



# Recent Development in Superconducting Filters

(Invited Talk)

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# Outline

- Introduction
- HTS materials and substrates
- Recent developed HTS Filters
- Summary

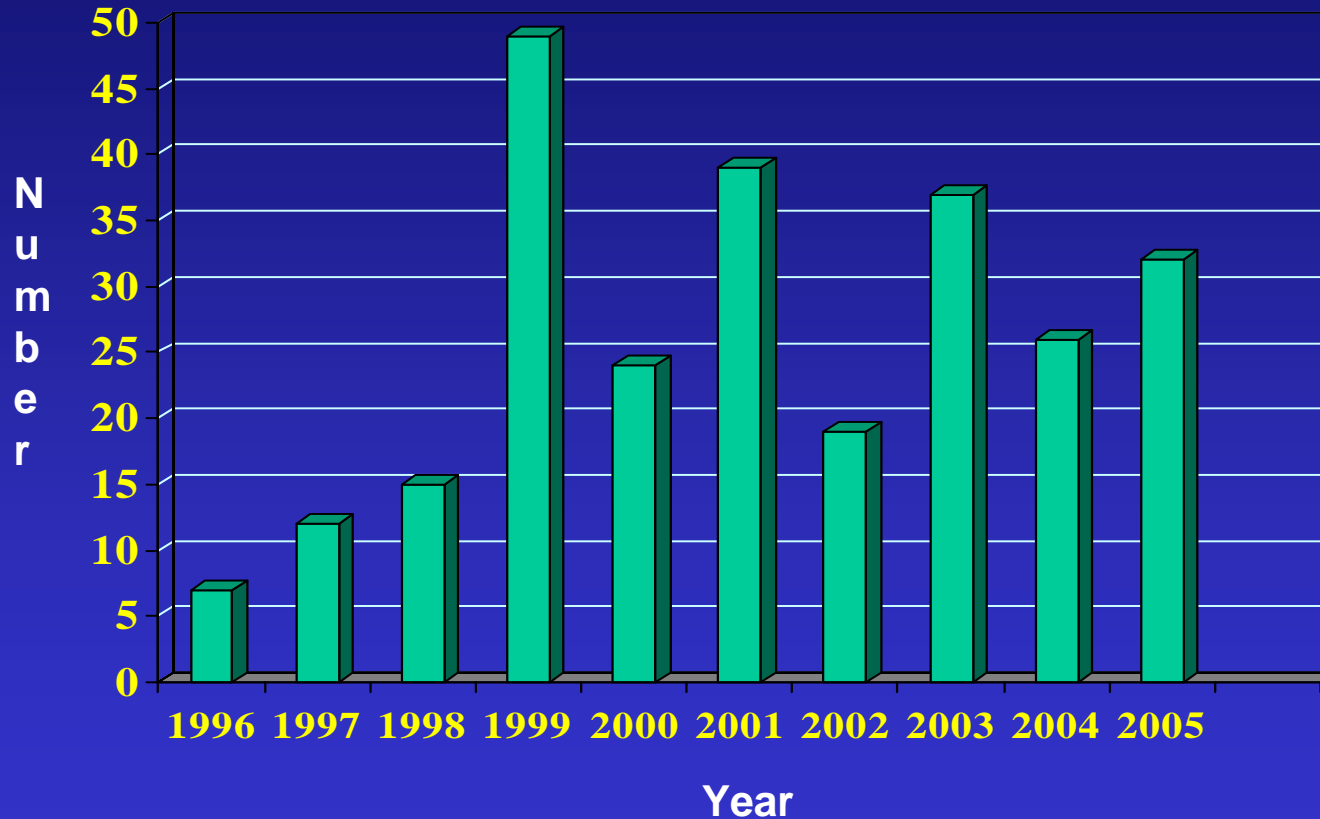
# Introduction

- The driving force behind the development of superconducting filters remains for mobile, satellite communications and some other niche applications.
- The extremely low resistance of superconducting materials has enabled the realization of miniature thin film filters with exceptional performances.

# Introduction- HTS Filter Publications

Total 260+ in recent 10 years

Search from IEEE Xplore



# What is the Superconductor and HTS?

- Superconductors are materials which, when cooled below a certain temperature, exhibit a zero intrinsic resistance to direct current (d.c.) flow.
- The temperature at which the intrinsic resistance undergoes an abrupt change is referred to as the critical temperature or transition temperature ( $T_c$ ).
- The superconductors with transition temperature greater than 77 K, the boiling point of liquid nitrogen, are referred to as the high-temperature superconductors (HTS).
- For alternating current (a.c.) flow, the surface resistance of the superconductor does not go to zero below  $T_c$ , but increases with increasing frequency.

# HTS Materials

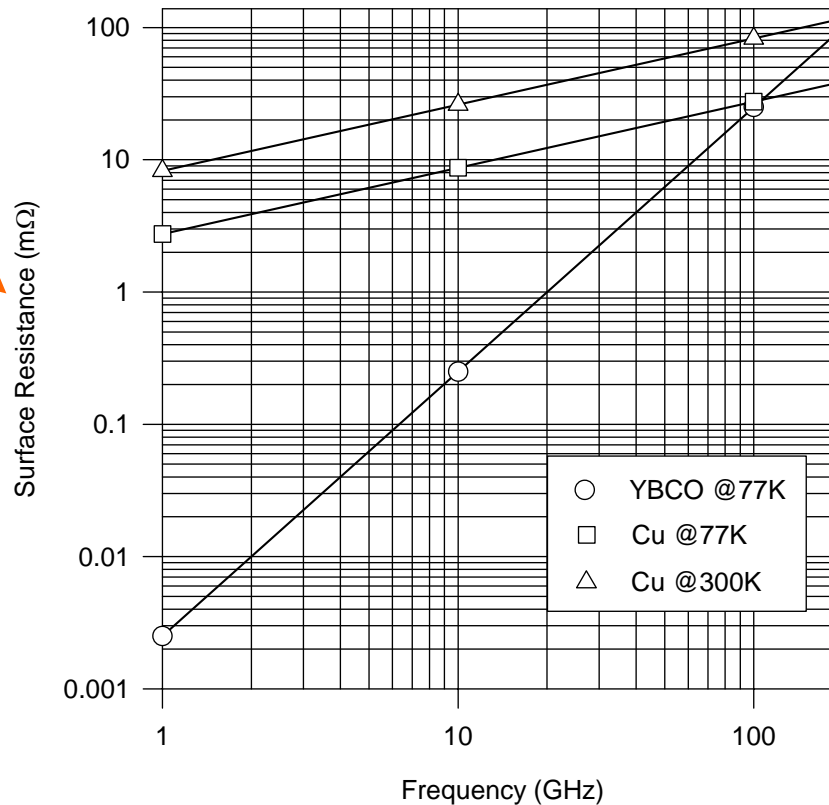
- There are many hundreds of high-temperature superconductors with varying transition temperature  $T_c$ .
- YBCO (yttrium barium copper oxide) and TBCCO (thallium barium calcium copper oxide) are the two most popular and commercially available HTS materials.

