HTS Materials and Devices for RF Applications

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- Potential markets / motivation for HTS RF electronics
- Preparation of materials
- Measurement of RF properties
- Northrop Grumman's interest in HTS
  - Analog subsystems for Cryoradar™
- Specific devices and applications
  - Microwave filters
  - Wireless communications
  - Oscillators
  - Delay lines
  - Tunable devices
  - Navy HTSSE program
- Comments on refrigeration
- Predictions

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HTS Materials and Devices for RF Applications: Bibliography

The proceedings of Applied Superconductivity Conferences from 1992 to 1998 are the best general sources for relevant papers. These are published in issue No. 2 of Vols. 3, 5, 7, and 9, respectively, of the *IEEE Trans. on Applied Superconductivity*.

- M. J. Lancaster, *Passive Microwave Device Applications of High-Temperature Superconductors* (Cambridge University Press, Cambridge, 1997).
- M. M. Fitelson, “Cryogenic Electronics in Advanced Sensor Systems,” IEEE Trans. on Applied Superconductivity 5(2), 3208 (1995).
- S. H. Talisa, M. A. Janocko, D. L. Meier, J. Talvacchio, C. Moskowitz, D. C. Buck, R. S. Nye, S. J. Pieseski, and G. R. Wagner, “High-Temperature Superconducting Space-Qualified Multiplexers and Delay Lines,” IEEE Trans. Microwave Theory and Techniques 44(7), 1229 (1996).
- M. M. Driscoll and R. W. Weinert, "Low-Noise, Microwave Signal Generation Using Cryogenic, Sapphire Dielectric Resonators: An Update," Proc. IEEE Symposium on Frequency Control, 157 (1992).

Viable Electronic Applications of HTS: Grouped by Markets

Radar / Military RF
- Front-end preselection
- Low-phase-noise waveform generator
- Antenna matching networks
- High dynamic range A/D conversion

Communications
- Low-loss, small-size filters
- Channelizers / multiplexers
- Spread spectrum comm
- High data-rate switching

Magnetic Anomaly Sensors
- Mine detection
- Submarine detection / ASW
- Geophysics

Medical Systems
- Magneto-encephalography
- Magneto-cardiography
- NMR and MRI pick-up coils

Computing
- Crossbar switches
- Cryo-CMOS MCM interconnects

Infrared Imaging
- On-FPA preprocessors
- VLWIR detection

Instrumentation
- Voltage and current standards
- Spectrum analyzer
- Sampling oscilloscope/ time-domain reflectometer

Passive RF Applications of HTS are Critical to the Cryogenic Electronics Industry

SQUID Sensors:
- Market is too small to develop industrial infrastructure

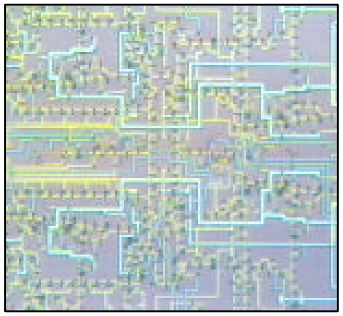
Instrumentation (e.g. voltage standards):
- Market is too small to develop industrial infrastructure

LTS Digital:
- High-speed signal processing capabilities demonstrated
- Integrated circuit fabrication well developed
- No one wants the size, cost, power consumption, and reliability risk of coolers

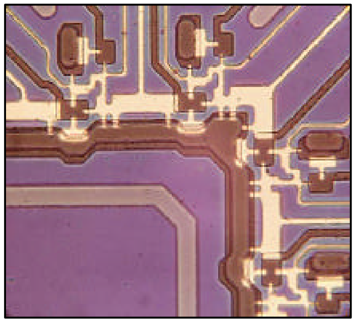
HTS Digital:
- Integrated circuit fabrication capability is relatively primitive

HTS Microwave Devices:
- Pay the bills at large and small companies specializing in superconducting electronics

LTS 2 x 2 Network Switch

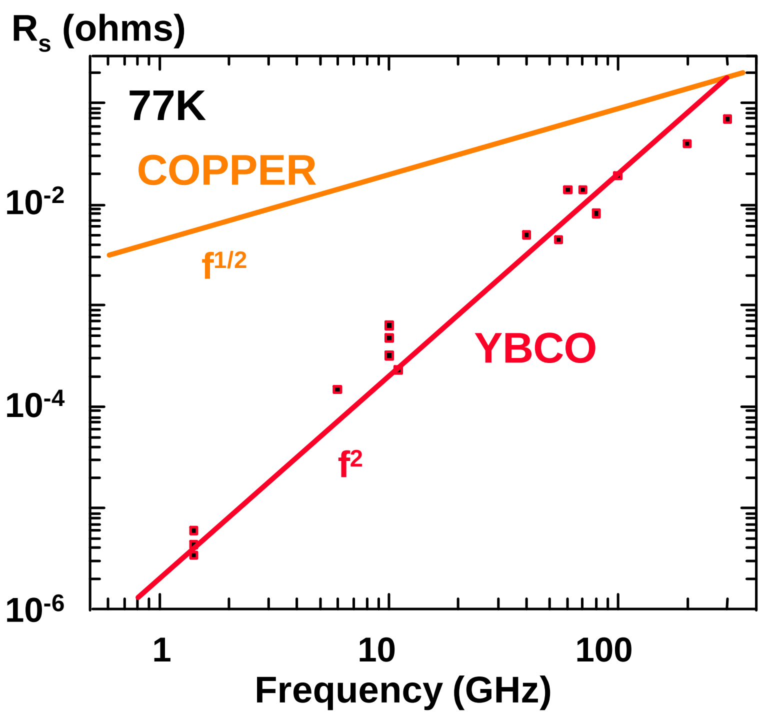


HTS 39-Jct Digital Circuit

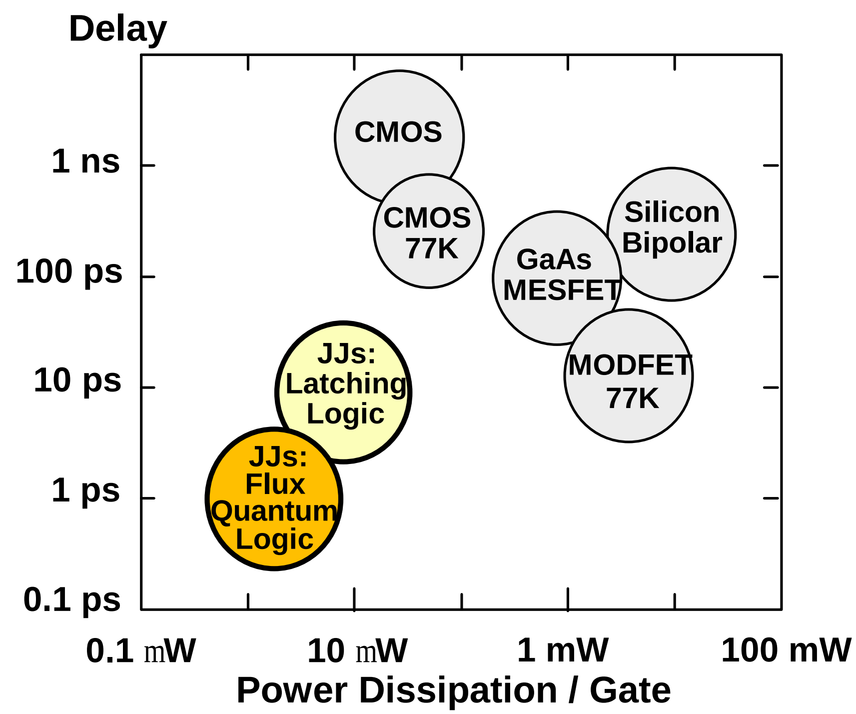


Orders of Magnitude Performance Advantage From Superconductivity and Cryogenics

1. Low Surface Resistance: Improved Performance of Microwave Devices



2. Reduced Power Dissipation and Delay: High-Speed Logic



3. Unique Quantum Accuracy: Voltage Standard, DAC, ADC

4. Low Noise from Cryogenic Operation

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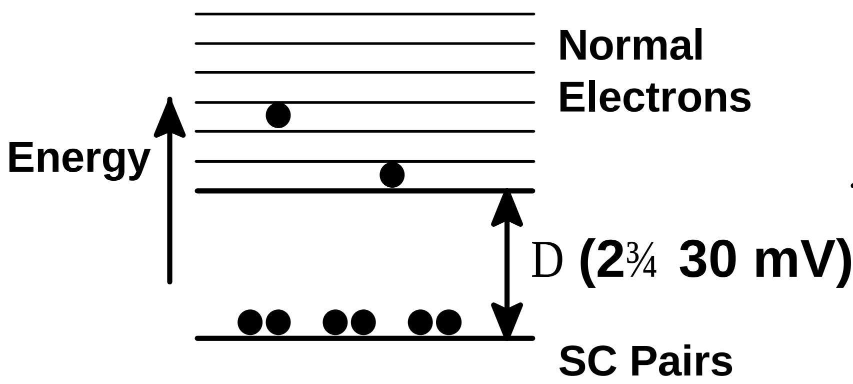
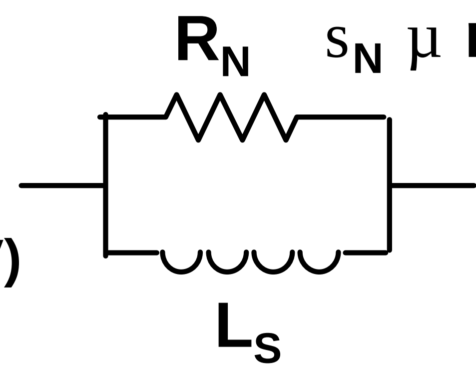
Two-Fluid Model of a Superconductor Relates dc and Microwave Properties





$\sigma_N \propto n_N \propto e^{-\Delta / kT}$

For a Normal Metal:

Skin depth, $\delta_N^2 \equiv \dfrac{1}{\mu_o \sigma_N \omega}$

$R_{surface} \propto (\omega / \sigma_N)^{1/2}$

>>

For a Superconductor:

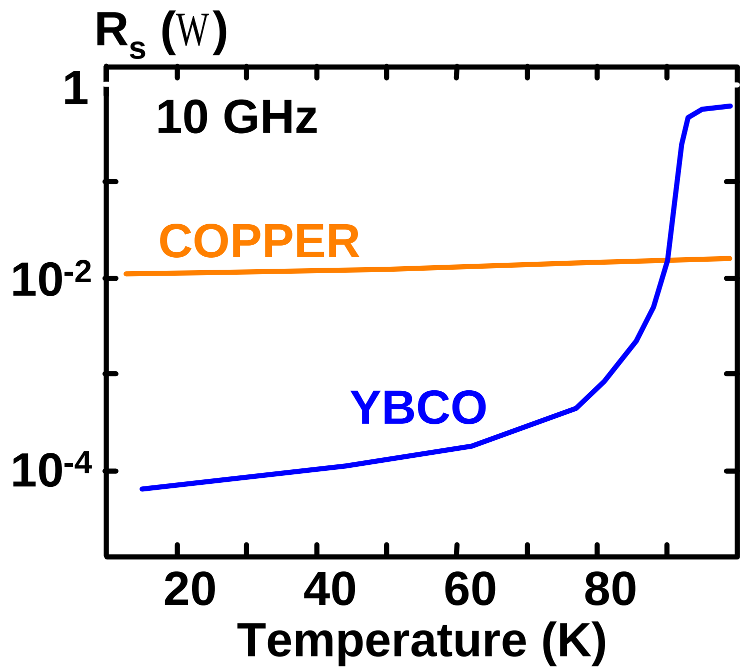
$\lambda^2 \equiv \dfrac{1}{\mu_o \sigma_S \omega}$

