Trimming and Tuning of HTS RF Devices

Jeffrey M. Pond

j.m.pond@ieee.org

Outline:

- **Introduction**
  - **acknowledgements**
  - **motivation**
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- Tuning technologies
  - general issues and conventional technology
  - ferrites
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- Conclusions

Acknowledgements:

- Mechanical Trimming: Rafi Herschtig, et.al. (K&L Microwave)
- Mechanical Tuning: Tim Dolan, et.al. (K&L Microwave)
- Ferrites: Dan Oates, et.al. (Lincoln Laboratory), Paul Arendt, et.al. (Los Alamos)
- Ferroelectrics: Jim Booth, et. al. (NIST), Steve Kirchoefer, et. al. (NRL), Robert Romanofsky, et.al. (NASA-Glenn), Bob Yandrofsky, et.al. (SCT)
- MEMS: N. Scott Barker. (NRL/Univ. of Michigan), Gabriel Rabiez, (Univ. of Michigan)

Motivation:

- HTS offers performance advantages allowing circuits designs and concepts that can not be realized by conventional technologies
  - design, fabrication, and packaging techniques are pushed beyond their capabilities to deliver a device or circuit that performs as de sired.
  - techniques are required to adjust the performance characteristics of a device or circuit after it is fabricated and assembled in order to compensate for these errors.

- Emerging microwave systems are simultaneously requiring frequency agility and higher performance
  - HTS is a natural to satisfy the performance criteria
  - conventional tuning technologies often have losses which would offset the natural advantages of HTS
  - there is a clear need for tuning technologies which are complimentary to HTS performance

- Developing high performance tunable HTS microwave circuits and systems will create a viable HTS market

Motivation (cont.):

- Consider a hypothetical case: An HTS filter in stripline:
  - center frequency is 1.0 GHz
  - bandwidth is 1.0 MHz (0.1%)
  - good passband shape requires multiple poles controlled to 0.1 MHz
  - required accuracy in 1 part in 10000 = 0.01%
- What are the implications for realizing this design?
- The lengths of our stripline resonators are going be determined by the phase velocity, $v_p = (L/C)^{1/2}$
- Requiring 0.01% accuracy for phase velocity means controlling C to 0.02% which requires
  - a 250 μm thick substrate be accurate to ± 25 nm
  - the relative dielectric constant of MgO be accurate to ± 0.002
- More complicated calculations will give the accuracy to which the thickness of the HTS, the penetration depth, and T_c must be controlled
- Parasitics, and design tool limitations will only complicate the problem

Outline:

- Introduction
  - acknowledgements
  - motivation
- **Distinction between Trimming and Tuning**
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- Tuning technologies
  - general issues and conventional technology
  - ferrites
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- Conclusions

Distinction Between Trimming and Tuning:

- Trimming: A post fabrication and assembly technique to adjust the device characteristics to match as closely as possible the designed char acteristics. Trimming compensates for
  - processing tolerences
  - design tool limitations and errors
  - variations in substrate thickness, dielectric constant, etc.
  - deposition run variations in HTS thickness, penetration depth, etc.
  - packaging parasitics

- Trimming techniques:
  - mechanical – usually screw adjustment
    - requires flexible mechanical access while device is cold
    - can use metal or dielectric to inductively or capacitively tune
  - electrical – requires biasing lines which adds parasitics
    - ferroelectrics
    - ferrites
    - etc.

Distinction Between Trimming and Tuning (continued):

- Tuning: The ability to modify the performance or characteristics of a device in real time on a continuing basis as part of its normal operational use. Uses could include
  - phase shifters and delay lines
  - tunable filters
    - center frequency
    - pass band
    - zero positioning
    - notch

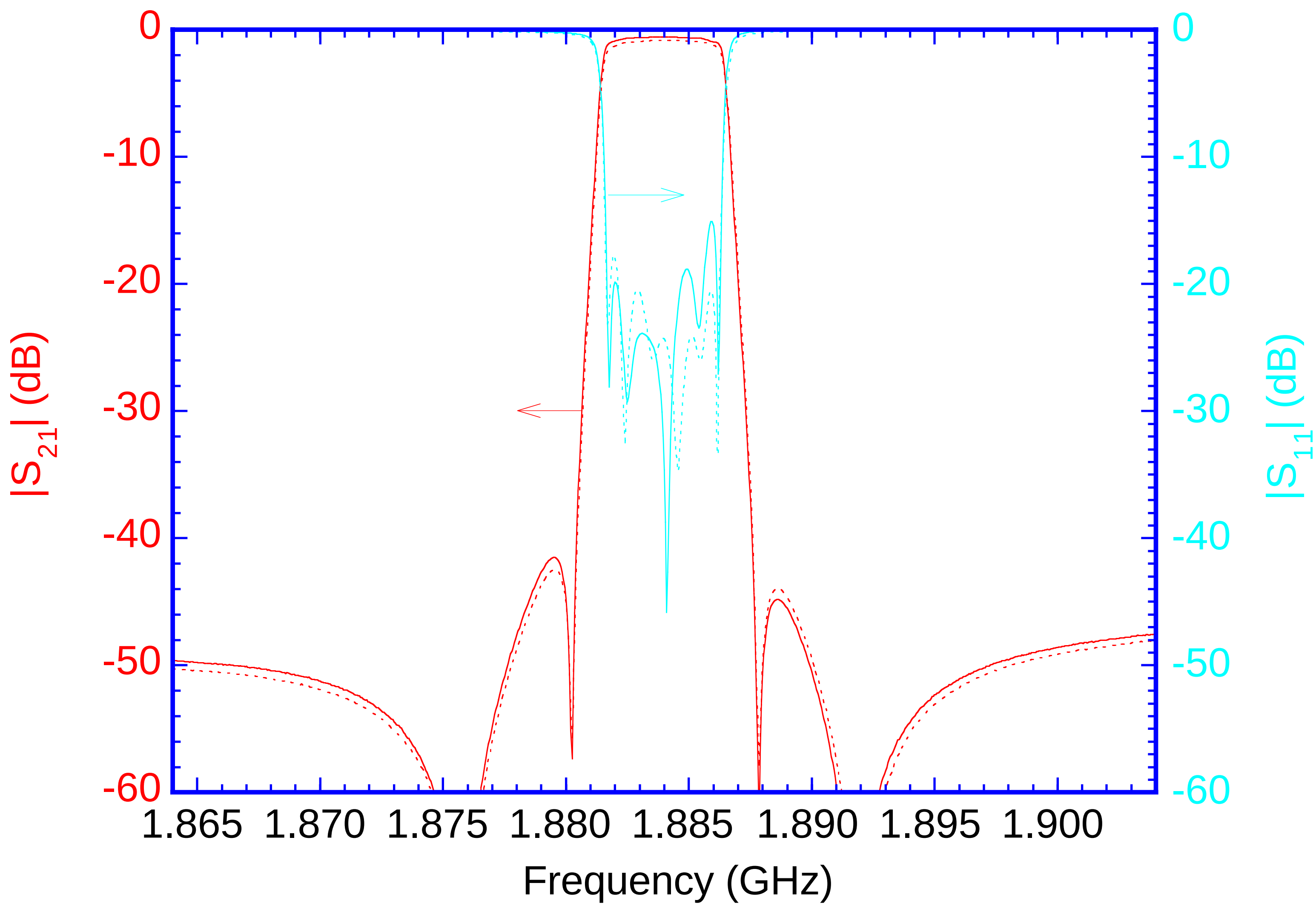
- Tuning techniques:
  - mechanical – servo/stepping motor
  - electrical – requires biasing lines which adds parasitics
    - ferroelectrics
    - ferrites
    - MEMS
    - GMR/CMR
    - semiconductor

Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- **Mechanical trimming while at operating temperatures**
  - **needs and requirements**
  - **equipment and technique**
  - **results**
- Tuning technologies
  - general issues and conventional technology
  - ferrites
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- Conclusions

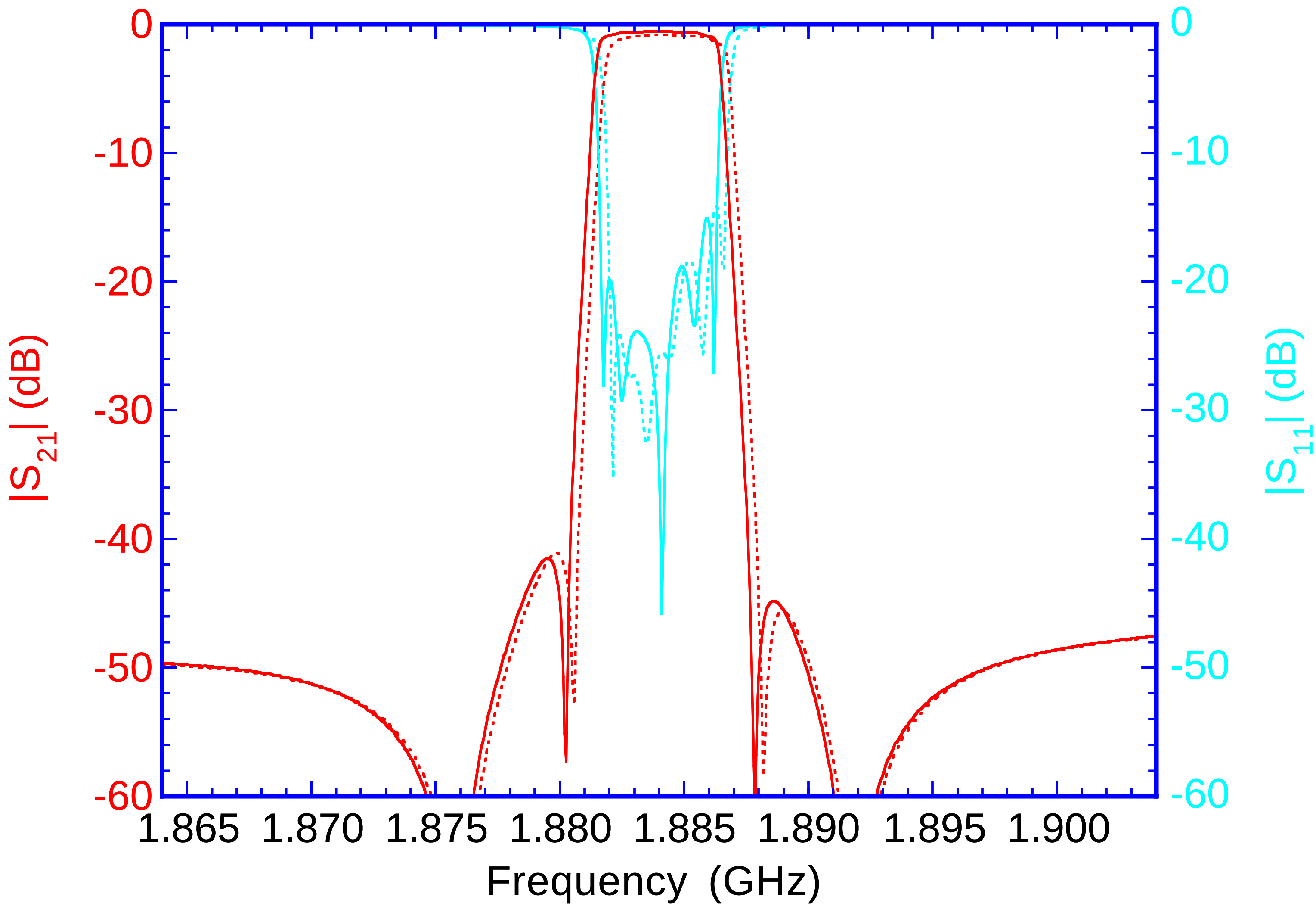
Comparison of Filter Response at 200K (solid) and 300K (dashed)

(filter was tuned at room temperature)

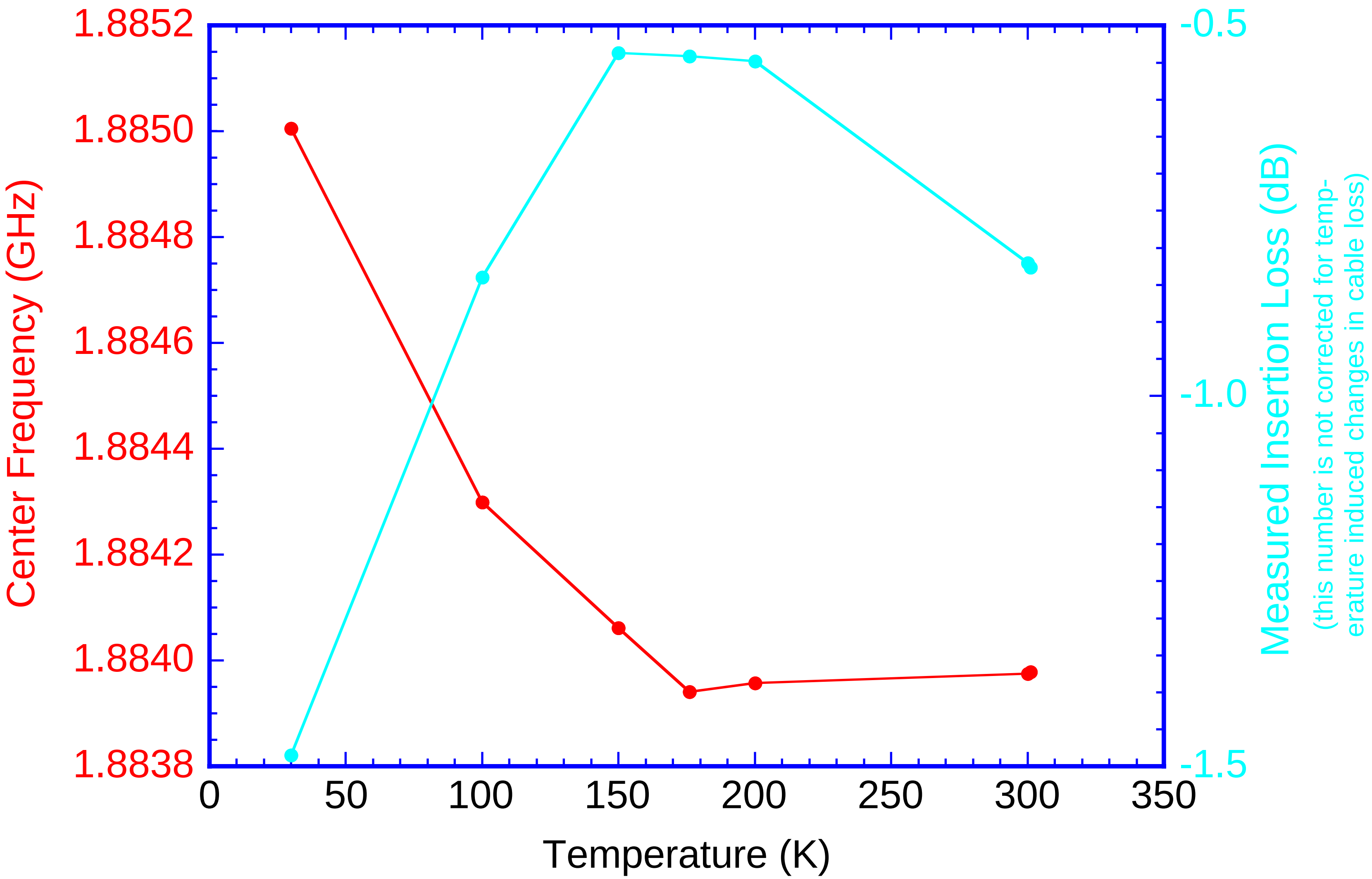


Comparison of Filter Response at 200K (solid) and 100K (dashed)