## Typical HTS materials

Materials	$T_c$ (K)
$\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO)	$\approx 92$
$\text{Tl}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_x$ (TBCCO)	$\approx 105$

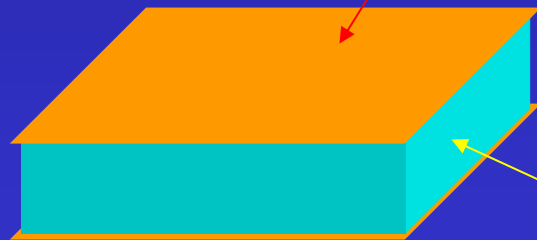
# Surface Resistance of HTS at RF/Microwave Frequencies

Micro ohms



# HTS Thin Film Technology

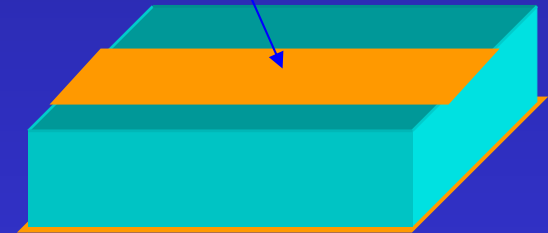
HTS thin films can be grown on a suitable substrate using sputtering, laser ablation, or other thin film deposition techniques.



Dielectric substrate

Devices can be patterned using wet or dry etching techniques, e.g.

**HTS microstrip**





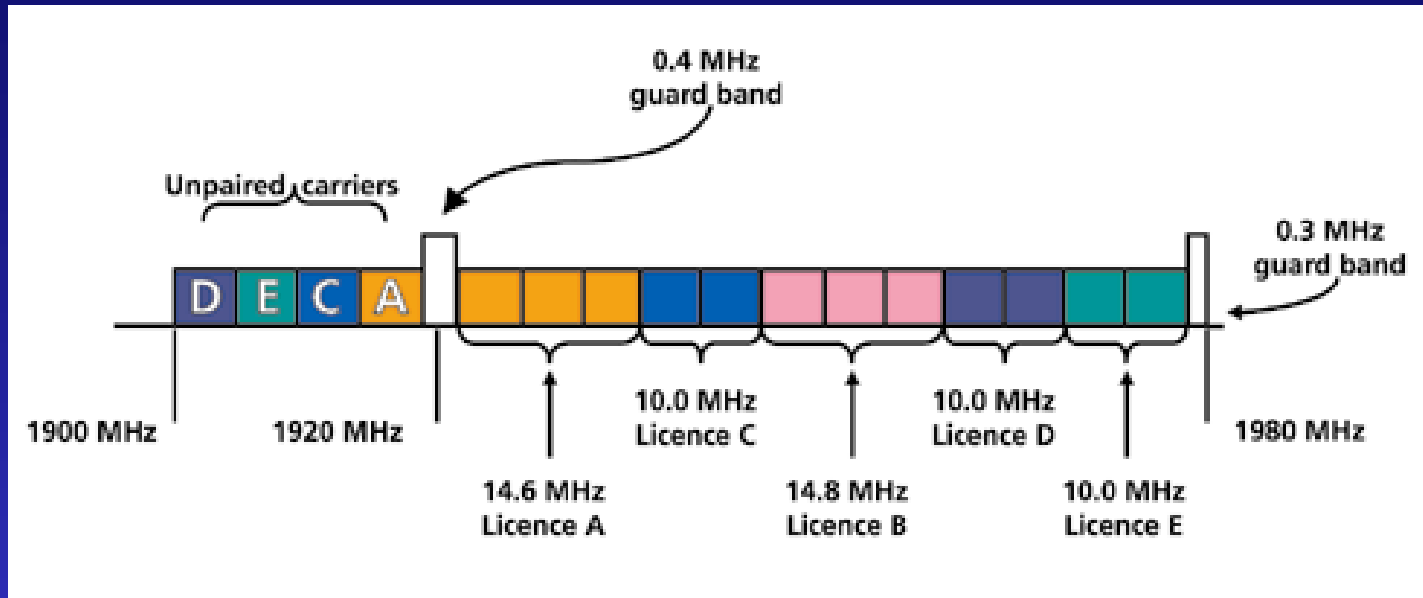
# Substrates for HTS Thin Films

- To obtain good quality film, the dimensions of crystalline lattice at the surface of the substrate should match that of lattice of HTS.
- For RF applications the substrate should also have a low dielectric loss at RF.
- There are three widely used substrates for growing HTS thin films for RF applications: Magnesium Oxide (MgO), Lanthanum Aluminate (LaAlO<sub>3</sub>), and Sapphire.

