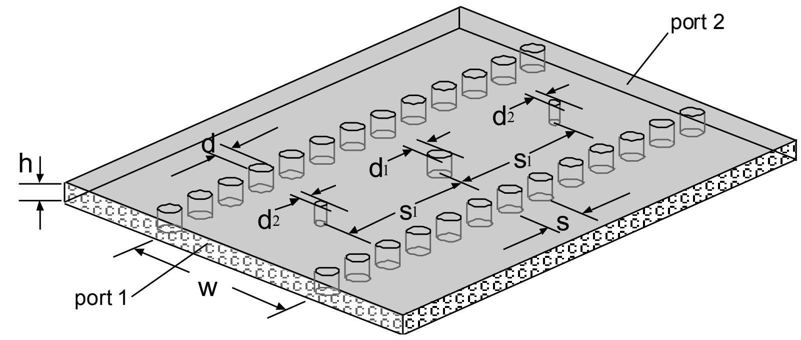


F. Xu and K. Wu, "Guided-Wave and Leakage Characteristics of Substrate Integrated Waveguide," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 53, No. 1, pp. 66-73, Jan. 2005.

EXAMPLE: SIW FILTER

SIW filter with three centered posts





overall computing time: 23 sec

w = 21.06 mm

d = 2 mm

s = 4 mm

d_1 = 2 mm

d_2 = 0.5 mm

s_1 = 14 mm

h = 1 mm

ε_r = 2

σ_d = 0.001 S/m

σ_c = $4 \cdot 10^7$ S/m

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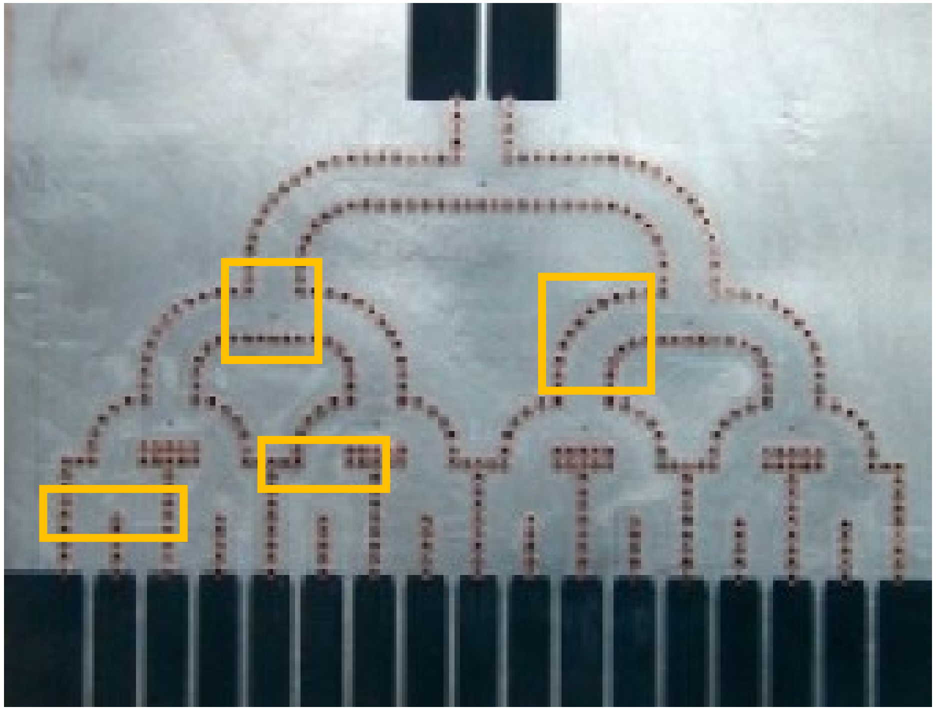
- Conclusions

