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# Matlab-Based Computer-Aided-Design Algorithm for Designing Stepped-Impedance Resonator Low-Pass Filters in Microstrip Technology

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## Abstract

An accurate MATLAB-based CAD algorithm for quickly designing microstrip-based stepped-impedance resonator (SIR) low-pass filter is reported. The algorithm uses a circuit-theory approach to implement speedy computations, compared to the time-consuming computations involved in using electromagnetic theory. The accuracy of the proposed algorithm is verified for two widely-different practical examples in the 0-4GHz frequency range, against results obtained using Ansoft/Ansys circuit simulation tool, and against results obtained using the 3D electromagnetic simulator HFSS. The agreement among the three sets of data is seen to be excellent for most cases, and is found to be practically acceptable in the worst-case.

**Index Terms:** Microstrip, Filter, CAD, MATLAB, MIC.

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## 1. Introduction

MATLAB is a well-known mathematical tool for carrying out computations in the world of modern engineering disciplines (see, for example, [1]-[2]). Microwave Integrated Circuits (MICs) and Monolithic Microwave Integrated Circuits (MMICs), on the other hand, are one of the most popular technologies used by designers in the field of radio frequency (RF) and microwave systems (see, for example, [3]-[14]).

One of the most commonly used transmission lines in the MIC/MMIC technology is the microstrip line

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shown schematically in Fig. 1.

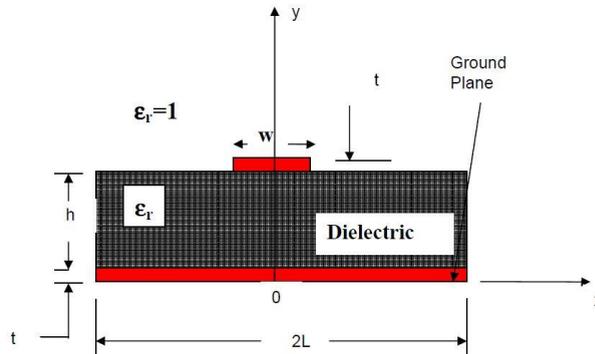


Fig. 1. The schematic of a microstrip line

The microstrip line is made up of a dielectric substrate material, one side of which is fully metalized and the other side of which has only a metallic strip of width  $W$  and thickness  $t$ . The height of the substrate is denoted by  $h$  and the substrate dielectric constant is denoted by  $\epsilon_r$ . The commercially-available values of  $h$  range from 5 mil to 120 mil where 1 mil is equal to 0.001 inch. The value of the substrate dielectric constant is dependent on the material used. For instance,  $\epsilon_r=9.8$  for a commercially-available Alumina ( $Al_2O_3$ ) substrate. The dimension  $L$  is chosen to be as large as possible, and is typically selected to be greater than  $5W$ . The thickness  $t$  of the strip metallization is typically in the  $\mu m$  range.

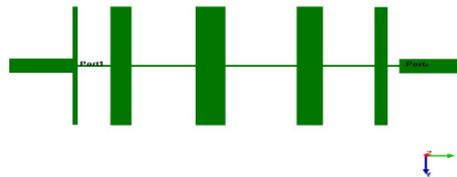


Fig. 2. The schematic of a stepped-impedance resonator (SIR) filter

The stepped-impedance resonator (SIR) filter is one highly-popular method of realizing low-pass filters in microstrip technology (see, for example, [3]-[10], [12]). As schematically shown in Fig. 2, this filter consists essentially of a cascaded chain of low-impedance (that is, high  $W$ ) and high-impedance (that is, low  $W$ ) microstrip lines. The circuit-theory-based design methodology for these types of filters consists essentially of a) determining the filter order based on the pass-band characteristics (Chebyshev, Butterworth, elliptic, or linear-phase) and the stop-band rejection specification, b) calculating the inductance and capacitance values needed in the chosen topology, and c) computing the widths and lengths of the various microstrips based on the substrate chosen. The detailed procedure is well-documented in literature (see, for example, [4], [5], [7], [8], [9], and [12]).

The electromagnetic (EM)-theory based analysis/design of SIR filters is usually done using the commercially-available 3D EM simulation tools like those sold by ANSYS/ANSOFT [15]. These tools are able to predict the real-life performance of SIR filters with sufficient accuracy (see, for example, [7]). The main disadvantages of such 3D simulation tools are their high cost, their somewhat-cumbersome user interfaces, and the relatively longer design effort involved. The circuit-theory-based simulations thus remain an attractive option for designing SIR filters.

In this work, we have developed a MATLAB-based analysis algorithm for SIR filters using the circuit-theory approach. We have made use of the well-known ABCD parameters to compute the overall performance of the filter, in terms of its insertion loss, its input/output return losses, and its stop-band rejection rate. We have compared our results with those obtained using ANSOFT/ANSYS circuit simulator, and with those obtained using the HFSS 3D simulator. Two widely different practical cases have been considered. We have concluded that our MATLAB-based algorithm is an attractive alternative to using the commercially-available simulation tools.

The rest of the paper is organized as follows. Section 2 presents the analysis equations for a single microstrip line. Section 3 presents the design equations for a single microstrip line. Section 4 presents the equations necessary to understand transmission (ABCD) parameters and scattering (S) parameters, and their inter-relationships. Section 5 presents the equations for computing the ABCD parameters of a single microstrip line. Section 6 presents the methodology for computing the ABCD parameters of a chain of cascaded transmission lines. Section 7 presents the procedure for designing and analyzing SIR filters, and sections 8 and 9 present comparisons of our results with those obtained using commercially-available simulation tools.

