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VHF and UHF Mechanically Coupled AlN MEMS Filters

Roy H. Olsson III, Cody Washburn, James E. Stevens, Melanie R. Tuck and Christopher Nordquist

Sandia National Laboratories, Albuquerque NM

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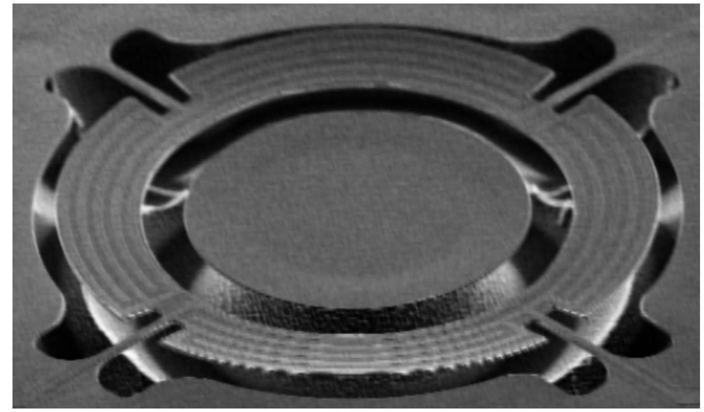
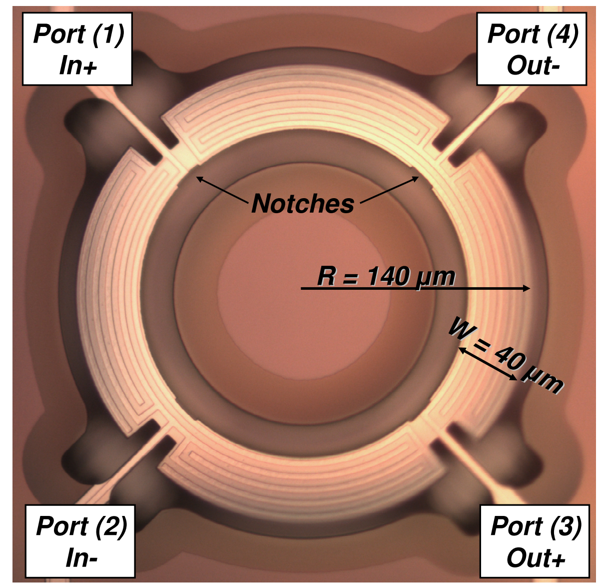
Outline

- Background and Motivation
  - *MEMS Filter Motivation*
  - *Mechanically Coupled Filter Architecture*
  - *Low Impedance Piezoelectric Transduction*
- VHF Mechanically Coupled Ring Resonator Filters
  - *100 MHz Mechanically Coupled Filter Measurements*
  - *Filter Temperature Sensitivity and Compensation*
- UHF Overtone Mechanically Coupled Ring Resonator Filters
  - *Filter Design and Measured Results*
  - *Performance Discussion*
- Conclusions and Acknowledgements

Piezoelectric MEMS Filter Research

- MEMS Filters
  - *Small*
  - *Many Frequencies on a Single Chip*
  - *Greater Coupling per Area for the VHF and a Portion of the UHF Band*
- Miniature High-Selectivity Filters and Filter Banks not Available in Commodity Driven Wireless Market
  - *RF Filters in Non-Commercial Bands*
  - *Miniature SAW IF Filter Replacement*
  - ***Filter Banks for Spectrum Analysis and Cognitive Radios***
    - Electrically Coupled Filters
    - Dual Mode Filters
    - ***Mechanically Coupled Filters***





5th Overtone Dual Mode Filter Images

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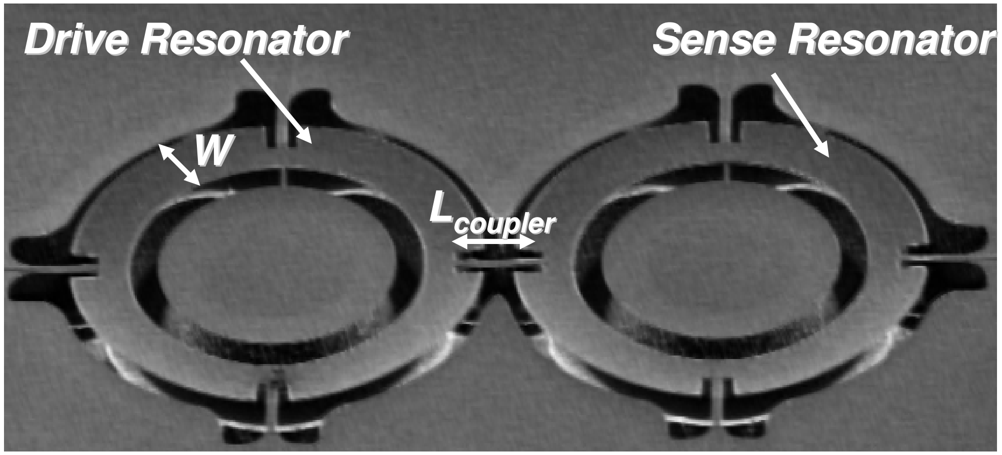
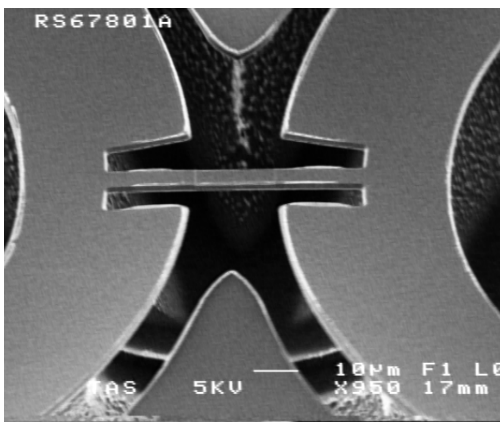
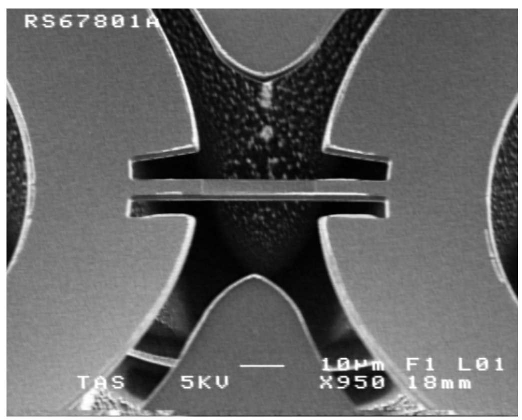
Filter Architecture and Design

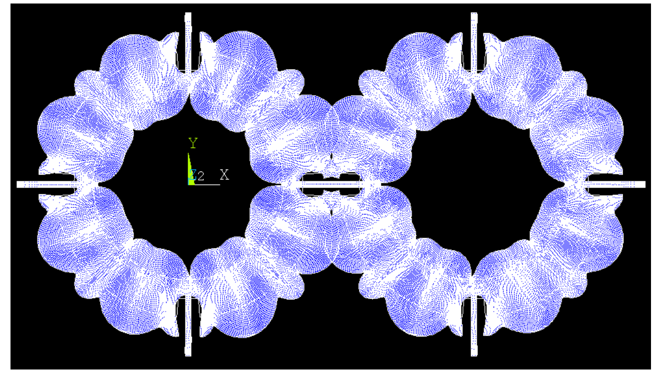




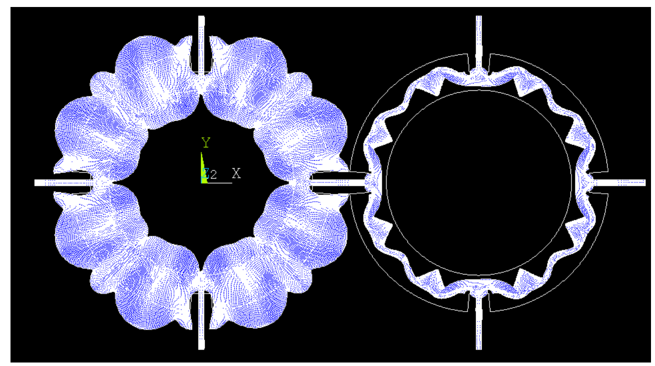
Narrowest Bandwidth when Coupled at Ring Center



Increase Bandwidth by Moving to Higher Velocity Coupling



f_{mode0}



f_{mode1}

Narrow Bandwidth MEMS Filter Architecture 1st Reported in PolySi by Li et al, Ultrasonics Symposium 2005

