New Configurations for RF/Microwave Filters

Presented by:

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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

Antenna → LNA → Mixer → LPF/BSF → QD → A/D
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

Conventional stub loaded

Conventional gap coupled

Single-level folded line

Conventional gap coupled

Multi-level folded line
Network Representation for Single Level Folded Line Filters

- 2N×2N port network

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

\[ [Y_A] = [M_v]^T \left[ \text{coth}(\gamma_k I) \right]_{\text{diag}} [Y_k]_{\text{diag}} [M_v]^{-1} \]

\[ [Y_B] = [M_v]^T \left[ \text{csch}(\gamma_k I) \right]_{\text{diag}} [Y_k]_{\text{diag}} [M_v]^{-1} \]

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

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

- Reduced 2-port scattering matrix
Folded Line Filter Section

Sub-network

Three-coupled transmission line
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

Individual section approach
Folded line filter sections

Cascaded folded line filter sections

Final filter response

Conventional stub loaded filter
Single Level Folded Line Bandstop Filters
(Example #1)

- Initial design of stub-loaded bandstop filter
- Specifications
  - N=3, f₀=1.5 GHz
  - Maximally flat amplitude response (Butterworth)
  - Δ=0.2 & 0.3
- Microstrip realization
  - εᵣ=2.2, h=31mil

- Design equations for N=3

\[
\begin{align*}
Z_1 &= Z_4(1+1/\Lambda g_0 g_1) \\
Z_{12} &= Z_4(1+\Lambda g_0 g_1) \\
Z_2 &= Z_4 g_0 / \Lambda g_2 \\
Z_3 &= Z_4 g_0 / g_4 (1+1/\Lambda g_3 g_4) \\
Z_{23} &= Z_4 g_0 / g_4 (1+\Lambda g_3 g_4) \\
Z_A \text{ and } Z_B &= \text{ terminating impedances} \\
Z_j (j = 1 \to n) &= \text{OC shunt stub impedances} \\
Z_{ij} (j = 2 \to n) &= \text{connecting line impedances} \\
g_j &= \text{prototype element values} \\
\Lambda &= \omega_0 a, \quad a = \cot \left( \frac{\pi}{2} \frac{\omega_1}{\omega_0} \right) \\
\Delta &= \frac{\omega_2 - \omega_1}{\omega_0}, \quad \omega_0 = \frac{\omega_1 + \omega_2}{2} \\
\omega_1 \text{ and } \omega_2 &= \text{bandstop edge frequencies}
\end{align*}
\]
Characteristic Impedances for Various Bandstop Filter Sections

<table>
<thead>
<tr>
<th>Δ</th>
<th>Z_A (Ω)</th>
<th>Z_1 (Ω)</th>
<th>Z_{12} (Ω)</th>
<th>Z_2 (Ω)</th>
<th>Z_{23} (Ω)</th>
<th>Z_3 (Ω)</th>
<th>Z_B (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>50</td>
<td>258</td>
<td>62</td>
<td>104</td>
<td>62</td>
<td>258</td>
<td>50</td>
</tr>
<tr>
<td>0.2</td>
<td>50</td>
<td>365.7</td>
<td>57.9</td>
<td>157.8</td>
<td>57.9</td>
<td>365.7</td>
<td>50</td>
</tr>
</tbody>
</table>

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)
Bandstop Filter Comparison ($\Delta = 0.2$)

- Microstrip realization
- $\varepsilon_r=2.2$, $h=31$ mil
- 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

<table>
<thead>
<tr>
<th></th>
<th>Conventional Bandstop</th>
<th>Folded line Bandstop</th>
</tr>
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<tbody>
<tr>
<td>$\Delta=0.2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smallest normalized width (w/h)</td>
<td>0.0032 (0.099 mil)</td>
<td>0.26 (8.06 mil)</td>
</tr>
<tr>
<td>Overall footprint</td>
<td>2948 sq mm</td>
<td>767 sq mm</td>
</tr>
<tr>
<td>Footprint comparison</td>
<td>100 %</td>
<td>26 %</td>
</tr>
</tbody>
</table>
Filter Response

