Workshop WMA

2009 International Microwave Symposium

Frequency Agile Ferroelectric Filters, Power Dividers, and Couplers

International Microwave Symposium 2009

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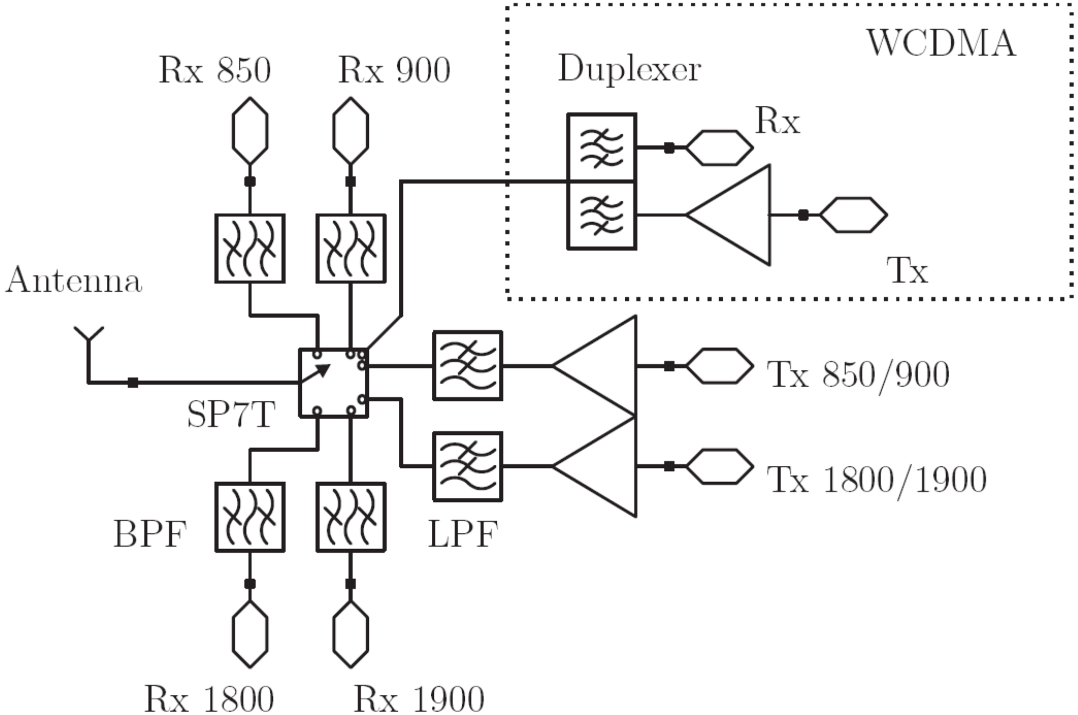
Outline

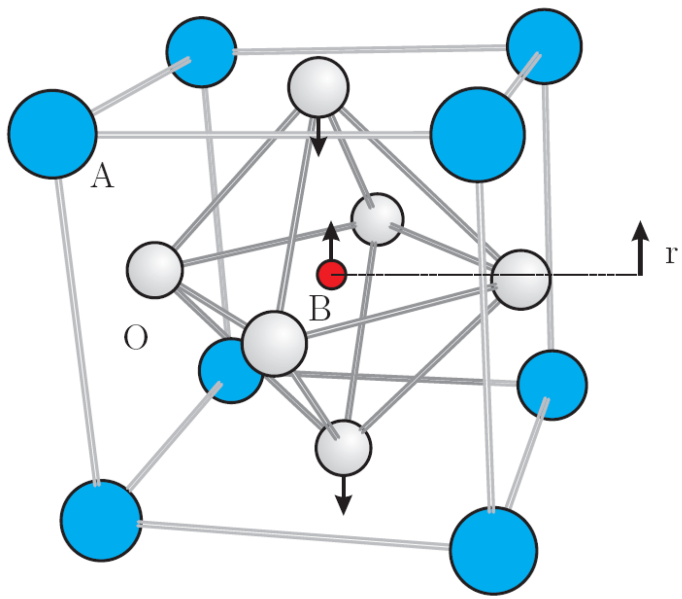
- Motivation
- Tunable Passive Components
  - Ferroelectric Varactors
- Frequency Agile Filters
- Frequency Agile Power Dividers & Couplers
- Prototype Implementation & Results
- Reconfigurable Amplifier Concept
- Conclusion & Outlook

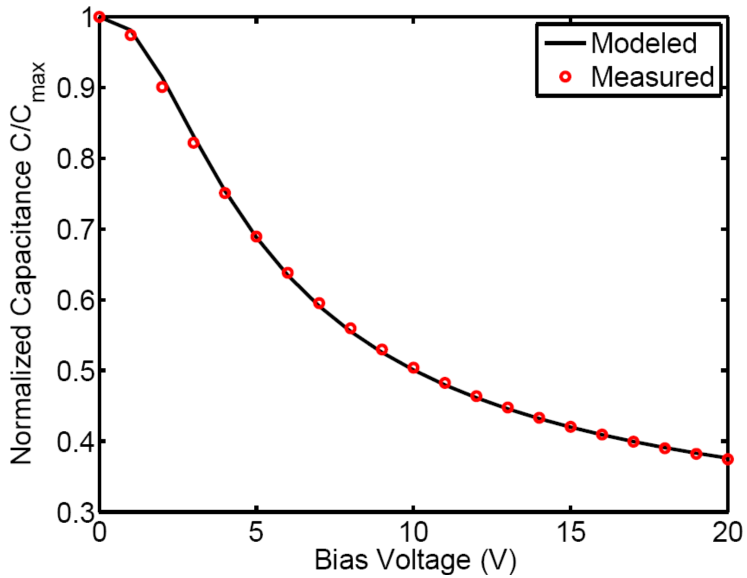
Motivation



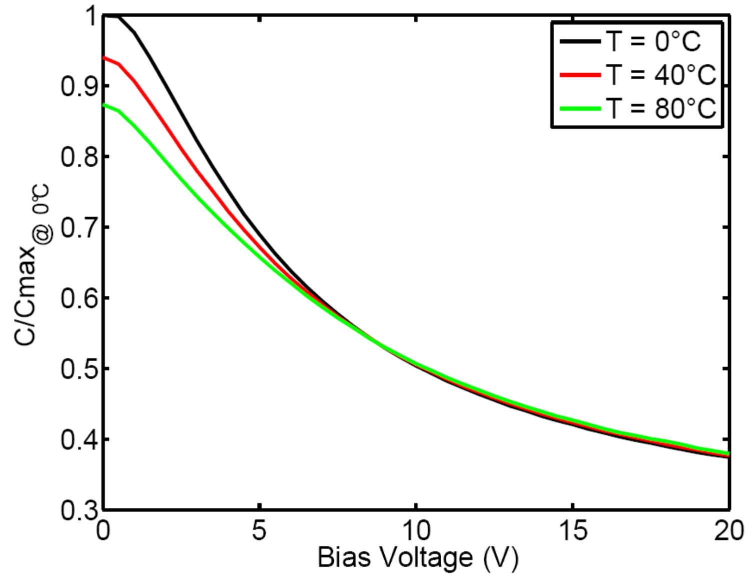
- Increasing number of communication bands
- Additional wireless services, e.g. GPS, WiMAX
- Demand for reconfigurable front-end solutions

Ferroelectric Materials - BST

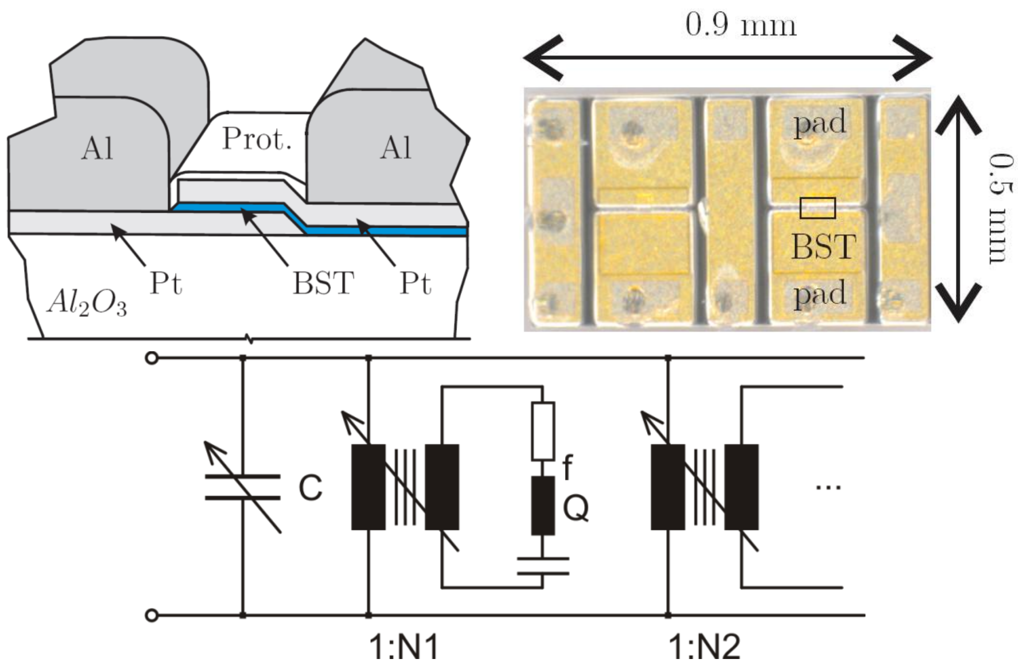


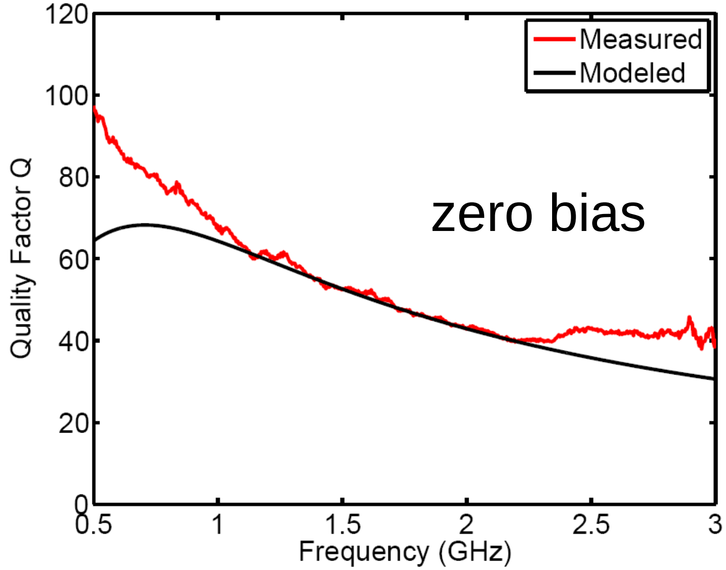


- Nonlinear response to E field variation
- Tunability of 60% at 20V
- Voltage and temperature dependence
- Piezoelectric behavior

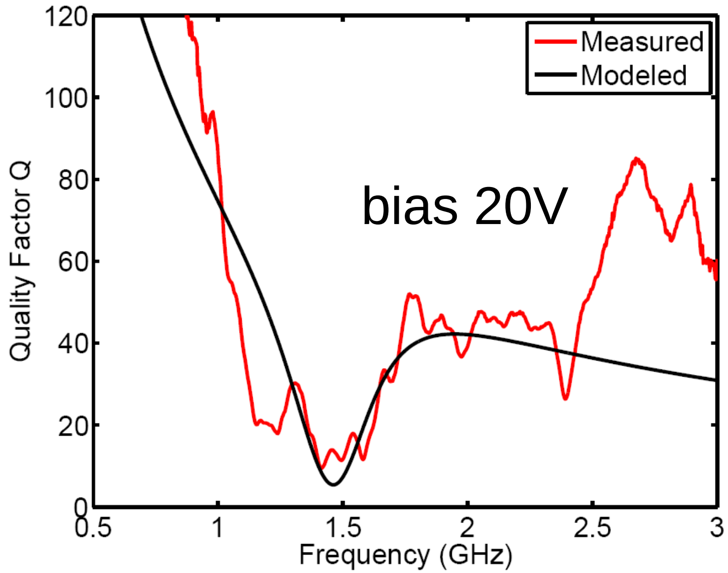


Ferroelectric Thin-Film Varactors

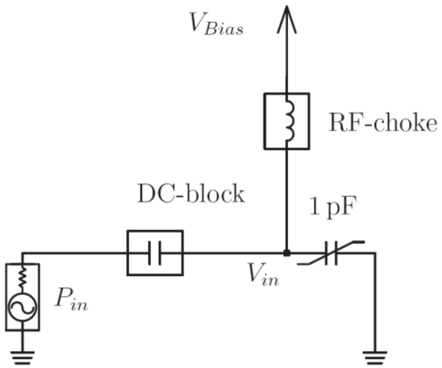


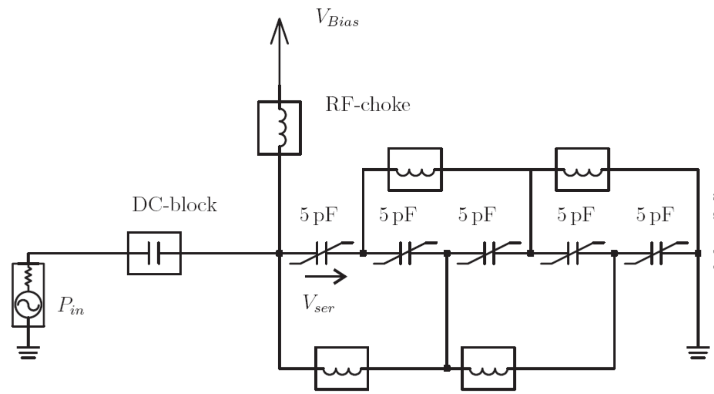


- Metal-Insulator-Metal (MIM)
- Compact dimensions
- Q around 40 @ 2 GHz
- Acoustic resonance
- ADS model available

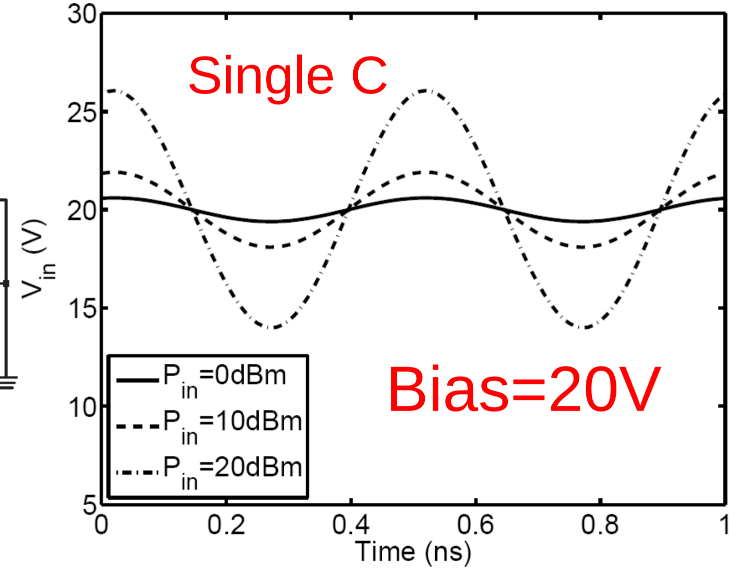


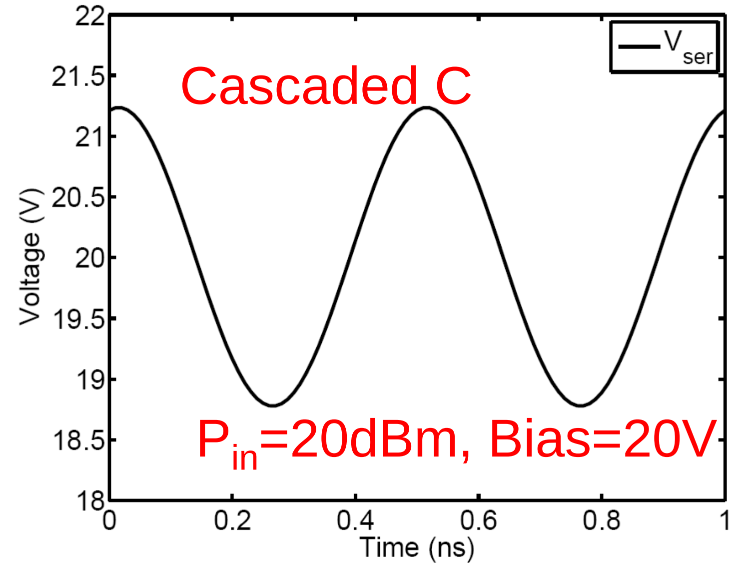
Ferroelectric Thin-Film Varactors





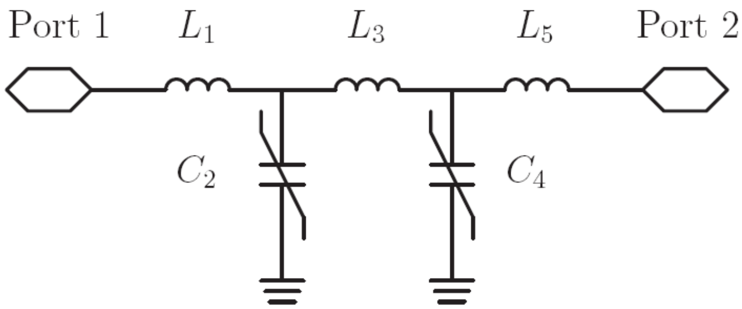
C_{cas}=n x C





- RF "modulates" capacitance
- RF swing is reduced by cascaded varactors
- Large capacitances are needed
- Possible for MIM capacitor