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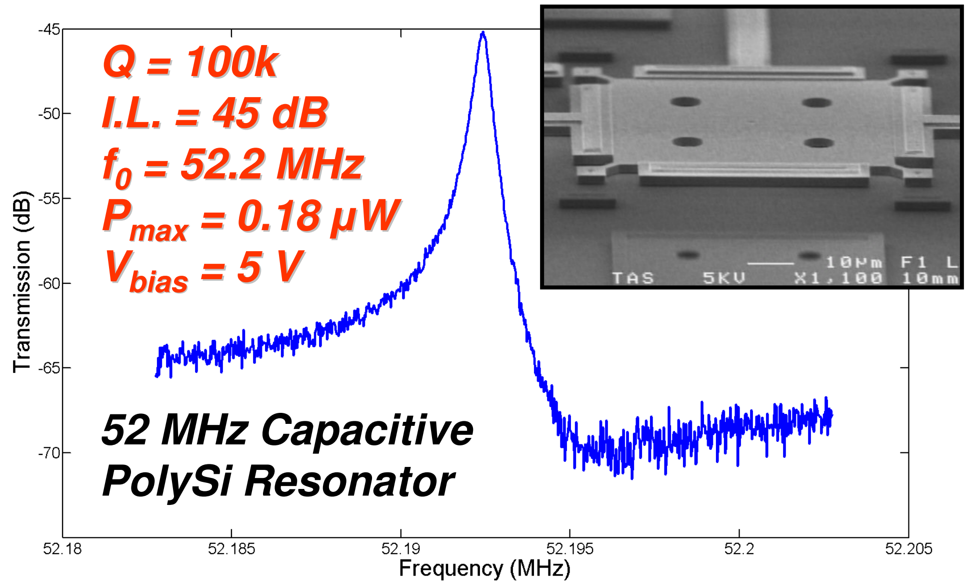
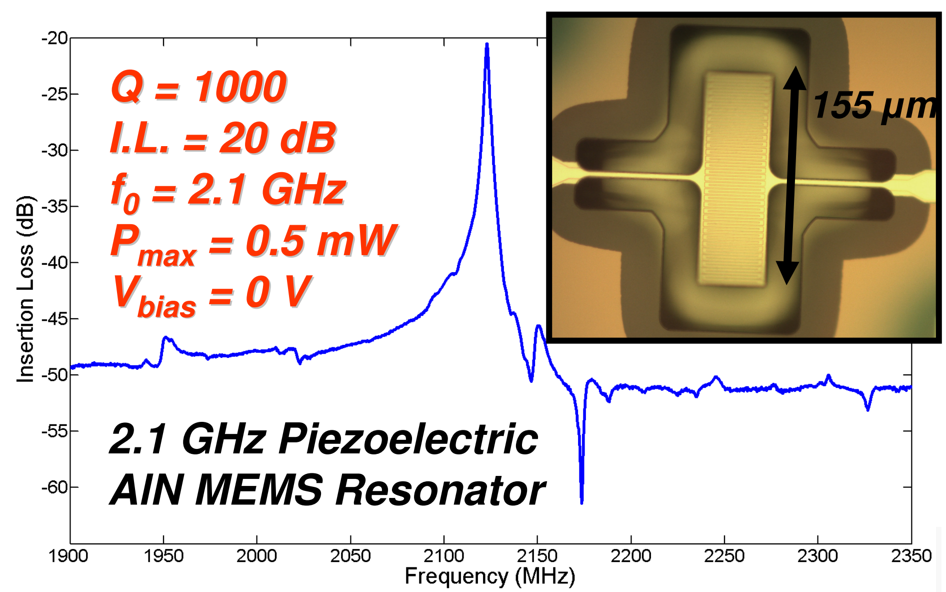
Piezoelectric Transduction

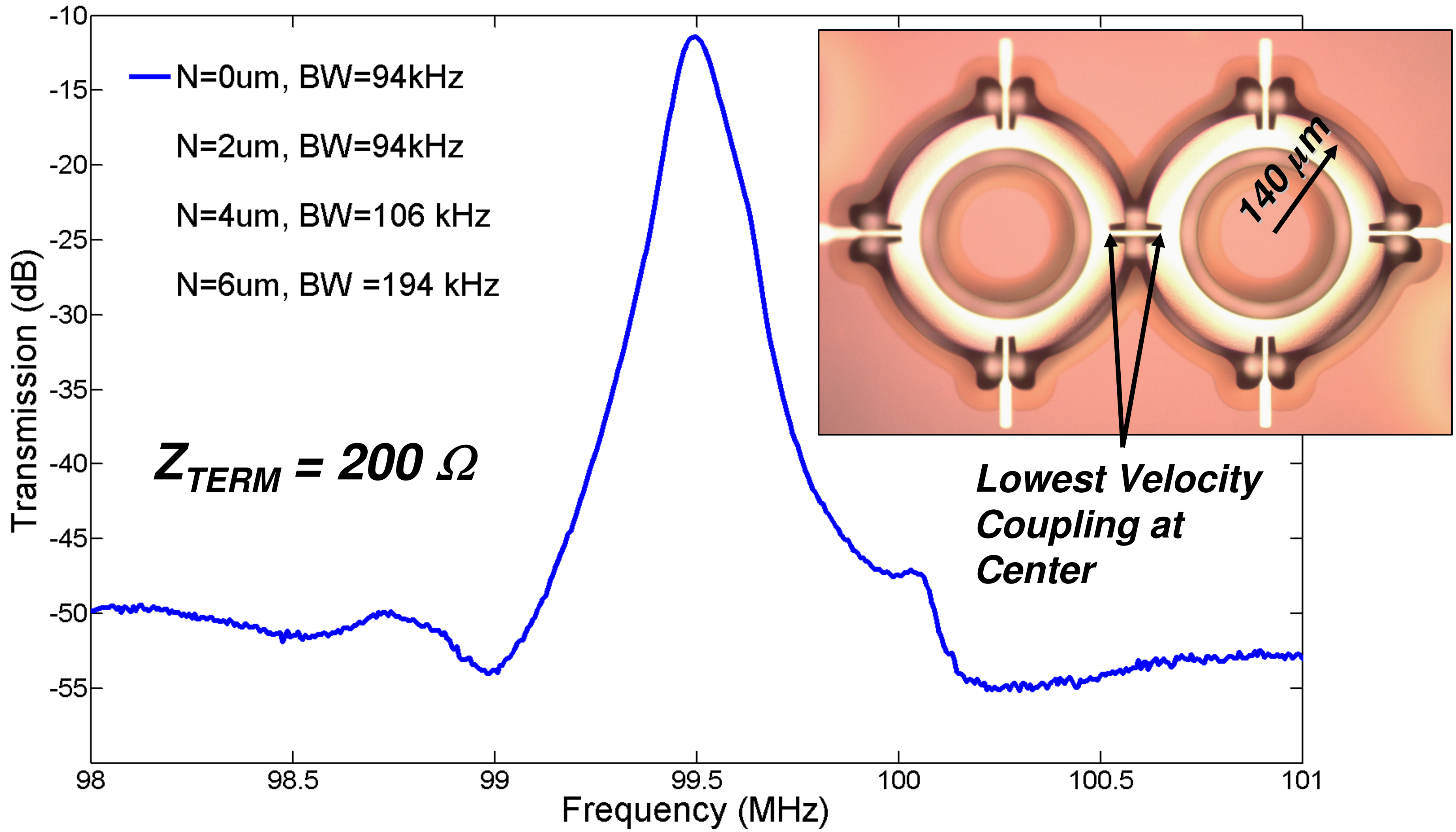
- **Capacitive Resonators**
  - High Impedance (20 kΩ)
  - High-Q (100k)
  - Force ≈ V^2
  - Low Power Handling (0.2 μW)
  - PolySi not Post-CMOS Compatible (High Temp.)



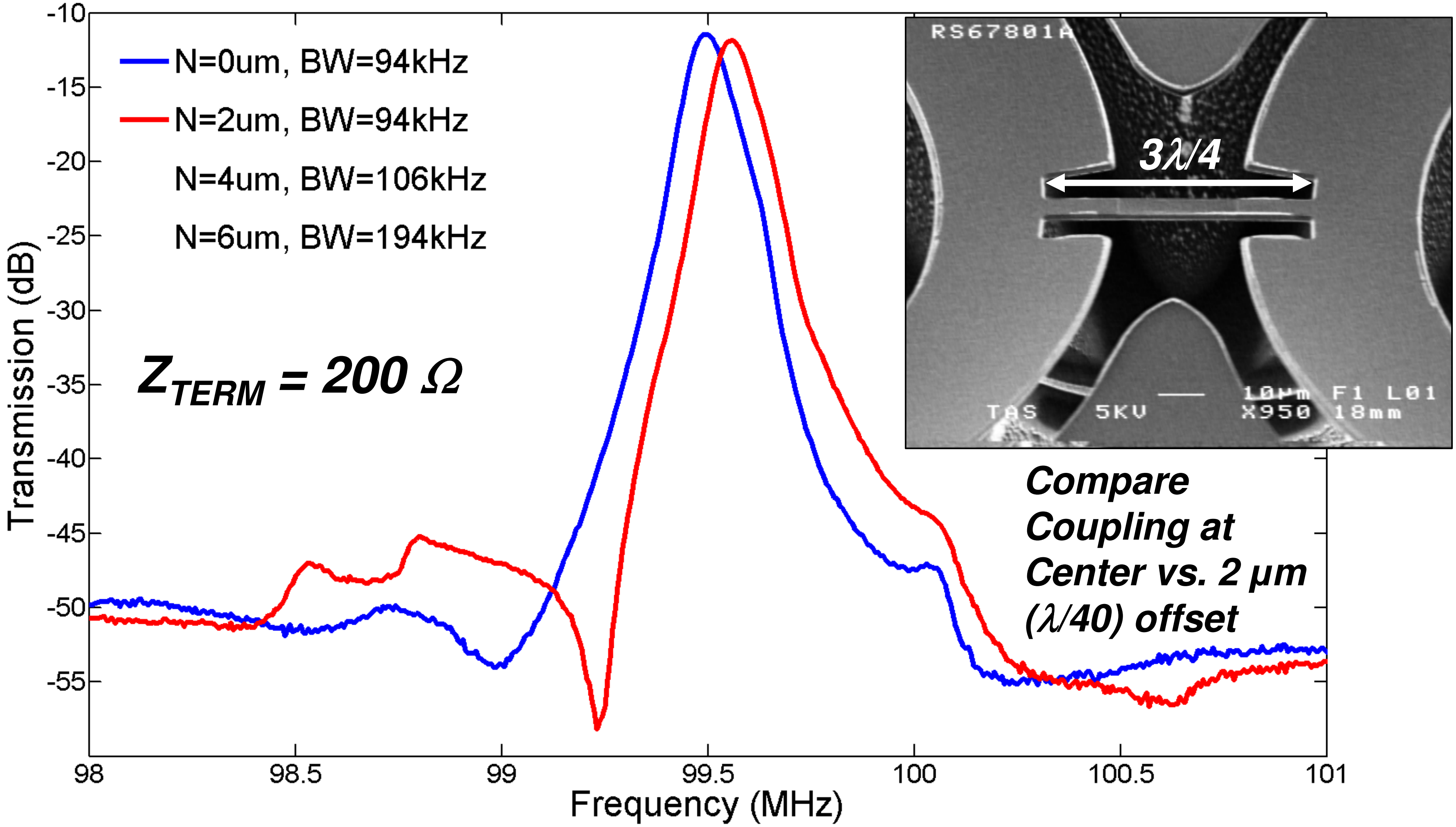
- **Piezoelectric Resonators**
  - Low Impedance (1 kΩ)
  - Lower Q (1000)
  - Force ≈ V
  - High Power Handling (0.5 mW)
  - AlN Post-CMOS Compatible