MODELING OF COMPLEX CIRCUITS

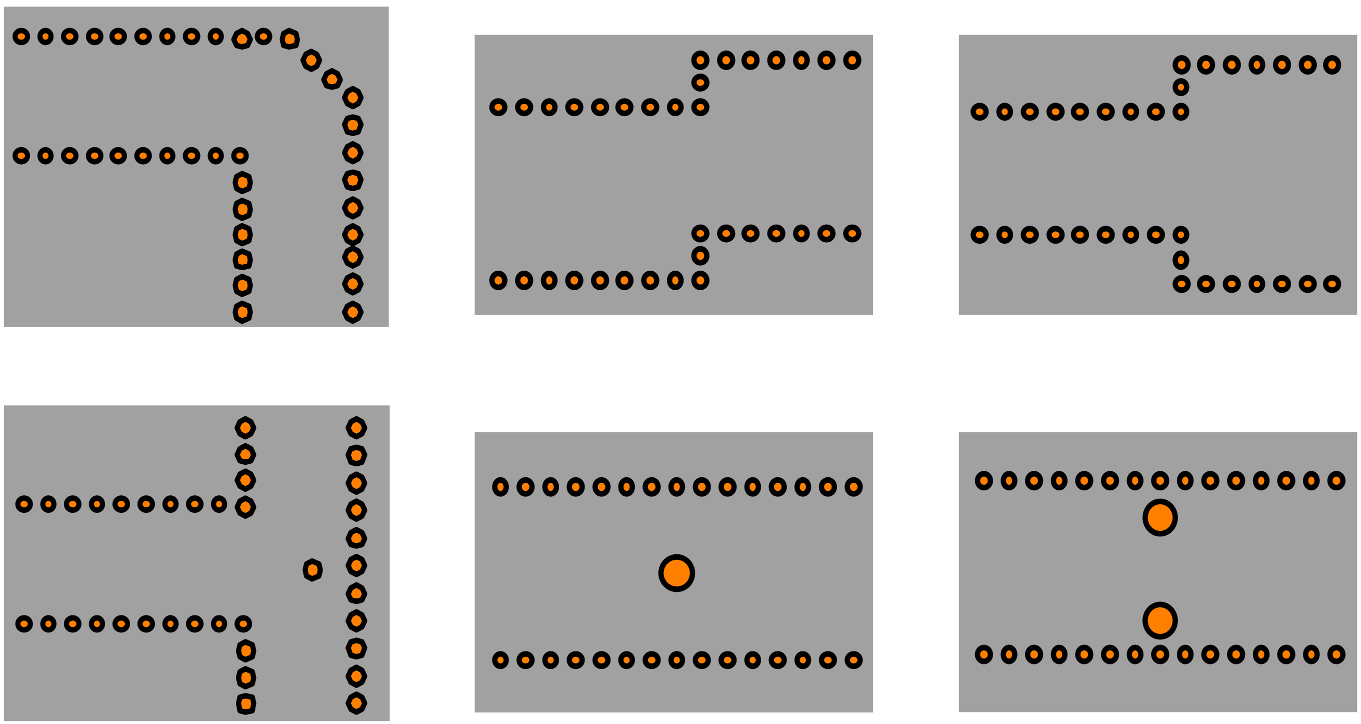
The **full-wave analysis** of complicated SIW components and circuits can be performed using existing numerical codes, but their optimization may be prohibitively time-consuming.



However, in most cases, a circuit consists of a cascade of closely spaced simple discontinuities.

Library of Equivalent Models

Multi-mode parametric circuit models of simple discontinuities would permit the synthesis of SIW components by using commercial CAD tools.



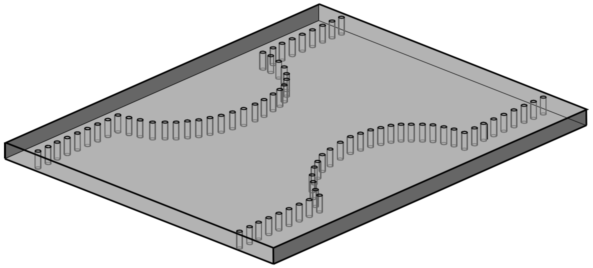
M. Bozzi, L. Perregrini, K. Wu, "A Novel Technique for the Direct Determination of Multi-mode Equivalent Circuit Models for Substrate Integrated Waveguide Discontinuities," *Inter. Journal RF Microwave Computer–Aided Engineering*, July 2009.

EQUIVALENT CIRCUIT MODELS

The modeling of SIW components by the BI-RME method permits to derive the **equivalent circuit models**.

In the **lossless case**, the BI-RME method yields the admittance matrix in the form:

$$Y_{ij} = \frac{1}{j\omega} A_{ij} + j\omega B_{ij} + j\omega^3 \sum_{m=1}^{M} \frac{C_{im} C_{jm}}{\omega_m^2 (\omega_m^2 - \omega^2)}$$



By extracting from the summation the term for ω→∝ we have:

$$Y_{ij} = \frac{1}{j\omega} A_{ij} + j\omega \left(B_{ij} - \sum_{m=1}^{M} \frac{C_{im} C_{jm}}{\omega_m^2} \right) + j\omega \sum_{m=1}^{M} \frac{C_{im} C_{jm}}{(\omega_m^2 - \omega^2)}$$

EQUIVALENT CIRCUIT MODELS

This expression permits a **direct identification of the equivalent circuit model** (no initial guess and fitting procedure!)