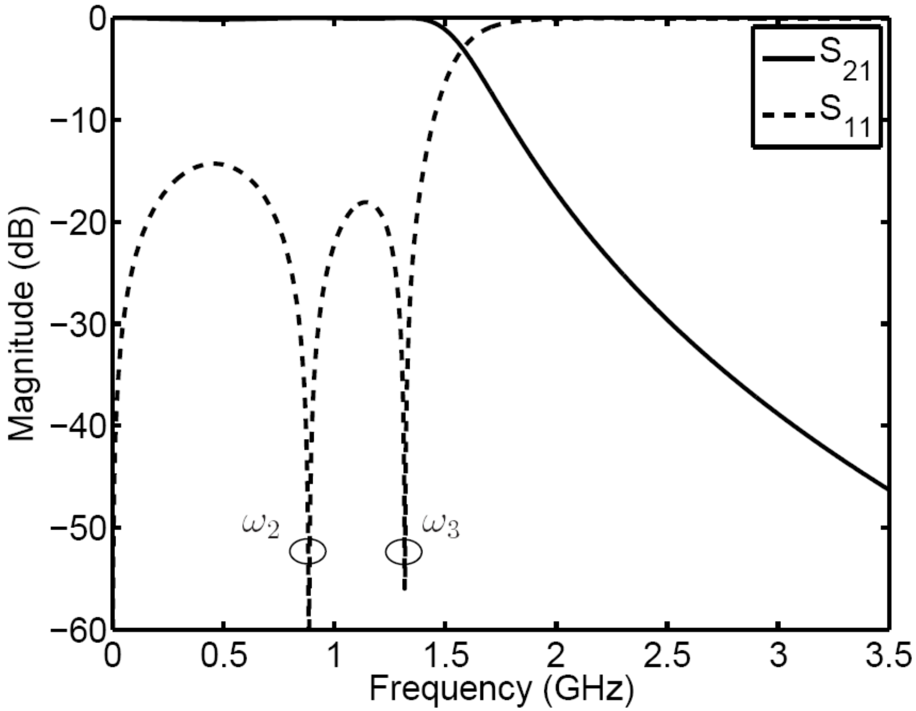
Analytical Filter Design – Lowpass



$$M_{i=1,3,5} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_i \\ 0 & 1 \end{bmatrix}$$

$$M_{j=2,4} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_j & 1 \end{bmatrix}$$

$$M_{total} = M_1 \cdot M_2 \cdot M_3 \cdot M_4 \cdot M_5$$



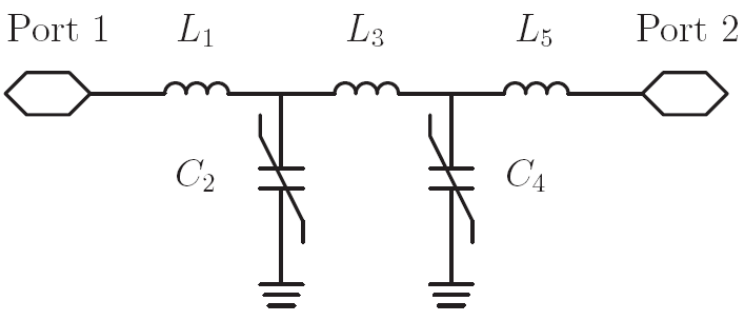
- Chebyshev lowpass filter
- Analytical formulas for zero locations

$$z_2 = \jmath\omega_2 = \pm\frac{\sqrt{2CL_3(-2L_1L_3 - 2L_1^2 + Z_0^2CL_3 + \alpha)}}{2CL_1L_3}$$

$$z_3 = \jmath\omega_3 = \pm\frac{\sqrt{2CL_3(-2L_1L_3 - 2L_1^2 + Z_0^2CL_3 - \alpha)}}{2CL_1L_3}$$

$$\alpha = \sqrt{-4L_1L_3^2Z_0^2C + 4L_1^4 + 4L_1^2L_3Z_0^2C + L_3^2Z_0^4C^2}$$

Frequency Agile Lowpass



$$z_2 = \jmath\omega_2 = \pm\frac{\sqrt{2CL_3(-2L_1L_3 - 2L_1^2 + Z_0^2CL_3 + \alpha)}}{2CL_1L_3}$$

$$z_3 = \jmath\omega_3 = \pm\frac{\sqrt{2CL_3(-2L_1L_3 - 2L_1^2 + Z_0^2CL_3 - \alpha)}}{2CL_1L_3}$$

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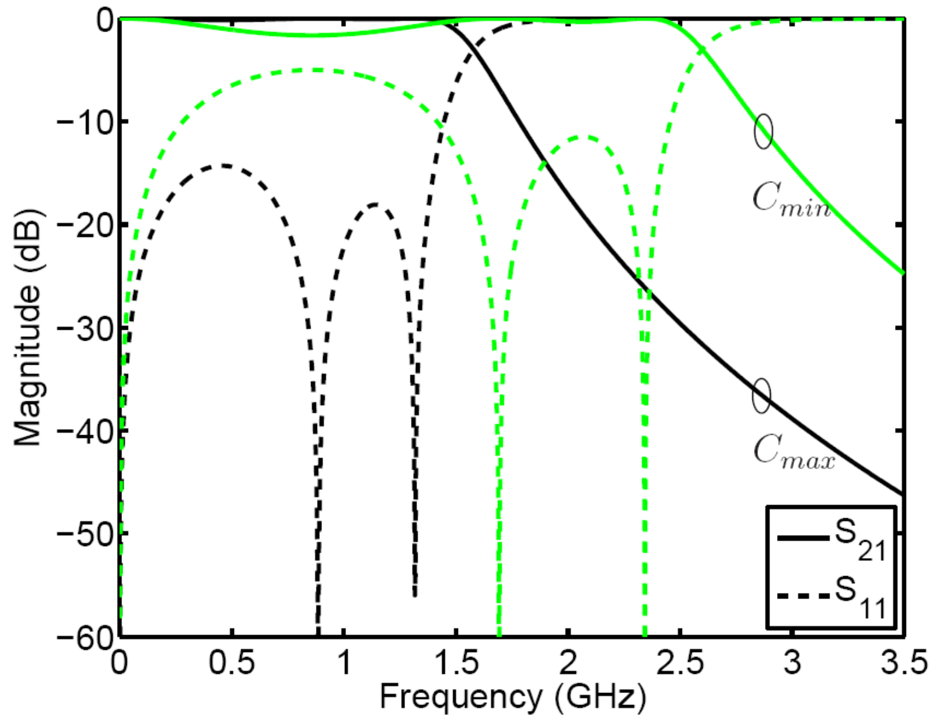
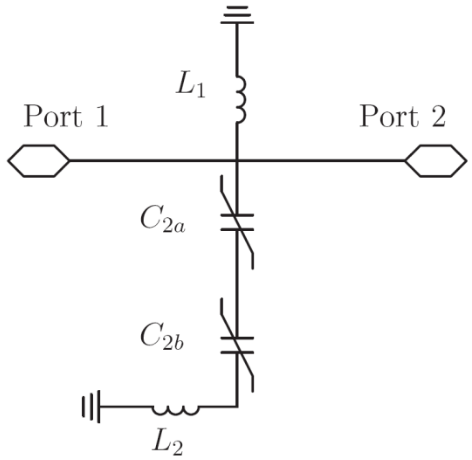


- Assumed tunability of 60% for BST varactors
- Multiband tuning from 1.5 – 2.3 GHz
- Changing C results in shifted zero locations

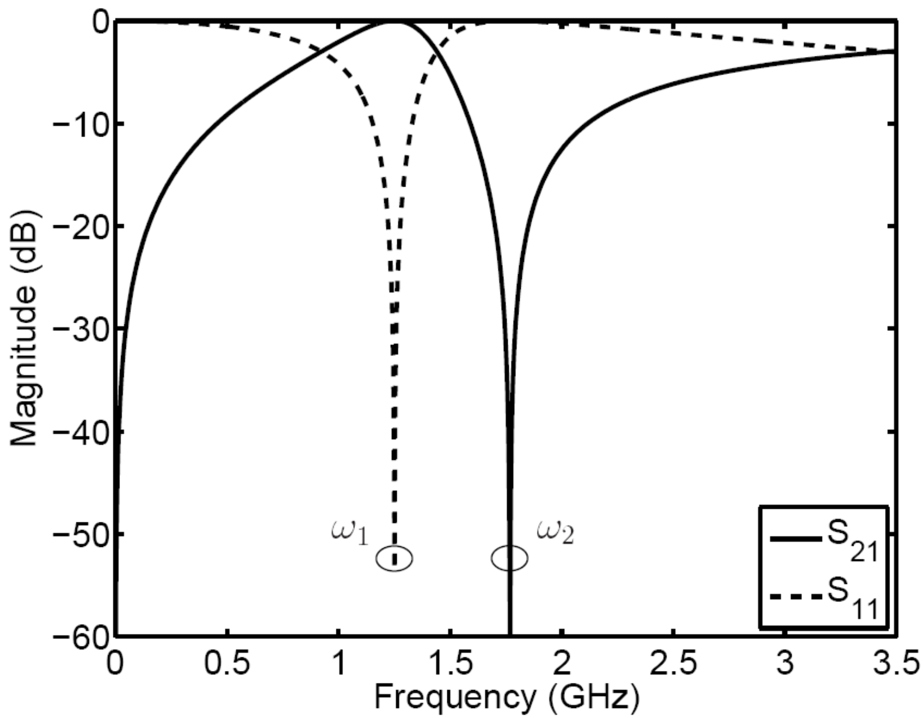
Analytical Filter Design – Notch Filter



$$M_1 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_1 & 1 \end{bmatrix}$$

$$M_2 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_2 & 1 \end{bmatrix}$$

$$Y_2 = 1/[2/(pC) + pL_2]$$

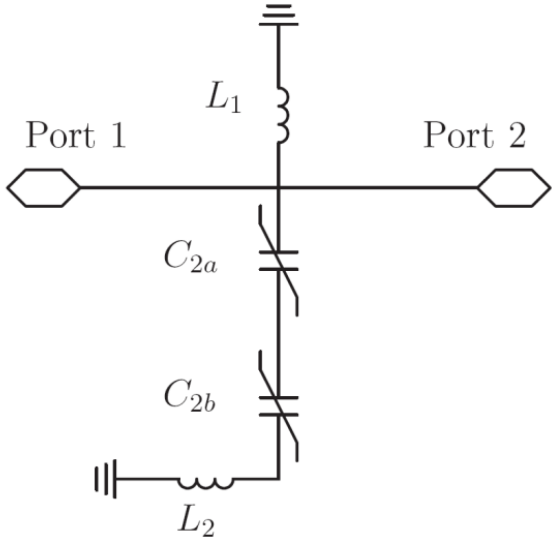


- Notch filter
- Analytical formulas for zero and pole locations

zero $z_1 = j\omega_1 = \pm\sqrt{-2/[(L_1 + L_2)C]}$

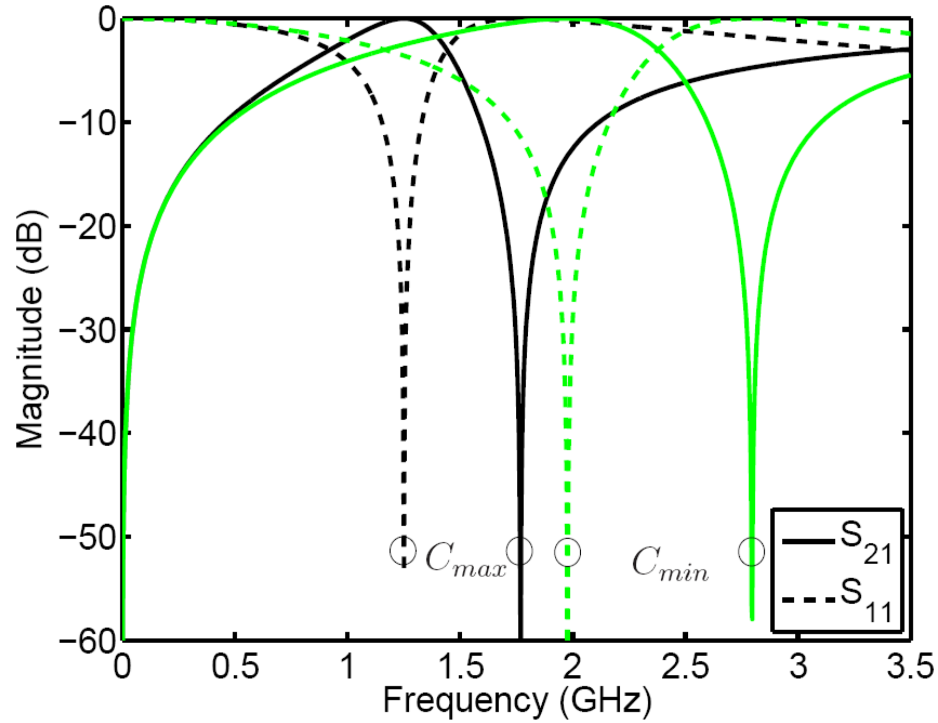
pole $p_2 = j\omega_2 = \pm\sqrt{-2/(L_2 C)}$

Frequency Agile Notch Filter



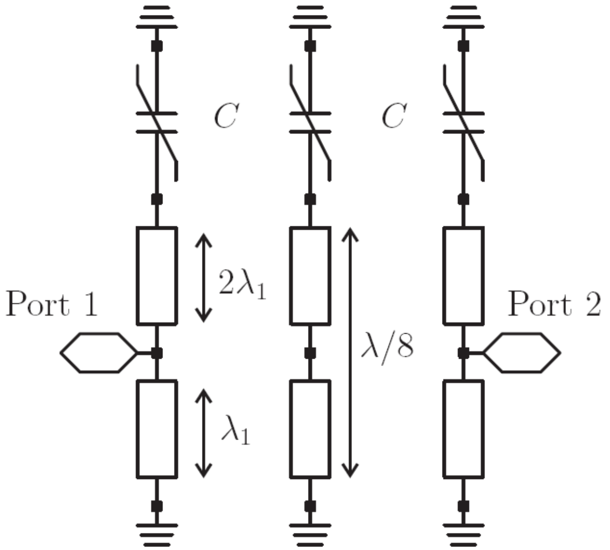
$$z_1 = \jmath\omega_1 = \pm\sqrt{-2/[(L_1 + L_2)C]}$$

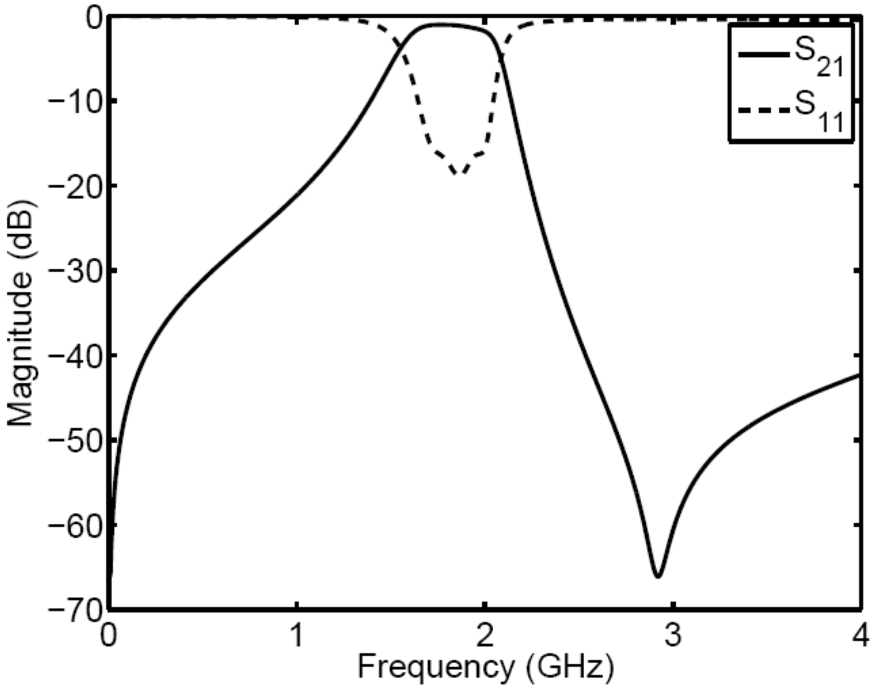
$$p_2 = \jmath\omega_2 = \pm\sqrt{-2/(L_2 C)}$$



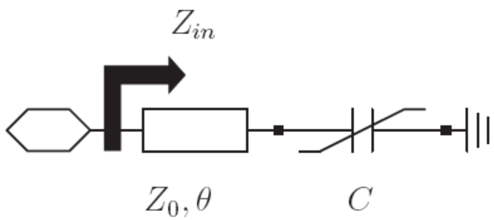
- Assumed tunability of 60% for BST varactors
- Multiband tuning from 1.7 – 2.7 GHz
- Changing C results in shifted zeros and poles

Analytical Filter Design – Combline Filter





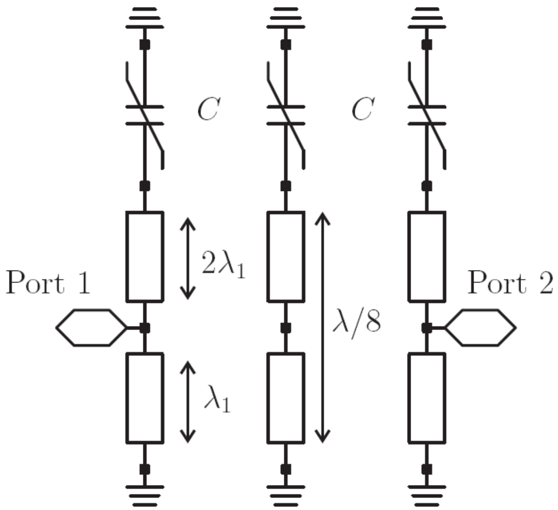
Tuning principle



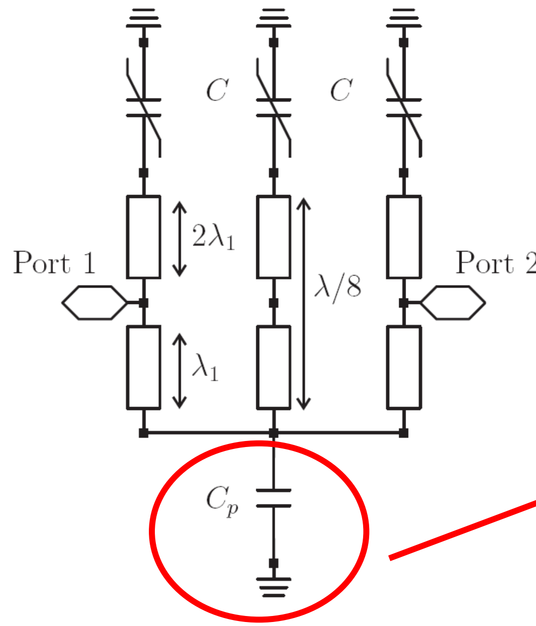
$$f = \frac{1}{2\pi C Z_0 \tan(\theta)}$$

- Compact filter dimensions
- Most suitable topology
- Asymmetric pole allocation