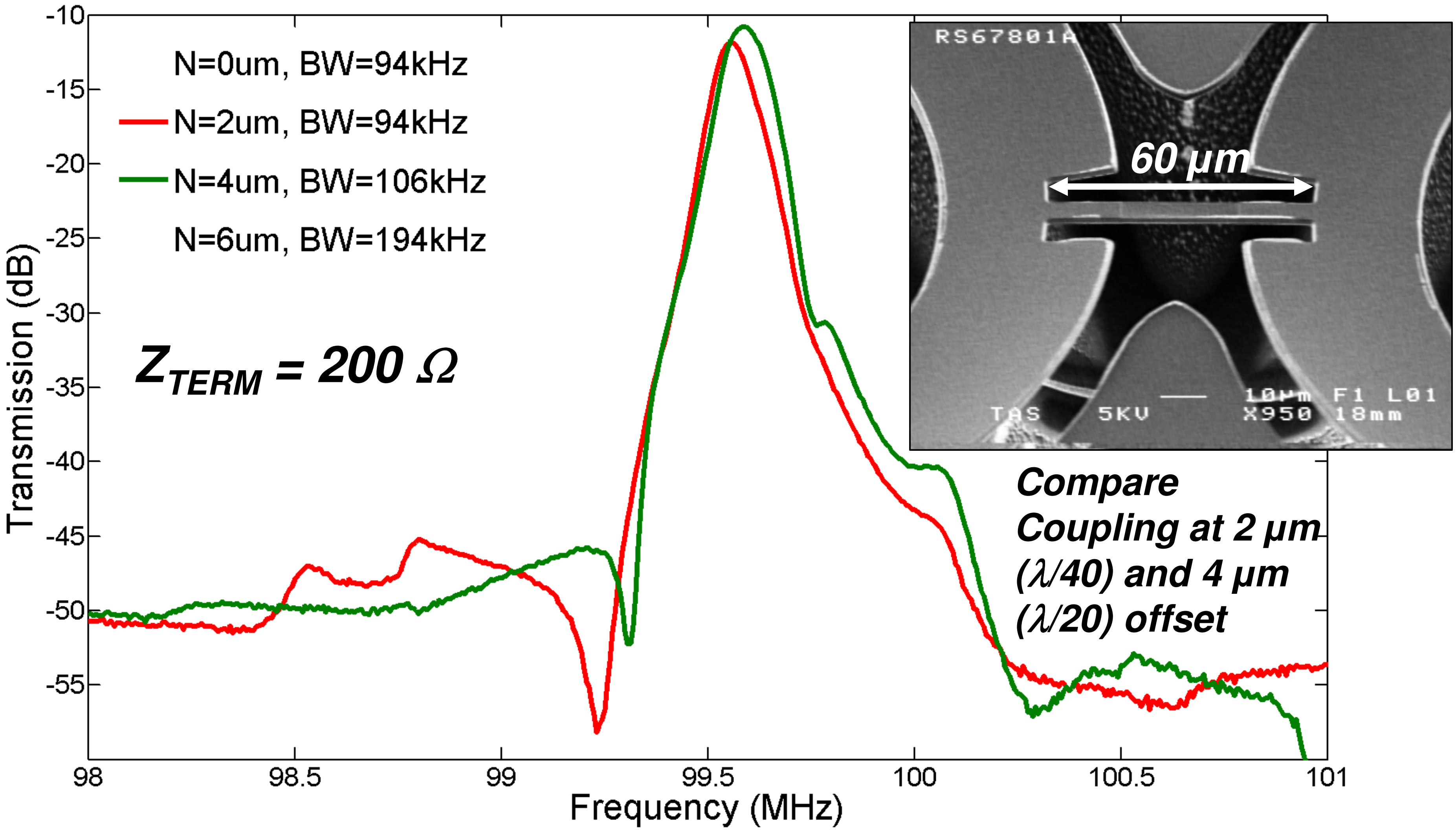
Measured Results



Measured Results



Measured Results



Compare Coupling at 2 µm (λ/40) and 4 µm (λ/20) offset

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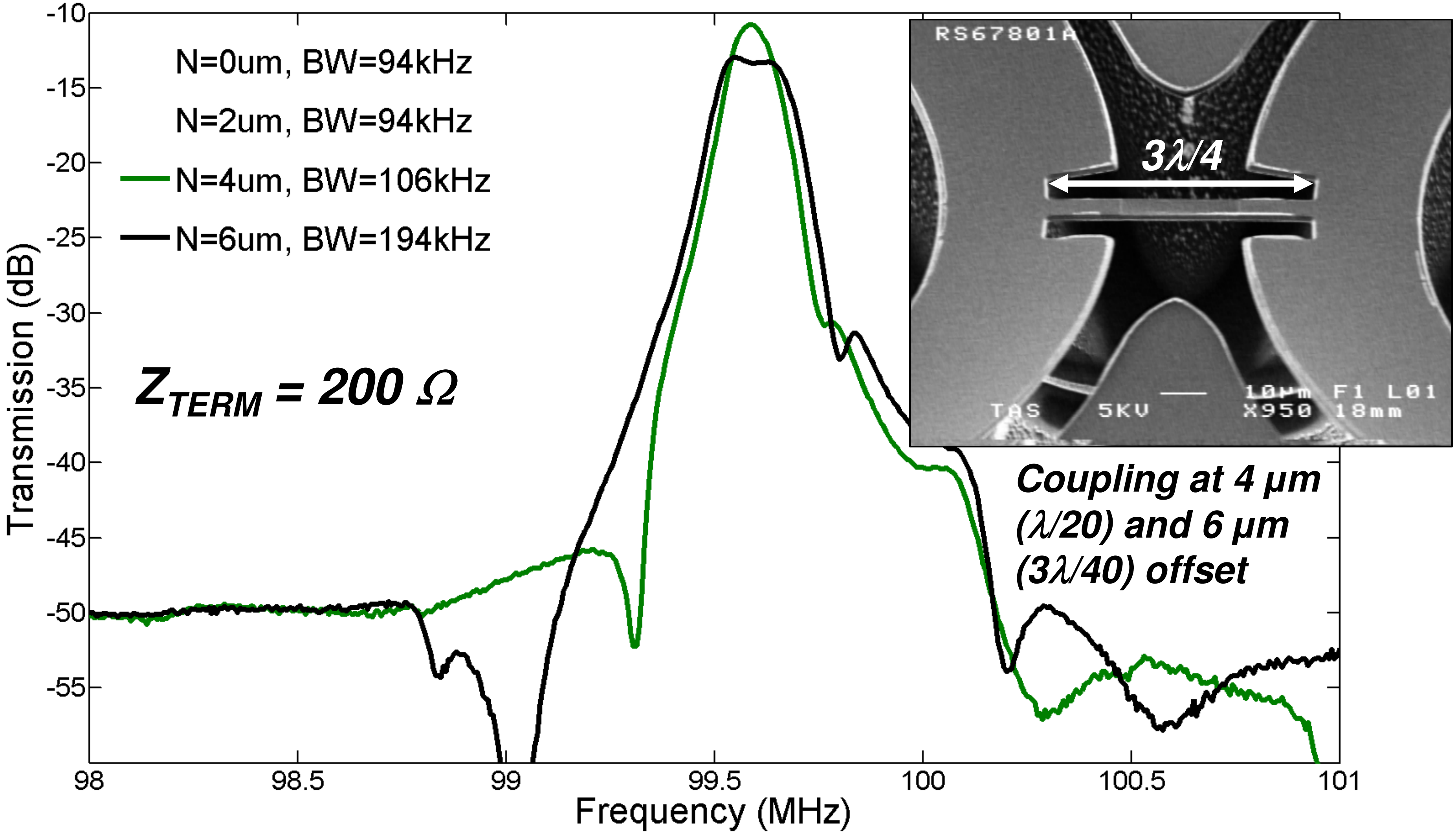
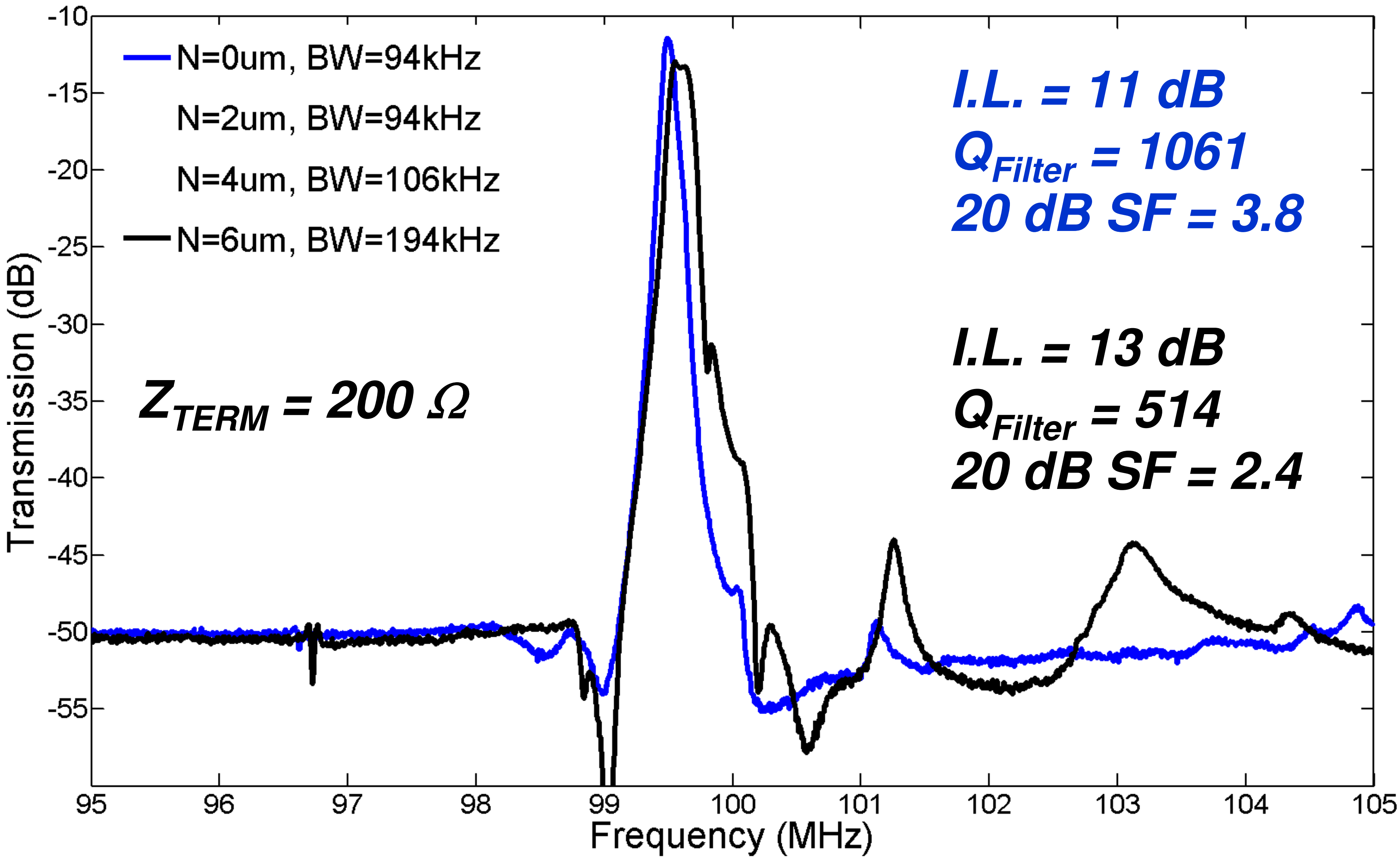