S\textsubscript{11}(Conventional filter theoretical)  
S\textsubscript{11}(Folded filter theoretical)  
S\textsubscript{11}(Folded filter MWS 2006\textsuperscript{®})  
S\textsubscript{21}(Conventional filter theoretical)  
S\textsubscript{21}(Folded filter theoretical)  
S\textsubscript{21}(Folded filter MWS 2006\textsuperscript{®})
Bandstop Filter Comparison (Δ = 0.3)

- Microstrip realization
- εᵣ=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

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Fabricated Folded Line Bandstop Filter

Microstrip Realization

$\varepsilon_r = 2.2, \ h = 31 \ mil$

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Folded Line Bandstop Filter Response

![Graph showing S11 dB vs Freq (GHz)]

- **S\(_{11}\)** (Folded filter theoretical)
- **S\(_{11}\)** (Measurement)
- **S\(_{11}\)** (Folded filter MWS 2006®)

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Folded Line Bandstop Filter Response (Cont’d)
Re-entry characteristics similar to conventional filters but higher frequencies are shifted due to increased coupling.
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

\[ Z_A \text{ and } Z_B = \text{Terminating impedances} \]
\[ Z_j (j = 1 \text{ to } n) = \text{OC shunt stub impedances} \]
\[ Z_{ij} (j = 2 \text{ to } n) = \text{Connecting line impedances} \]
## Characteristic Impedances for Various Lowpass Filter Sections

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<tr>
<th>$Z_A (\Omega)$</th>
<th>$Z_1 (\Omega)$</th>
<th>$Z_{12} (\Omega)$</th>
<th>$Z_2 (\Omega)$</th>
<th>$Z_{23} (\Omega)$</th>
<th>$Z_3 (\Omega)$</th>
<th>$Z_B (\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>

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

- 50Ω microstrip line $\rightarrow w = 98$ mil
- 25 Ω microstrip line $\rightarrow w = 243$ mil (6.17 mm)
- (1/2 ounce copper, 0.7 mil)
Lowpass Filter Comparison

- Microstrip realization
- $\varepsilon_r=2.2, \ h=31\text{mil}$
- Conventional stub-loaded filter measured 755 sq mm
- Folded line filter measured 535 sq mm!!
# Footprint & Critical Conductor Width Comparison

<table>
<thead>
<tr>
<th></th>
<th>Conventional Lowpass</th>
<th>Folded line Lowpass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c = 1.5 \text{ GHz}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Largest normalized width (w/h)</td>
<td>7.9 (244.9 mil)</td>
<td>3.63 (112.5 mil)</td>
</tr>
<tr>
<td>Overall footprint</td>
<td>755 sq mm</td>
<td>535 sq mm</td>
</tr>
<tr>
<td>Footprint comparison</td>
<td>100 %</td>
<td>71 %</td>
</tr>
</tbody>
</table>
Fabricated Folded Line Lowpass Filter

Microstrip Realization

$\varepsilon_r=2.2, \ h=31\ mil$

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Folded Line Lowpass Filter Response (Cont’d)

![Graph showing S21 (dB) vs. Freq (GHz)]

- **S11** (Folded filter theoretical)
- **S11** (Measurement)
- **S11** (Folded filter MWS 2006®)
Multi Level Transmission Line Models

Cross-sectional View

Top metallization layer

Bottom metallization layer

Ground planes hidden

Stripline Realization

Microstrip Realization

$\varepsilon_r = 2.2$  $h = 62\ mil$

$\varepsilon_r = 2.2$  $h = 62\ mil$

$\varepsilon_r = 2.2$  $h = 62\ mil$

$\varepsilon_r = 2.2$  $h = 62\ mil$

$\varepsilon_r = 2.2$  $h = 31\ mil$

$\varepsilon_r = 2.2$  $h = 31\ mil$

Ground plane

Via
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

Hole in ground plane
Top metallization layer
Through hole via
Ground plane
Bottom metallization layer

