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BROADBAND PHYSICS-BASED MODELING OF MICROWAVE PASSIVE DEVICES THROUGH FREQUENCY MAPPING

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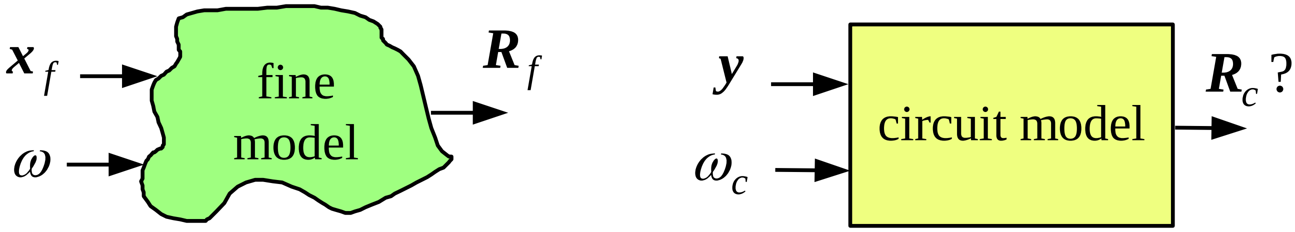
Basic Concepts and Notation



fine models: EM simulators, measurements

the objective is to develop empirical models valid over a wide frequency range

$\boldsymbol{x}_f$: an *n*-dimensional vector representing the physical parameters

$\boldsymbol{y}$: a vector representing the elements of the circuit model

ω : the fine model frequency (the actual frequency)

ω_c: the circuit model frequency

Frequency Mapping

frequency mapping is a transformation from the fine model frequency and parameters to the circuit model frequency

frequency mapping has been utilized in the Space Mapping context *(Bandler et al., 1994, 1999, 2000)*

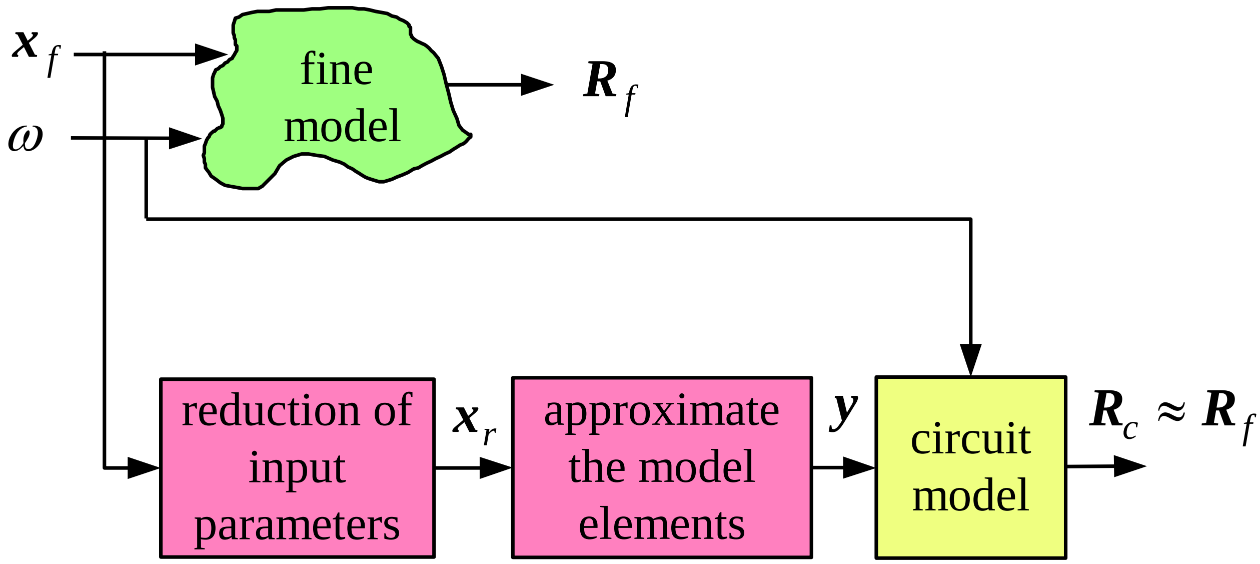
frequency transformations have roots in classical filter design, for example, low-pass to band-pass or high-pass transformations

dimensional analysis (*Buckingham, 1914, Watson et al., 1999*) is applied to determine the functionality of the circuit model elements and the frequency mapping of the geometrical and physical parameters

the circuit model frequency should be an odd function of the fine model frequency