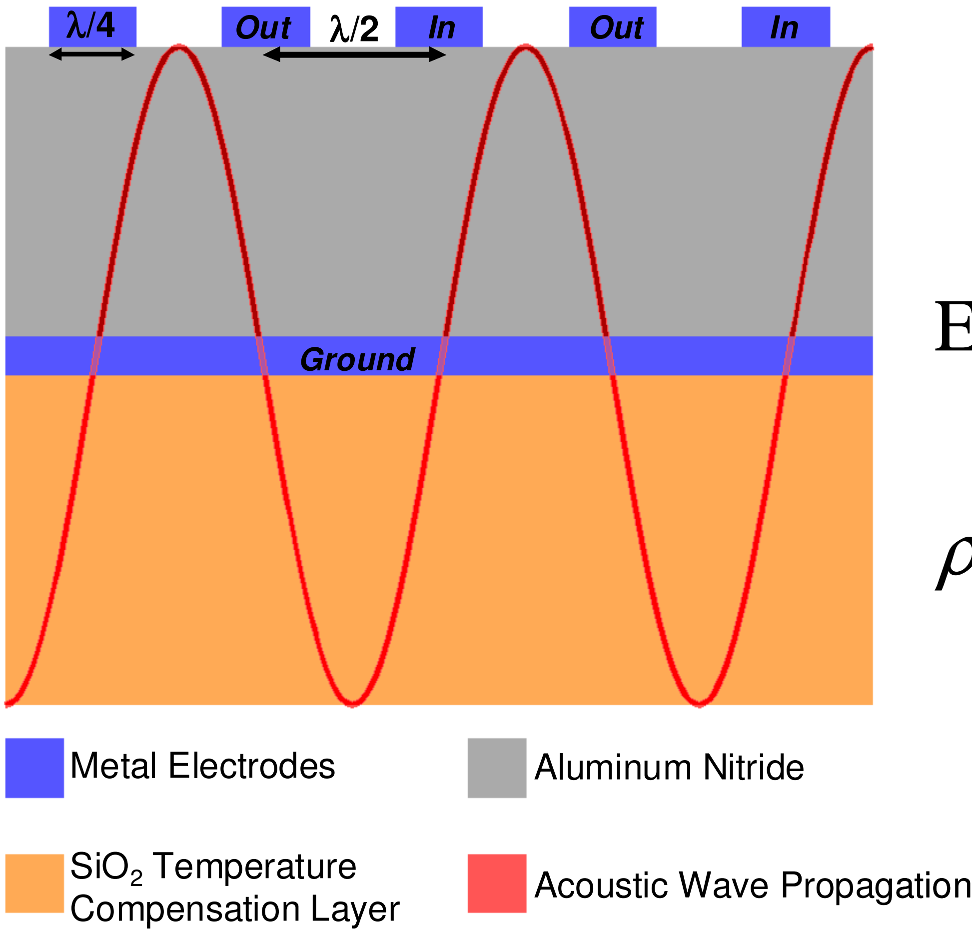
Measured Results



Wideband Measured Results



Filter Temperature Stability and Compensation



Resonator Cross-section

$$f_0 \approx \sqrt{\frac{E}{\rho}}$$

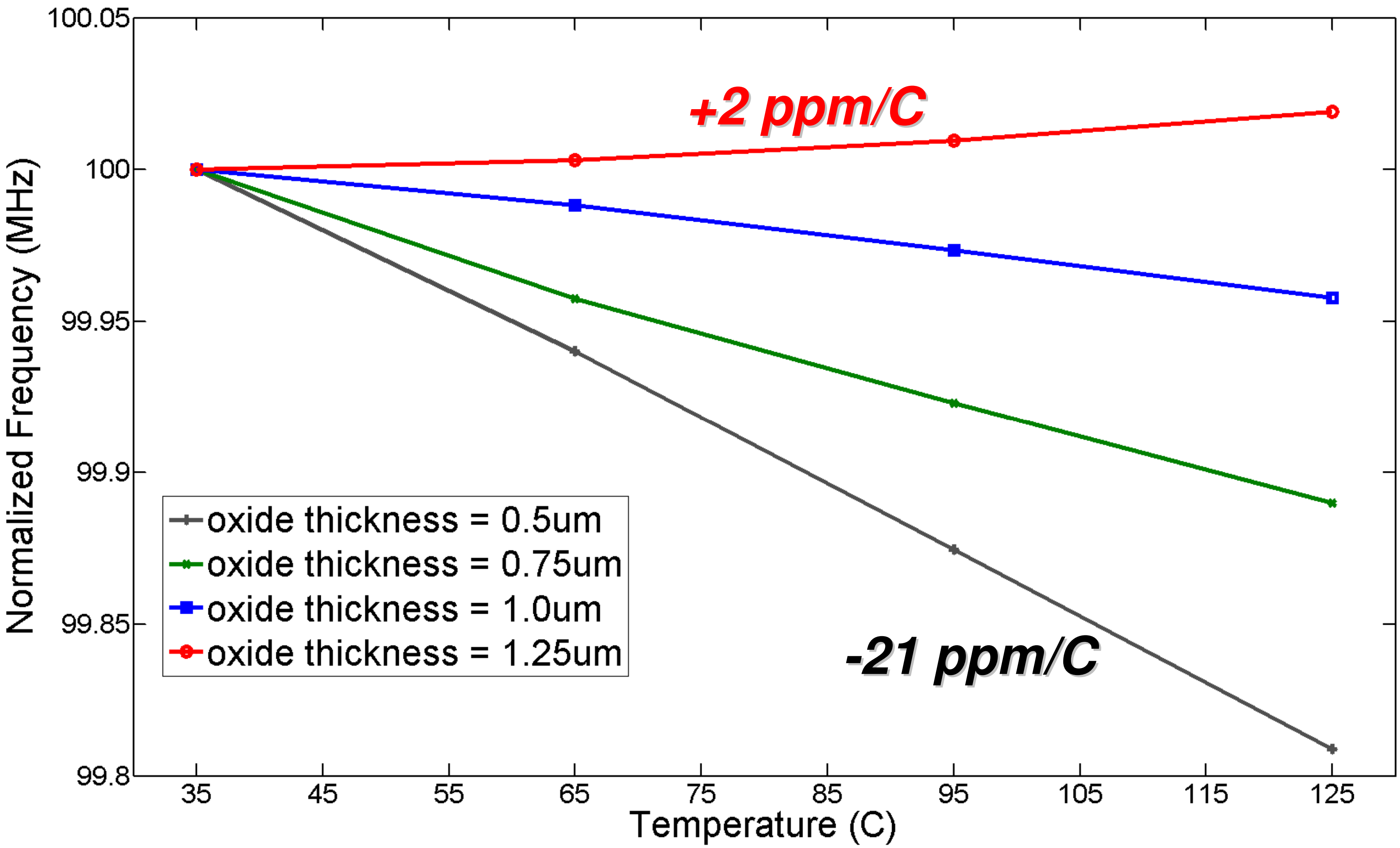
$$E_{TOTAL} = \frac{(E_{AlN} t_{AlN} + E_{oxide} t_{oxide})}{t_{AlN} + t_{oxide}}$$