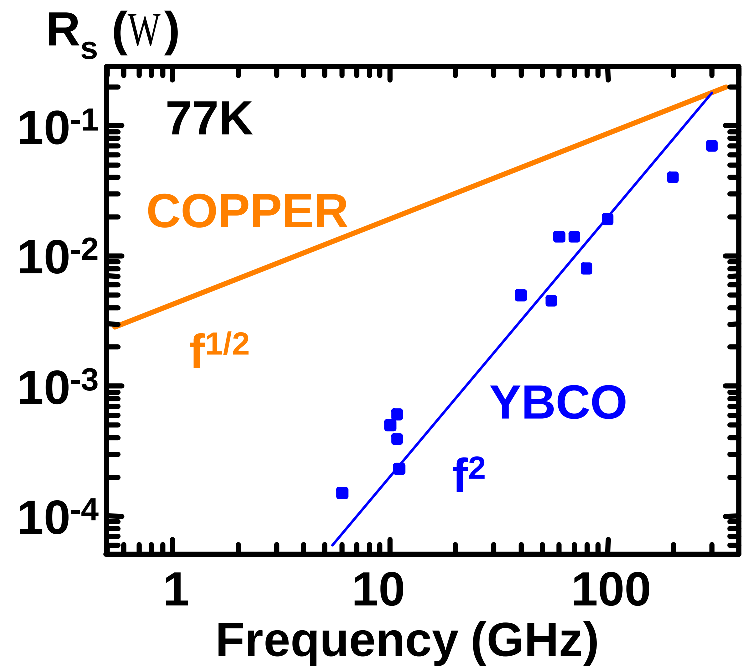
Magnetic penetration depth is independent of frequency

$R_{surface} \propto \omega^2 \sigma_N$

What did we have to learn to do? Low RF Surface Resistance of YBCO

- Epitaxial films grown on single-crystal substrates
- C-axis orientation (Cu-O planes parallel to substrate)





Having obtained low R_s, other factors will determine whether passive HTS devices are ultimately successful:

- **manufacturing costs - CAIV**
- **power handling**
- **dynamic range (linearity)**
- **weight and volume**

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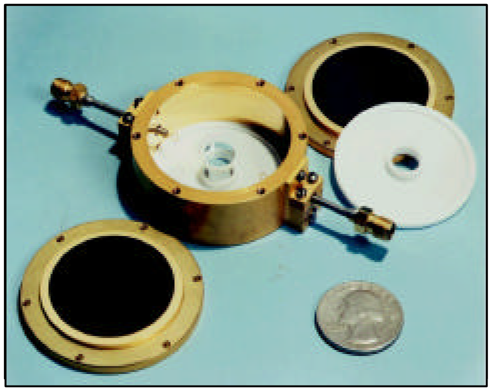
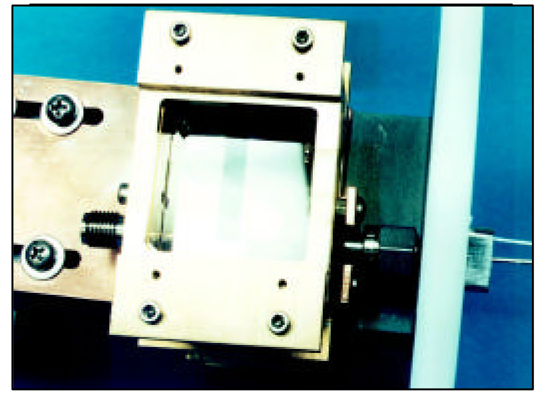
Large-Area, Double-Sided YBCO Films: Materials Base for a First Generation of Devices

STALO Resonator

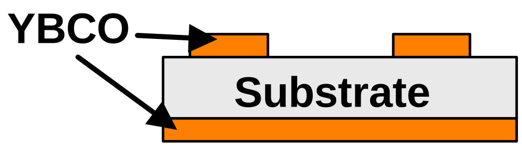


Single Film Layer

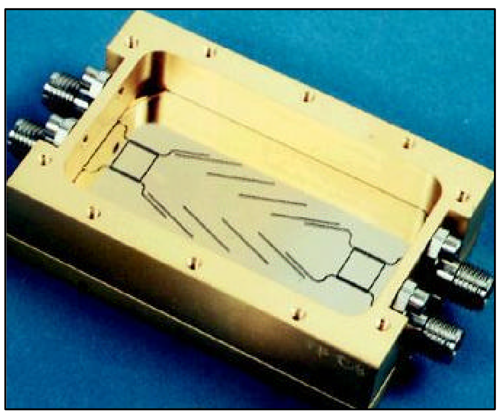
UHF Antenna



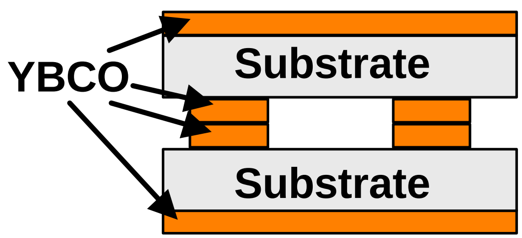
Microstrip Transmission Lines



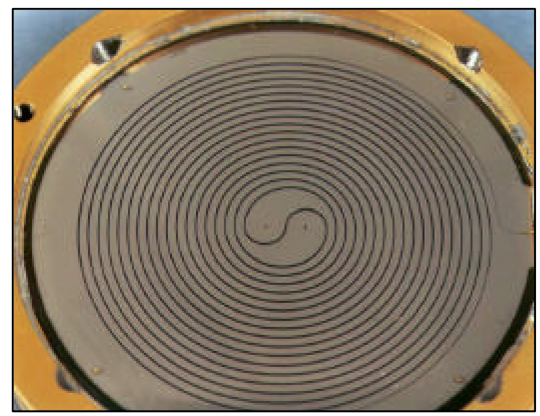
Filterbank Channel



Stripline Transmission Lines



Delay Line



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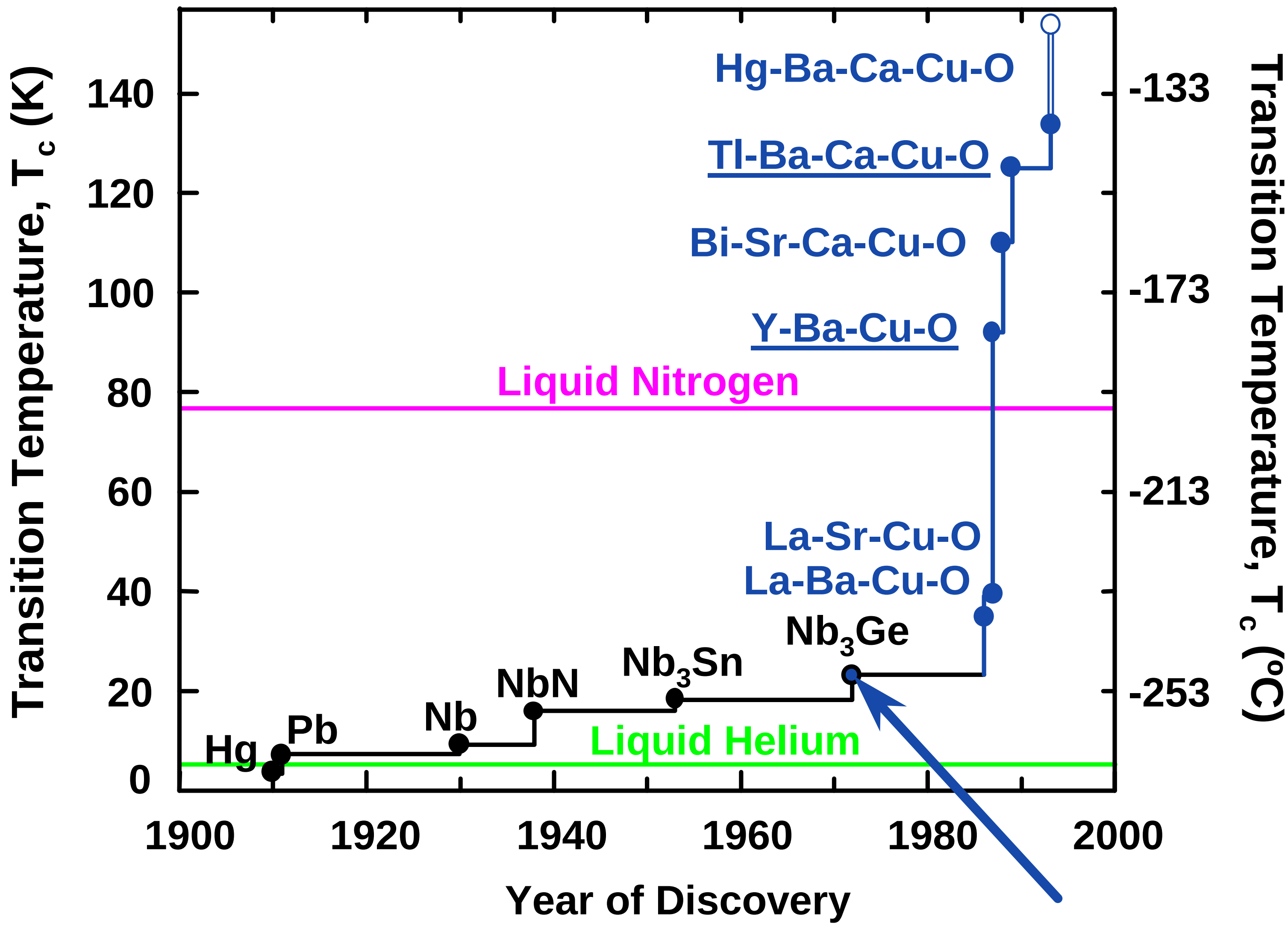
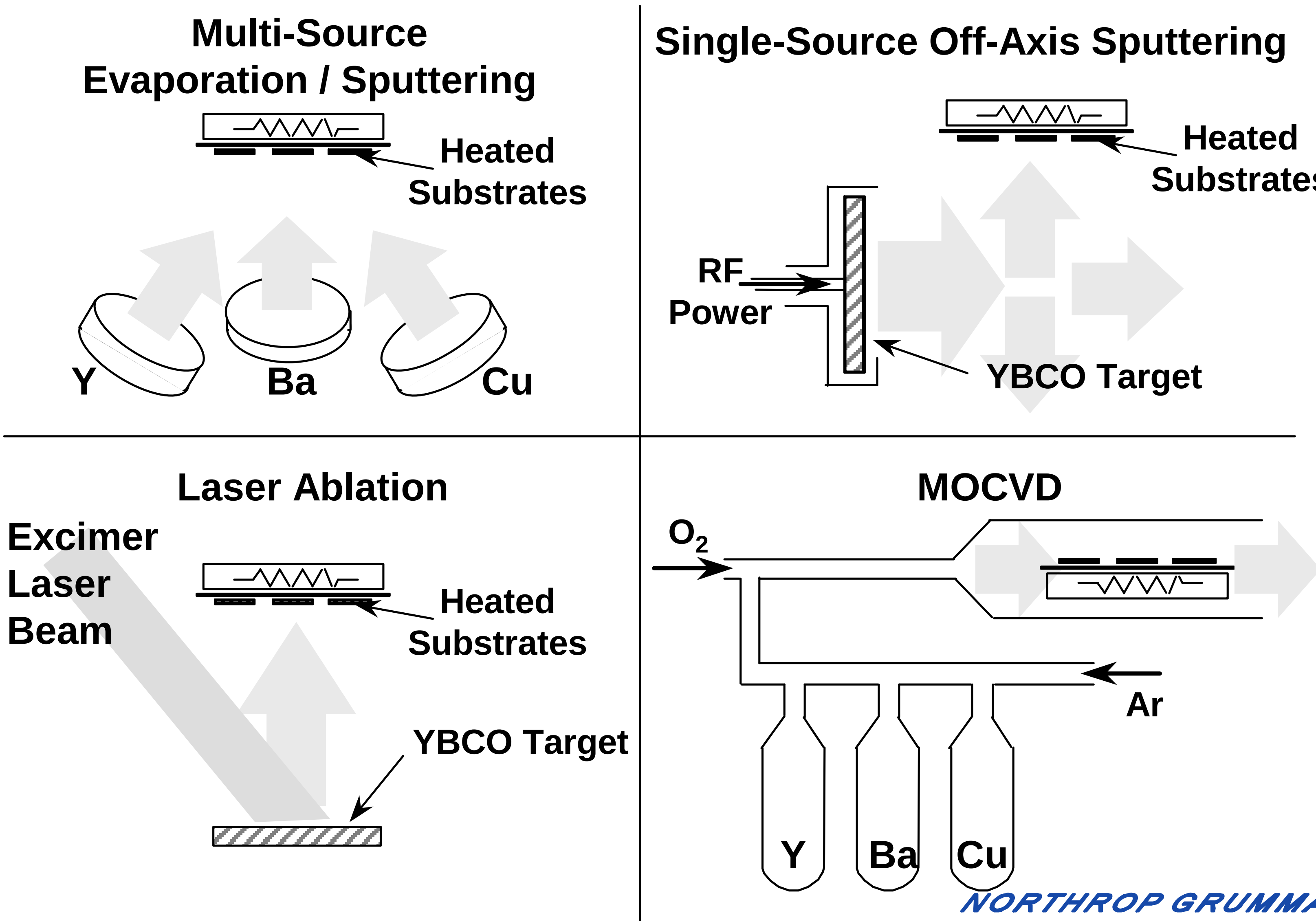
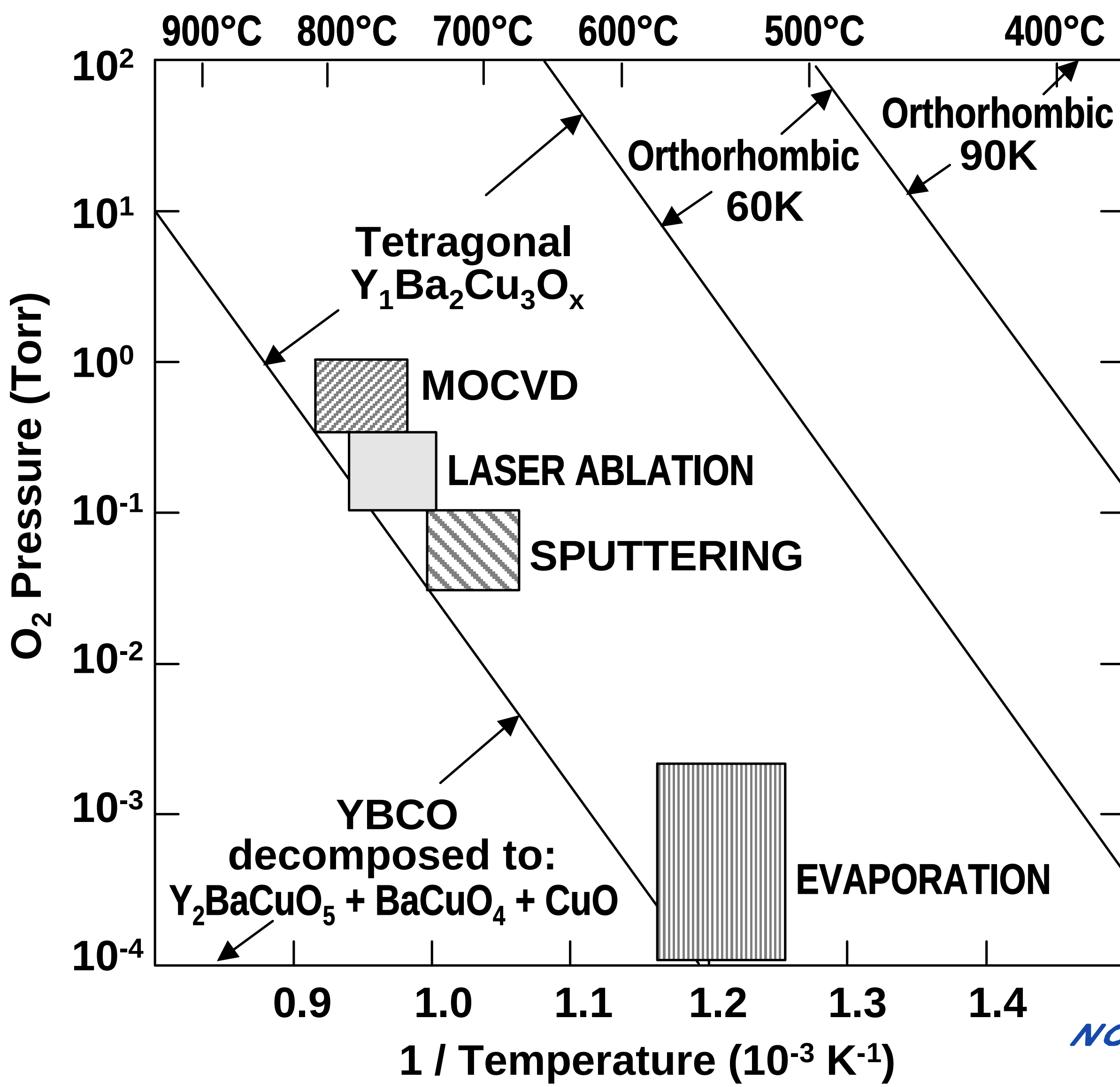
High-T_c Superconductors Reduce Refrigeration Requirements