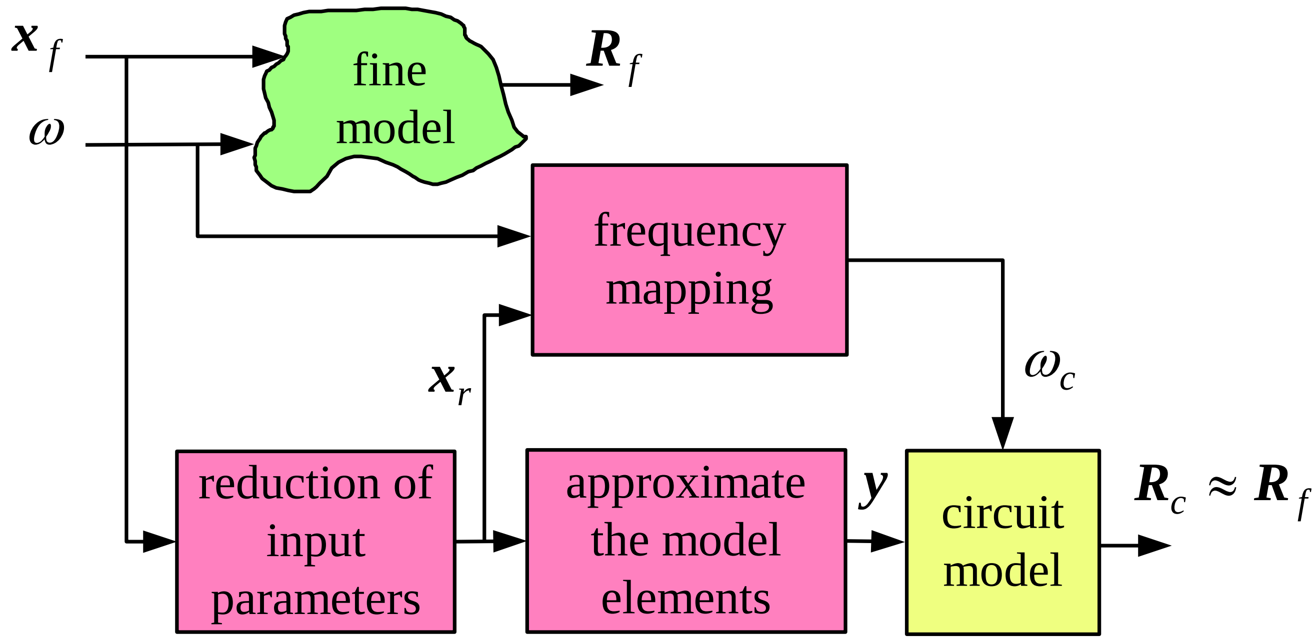
Artificial Neural Networks (ANN) or Rational Functions (RF) can be used to approximate the circuit model elements and frequency mapping

Frequency Independent Empirical Models (FIEM)



$\boldsymbol{x}_r$: an m-dimensional vector representing the reduced set of input parameters, where $m < n$

Frequency Dependent Empirical Models (FDEM)



the circuit model elements and the frequency mapping are evaluated by solving

$$\min_{\boldsymbol{w}_1,\boldsymbol{w}_2} \left\| \, [\boldsymbol{e}_{11}^T \cdots \boldsymbol{e}_{1M}^T \; \boldsymbol{e}_{21}^T \cdots \boldsymbol{e}_{2M}^T \cdots \boldsymbol{e}_{N1}^T \cdots \boldsymbol{e}_{NM}^T \,]^T \right\|$$

where N is the total number of training points, M is the number of frequency points per frequency sweep and

$$\boldsymbol{e}_{ij} = \boldsymbol{R}_f(\boldsymbol{x}_{f\,i}, \omega_j) - \boldsymbol{R}_c(\boldsymbol{Q}(\boldsymbol{x}_{r\,i}, \boldsymbol{w}_1), \Omega(\boldsymbol{x}_{r\,i}, \omega_j, \boldsymbol{w}_2))$$

Transformation of FDEMs into FIEMs

this involves one-port impedance synthesis, which states that the impedance we want to realize should be a real rational function

the circuit model frequency can take the form

$$\omega_c = \omega \frac{f_1 - \omega^2 f_2}{f_3 - \omega^2 f_4}$$

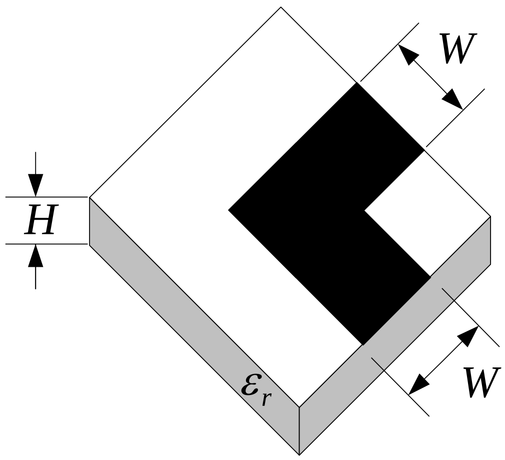
the impedance associated with an inductor L in the FDEM is given by