$$\rho_{TOTAL} = \frac{(\rho_{AlN} t_{AlN} + \rho_{oxide} t_{oxide})}{t_{AlN} + t_{oxide}}$$

$$E_{AlN} \approx -65\, ppm/K$$

$$E_{oxide} \approx +185\, ppm/K$$

Temperature Stability vs. Oxide Thickness



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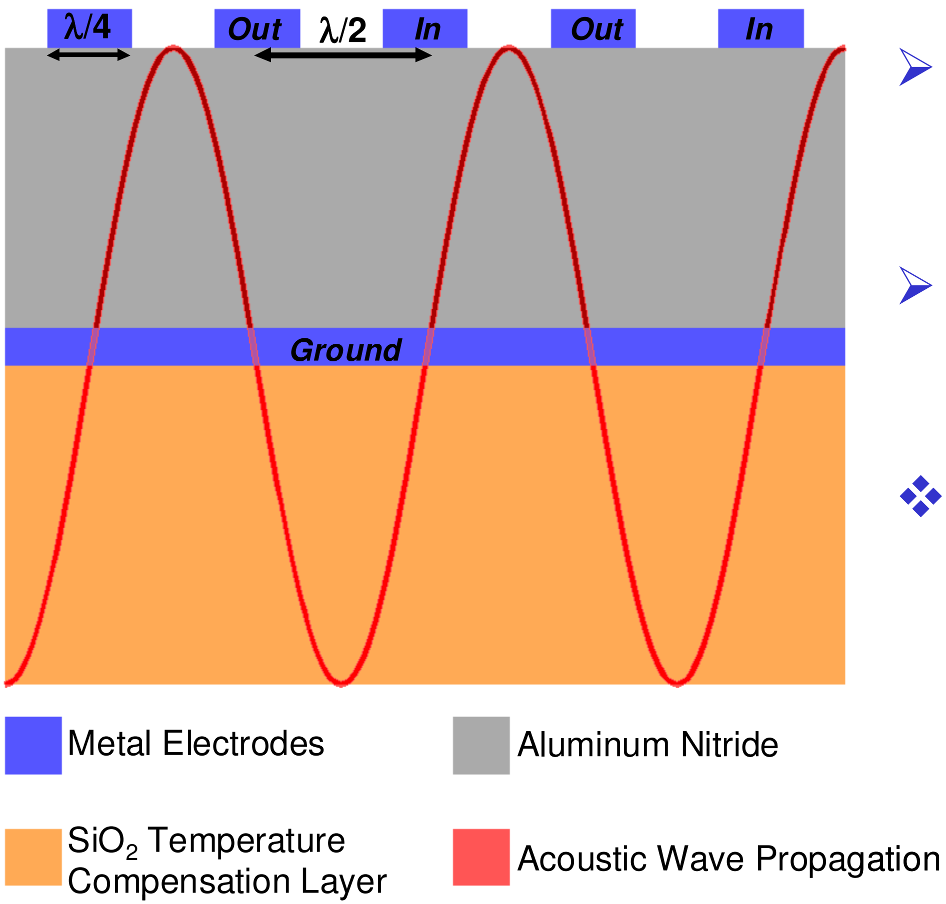
Temperature Compensation Limits