**Substrates for HTS films**

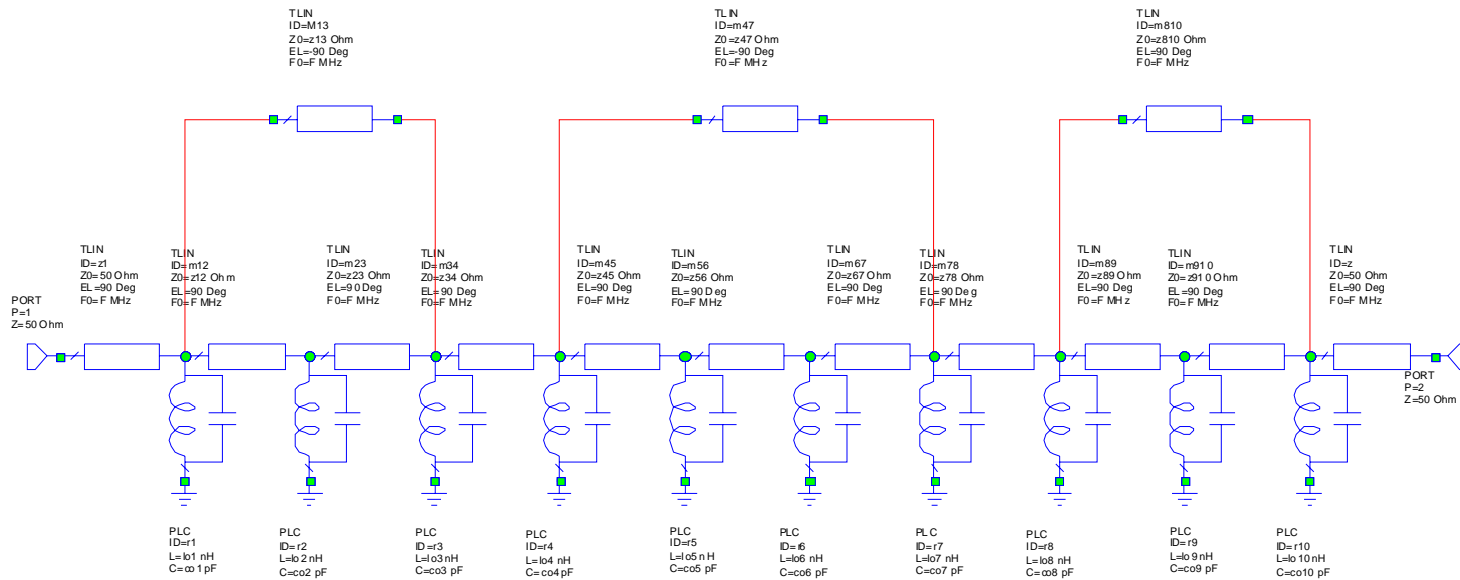
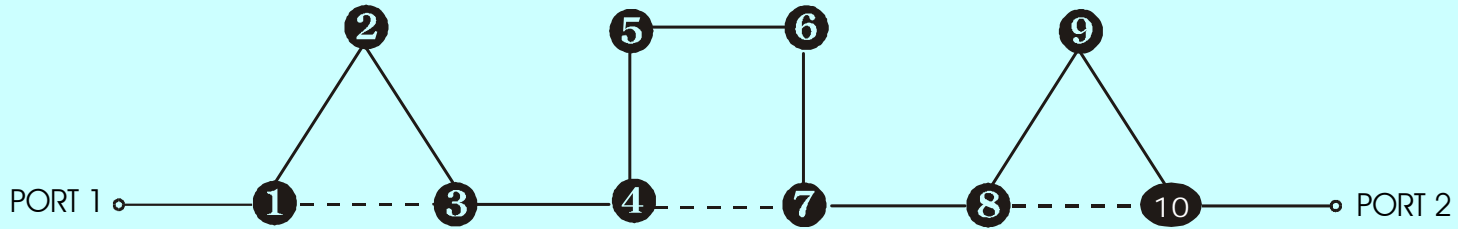
substrate	$\epsilon_r$ (typical)	$\tan \delta$ (typical)
LaAlO <sub>3</sub>	24.2 @ 77K	$7.6 \times 10^{-6}$ @ 77K and 10 GHz
MgO	9.6 @ 77K	$5.5 \times 10^{-6}$ @ 77K and 10 GHz
Sapphire	11.6    c-axis @ 77K 9.4 $\perp$ c-axis @ 77K	$1.5 \times 10^{-8}$ @ 77K and 10 GHz

# HTS filters for licensed frequency spectrum of mobile communications

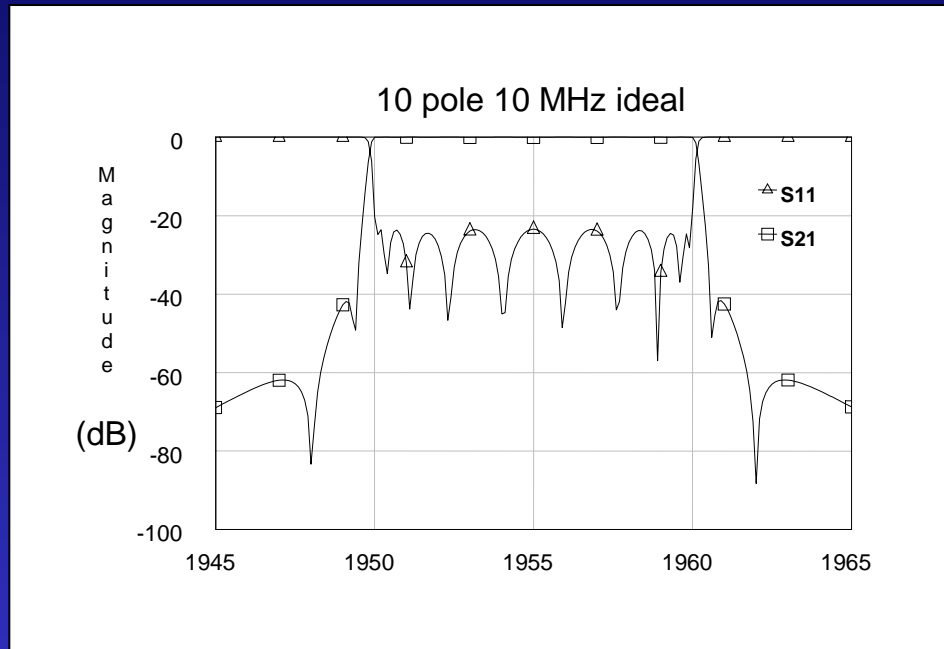


- Implement CQT (cascaded-quadruplet-trisection) or CQ designs for low insertion loss, high selectivity and/or linear group delay.
- Implement HTS filters on sapphire wafers for low-cost