### Nomenclature

c	speed of light in vacuum/free-space/air
C <sub>cap</sub>	capacitance
f	frequency
h	substrate height
l	microstrip length
L	sidewall location
L <sub>ind</sub>	inductance
t	strip thickness
v	phase-velocity of signal
W	width of microstrip
Z <sub>0</sub>	characteristic impedance of microstrip
β	phase-constant of signal
ε <sub>r</sub>	dielectric constant of substrate
ε <sub>re</sub>	effective dielectric constant of microstrip
λ	wavelength of signal in free-space
λ <sub>g</sub>	guided wavelength of signal

## 2. Analysis Equations for a Single Microstrip

The following semi-empirically derived formula [8] for the effective dielectric constant of a single microstrip has been used. Note that the effective dielectric constant ε<sub>re</sub> and the substrate dielectric constant ε<sub>r</sub> are both dimensionless quantities. The same is also true for the aspect ratio W/h of the microstrip.

$$\epsilon_{re} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\left( \sqrt{1 + 12 \frac{h}{W}} \right)} \quad (1)$$

The characteristic impedance, Z<sub>0</sub>, of the microstrip has been calculated using the following formulas [8].

$$Z_0(\text{ohm}) = \frac{60}{\sqrt{\epsilon_{re}}} \ln\left(\frac{8h}{W} + \frac{W}{4h}\right) \quad (2a)$$

for  $W/h < 1$  and

$$Z_0(\text{ohm}) = \frac{120\pi}{\sqrt{\epsilon_{re}} \left[ \frac{W}{h} + 1.393 + 0.667 \ln\left(\frac{W}{h} + 1.444\right) \right]} \quad (2b)$$

for  $W/h > 1$ .

The effects of strip thickness,  $t$ , are ignored in deriving (1), (2a) and (2b). This is acceptable for most of the practically used values of  $t$ . However, if the value of  $t$  is large, the modified formulas for including the effect of  $t$  in  $\epsilon_{re}$  and  $Z_0$  are available in [8].

The phase-velocity of the signal inside the microstrip is given by

$$v = \frac{c}{\sqrt{\epsilon_{re}}} \quad (3)$$

where  $c$  is the speed of light in vacuum.

The guided wavelength (that is, the wavelength of the signal inside the microstrip) is given by

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{re}}} \quad (4)$$

where the free-space wavelength  $\lambda_0$  of the signal is given by the well-known equation

$$\lambda_0 = \frac{c}{f} \quad (5)$$

where  $f$  is the operating frequency in Hz. The phase-constant of the signal (that is, the phase-shift introduced in the signal per unit length of the microstrip) is given by

$$\beta = \frac{2\pi}{\lambda_g} \quad (6)$$

### 3. Design Equations for a Single Microstrip

The purpose of (1) to (6) presented in the previous section is to calculate the performance of the microstrip line (that is, to calculate its effective dielectric constant, its characteristic impedance, its phase-constant, etc.) for a given set of values of  $W$ ,  $h$ , and  $\epsilon_r$ . For design purposes, the reverse is necessary. That is, one is interested in finding  $W$  for a given set of values of  $\epsilon_r$ ,  $h$ , and  $Z_0$ . The equations for doing so are given below.

$$\frac{W}{h} = \frac{8 \exp(A)}{\exp(2A) - 2} \quad (7a)$$

for  $W/h < 2$  and

$$\frac{W}{h} = \frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left( \ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \right] \quad (7b)$$

for  $W/h > 2$ .

The parameters A and B are defined as follows.

$$A = \frac{Z_0}{60} \sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1} \left( 0.23 + \frac{0.11}{\epsilon_r} \right) \quad (8)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}} \quad (9)$$

#### 4. Transmission Parameters, Scattering Parameters, Insertion Loss, and Return Loss

A large number of RF/microwave components, including filters and microstrip lines, can be represented by a two-port network as shown in Fig. 3 (taken from [8]). The input port (port 1) is characterized by input voltage  $V_1$  and input current  $I_1$  and the output port (port 2) is characterized by output voltage  $V_2$  and output current  $I_2$ .

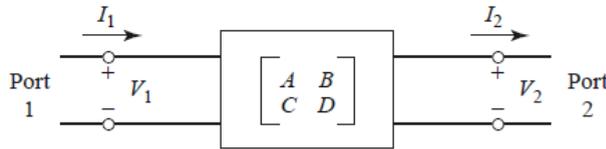


Fig.3. Two-port representation of RF/microwave components

The ABCD parameters (also known as transmission parameters) of a two-port network are defined by the following equations (using the voltage polarities and current directions shown in Fig. 3).

$$V_1 = AV_2 + BI_2 \quad (10)$$

$$I_1 = CV_2 + DI_2 \quad (11)$$

Another method used (especially at high frequencies) is to represent a two-port network in terms of incident and reflected signals at port 1 (that is,  $a_1$  and  $b_1$ ) and the same at port 2 (that is,  $a_2$  and  $b_2$ ). This is shown in Fig.