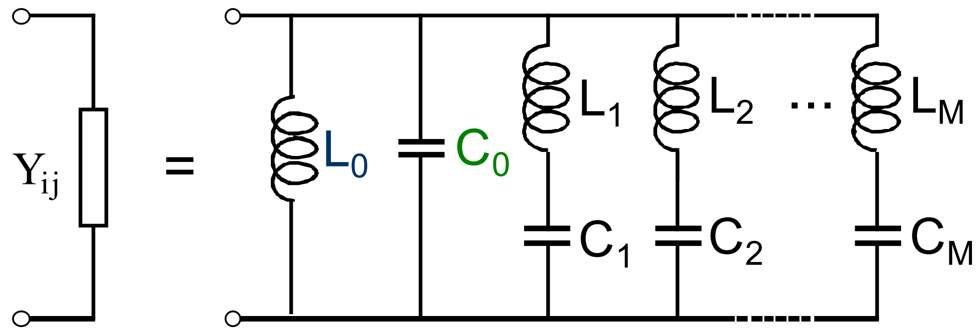
$$Y_{ij} = \underbrace{\frac{1}{j\omega}A_{ij}}_{L_0^{-1}} + j\omega \underbrace{\left(B_{ij} - \sum_{m=1}^{M}\frac{C_{im}C_{jm}}{\omega_m^2}\right)}_{C_0} + \underbrace{j\omega\sum_{m=1}^{M}\frac{C_{im}C_{jm}}{(\omega_m^2-\omega^2)}}_{\text{LC series}}$$

$$L_{0,ij} = \frac{1}{A_{ij}}$$

$$C_{0,ij} = B_{ij} - \sum_{m=1}^{M}\frac{C_{im}C_{jm}}{\omega_m^2}$$

$$L_{m,ij} = \frac{1}{C_{im}C_{jm}}$$

$$C_{m,ij} = \frac{1}{\omega_m^2 L_{m,ij}} = \frac{C_{im}C_{jm}}{\omega_m^2}$$



M. Bozzi, L. Perregrini, K. Wu, "Direct Determination of Multi-mode Equivalent Circuit Models for Discontinuities in Substrate Integrated Waveguide Technology," *International Microwave Symposium* (IMS2006), San Francisco, California, 2006.

In the **lossy case**, the BI-RME method yields the $\boldsymbol{Y}$ matrix in the form:

$$Y_{ij}(k_0) = \frac{A_{ij}}{j\eta_0 k_0} + \sigma_d B_{ij} + \frac{jk_0\varepsilon_r}{\eta_0} B_{ij} + \frac{k_0^2 \varepsilon_r^{3/2}}{\eta_0} \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{k_p Q_p \left(k_p^2 + jk_0 k_p \varepsilon_r^{1/2} / Q_p - k_0^2 \varepsilon_r\right)} + \frac{jk_0^3 \varepsilon_r^2}{\eta_0} \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{k_p^2 \left(k_p^2 + jk_0 k_p \varepsilon_r^{1/2} / Q_p - k_0^2 \varepsilon_r\right)}$$

The expression of the $\boldsymbol{Y}$ matrix can be recast in the form:

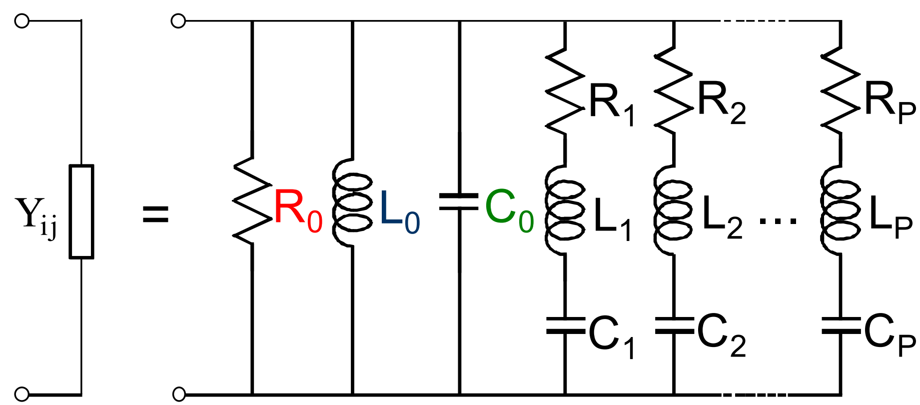
$$Y_{ij}(\omega) = \frac{1}{j\omega} \frac{A_{ij}}{\mu_0} + \sigma_d B_{ij} + j\omega \left[\varepsilon_0 \varepsilon_r B_{ij} - \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{\mu_0 \omega_p^2} \right] + j\omega \frac{1}{\mu_0} \sum_{p=1}^{P} \frac{C_{ip} C_{ip}}{\omega_p^2 + j\omega\omega_p / Q_p - \omega^2}$$