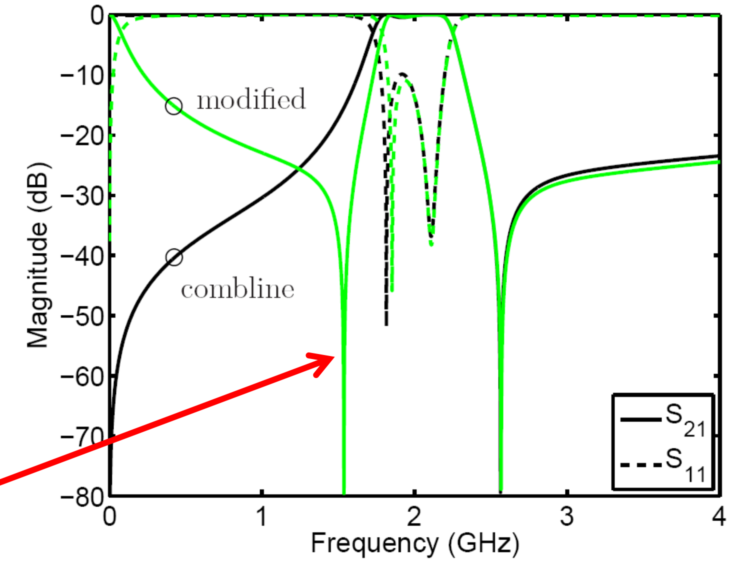
Modified Combline Filter

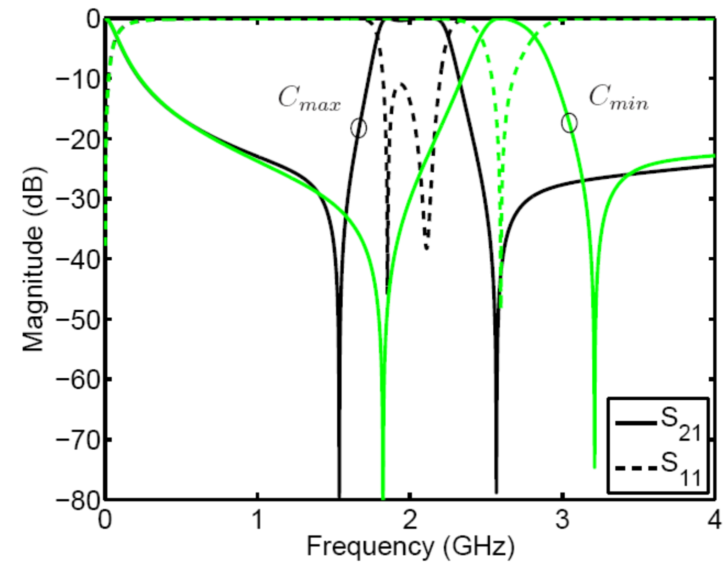


Original



Modified

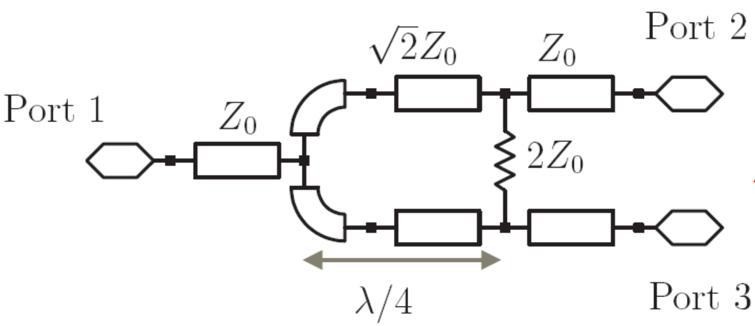




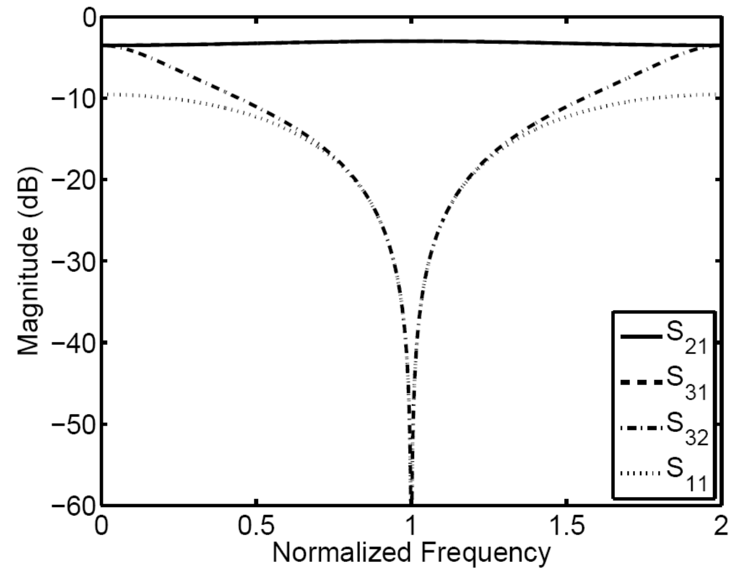
- Second attenuation pole is shifted from DC to lower stopband
- Symmetric pass- to stopband transition

λ/4 Based Microwave Circuits

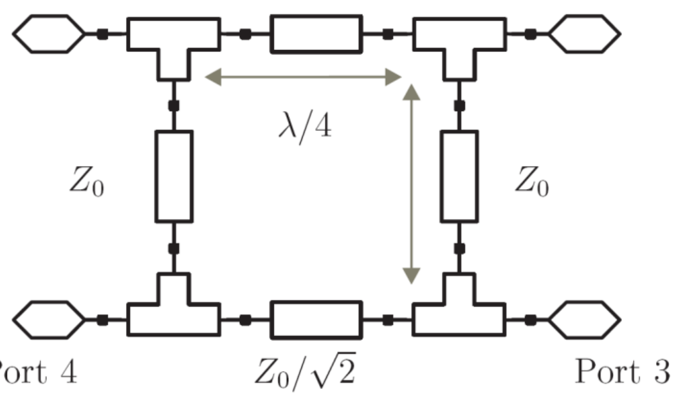
Wilkinson divider



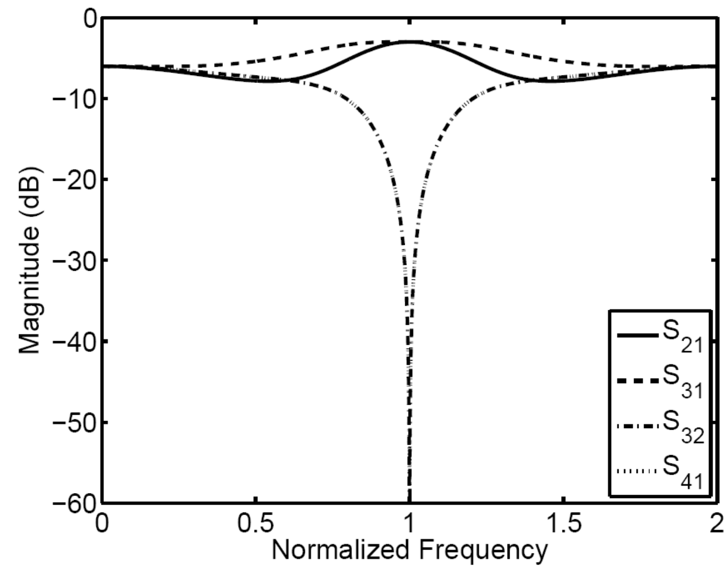
Δφ=0 deg



Branch-Line coupler

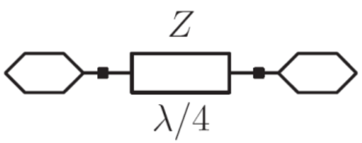


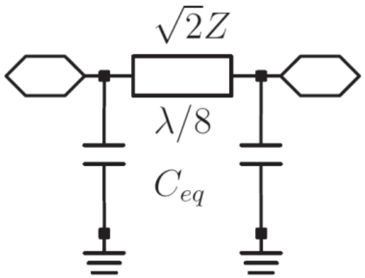
Δφ=90 deg



- Well known 3dB couplers
- Based on λ/4 segments

Equivalent λ/4 Segments – Distributed Lowpass





Quarter-wavelength segment

$$M = \begin{bmatrix} 0 & jZ \\ j/Z & 0 \end{bmatrix} \quad (1)$$

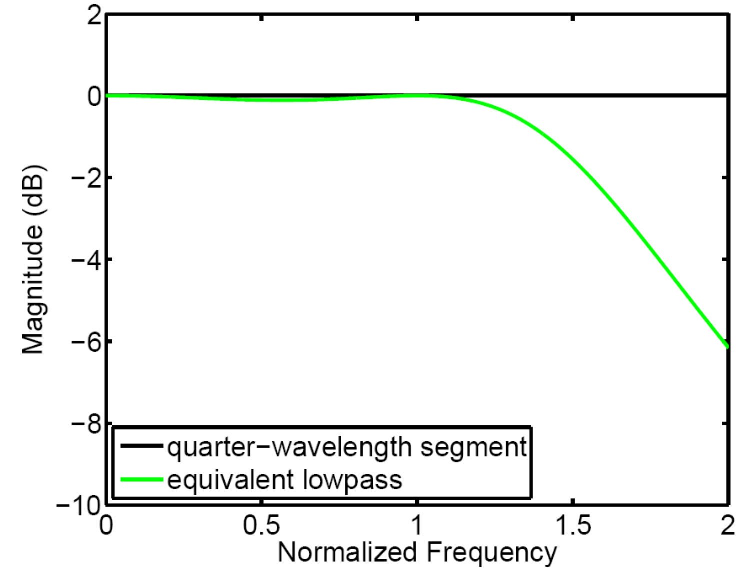
Equivalent lowpass segment

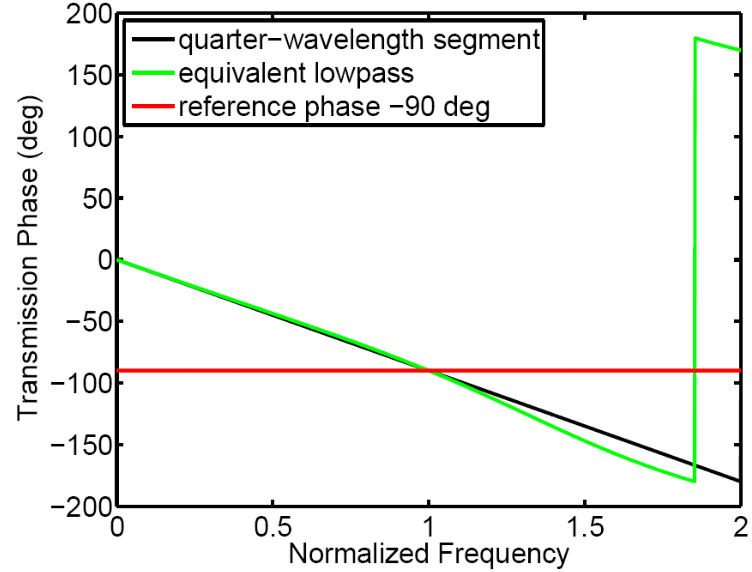
$$\begin{bmatrix} -\omega C_{eq} Z + 1/\sqrt{2} & jZ \\ j[\omega\sqrt{2}C_{eq}Z + (1/2) - \omega^2 C_{eq}^2 Z^2]/Z & -\omega C_{eq} Z + 1/\sqrt{2} \end{bmatrix} \quad (2)$$

Comparing (1) and (2) results in

$$C_{eq} = \frac{1}{\omega\sqrt{2}Z} = \frac{1}{2\pi f\sqrt{2}Z}$$

- Scalable equivalent circuit
- Signifficant size reduction





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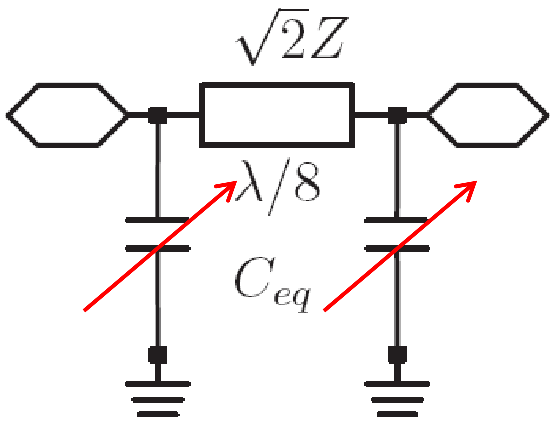
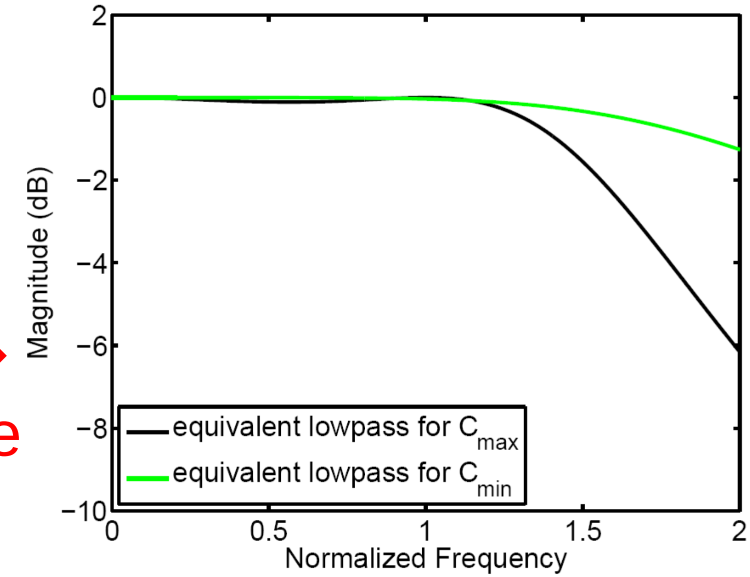
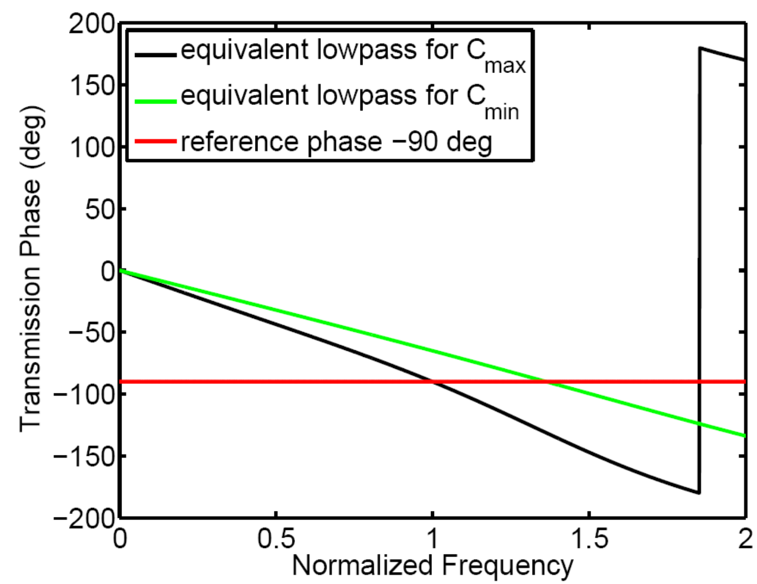
Frequency Agile λ/4 Segments



$$C_{eq} = \frac{1}{\omega\sqrt{2}Z} = \frac{1}{2\pi f\sqrt{2}Z}$$

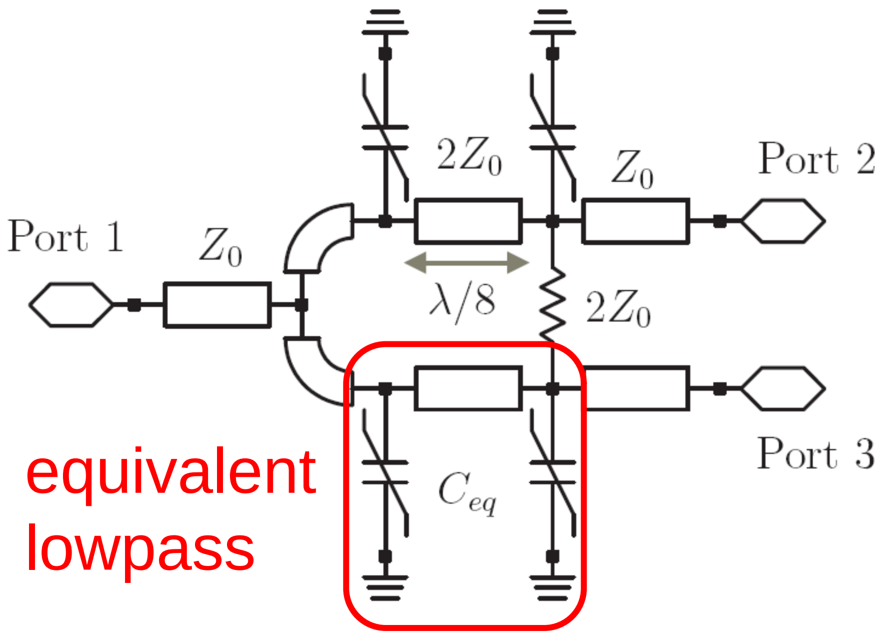
Tuning of C_{eq} → shifts resonance

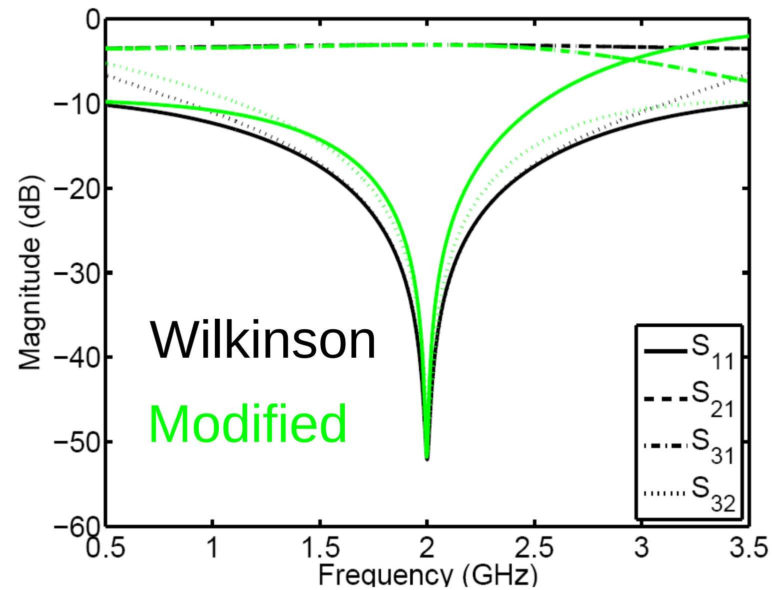


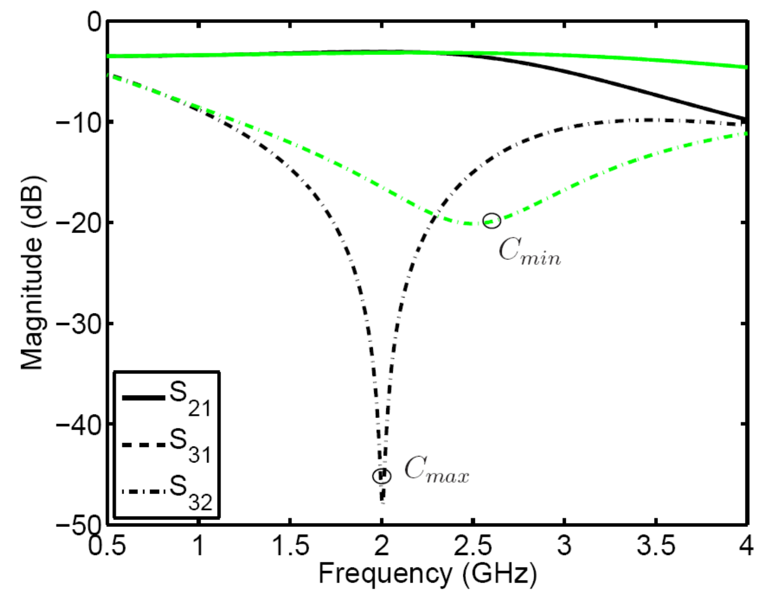


- Scalable network
- Slightly detuned Z
- Perfect phase shift
- Multiband function
- Assumed tunability of 60%

