New Configurations for RF/Microwave Filters

Presented by:

Jeremy Fejfar

Applications Engineer

CST of America, Inc.

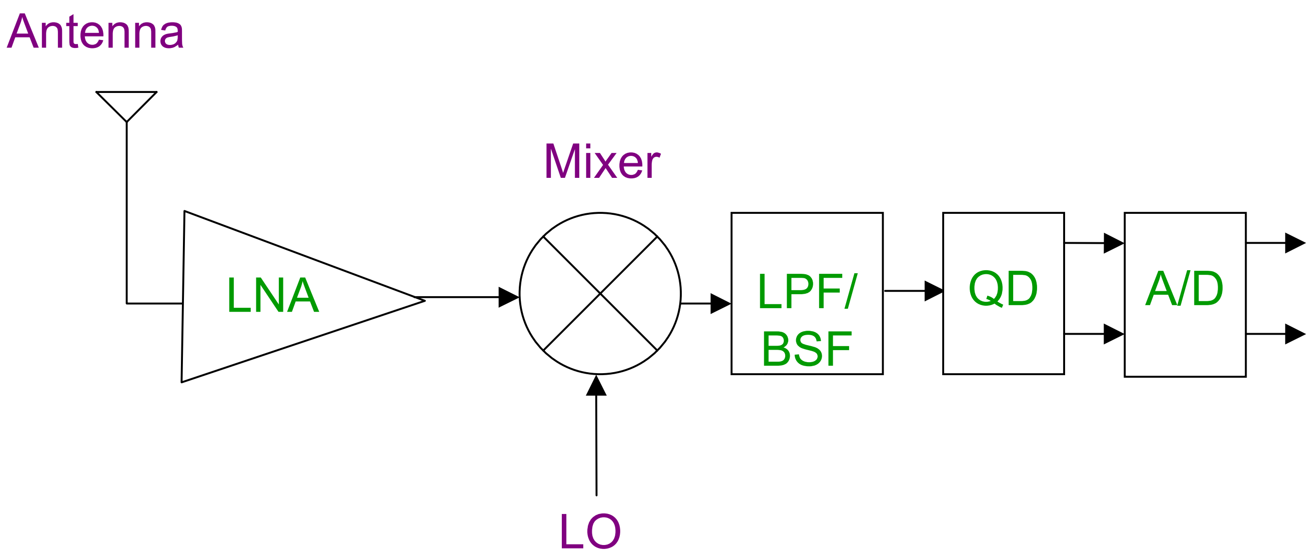
Outline

- Introduction
- Conventional Filter Theory
- Need for Folded Transmission Lines
- Single-level Folded line Bandstop and Lowpass Filters
- Multi-level Folded line Bandstop and Lowpass Filters
- Advantages of Folded Line Filters
- Conclusions

Introduction

- The explosive growth in miniature wireless communication hardware drives the need for miniaturization
- Increasing role of embedded passives
- Off-chip and On-chip applications
- Novel filter configurations desired
- Focus on Bandstop and Lowpass filters

Typical Receiver Architecture



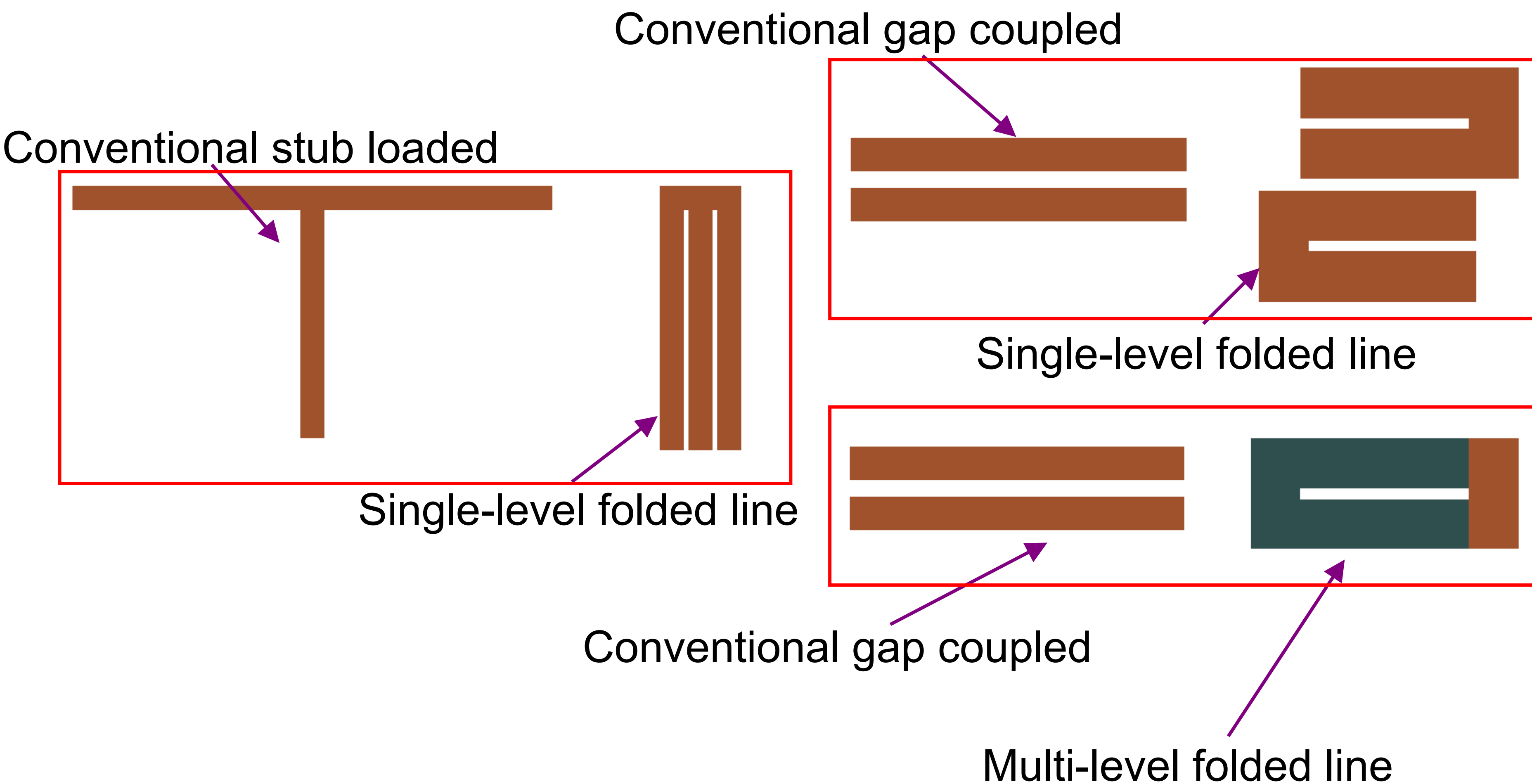
Conventional Design Methodology: Limiting Factors

- < 1 GHz – Typically Lumped Configurations
- > 10 GHz – Typically Distributed Configurations
- Lower RF, microwave frequencies (1-10 GHz)
  - Large component footprints
  - Stub loaded filters → extremely narrow or wide line widths → impractical for physical implementation

Folded Filter Methodology

- Folding the transmission lines yields a more compact footprint
- Common design methodology for both bandstop and lowpass filters
- Conventional filter theory still applicable in the first phase of the design

Folded Line Examples



Network Representation for Single Level Folded Line Filters

- 2N×2N port network

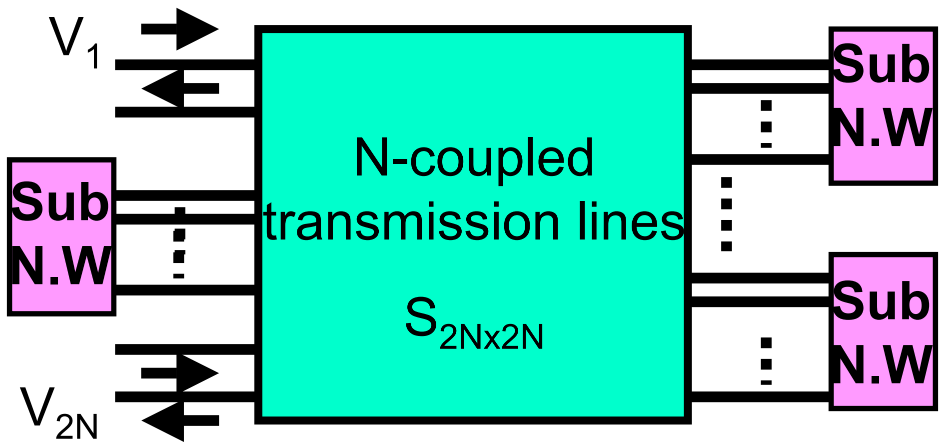
$$[Y] = \begin{bmatrix} Y_A & Y_B \\ Y_B & Y_A \end{bmatrix}$$

$$[Y_A] = [M_v]^T [\coth(\gamma_k l)]_{diag} [Y_k]_{diag} [M_v]^{-1}$$

$$[Y_B] = [M_v]^T [\mathrm{csch}(\gamma_k l)]_{diag} [Y_k]_{diag} [M_v]^{-1}$$

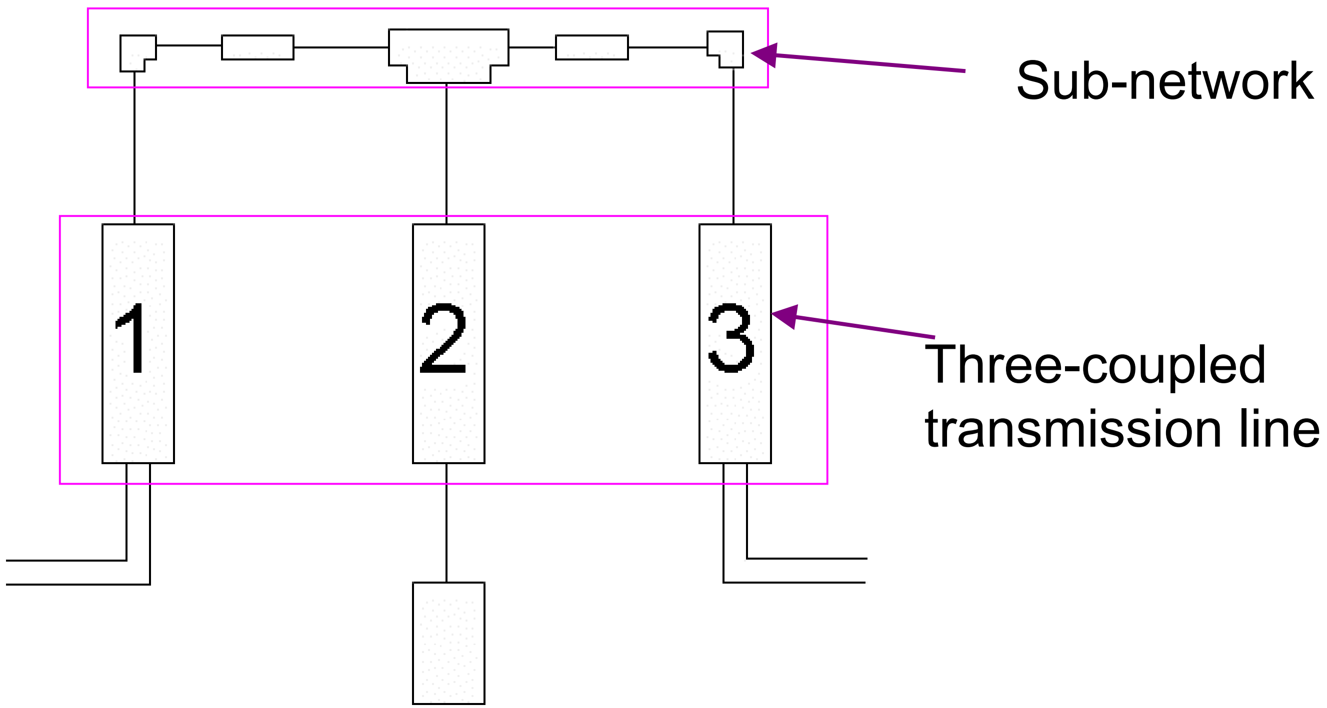
$$[Y_k] \approx [M_v]^{-1} [Y_{SH}][M_v]$$

$$[Y_{SH}] = [G] + j\omega[C] \ ;[Z_S] = [R] + j\omega[L]$$



- Reduced 2-port scattering matrix

Folded Line Filter Section



Filter Design Procedure

Specifications

↓

Lowpass filter prototype values

↓

Richard's transformations /
Kuroda's identities

↓

Impedance and frequency scaling

↓

Length=$\lambda/8$ for lowpass
Length=$\lambda/4$ for bandstop

↓

Physical design

↓ ← Conventional stub loaded filter

Individual section approach
Folded line filter sections

↓

Cascaded folded line filter sections

↓

Final filter response

Single Level Folded Line Bandstop Filters (Example #1)