This expression permits a direct identification of the equivalent circuit:

$$Y_{ij}(\omega) = \underbrace{\frac{1}{j\omega}\frac{A_{ij}}{\mu_0}}_{L_0^{-1}} + \underbrace{\sigma_d B_{ij}}_{R_0} + \underbrace{j\omega\left[\varepsilon_0\varepsilon_r B_{ij} - \sum_{p=1}^{P}\frac{C_{ip}C_{ip}}{\mu_0\omega_p^2}\right]}_{C_0} + \underbrace{j\omega\frac{1}{\mu_0}\sum_{p=1}^{P}\frac{C_{ip}C_{ip}}{\omega_p^2 + j\omega\omega_p/Q_p - \omega^2}}_{\text{RLC series}}$$

$$R_0 = \frac{1}{\sigma_d B_{ij}} \qquad L_0 = \frac{\mu_0}{A_{ij}} \qquad C_0 = \varepsilon_r\varepsilon_0 B_{ij} - \sum_{p=1}^{P}\frac{C_{ip}C_{ip}}{\mu_0\omega_p^2}$$

$$R_p = \frac{\mu_0\omega_p}{Q_p C_{ip} C_{ip}} \qquad L_p = \frac{\mu_0}{C_{ip}C_{ip}} \qquad C_p = \frac{C_{ip}C_{ip}}{\mu_0\omega_p^2}$$



M. Bozzi, L. Perregrini, K. Wu, "Modeling of Losses in Substrate Integrated Waveguide by Boundary Integral-Resonant Mode Expansion Method," *2008 IEEE MTT-S International Microwave Symposium* (IMS2008), Atlanta, GA, 2008.

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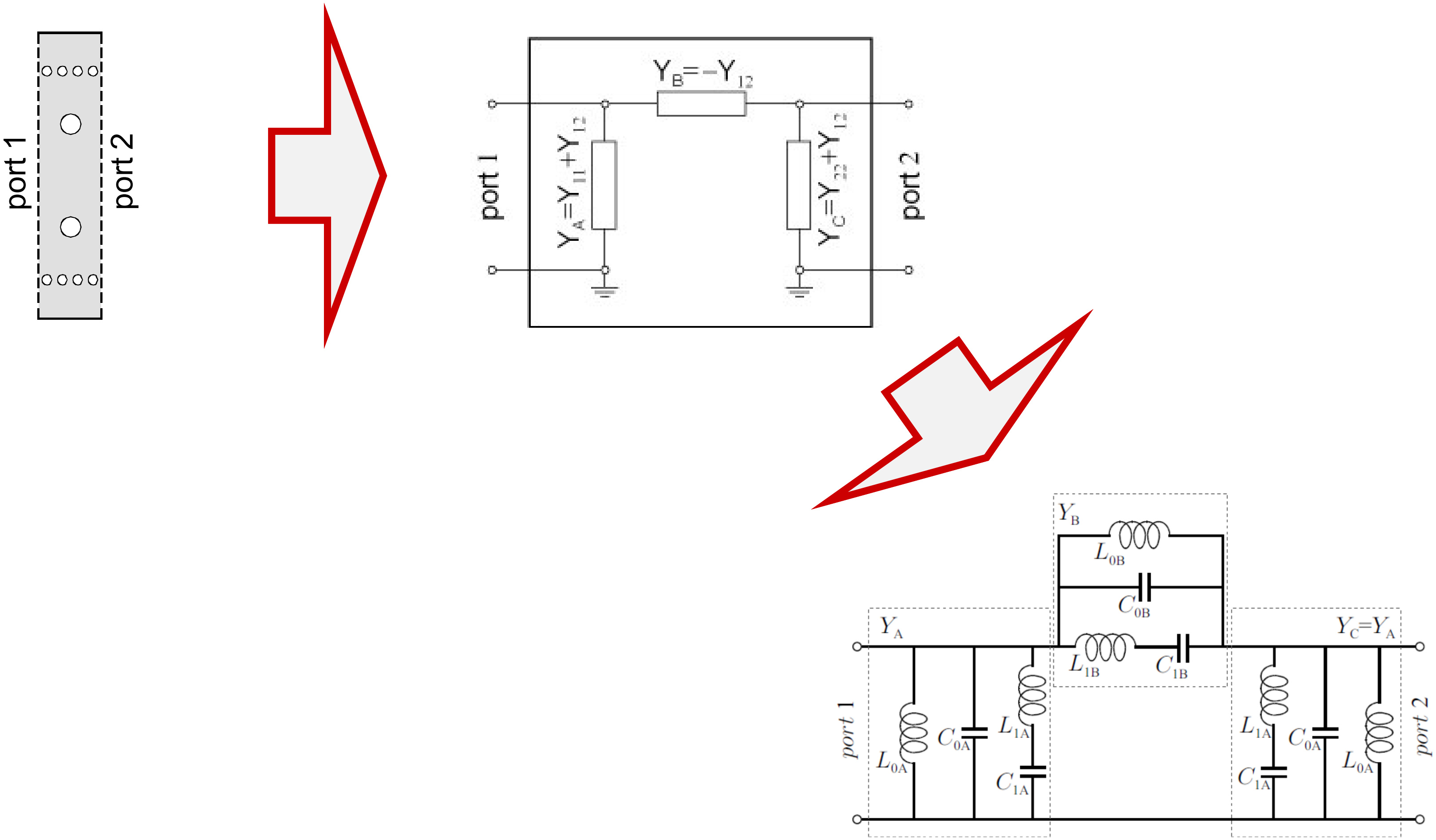
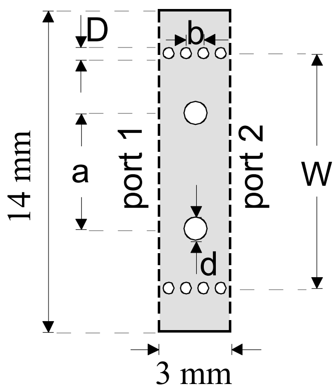
A **pi-type equivalent circuit model** is adopted to represent the SIW discontinuities.