4 (taken from [10]). In this case, we define four scattering parameters, also abbreviated as S-parameters), namely,  $S_{11}$ ,  $S_{12}$ ,  $S_{21}$ , and  $S_{22}$ .

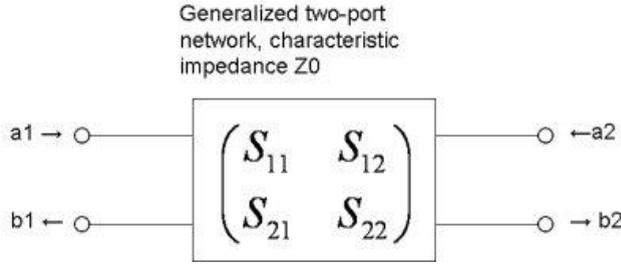


Fig.4. Scattering-parameter representation of RF/microwave components

The equations for defining the S-parameters follow.

$$b_1 = S_{11}a_1 + S_{12}a_2 \tag{12}$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{13}$$

The equations for computing the S-parameters, from a given set of ABCD-parameter values, are given below.

$$S_{11} = \frac{A + \frac{B}{Z_0} - CZ_0 - D}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{14}$$

$$S_{12} = \frac{2(AD - BC)}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{15}$$

$$S_{21} = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{16}$$

$$S_{22} = \frac{-A + \frac{B}{Z_0} - CZ_0 + D}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{17}$$

Note that for reciprocal networks like filters and transmission lines,

$$AD - BC = 1 \tag{18}$$

and hence

$$S_{12} = S_{21} \quad (19a)$$

and

$$S_{11} = S_{22} \quad (19b)$$

The insertion loss (IL) of a filter is defined by the following equation:

$$IL(dB) = 20 \log(X) \quad (20)$$

where  $X$  is the magnitude of the transmission coefficient  $T$ . In case of filters,  $T$  is defined to be equal to  $S_{12}$  (or  $S_{21}$ ). Hence, we write

$$X = |S_{12}| = |S_{21}| \quad (21)$$

The input return loss  $RL_{input}$  and output return loss  $RL_{output}$  are defined by the following equations:

$$RL_{input}(dB) = -20 \log\{|S_{11}|\} \quad (22a)$$

$$RL_{output}(dB) = -20 \log\{|S_{22}|\} \quad (22b)$$

where  $S_{11}$  is known as the input reflection coefficient and  $S_{22}$  is known as the output reflection coefficient.

## 5. Transmission Parameters and Scattering Parameters of a Single Microstrip Line

For a single microstrip line shown in Fig. 5, with characteristic impedance  $Z_0$ , phase-constant  $\beta$ , and physical length  $l$ , the equations for calculating the ABCD parameters are given below. These equations are applicable to lossless lines only. For lossy lines, suitably-modified equations can be used [8].

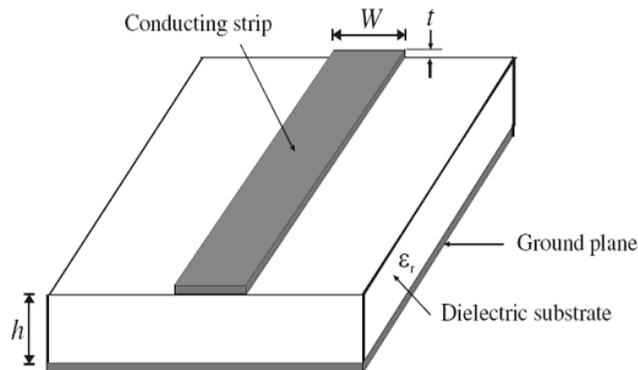


Fig.5. A single microstrip line

$$A = \cos(\beta l) \tag{23}$$

$$B = jZ_0 \sin(\beta l) \tag{24}$$

$$C = \frac{j}{Z_0} \sin(\beta l) \tag{25}$$

$$D = \cos(\beta l) \tag{26}$$

Once the ABCD parameters are known, one can use (14)-(17) to compute the S-parameters.

### 6. Transmission Parameters of a Chain of Cascaded Components

For a chain of cascaded components of the kind shown in Fig. 6, the overall ABCD-matrix can be computed by multiplying the individual ABCD-matrices in the correct sequence [8]. This single fact alone makes the use of ABCD parameters very popular in the RF/microwave designer community.

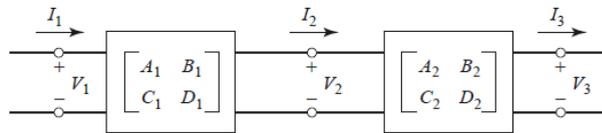


Fig.6. A chain of cascaded components

Once the overall ABCD parameters are known, one can use (14)-(17) to compute the overall S-parameters.

### 7. Procedure for Designing and Analyzing the Stepped-Impedance Resonator Filter

The stepped-impedance resonator (SIR) low-pass filter consists of several cascaded microstrip lines, starting with a low-characteristic-impedance line (say  $Z_0=Z_{0L}$ , with  $10\Omega$  to  $20\Omega$  being a recommended range for  $Z_{0L}$ ), followed by a high-characteristic-impedance line (say  $Z_0=Z_{0H}$ , with  $80\Omega$  to  $100\Omega$  being a recommended range for  $Z_{0H}$ ), and so on. The case of five such cascaded microstrip lines is schematically shown in Fig. 7.