Reduced Size Tunable Wilkinson Divider







- Size reduction 50%
- Multiband tuning
- Assumed tunability 60%

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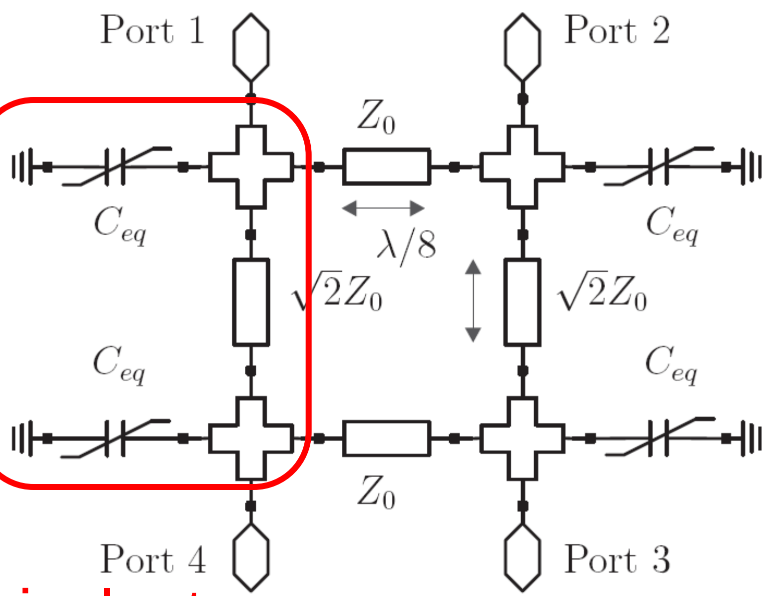
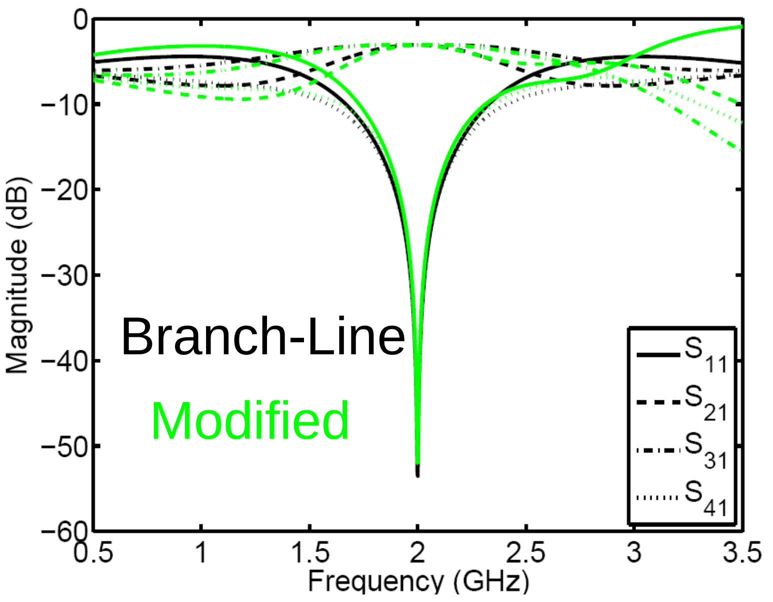
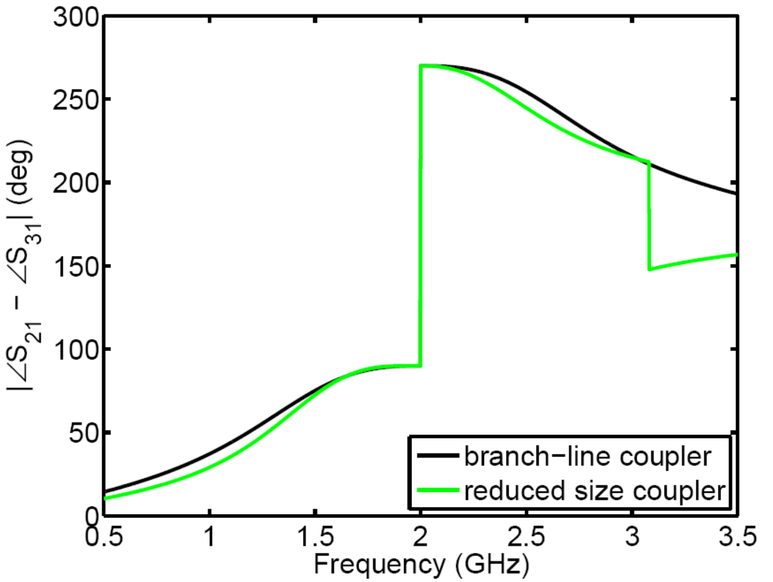
Reduced Size Branch-Line Coupler



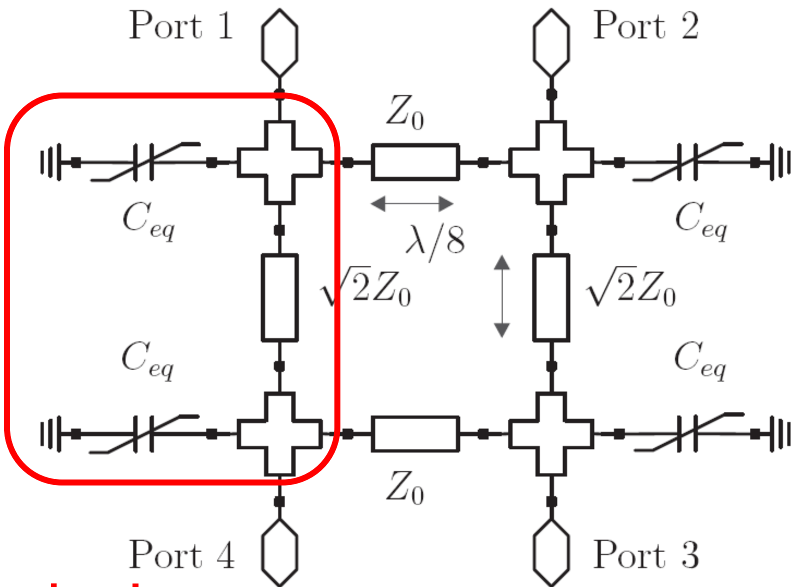
equivalent
lowpass



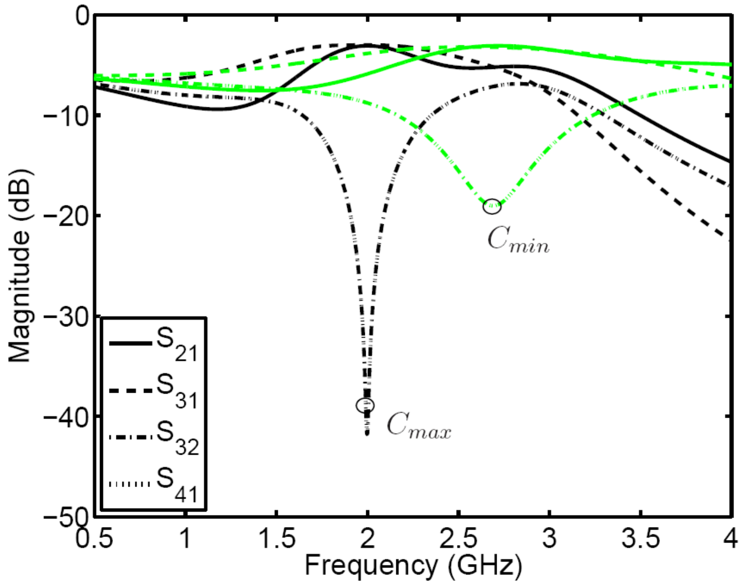


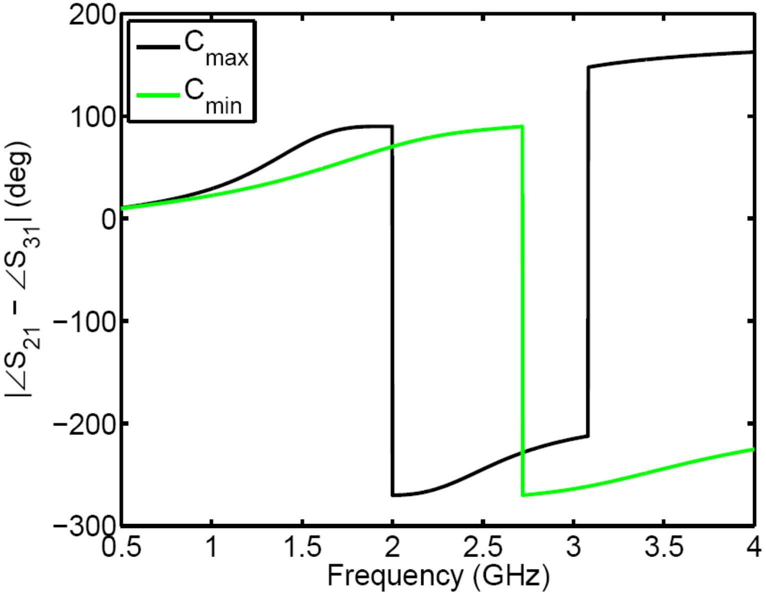
- Size reduction 50%
- Perfect phase match
- C_{eq} serves as shunt element for both segments

Reduced Size Tunable Branch-Line Coupler



equivalent
lowpass





- Size reduction 50%
- Perfect phase shift
- Multiband operation with tunability of 60% for C_{eq}

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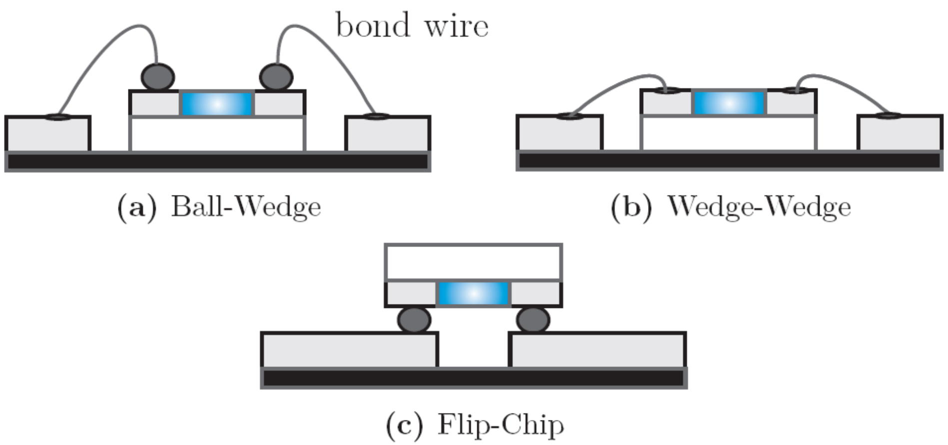
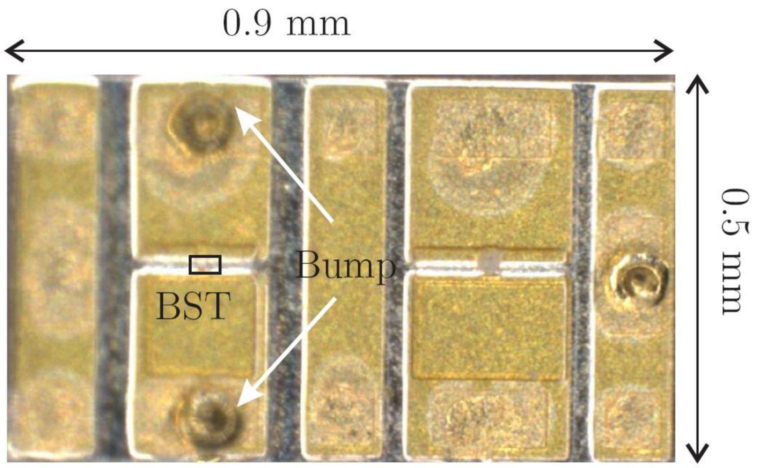
Prototype Implementation & Assembly

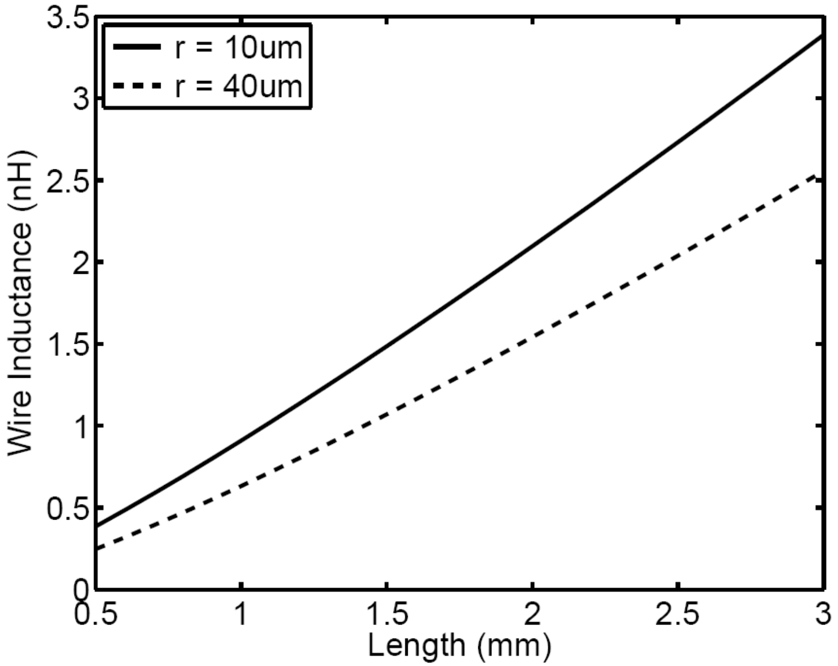




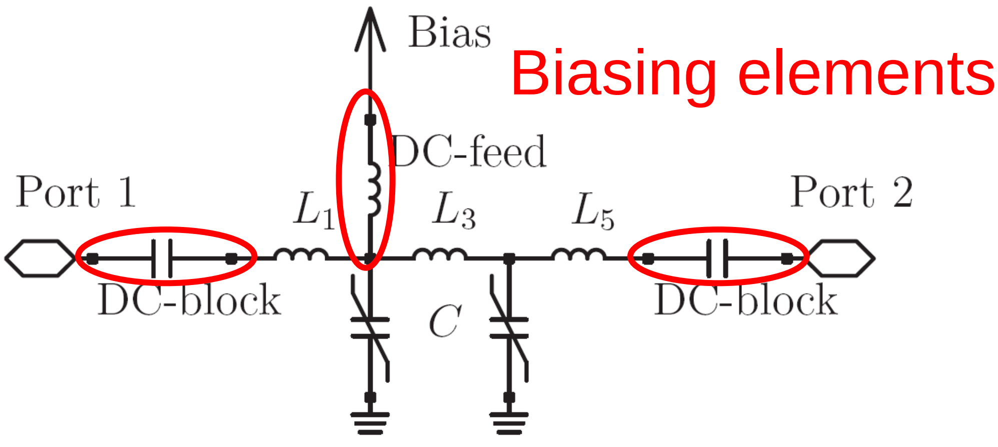
Wire inductance

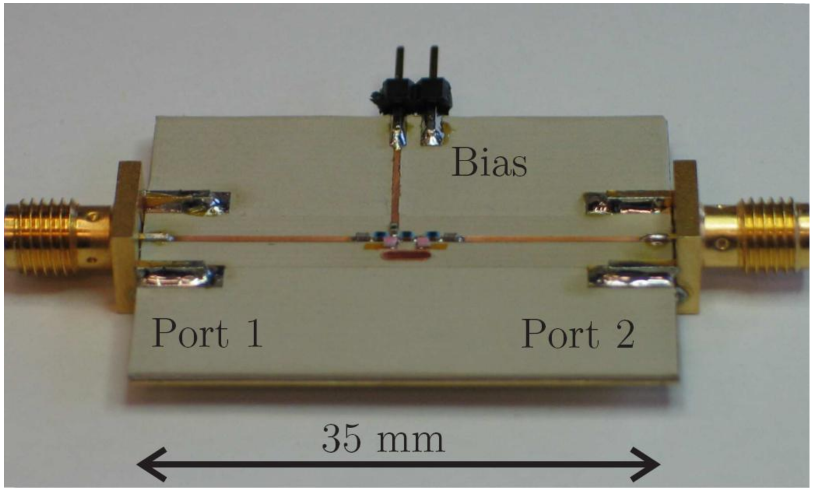
$$L \approx \frac{\mu_0 l}{2\pi}\left[ln\left(\frac{2l}{r}\right) - \frac{3}{4}\right]$$

- Wire assemblies suffer from parasitics
- Flip-Chip is favorable
- Reduced footprint

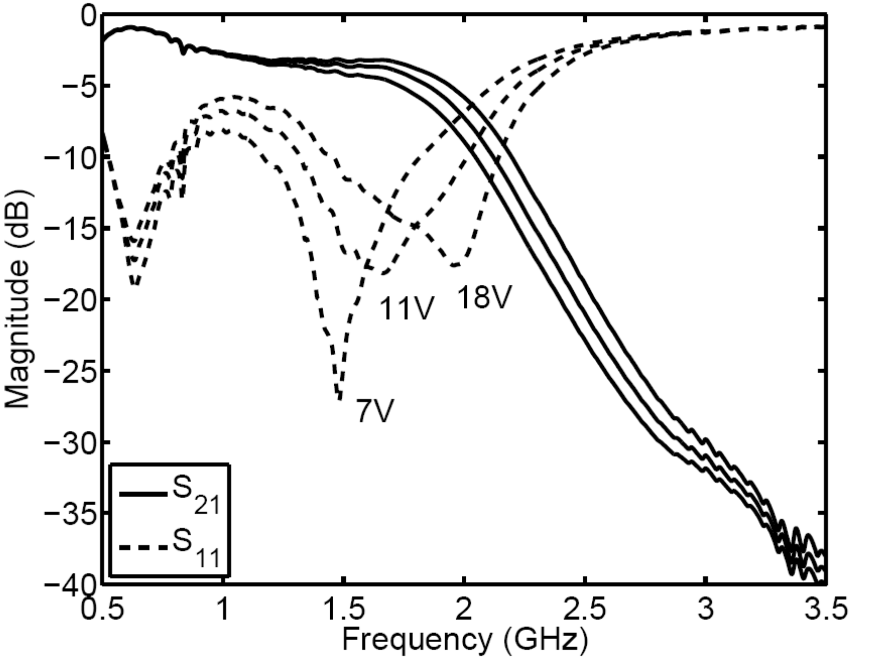


Tunable Lowpass (1)