# 10-pole CQT 10-MHz HTS Filter Design

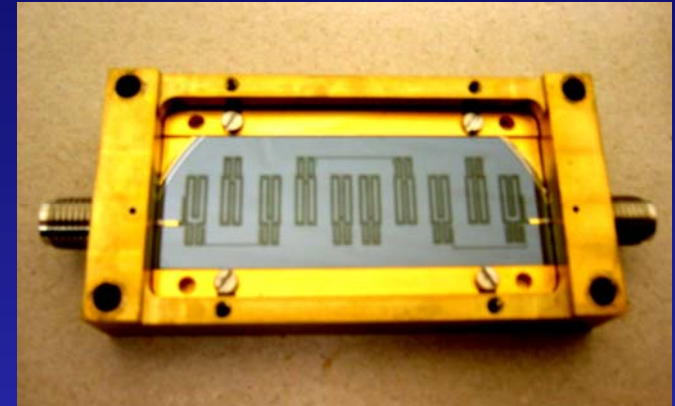
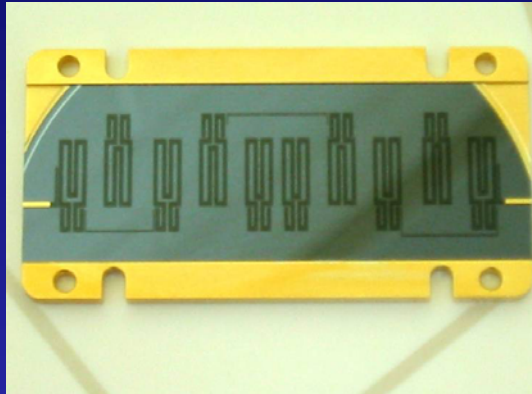


# 10-pole CQT 10-MHz HTS Filter Design



# 10-pole CQT 10-MHz HTS Filter

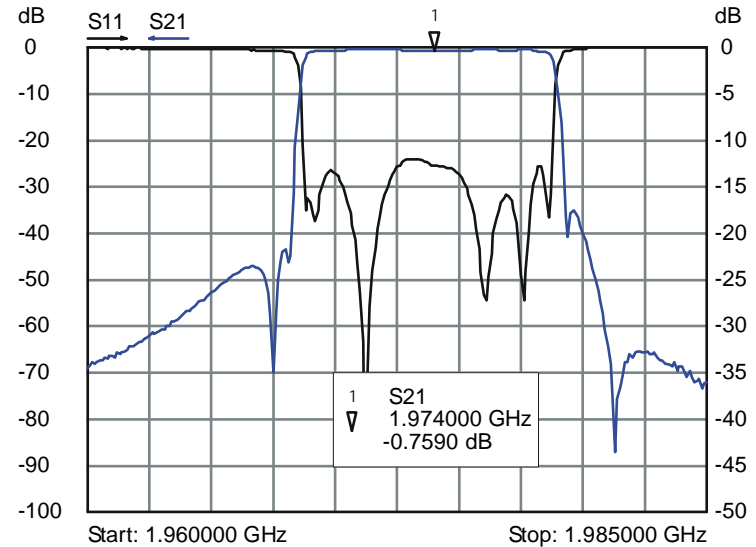
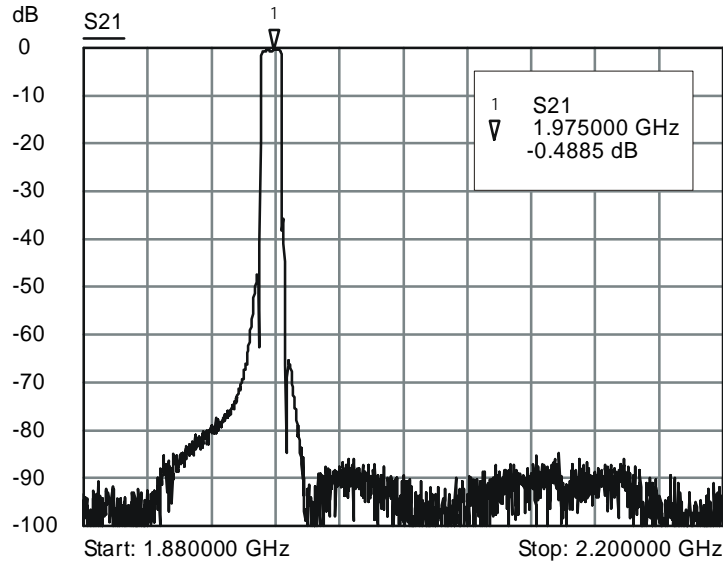
## Fabrication & packaging



- The designed filter was fabricated on a 0.43mm-thick sapphire wafer with double-sided YBCO films.
- The YBCO thin films have a thickness of 300 nm and a characteristic temperature of 87K.
- Both sides of the wafer are gold-plated with 200 nm thick gold (Au). The gold RF contacts are epoxy bonded to K-connectors with sliding contacts.
- The fabricated HTS filter used a wafer size of 47x17 mm.