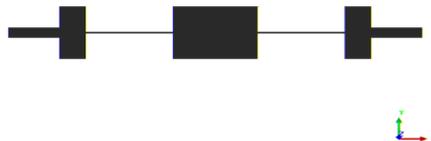


Fig.7. A stepped-impedance-resonator (SIR) low-pass filter containing five cascaded microstrip lines

The design and analysis of such filters consists essentially of the following steps:

- Decide the type of passband response that is desired.* Depending on the intended practical application, this could mean choosing either a maximally-flat (Butterworth) response, or an equal-ripple (Chebyshev) response, or an elliptic response, or a linear-phase response.
- Decide the number of sections.* Depending on the passband response chosen in step a, and depending on the stopband rejection rate specification, this step can be achieved using Fig. 8.26 of [8] for a maximally-flat response, Fig. 8.27 of [8] for an equal-ripple response, etc. Choosing too many sections may affect the compactness of the design and choosing too few sections may affect the stopband performance. Hence, a suitable trade-off between these two conflicting demands is made.
- Choose the inductance ( $L_{ind}$ ) and capacitance ( $C_{cap}$ ) values for each microstrip line section.* This can be done using the appropriate design tables (for example, Table 8.3 in [8] for maximally-flat response).
- Compute microstrip widths.* This can be done using (7)-(9) with  $Z_0=Z_{oL}$  for high-W lines, and with  $Z_0=Z_{oH}$  for low-W lines. One, of course, has to choose  $Z_{oL}$  and  $Z_{oH}$  first. The recommended values for  $Z_{oL}$  are anywhere between  $10\Omega$  and  $20\Omega$  as already mentioned. The recommended values for  $Z_{oH}$  are anywhere between  $80\Omega$  and  $110\Omega$  as already mentioned.
- Compute lengths of various microstrip lines.* As already mentioned, high-W microstrip lines represent low- $Z_0$ , that is,  $Z_0=Z_{oL}$ . Similarly, low-W microstrip lines represent high- $Z_0$ , that is,  $Z_0=Z_{oH}$ . It can also be shown [8] that high-W lines represent shunt capacitors and low-W lines represent series inductors. For high-W lines, the physical lengths can be computed using the following equation:

$$\beta l = \frac{C_{cap} Z_{oL}}{Z_o} \quad (27)$$

Similarly, for low-W lines, the physical lengths can be computed using the following equation:

$$\beta l = \frac{L_{ind} Z_o}{Z_{oH}} \quad (28)$$

### Design example 1

As the first example, we considered the following design goals:

- Substrate to be used: Alumina ( $Al_2O_3$ ) with  $h=25$  mil,  $\epsilon_r=9.8$
- Passband frequency range: 0 to 1.5 GHz
- Passband response: chebyshev (equal-ripple)
- Stopband rejection: at least 20 dB at 3 GHz
- Input return loss: better than 10 dB
- Output return loss: better than 10 dB

Following the design algorithm outlined in section 7 and using the various mathematical equations presented in sections 2,3,4,5, and 6, we obtained a five-section design with widths and lengths of the various microstrip sections as listed below.

$$\begin{aligned} W_1 &= 114 \text{ mil}, l_1 = 193 \text{ mil} \\ W_2 &= 8 \text{ mil}, l_2 = 346 \text{ mil} \\ W_3 &= 114 \text{ mil}, l_3 = 291 \text{ mil} \end{aligned}$$

$W_4=8$  mil,  $l_4=346$  mil  
 $W_5=114$  mil,  $l_5=193$  mil

A MATLAB program was written (see appendix A for complete listing of the program) to analyze the performance of the design, that is, to find its four S-parameters, and then to calculate its input return loss, output return loss, insertion loss, and phase characteristic. The design was also simulated using Ansoft's circuit simulator and using the 3D HFSS EM simulator version 12.0.

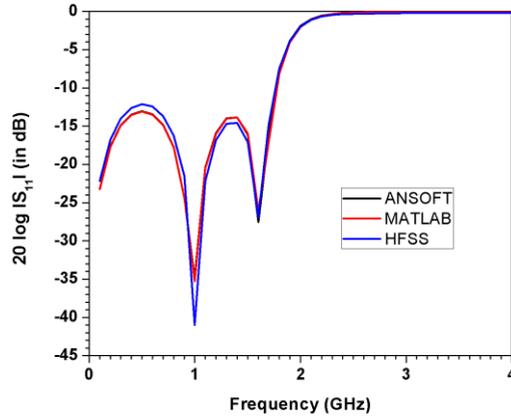


Fig.8. Design example 1: comparison of input/output return loss data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

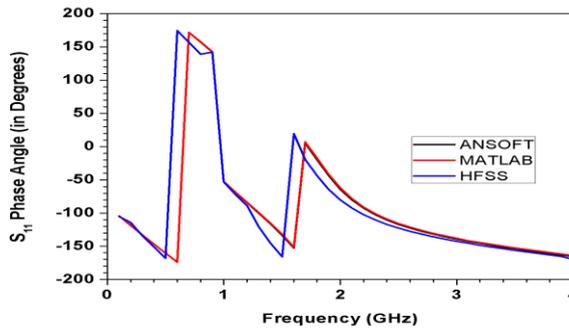


Fig.9. Design example 1: comparison of input/output reflection coefficient's phase-angle data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