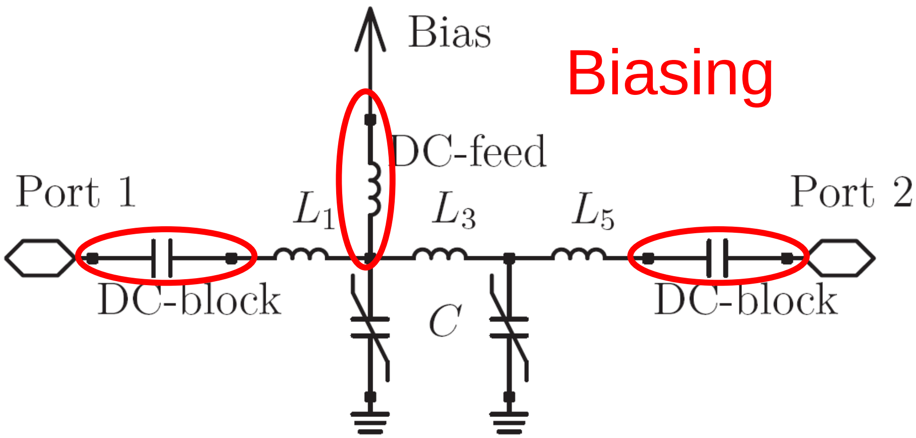


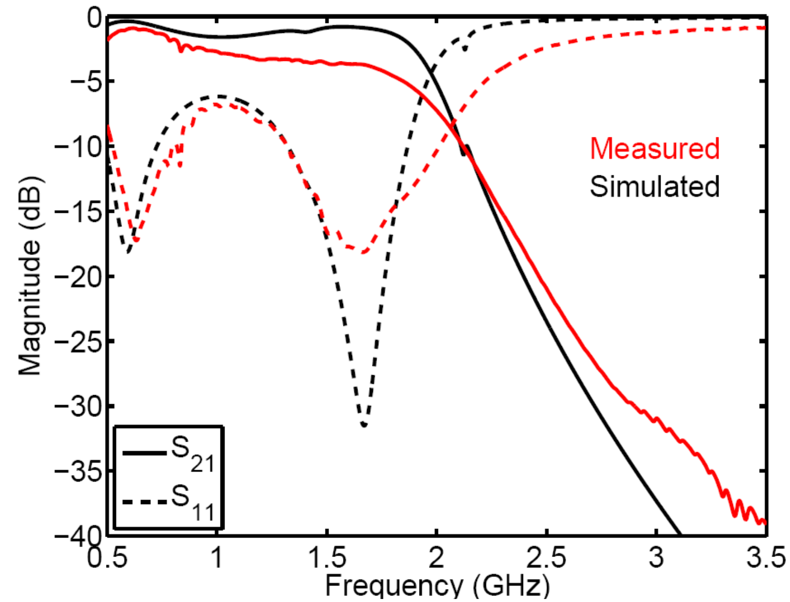


- Biasing components
- Compact dimensions
- Tuning range of 30%
- 1.5-2GHz multiband
- High losses due to moderate Q and RF isolation

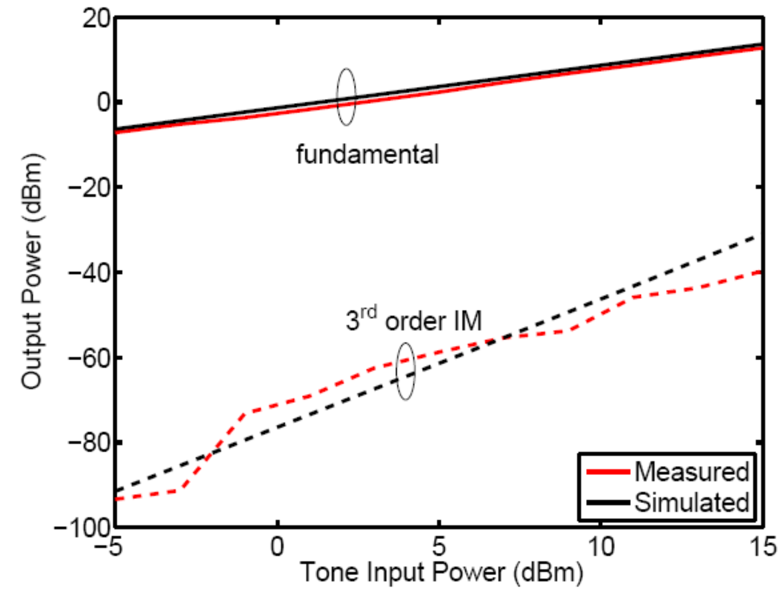


Tunable Lowpass (2)

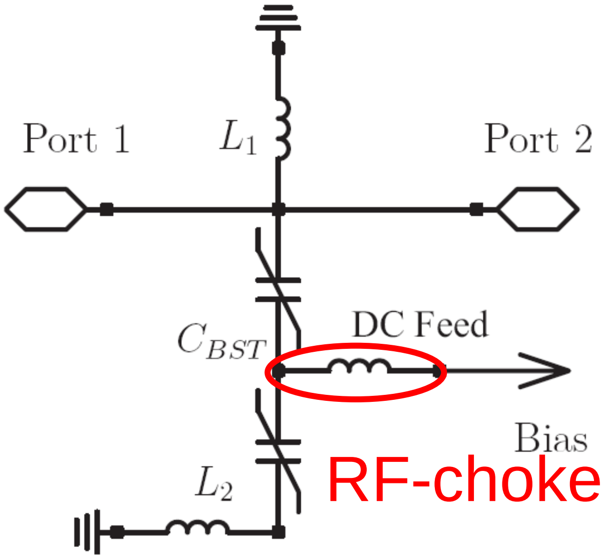


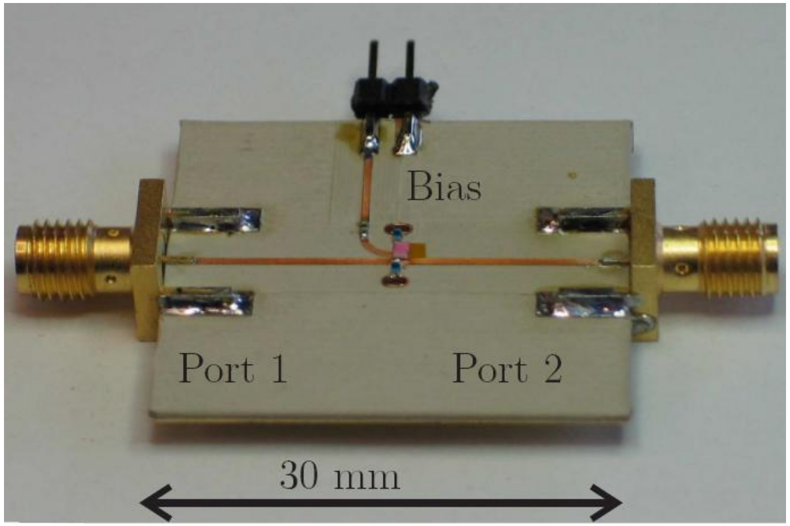


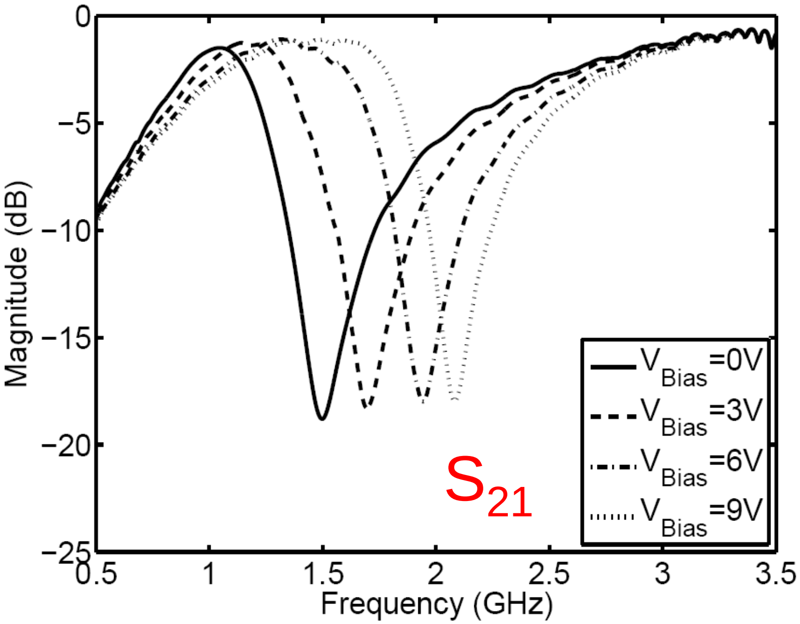
- Good agreement
- Increased loss due to varactor imbalances and prototype assembly
- Two-tone test @ 1.95GHz with Δf=5MHz and Bias=20V



Tunable Notch Filter (1)

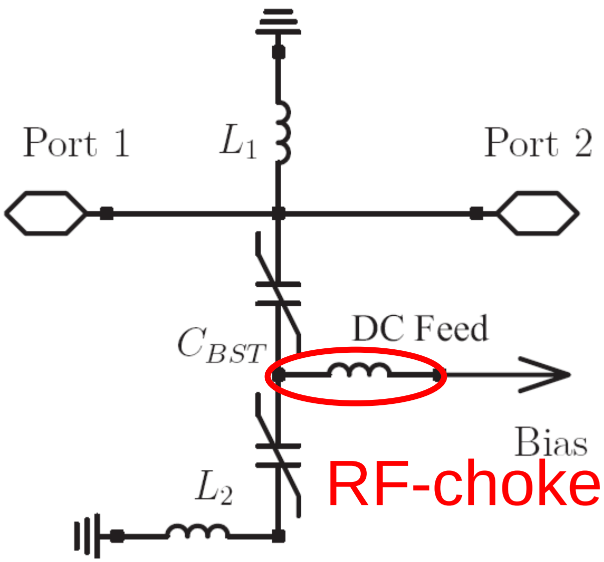


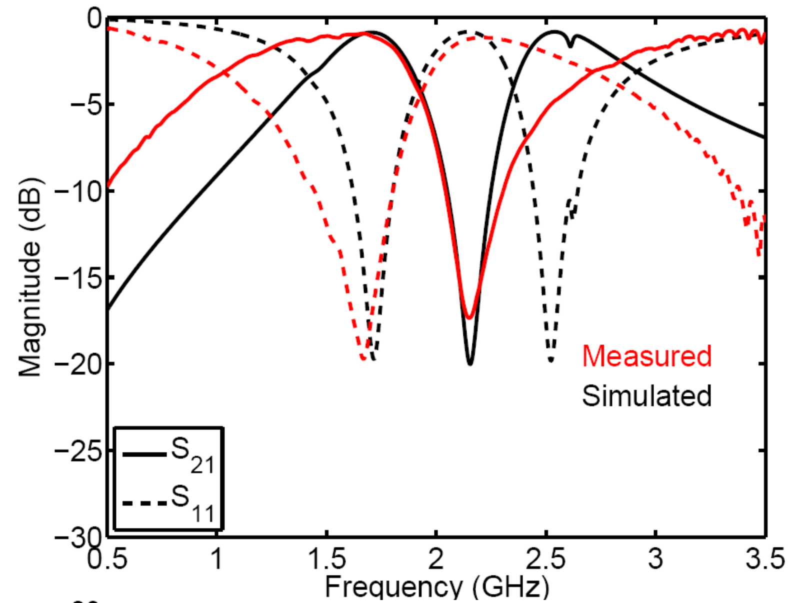




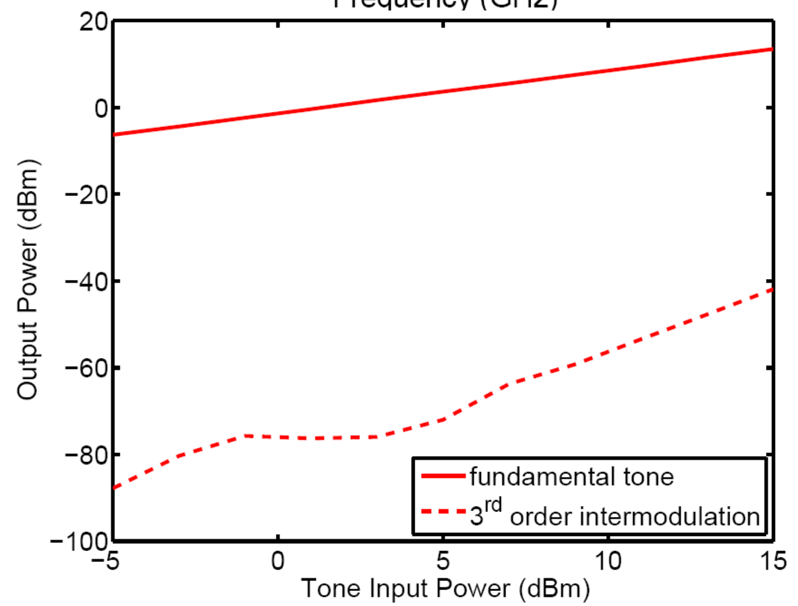
- Cascaded varactors simplify biasing
- Compact design
- Tuning 1.5-2.1GHz
- Multiband operation
- Low losses

Tunable Notch Filter (2)

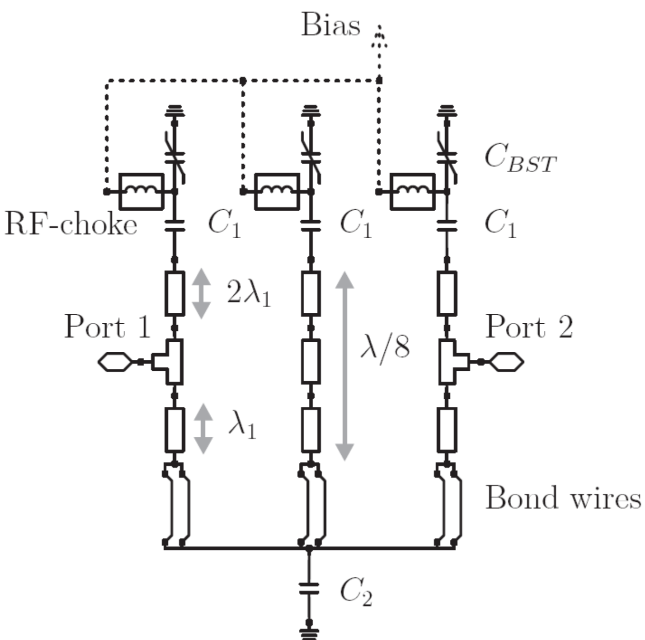


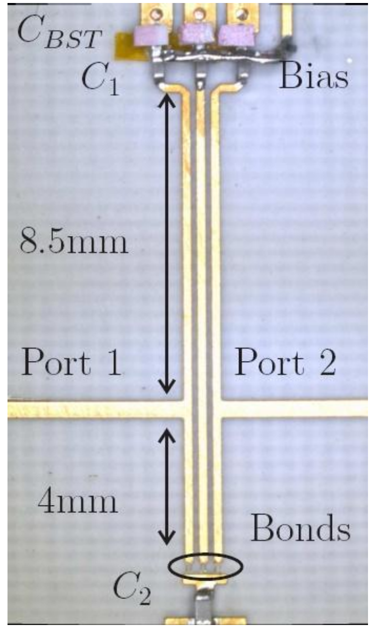


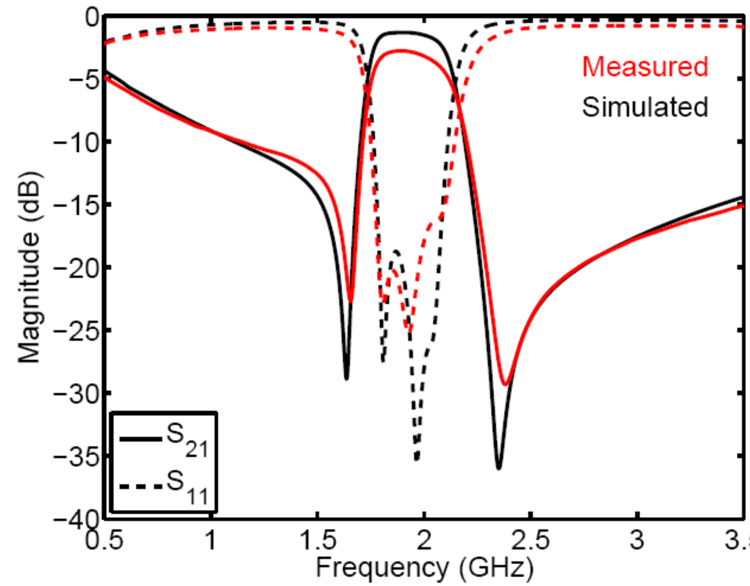
- Good agreement between simulation and measurement
- Two-tone test @ 1.95GHz with Δf=5MHz and Bias=20V

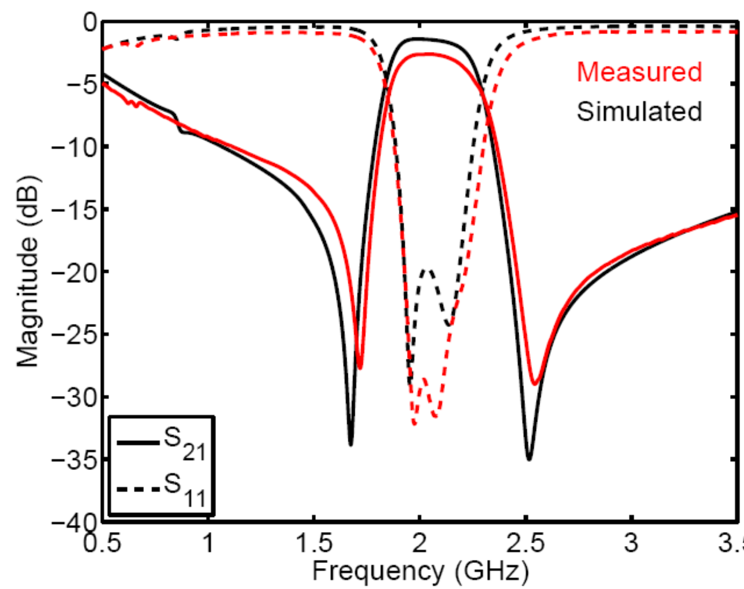


Tunable Combline Filter (1)