- Initial design of stub-loaded bandstop filter
- Specifications
  - N=3, f_0=1.5 GHz
  - Maximally flat amplitude response (Butterworth)
  - Δ=0.2 & 0.3
  - Microstrip realization
  - ε_r=2.2, h=31mil

- Design equations for N=3

$$Z_1 = Z_A(1+1/\Lambda g_0 g_1) \quad Z_{12} = Z_A(1+\Lambda g_0 g_1)$$

$$Z_2 = Z_A g_0 / \Lambda g_2 \qquad Z_3 = Z_A g_0 / g_4(1+1/\Lambda g_3 g_4)$$

$$Z_{23} = Z_A g_0 / g_4(1+\Lambda g_3 g_4)$$

Z_A and Z_B = terminating impedances

Z_j ($j = 1$ to n) = OC shunt stub impedances

Z_{1j} ($j = 2$ to n) = connecting line impedances

g_j = prototype element values

$$\Lambda = \omega_0 a, \quad a = \cot\left(\frac{\pi}{2}\frac{\omega_1}{\omega_0}\right)$$

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0}, \quad \omega_0 = \frac{\omega_1 + \omega_2}{2}$$

ω_1 and ω_2 = bandstop edge frequencies

Characteristic Impedances for Various Bandstop Filter Sections

Δ	Z_A (Ω)	Z_1 (Ω)	Z_{12} (Ω)	Z_2 (Ω)	Z_{23} (Ω)	Z_3 (Ω)	Z_B (Ω)
0.3	50	258	62	104	62	258	50
0.2	50	365.7	57.9	157.8	57.9	365.7	50

N=3, Maximally flat response , f_0=1.5 GHz

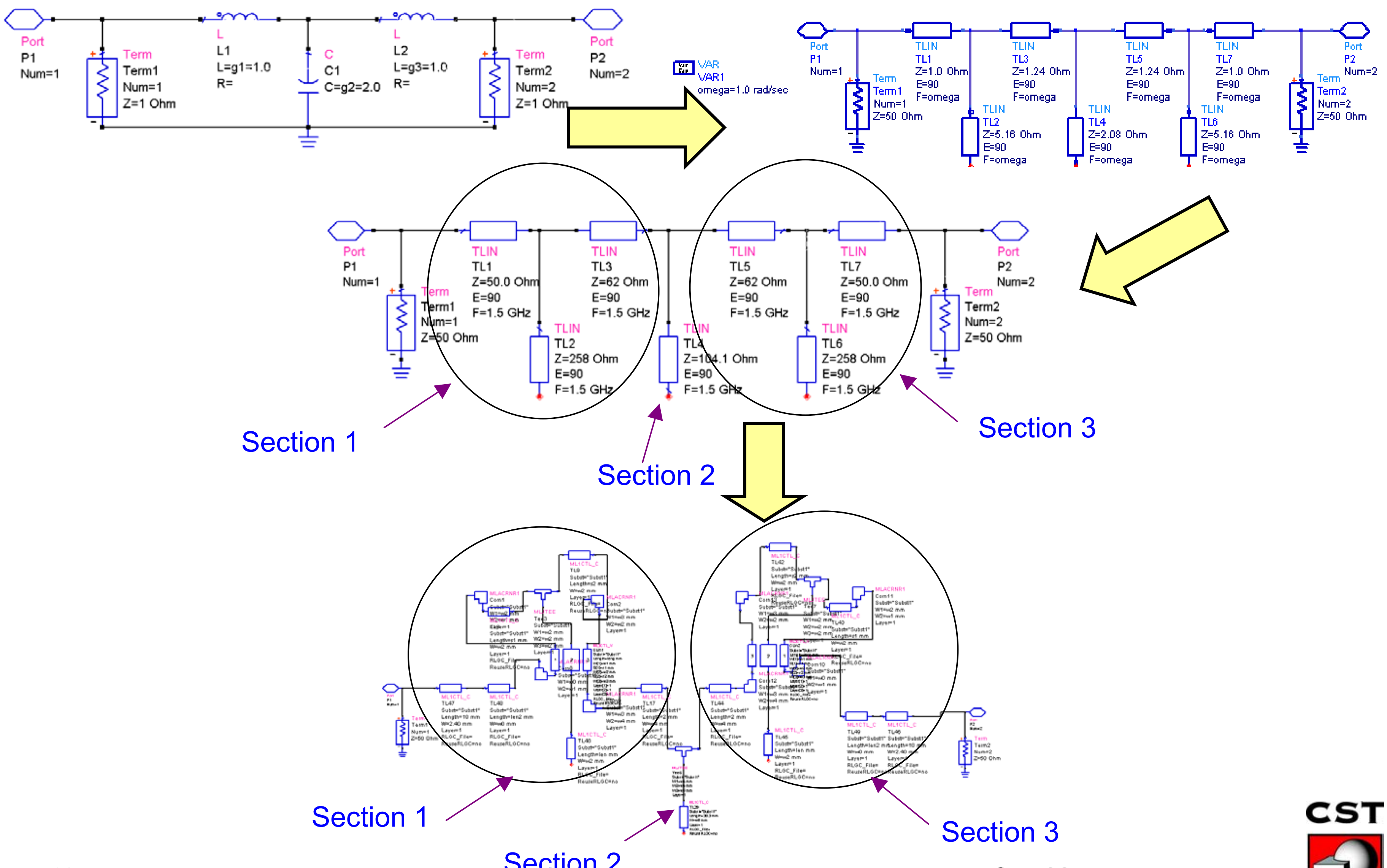
50Ω microstrip line → w = 98 mil

365.7Ω microstrip line → w = 0.1 mil

258 Ω microstrip line → w = 1 mil

(1/2 ounce copper, 0.7 mil)

Design Flow for the Folded Line Bandstop Filters (Single-Level)



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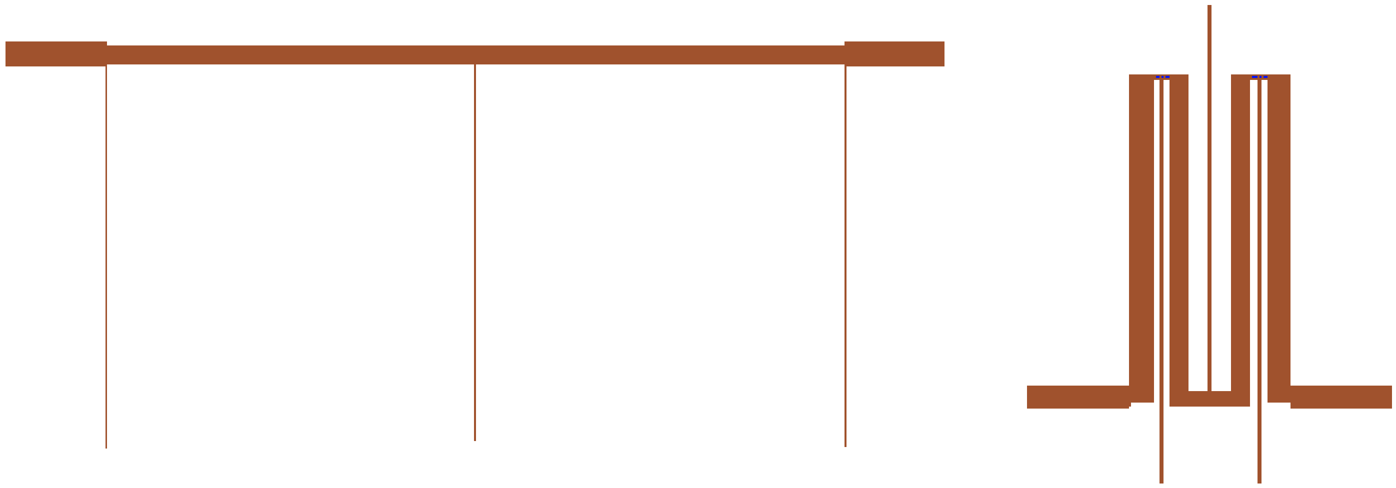
Bandstop Filter Comparison (Δ = 0.2)



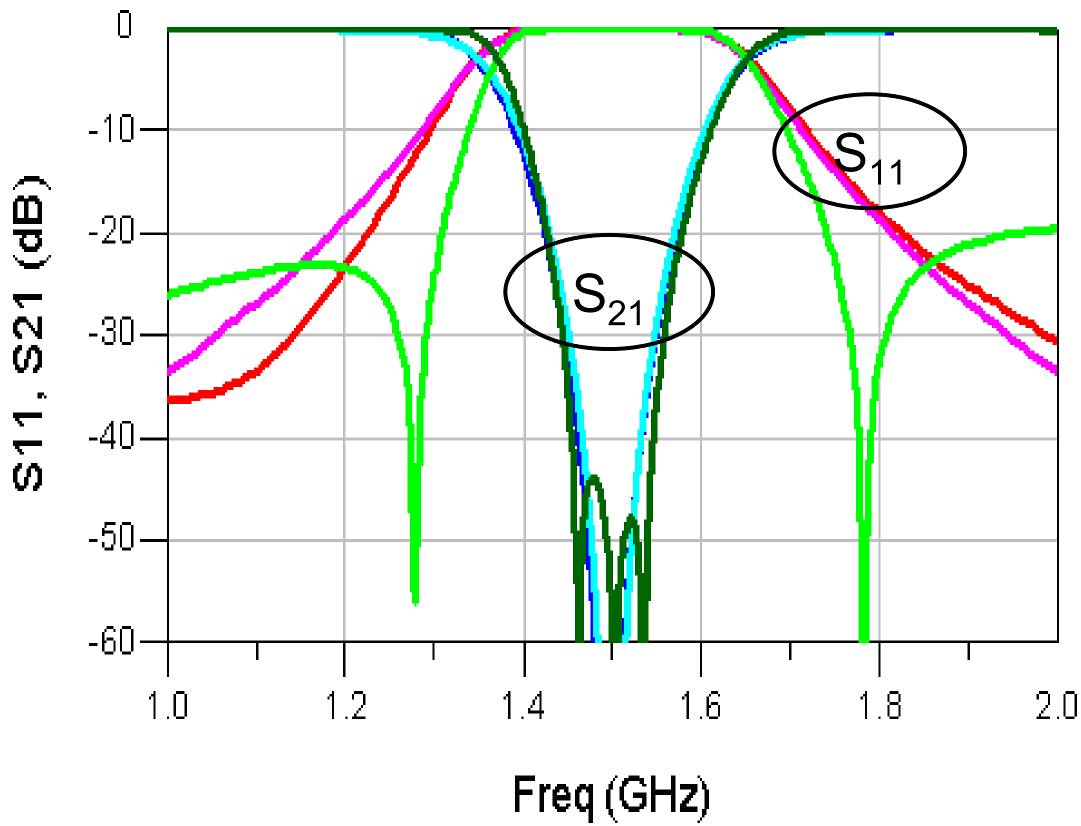
Conventional Folded

- Microstrip realization
- ε_r=2.2, h=31mil
- Conventional stub-loaded filter measured 2948 sq mm
- Folded line filter measured 767 sq mm !!
- Please note the 'aspect ratio' for conventional -> printing artifact ->line widths are too small to be shown accurately

Footprint & Critical Conductor Width Comparison

Δ=0.2	Conventional Bandstop	Folded line Bandstop
Smallest normalized width (w/h)	0.0032 (0.099 mil)	0.26 (8.06 mil)
Overall footprint	2948 sq mm	767 sq mm
Footprint comparison	100 %	26 %

Filter Response



S_{11}(Conventional filter theoretical)

S_{11}(Folded filter theoretical)

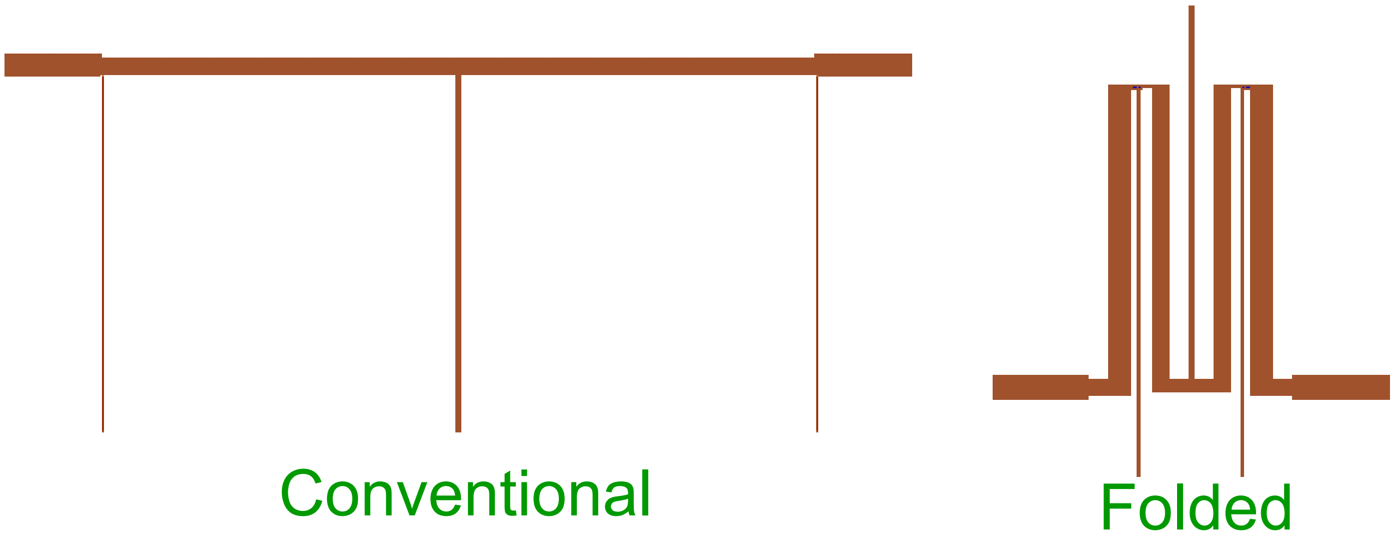
S_{11}(Folded filter MWS 2006®)