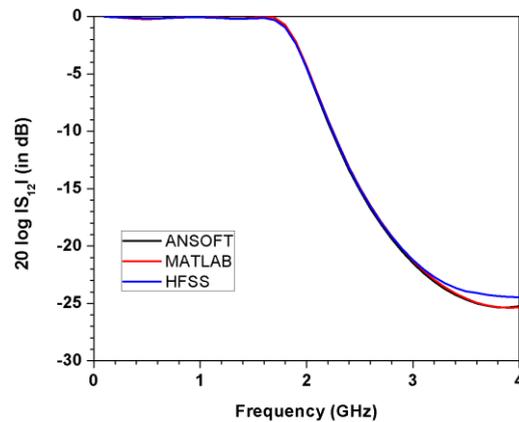


Fig.10. Design example 1: comparison of insertion loss data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

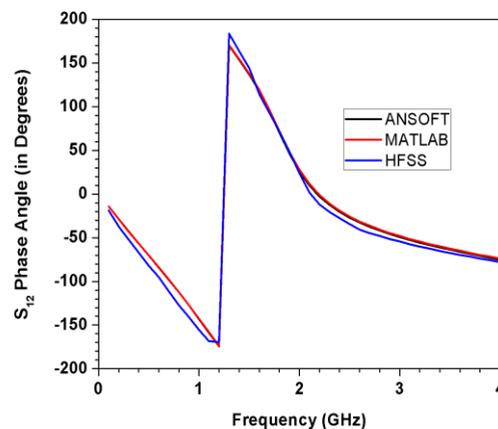


Fig.11. Design example 1: comparison of transmission coefficient's phase-angle data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

Figs. 8, 9, 10, and 11 show comparisons of the three sets of computed data, over a frequency range of DC to 4 GHz. Fig. 8 is for the input/output return loss in -dB. Fig. 9 is for the phase-angle (in degrees) of the input/output reflection coefficient. Fig. 10 is for the insertion-loss in -dB, and Fig. 11 is for the transmission-coefficient's phase-angle (in degrees). A good agreement among the various curves is seen, excepting some inconsequential discrepancies at transition-points in the phase-angle curves. This establishes the worthiness of the proposed circuit-theory-based MATLAB algorithm. It needs to be pointed out that minor discrepancies between HFSS data and circuit-theory-based data (whether obtained using our MATLAB program or using Ansoft circuit simulator) are understandable, since 3D EM simulators account for discontinuity effects, dispersion, etc. which circuit-theory cannot account for.

**Design example 2**

As the second design example, we considered the following design goals:

- a. Substrate to be used: FR4 with  $h=60$  mil,  $\epsilon_r=4.4$
- b. Passband frequency range: 0 to 1.2 GHz
- c. Passband response: butterworth (maximally-flat)
- d. Stopband rejection: at least 20 dB at 2.2 GHz
- e. Input return loss: better than 10 dB
- f. Output return loss: better than 10 dB

Following the design algorithm outlined in section 7 and using the various mathematical equations presented in sections 2,3,4,5, and 6, we obtained an eight-section design with widths and lengths of the various microstrip sections as listed below.

- $W_1=886$  mil,  $l_1=50$  mil
- $W_2=7$  mil,  $l_2=257$  mil
- $W_3=886$  mil,  $l_3=215$  mil
- $W_4=7$  mil,  $l_4=454$  mil
- $W_5=886$  mil,  $l_5=254$  mil
- $W_6=7$  mil,  $l_6=385$  mil
- $W_7=886$ mil,  $l_7=144$  mil
- $W_8=7$  mil,  $l_8=90$  mil

A MATLAB program was again written (see appendix A for complete listing of the program) to analyze the performance of the design, that is, to find its four S-parameters, and then to calculate its input return loss, output return loss, insertion loss, and phase characteristic. The design was also simulated using Ansoft’s circuit simulator and using the 3D HFSS EM simulator version 12.0. The comparisons of our data with data obtained using Ansoft circuit simulator and the HFSS simulator are shown in Figs. 12, 13, 14, and 15. Barring some understandable discrepancies due to reasons already discussed (discontinuity effects, dispersion, etc.) in the previous section, the agreement among the three sets of data is again seen to be good enough for all practical purposes.

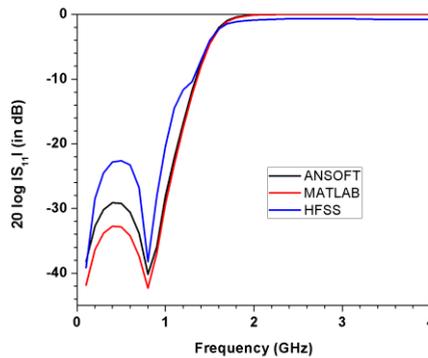


Fig.12. Design example 2: comparison of input/output return loss data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

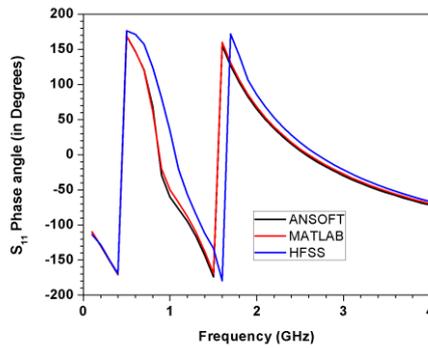


Fig. 13. Design example 2: comparison of input/output reflection coefficient's phase-angle data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