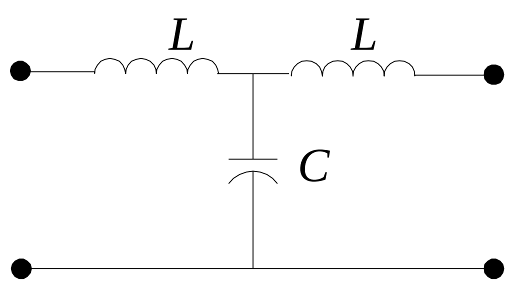
$$Z_L = j\,\omega_c L = j\,\omega L \frac{f_1 - \omega^2 f_2}{f_3 - \omega^2 f_4}$$

this impedance can be realized using one-port impedance synthesis such as the first Foster or second Foster or ladder realization

FIEM of the Microstrip Right Angle Bend

the fine and the circuit models





$$\boldsymbol{x}_f = [W \quad H \quad \varepsilon_r]^T \qquad \boldsymbol{y} = [L \quad C]^T$$

applying dimensional analysis the circuit model elements are given by

$$\frac{L}{H} = \mu \ \phi_1(\frac{W}{H}), \quad \frac{C}{H} = \varepsilon \ \phi_2(\frac{W}{H}, \varepsilon_r)$$

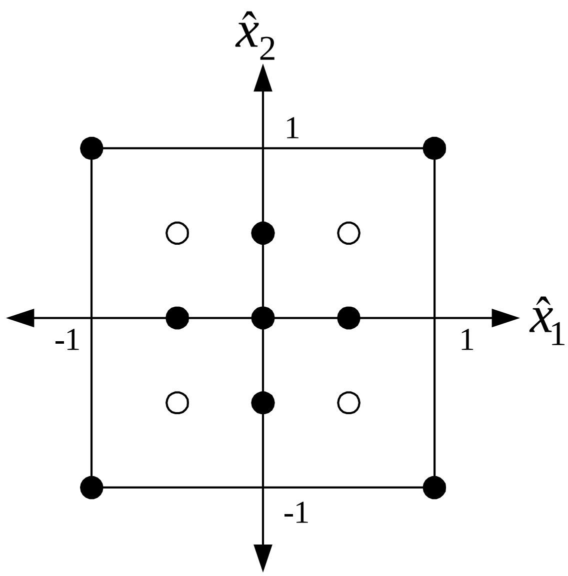
$$[L/H \quad C/H]^T = \boldsymbol{Q}(\boldsymbol{x}_r), \quad \boldsymbol{x}_r = [W/H \quad \varepsilon_r]^T$$

FIEM of the Microstrip Right Angle Bend

the region of interest

$$0.2 < W/H < 6$$
$$2 < \varepsilon_r < 11$$
$$1 \text{ GHz} < freq < 11 \text{ GHz}$$

the training points are chosen according to Central Composite Design (CCD) (*Montgomery, 1996*) plus 4 more points (13 training points)

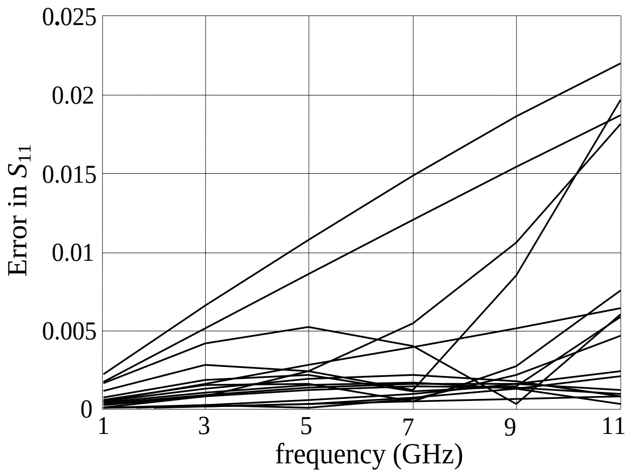


the circuit model elements are approximated by a three layer perceptron ANN with 5 hidden neurons and by RF