Film Deposition Techniques for Epitaxial Oxide Superconductors

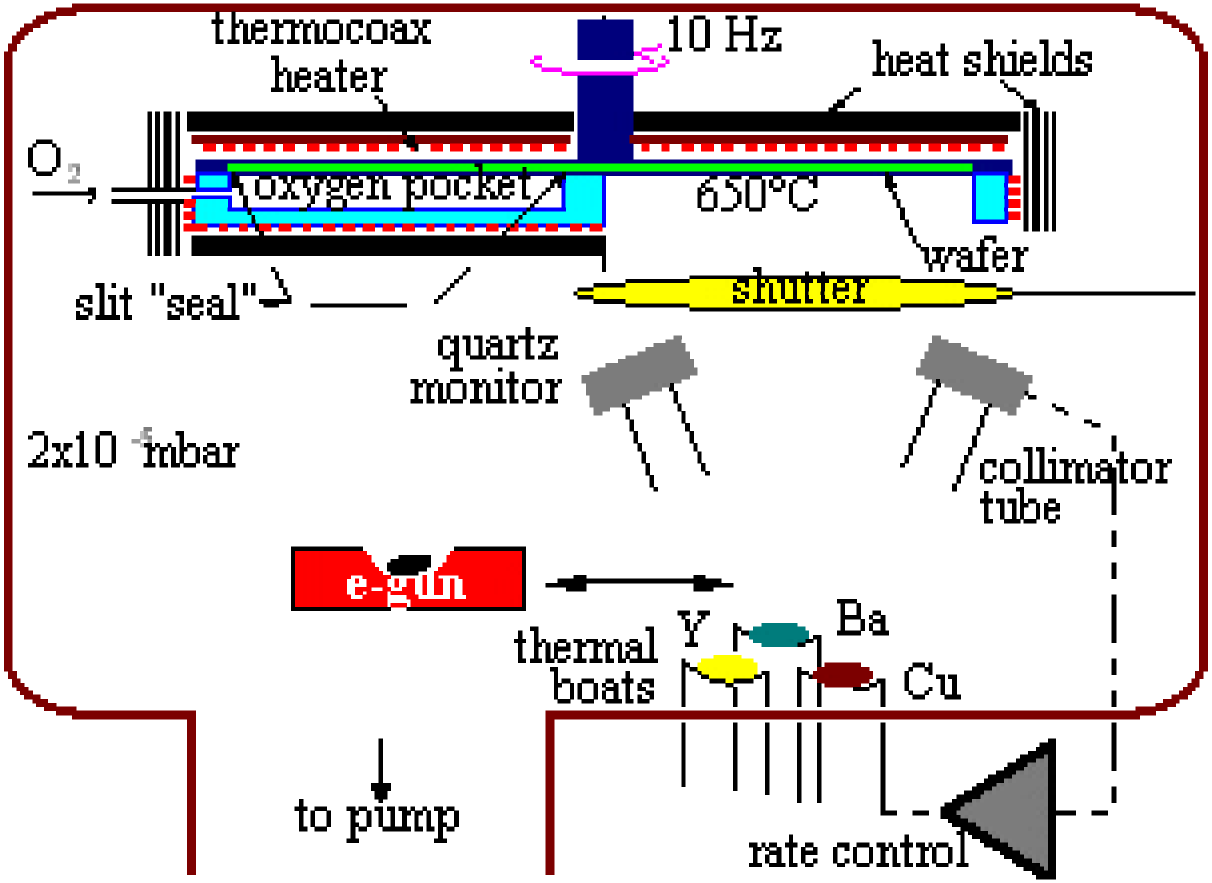


Oxygen Phase Diagram for YBCO: Oxygen Order and Stoichiometry are Keys to Performance



- **Shaded areas indicate typical growth conditions for high-quality YBCO films**

Film Growth for Microwave Applications: The Garching Process™



All of the sophistication of this process is in the heater design

- **High vacuum permits high deposition rates and good rate control**
- **Oxygen gas pocket permits YBCO phase formation**

Measurement of RF Surface Resistance

Most measurements of R_s use a resonant cavity and infer R_s from the measured Q where,

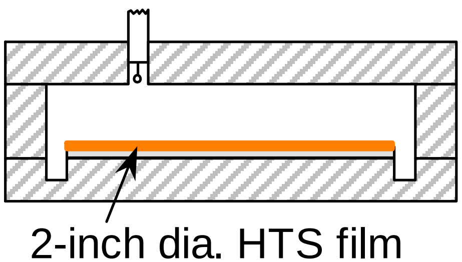
$$1 / Q = 1 / Q_s + 1 / Q_{dielectric} + 1 / Q_{radiation} + 1 / Q_{normal\text{-}metal}$$

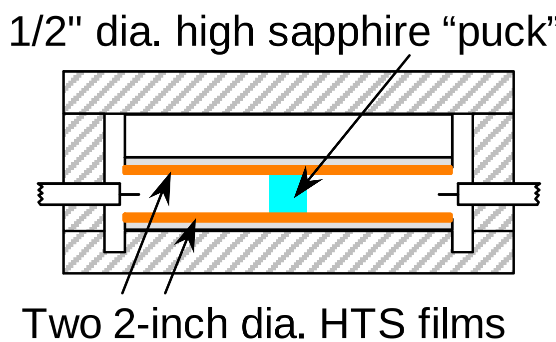
- $1/Q$: **Measured**
- $1/Q_s$: $R_s \; \mu \; 1 / Q_s$
- $1/Q_{dielectric}$: **If the cavity is loaded with a dielectric (= tan d)**
- $1/Q_{radiation}$: **Energy may be lost by radiation**
- $1/Q_{normal\text{-}metal}$: **e.g., cavity with Cu walls**

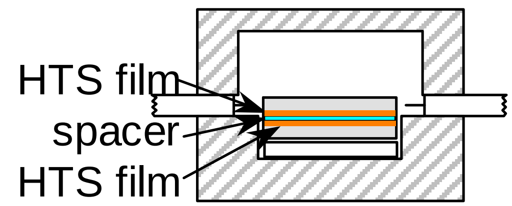
- **For a sensitive measurement, Q_s should be the smallest of all of these Q_s, i.e., the low-loss superconductor should be the lossiest part of the device**
- **A well-designed measurement apparatus will have low Q_s even when R_s is small**
- **In contrast, a well-designed device will have a high Q**

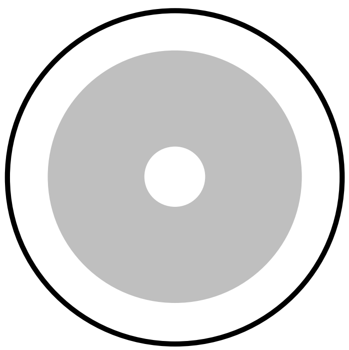
Measurement Techniques for R_s

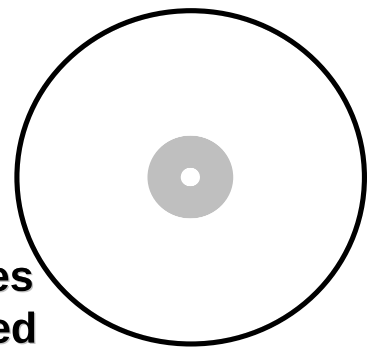
CYLINDRICAL COPPER CAVITY (End-Wall Replacement)	HTS / DIELECTRIC RESONATOR	PARALLEL-PLATE RESONATOR (Taber Technique)

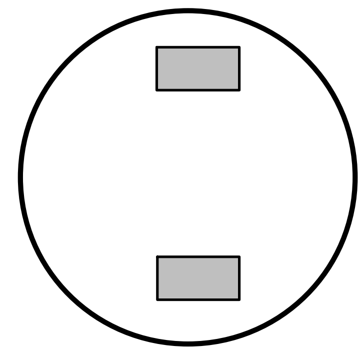












Gray indicates area measured

Large area but poor sensitivity (~5 mW)

Small area; excellent sensitivity (> 10x reference film)