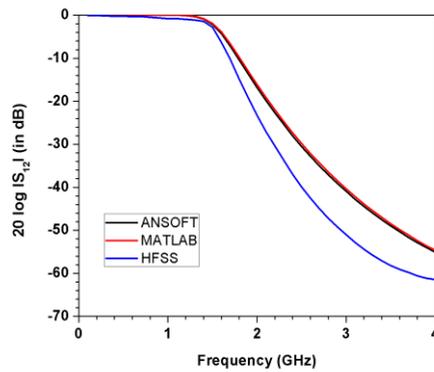


Fig. 14. Design example 2: comparison of insertion loss data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

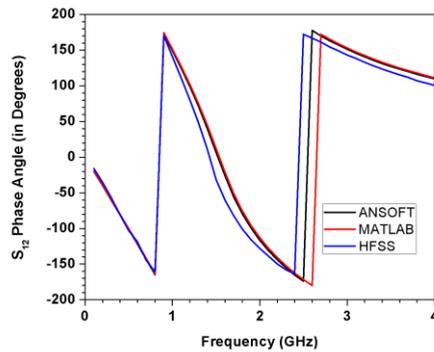


Fig. 15. Design example 2: comparison of transmission coefficient's phase-angle data obtained using MATLAB, using Ansoft circuit simulator, and using HFSS simulator

## 8. Conclusions

The use of circuit-theory approach in analyzing and designing stepped-impedance resonator low-pass microstrip filters has been investigated, using MATLAB. Two widely-different practical examples have been analyzed using MATLAB, and results compared with results obtained using Ansys/Ansoft circuit simulator and results obtained using 3D EM simulation tool HFSS. MATLAB results agree well with those obtained using other tools. The computationally-efficient MATLAB algorithm reported herein will hence be a useful addition to the CAD toolbox for RF/microwave designers.

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## Author(s) Profiles



Luv Kumar Tomar (born September 22, 1993) is a fourth year undergraduate student in the Department of Electronics at Carleton University, Ottawa, Canada. He is passionately interested in simulation and modeling of electronic circuits, including RF circuits.



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**Raghuvir Tomar** (born January 19, 1955) is a Professor in Electronics and Communication Engineering at The LNM Institute of Information Technology, India. He has co-authored more than fifty research papers on a wide variety of topics in the domain of electromagnetics and microwaves. He has about twenty-years of industry experience and more than ten-years of academic experience. Simulation and modeling of RF/microwave components, sub-systems, and systems are one of his key passions. He is a Senior Member of the IEEE and a Fellow of the IETE (India).



**Prakash Bhartia** is the Executive Vice President and Vice President of Engineering at NATEL Engineering Co., Inc., California, U.S.A. He has over twenty-five year experience at Canadian Department of Defence. He held four Director level positions and served as Director General of the Defence R&D Laboratories in Halifax and Ottawa. He has published extensively and has more than 200 research publications, nine books, and five patents to his credit. He is a Fellow of the IEEE.

## Appendix A. MATLAB program listing for design example 1 and design example 2

The full listing of the MATLAB code that was written for design example 1 follows.

```
%MATLAB PROGRAM FOR COMPUTING THE PERFORMANCE OF A STEPPED IMPEDANCE  
RESONATOR (SIR) FILTER IN MICROSTRIP TECHNOLOGY: EXAMPLE 1  
%DESIGN GOALS: 25mil thick Alumina (Al2O3) substrate  
(ER=9.8,h=25mil=0.000635m)  
%Passband: 0 to 1.5GHz,  
%Chebyshev Response in passband with 0.2dB ripple maximum  
%Input return loss: better than 10dB in passband  
%Output return loss: better than 10dB in passband  
%Stopband rejection: at least 3dB at 2GHz, at least 20dB for f>3GHz  
%PARAMETER DEFINITIONS: The design consists of five cascaded microstrips  
% with widths W1,W2,W3,W4 and W5 and physical lengths as P1,P2,P3,P4 and  
P5.  
%All lengths (including substrate height) are in m  
%All frequencies are in Hz  
%Input/output impedance Z0=50 ohm  
disp ('STEPPED IMPEDANCE MICROSTRIP FILTER DESIGN EXAMPLE 1');  
for i=0.1:0.1:4  
F=i*10^9;  
Z0=50;
```

```

H=0.000635;
ER=9.8;
T=0;
W1=0.0029;
P1=0.0049;
W2=0.0002;
P2=0.0088;
W3=0.0029;
P3=0.0074;
W4=W2;
P4=P2;
W5=W1;
P5=P1;
%CALCULATION OF ABCD PARAMETERS OF INDIVIDUAL MICROSTRIPS
[A1, B1, C1, D1] = ABCD_single_microstrip_line(W1,H,T,ER,F,P1);
[A2, B2, C2, D2] = ABCD_single_microstrip_line(W2,H,T,ER,F,P2);
[A3, B3, C3, D3] = ABCD_single_microstrip_line(W3,H,T,ER,F,P3);
[A4, B4, C4, D4] = ABCD_single_microstrip_line(W4,H,T,ER,F,P4);
[A5, B5, C5, D5] = ABCD_single_microstrip_line(W5,H,T,ER,F,P5);
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1 AND LINE 2
A12=A1*A2+B1*C2;
B12=A1*B2+B1*D2;
C12=C1*A2+D1*C2;
D12=C1*B2+D1*D2;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, AND LINE 3
A123=A12*A3+B12*C3;
B123=A12*B3+B12*D3;
C123=C12*A3+D12*C3;
D123=C12*B3+D12*D3;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, LINE 3, AND
%LINE 4
A1234=A123*A4+B123*C4;
B1234=A123*B4+B123*D4;
C1234=C123*A4+D123*C4;
D1234=C123*B4+D123*D4;
%CALCULATION OF OVERALL ABCD PARAMETERS OF THE FILTER
A12345=A1234*A5+B1234*C5;
B12345=A1234*B5+B1234*D5;
C12345=C1234*A5+D1234*C5;
D12345=C1234*B5+D1234*D5;
%CALCULATION OF S-PARAMETERS OF THE FILTER
DEN=A12345+(B12345/Z0)+(C12345*Z0)+D12345;
NUMS11=A12345+(B12345/Z0)-(C12345*Z0)-D12345;
S11=NUMS11/DEN;
S11M=abs (S11);
RLIN=-20*log10 (S11M);
ANGS11=angle (S11);
ANGS11DEG=ANGS11*180/pi;
NUMS12=2;