S_{21}(Conventional filter theoretical)

S_{21}(Folded filter theoretical)

S_{21}(Folded filter MWS 2006®)

Bandstop Filter Comparison (Δ = 0.3)



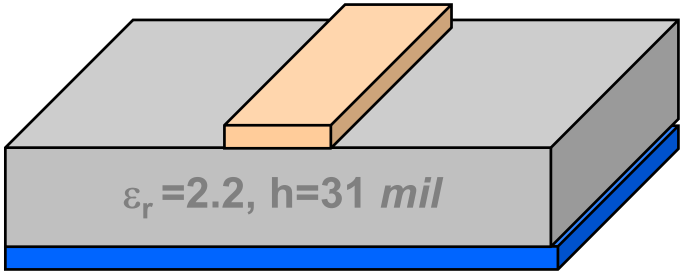
- Microstrip realization
- ε_r=2.2, h=31mil
- Conventional stub-loaded filter measured 2948 sq mm
- Folded line filter measured 1015 sq mm !!
- Please note the 'aspect ratio' for conventional -> printing artifact ->line widths are too small to be shown accurately

Footprint & Critical Conductor Width Comparison

Δ=0.3	Conventional Bandstop	Folded line Bandstop
Smallest normalized width (w/h)	0.032 (0.99 mil)	0.5 (15.5 mil)
Overall footprint	2948 sq mm	1015 sq mm
Footprint comparison	100 %	34 %

Fabricated Folded Line Bandstop Filter

Microstrip Realization



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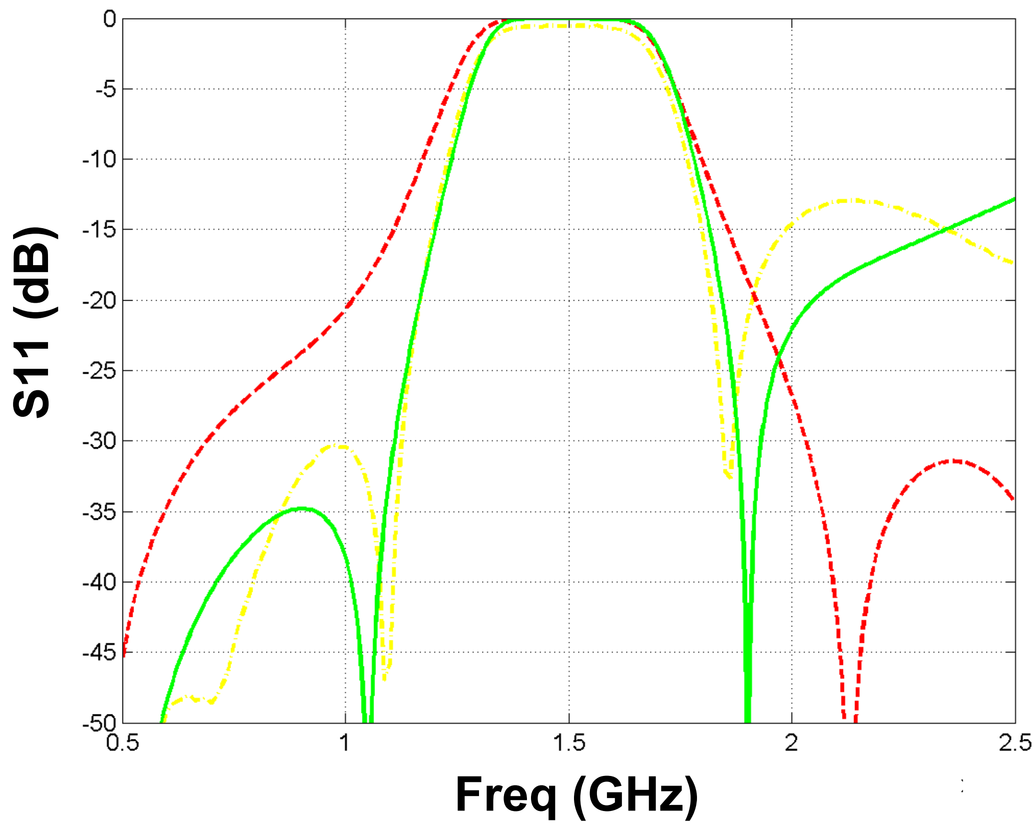
Folded Line Bandstop Filter Response

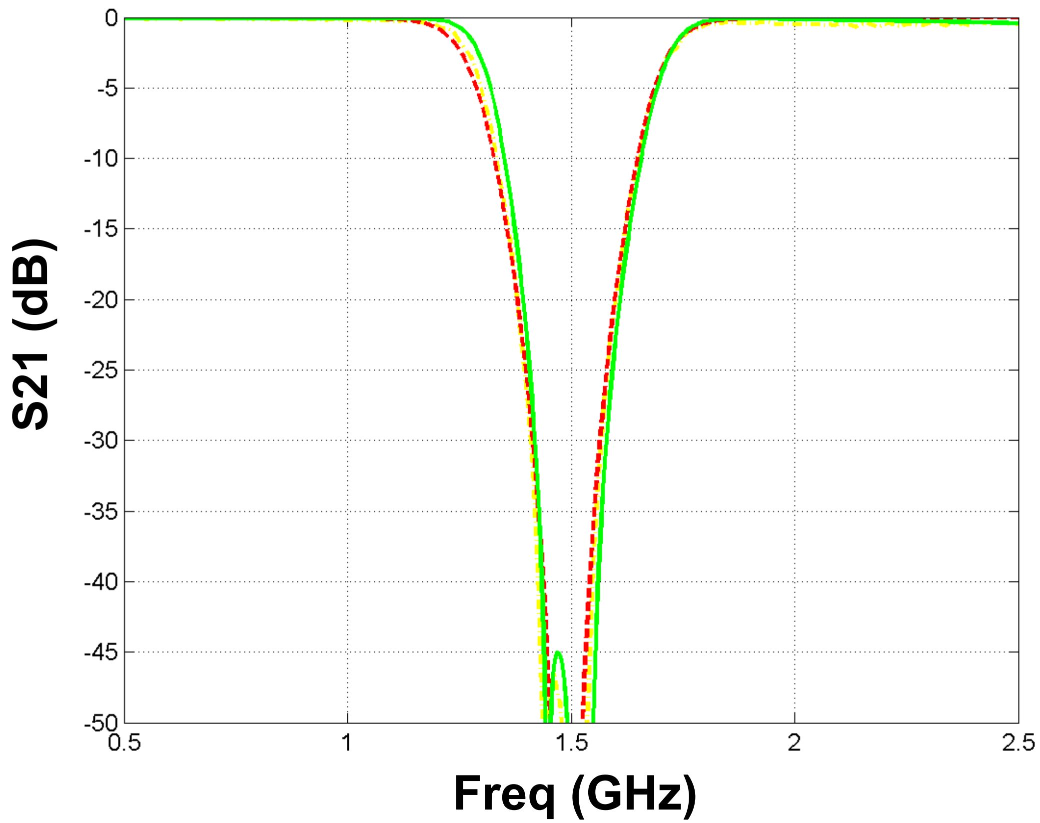


S_{11}(Folded filter theoretical)

S_{11}(Measurement)

S_{11}(Folded filter MWS 2006®)

Folded Line Bandstop Filter Response (Cont'd)



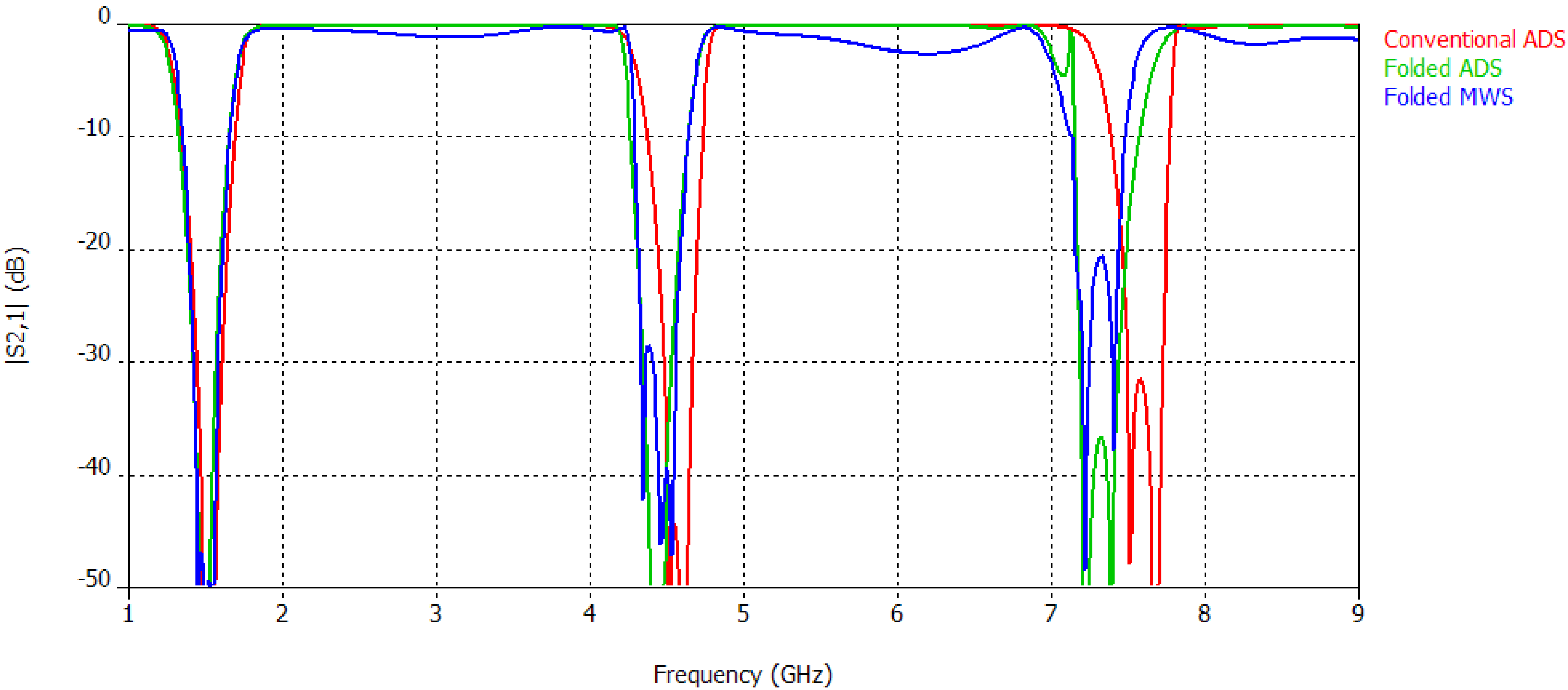
S_{21}(Folded filter theoretical)

S_{21}(Measurement)

S_{21}(Folded filter MWS 2006®)

Folded Line Bandstop Filter Response (Cont'd)