Good sensitivity but wafer must be diced

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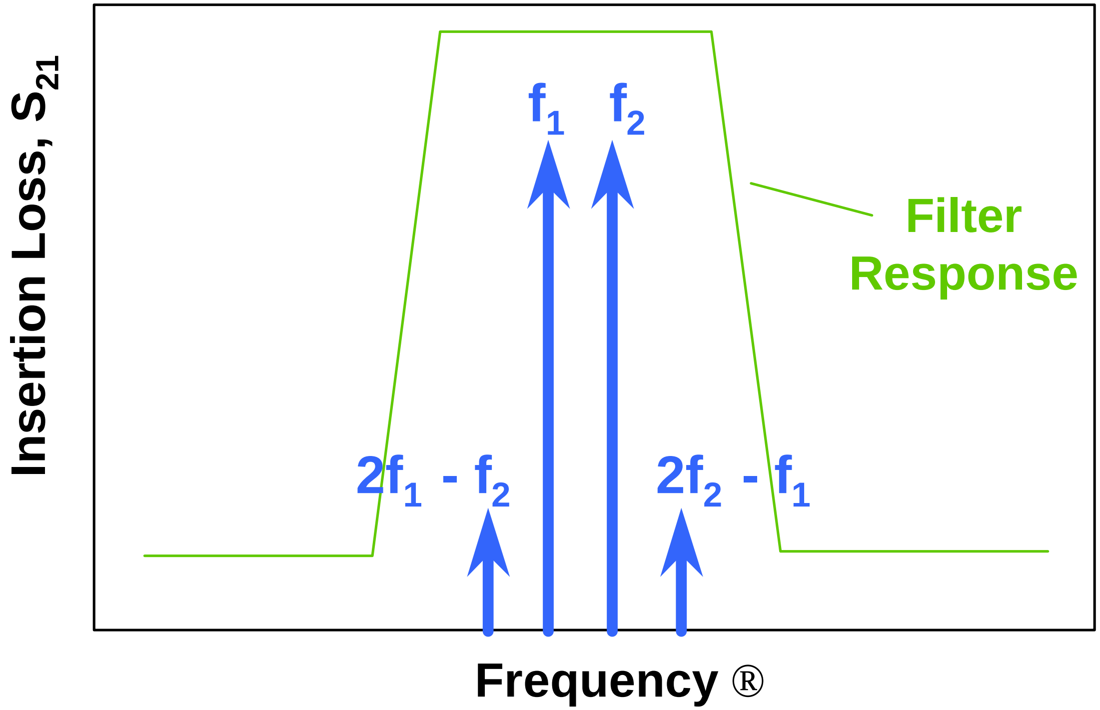
Measurement of Non-Linear Response



1. Apply two high-power tones within filter passband
2. Measure output power as a function of input power at f_1, f_2, $2f_2 - f_1$, and $2f_1 - f_2$ (Third-order products would not exist for a perfectly linear response)
   - System Dynamic Range is a function of materials and design (keep current density low)
   - LNAs usually limit dynamic range

Summary of RF Properties of HTS Films

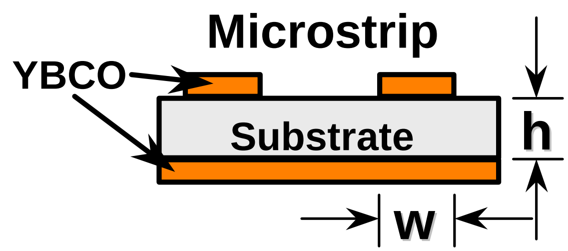
- Only epitaxial c-axis films have the low rf loss, R_s(77K, 10 GHz) < 1 mW, needed for applications
  - TBCCO or YBCO but l(T) for YBCO is still changing at 77K
- High-quality films and clever device designs that minimize current density permit up to 100s W devices - no problem for receive applications
- Low signal attenuation is only one benefit of HTS
  - Cryogenic operation ® Low noise
  - Elimination of amplification stages ® High dynamic range
- Yield is longer a critical factor but overall film production costs are still high

Transmission-Line Dimensions for Microstrip and Stripline

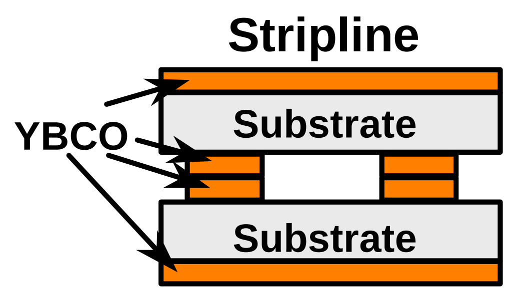
The primary requirement is for a 50 Ω characteristic impedance,

$$Z = (L/C)^{1/2} = \text{function of } (h/w)$$

For a 50 Ω line on $LaAlO_3$ (ε = 24), the conductor width must be:



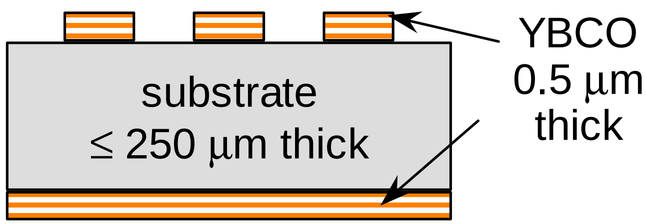
	Wafer Thickness	
	10 mils	20 mils
Microstrip	88 μm	176 μm
Stripline	22 μm	44 μm



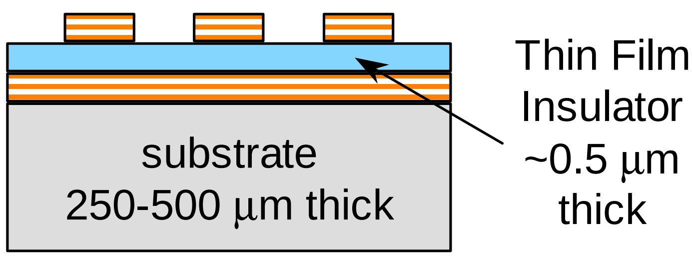
- Reducing wafer thickness reduces the overall device size proportionally
- For thin-film dielectrics (e.g. 1 μm) linewidths must be < 1/2 μm

Optimum Dielectric Thickness for Compact HTS Microwave Components

For HTS Microstrip Transmission Lines,
2 Configurations Now Available (also applies to stripline):



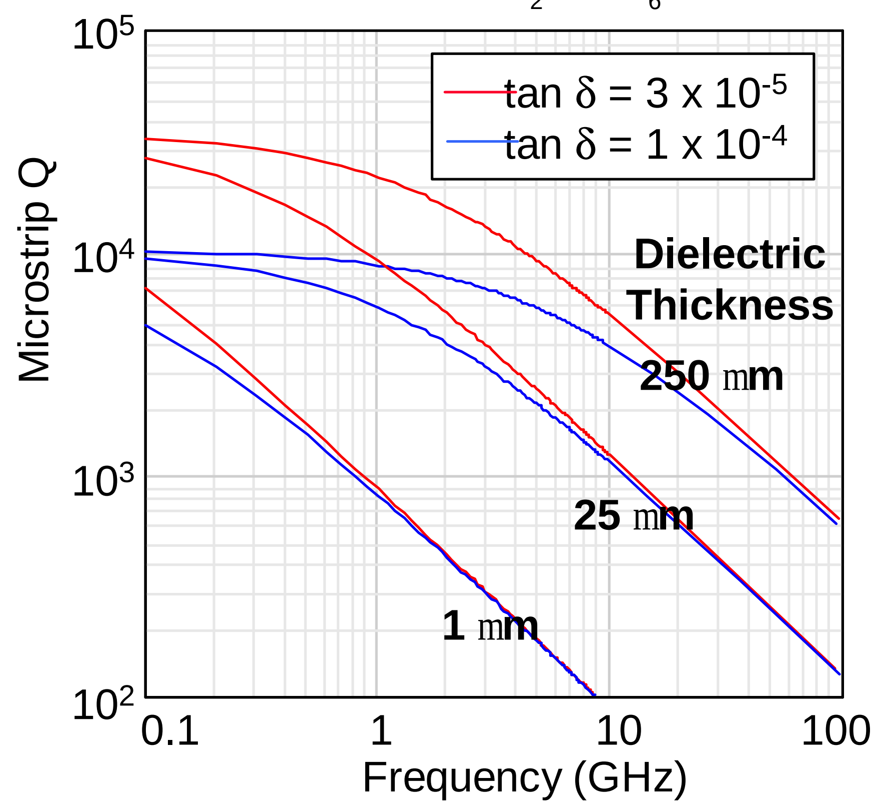
Substrate Dielectric:
- **Low HTS Conductor Loss**
- **Relatively Large Size**



Thin Film Dielectric:
- **Extremely Compact**
- **Relatively High Conductor Loss**

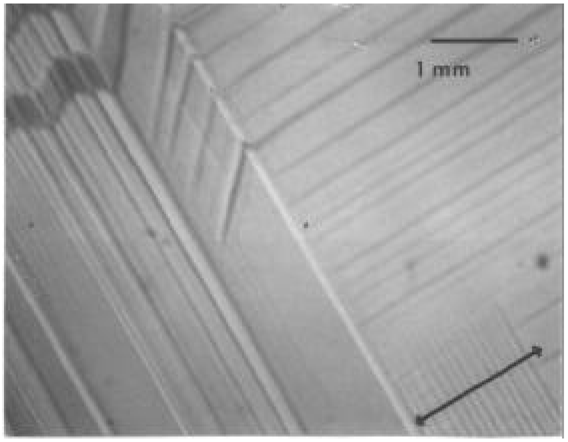
Ideally, use an intermediate dielectric thickness

Materials Parameters:
- R_s(77K, 10 GHz) = 0.5 mΩ
- Single Crystal: $LaAlO_3$
- Dielectric Films: Sr_2AlTaO_6



Substrates for HTS Microwave Devices

$LaAlO_3$ was the most widely used substrate for development programs



Problems with $LaAlO_3$:

- **anisotropic dielectric constant**
- **movement of twin boundaries**
- **for mm-wave applications, the high e results in structures that are too small**

Problems with alternate substrates:

- **Thermal expansion mismatch of Si and sapphire to YBCO limits films thicknesses**
- **Loss tangent is much too high in YSZ, somewhat too high in $NdGaO_3$**
- **30% $LaAlO_3$ + 70% $Sr(Ta,Al)O_3$ (LSAT) is untwinned but e is not sufficiently uniform**
- **MgO is not readily available in large wafers; cleaves easily Nevertheless, best alternative available today**

HTS Technology Enables CRYORADAR™ to Find Targets in Clutter

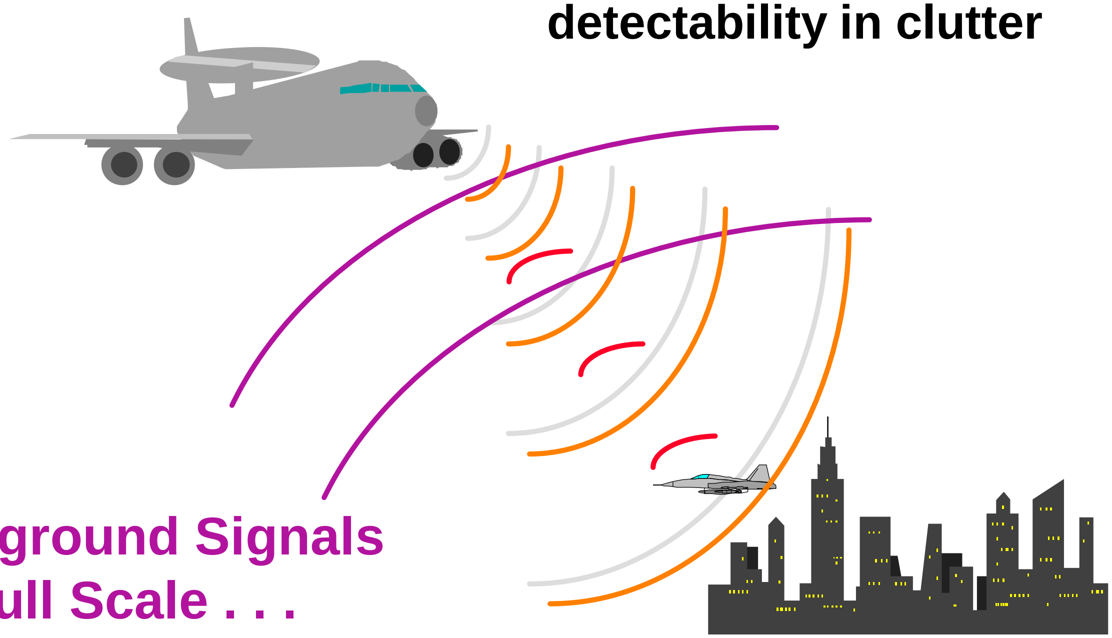
Cryoelectronic Radar Subsystems Provide:

Pure Transmit Signal

- **100x increase in microwave resonator Q**
- **50x increase in dynamic range**
- **50x reduction in size**

Low Noise / High Dynamic Range Reception

- **10x increase in speed**
- **10x reduction in power of logic circuits**
- **~20 dB improvement in target detectability in clutter**



Large Background Signals Establish Full Scale . . .
but Small Signals Can Be Important

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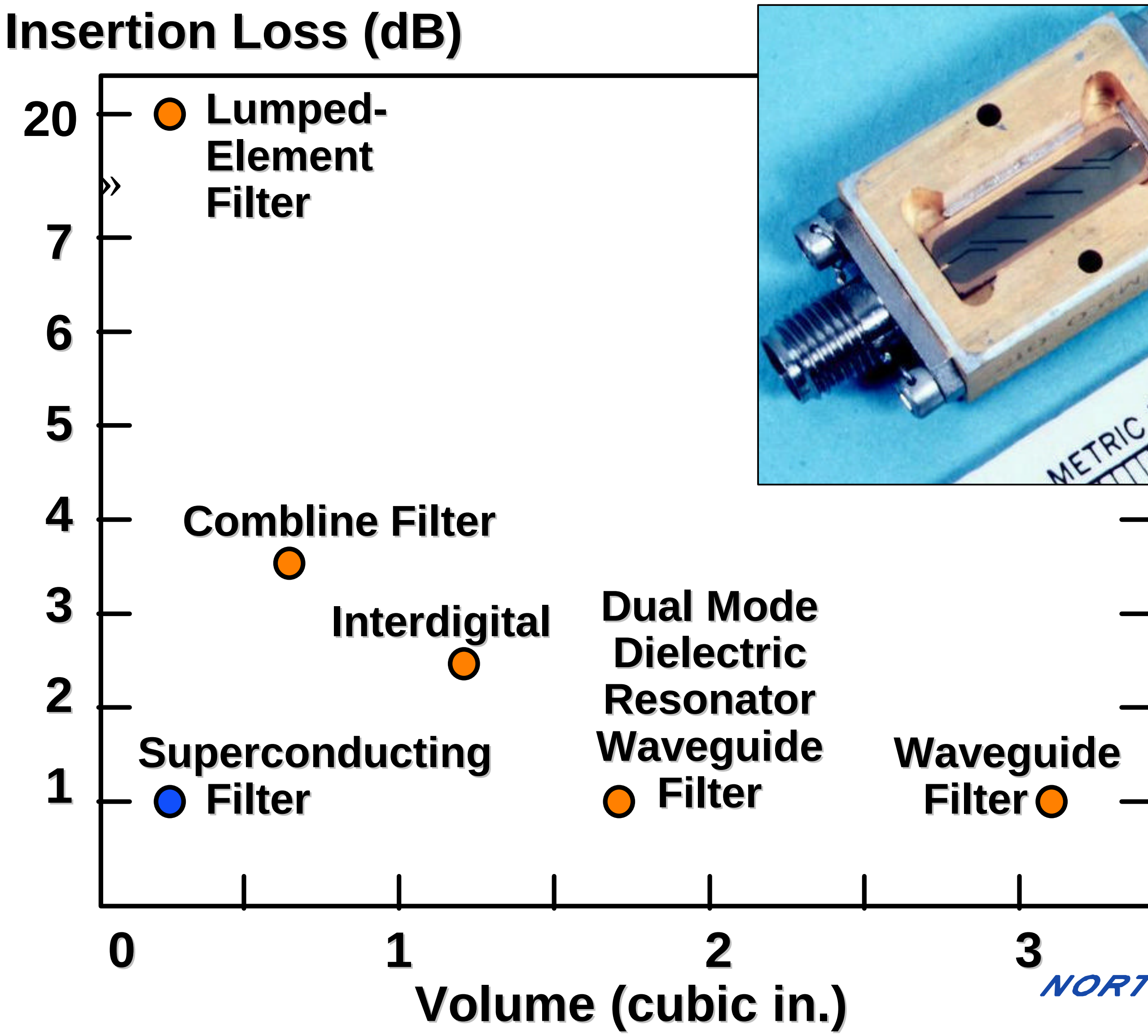
Superconducting Filters Uniquely Provide Low Loss and Small Volume

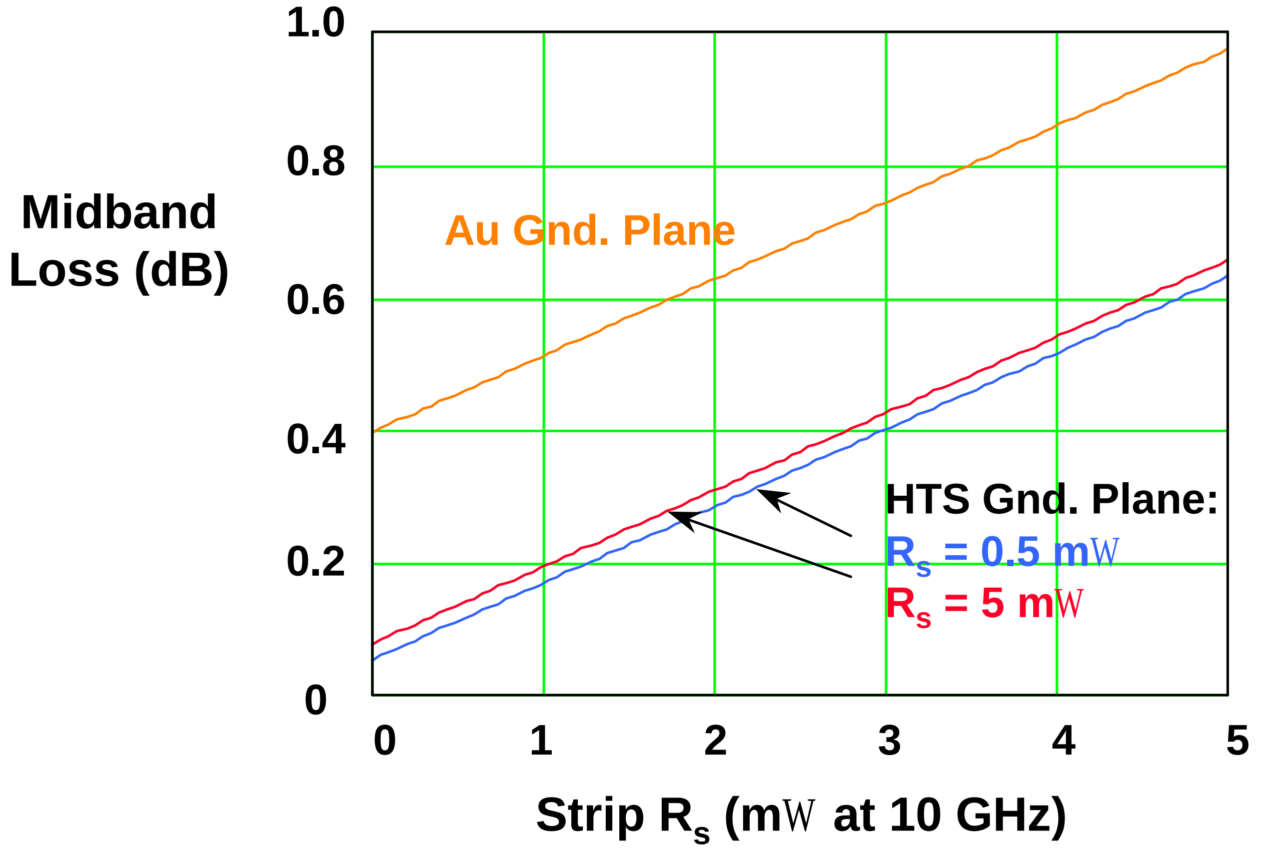


- X-Band Filters
- Refrigeration volume amortized over a bank of filters

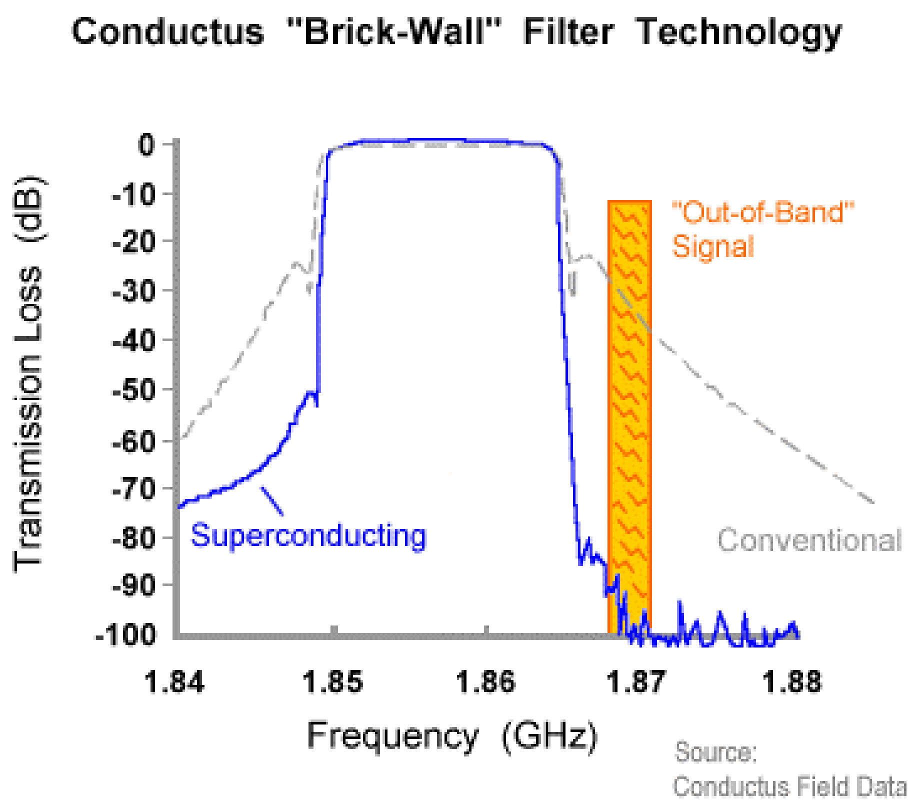
Filter Loss Calculation

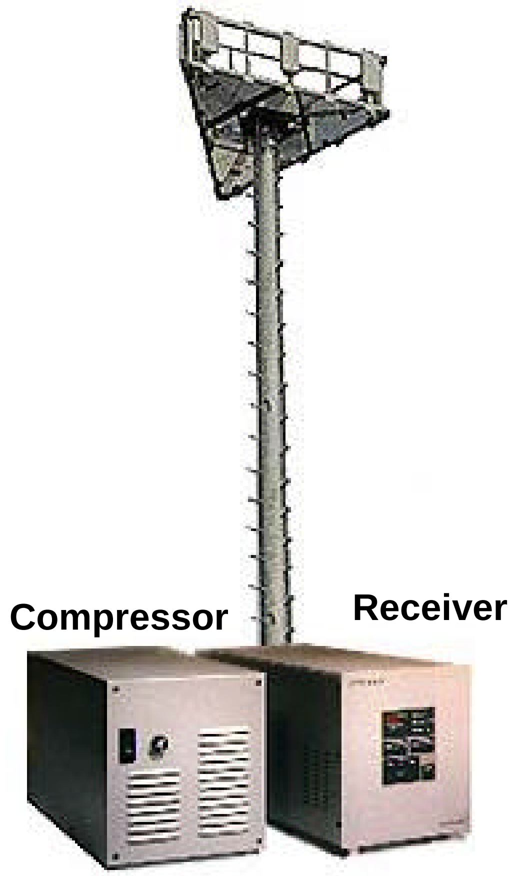
4-Pole Chebychev Filter, 1.25% Bandwidth

Center Frequency at 4 GHz



Conductus is Betting Its Existence on HTS Filters for Cellular and PCS Base Stations