```

```
S12=NUMS12/DEN;
S12M=abs (S12);
IL=-20*log10 (S12M);
ANGS12=angle (S12);
ANGS12DEG=ANGS12*180/pi;
F,RLIN, IL, ANGS11DEG,ANGS12DEG
end
```

```
function [ A, B, C, D ] = ABCD_single_microstrip_line( W,h,t,ER, f, l )
%Function used to calculate the ABCD parameters of a single microstrip
line from its strip width (W in m), substrate height (h
in m), substrate dielectric constant (ER), thickness of metallization (t
in m), operating frequency (f in Hz), and physical length (l in m).
[EREF,Z0] = Calculate_Z0_EREF (h,W,t,ER);
Vp = 3*(10^8)/((EREF)^0.5);
Beta = 2*pi*f/Vp;
A = cos(Beta*l);
B = i*Z0*sin(Beta*l);
C = j*(1/Z0)*sin(Beta*l);
D = cos(Beta*l);
end
```

```
function [ EREF, Z0 ] = Calculate_Z0_EREF( h, W, t, ER )%Function used to
calculate the effective dielectric constant (EREF) and characteristic
impedance (Z0) of a microstrip line for a given substrate height (h),
strip width (W), strip thickness (t),
%and dielectric constant of the substrate (ER).
```

```
if (W/h < 1)
    Eeff = ((ER + 1)/2) + ((ER - 1)/2)*(1 + 12*((h/W)^(-0.5)) + 0.04*(1 -
(W/h))^2);
    Z0 = (60/(Eeff^0.5))*log(8*(h/W) + 0.25*(W/h));
```

```
else
    Eeff = ((ER + 1)/2) + ((ER - 1)/2)*((1 + 12*(h/W))^(-0.5));
    Z0 = 120*pi*(Eeff^(-0.5))/(W/h) + 1.393 + (2/3)*log((W/h) + 1.444));
```

```
end
```

```
EREF = Eeff;
```

```
end
```

The full listing of the MATLAB code that was written for design example 2 follows.

```
%MATLAB PROGRAM FOR COMPUTING THE PERFORMANCE OF A STEPPTED IMPEDANCE
%RESONATOR (SIR) FILTER IN MICROSTRIP TECHNOLOGY: EXAMPLE 2
%DESIGN GOALS: 60mil thick FR4 substrate (ER=4.4,h=60mil=0.0016m)
```

```

%Passband: 0 to 1.2GHz,
%Maximally-Flat Response in passband
%Input return loss: better than 10dB in passband
%Output return loss: better than 10dB in passband
%Stopband rejection: at least 3dB at 2GHz, at least 20dB for f>3GHz
%PARAMETER DEFINITIONS: The design consists of eight cascaded microstrips
%with widths W1,W2,W3,W4,W5,W6,W7 and W8 and physical lengths as
P1,P2,P3,P4,P5,P6,P7 and P8.
%All lengths (including substrate height) are in m
%All frequencies are in Hz
%Input/output impedance Z0=50 ohm
disp ('STEPPED IMPEDANCE MICROSTRIP FILTER DESIGN EXAMPLE 2');
for i=0.1:0.1:4
F=i*10^9;
Z0=50;
H=0.0016;
ER=4.4;
T=0;
W1=0.0225;
P1=0.00128;
W2=0.00018;
P2=0.00653;
W3=W1;
P3=0.00547;
W4=W2;
P4=0.01153;
W5=W1;
P5=0.00645;
W6=W4;
P6=0.00977;
W7=W5;
P7=0.00365;
W8=W6;
P8=0.00229;
%CALCULATION OF ABCD PARAMETERS OF INDIVIDUAL MICROSTRIPS
[A1, B1, C1, D1] = ABCD_single_microstrip_line(W1,H,T,ER,F,P1);
[A2, B2, C2, D2] = ABCD_single_microstrip_line(W2,H,T,ER,F,P2);
[A3, B3, C3, D3] = ABCD_single_microstrip_line(W3,H,T,ER,F,P3);
[A4, B4, C4, D4] = ABCD_single_microstrip_line(W4,H,T,ER,F,P4);
[A5, B5, C5, D5] = ABCD_single_microstrip_line(W5,H,T,ER,F,P5);
[A6, B6, C6, D6] = ABCD_single_microstrip_line(W6,H,T,ER,F,P6);
[A7, B7, C7, D7] = ABCD_single_microstrip_line(W7,H,T,ER,F,P7);
[A8, B8, C8, D8] = ABCD_single_microstrip_line(W8,H,T,ER,F,P8);
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1 AND LINE 2
A12=A1*A2+B1*C2;
B12=A1*B2+B1*D2;
C12=C1*A2+D1*C2;
D12=C1*B2+D1*D2;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, AND LINE 3