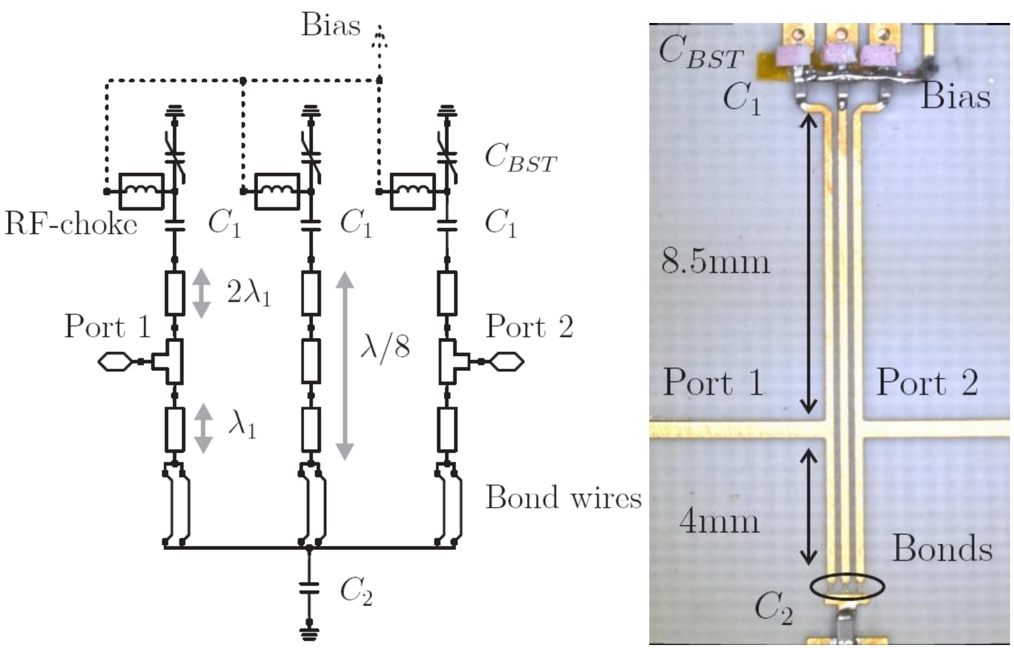






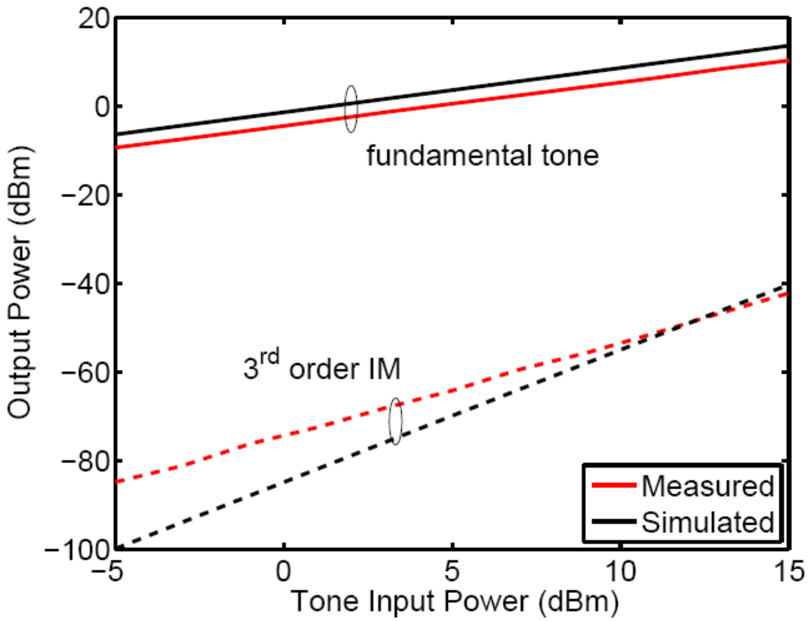
- Good agreement
- Compact dimensions
- IL < 3dB and RL > 20dB
- Tuning 1.8-2GHz

Tunable Combline Filter (2)

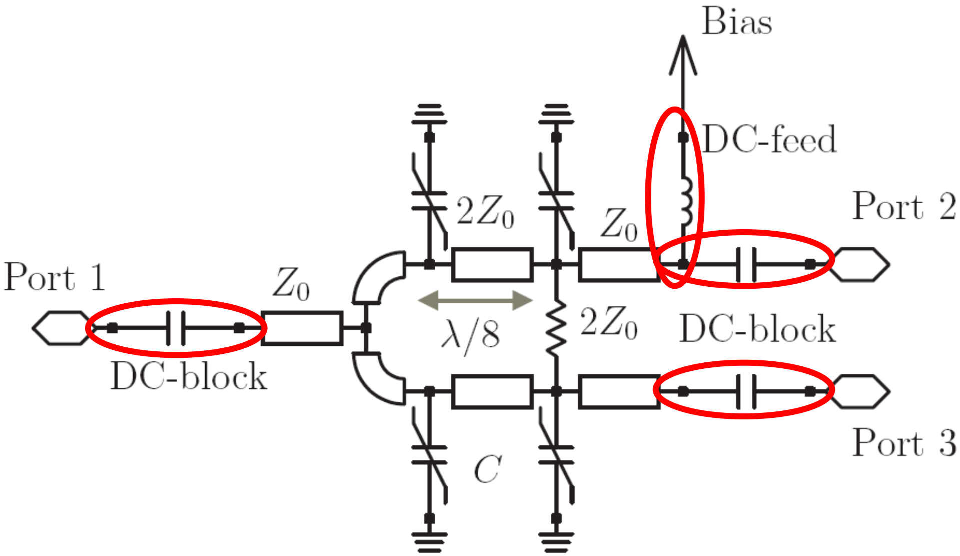


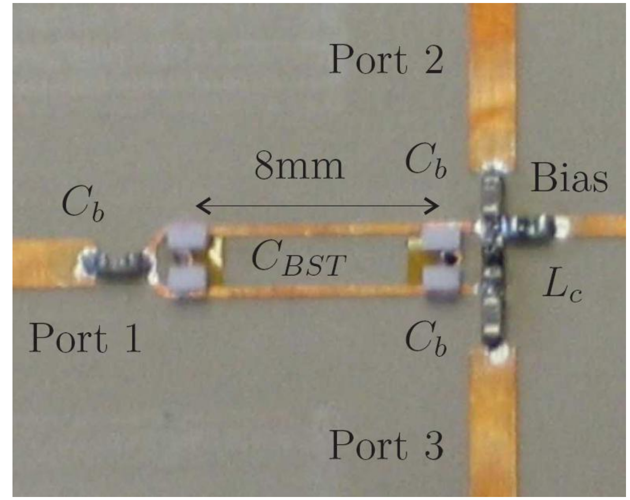
Bias (V)	f_0 (GHz)	IL (dB)	RL (dB)
0	1.85	2.8	20
5	1.90	2.7	22
10	1.97	2.6	26
15	2.02	2.6	28

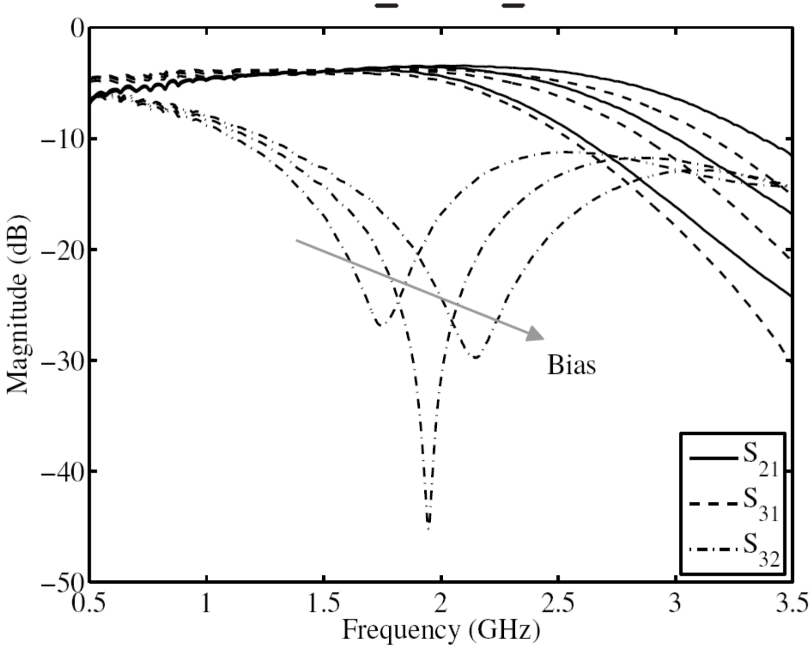
- Two-tone test @1.95GHz with Δf=5MHz and Bias=5V
- Output 3rd order intercept point OIP3=36.5dBm

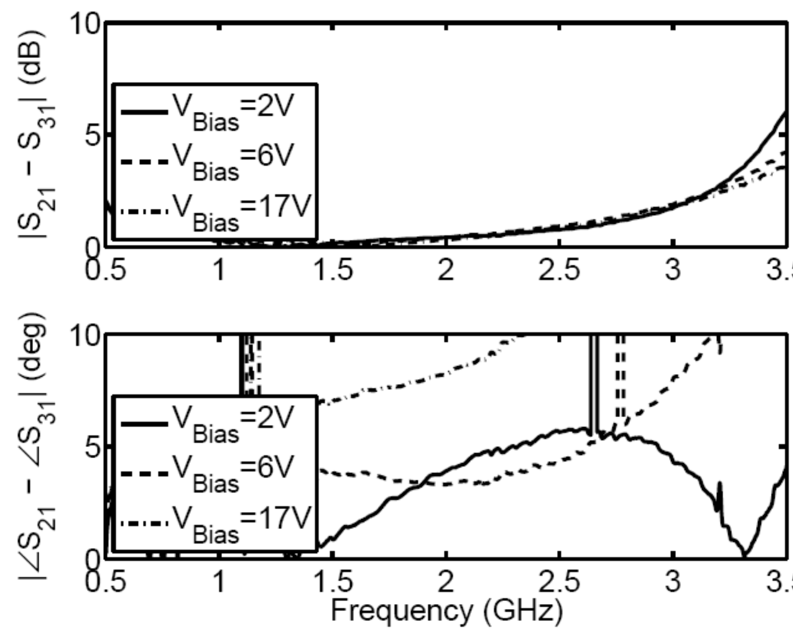


Tunable Wilkinson Divider (1)

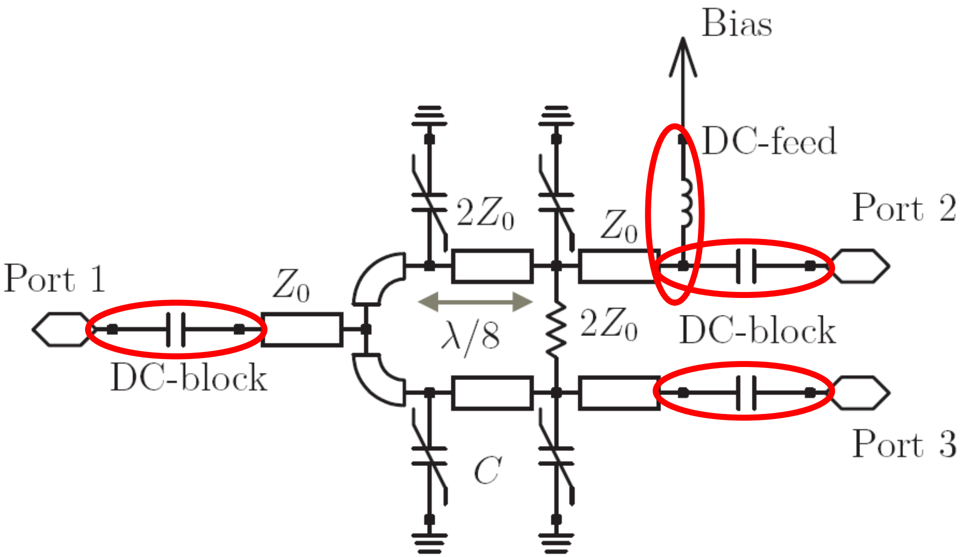


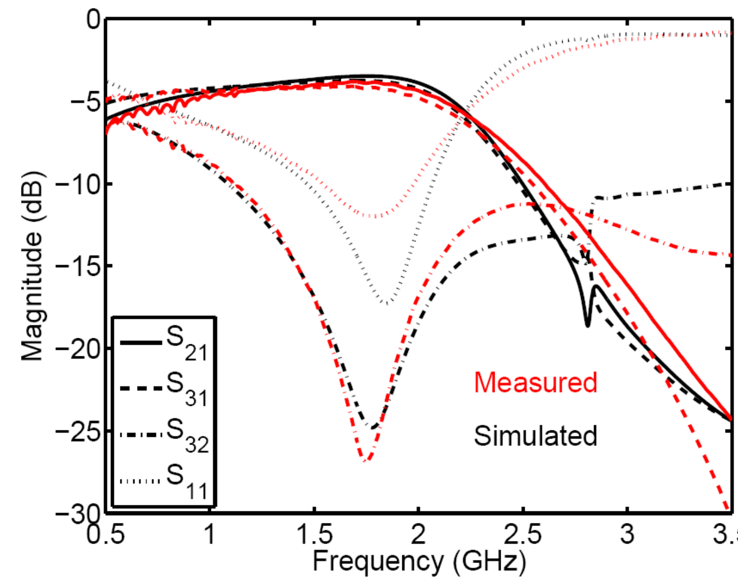




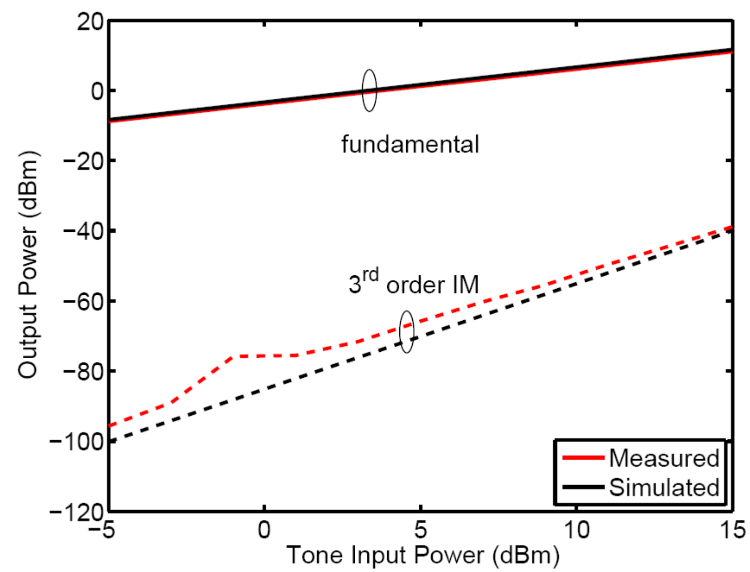


Tunable Wilkinson Divider (2)





- IL < 1.2dB, Isolation > 25dB
- Size reduction 50%
- Lowpass filtering S_{21},S_{31}
- Attenuation > 20dB at $2f_0$
- Tuning range 1.7-2.1GHz



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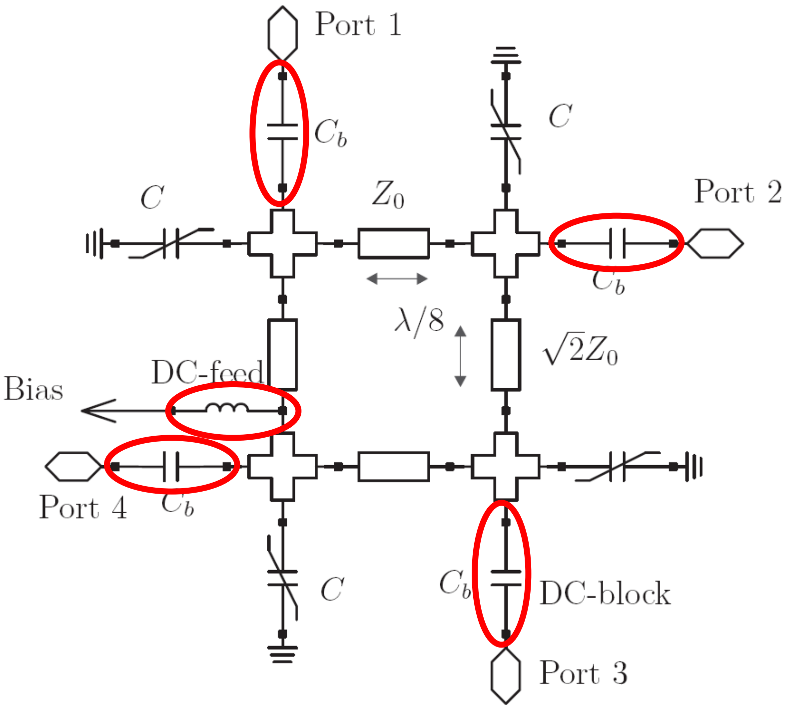
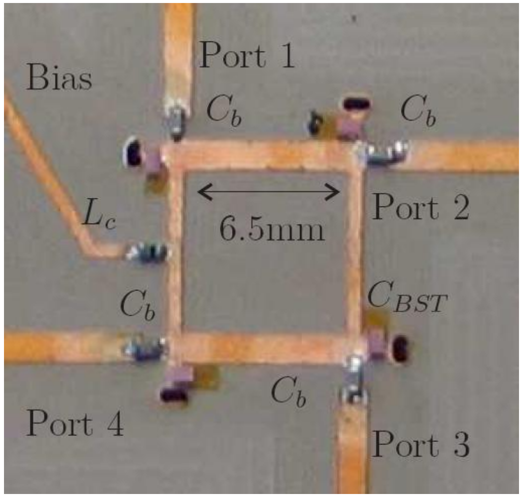
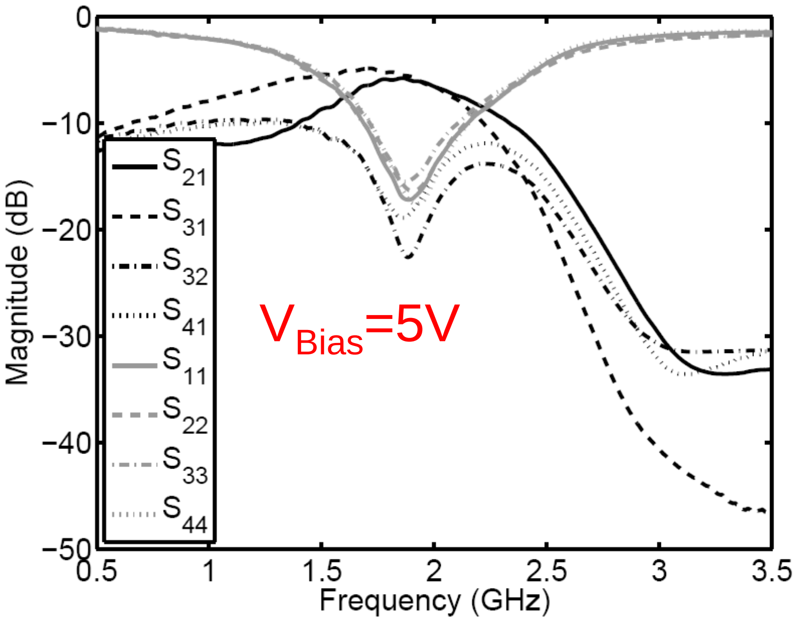
Tunable Branch-Line Coupler (1)