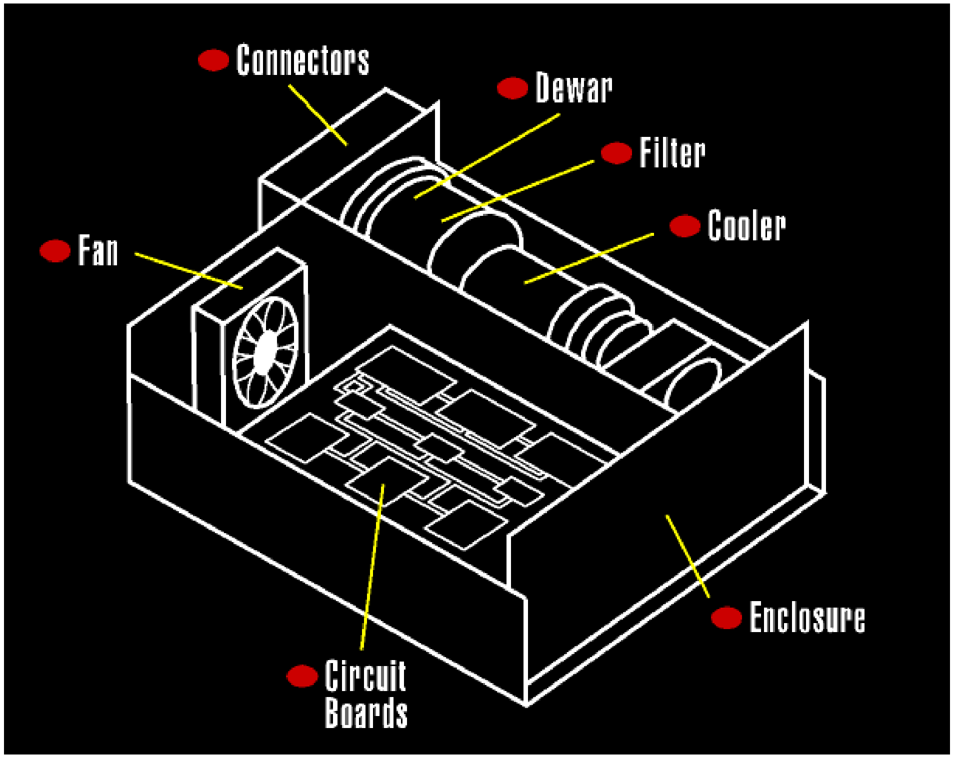




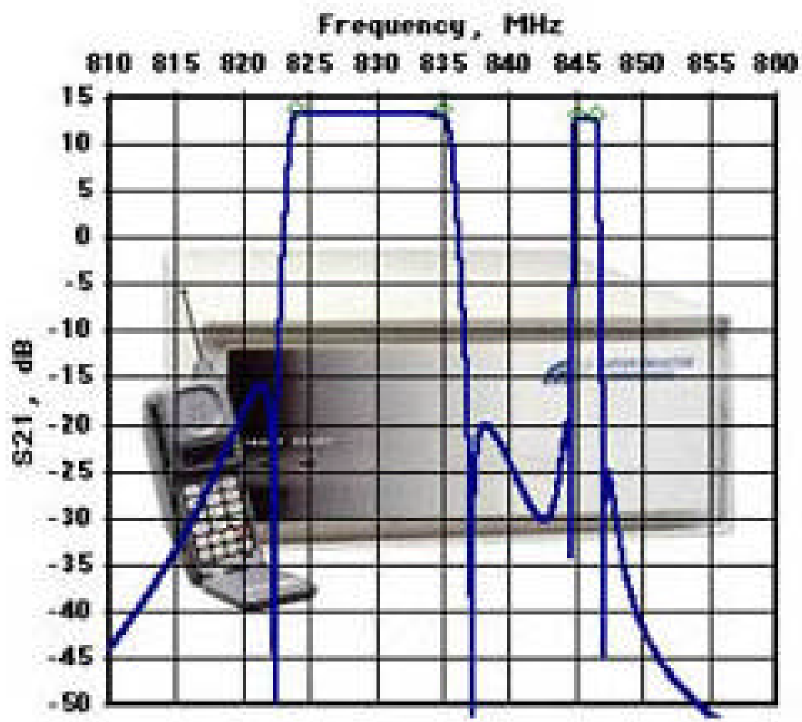
- YBCO Filters combined with cryogenic LNA reduce noise
- Low insertion loss permits higher number of poles, sharper skirts
- Compact, lightweight systems can be mounted on towers
- Cellular systems (800 MHz) in the field; PCS ir
- Similar military systems fielded

CONDUCTUS®

STI is Betting Its Existence on HTS Filters for Cellular and PCS Base Stations



Cellular A-Band



- **TBCCO Filters combined with cryogenic LNA reduce noise**
- **Low insertion loss permits higher number of poles, sharper skirts**
- **Compact, lightweight systems can be mounted on towers**
- **Cellular systems (800 MHz) in the field; PCS in development**
- **Similar military systems fielded**
- **Recently added spectrum for A and B is, "The FCC's gift to HTS"**

SUPERCONDUCTOR TECHNOLOGIES

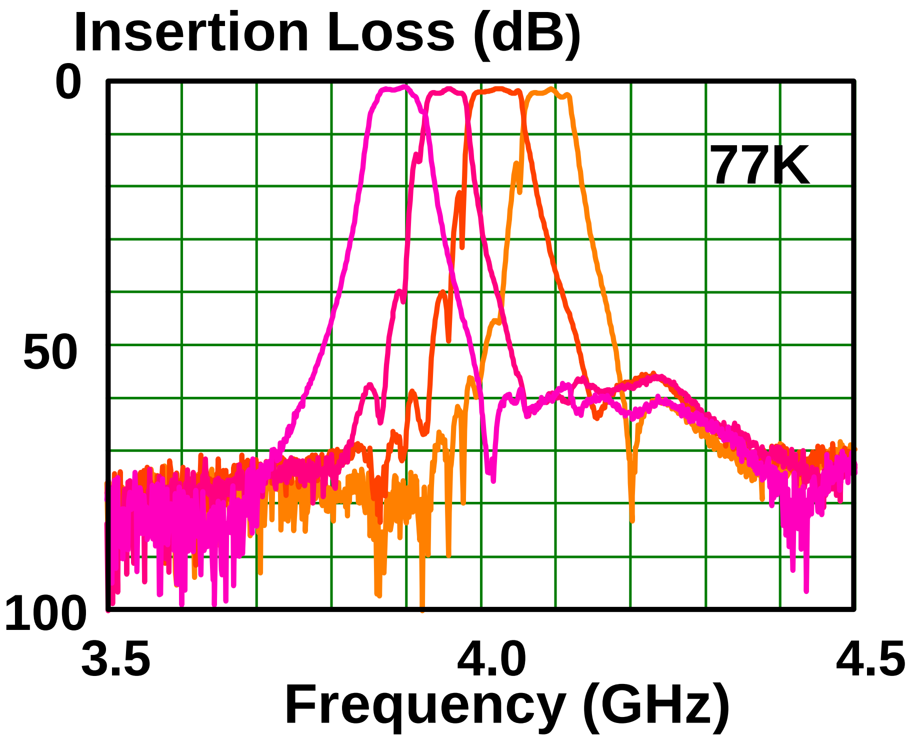
Cryocooler Technology is Making Significant Advances in Affordability, Reliability, and Size

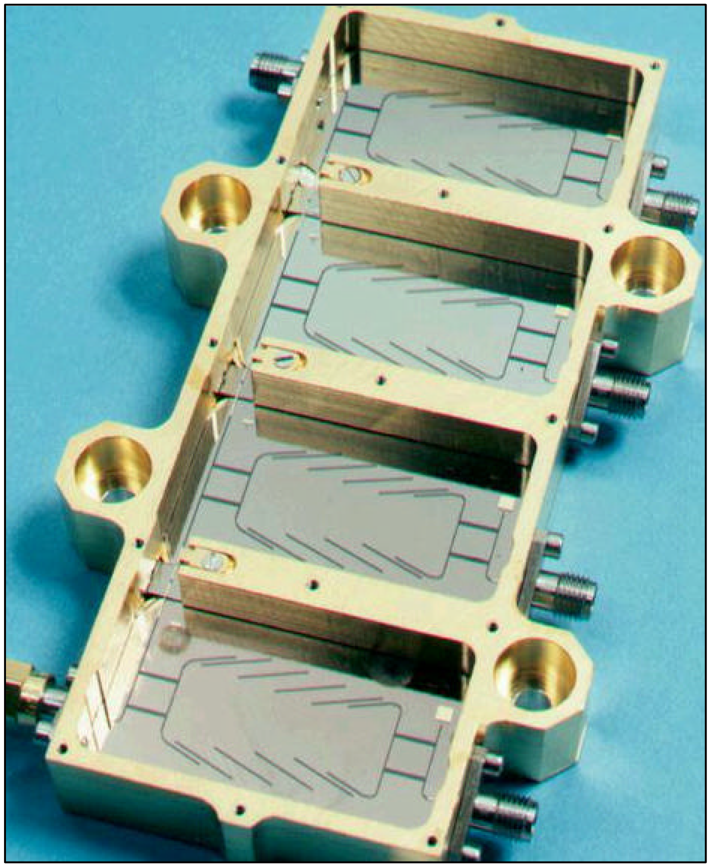
- **Most users want integrated, closed-cycle cryocoolers - their existence transparent to the operator**
- **Only volume sales can bring down cooler costs**

	1992	1994	1996/97	1999
Cost	$20k	$15k	$3k	$1.5k
Reliability (MTBF)	5,000 hrs.	15,000	40,000	100,000
Size	1x			1/3x

- **Based on 4W Heat Lift at 77K**

HTS Four-Channel Filterbank: Example of HTSSE II Device





- Centered at 4 GHz
- 50 MHz-Wide Channels
- 4 YBCO Films on 2” Wafers
- Integrated 50 W Terminations
- Integrated Branchline Couplers
- Integrated Channel Interconnections

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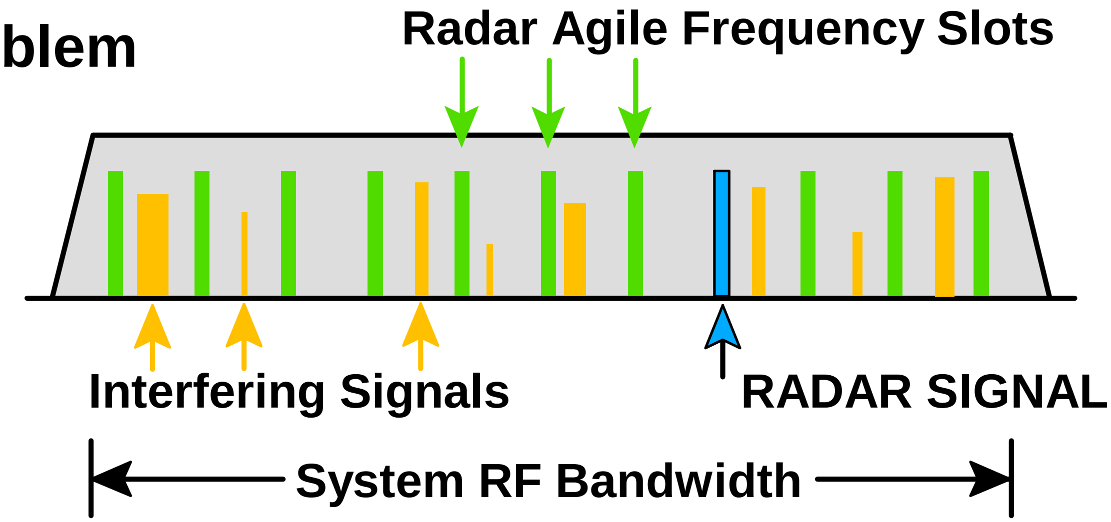
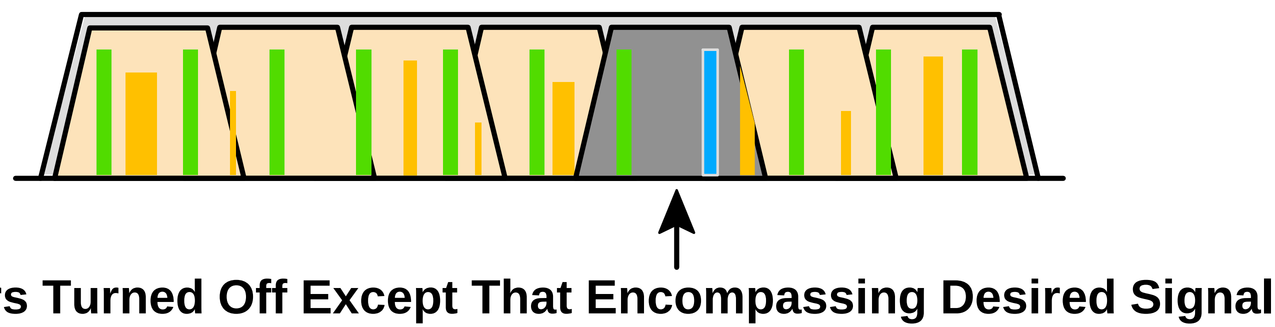
Motivation for Switched Filterbanks