```

```
A123=A12*A3+B12*C3;
B123=A12*B3+B12*D3;
C123=C12*A3+D12*C3;
D123=C12*B3+D12*D3;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, LINE 3, AND
%LINE 4
A1234=A123*A4+B123*C4;
B1234=A123*B4+B123*D4;
C1234=C123*A4+D123*C4;
D1234=C123*B4+D123*D4;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, LINE 3,
LINE4 AND
%LINE 5
A12345=A1234*A5+B1234*C5;
B12345=A1234*B5+B1234*D5;
C12345=C1234*A5+D1234*C5;
D12345=C1234*B5+D1234*D5;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, LINE 3,
LINE4, LINE5 AND
%LINE 6
A123456=A12345*A6+B12345*C6;
B123456=A12345*B6+B12345*D6;
C123456=C12345*A6+D12345*C6;
D123456=C12345*B6+D12345*D6;
%CALCULATION OF ABCD PARAMETERS OF CASCADE OF LINE 1, LINE 2, LINE 3,
LINE4, LINE5, LINE6 AND
%LINE 7
A1234567=A123456*A7+B123456*C7;
B1234567=A123456*B7+B123456*D7;
C1234567=C123456*A7+D123456*C7;
D1234567=C123456*B7+D123456*D7;
%CALCULATION OF ABCD PARAMETERS OF THE OVERALL FILTER
A12345678=A1234567*A8+B1234567*C8;
B12345678=A1234567*B8+B1234567*D8;
C12345678=C1234567*A8+D1234567*C8;
D12345678=C1234567*B8+D1234567*D8;
%CALCULATION OF S-PARAMETERS OF THE FILTER
DEN=A12345678+(B12345678/Z0)+(C12345678*Z0)+D12345678;
NUMS11=A12345678+(B12345678/Z0)-(C12345678*Z0)-D12345678;
S11=NUMS11/DEN;
S11M=abs (S11);
RLIN=-20*log10 (S11M);
ANGS11=angle (S11);
ANGS11DEG=ANGS11*180/pi;
NUMS12=2*(A12345678*D12345678-B12345678*C12345678);
S12=NUMS12/DEN;
S12M=abs (S12);
IL12=-20*log10 (S12M);
ANGS12=angle (S12);
```

```

ANGS12DEG=ANGS12*180/pi;
NUMS21=2;
S21=NUMS21/DEN;
S21M=abs (S21);
IL21=-20*log10 (S21M);
ANGS21=angle (S21);
ANGS21DEG=ANGS21*180/pi;
NUMS22=-A12345678+(B12345678/Z0)-(C12345678*Z0)+D12345678;
S22=NUMS22/DEN;
S22M=abs (S22);
RLOUT=-20*log10 (S22M);
ANGS22=angle (S22);
ANGS22DEG=ANGS22*180/pi;
F,RLIN, IL12,IL21,RLOUT, ANGS11DEG,ANGS12DEG,ANGS21DEG,ANGS22DEG
End

```

```

function [ A, B, C, D ] = ABCD_single_microstrip_line( W,h,t,ER, f, l )
%Function used to calculate the ABCD parameters of a single microstrip
line from its strip width (W in m), substrate height (h
%in m), substrate dielectric constant (ER), thickness of metallization (t
%in m), operating frequency (f in Hz), and physical length (l in m).
[EREF,Z0] = Calculate_Z0_EREF (h,W,t,ER);
Vp = 3*(10^8)/((EREF)^0.5);
Beta = 2*pi*f/Vp;
A = cos(Beta*l);
B = i*Z0*sin(Beta*l);
C = j*(1/Z0)*sin(Beta*l);
D = cos(Beta*l);
end

```

```

function [ EREF, Z0 ] = Calculate_Z0_EREF( h, W, t, ER )%Function used to
calculate the effective dielectric constant (EREF) and characteristic
impedance (Z0) of a microstrip line for a given substrate height (h),
strip width (W), strip thickness (t),
%and dielectric constant of the substrate (ER).

```

```

if (W/h < 1)
    Eeff = ((ER + 1)/2) + ((ER - 1)/2)*(1 + 12*((h/W)^(-0.5)) + 0.04*(1 -
(W/h))^2);
    Z0 = (60/(Eeff^0.5))*log(8*(h/W) + 0.25*(W/h));

```

```

else
    Eeff = ((ER + 1)/2) + ((ER - 1)/2)*((1 + 12*(h/W))^(-0.5));
    Z0 = 120*pi*(Eeff^(-0.5))/((W/h) + 1.393 + (2/3)*log((W/h) + 1.444));

```

```
end
```

```
EREF = Eeff;
```

```
end
```