# 10-pole CQT 10-MHz HTS Filter

## Measured performance



**Excellent narrow-band response with a good rejection over the entire UMTS transmission band (2110 - 2170 MHz).**

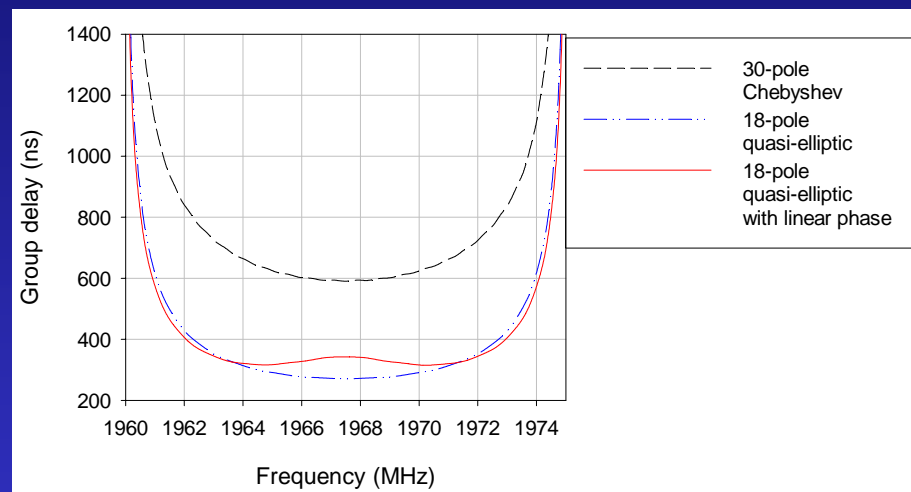
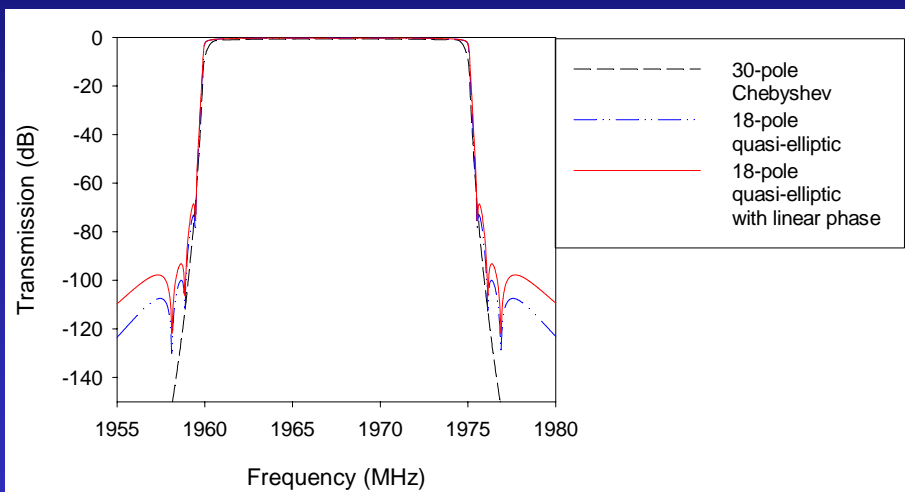
# 18-pole HTS Filter with Group Delay Equalisation

## Introduction

- The selectivity can be significantly increased with the use of high-order filters, and there is a trend to develop high-order HTS filters to take advantages of miniature high Q HTS resonators .
- Unfortunately, higher order selective-only filters tend to result in a poorer phase performance even over the band center.

# 18-pole HTS Filter with Group Delay Equalisation

## Introduction



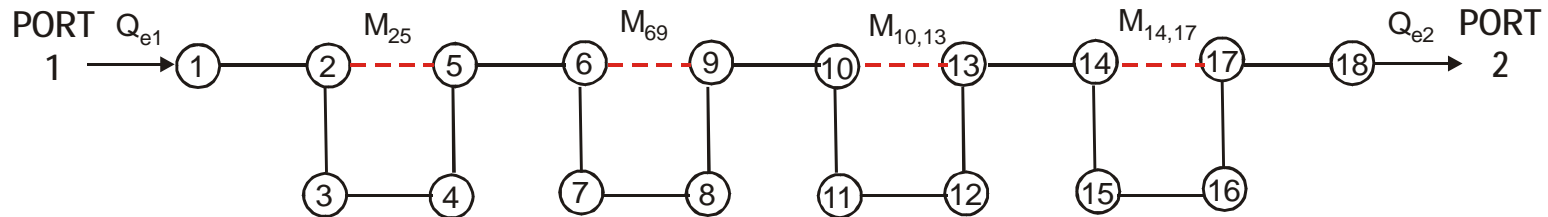
All the three filters have a pass band of 15 MHz from 1960 MHz to 1975 MHz with the same ripple level, and are supposed to meet a selectivity of 70-dB rejection bandwidth of about 16 MHz



# 18-pole HTS Filter with Group Delay Equalisation

## Design

### Coupling structure (cascaded quadruplet)

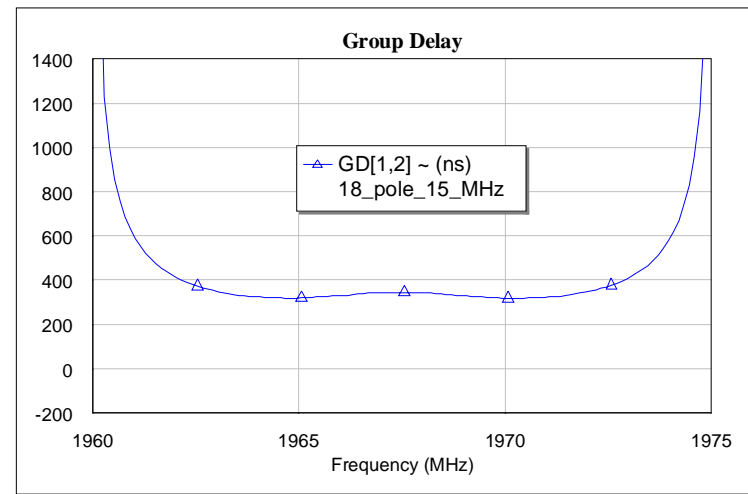
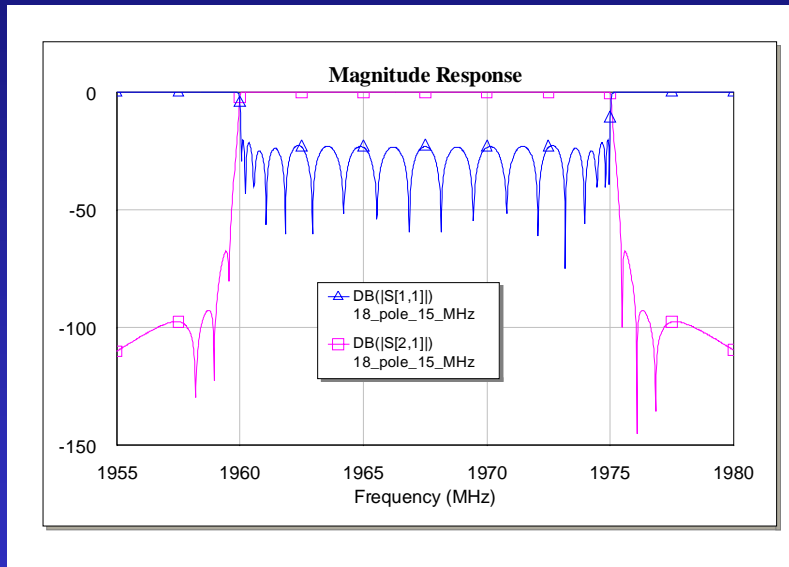


For our design, only one quadruplet section, which consists of the resonators 10 to 13, will be used for the group delay equalization, while the other three quadruplet sections are arranged for the high selectivity.