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
  
  \[ L(w) = 0.5054 \times \exp(-1.7014 \times w^{0.8846}) + 0.4298 \text{ nH} \]
  
  \[ C(w) = 0.2209 \times \exp(0.2564 \times w^{0.9555}) - 0.1918 \text{ pF} \]
  
  \[ R(w) = -0.0026 \times \exp(1.6083 \times w^{0.5072}) + 0.0911 \text{ Ω} \]

  Diameter of the via = \( \frac{1}{2} \) width of the strip
  
  Diameter of the antipad = 0.4 mm + diameter of the via
Via R, L, C Vs. Line Width

Line width w (mm)

L (nH), C (pF), R (ohms)

MWS 2006®
Closed form equations
Design Procedure for Multilevel Bandstop and Lowpass Filters

1. Specifications
2. Physical design
3. Individual section approach/
   Single level folded line filter sections
4. Multi level folded line filter sections
5. Cascaded multi level folded line filter sections
6. 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)
  - \( \Delta = 0.3 \)
  - BTB microstrip realization
  - \( \varepsilon_r = 2.2, h = 31 \)mil for both dielectric layers
Bandstop Filter Comparison ($\Delta=0.3$)

- BTB microstrip platform
- $\varepsilon_r=2.2, h=31\text{mil}$ 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

Top metallization layer

Bottom metallization layer

Ground plane and dielectrics are hidden for better visibility
# Footprint & Critical Conductor Width Comparison

<table>
<thead>
<tr>
<th>$\Delta=0.3$</th>
<th>Conventional Bandstop</th>
<th>Single Level Folded Line Bandstop</th>
<th>Multi Level Folded Line Bandstop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smallest normalized width $(w/h)$</td>
<td>0.032 (0.99 mil)</td>
<td>0.5 (15.5 mil)</td>
<td>0.4 (12.4 mil)</td>
</tr>
<tr>
<td>Overall footprint</td>
<td>2948 sq mm</td>
<td>1015 sq mm</td>
<td>532 sq mm</td>
</tr>
<tr>
<td>Footprint comparison</td>
<td>100 %</td>
<td>34 %</td>
<td>18 %</td>
</tr>
</tbody>
</table>
Fabricated Folded Line Bandstop Filter

BTB Microstrip Realization

Top metallization layer

Bottom metallization layer

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\( \varepsilon_r = 2.2 \), \( h = 31 \text{ mil} \)
Folded Line Bandstop Filter Response

![Graph showing S11(dB) vs Freq (GHz) for different cases: Folded filter theoretical, Measurement, Folded filter MWS 2006®.](image)

- **S11(Folded filter theoretical)**
- **S11(Measurement)**
- **S11(Folded filter MWS 2006®)**
Folded Line Bandstop Filter Response (Cont’d)
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
  - $\varepsilon_r=2.2$, $h=31$mil for both dielectric layers
New Lowpass Filter Configuration

- BTB microstrip realization
- $\varepsilon_r=2.2$, $h=31$ mil 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

Top metallization layer

Bottom metallization layer

Ground plane and dielectrics are hidden for better visibility
# Footprint & Critical Conductor Width Comparison

<table>
<thead>
<tr>
<th>f&lt;sub&gt;c&lt;/sub&gt;=1.5 GHz</th>
<th>Conventional Lowpass</th>
<th>Single Level Folded Line Lowpass</th>
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<tr>
<td>Largest normalized width (w/h)</td>
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<td>Overall footprint</td>
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<tr>
<td>Footprint comparison</td>
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<td>31 %</td>
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Fabricated Folded Line Lowpass Filter

BTB Microstrip Realization

Top metallization layer

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Bottom metallization layer
Folded Line Lowpass Filter Response

![Graph showing S11 response](image)

- **S_{11}(Folded filter theoretical)**
- **S_{11}(Measurement)**
- **S_{11}(Folded filter MWS 2006®)**

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Folded Line Lowpass Filter Response (Cont’d)

![Graph showing S21 response with theoretical, measurement, and MWS 2006® curves.]

- **S21 (Folded filter theoretical)**
- **S21 (Measurement)**
- **S21 (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