Resonator Cross-section

AlN Thickness Control

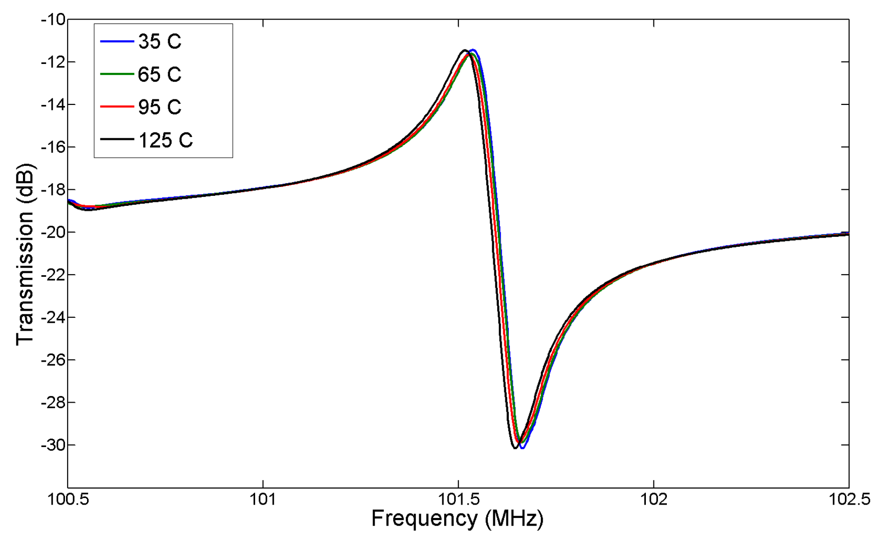
- Wafer to Wafer

$$\sigma_{thickness}(AlN) = 0.2\%$$

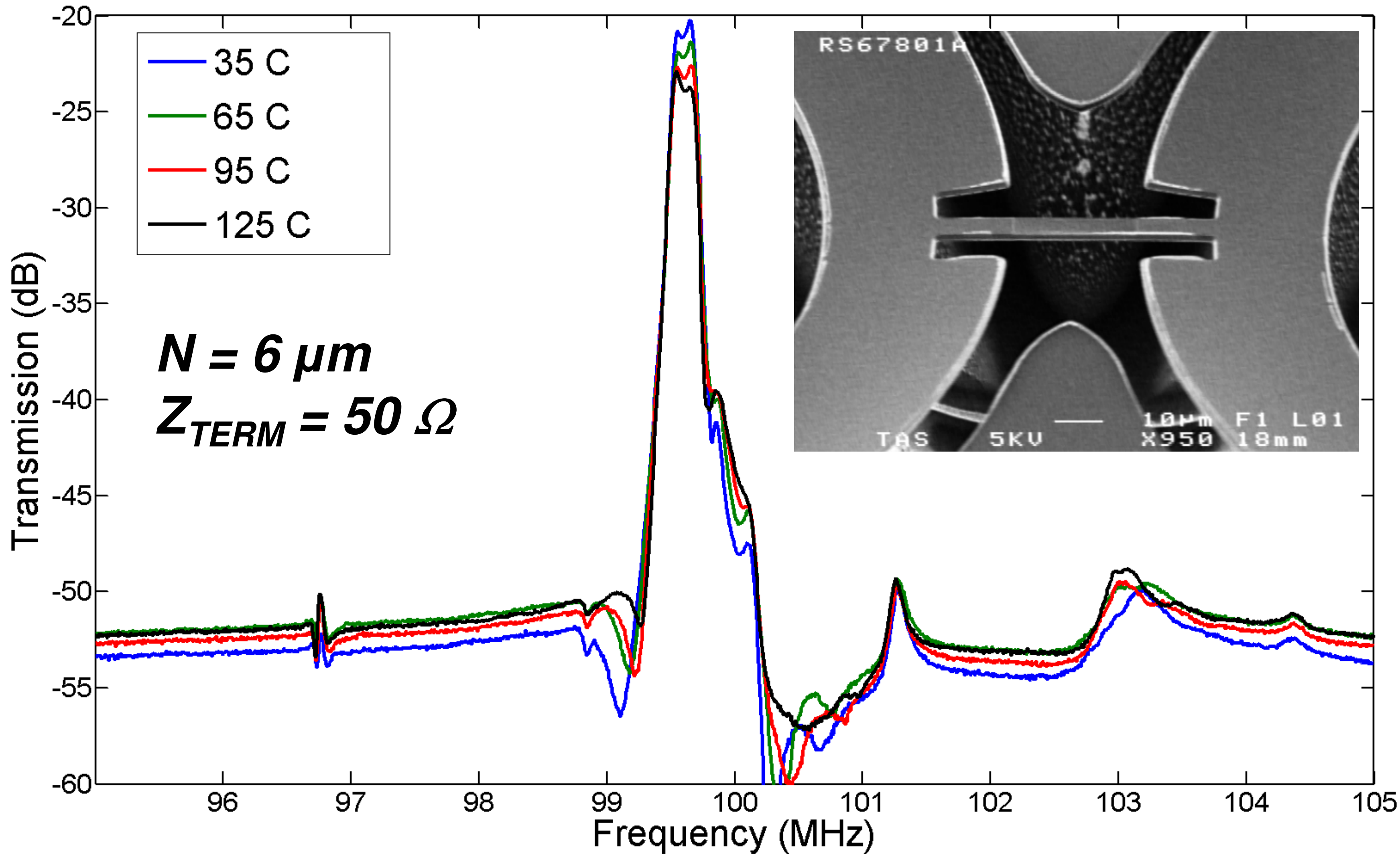
- Within Wafer

$$\sigma_{thickness}(AlN) < 1\%$$

- ± 26 ppm across -55 to 125 C



Temperature Stability Filter Impact



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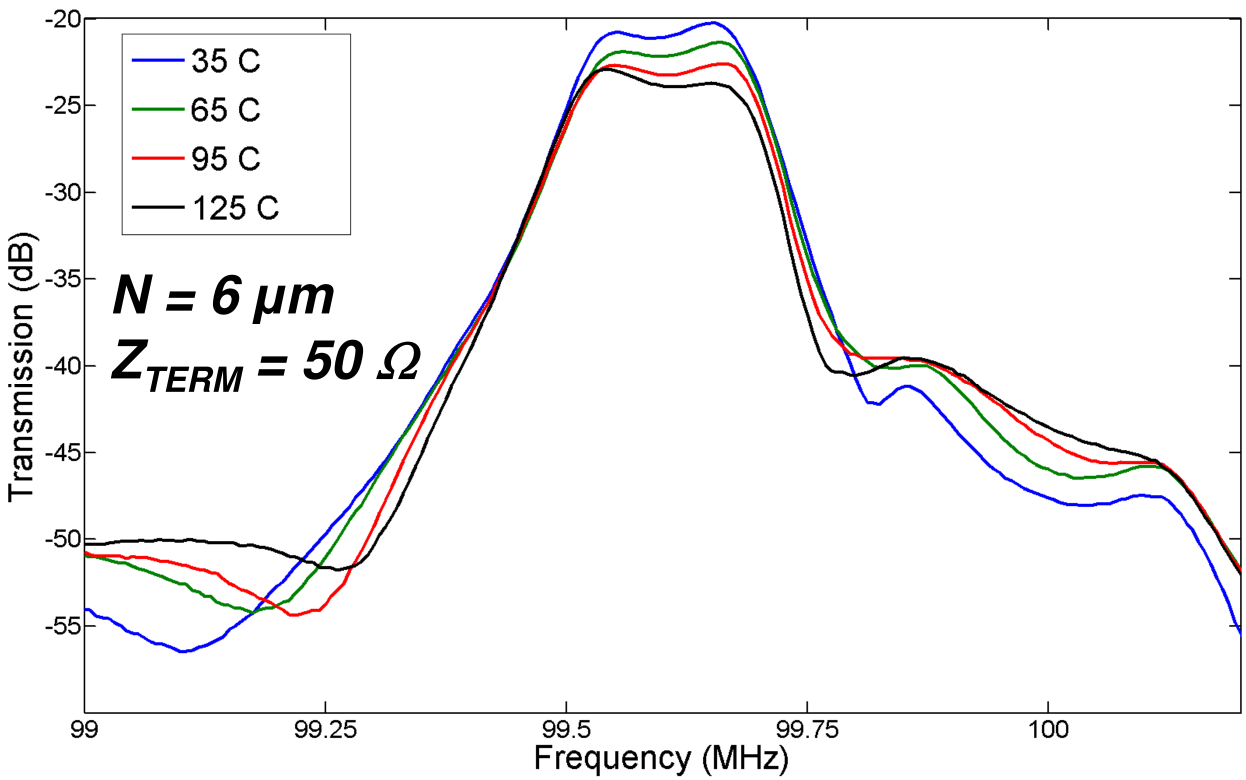
Temperature Stability Filter Impact



Useable 3dB Bandwidth (35-125 C) = 181 kHz

Max. 3dB Bandwidth (35-125 C) = 194 kHz

% Useable Bandwidth (35-125 C) = 93.3%

6.7% Bandwidth Dedicated to Temperature Drift

Oxide Thickness (µm)	f(-3db) min @35 C (MHz)	f(-3db) min @125 C (MHz)	f(-3db) min @35 C (MHz)	f(-3db) max @125 C (MHz)	Useable Band-width
0.5	106.900	106.69796	107.0875	106.8851	0 kHz
1.1	99.5125	99.5000	99.69375	99.69375	181.25 kHz

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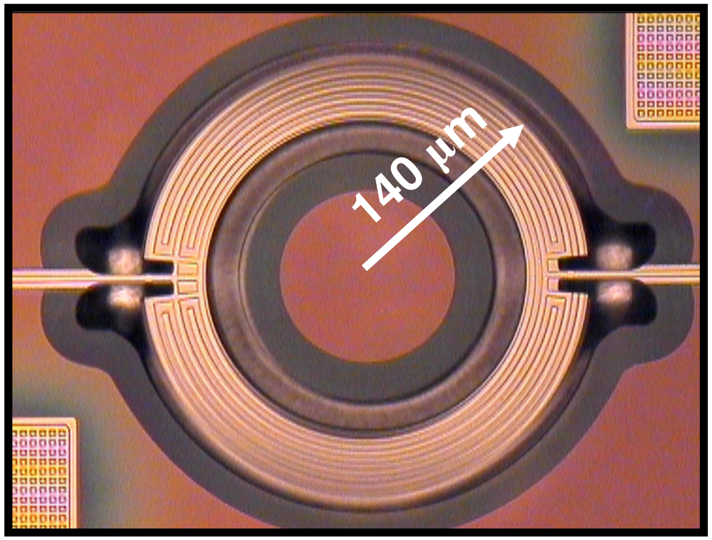
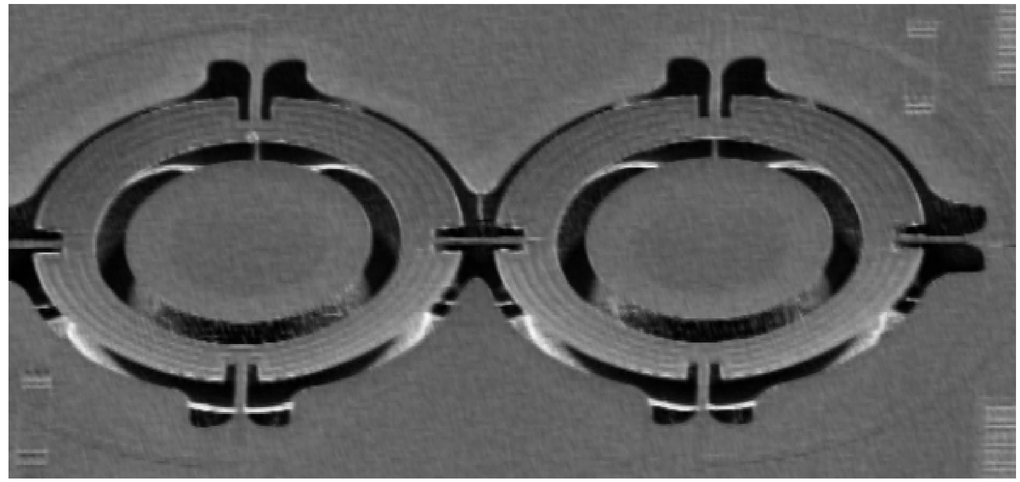
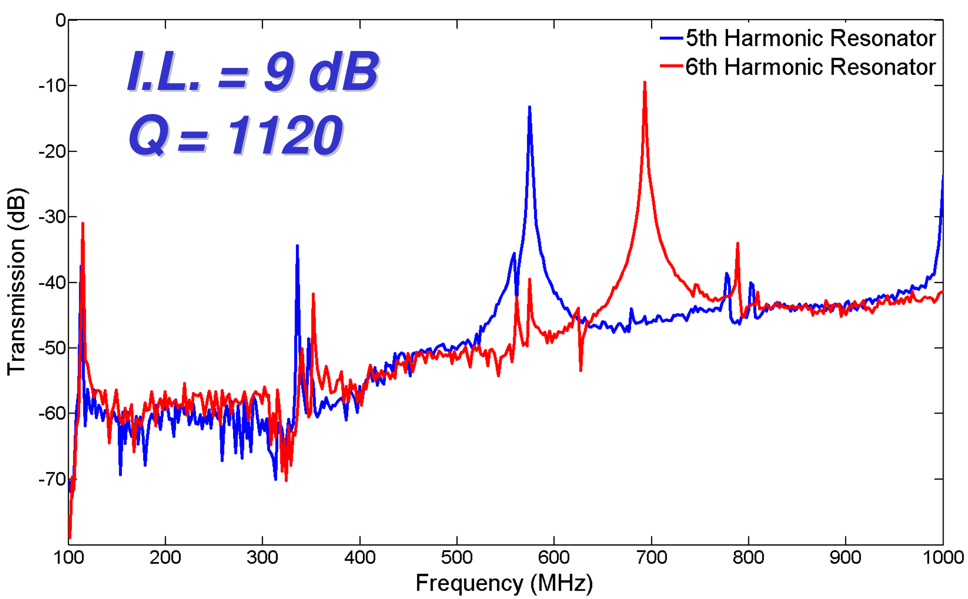
Scaling to Higher Frequency (Overtone Operation)