# 18-pole HTS Filter with Group Delay Equalisation

## Design

### Circuit modelling



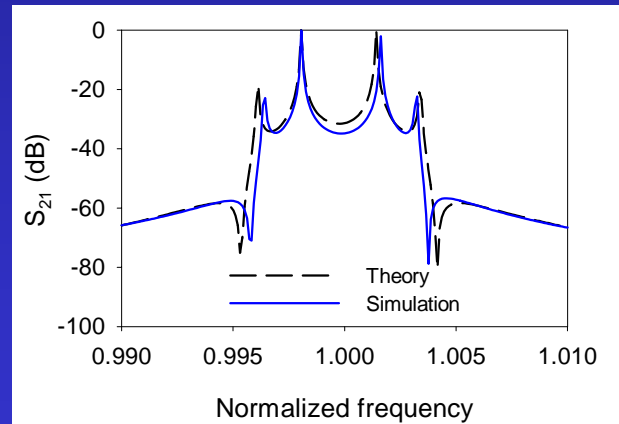
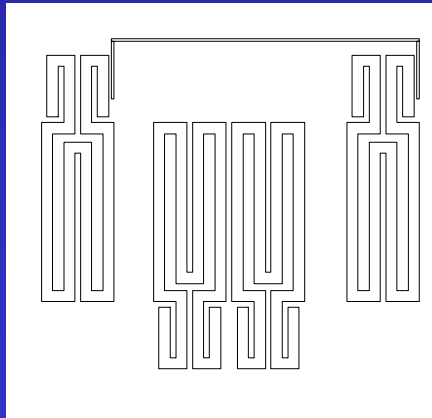
The 18-pole filter was designed to have a 15 MHz pass band at a center frequency of 1967.5 MHz.

# 18-pole HTS Filter with Group Delay Equalisation

## Implementation of Microstrip Quadruplet A

The desired coupling matrix for the first quadruplet, i.e. coupled resonators 2, 3, 4 and 5, is given by

$$\begin{bmatrix} 0 & M_{23} & 0 & M_{25} \\ M_{23} & 0 & M_{34} & 0 \\ 0 & M_{34} & 0 & M_{45} \\ M_{25} & 0 & M_{45} & 0 \end{bmatrix} = 10^{-2} \cdot \begin{bmatrix} 0 & 0.4089 & 0 & 0.1822 \\ 0.4089 & 0 & -0.5706 & 0 \\ 0 & -0.5706 & 0 & 0.3460 \\ 0.1822 & 0 & 0.3460 & 0 \end{bmatrix} \quad (1)$$

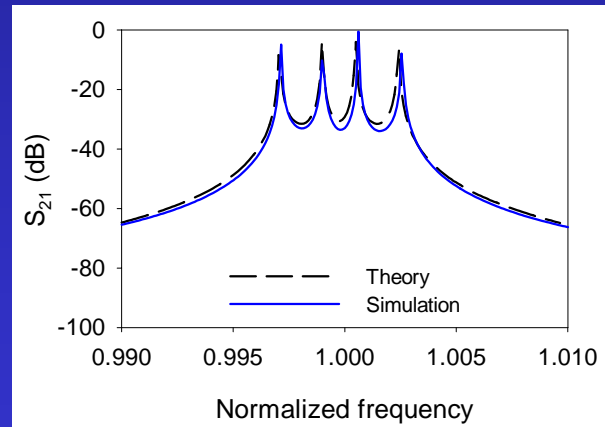
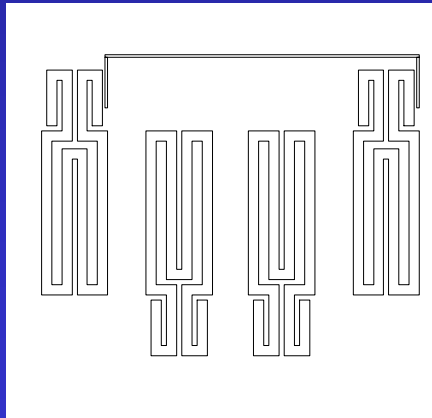


# 18-pole HTS Filter with Group Delay Equalisation

## Implementation of Microstrip Quadruplet B

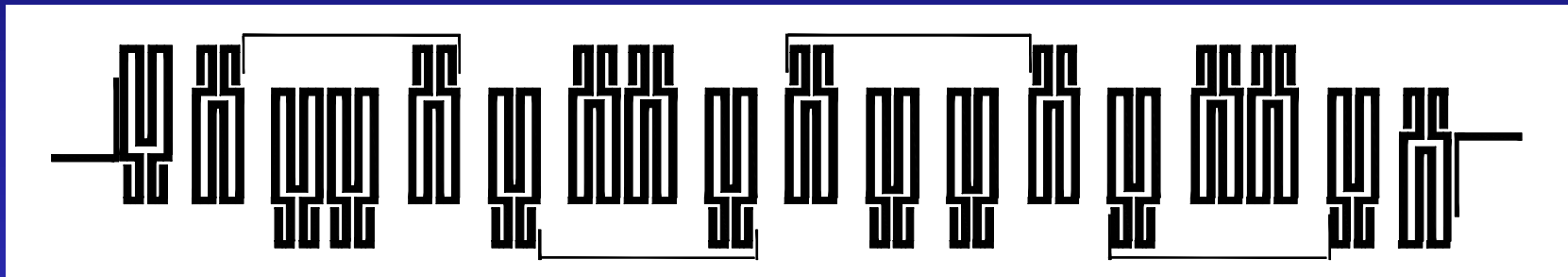
The desired coupling matrix for the first quadruplet, i.e. coupled resonators 10, 11, 12 and 13, is given by

$$\begin{bmatrix} 0 & M_{10,11} & 0 & M_{10,13} \\ M_{10,11} & 0 & M_{11,12} & 0 \\ 0 & M_{11,12} & 0 & M_{12,13} \\ M_{10,13} & 0 & M_{12,13} & 0 \end{bmatrix} = 10^{-2} \cdot \begin{bmatrix} 0 & 0.3419 & 0 & 0.1785 \\ 0.3419 & 0 & 0.2047 & 0 \\ 0 & 0.2047 & 0 & 0.3423 \\ 0.1785 & 0 & 0.3423 & 0 \end{bmatrix} \quad (2)$$