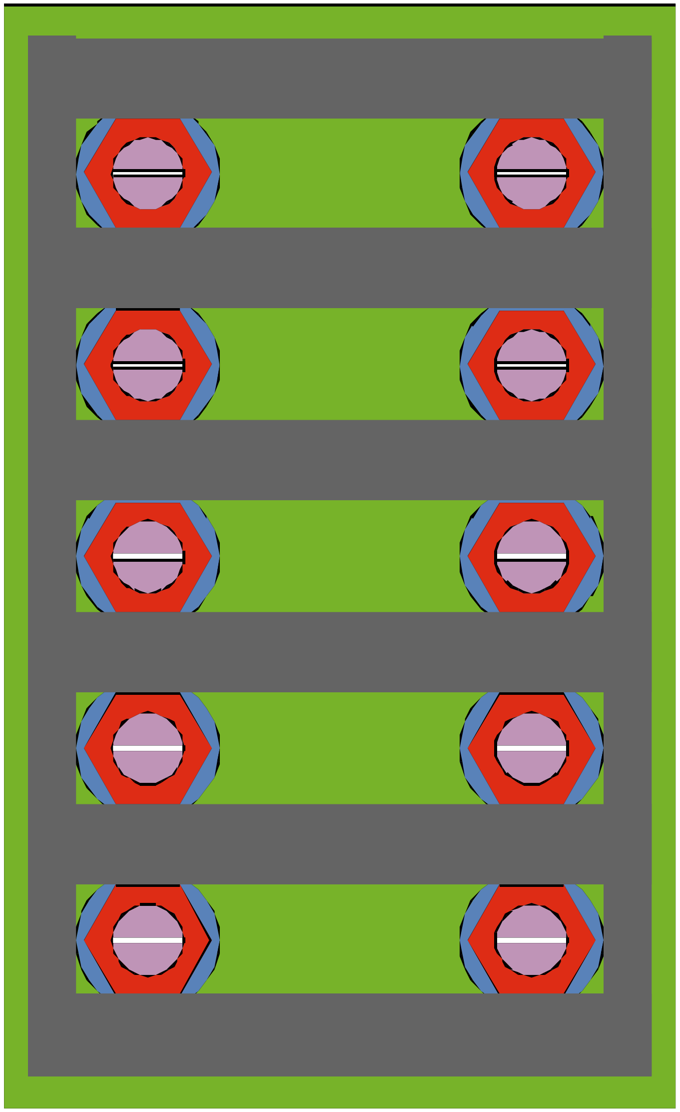
(filter was tuned at room temperature)

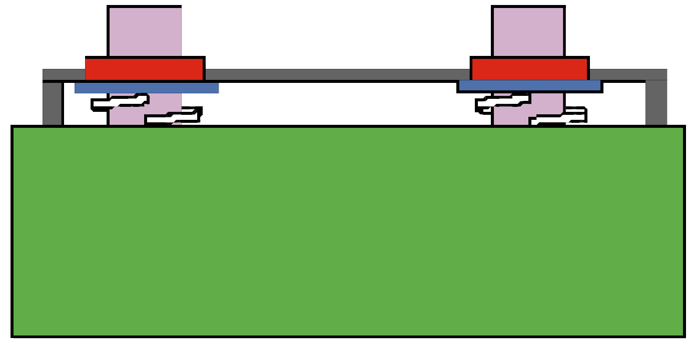


Temperature Dependence of the Center Frequency and Insertion Loss After Tuning at Room Temperature



Modified Tuning Screw Design for Cryogenic Tuning



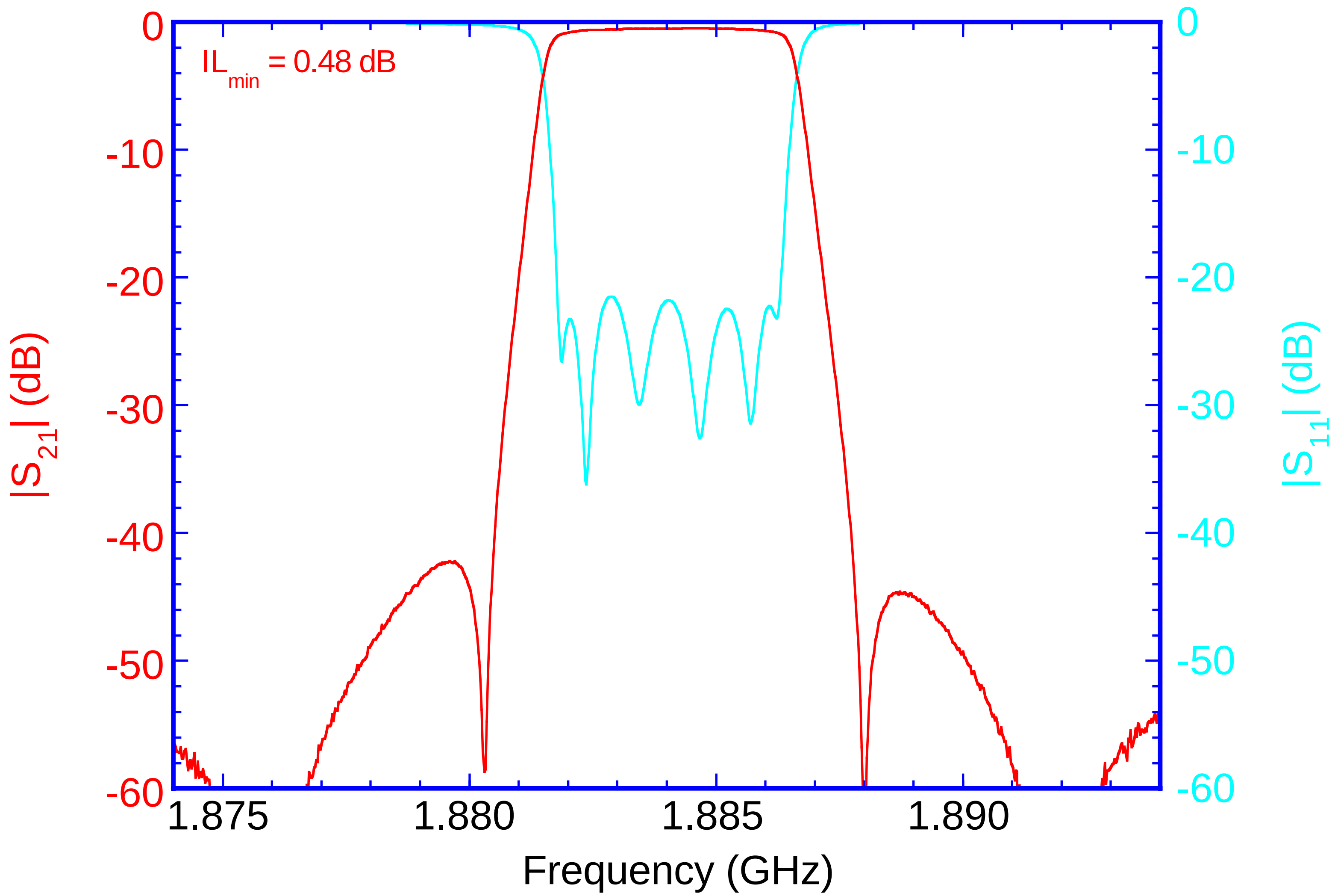


A Plexiglass Desiccator Cover for Visual and Mechanical Access (Rotation, Wobble, and Linear)

Simple Mechanical Feedthrough (Rotation, Linear, and Wobble) for Tuning Input and Output Coupling Antennas

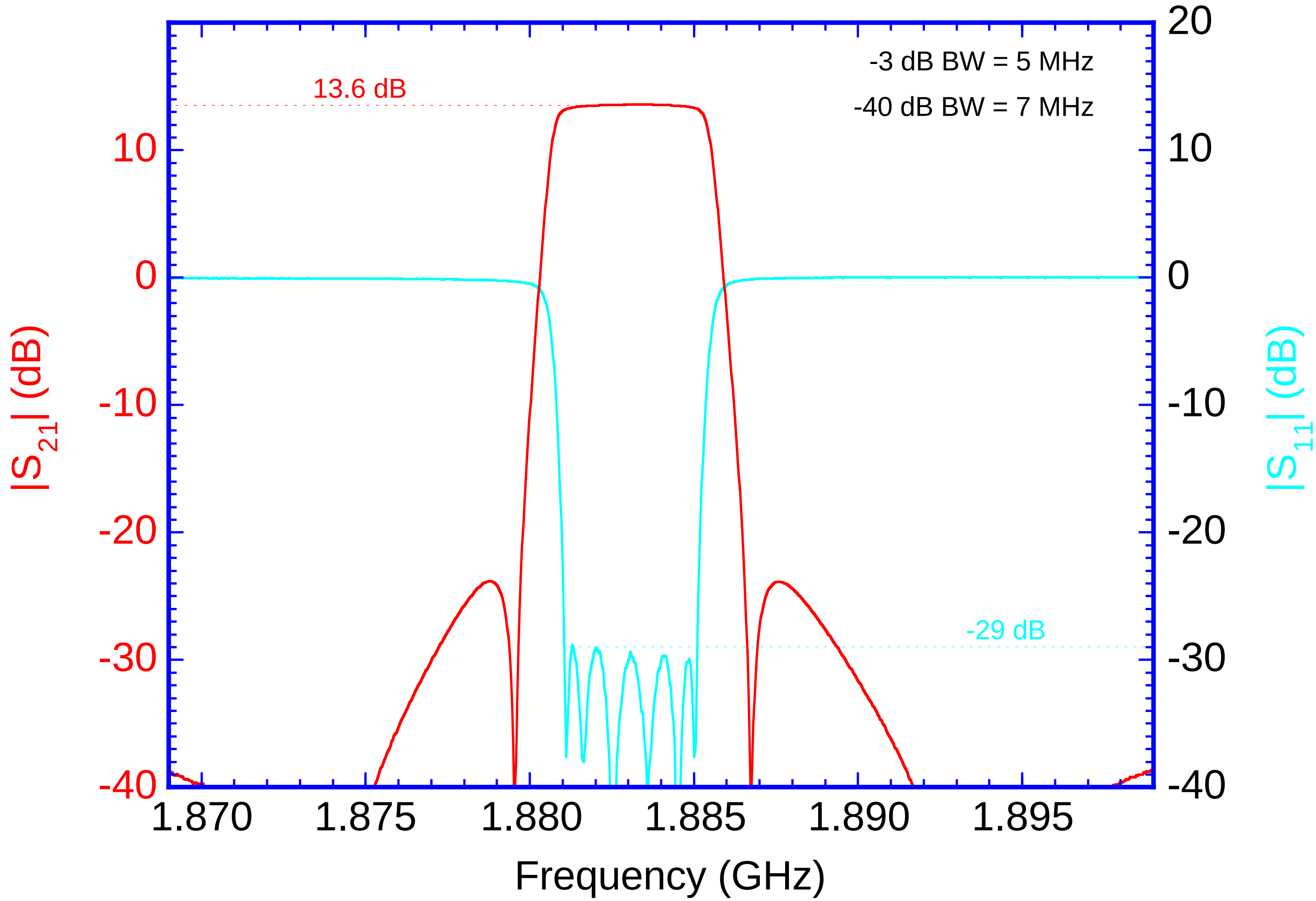
Measured Filter Response after Tuning at 150 K

(tuning of all six resonant frequencies and four coupling coefficients)