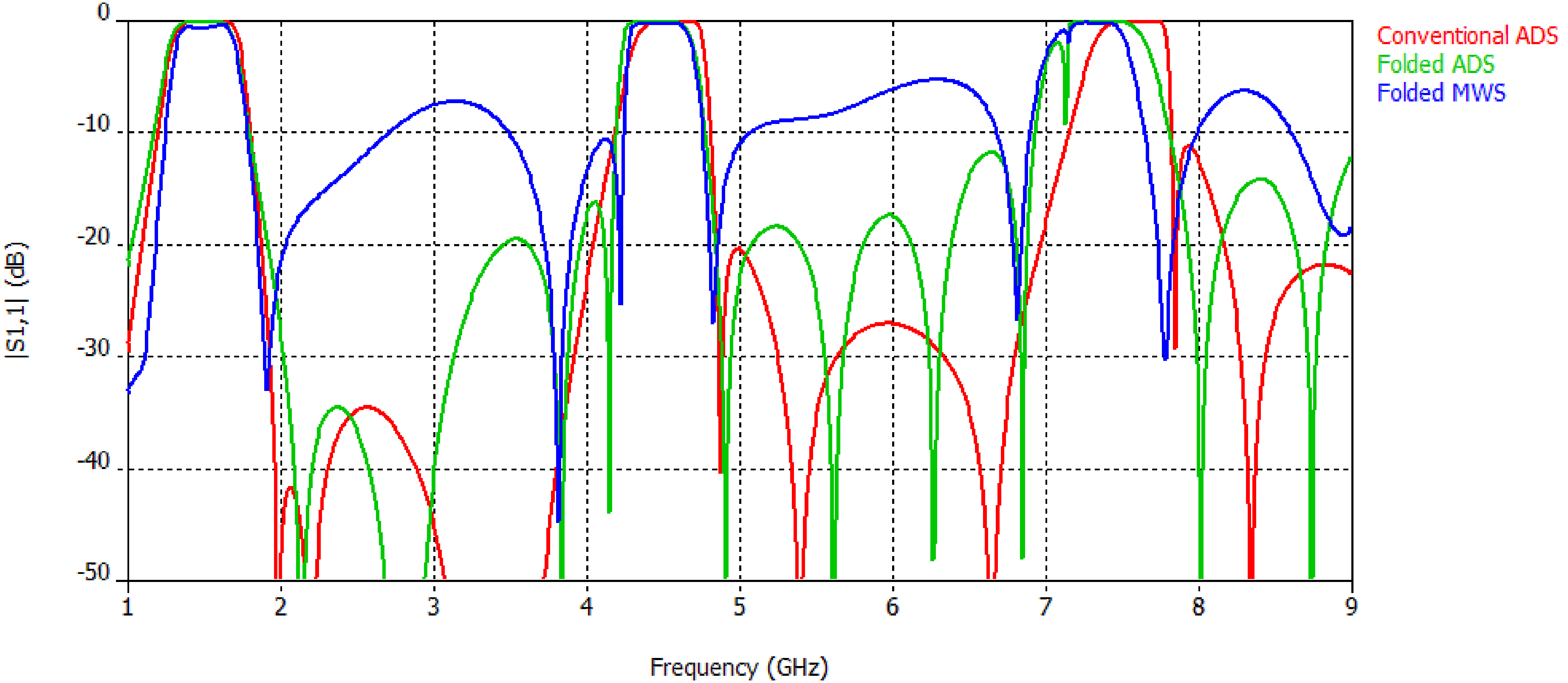
Re-entry characteristics



Re-entry characteristics similar to conventional filters but higher frequencies are shifted due to increased coupling.

Folded Line Bandstop Filter Response (Cont'd)

Re-entry characteristics



Re-entry characteristics similar to conventional filters but higher frequencies are shifted due to increased coupling.

Single Level Folded Line Lowpass Filters (Example #2)

- Initial design of stub-loaded lowpass filter
- Specifications
  - N=3, f_c=1.5 GHz
  - Maximally flat response (Butterworth)
  - Microstrip platform
  - ε_r=2.2, h=31mil

- Lumped-element prototype
- Richard's transformations
- Unit elements
- Kuroda's identities
- Impedance scaling
- Frequency scaling

Z_A and Z_B = Terminating impedances

Z_j ($j = 1$ to n) = OC shunt stub impedances

Z_{1j} ($j = 2$ to n) = Connecting line impedances

Characteristic Impedances for Various Lowpass Filter Sections

$Z_A(\Omega)$	$Z_1(\Omega)$	$Z_{12}\,(\Omega)$	$Z_2\,(\Omega)$	$Z_{23}\,(\Omega)$	$Z_3\,(\Omega)$	$Z_B\,(\Omega)$
50	100	100	25	100	100	50

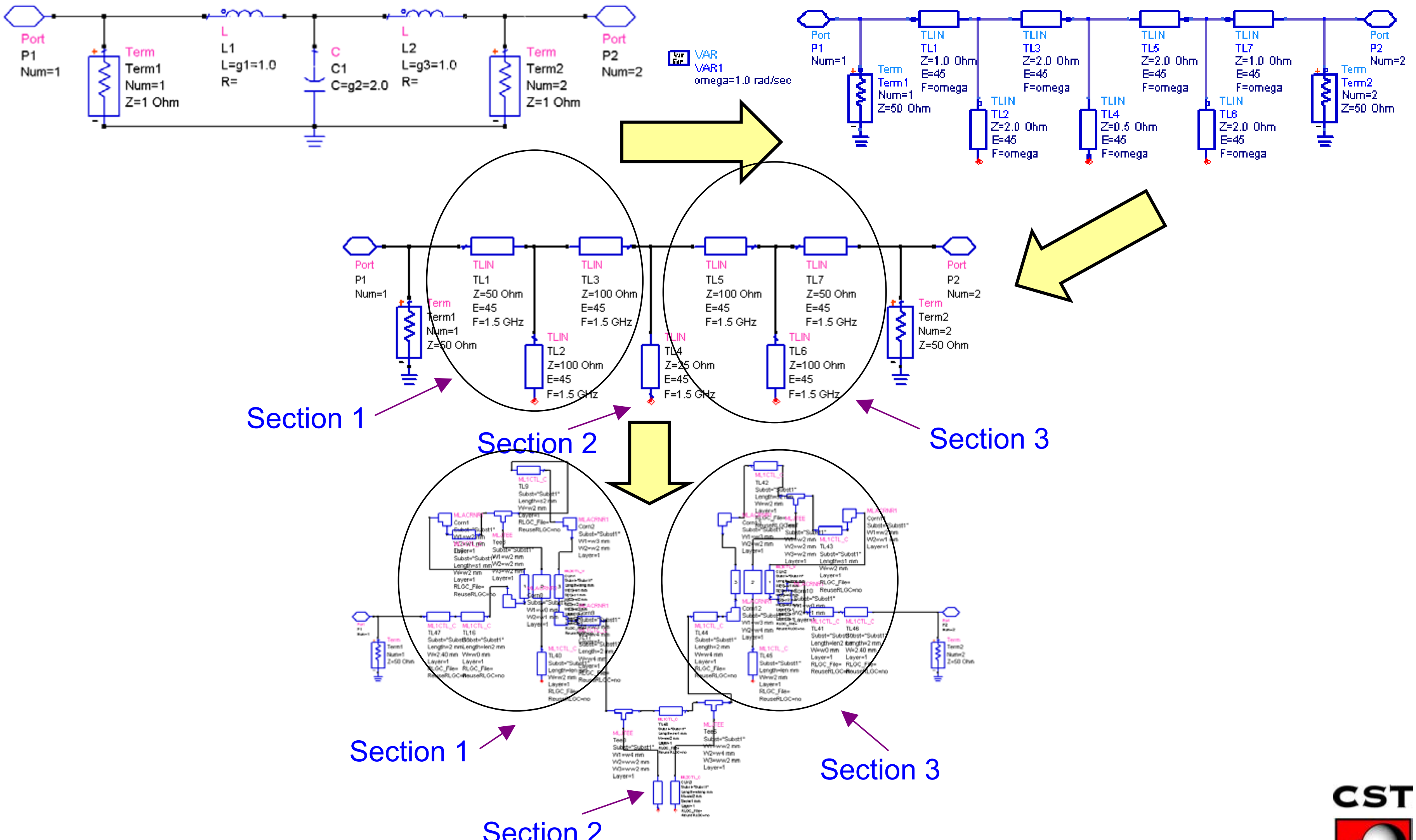
N=3,Maximally flat response , f_c=1.5 GHz

50Ω microstrip line → w = 98 mil

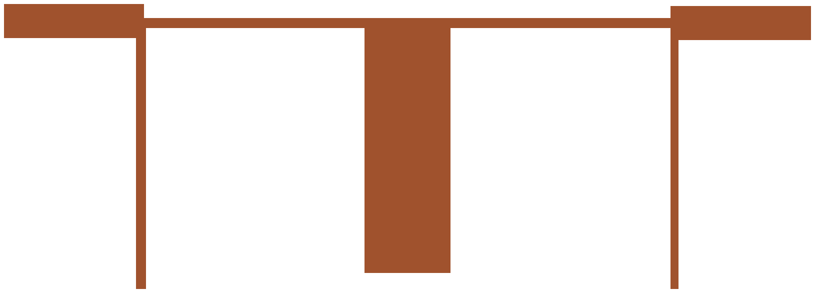
25 Ω microstrip line → w =243 mil (6.17 mm)

(1/2 ounce copper, 0.7 mil)

Design Flow for the Folded Line Lowpass Filters (Single-Level)



Lowpass Filter Comparison



Conventional

Folded

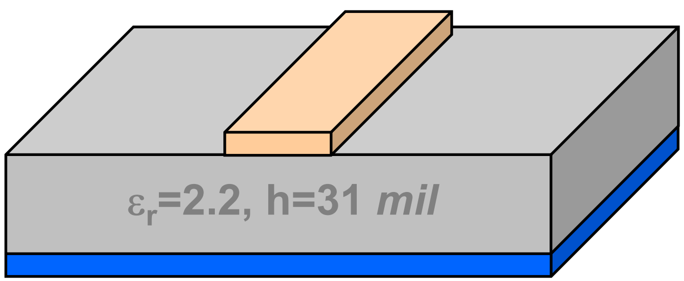
- Microstrip realization
- ε_r=2.2, h=31mil
- Conventional stub-loaded filter measured 755 sq mm
- Folded line filter measured 535 sq mm !!

Footprint & Critical Conductor Width Comparison

f_c=1.5 GHz	Conventional Lowpass	Folded line Lowpass
Largest normalized width (w/h)	7.9 (244.9 mil)	3.63 (112.5 mil)
Overall footprint	755 sq mm	535 sq mm
Footprint comparison	100 %	71 %

Fabricated Folded Line Lowpass Filter

Microstrip Realization



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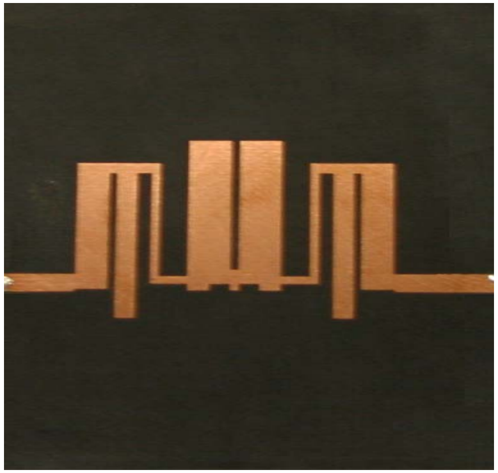
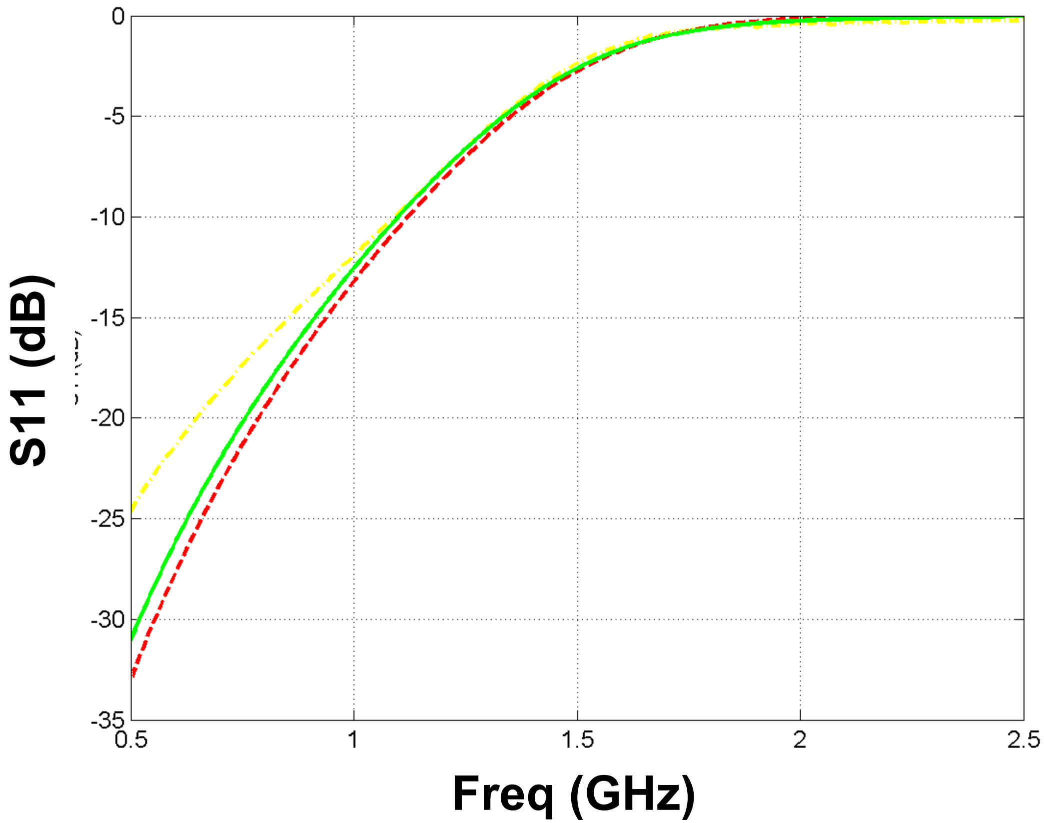