EXAMPLE: SIW DISCONTINUITY



W =10.35 mm

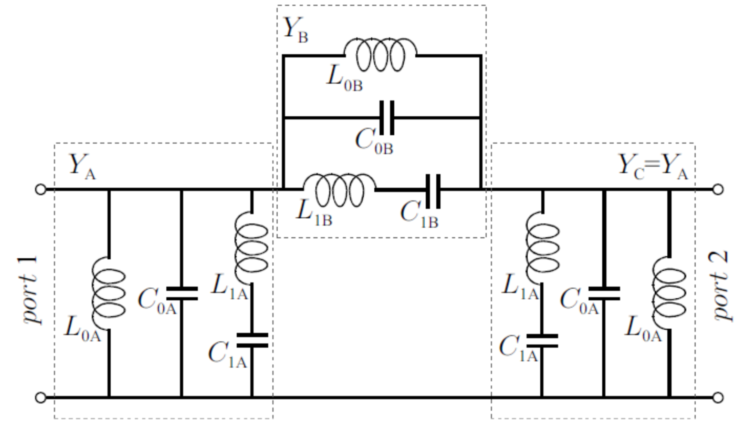
a=5 mm

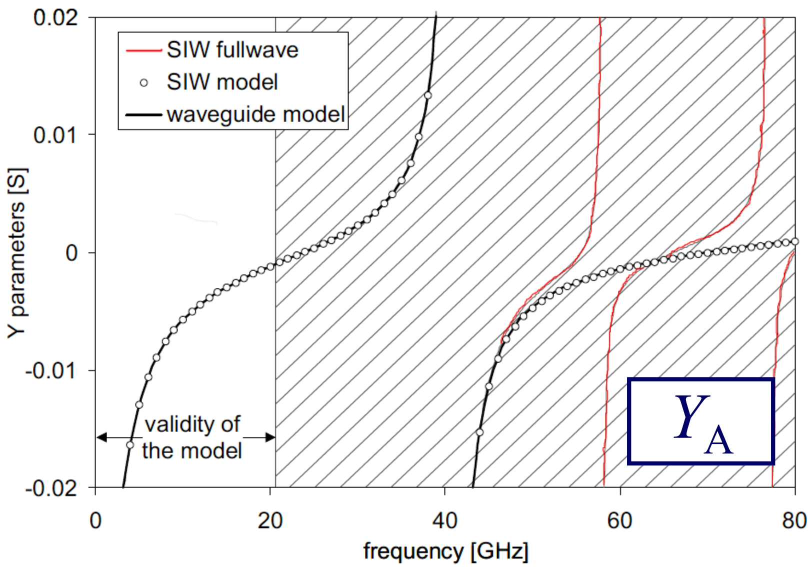
b=0.75 mm

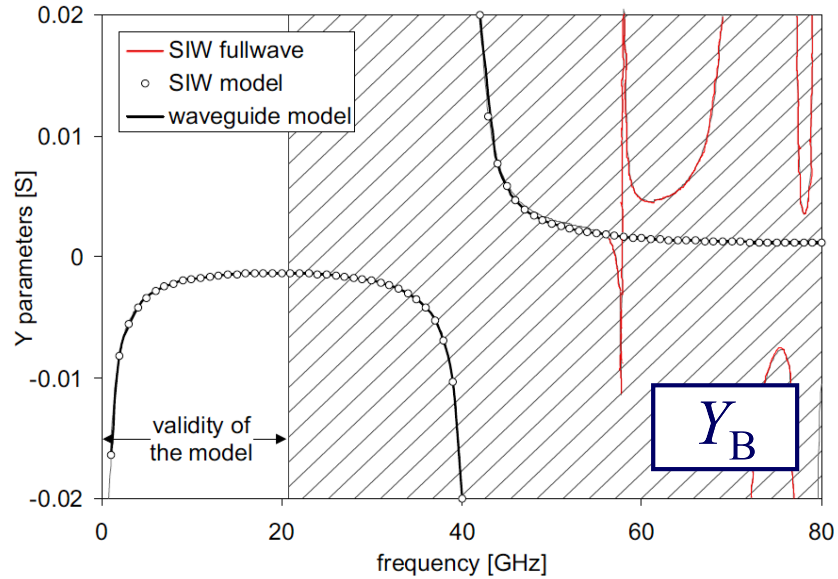
d=1 mm

D=0.5 mm

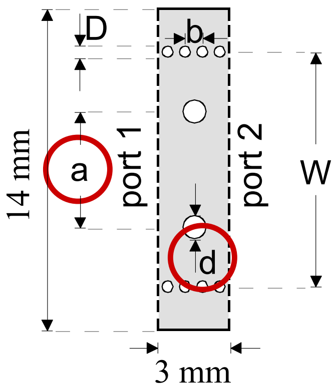
ε_r=2.2



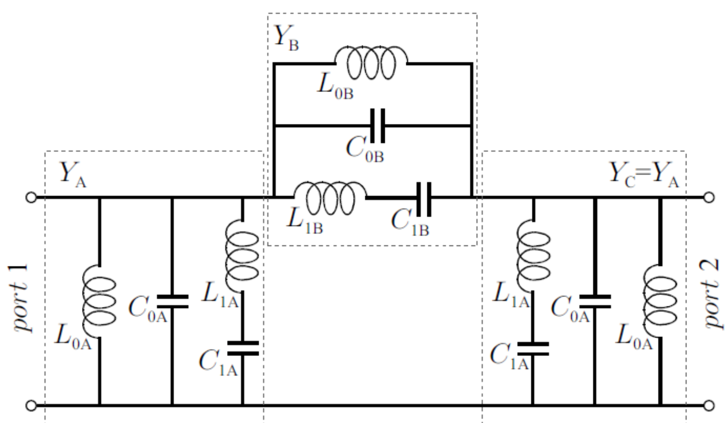