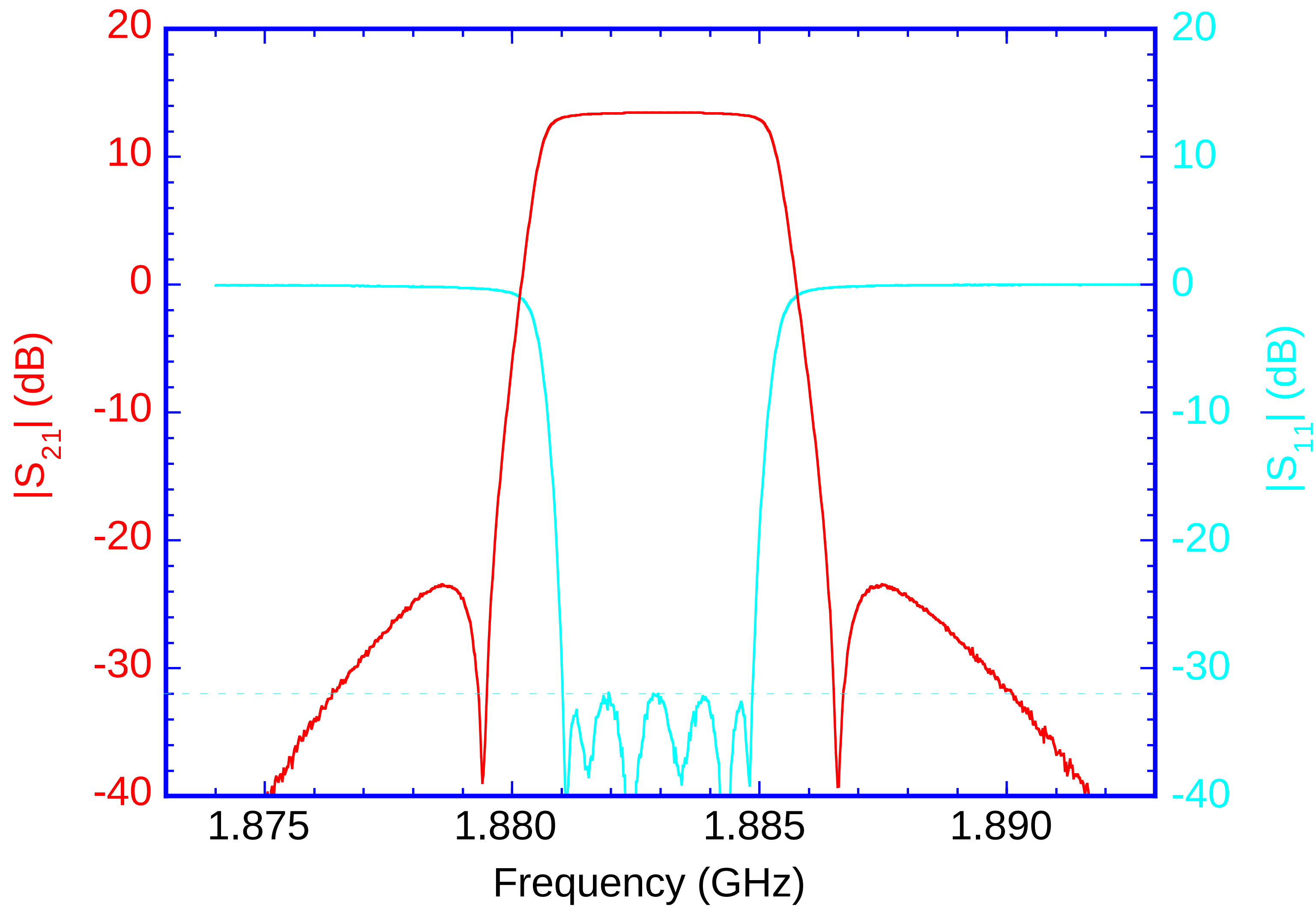
Measured Cryogenic Receiver Passband Characteristics
Transmission and Reflection Response at 130K

(tuning of all six resonant frequencies, four coupling coefficients, and input and output antennas)



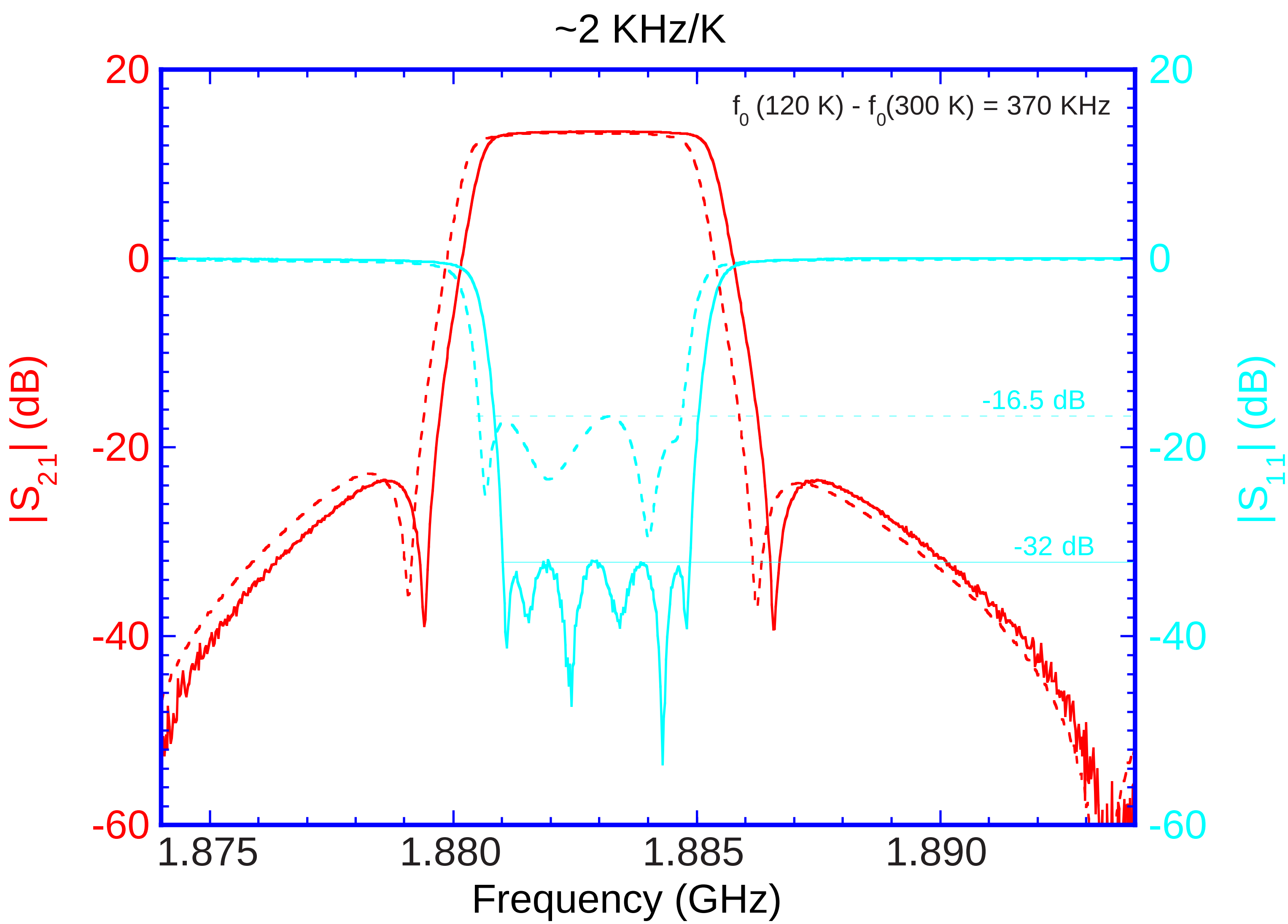
Measured Cryogenic Receiver Passband Characteristics
Transmission and Reflection Response at 120K

(tuning of all six resonant frequencies, four coupling coefficients, and input and output antennas)



Passband Charateristics at 120K (solid) and 300K (dashed)

(Receiver Tuned at 120K and then Thermally Cycled Several Times Before Measurement at 300K)



Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- **Tuning technologies**
  - **general issues and conventional technology**
  - ferrites
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- Conclusions

Tuning Issues: Need to obtain the advantages of tuning device properties without degrading performance

- Speed of tuning
  - some applications have no real speed requirement (e.g. tuning a filter transmission zero to knock out a constant interferring signal)
  - some applications have very fast (<< 1μsec) tuning requirements (e.g. phased arrays

- Microwave Losses
  - loss in the tunable media or device itself
  - parasitic losses associated with biasing circuitry

- Tunability
  - % change in reactance of tunable media or device
  - % change in device characteristics (center frequency)

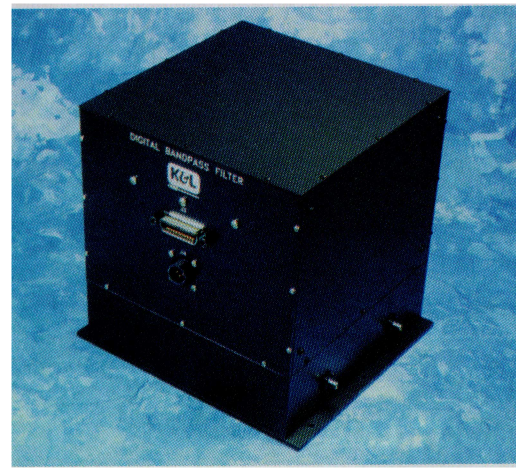
- Figure of Merit
  - commonly defined as: $2Q\Delta f/f$

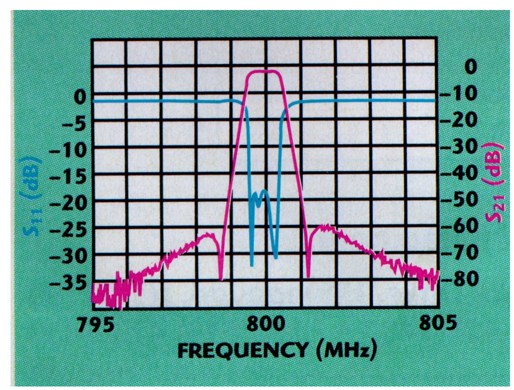
Tuning Issues (continued): Need to obtain the advantages of tuning device properties without degrading performance

- Design and Fabrication
  - design complicated by biasing circuitry
  - materials compatability issues especially with cryogenic cycling
- Cryogenic system impact
  - dissipation in tuning media/element increases thermal load
  - control leads increase thermal load
- Signal strength considerations
  - power handling capacity of tuning media/element
  - nonlinearities contribute to mixing and increase IP3

K& L Microwave Tunable Dielectrically Loaded Waveguide Filter

- Individual stepper motors for each resonator
- Five pole filter tunable from 750 to 850 MHz
- 3 dB bandwidth = 0.953 MHz (0.12%)
- Typical tuning range is 18%
- 1.72 dB insertion loss
- ~15 s to tune across the band
- Unloaded Q between 15000 and 28000





Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- **Tuning technologies**
  - general issues and conventional technology
  - **ferrites**
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- Conclusions

Ferrites for Tuning:

- One of the most popular room temperature “control component” technologies for phase shifters, circulators, etc.
- Many standard room temperature microwave ferrites exhibit high loss at cryogenic temperatures. Some solutions do exist with careful material preparation
- Switching speed are > 1 μsec
- Usually requires “bulk” ferrite in order to have large enough % of the field in the ferrite to get reasonable tuning range. Thin films are less promising.
- Good combination of low loss tangent (high Q) and tuning range yields good figure of merit (170 with HTS)
- Considerable development and a very promising solution for practical application to many real world problems

Magnetically Tunable Superconducting Filters

D. E. Oates, G. F. Dionne, and A. C. Anderson
M.I.T. Lincoln Laboratory

P. N. Arendt, R. F. DePaula, J. R. Groves,
S. R. Foltyn, and Q. X. Jia
Los Alamos National Laboratory

This work was supported by DARPA

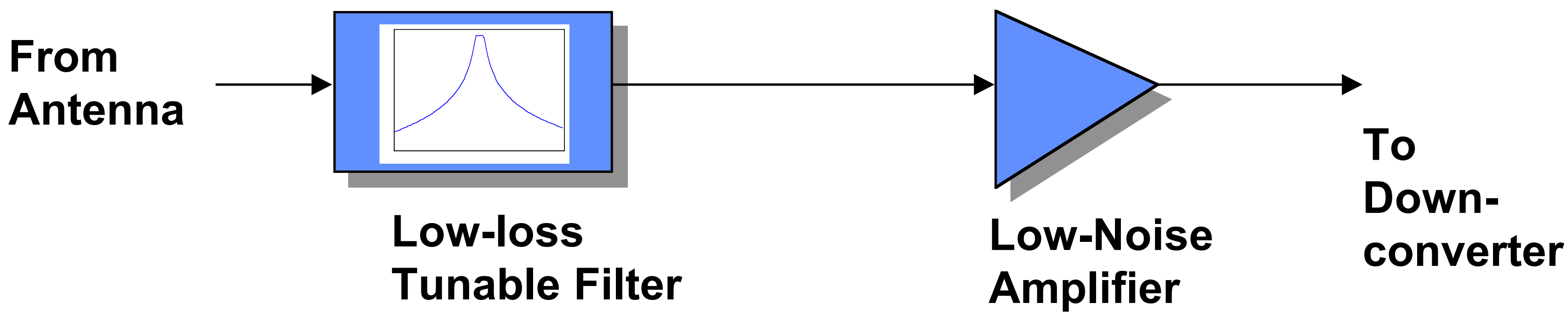
Outline

- Motivation
- Principle of operation
- Results resonators and filters
- Switching speed measurements
- Future work
- Summary