- Overtone MEMS Filters
  - *Previously scaled resonators to 1 GHz with low insertion loss*
  - *Use overtone operation to scale mechanically coupled filters*
  - *Allows balun and fully differential operation for improved out-of-band rejection*

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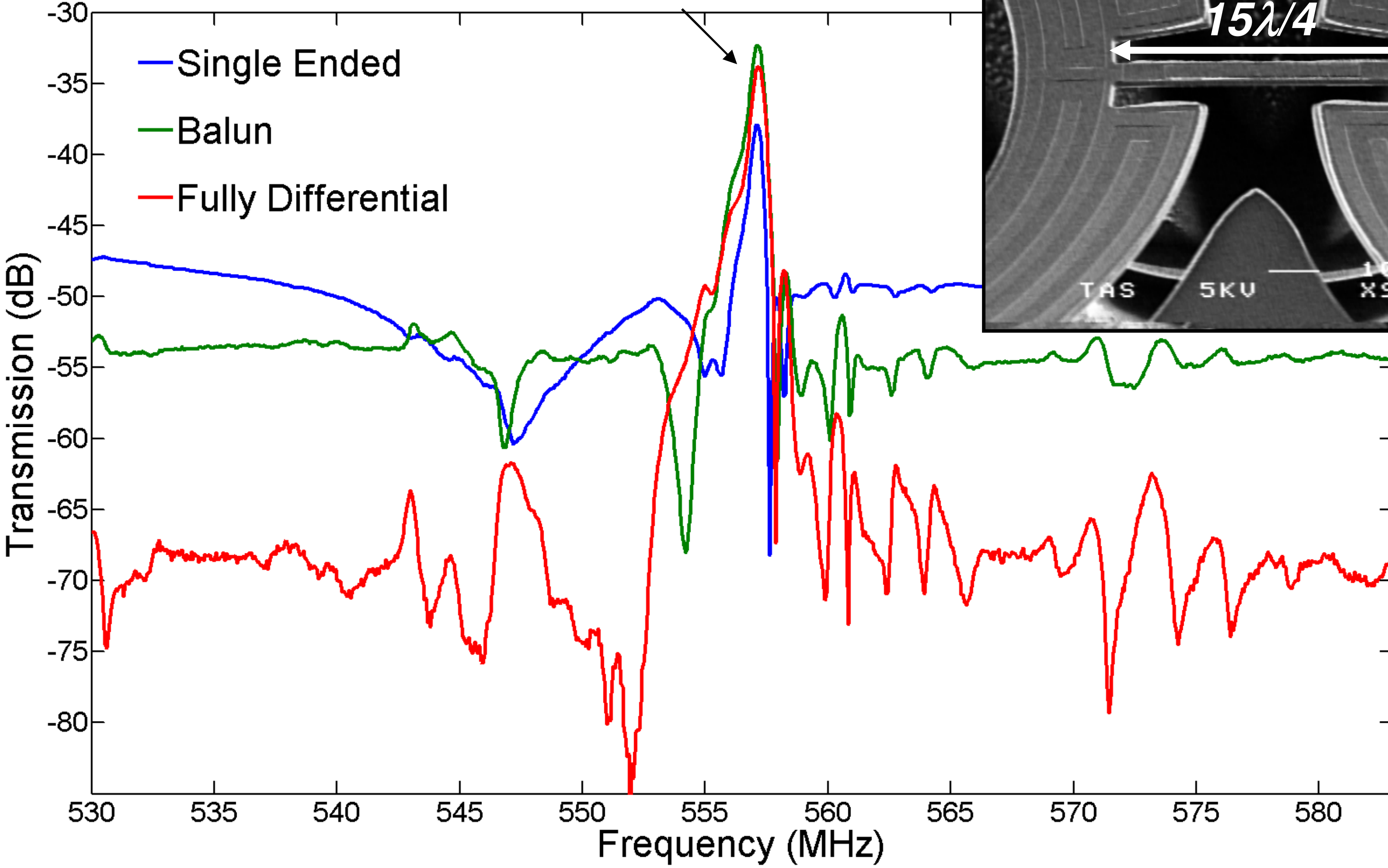
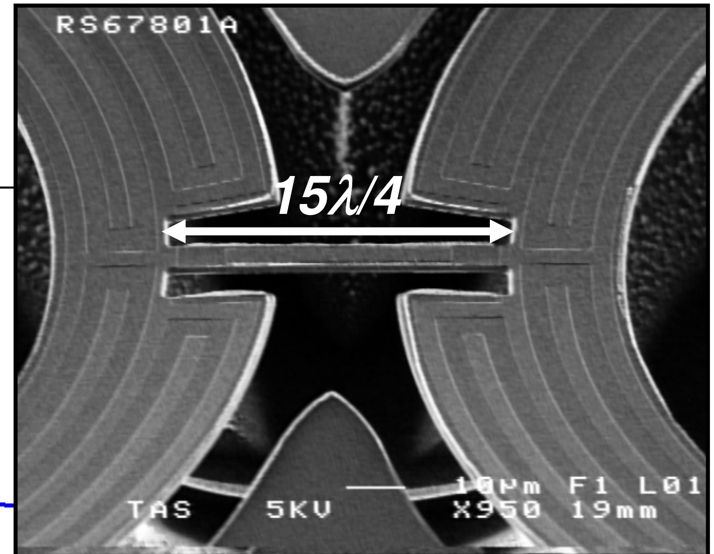
5^{th} Overtone Filter Measured Results

Fully Differential Operation Improves Stop-Band Rejection by 23 dB

Higher Than Expected Insertion Loss Based on Previous Results





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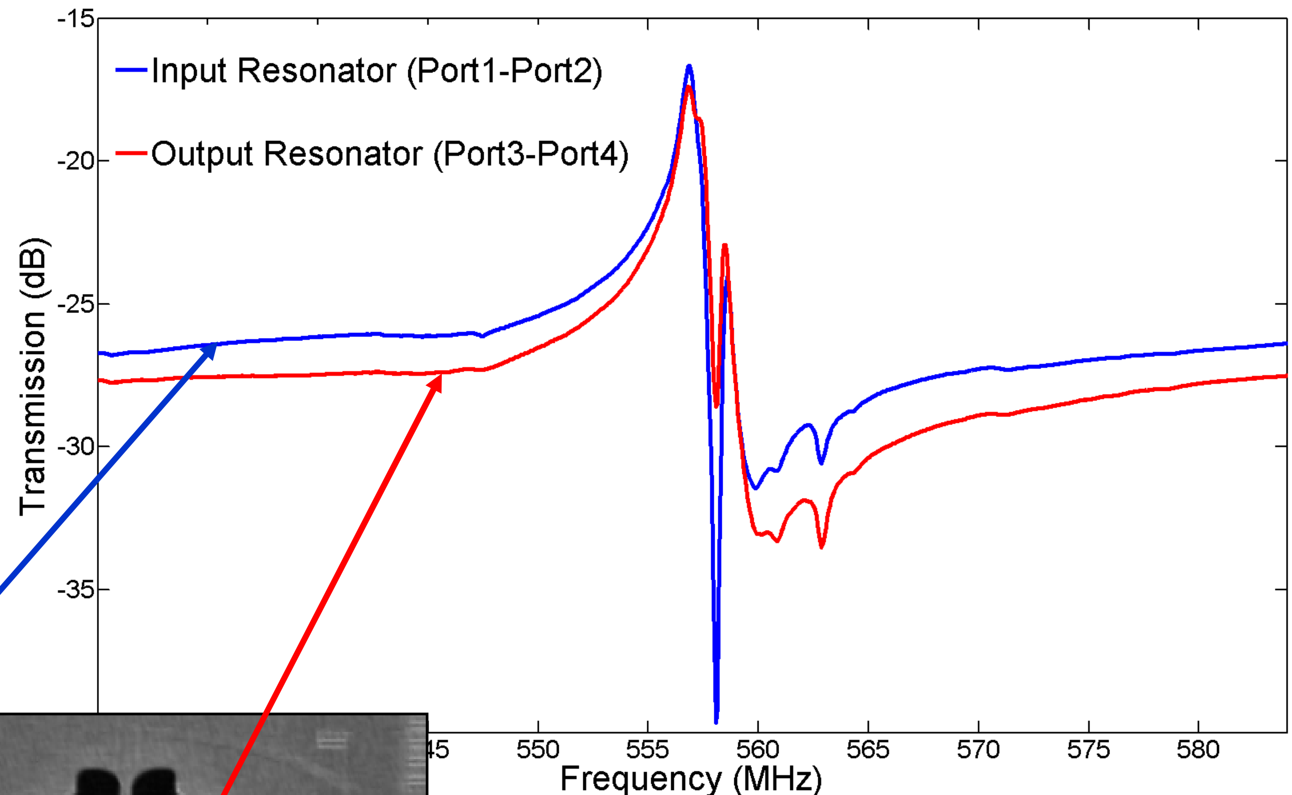
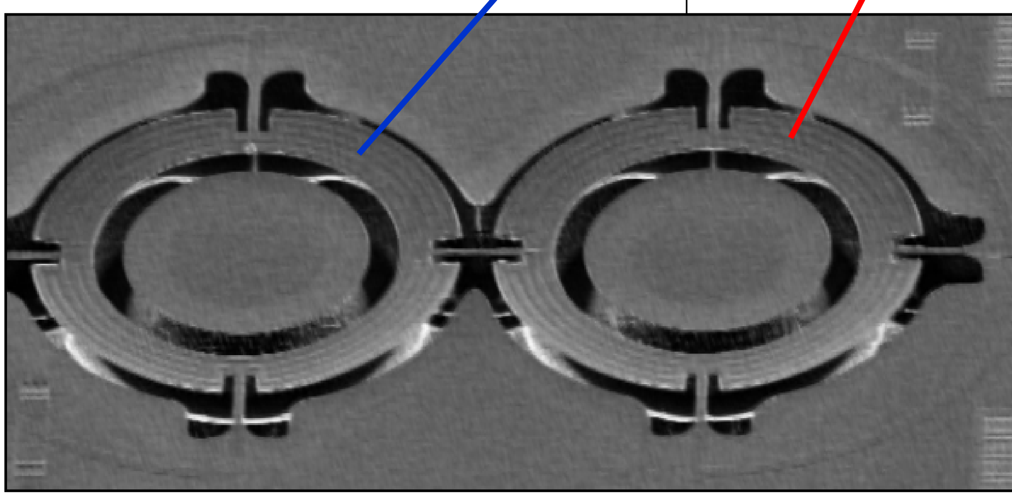
Overtone Filter Discussion