# 18-pole HTS Filter with Group Delay Equalisation

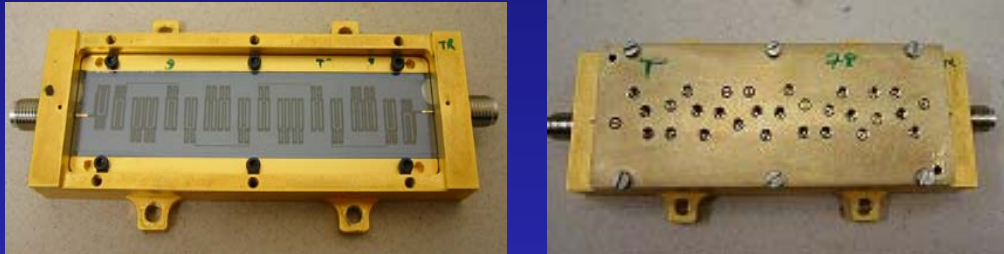
**Final layout of 18-pole HTS microstrip filter**



The overall chip size is 74 mm x 17 mm on sapphire substrate

# 18-pole HTS Filter with Group Delay Equalisation

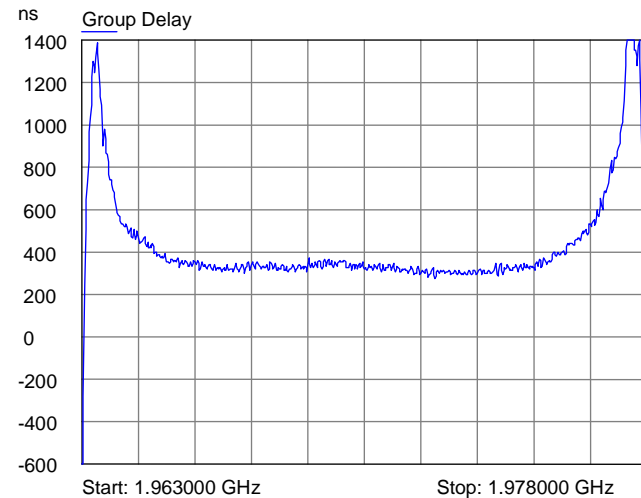
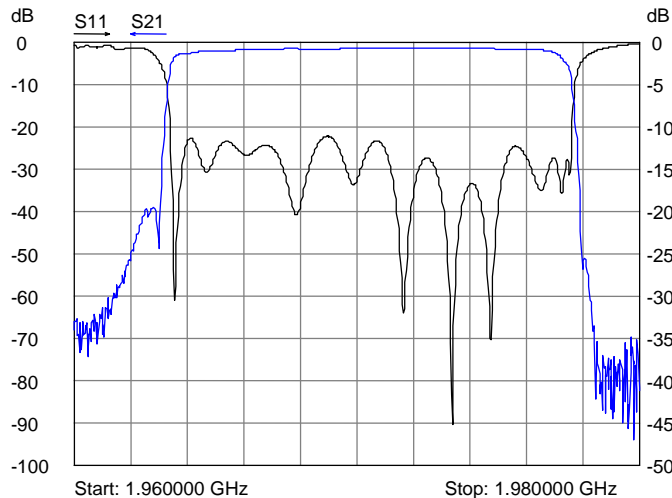
## Fabricated 18-pole HTS microstrip filter



The filter was then fabricated on a 0.43mm-thick sapphire ( $\text{Al}_2\text{O}_3$ ) wafer with double-sided YBCO films. The YBCO thin films have a thickness of 300 nm and a characteristic temperature of 87K. Both sides of the wafer are gold-plated with 200 nm thick gold (Au) for the RF contacts.

# 18-pole HTS Filter with Group Delay Equalisation

## Measured responses



The measured bandwidth is close to 15 MHz. The insertion loss of 1.4 dB at the band center was measured, including the losses of the contacts. The resonator Q is estimated to be larger than 50,000.

# Design and Development of a Prototype of Hybrid Superconducting Receiver Front-End for UMTS Wireless Network: First Results and Application Perspectives

Fabrizio Ricci, Vincenzo Boffa, Guojun Dai, Giuseppe Grassano, Renata Mele, Riccardo Tebano, Domenico Arena, Giorgio Bertin, Nicola Pio Magnani, Giovanna Zarba, Antonello Andreone, Antonio Cassinese, and Ruggero Vaglio

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

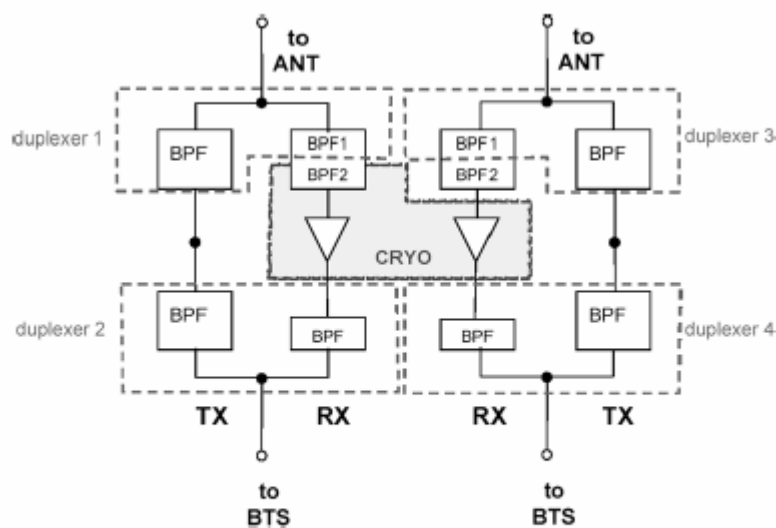


Fig. 1. Block diagram of the core parts of HTS RFE prototype. Overall layout of the prototype consists of two channels with two duplexers and LNAs each. The cryogenic superconducting filter is inserted in one chain only.