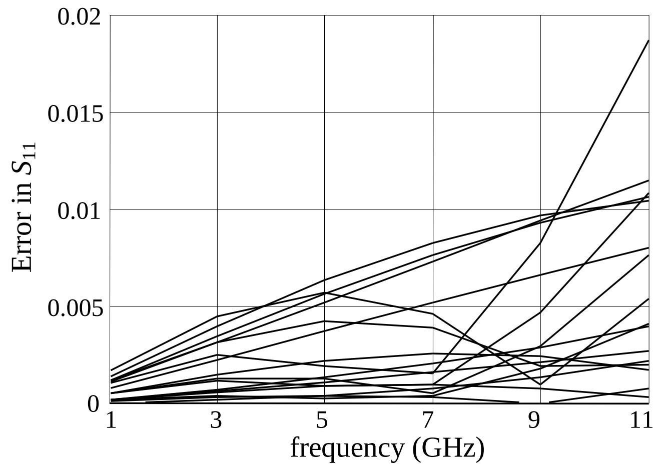
the ANN and the RF were implemented in OSA90/hope and the Huber optimizer was used for training

FIEM of the Microstrip Right Angle Bend

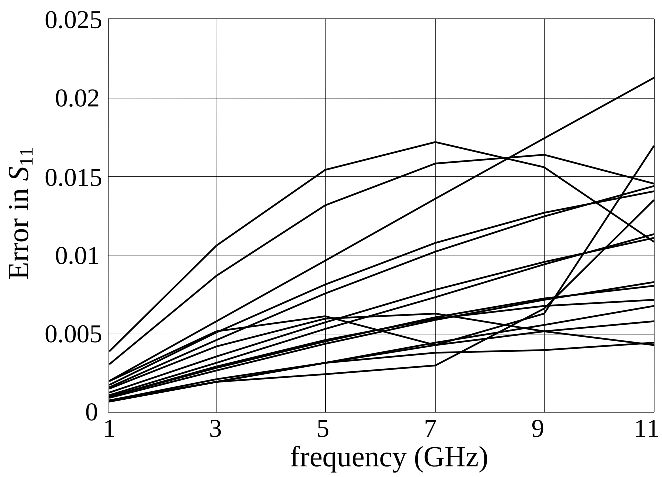
the error in S_{11} with respect to ***em***™ at 16 test points in the region of interest



the FIEM is developed by ANNs



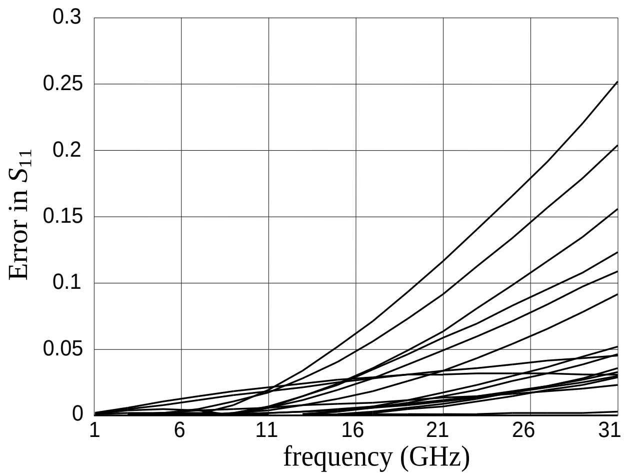
the FIEM is developed by RFs



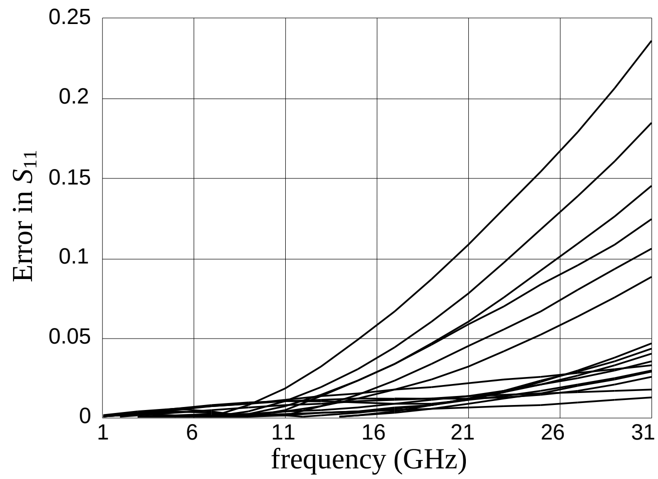
Jansen's model (1989)