Folded Line Lowpass Filter Response

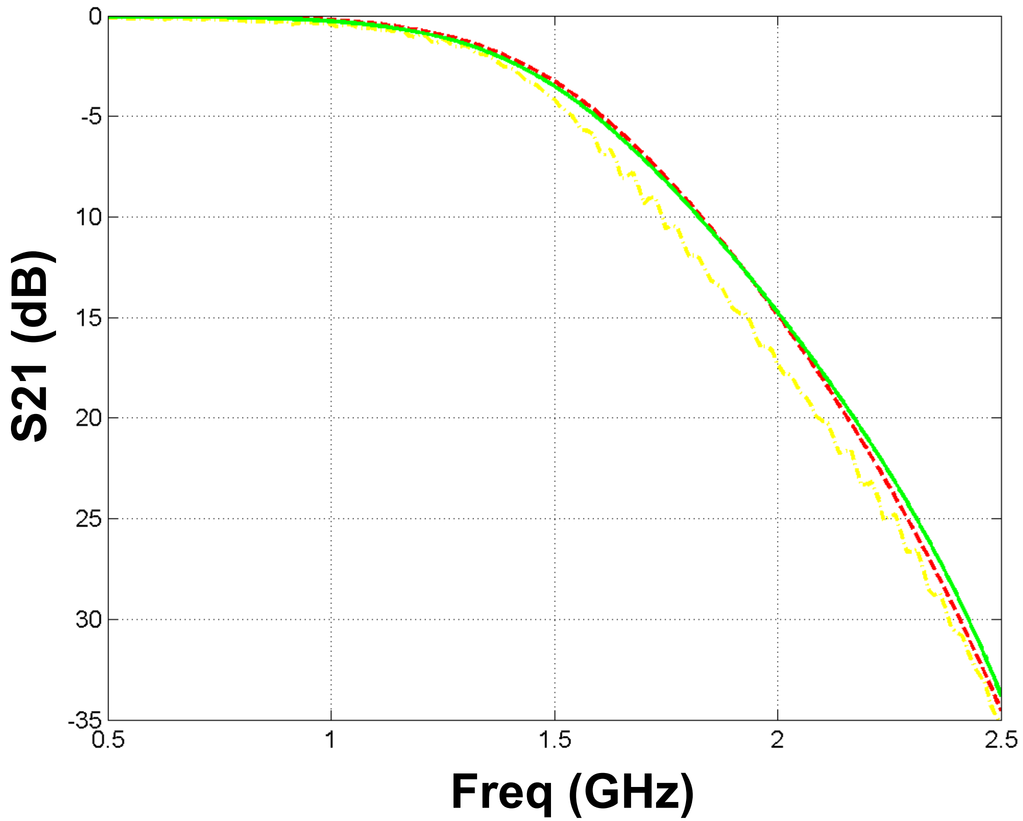


S_{11}(Folded filter theoretical)

S_{11}(Measurement)

S_{11}(Folded filter MWS 2006®)

Folded Line Lowpass Filter Response (Cont'd)



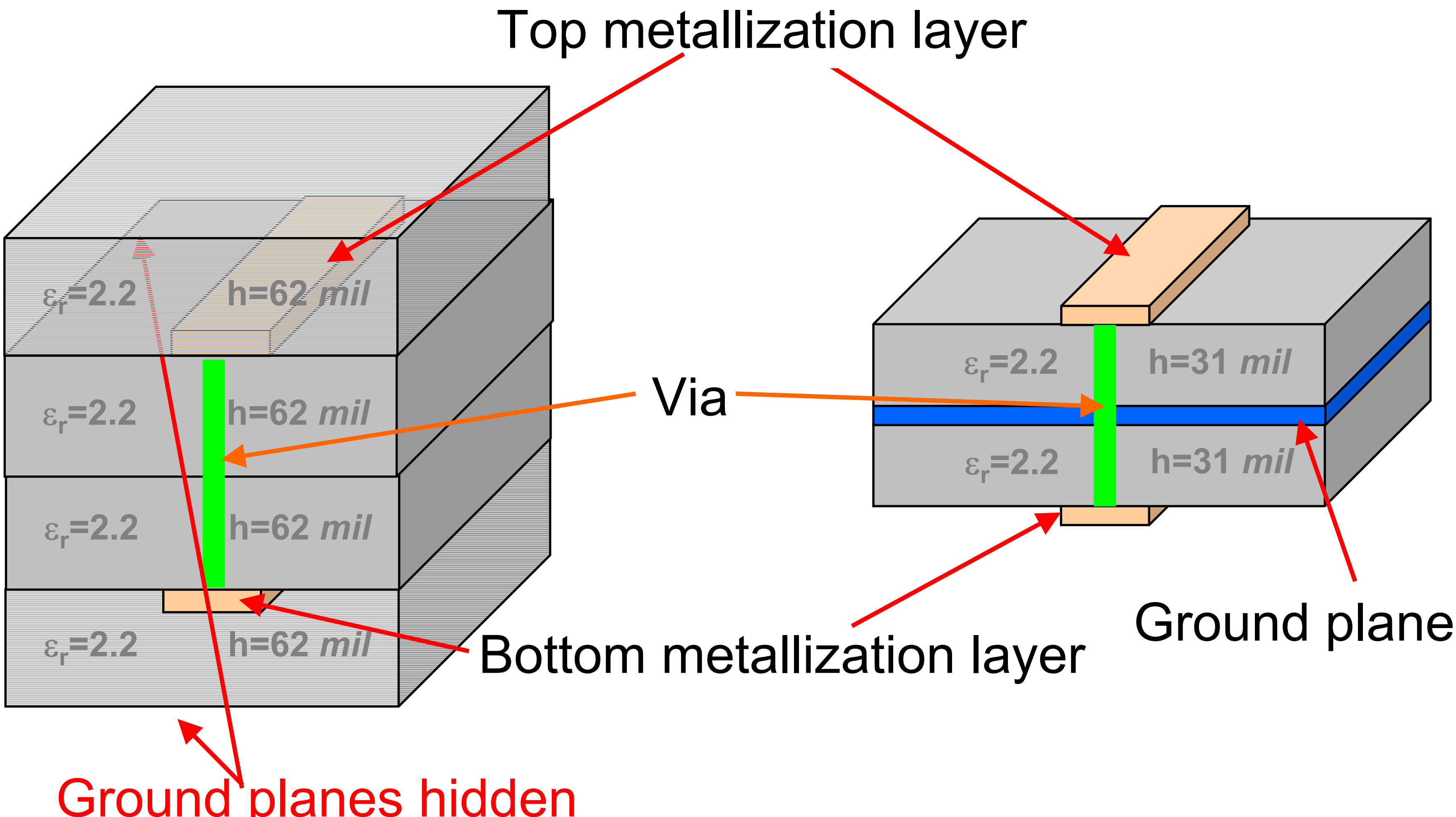
S_{11}(Folded filter theoretical)

S_{11}(Measurement)

S_{11}(Folded filter MWS 2006®)

Multi Level Transmission Line Models

Cross-sectional View



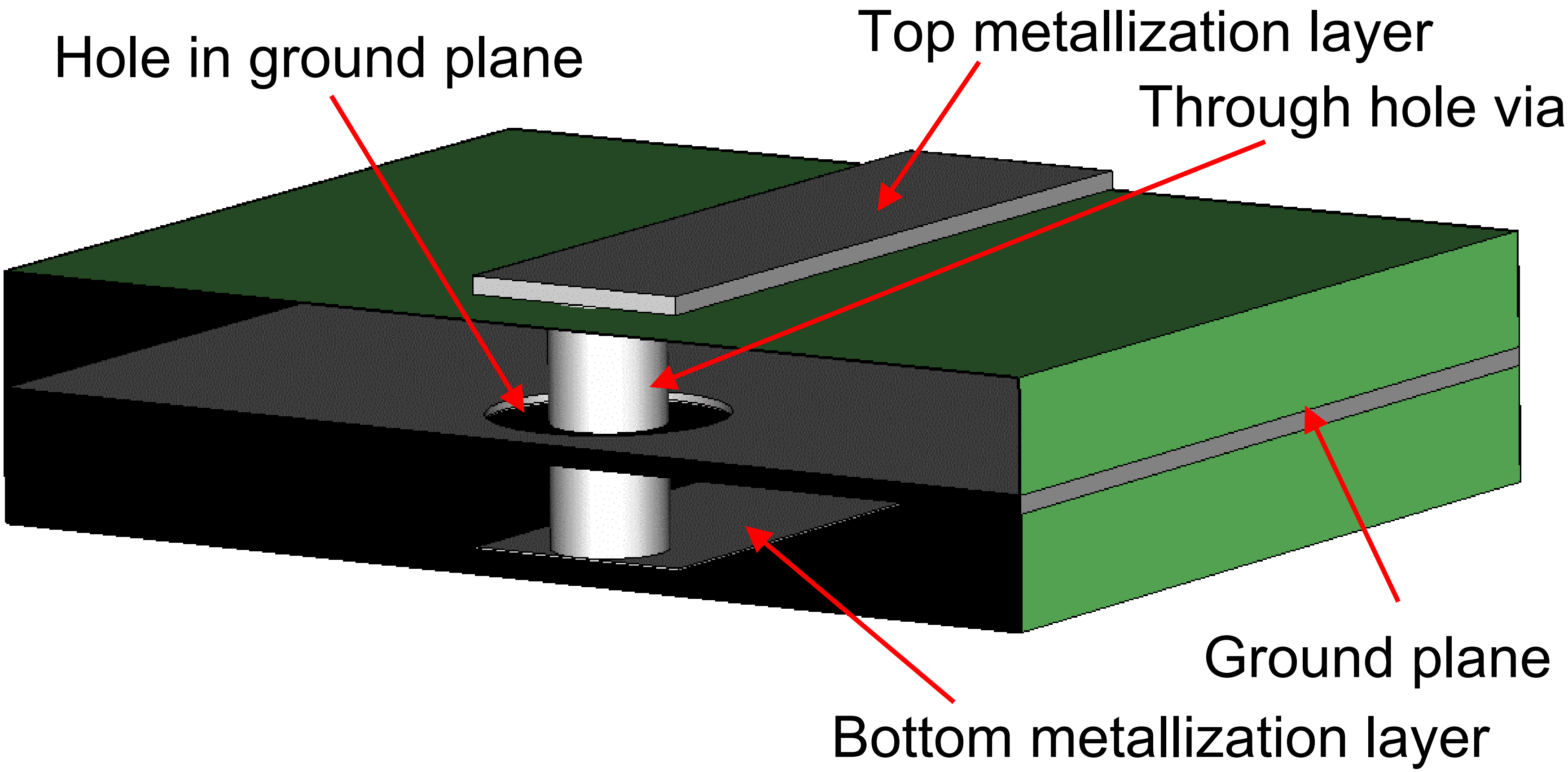
Stripline Realization

Microstrip Realization

Importance of the Ground Plane (BTB Microstrip Realization)

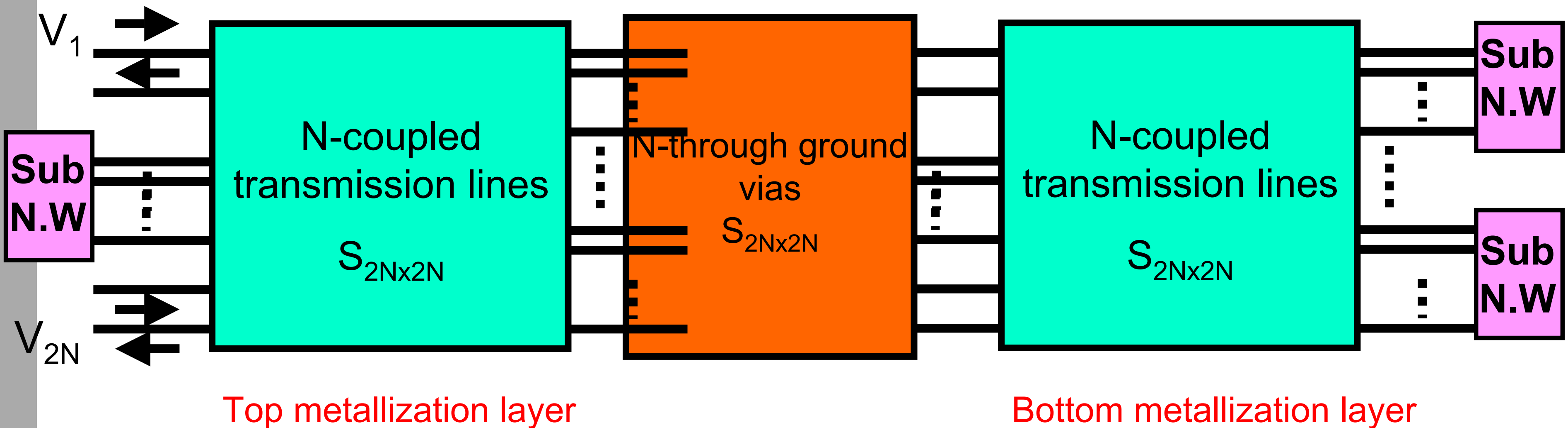
- Isolates the top and bottom metallization layers
- More practical via dimensions
- Less prone to alignment errors