The Problem
Overloaded Radar Front End

Solution

Frequency-agile protection for sensitive front end



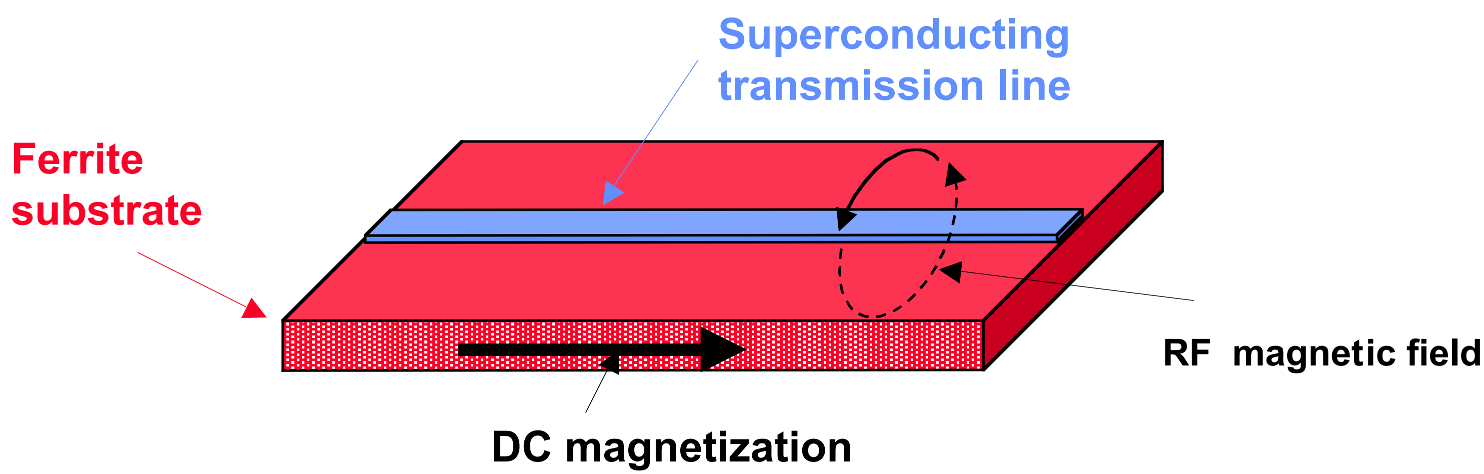
- Tunable filter to accommodate frequency agility
- Tunable notch filter also possible
- Conventional solution: YIG and varactor filters

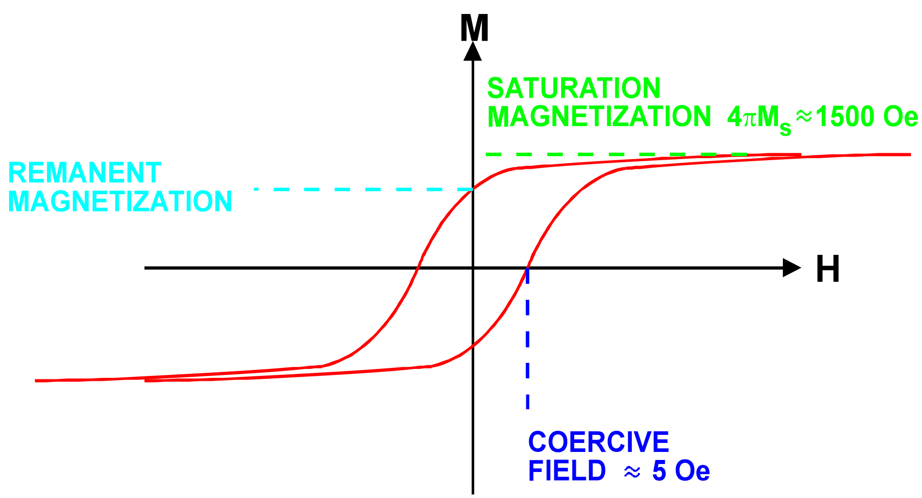
Requirements

- Low loss for low noise figure and high sensitivity
- Sharp skirts for strong suppression
- Fast tunability for frequency hopping
- Highly linear operation to prevent spurious signals

Superconducting filters in compact geometry

Superconductor/Ferrite Tunable Devices
Principle of Operation





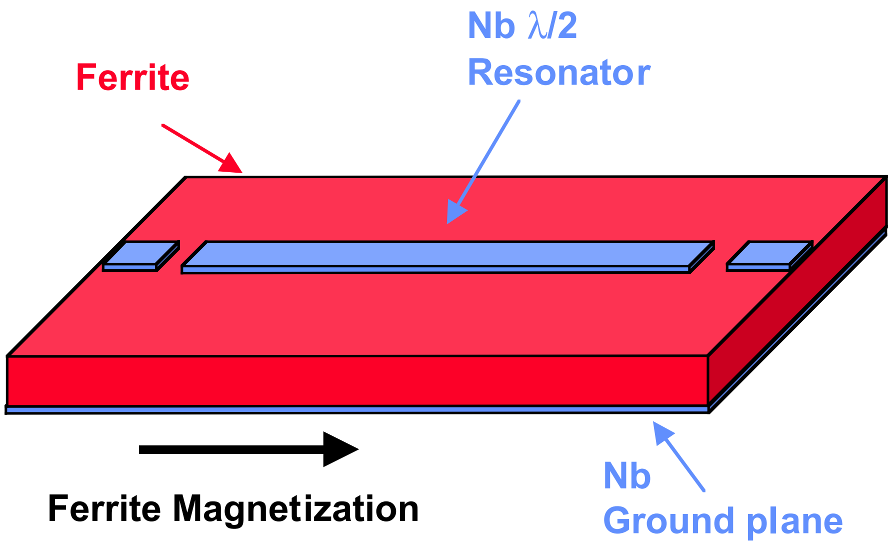
- Tunability by permeability of ferrite
- Low loss at microwave frequencies
- Use of hysteresis loop yields low-field and low-energy tuning
- Closed magnetic circuit (not shown)
- Low-field tuning (compared with resonant devices) gives rapid tunability

Outline

- Motivation
- Principle of operation
- Results
  - Niobium (low-T_c) on polycrystal ferrite
  - YBCO (high-T_c) on ferrite by IBAD
- Switching speed measurements
- Future work
- Summary

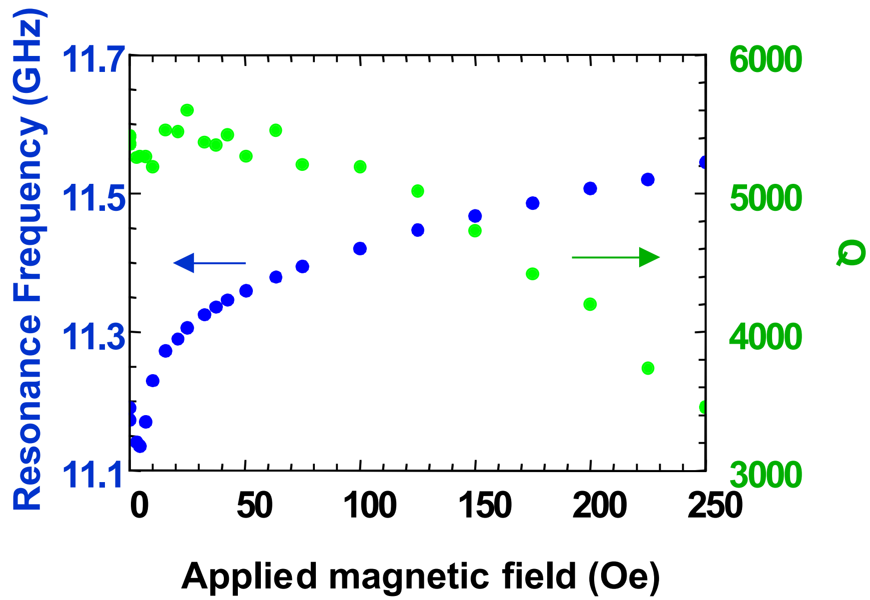
Tunable Niobium Resonator

Tunable Niobium/Ferrite Resonator



- Tunability by permeability of ferrite
- Low-loss ferrites
- Low-field and low-energy tuning
- Rapid tunability
- Closed magnetic circuit (not shown)

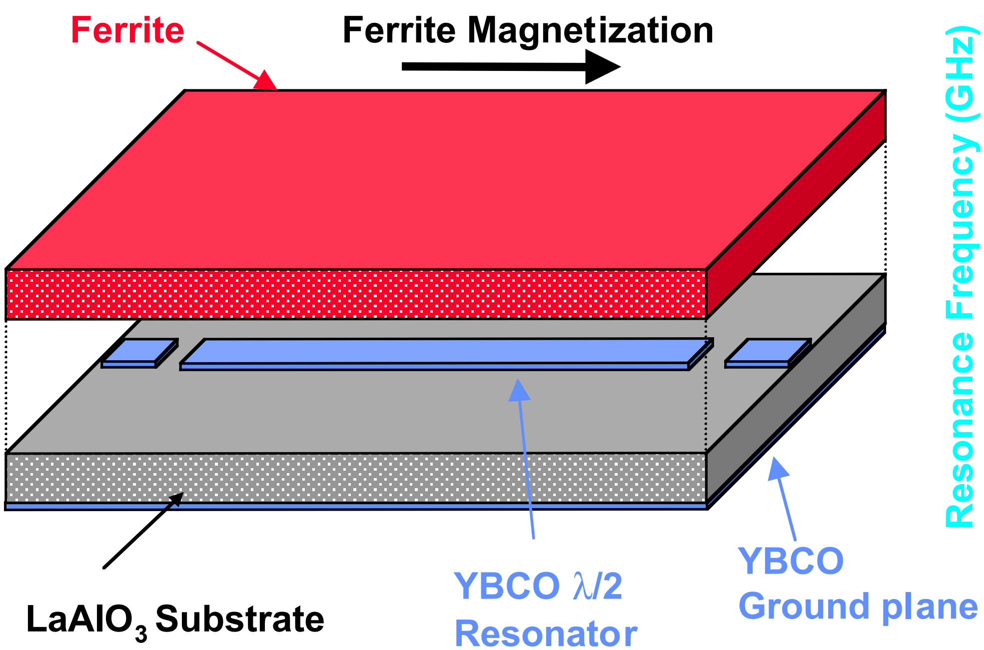
Measured Results
T = 4 K



- Figure of merit = $2Q\Delta f/f$ =300
- Q Limited by ferrite

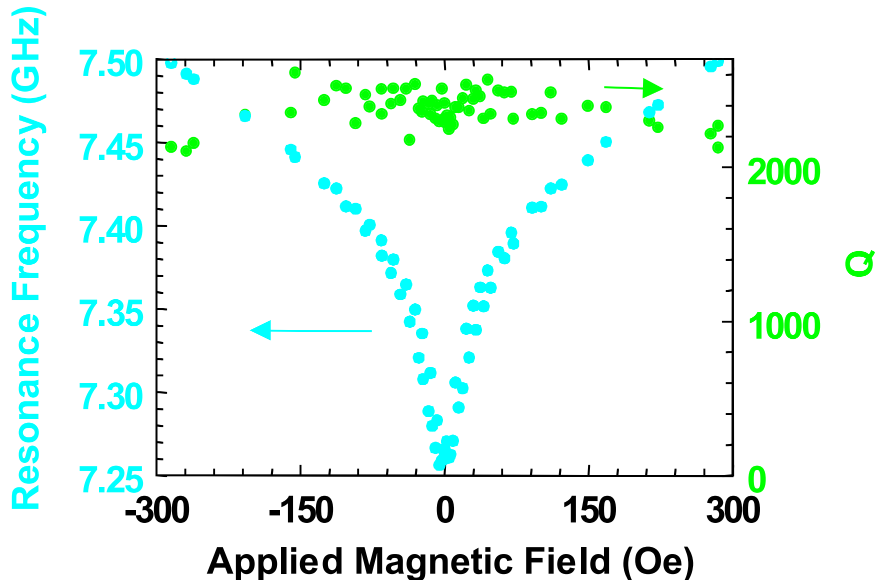
YBCO Resonator

Tunable YBCO/Ferrite Resonator



Resonator Frequency and Q

T= 77 K

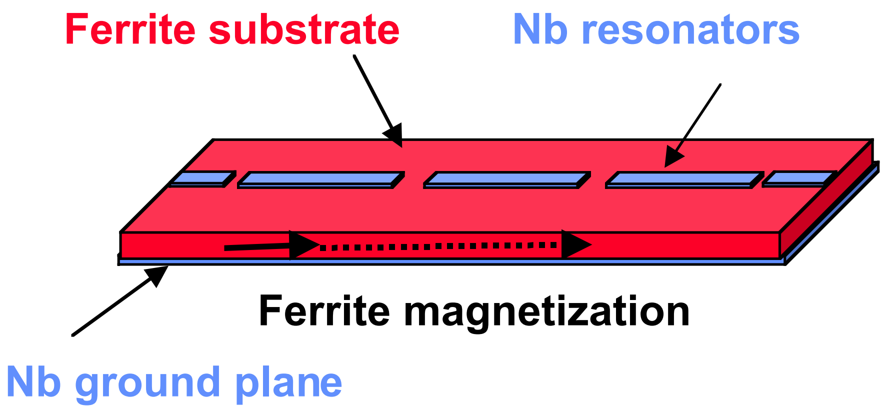


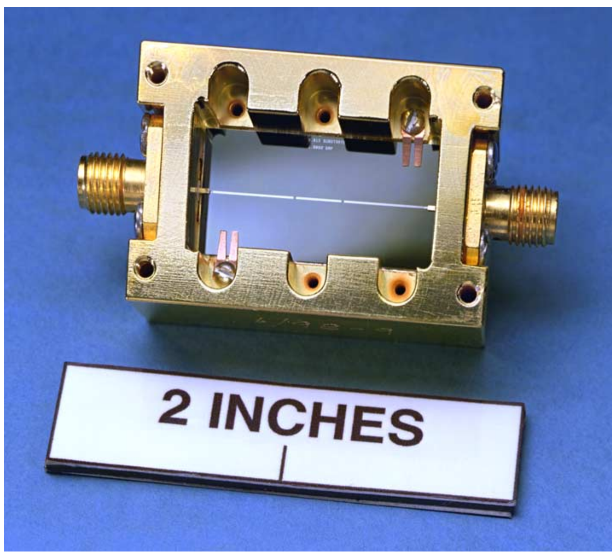
- Figure of merit = 2QΔf/f = 170 with YBCO and 300 with niobium
- Q Limited by radiation