FIEM of the Microstrip Right Angle Bend

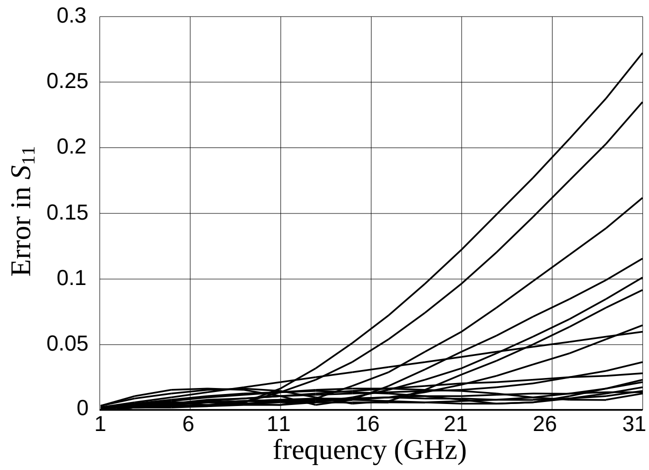
the error in S_{11} with respect to ***em***™ over a broad frequency range



the FIEM is developed by ANNs



the FIEM is developed by RFs



Jansen's model (1989)

FDEM of the Microstrip Right Angle Bend

frequency range from 1 GHz to 31 GHz

applying dimensional analysis to the frequency mapping and noticing that ω_c is an odd function of ω we get

$$\omega_c = \omega\ f(\frac{W}{H}, \varepsilon_r, (\frac{\omega H}{c})^2)$$

where c is the speed of light

the model elements and the circuit model frequency ω_c are approximated by RFs

FDEM of the Microstrip Right Angle Bend

expressions of the elements of the FDEM of the microstrip right angle bend

element	expression
L/H(nH/mil)	$0.03192\dfrac{-0.09-0.018x_1+0.3x_1^2}{1+2.853x_1^2}$
C/H(pF/mil)	$0.000225(-0.46+0.162x_1-0.014x_2+0.275x_1^2+2.855x_1x_2+0.262x_1^2x_2)$
ω_c/ω	$\dfrac{f_1(x_1,x_2,x_3)}{f_2(x_1,x_2,x_3)}$

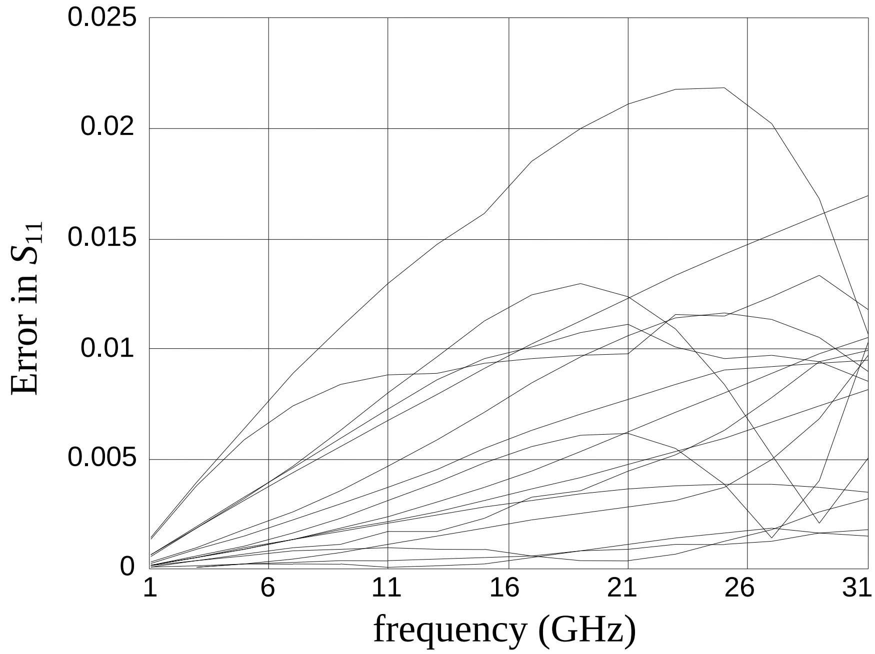
$$f_1(x_1,x_2,x_3)=0.759-0.0192x_1-0.0179x_2+0.0187x_3+0.0738x_1^2+0.0026x_1x_2 -0.1405x_1x_3+0.0079x_2x_3+0.0018x_1^3-0.0071x_1^2x_2+0.1188x_1^2x_3 +0.0017x_1x_2^2+0.0419x_1x_2x_3-0.0022x_2^2x_3$$