A Back-to-Back Microstrip Geometry



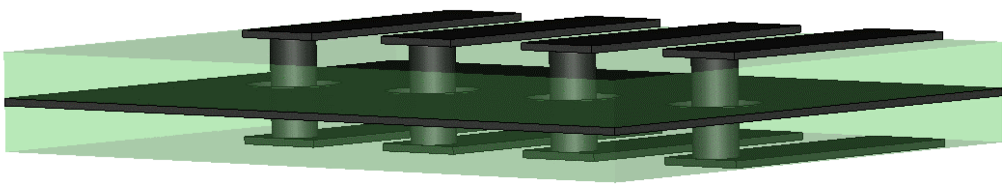
3D View

Network Representation for Multi Level Folded Line Filters

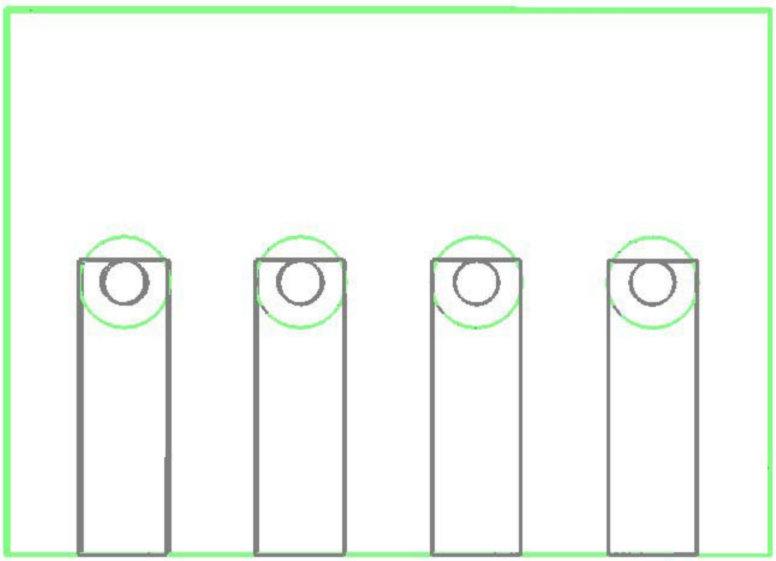


- 2N x 2N port networks
- Cascade of three separate networks
- Reduced 2-port scattering matrix

Composite Geometry

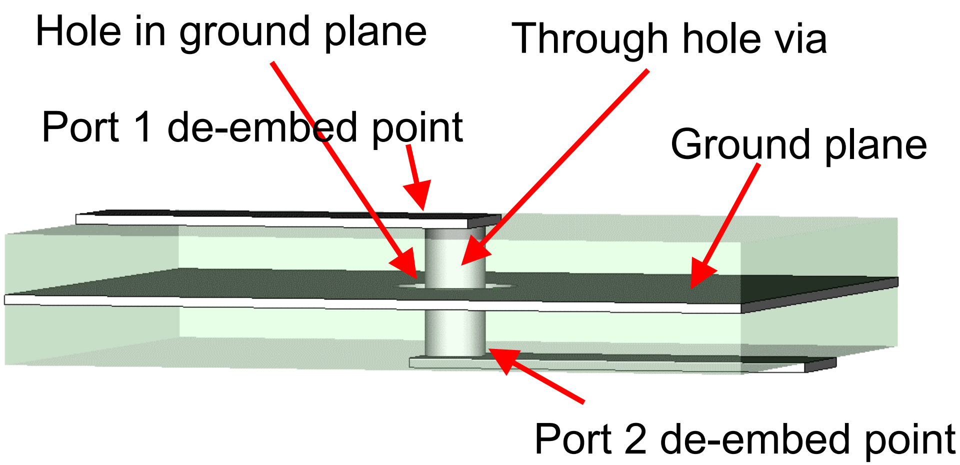


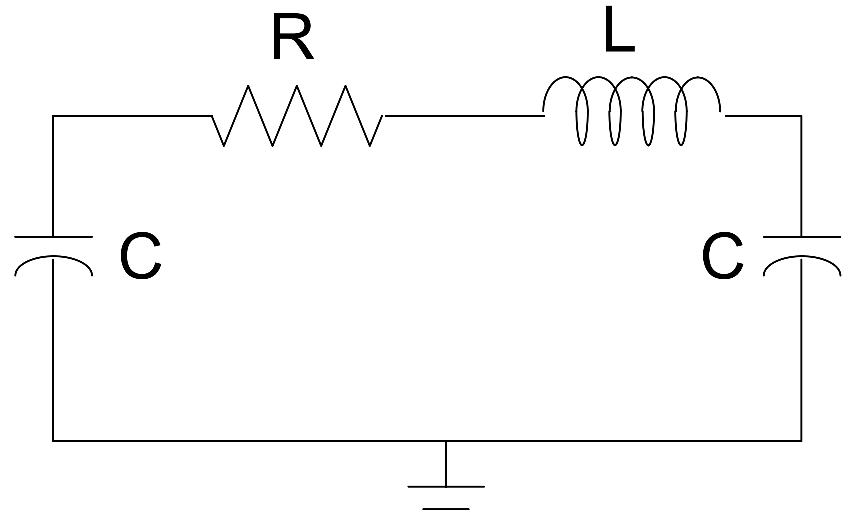
3D View



Overhead View

Via Model Extraction





- Closed form design equations

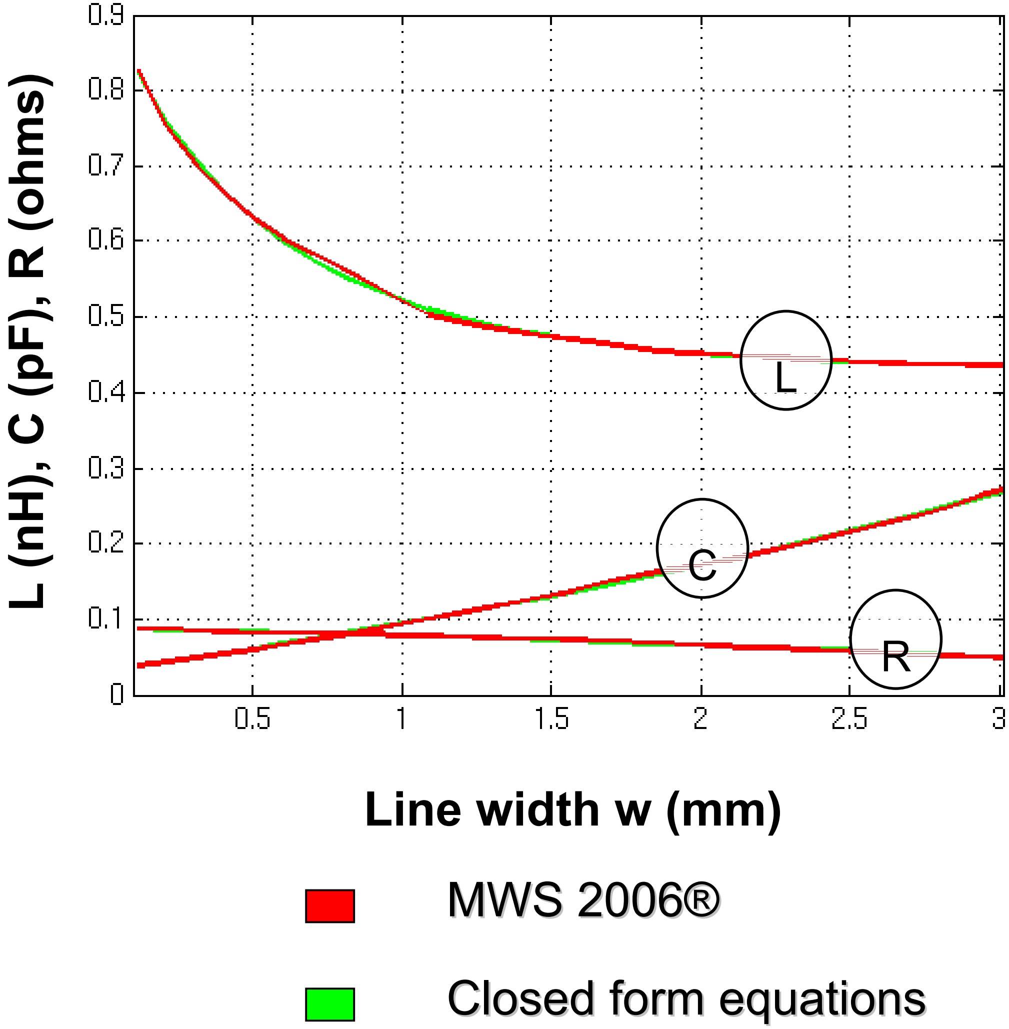
$$L(w)= 0.5054*\exp(-1.7014*w^{0.8846})+ 0.4298 \text{ nH}$$

$$C(w)= 0.2209*\exp(0.2564*w^{0.9555}) - 0.1918 \text{ pF}$$

$$R(w)= -0.0026*\exp(1.6083*w^{0.5072}) + 0.0911\ \Omega$$

Diameter of the via = ½ width of the strip
Diameter of the antipad = 0.4 mm + diameter of the via

Via R, L, C Vs. Line Width



Design Procedure for Multilevel Bandstop and Lowpass Filters

Specifications

↓

Physical design

↓

Individual section approach/
Single level folded line filter sections

↓

Multi level folded line filter sections

↓

Cascaded multi level folded line filter sections

↓

Final filter response

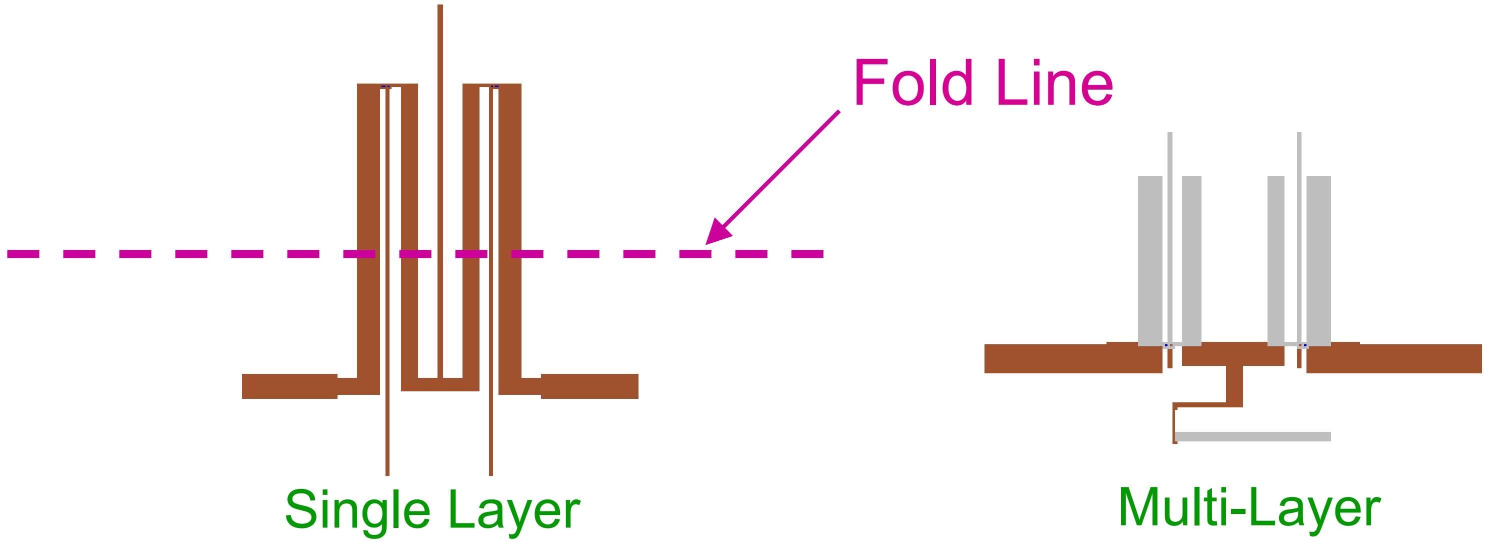
Conventional stub loaded filter

Single level folded line filter

Multi Level Folded Line Bandstop Filters (Example #3)