Superconductor/Ferrite Tunable Filter

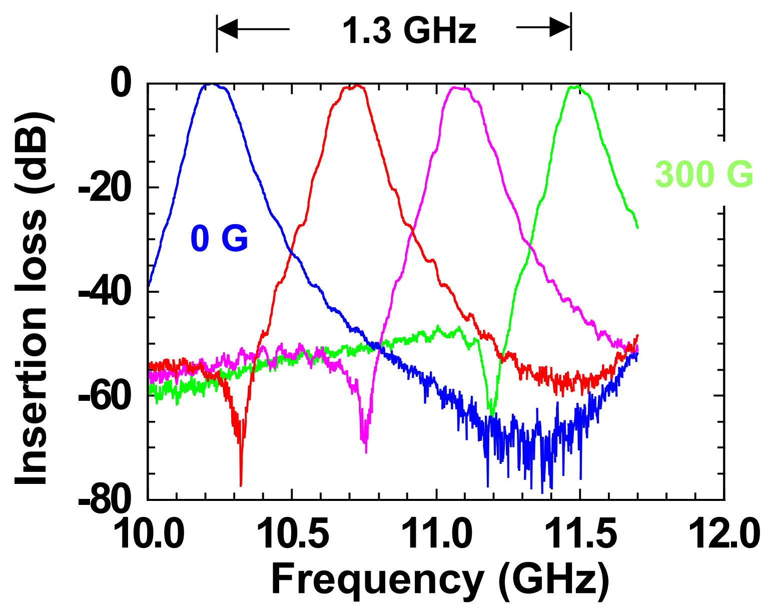
Niobium on Ferrite

3-Pole 1%-Bandwidth Design





Measured Response



Initial Results

- 13% tunability
- 0.6 dB insertion loss
- < 1 μs tuning time
- Low-energy tuning

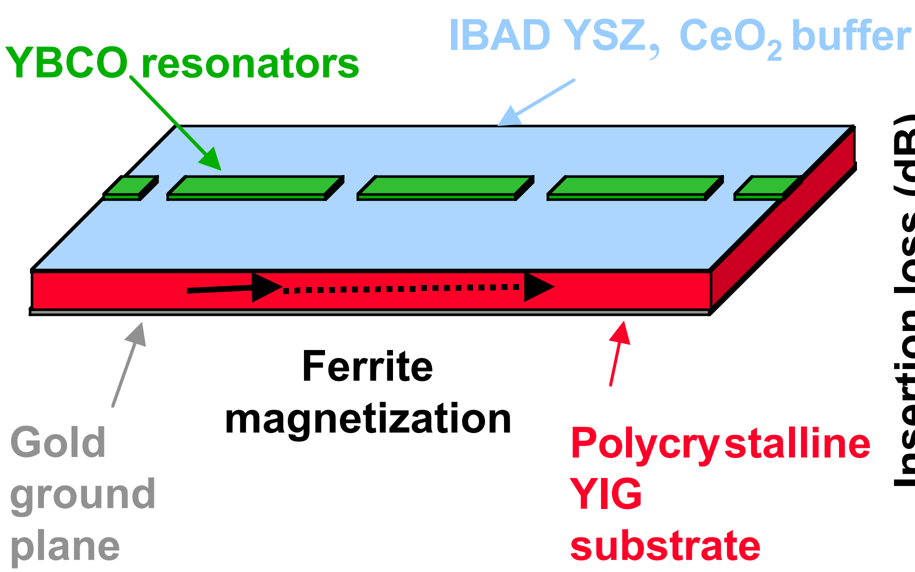
High-T_c Material Deposition

- YBCO and other high-T_c materials need to be grown epitaxially on a lattice-matched substrate
- Impossible directly on polycrystalline ferrite
- Ion-beam assisted deposition (IBAD) produces oriented buffer layer on noncrystalline substrates
- High-quality YBCO can be grown on buffer layer

HTS Tunable Filter

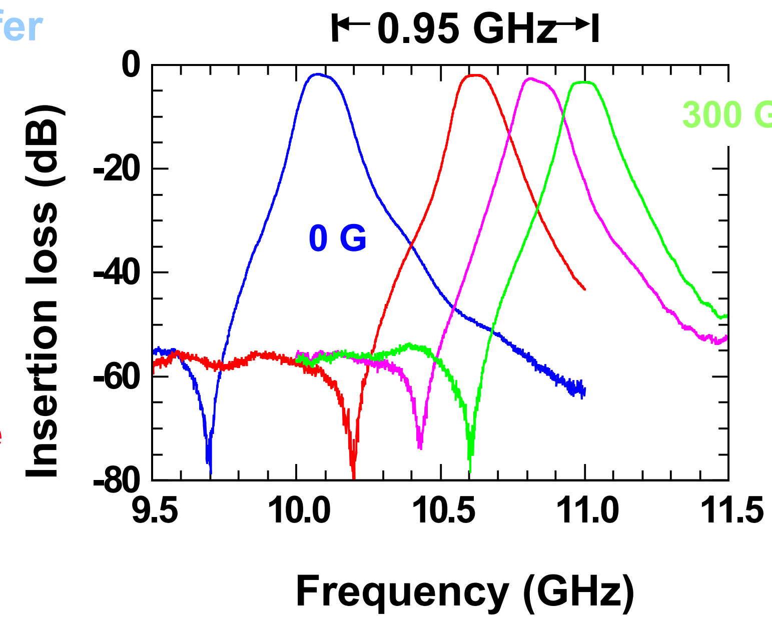
YBCO on YIG by Ion-Beam-Assisted Deposition (IBAD)

3-Pole Tunable Filter



Measured response

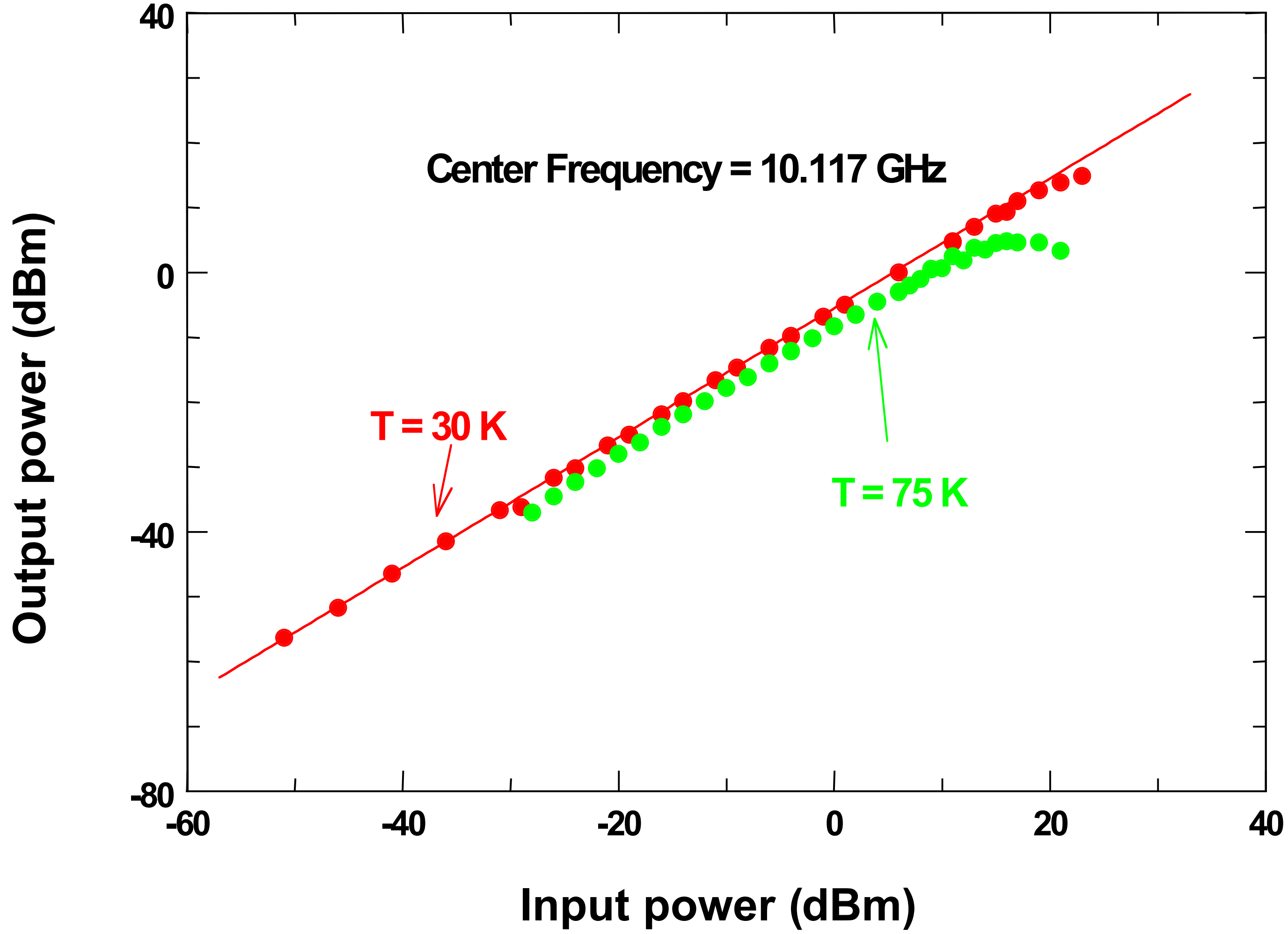
T = 77 K



- 9% Tunability
- 2-dB Insertion loss
- 10-mW power handling

IBAD and YBCO deposited at Los Alamos National Laboratory

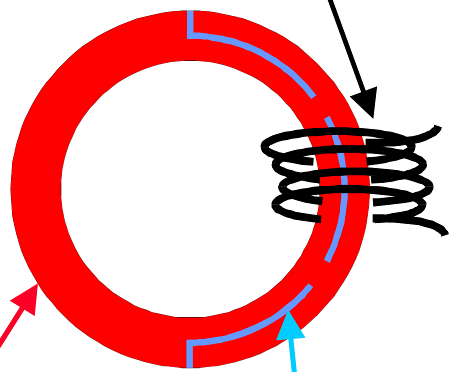
Power Handling IBAD YBCO

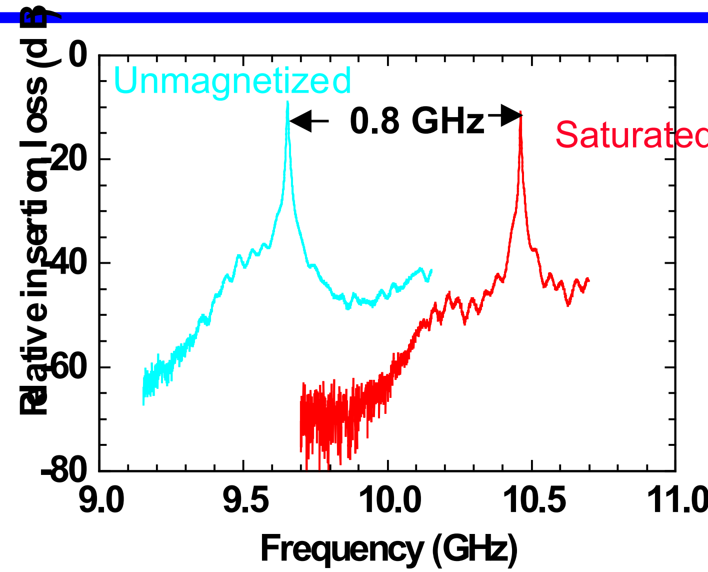


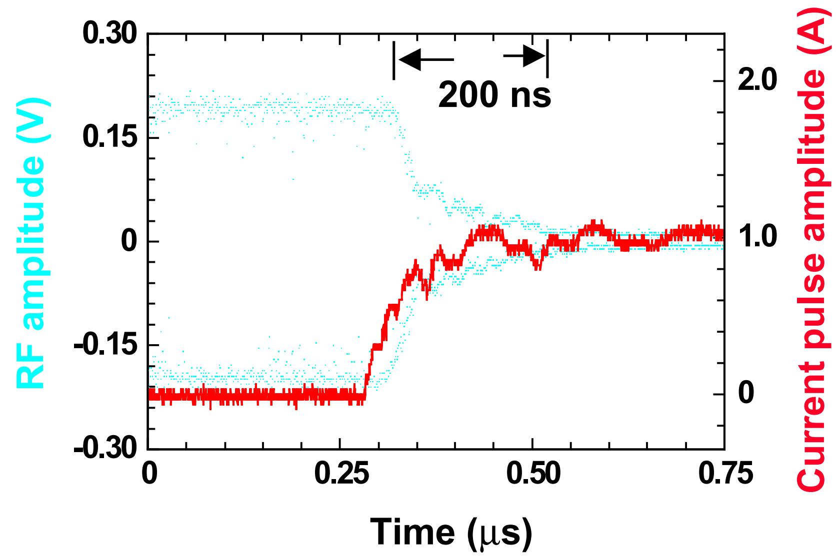
Outline

- Motivation
- Principle of operation
- Results resonators and filters
- Switching speed measurements
- Future work
- Summary