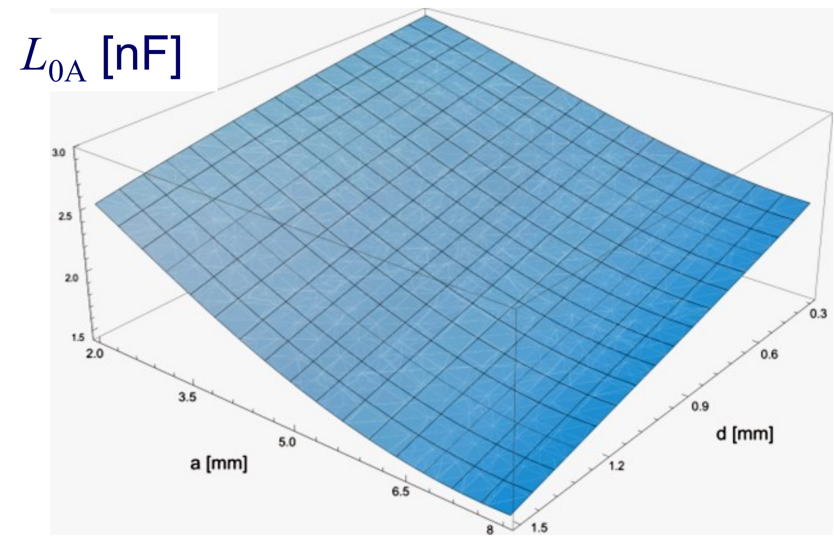


PARAMETRIC CIRCUIT MODELS



Multiple analyses by changing some geometrical dimensions allow for finding **parametric models** (polynomial interpolation is adopted).





smooth variation of L_{0A} versus a and d.