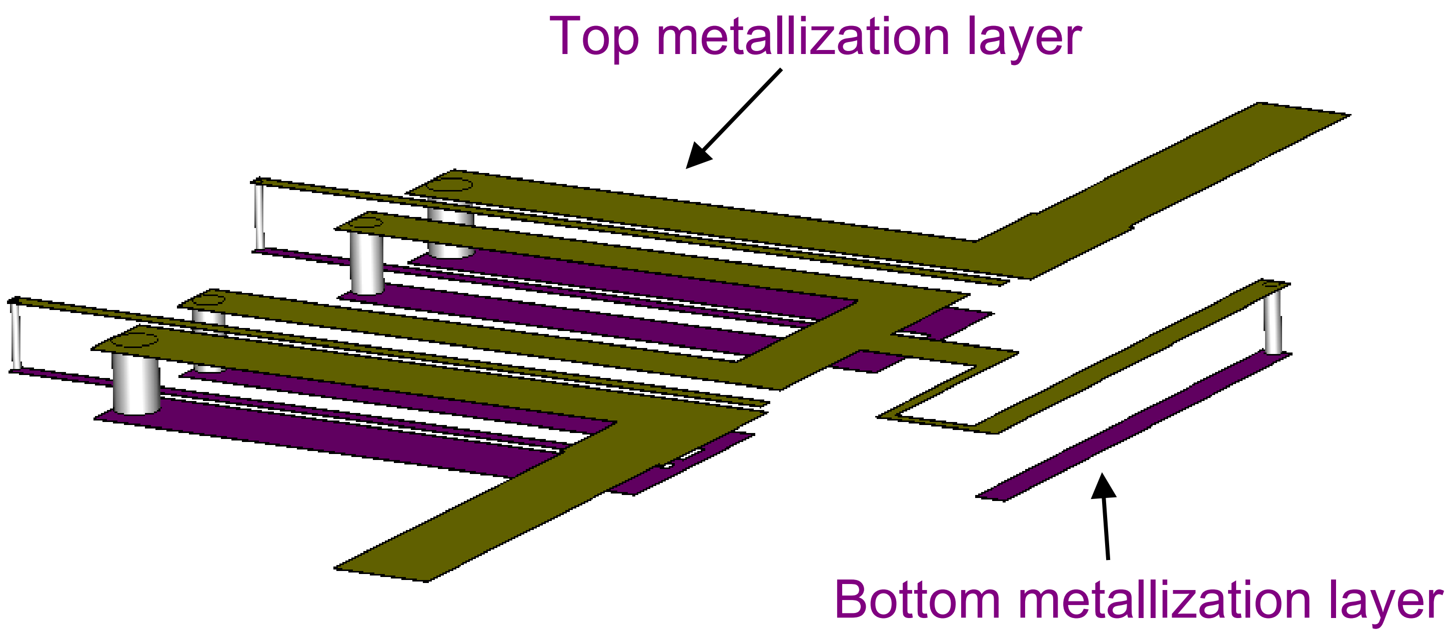
- Initial design specifications of stub-loaded bandstop filter
- N=3, f_0=1.5 GHz
- Maximally flat response (Butterworth)
- Δ=0.3
- BTB microstrip realization
- ε_r=2.2, h=31mil for both dielectric layers

Bandstop Filter Comparison (Δ=0.3)



- BTB microstrip platform
- ε_r=2.2,h=31mil for both dielectric layers
- Conventional stub-loaded filter measured 2948 sq mm
- Folded line filter measured 532 sq mm !!

3D View of the Multilevel Folded Line Bandstop Filter



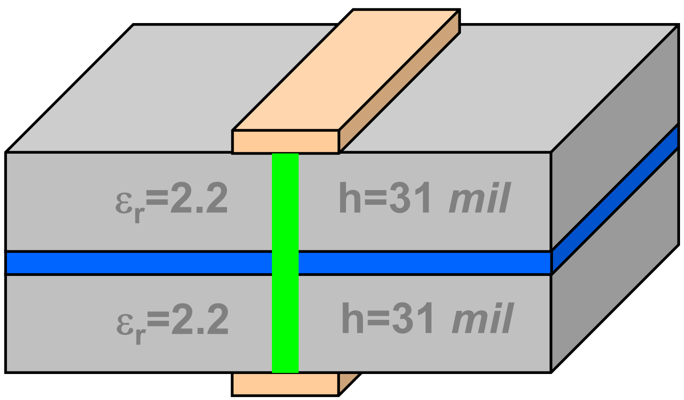
Ground plane and dielectrics are hidden for better visibility

Footprint & Critical Conductor Width Comparison

Δ=0.3	Conventional Bandstop	Single Level Folded Line Bandstop	Multi Level Folded Line Bandstop
Smallest normalized width (w/h)	0.032 (0.99 mil)	0.5 (15.5 mil)	0.4 (12.4 mil)
Overall footprint	2948 sq mm	1015 sq mm	532 sq mm
Footprint comparison	100 %	34 %	18 %

Fabricated Folded Line Bandstop Filter

BTB Microstrip Realization



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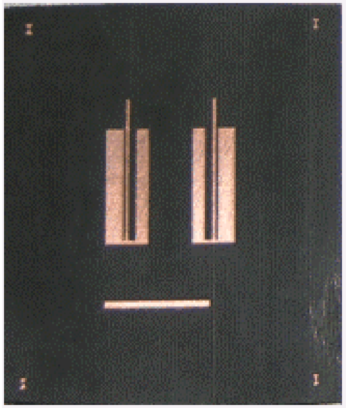
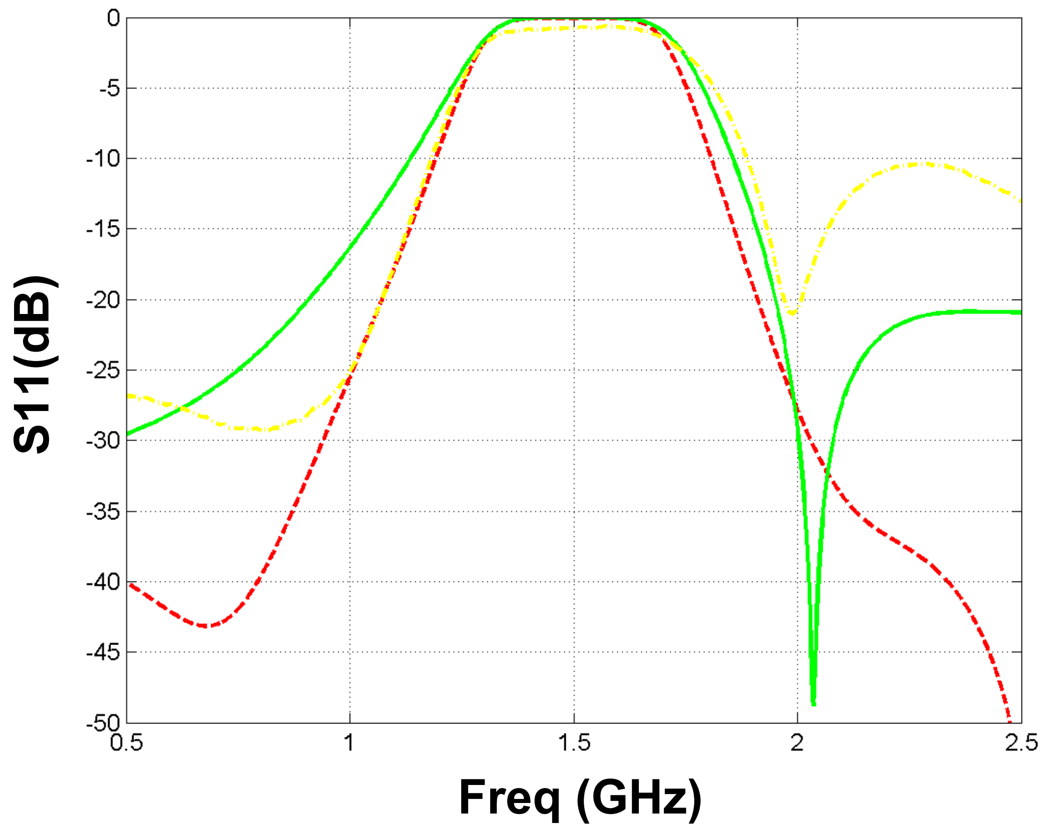
Top metallization layer



Bottom metallization layer

Folded Line Bandstop Filter Response

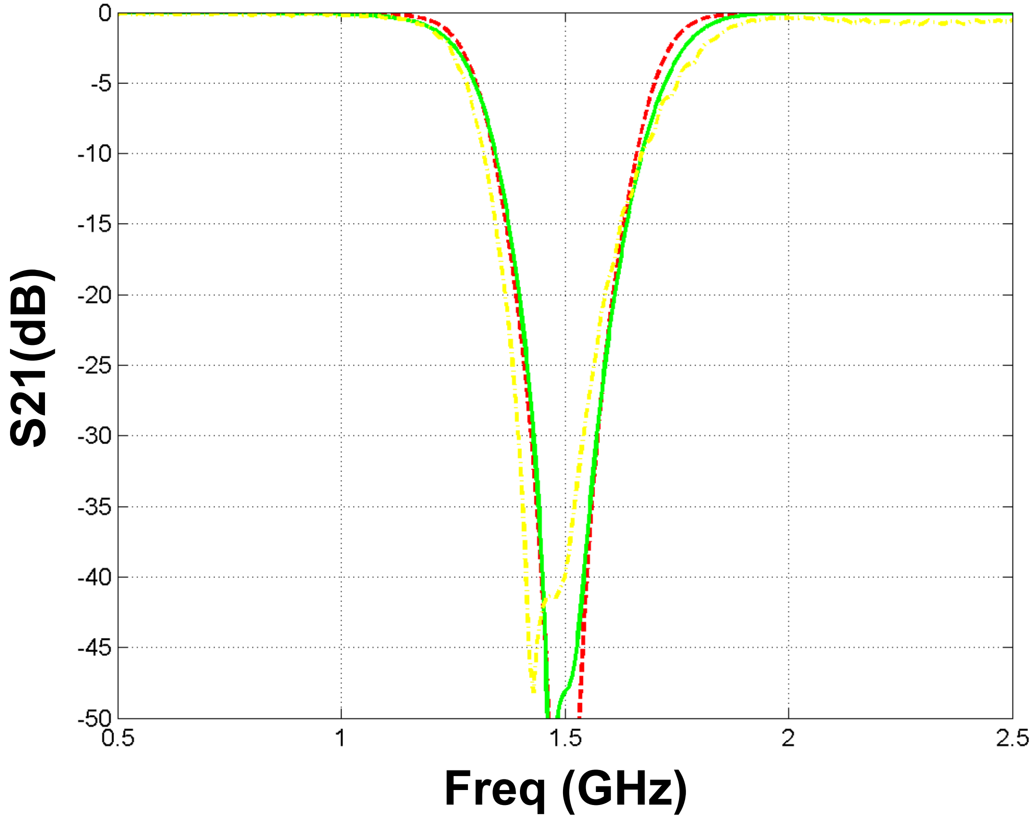


S_{11}(Folded filter theoretical)

S_{11}(Measurement)

S_{11}(Folded filter MWS 2006®)

Folded Line Bandstop Filter Response (Cont'd)



S_{21}(Folded filter theoretical)

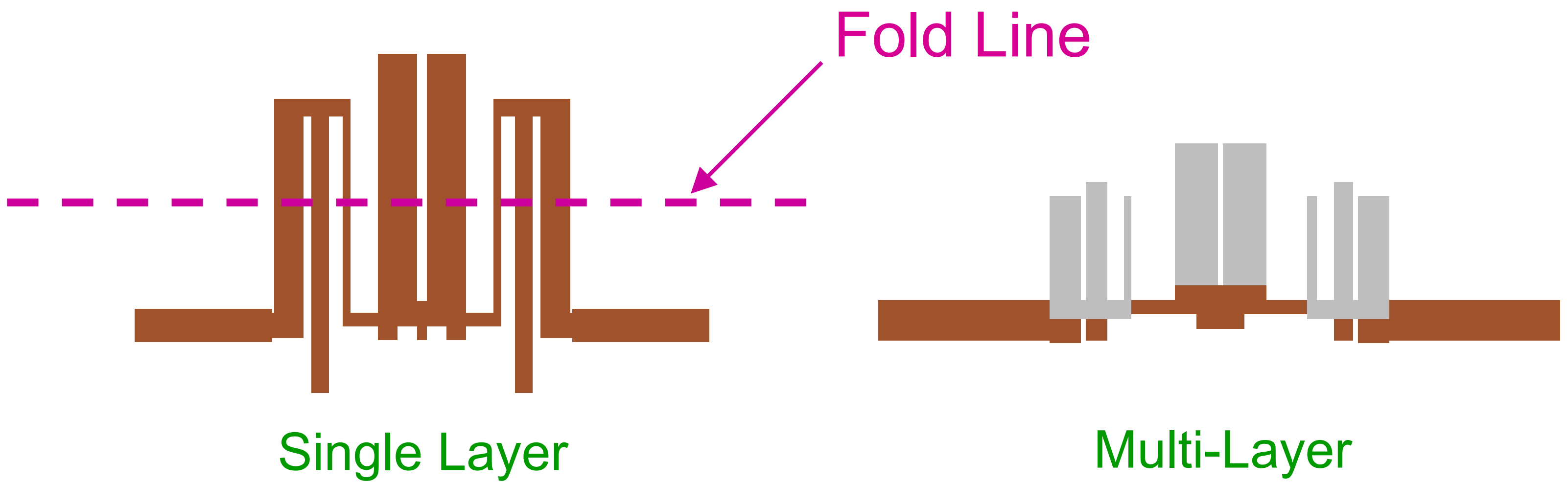
S_{21}(Measurement)