Tunable Resonator with Closed Magnetic Circuit

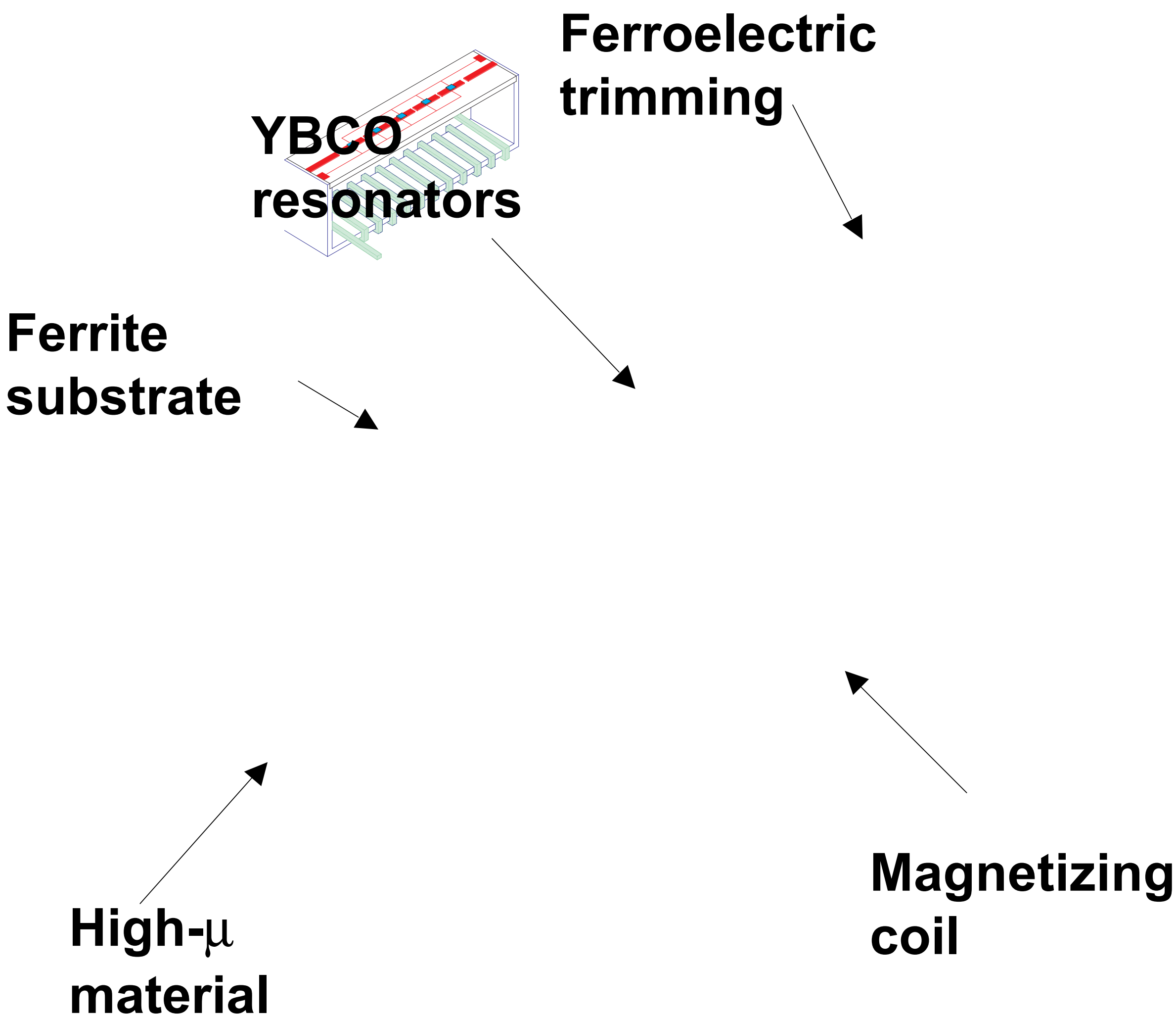






- Closed magnetic circuit for large tuning range and low-energy sub-μs tuning time

Superconductor/Ferrite Tunable Filter with Ferroelectric Trimming



Summary of Superconductor/Ferrite Filters

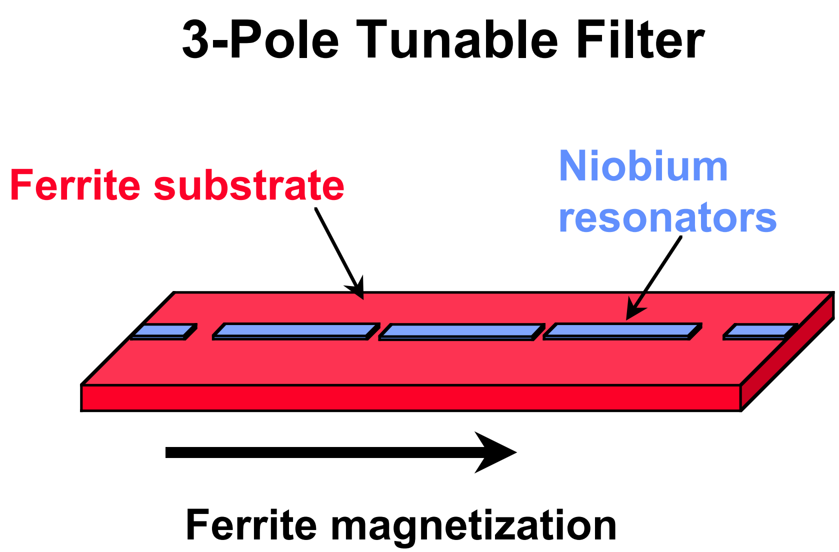
Demonstrated Features

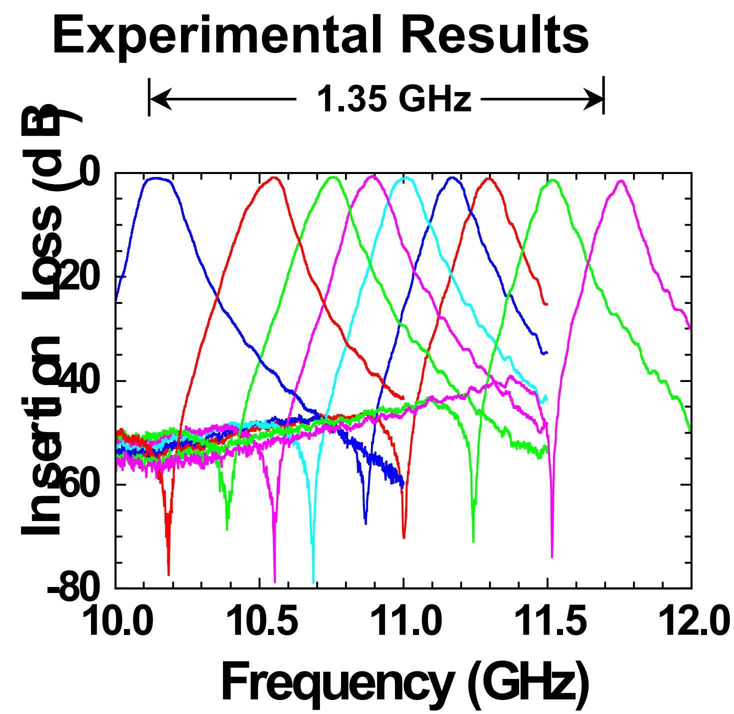
- Tunable 3-pole filter with IBAD YBCO on polycrystalline ferrite at 77 K
- For niobium at 4 K:
  - Adequate tunability > 10%
  - 3-pole 1%-bandwidth filter with <1-dB insertion loss
  - 3rd-order intermods -60 dBc at +10 dBm input
  - High Q resonators
    - > 5000 at 10 GHz
  - Figure of merit $2Q\Delta f/f$
    - > 300 demonstrated
    - > 1000 projected
  - High-speed tuning
    - τ < 200 ns

Further Work

- Extend filter to 4 or 5 poles
- Narrower bandwidth
- Improve ferrite loss and tunability with modified ferrites
- Higher-Q material including single crystals
- Improved YBCO on ferrite
- Trimming with ferroelectrics

Superconductor/Ferrite Tunable Filter

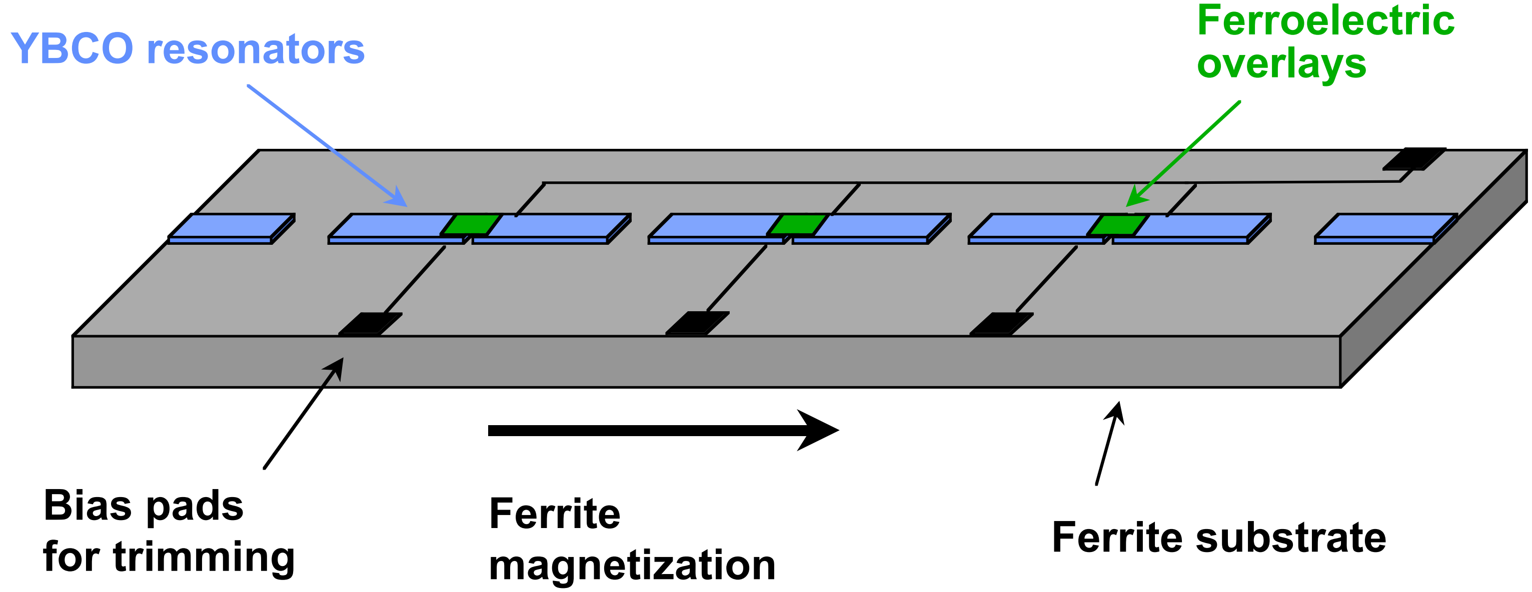




- 3-Pole 1%-bandwidth filter
- >10% tunability
- Third-order intermods -60 dB at +5 dBm
- Niobium resonators at 4 K
- Will be extended to YBCO at 77 K

Superconductor/Ferrite Tunable Filter with Ferroelectric Trimming

Proposed 3-Pole Tunable Filter



Program Goals

- Compact, X-band, 3-pole, 1%-bandwidth filter
- Tunability 10%
- Tuning time 1 μs
- Low-energy tuning
- Insertion loss less than 1 dB

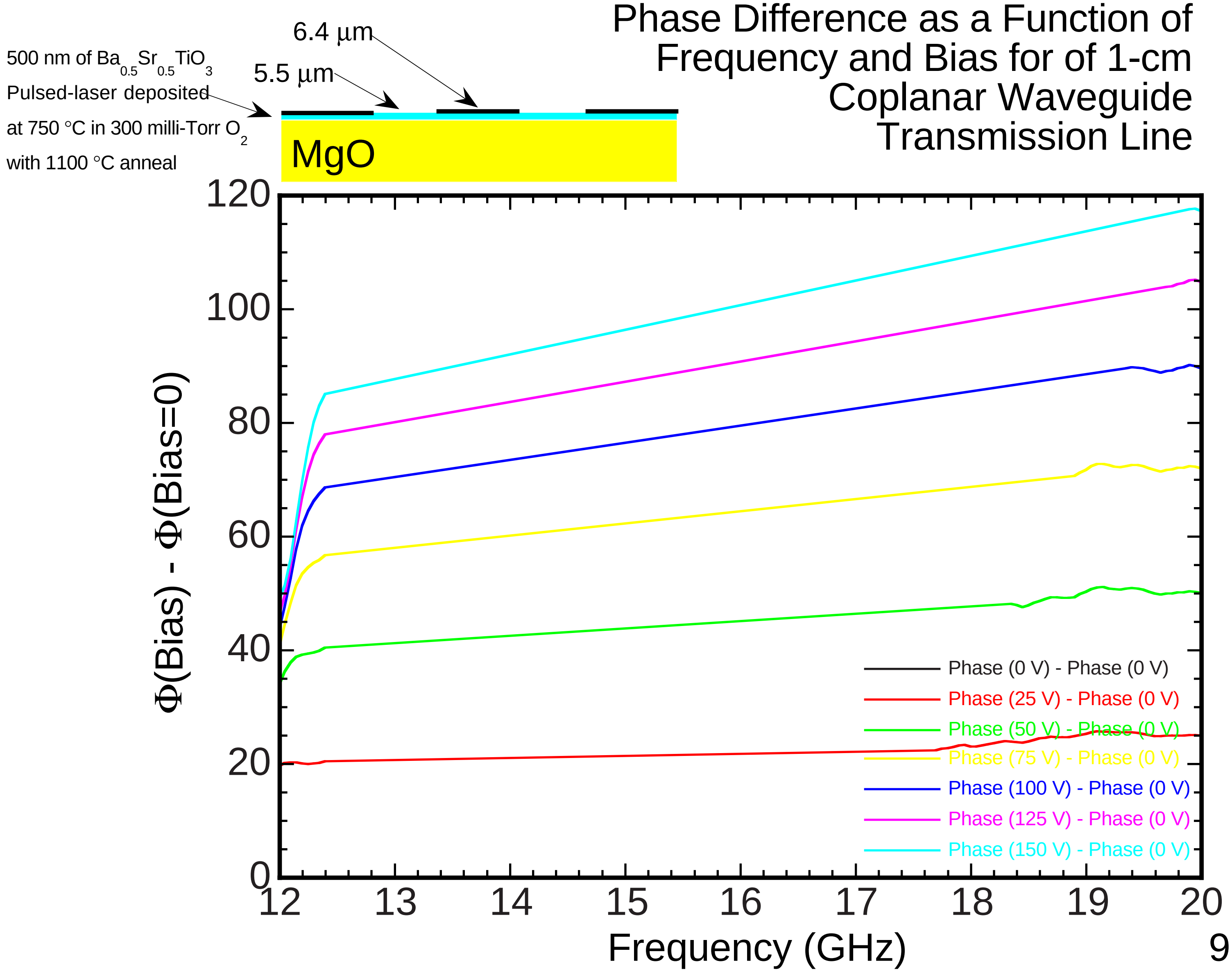
Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- **Tuning technologies**
  - general issues and conventional technology
  - ferrites
  - **ferroelectrics**
  - microelectromechanical systems (MEMS)
- Conclusions