- Filter Insertion Loss
  - *Input/Output Resonators Show Strong Coupling and Matched Frequencies*
  - *Q_{Filter} = 1000 but*
  - *$Q_{Resonator}$ = 495*





- *Degraded resonator Q from additional anchors*
- *Coupling occurs only over 1/5th of low velocity coupling locations*

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Conclusions

- MEMS Filter Motivation
  - *Small Size, Strong Coupling per Area*
  - *Many Frequencies per Wafer*
  - *Narrow Band Operation*
  - *Filter Banks for Spectrum Analysis and Cognitive Radio*

- VHF Mechanically Coupled Filters
  - *Filter Architecture and Design*
  - *Bandwidth Control*
  - *Temperature Drift Reduced for Narrow Bandwidth Filters*

- UHF Overtone Mechanically Coupled Filters
  - *Filter Topology Scaled to 550 MHz*
  - *Unexpected Insertion Loss*
    - Resonator Q degraded by additional anchors (anchor loss limited)
  - *Additional Work Needed to Evaluate Overtone Mechanical Coupling Efficiency*

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Acknowledgments

Acknowledgement

Microelectronics Development Laboratory Staff at Sandia National Laboratories

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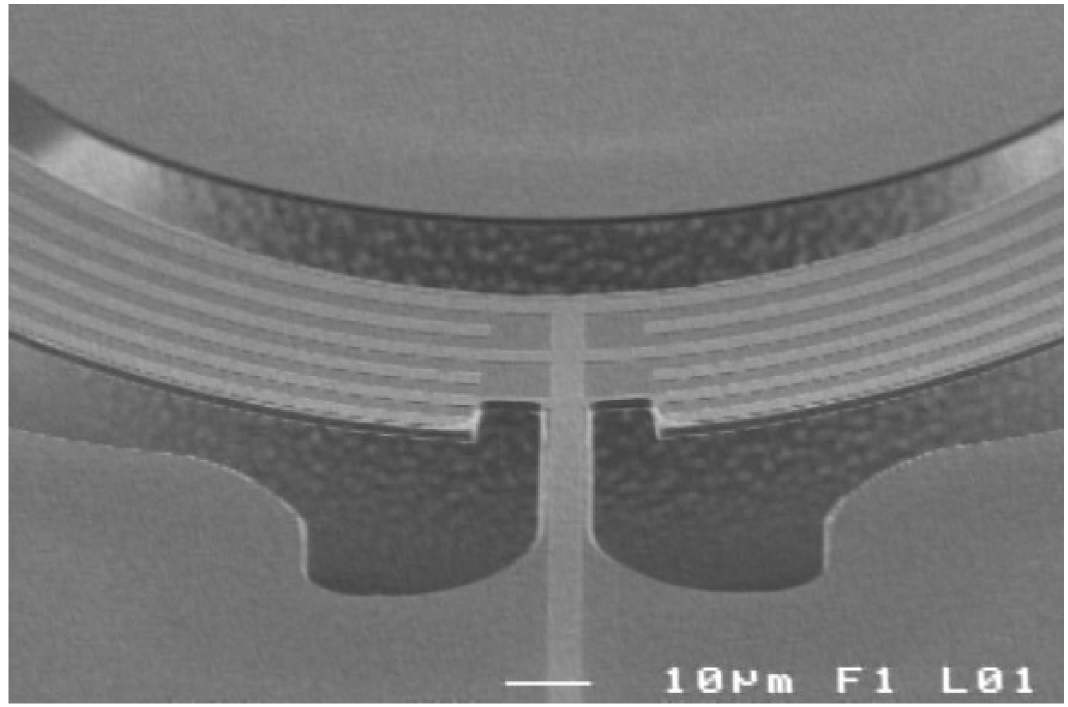

Contact Information

Roy Olsson (rholsso@sandia.gov)

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Backup Slides

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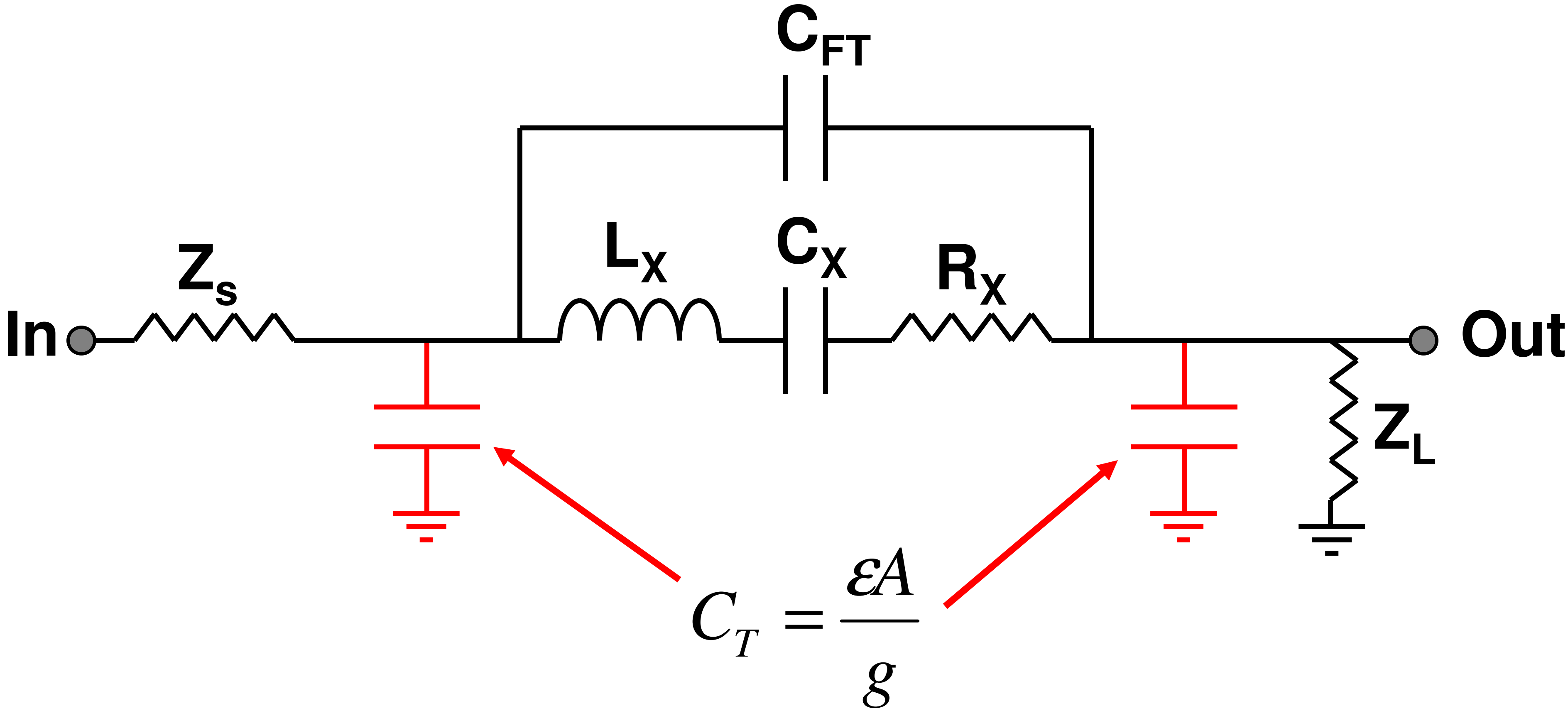
Transducer Capacitance



In most capacitively transduced devices, $Z(C_T) < R_X$ above a few 100 MHz

$$R_x = \frac{k_{beam} g^4}{\omega_0 Q V_P^{\,2} (\varepsilon A)^2}$$

Increase Overlap Area, Dielectric