The Problem



The Solution: A Switched Filterbank



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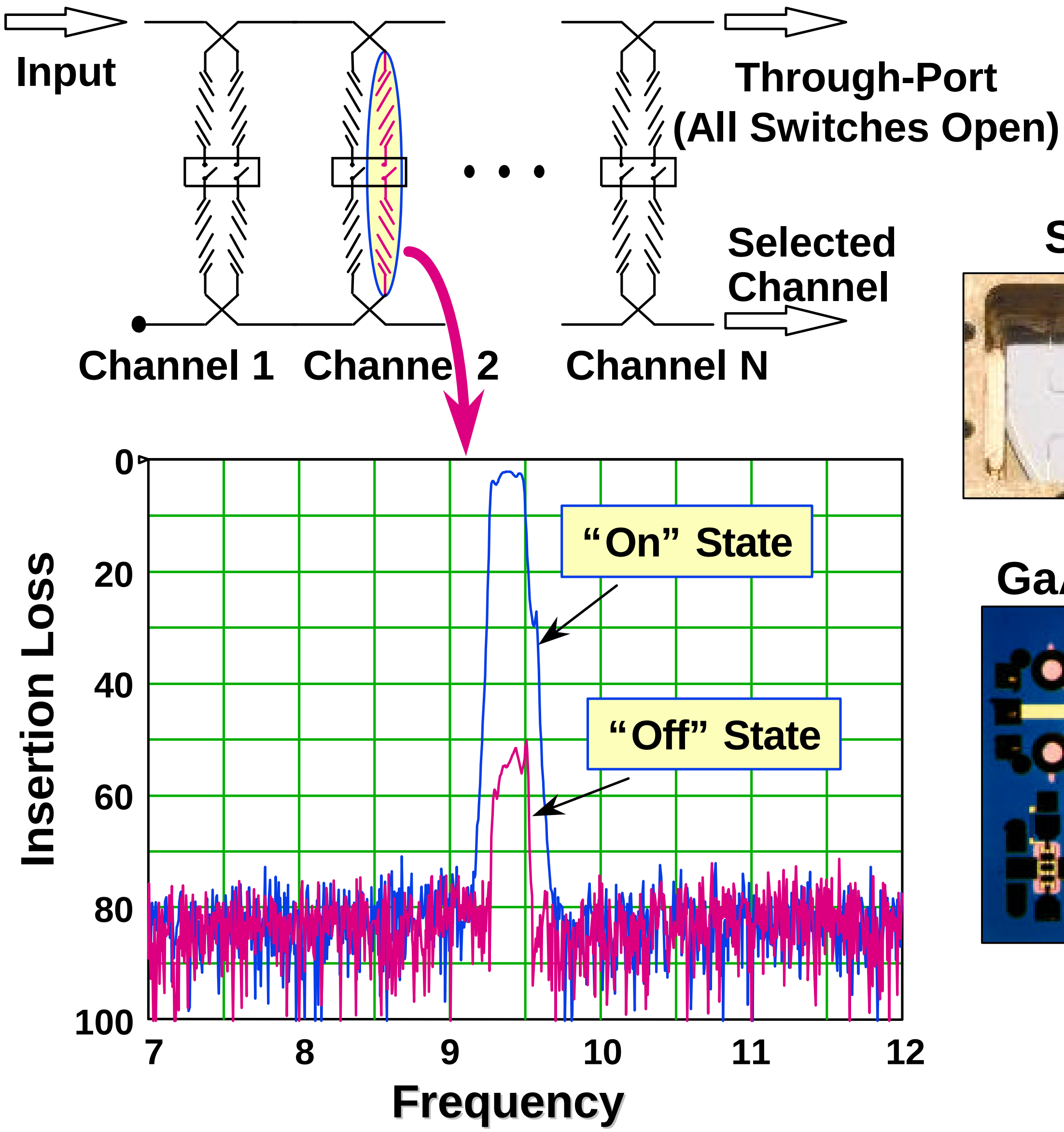
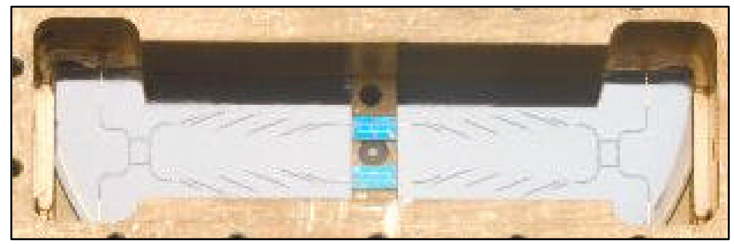
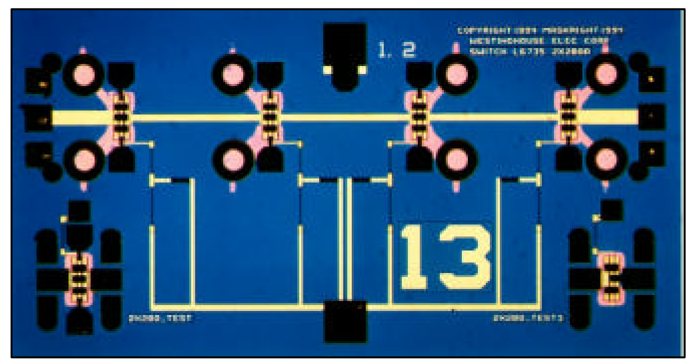
Preselector Switched Filterbank: YBCO Films Packaged with GaAs FET Switches



Switched Filter Channel



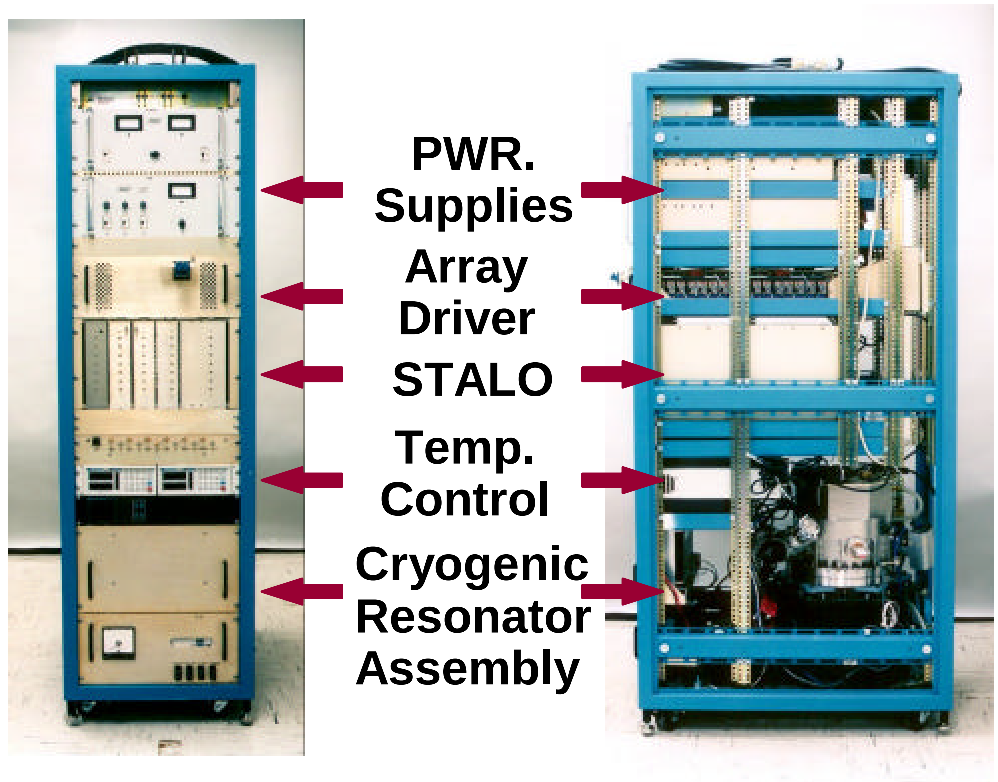
GaAs Etch-Back FET Switch



Cryo Resonator for STALO: Example of Cryocooler Integration

Key Fabrication Issues
- Vibration Isolation
- Grounding HTS Films
- Frequency Trimming
- Temperature Stability

System Delivered to NRL in 1997
- Demonstrated in Navy Radar Testbed
- Significant Improvement in Radar Sensitivity (Limited by ADC Used)



Advanced cryo package will reduce volume by 10x

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Introduction / Motivation for Tunable Microwave Devices

- **Interest is in materials where dielectric constant,** e **(<u>E</u>), is a function of applied electric field**
- **Used to produce**
  tunable capacitors: capacitance, **C** μ e **(<u>E</u>)**

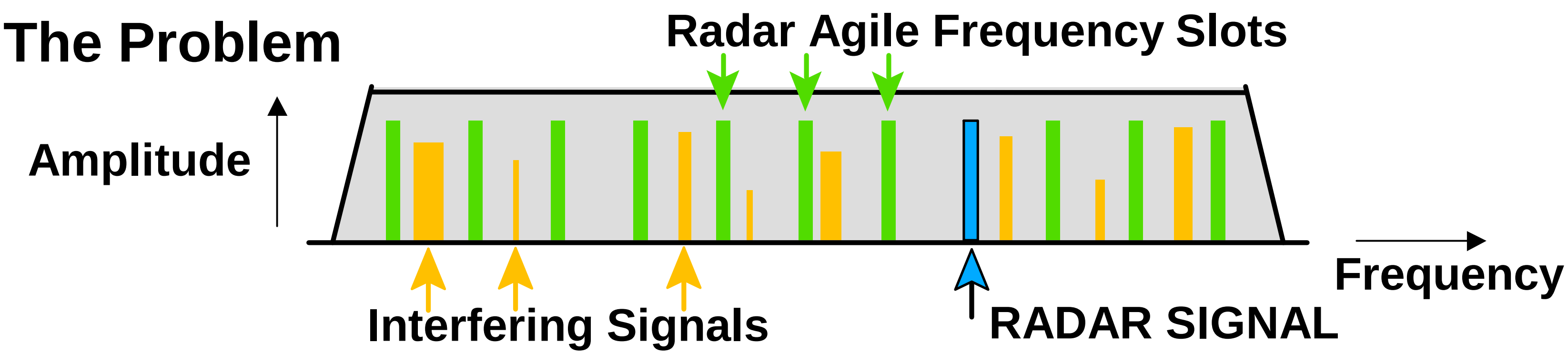
  For a length of transmission line:
  tunable resonators: wavelength, **f** μ **$(CL)^{1/2}$** μ **(e m) $^{1/2}$**

  tunable delay: phase velocity, **v_p** μ **$(1 / CL)^{1/2}$** μ **(e m) $^{-1/2}$**

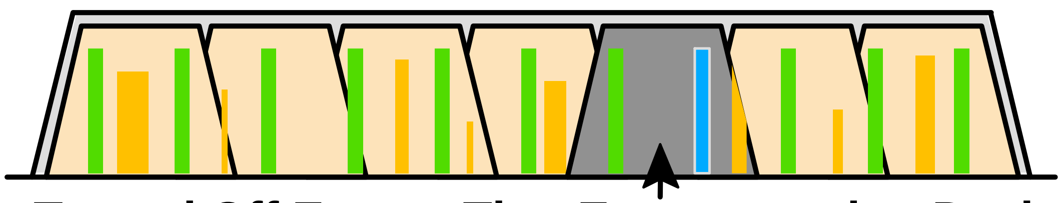
  However, characteristic impedance, **Z** μ **$(L / C)^{1/2}$** μ **(m / e) $^{1/2}$**
  Ideally, impedance would be independent of tuning
- **Analogous magnetic field tuning is easier, already in use, but potential for** dm / m **is smaller than for** de / e
- **DARPA's program, "Frequency Agile Materials for Electronics," (FAME) started in 1998**
  - goal is for factor of 2 shift in frequency