Ferroelectrics for Tuning:

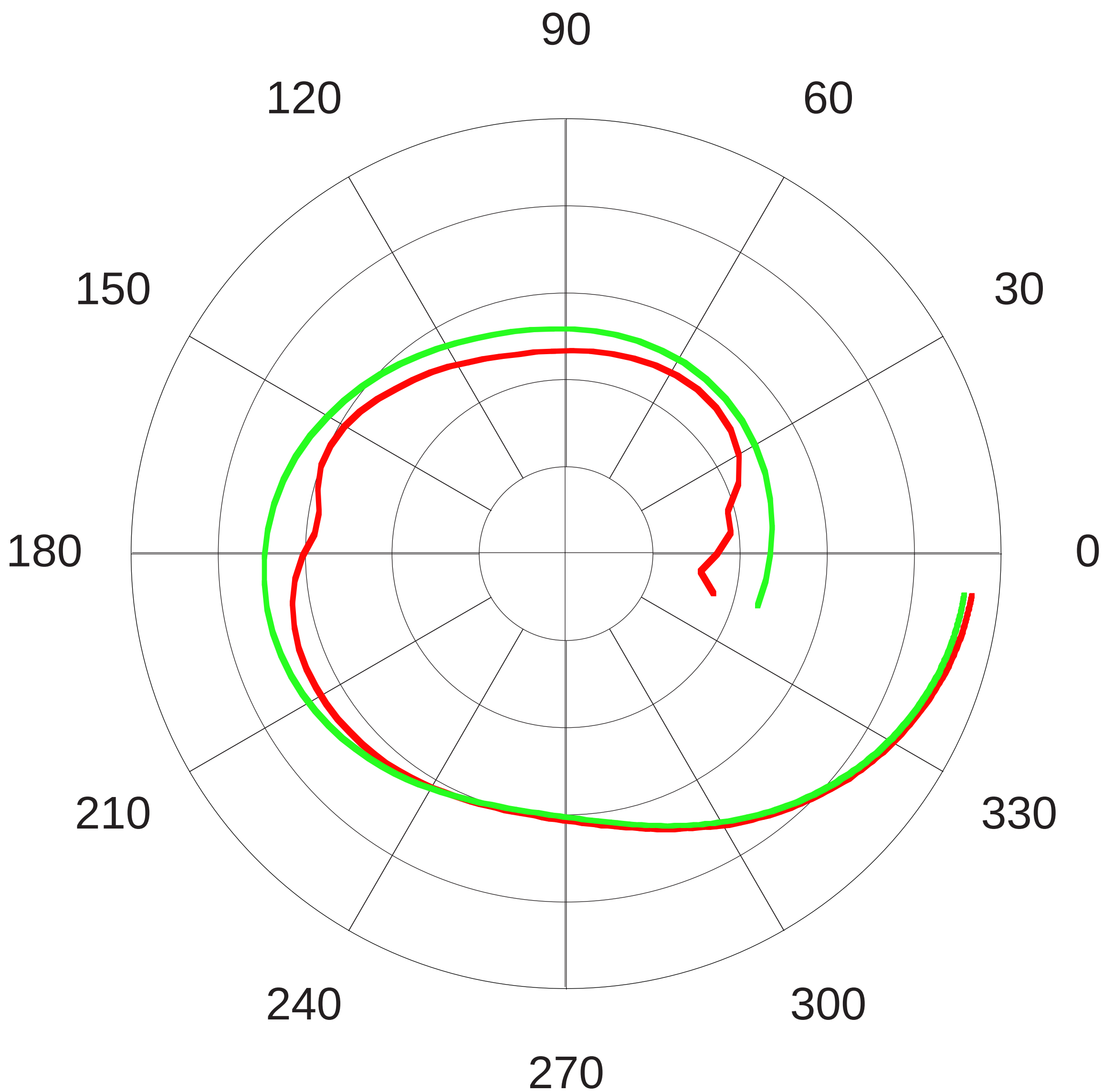
- Large relative permittivity leads to to field concentration in ferroelectrics. Thin films are a viable approach
- Many metal-oxide based ferroelectrics (e.g. $Sr_xBa_{1-x}TiO_3$) have structural similarities to HTS materials and are amenable to similar deposi tion processes and are compatible
- Switching speed are theoretically less than 1 nsec. Potentially a very fast technology.
- Much of the material development is presently focused at room temperature operation but should transition to cryogenic applications
- Figure of Merit of > 20 from recent room temperature measurements
- Virtually no current (except when changing bias) means lightweigth power supply, thin bias lines, low thermal load

Phase Difference as a Function of Frequency and Bias for of 1-cm Coplanar Waveguide Transmission Line



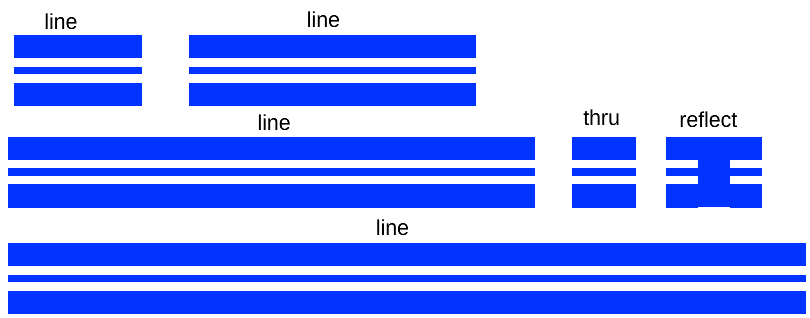
99040804b

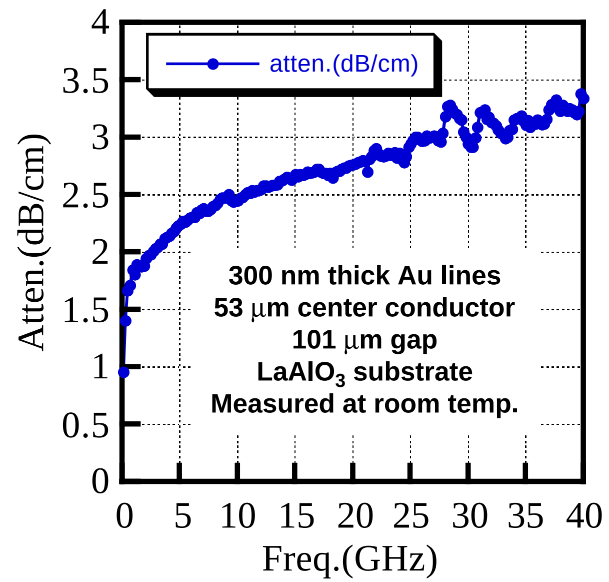
S_{21} Measured Data and Model (0.05 - 5.0 GHz)



Summary of Dielectric Film Measurements at Microwave Frequencies using Wafer Probing Techniques at NIST, Boulder

Use on-wafer multiline TRL calibrations to obtain propagation constant vs. frequency for sets of CPW transmission lines





Complex propagation constant $\gamma(\omega)$:

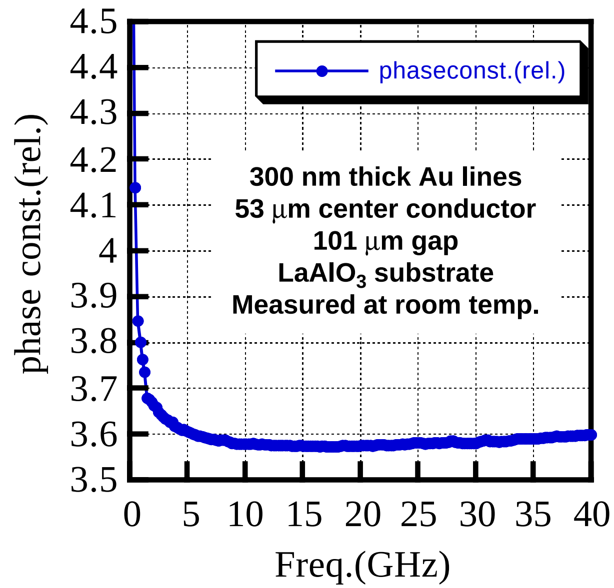
$$\gamma = \alpha + i\frac{\omega}{c}\varphi_{rel}$$

α = atten. const.

ϕ_{rel} = relative phase const.

ω = angular freq.

c = speed of light

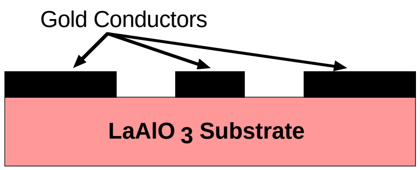


NIST
High-T_C Electronics Project

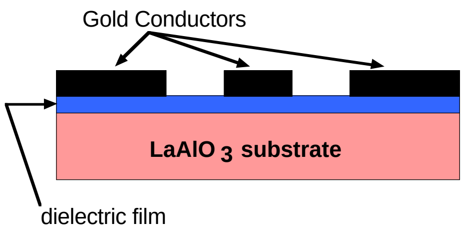
Summary of Dielectric Film Measurements at Microwave Frequencies using Wafer Probing Techniques at NIST, Boulder

•Approach: Compare propagation constant measurements of samples with and without dielectric thin film

Reference Sample:



Test Sample:



•Obtain capacitance and conductance per unit length from propagation constant data for fixed temperature, bias voltage.

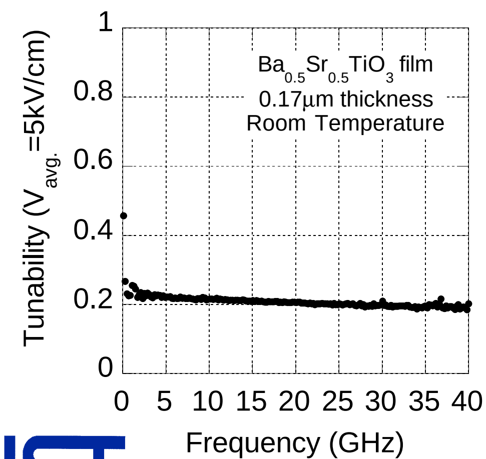
•Extract film characteristics from CPW capacitance C(ω) and conductance G(ω):

$$\text{Loss Tangent(V)} = G_{film}(V)/\omega C_{film}(V)$$

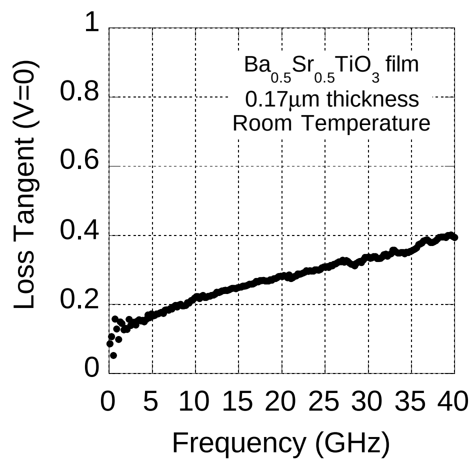
$$\text{Tunability(V)} = \frac{C_{film}(0) - C_{film}(V)}{C_{film}(0)}$$

$$\text{Figure of Merit K(V)} = \frac{\text{Tunability(V)}}{\text{Max. Loss Tangent}}$$