Example: SIW Filter

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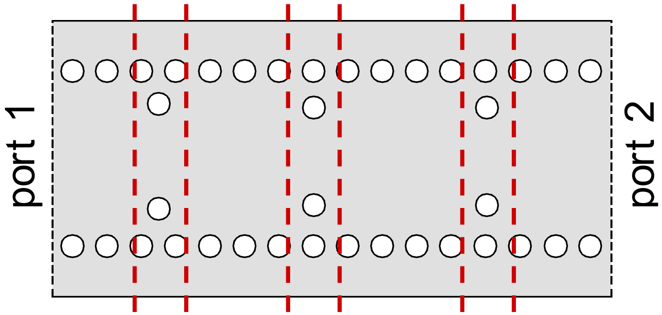
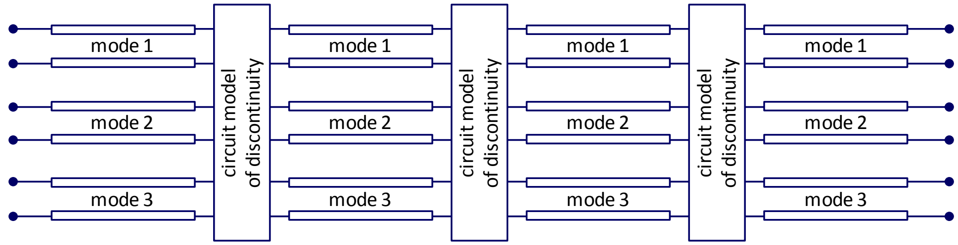
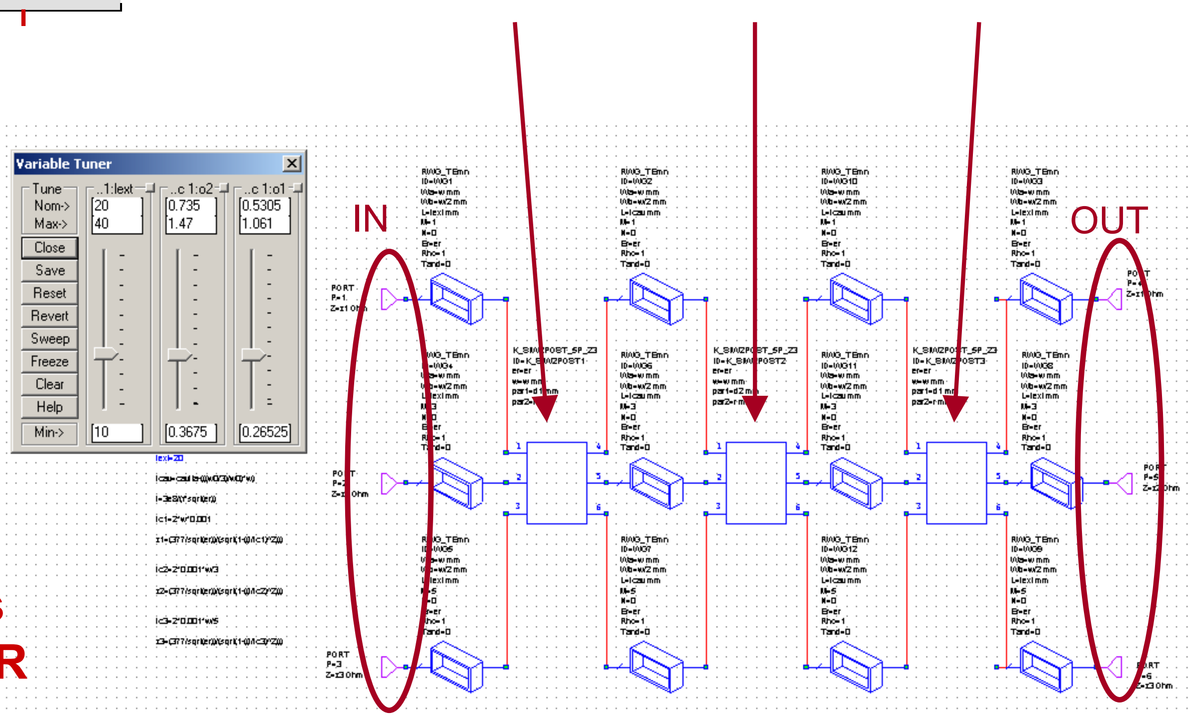