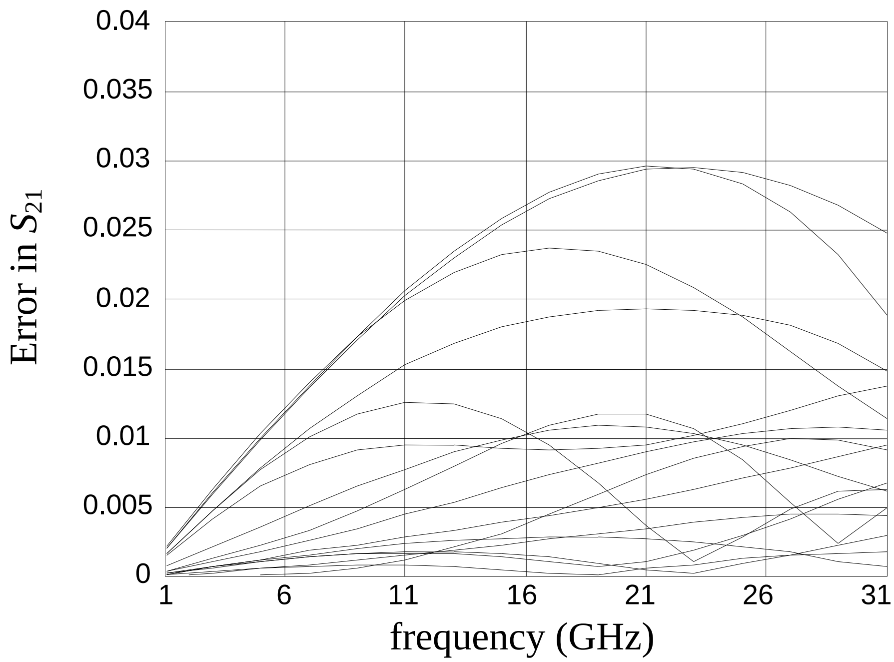
$$f_2(x_1,x_2,x_3)=1+0.0282x_1-0.0086x_2-0.0175x_3+0.0051x_1^2-0.0063x_1x_2 +0.1674x_1x_3+0.0037x_2^2-0.0067x_2x_3+0.0055x_1^3-0.0028x_1^2x_2 +0.0011x_1^2x_3+0.0056x_1x_2x_3-0.0012x_2^2x_3$$

where $x_1=W/H,\ x_2=\varepsilon_r,\ x_3=1.816\text{e-}7\,(\omega(\text{GHz})H(\text{mil}))^2$

FDEM of the Microstrip Right Angle Bend

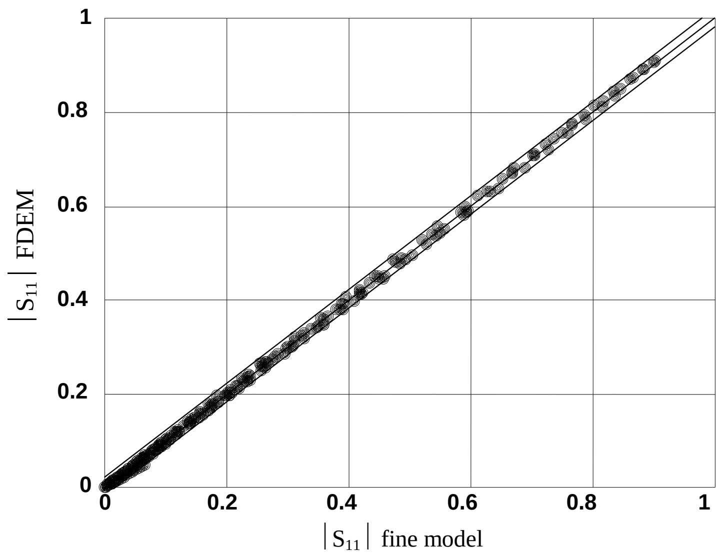
the error in S_{11} and S_{21} at 16 test points in the region of interest