Motivation for Tunable Filters

The Problem

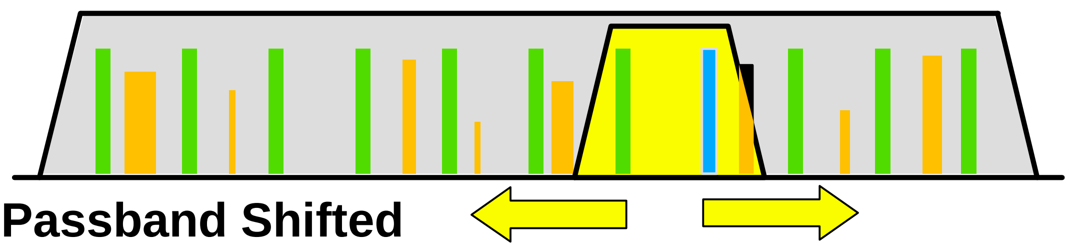


Potential Solution #1: A Switched Filterbank



All Filters Turned Off Except That Encompassing Desired Signal

Potential Solution #2: A Single Tunable Filter



Filter’s Passband Shifted
to Match Signal Frequency

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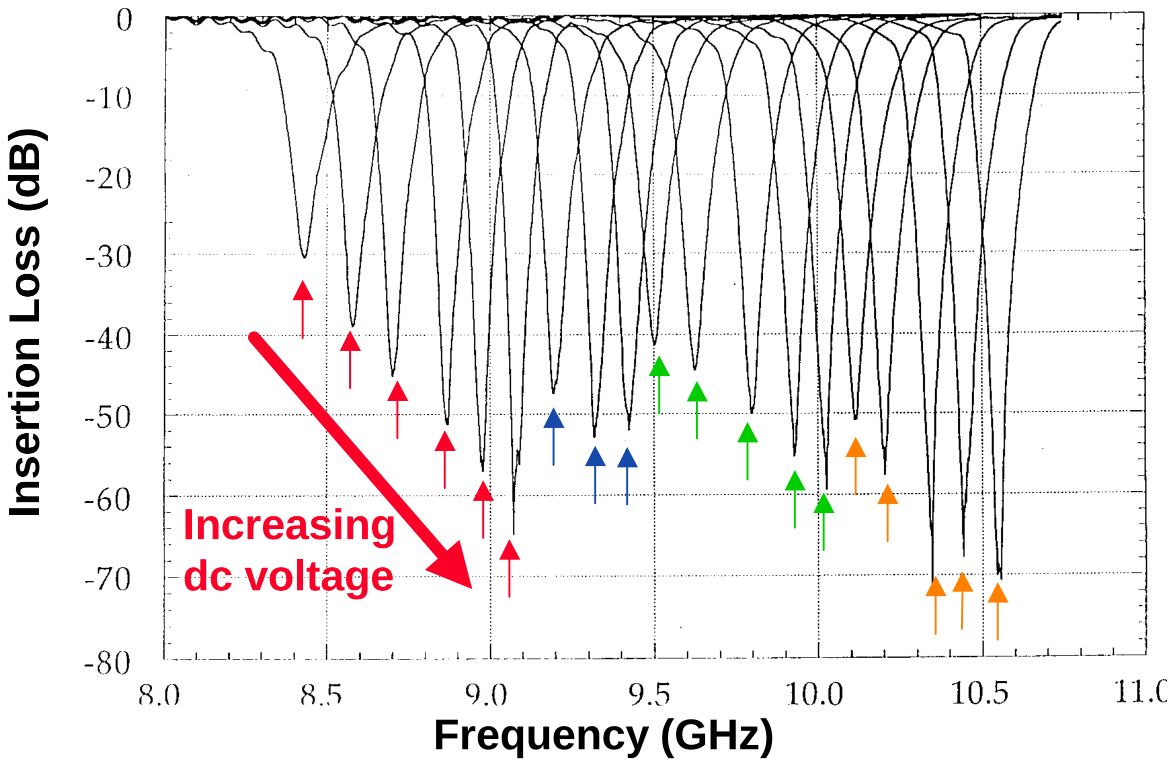
Integrated HTS / Ferroelectric Band Reject Filter



Superconducting Core Technology, Inc.

$SrTiO_3$ film covers interdigitated capacitor

- **Four notch filters, each with 5% tuning range, Q » 200, K » 10**
- **Thin-film $SrTiO_3$ ferroelectrics and YBCO conductors (60 K operation)**
- **Note higher Q with applied field**

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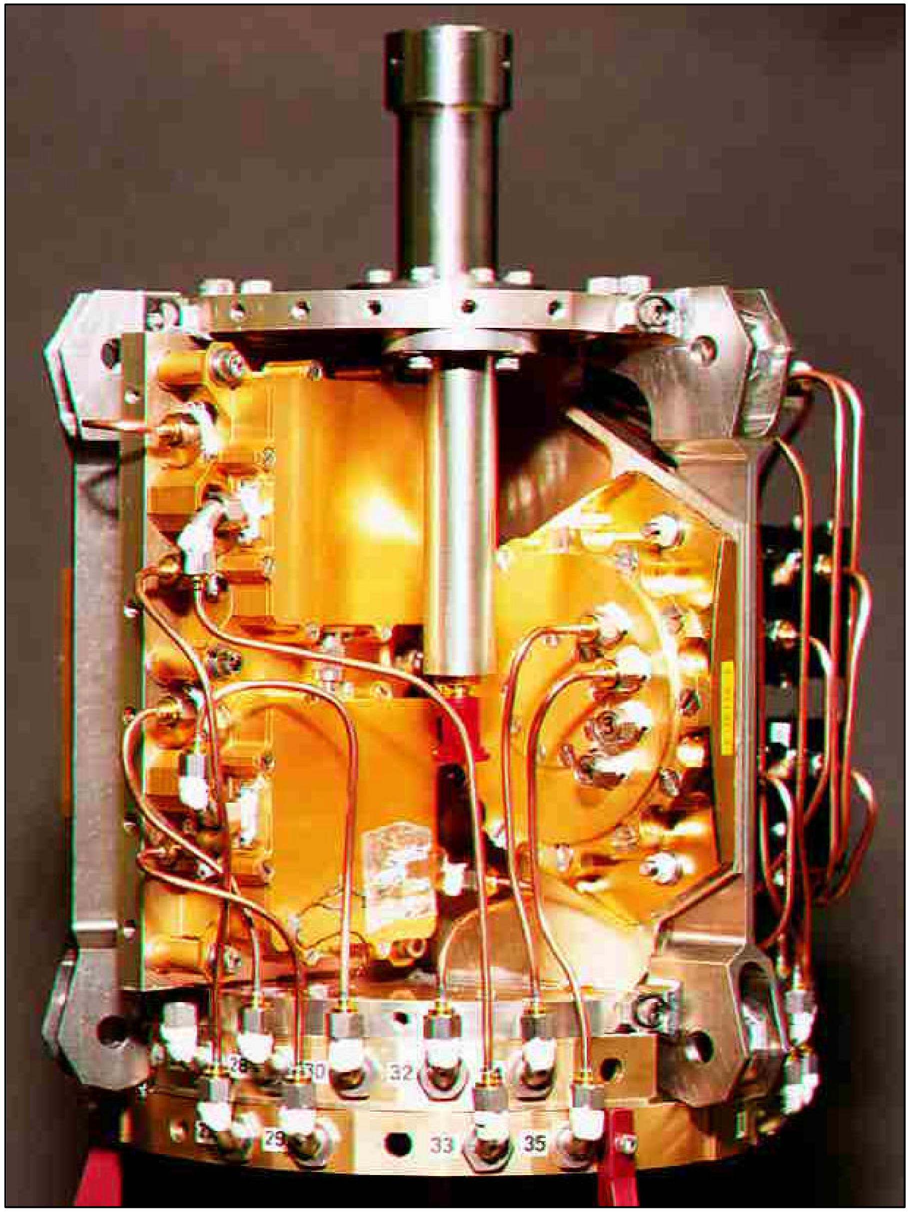
Other RF Devices Based on HTS

- **China Lake NWC: Electrically short UHF antenna matching networks; HTS improves antenna efficiency**
- **Brucker Instruments: NMR or MRI pick-up coils improve sensitivity for small samples and low magnetic fields**
- **Neocera, Inc.: RF circulators for antenna manifolds, etc.; compact and low loss but HTS films are exposed to H = 0.2 tesla**
- **Lincoln Labs: Variable phase shifters for beam steering combine HTS and ferrites**

Navy High-T_c Superconductor Space Experiments (HTSSE I and II)



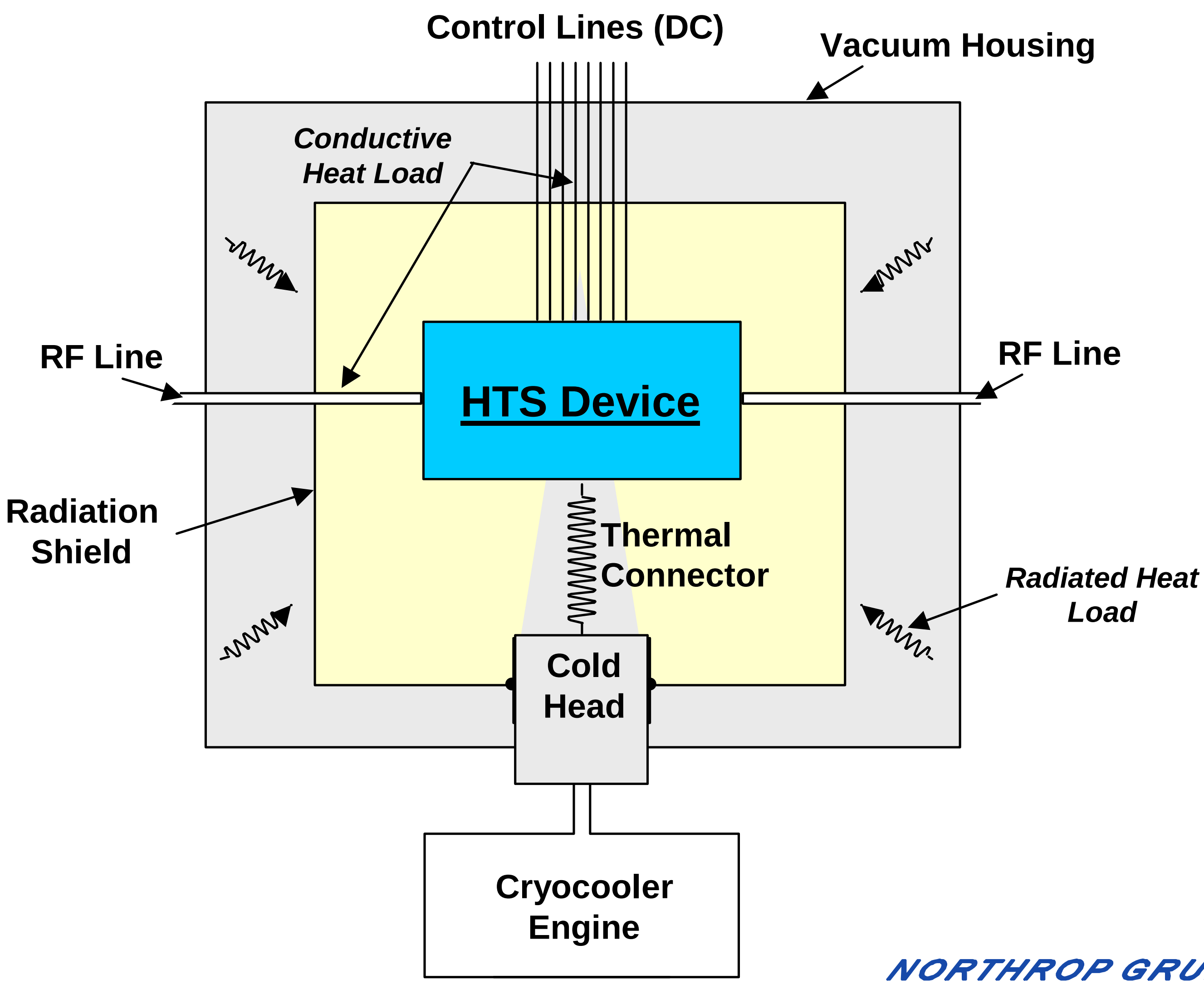
HTSSE I

- Simple passive devices, mostly filters and resonators
- "Failed to achieve orbit"

HTSSE II

- More complex subsystems but still just for testing
- Originally scheduled for August, 1996 launch - delayed
- Launched Feb 23, 1999

Cryogenic Packaging Fundamentals



Conclusions

- Analog HTS electronics are based on low RF surface resistance
- Materials technology is relatively mature
  - No trade-off between LTS and HTS
  - Device performance can be accurately modeled
- Microwave filters for the commercial wireless market
  - Best (only?) hope for a substantial market -- big enough for volume to reduce costs and pay for special tools
  - Assist defense electronics development with experience in scaling up production of films, packaging, and cryocooler integration
- Performance has been demonstrated for a range of devices -- but few applications are based solely on performance
- Cost and reliability of cryocoolers is a major barrier to wider application