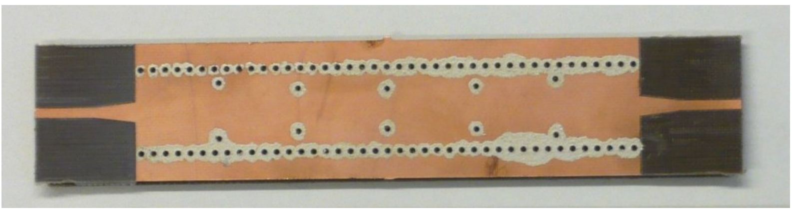




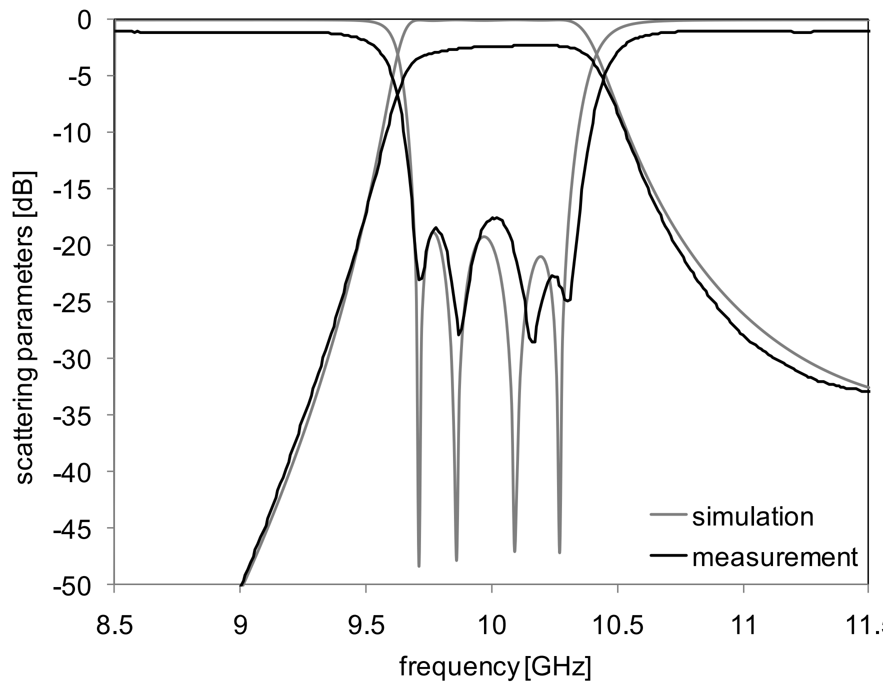
SIW circuit models implemented in AWR Microwave Office!

EXAMPLE: 4-POLE SIW FILTER

4-pole filter with iris windows



dielectric substrate Arlon Diclad 880
(ε_r=2.2, thickness 0.508 mm)



Measured input matching 17.5 dB, insertion loss 2.3 dB (9.70–10.30 GHz).

Simulation with **multi-mode lossless equivalent circuits** (3 odd modes).
Fabricated and measured at CTTC, Spain.

EXAMPLE: 8-POLE SIW FILTER

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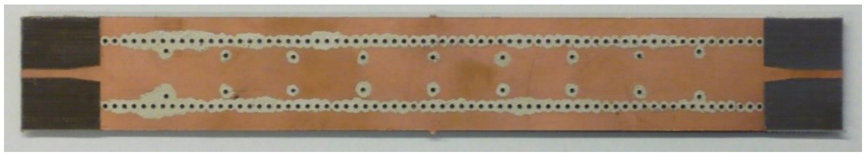
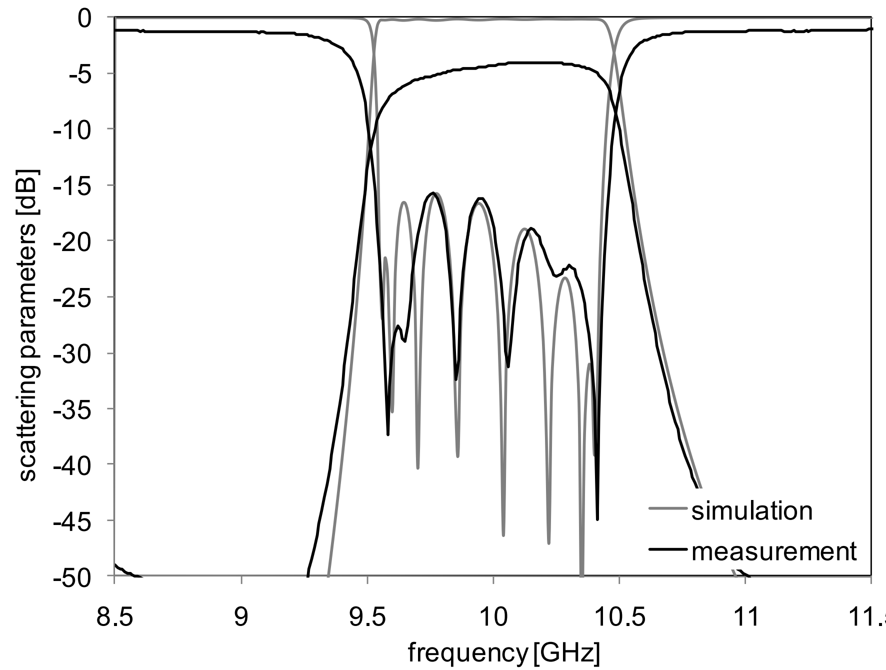
8-pole filter with iris windows



dielectric substrate Arlon Diclad 880
(ε_r=2.2, thickness 0.508 mm)



Measured input matching 15.7 dB, insertion loss 4.0 dB (9.55–10.45 GHz).

Computing time for one analysis (in 300 frequency points):
1.28 sec by using the equivalent circuits, **25 min** by using HFSS.

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