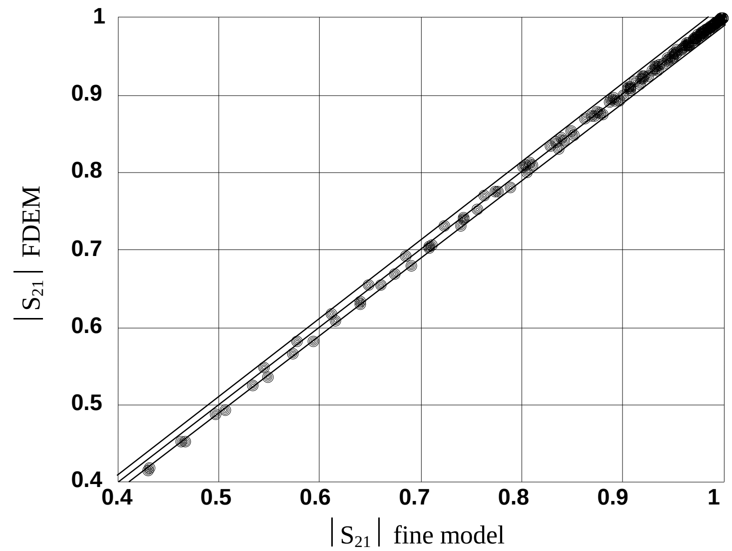


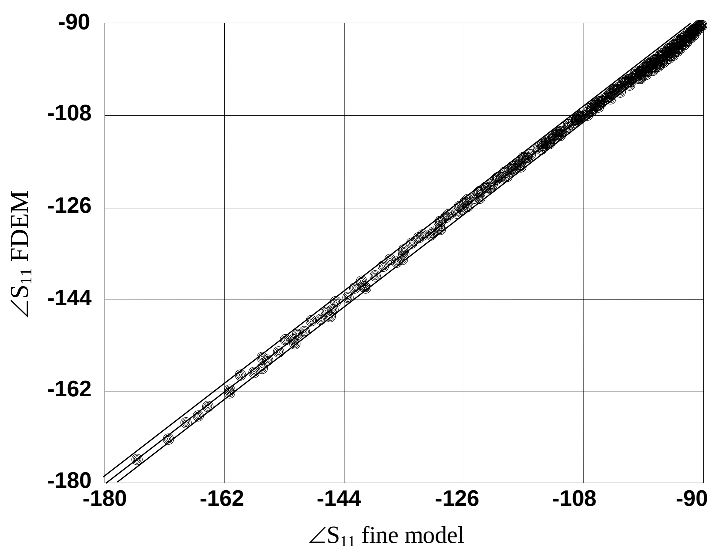


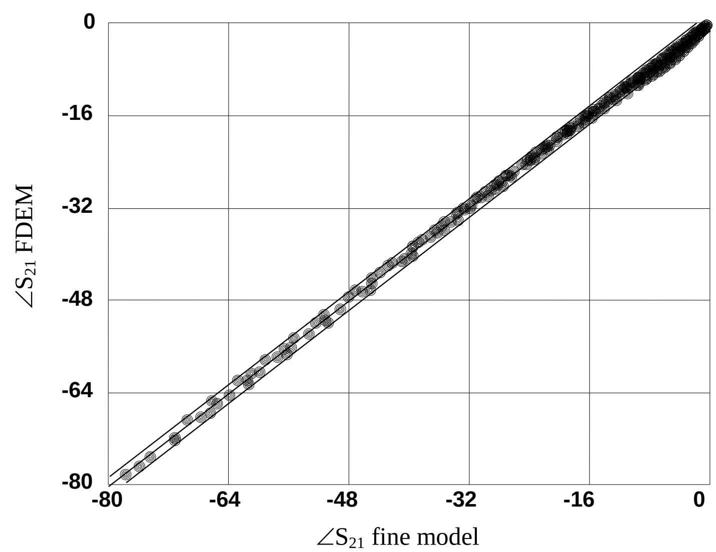
FDEM of the Microstrip Right Angle Bend

the scattering parameters obtained by the FDEM and the fine model (Sonnet's ***em***) of the microstrip right angle bend



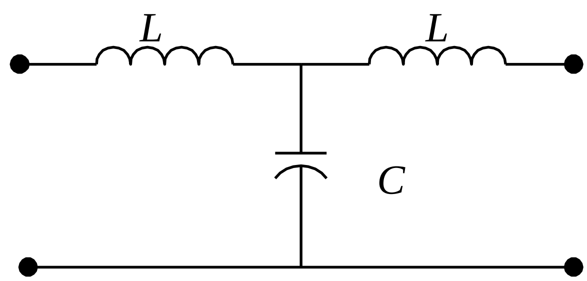






Extraction of an Equivalent FIEM from the FDEM of the Microstrip Right Angle Bend

the FDEM of the microstrip right angle bend is



the working frequency is ω_c

the equivalent impedance of L is

$$Z_L = j\omega_c L$$
$$= j\omega L \frac{f_1(x_1,x_2) - \omega^2 x_3 f_2(x_1,x_2)}{f_3(x_1,x_2) - \omega^2 x_3 f_4(x_1,x_2)}$$