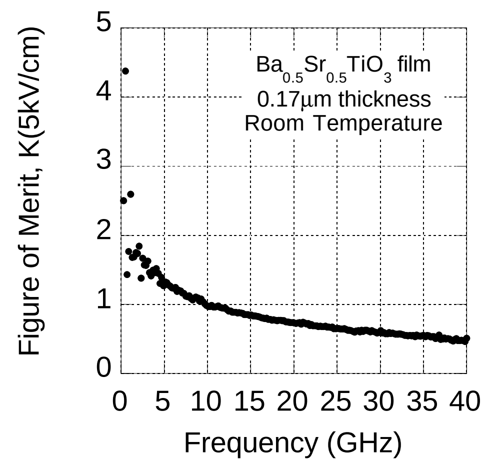
Film Tunability vs. Frequency



Film Loss Tangent vs. Frequency



Film Figure of Merit vs. Frequency



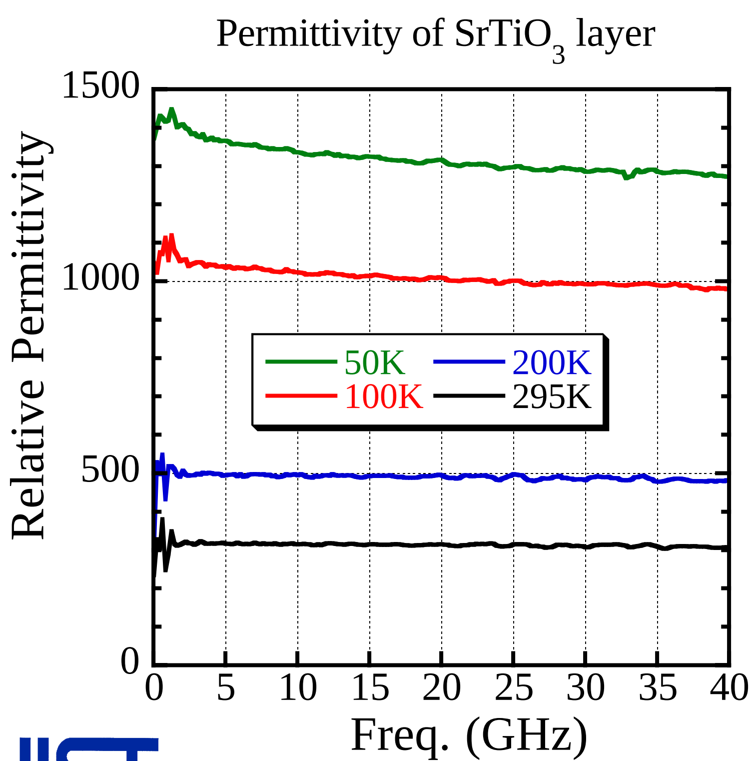
NIST

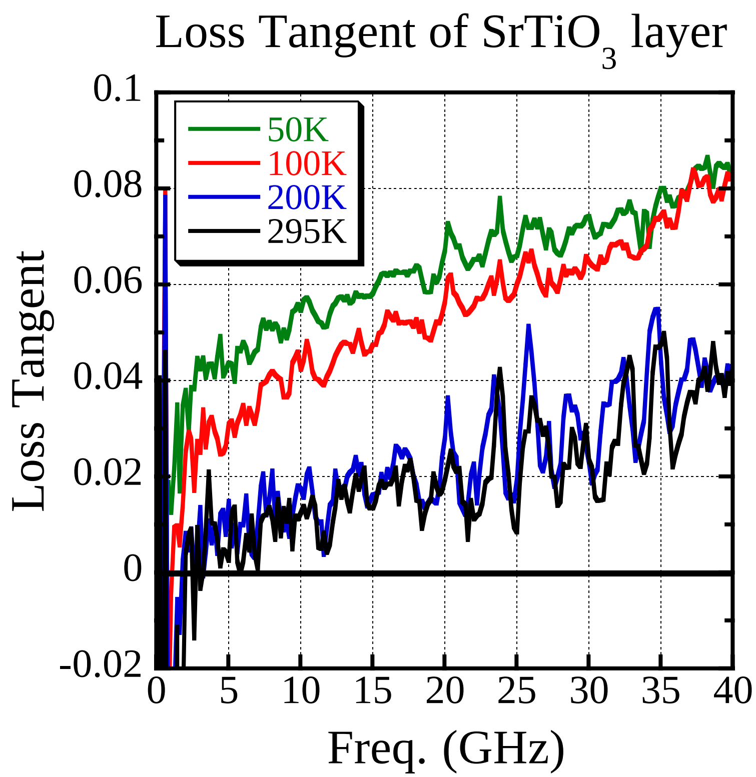
High-T_C Electronics Project

Summary of Dielectric Film Measurements at Microwave Frequencies using Wafer Probing Techniques at NIST, Boulder

Use of cryogenic probe station allows for measurement of ferroelectric films at variable temperatures

Obtain permittivity from C(ω) data using conformal mapping.





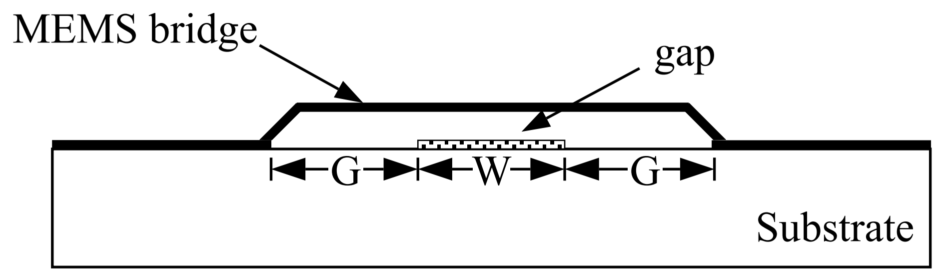
Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- **Tuning technologies**
  - general issues and conventional technology
  - ferrites
  - ferroelectrics
  - **microelectromechanical systems (MEMS)**
- Conclusions

MEMS for Tuning:

- Last few years has seen explosion in application of MEMS to rf and microwave systems – much of the effort is foced on switches
- Most development is focused at room temperature operation. Often Si based technology since the potential market is large.
- Only relatively recently have there been efforts made to apply this technology to tuning HTS – little is publically available
- Switching speed are approaching 1 μsec. Competitive with ferrites.
- Transmission line conductor losses determine attenuation in 300K MEMS phase shifter – HTS has potential for substantial performance improvement
- Issues for application to HTS tuning include:
  - coefficient of thermal expansion matching
  - temperature dependence/difference of mechanical properties of materials

Voltage Actuation of MEMS Bridge



Force

$$F = \frac{\varepsilon_o W w}{2g^2} V_{bias}^2 \quad (N)$$

Spring Constant

$$k = \frac{32Et^3w}{L^3} + \frac{8\sigma(1-\upsilon)tw}{L} \quad (N/m)$$

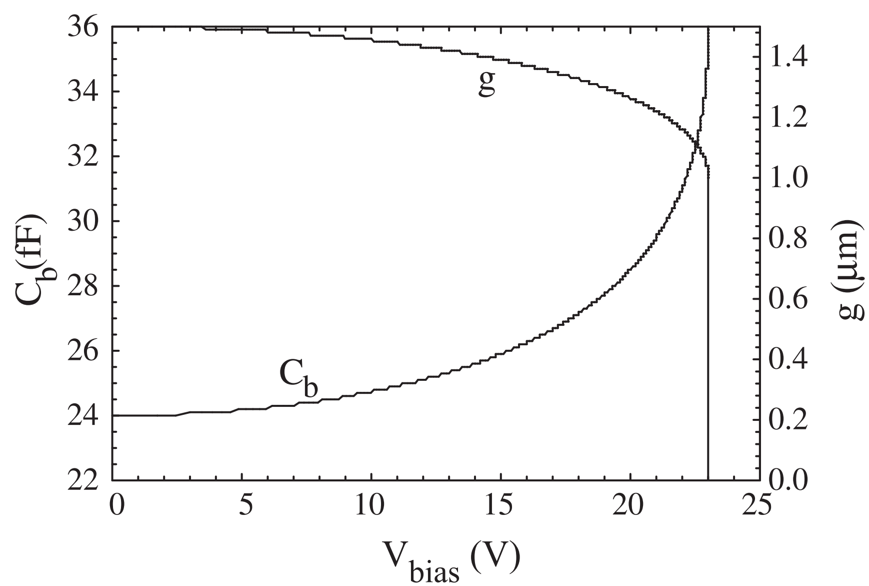
Static Equation

$$F = k(g_o - g)$$

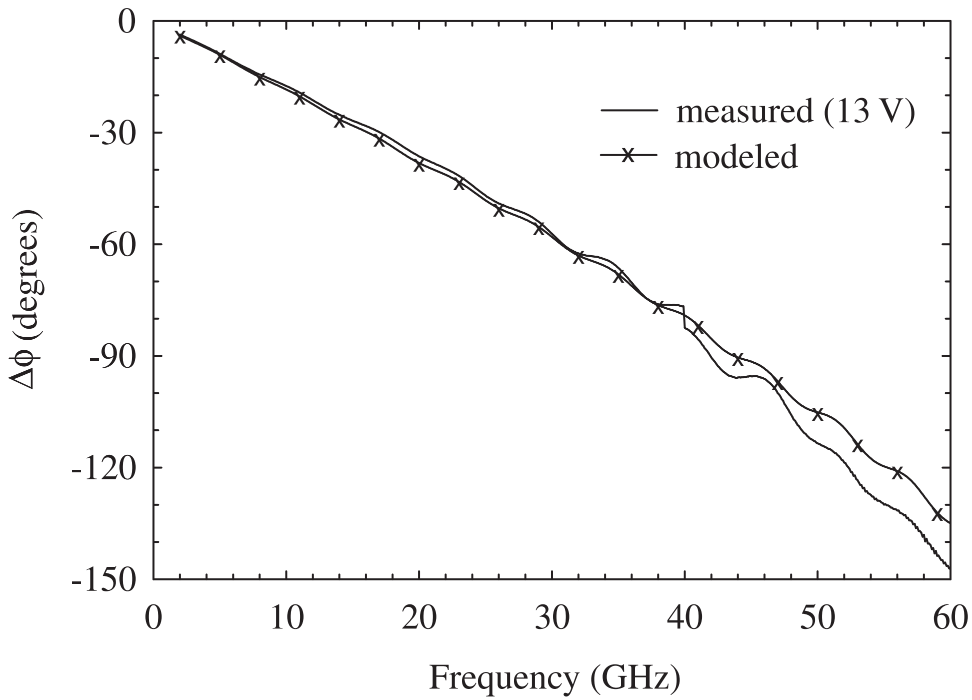
Pull-Down Voltage

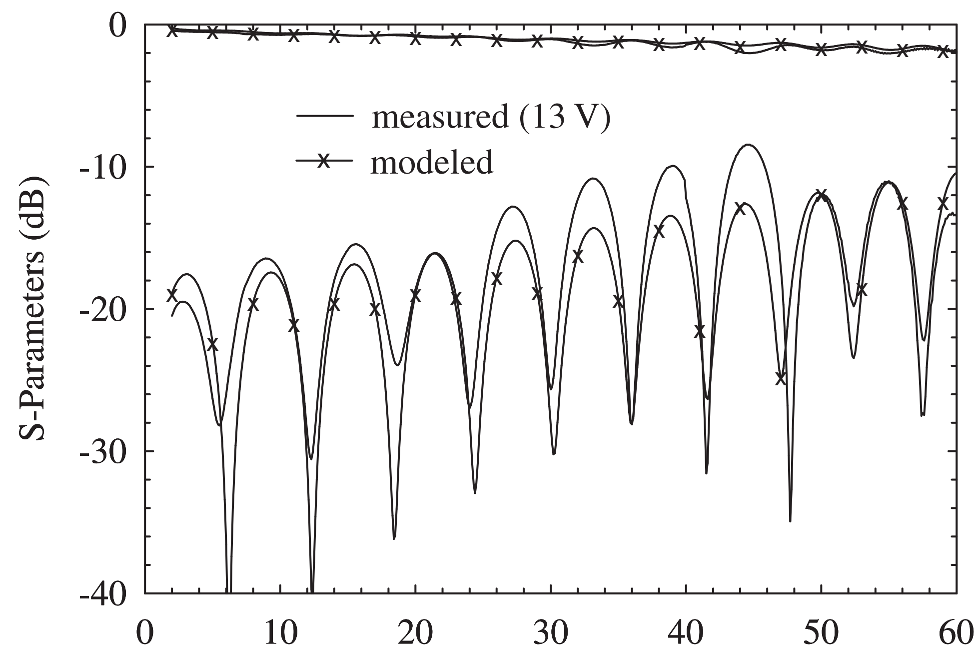
$$V_p = \sqrt{\frac{8k}{27\varepsilon_o W} g_o^3} \quad (V)$$

σ	V_p (t=1 μm)	V_p (t=0.5 μm)
0 MPa	10 V	4 V
20 MPa	21 V	14 V
100 MPa	43 V	30 V



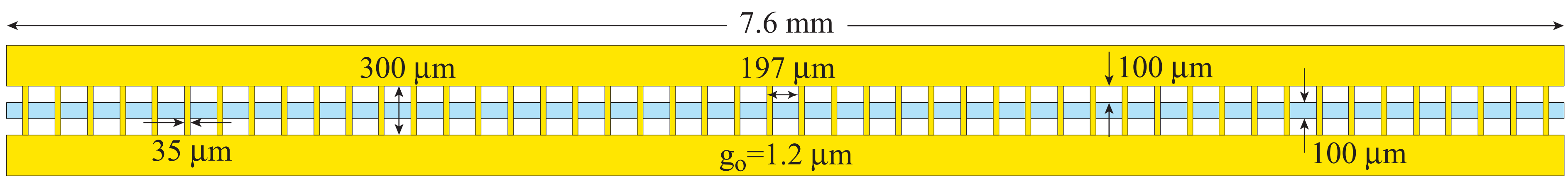
Optimal Distributed MEMS Transmission Line





C_{bu}	34.6 fF
C_{bd}	40.6 fF
L_b	11 pH
A(@ 20 GHz)	0.46 dB/cm

Z_o	96 Ω
Z_{lu}	47 Ω
Z_{ld}	45 Ω
C_{bd}/C_{bu}	1.17



Outline:

- Introduction
  - acknowledgements
  - motivation
- Distinction between Trimming and Tuning
- Mechanical trimming while at operating temperatures
  - needs and requirements
  - equipment and technique
  - results
- Tuning technologies
  - general issues and conventional technology
  - ferrites
  - ferroelectrics
  - microelectromechanical systems (MEMS)
- **Conclusions**

Conclusions:

- Trimming is often necessary in high performance HTS circuits
  - it can be designed into package while preserving performance
  - apparatus for trimming at cryogenic temperatures is relatively easy
- Tuning of HTS devices & circuits is receiving a great deal of R&D effort
- Ferrite tuning is the most developed and exhibits the best performance
  - useful tuning range demonstrated
  - tuning speed is fast enough for many applications
  - losses are encouragingly low and can expect to improve
- Considerable R&D investment in ferroelectric tuning shows promise
  - complicated materials systems is difficult to understand
  - has promise of very fast tuning speeds
  - need to improve tuning range of materials with high Qs
- MEMS tuning holds great promise but needs investment
- Tunable HTS technology has great potential
  - lots of good R&D is needed in the near term
  - very good prospects for a viable market in the longer term

Conclusions (cont.):

- Research needed to address
  - understanding and control of microwave losses in ferrites and ferroelectrics at cryogenic temperatures
  - mechanical properties of materials at cryogenic temperatures for MEMS applications
  - novel circuit topologies which can leverage these technologies
  - new tuning technologies and concepts

- Practical applications of these technologies will require development in the areas of:
  - materials compatibility over extreme temperature ranges and multiple thermal cycles
  - biasing circuits (techniques, layouts and design rules) that will preserve microwave performance
  - packaging