S_{21}(Folded filter MWS 2006®)

Multi Level Folded Line Lowpass Filters (Example #4)

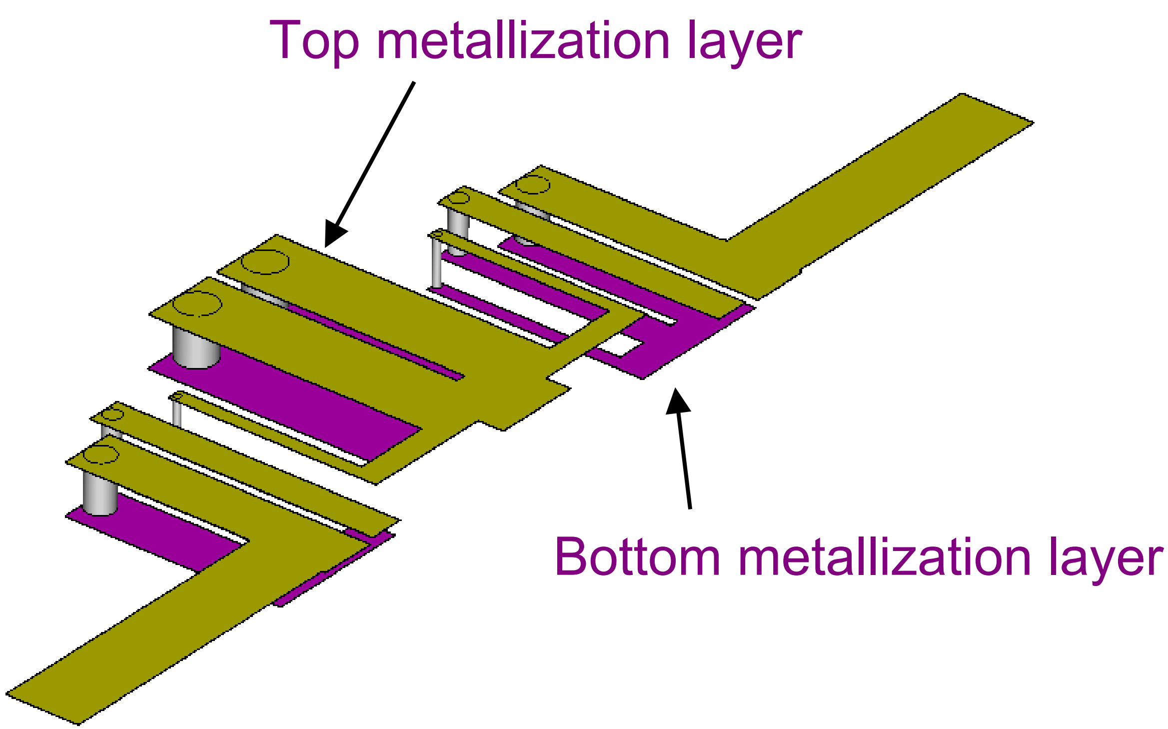
- Initial design specifications of stub-loaded lowpass filter
  - N=3, f_c=1.5 GHz
  - Maximally flat response (Butterworth)
  - BTB microstrip platform
  - ε_r=2.2, h=31mil for both dielectric layers

New Lowpass Filter Configuration



- BTB microstrip realization
- ε_r=2.2, h=31mil for both dielectric layers
- Conventional stub-loaded filter measured 755 sq mm
- Folded line filter measured 235 sq mm !!

3D View of the Multilevel Folded Line Lowpass Filter



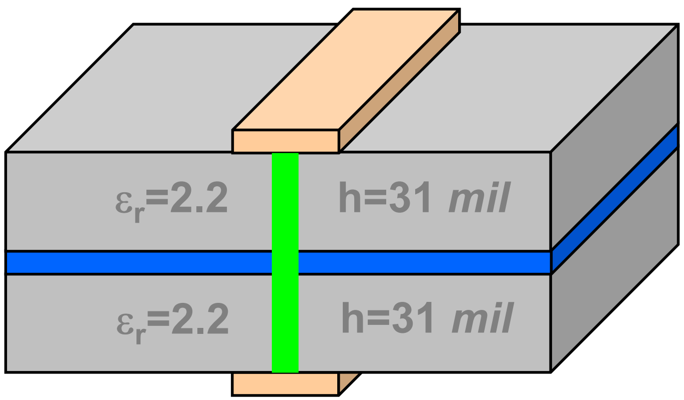
Ground plane and dielectrics are hidden for better visibility

Footprint & Critical Conductor Width Comparison

f_c=1.5 GHz	Conventional Lowpass	Single Level Folded Line Lowpass	Multi Level Folded Line Lowpass
Largest normalized width (w/h)	7.9 (244.9 mil)	3.63 (112.5 mil)	3.21 (99.5 mil)
Overall footprint	755 sq mm	535 sq mm	235 sq mm
Footprint comparison	100 %	71 %	31 %

Fabricated Folded Line Lowpass Filter

BTB Microstrip Realization



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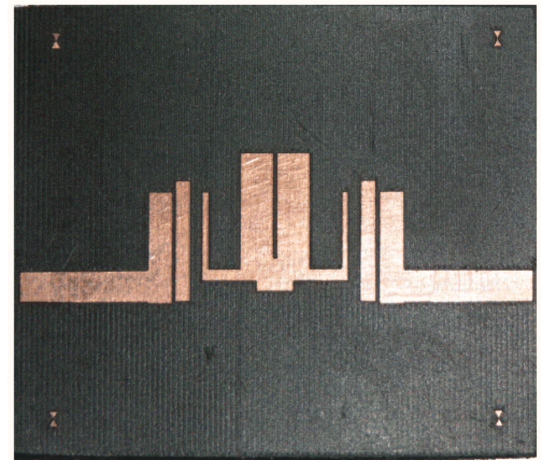
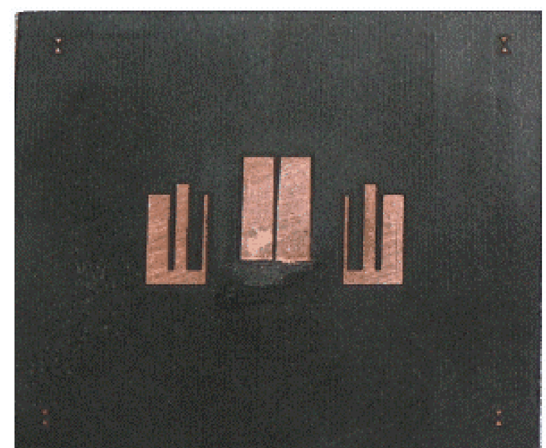
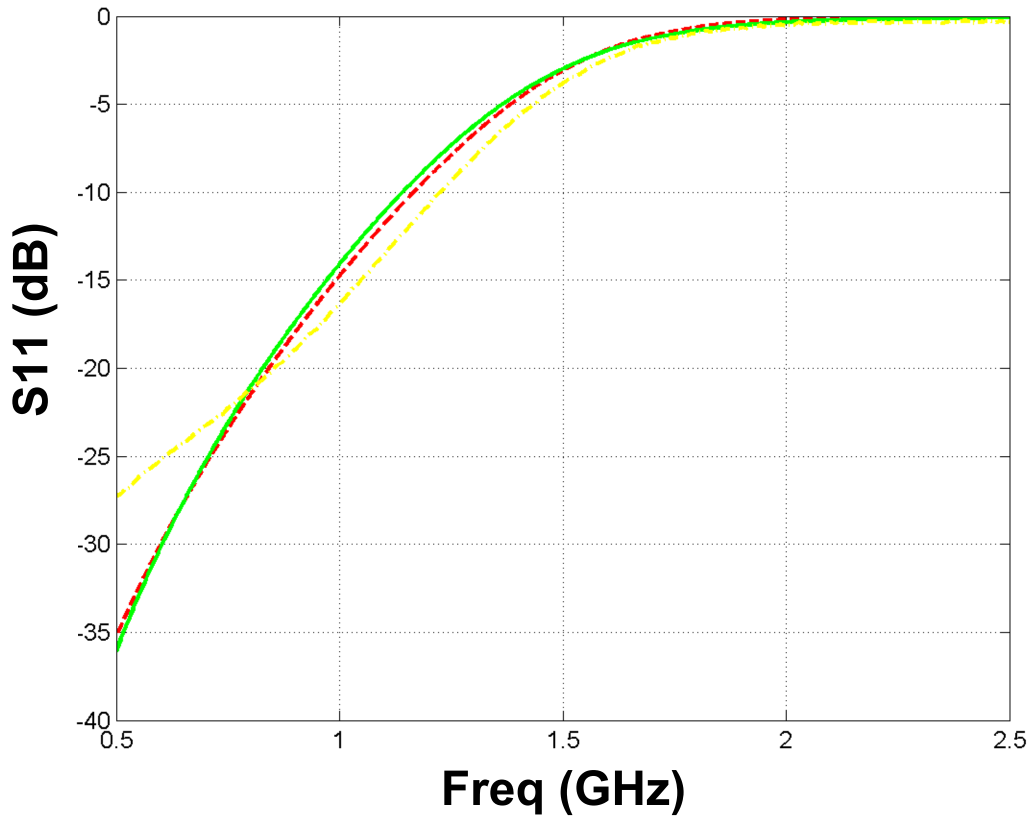
Top metallization layer





Bottom metallization layer

Folded Line Lowpass Filter Response

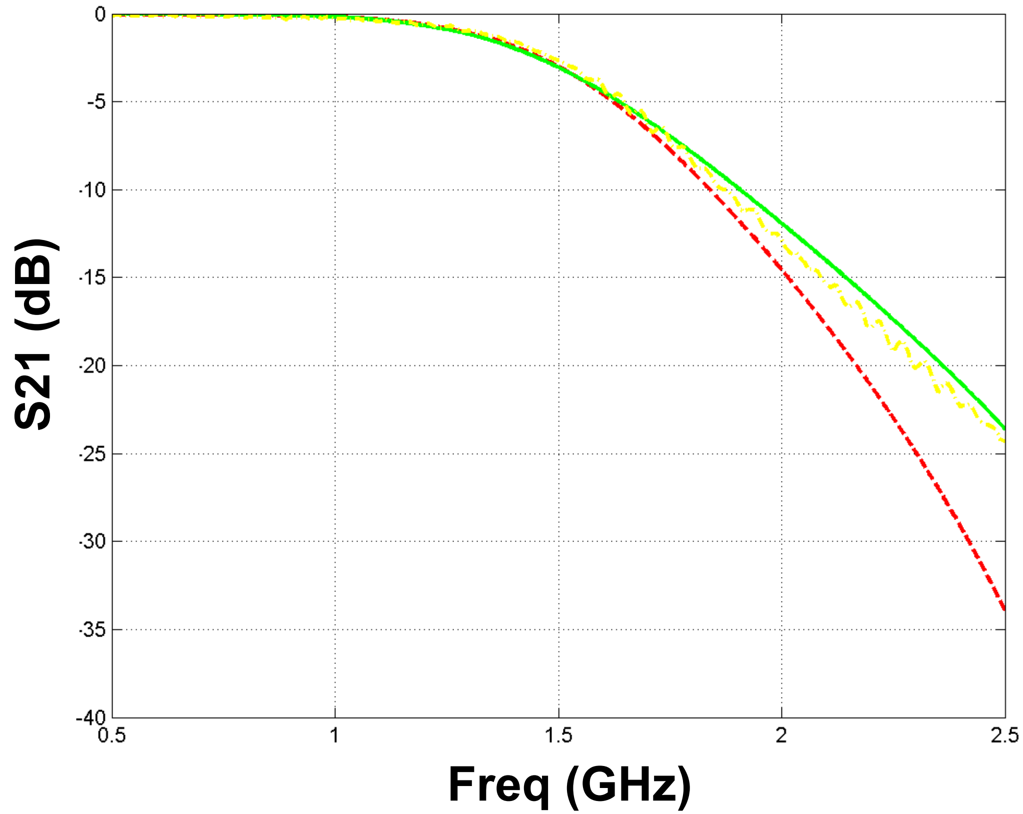


S_{11}(Folded filter theoretical)

S_{11}(Measurement)

S_{11}(Folded filter MWS 2006®)

Folded Line Lowpass Filter Response (Cont'd)



S_{21}(Folded filter theoretical)

S_{21}(Measurement)

S_{21}(Folded filter MWS 2006®)

Advantage Summary of Folded Topologies

- Uses a common design methodology for both bandstop and lowpass filters
- More compact footprints than conventional
- More feasible physical dimensions (i.e. aspect ratio) for a practical implementation
- Embedded ground plane aids in the design of multi level filters
- Equivalent electrical performance to that of the conventional filters
- Host of embedded passive and RFIC applications in the 1-10 GHz range