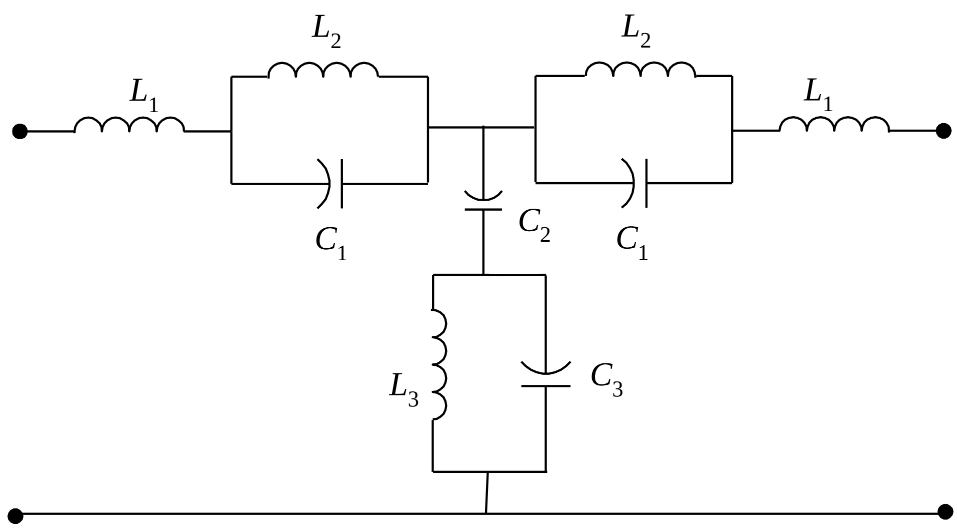
the equivalent impedance of C is

$$Z_C = \frac{1}{j\omega_c C}$$
$$= \frac{1}{j\omega C} \frac{f_3(x_1,x_2) - \omega^2 x_3 f_4(x_1,x_2)}{f_1(x_1,x_2) - \omega^2 x_3 f_2(x_1,x_2)}$$

$x_1 = W/H$, $x_2 = \varepsilon_r$ and $x_3 = 1.816 * 10^{-7} H^2$

Extraction of an Equivalent FIEM from the FDEM of the Microstrip Right Angle Bend

the equivalent FIEM is



Conclusions

we present a unified computer-aided modeling methodology for developing broadband models of microwave passive components

we integrate full-wave EM simulations, artificial neural networks, multivariable rational functions, dimensional analysis and frequency mapping

two types of models are considered: FIEMs and FDEMs

FDEMs can be transformed to equivalent FIEMs if we use a RF to approximate the frequency mapping

examples include a microstrip right angle bend, a microstrip via and a CPW step junction

Dimensional Analysis for the Frequency Mapping of the Microstrip Right Angle Bend

$$\pi = H^{x_1} W^{x_2} c^{x_3} \varepsilon^{x_4} \varepsilon_0^{x_5} \omega^{x_6} \omega_c^{x_7}$$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7
	H	W	c	ε	ε_0	ω	ω_c
Kg	0	0	0	-1	-1	0	0
M	1	1	1	-3	-3	0	0
S	0	0	-1	4	4	-1	-1
A	0	0	0	2	2	0	0

#of independent π terms =7-3=4

these terms can be evaluated by solving

$$-x_4 - x_5 = 0, \quad x_1 + x_2 + x_3 = 0, \quad x_3 - x_6 - x_7 = 0$$

that is

Dimensional Analysis for the Frequency Mapping of the Microstrip Right Angle Bend

$$x_4 = -x_5, \quad x_3 = -x_1 - x_2, \quad x_6 = -x_7 + x_1 + x_2$$

the solutions are

x_1	x_2	x_5	x_7	x_3	x_4	x_6
1	0	0	0	-1	0	1
0	1	0	0	-1	0	1
0	0	1	0	0	-1	0
0	0	0	1	0	0	-1

the three π terms are given by

$$\pi_1 = \frac{\omega H}{c}, \quad \pi_2 = \frac{\omega W}{c}, \quad \pi_3 = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r, \quad \pi_4 = \frac{\omega_c}{\omega}$$

from π_1 and π_2 we get $\pi_2' = W / H$

Dimensional Analysis for the Frequency Mapping of the Microstrip Right Angle Bend

the circuit model frequency is given by

$$\omega_c = \omega \; f\left(\frac{W}{H}, \varepsilon_r, \left(\frac{\omega H}{c}\right)\right)$$