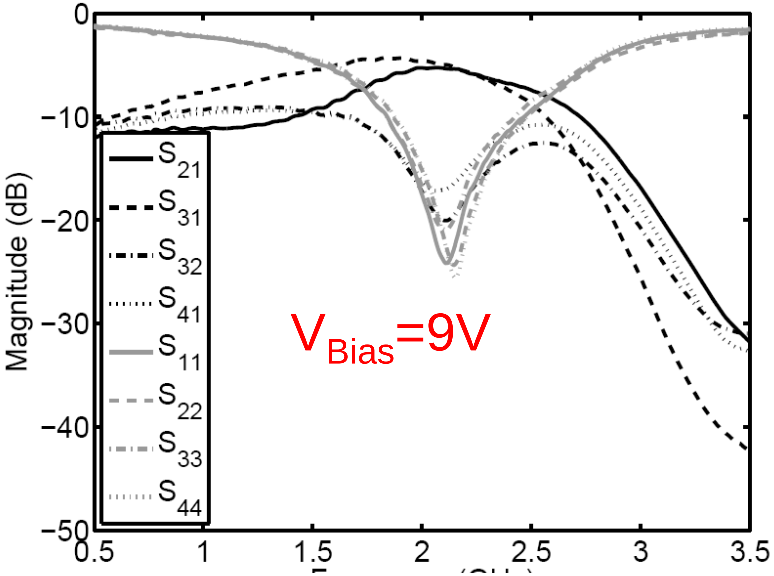


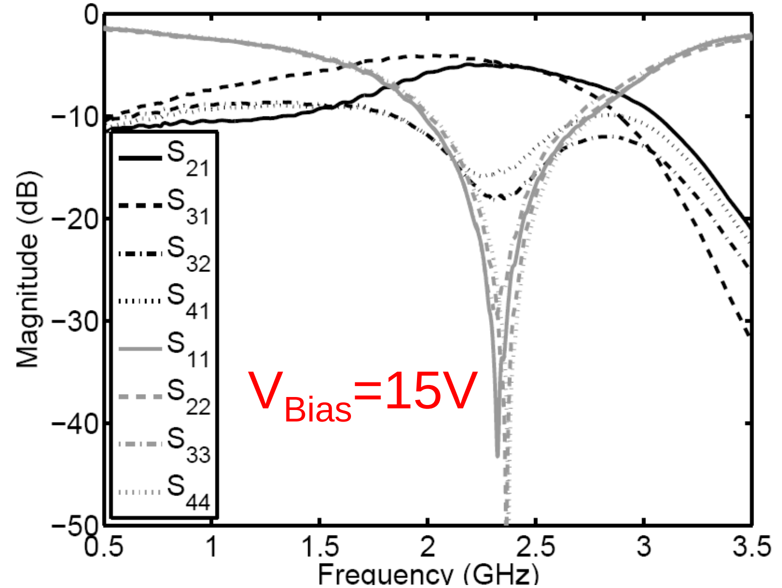


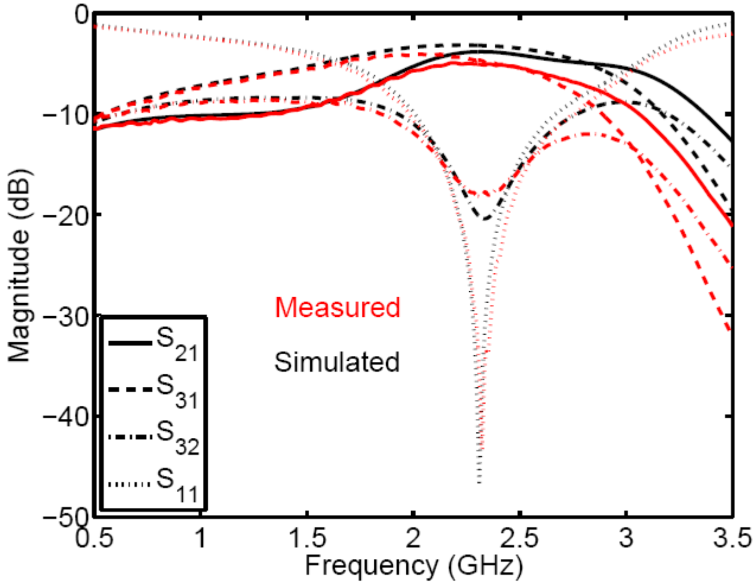


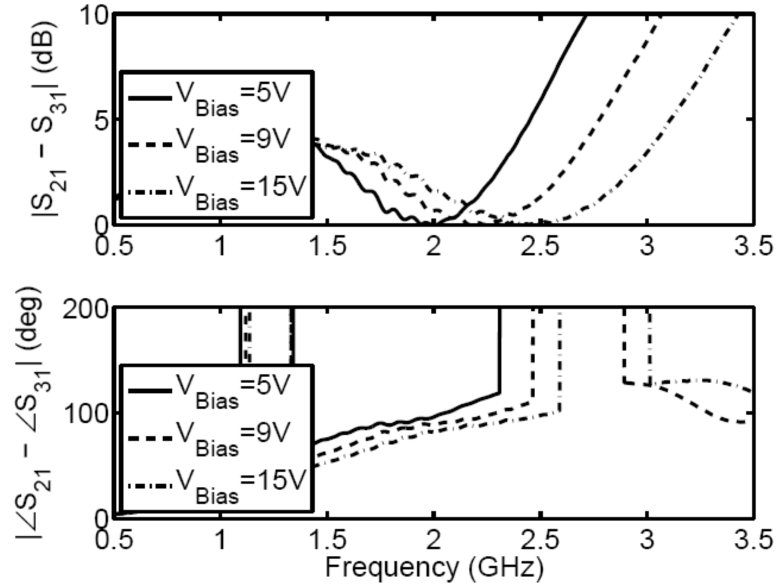
- Size reduction 50%
- Lowpass filtering at all transmission paths
- Attenuation > 30dB at second harmonic

Tunable Branch-Line Coupler (2)

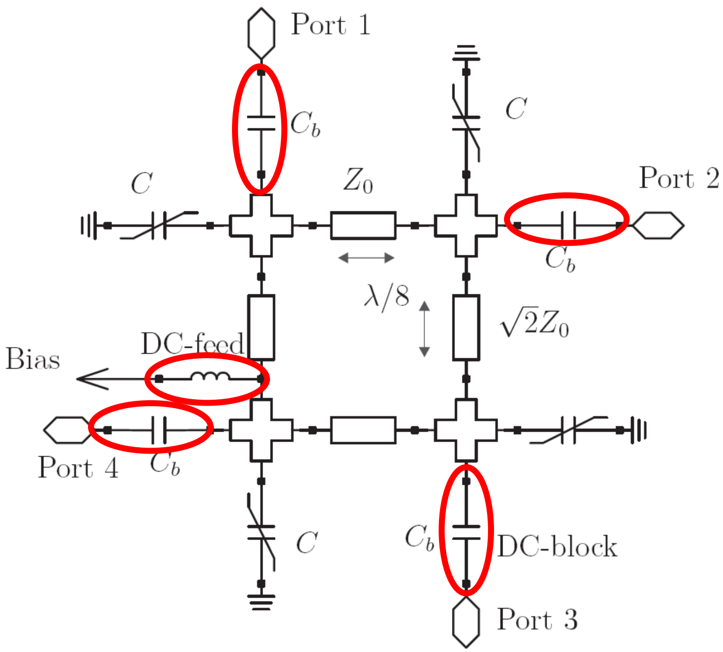


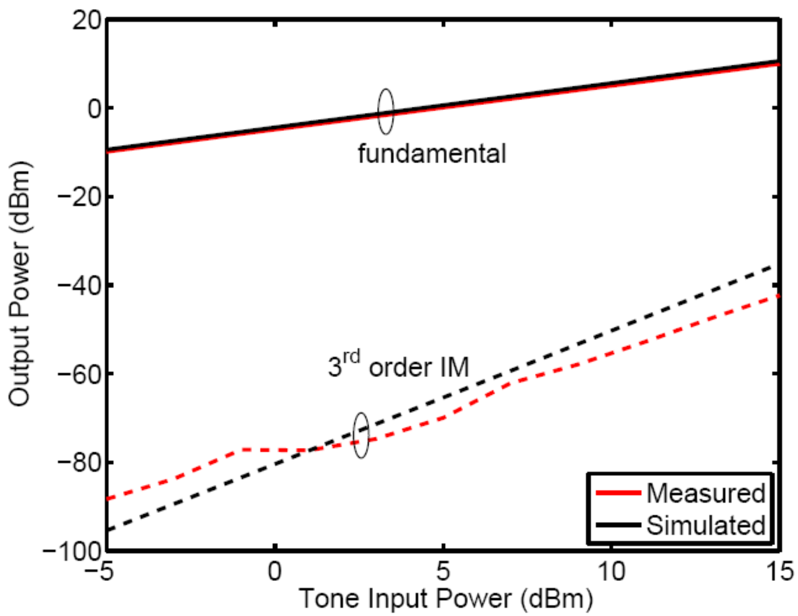




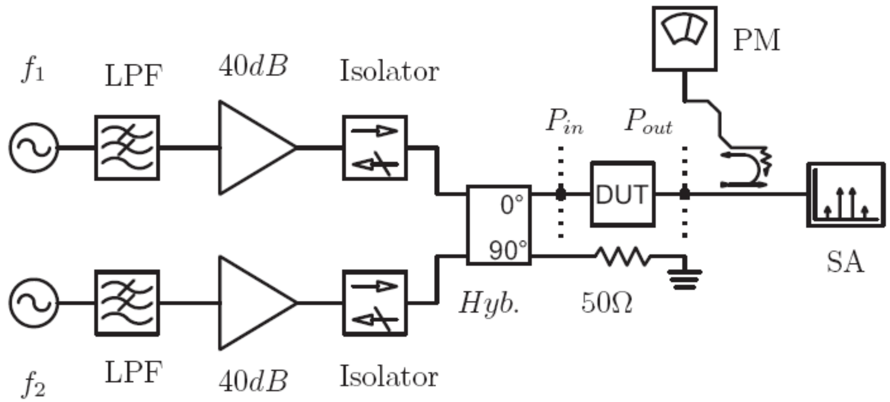


Tunable Branch-Line Coupler (3)





- Tuning range 1.8-2.3GHz
- IL < 2.7dB, RL > 15dB
- Amplitude error < 0.4dB
- Phase error < 5deg

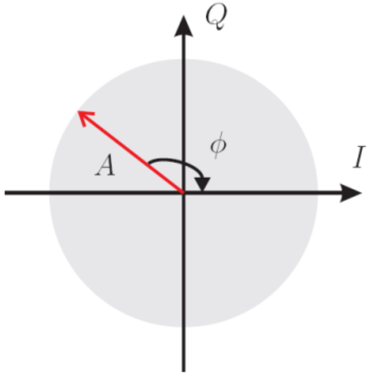


System Considerations – Modulated Signals

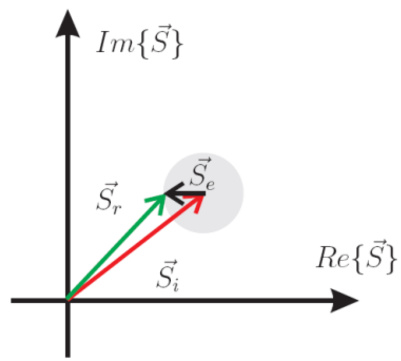
Arbitrary Modulated Signal

$$s(t) = A\cos(\phi)\cos(2\pi f t) - A\sin(\phi)\sin(2\pi f t) = I\cos(2\pi f t) + Q\sin(2\pi f t).$$

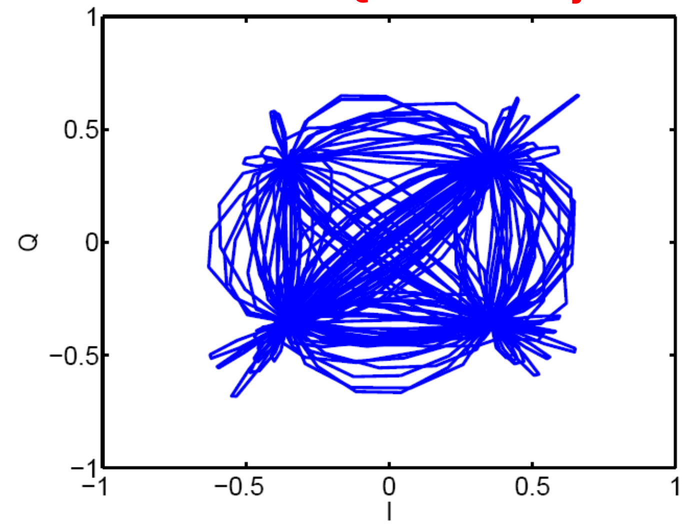
Baseband



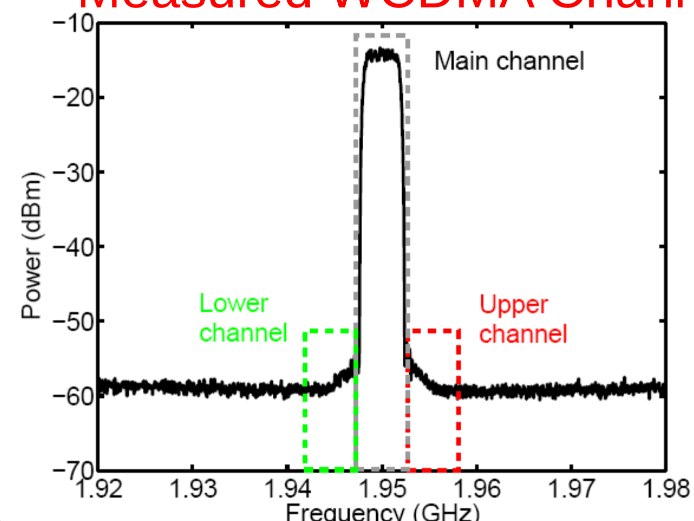
EVM



Measured QPSK Trajectory



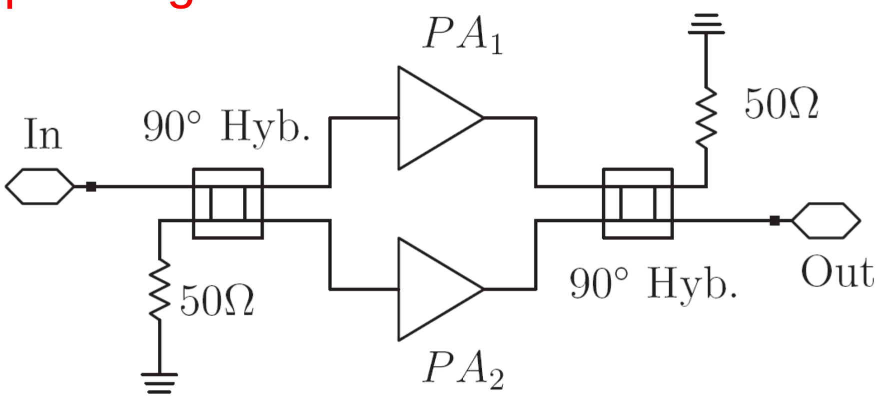
Measured WCDMA Channel

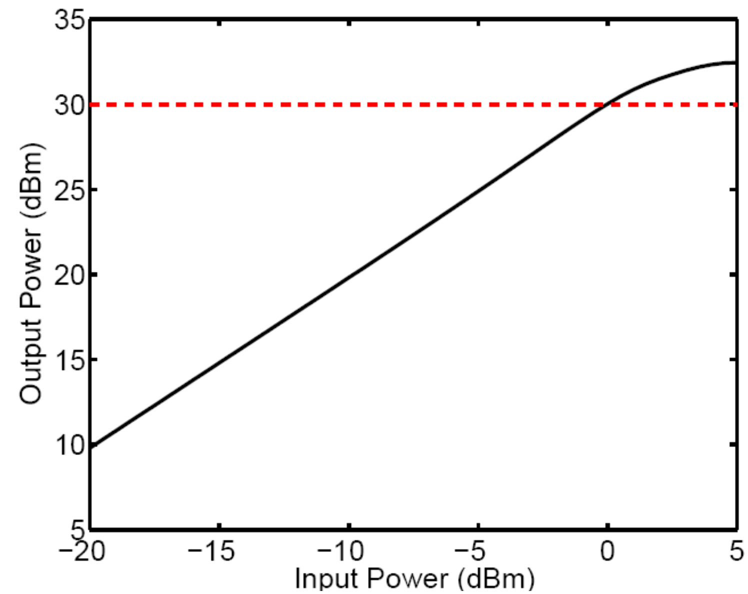


- 3GPP WCDMA signal
- Specified EVM 17,5%
- Specified ACLR 33dB

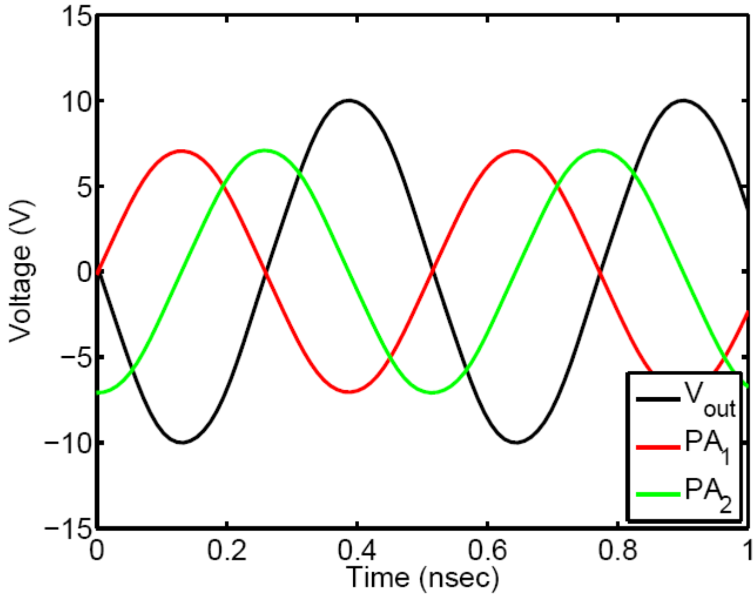
System – Balanced Amplifier

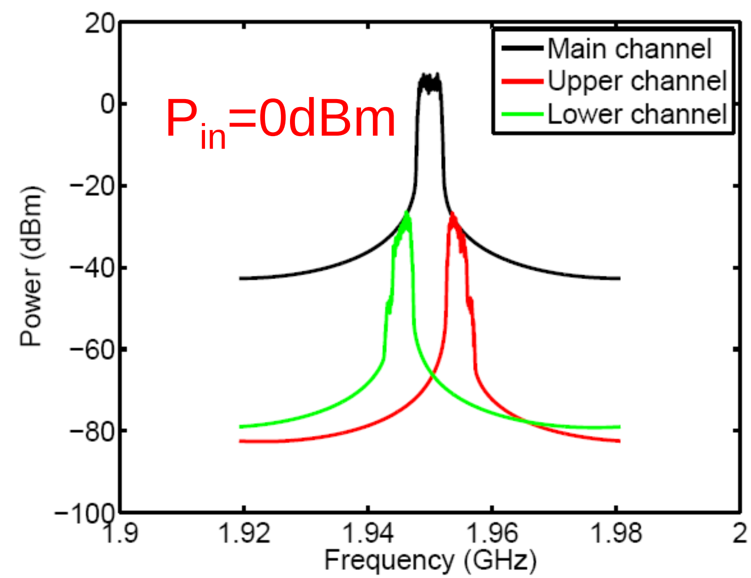
Operating at transmit band f=1.95 GHz





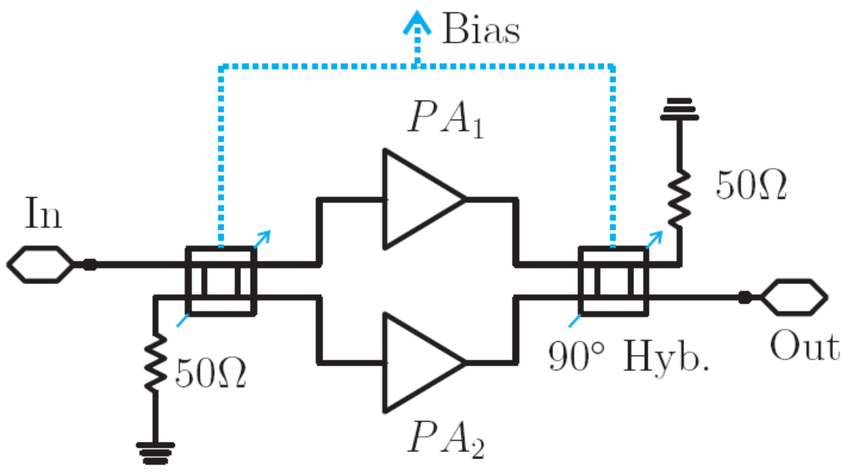
Voltage waveforms at P_{in}=0dBm

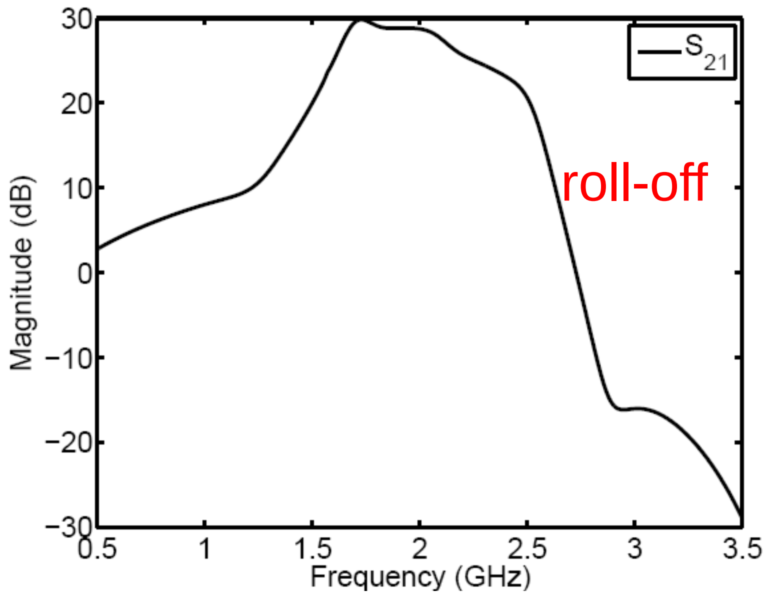


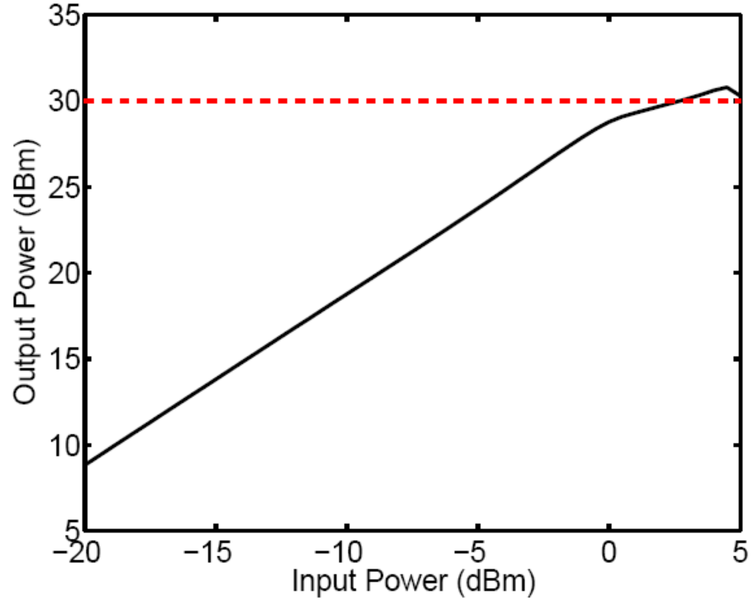


System – Reconfigurable Balanced Amplifier (1)

Operating at transmit band f=1.95 GHz







- Size reduction 50%
- Lowpass filtering
- Increased loss
- Bias voltage 5V
- Strong nonlinearities due to BST-varactors

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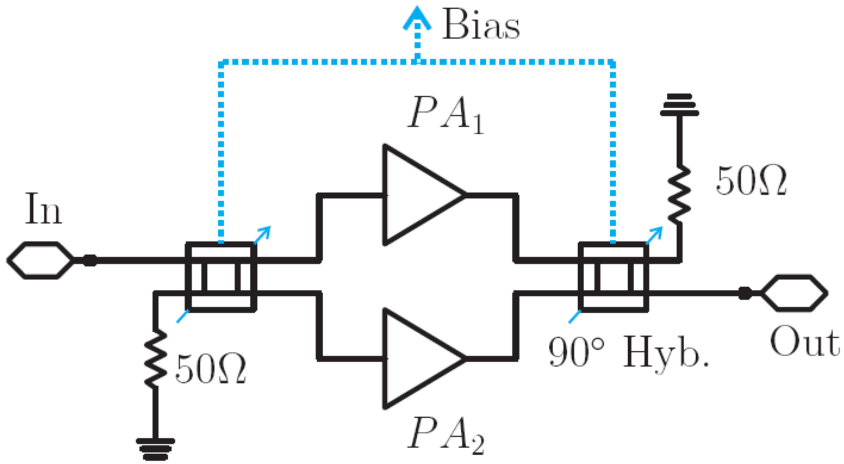
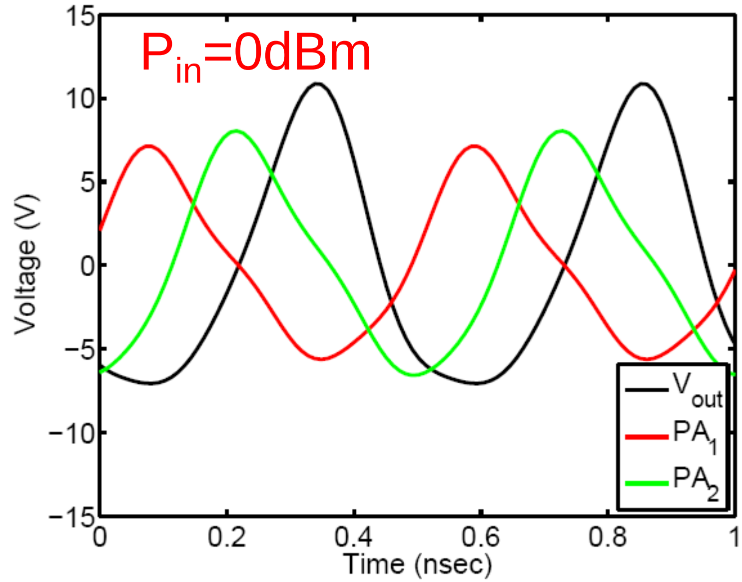
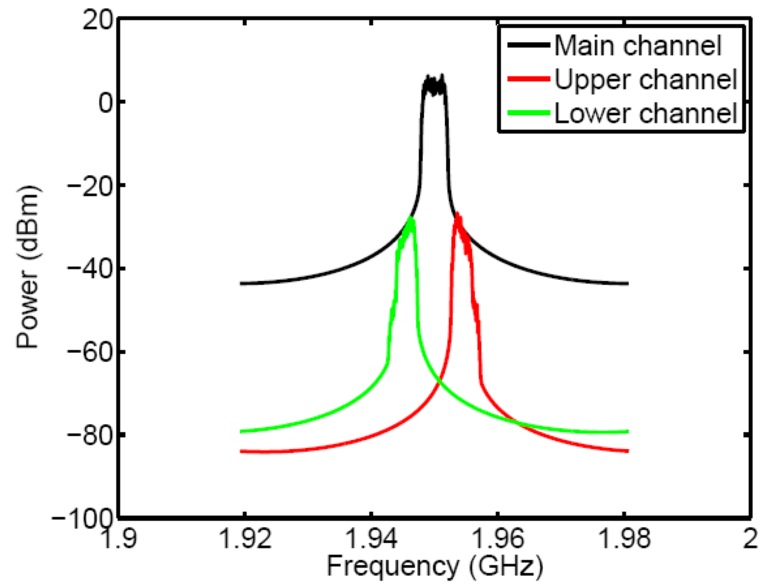
System – Reconfigurable Balanced Amplifier (2)

Operating at transmit band f=1.95 GHz



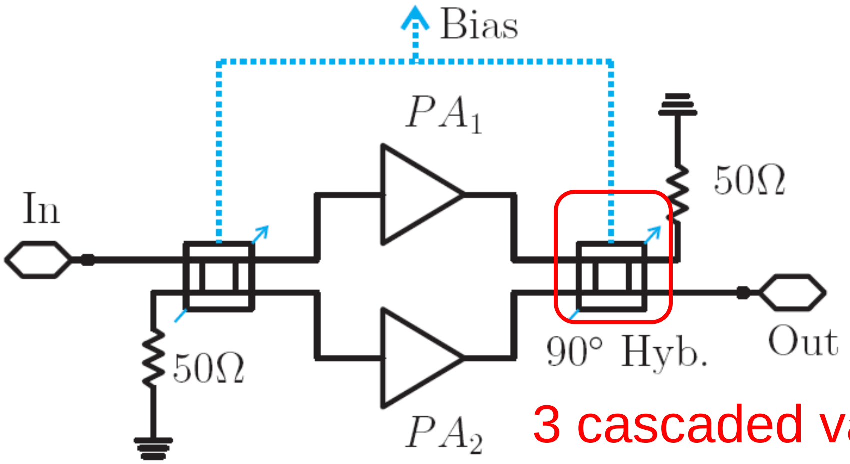




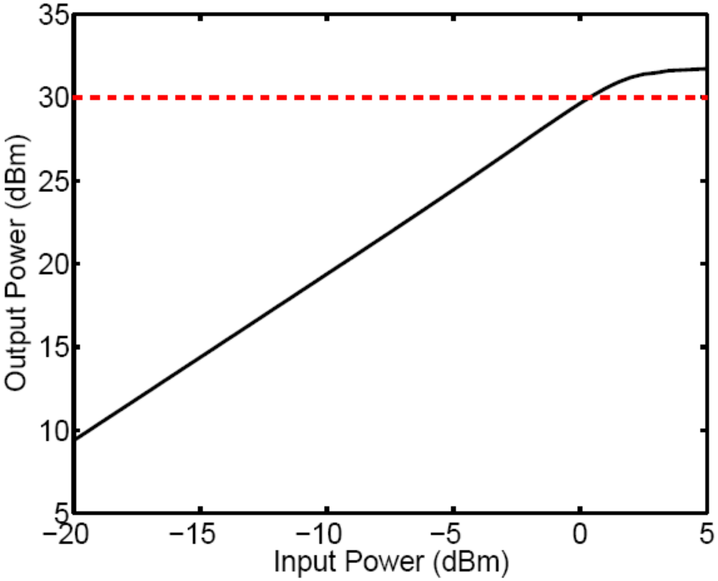
- Distortion at voltage waveforms
- Performance still within specification
- Simulated EVM < 10%
- Simulated ACLR ~ 35dB

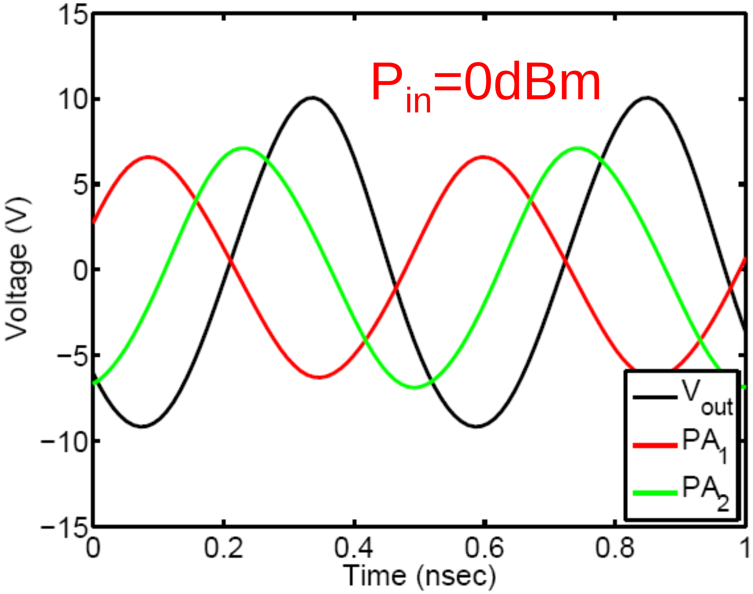
Tunable coupler with 3 cascaded varactors

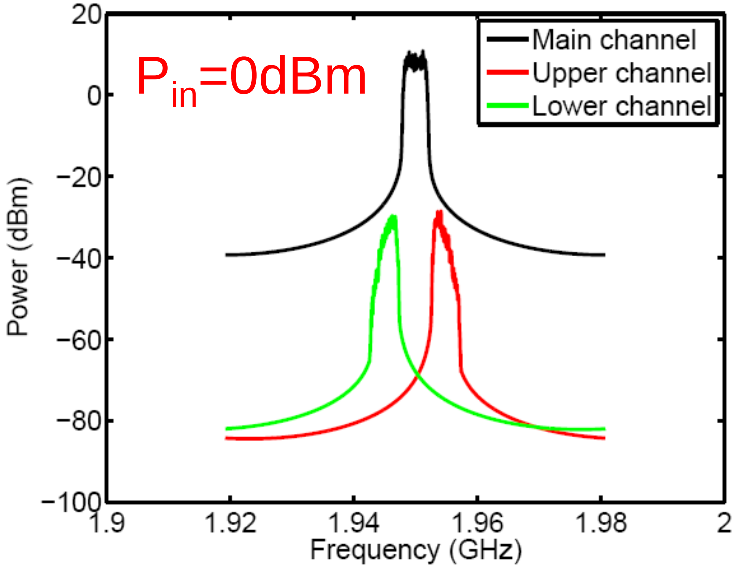
Operating at transmit band f=1.95 GHz



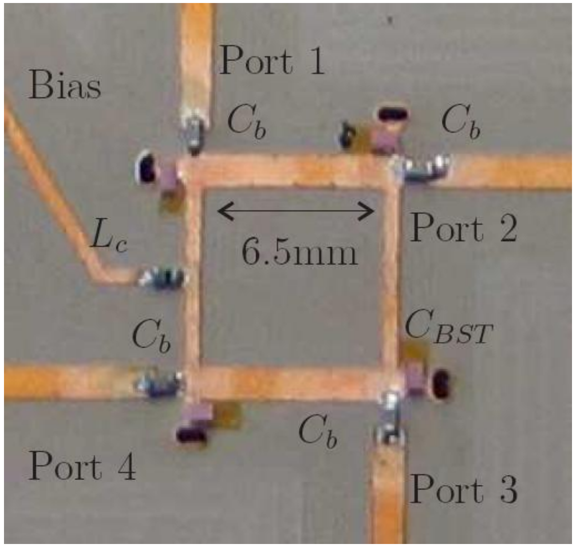
3 cascaded varactors

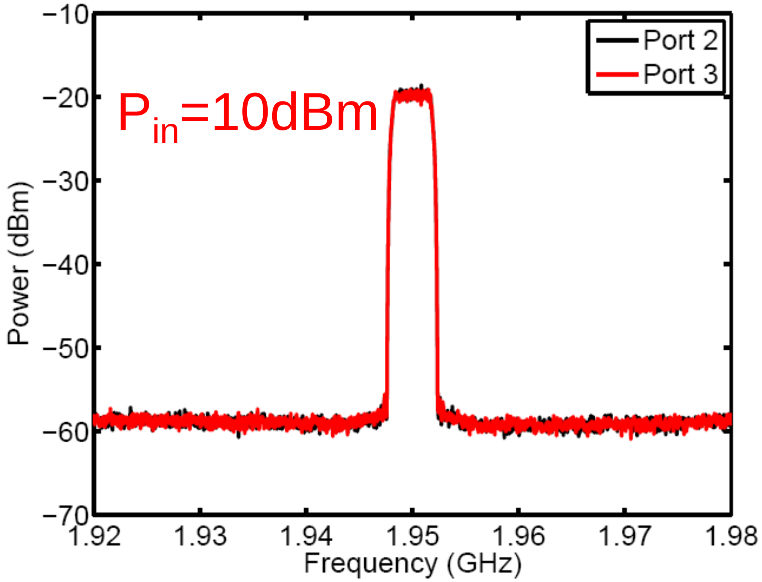


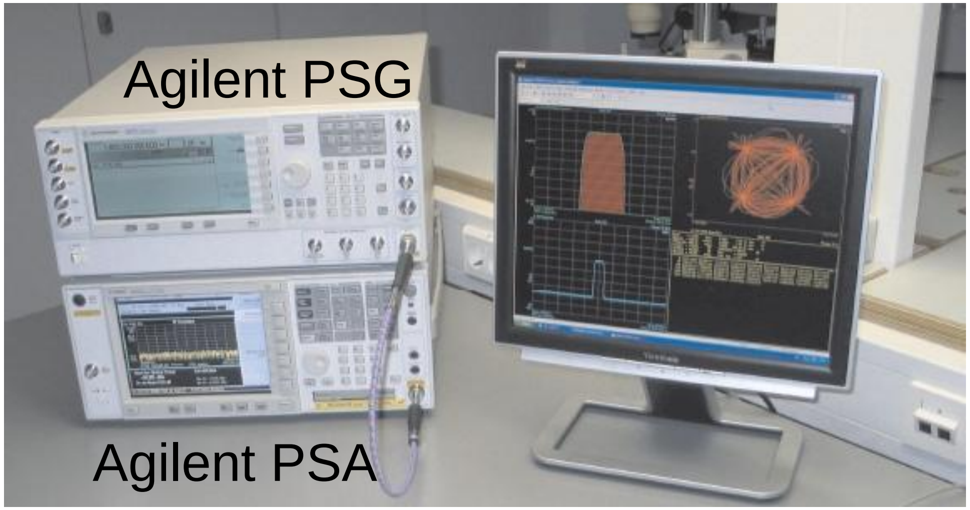


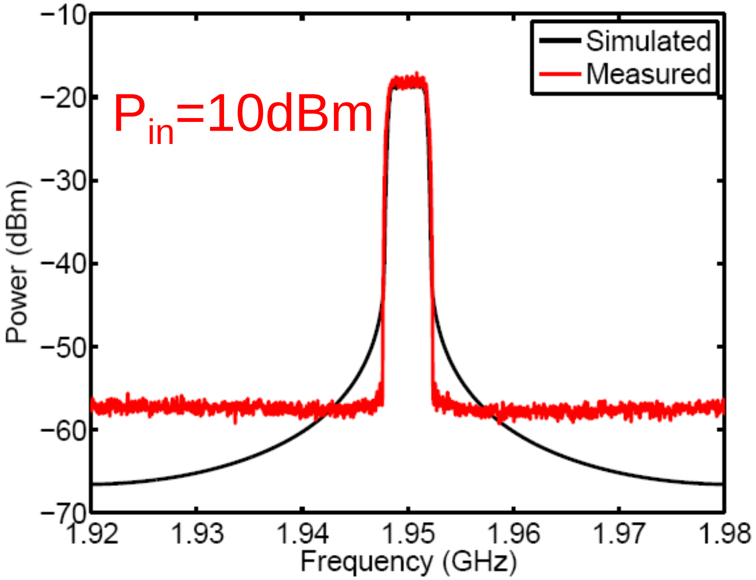


Verification – Tunable Branch-Line Coupler









Conclusion & Outlook

Conclusion

- Potential of ferroelectrics in tunable front-end
- Reliable modeling and characterization
- Candidates for tunable microwave circuits
  - Frequency agile filters
  - Reduced size tunable dividers and couplers
- Prototype implementation & results
- Overall good agreement to simulation

Outlook

- Integration of tunable subsystems into front-end