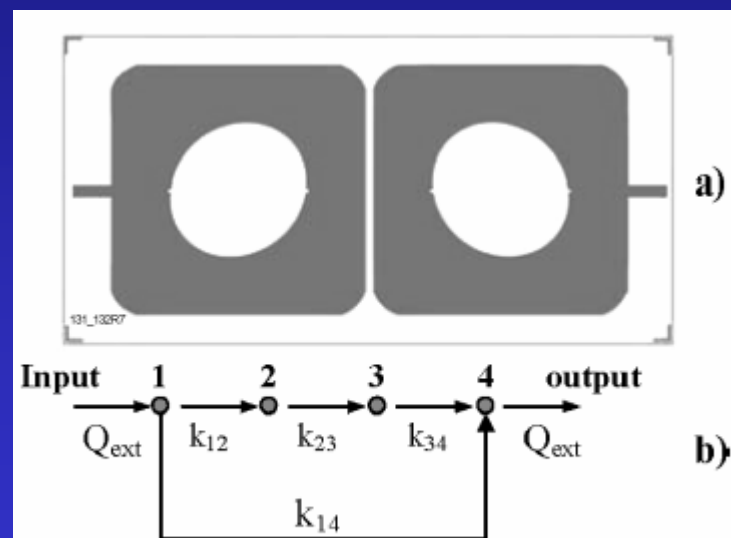


Fig. 2. Layout of the 4-pole quasielliptical filter (a) and node diagram (b).



# 4-pole HTS Elliptic Filter

2005

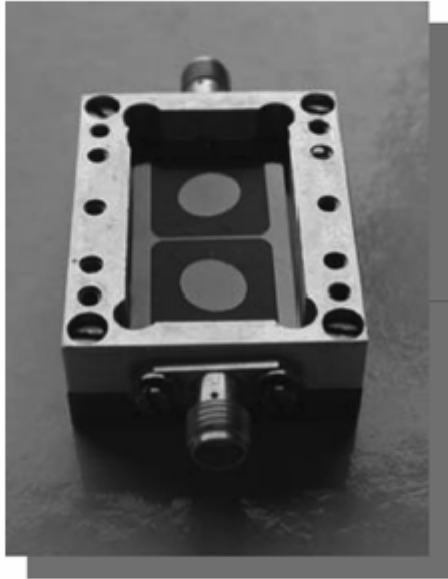


Fig. 4. Photograph of the 4-poles HTS elliptic filter.

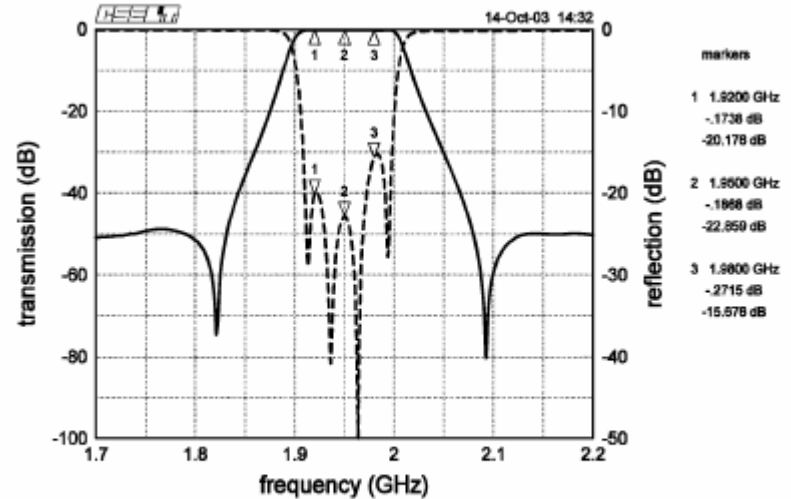


Fig. 5. Measured response of the 4-poles HTS elliptic filter.

The filters were fabricated by using e-beam lithography and wet etching process. YBCO film is double side polished type. YBCO film thickness is 700 nm in both sides and one side is protected with a gold layer. The substrate is  $\text{LaAlO}_3$  with the thickness of 0.5 mm.

# Superconducting filters for radio astronomy

Birmingham University, 2006

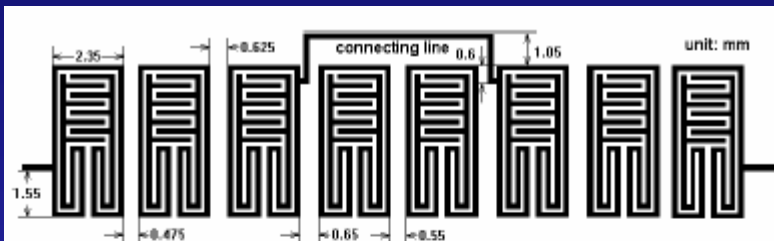


Fig. 3. Layout of an 8-pole microstrip HTS filter.

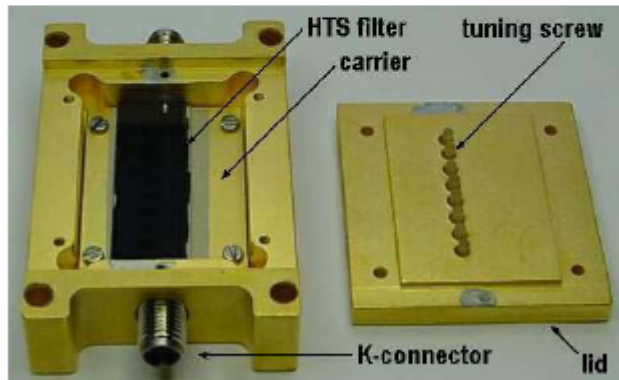
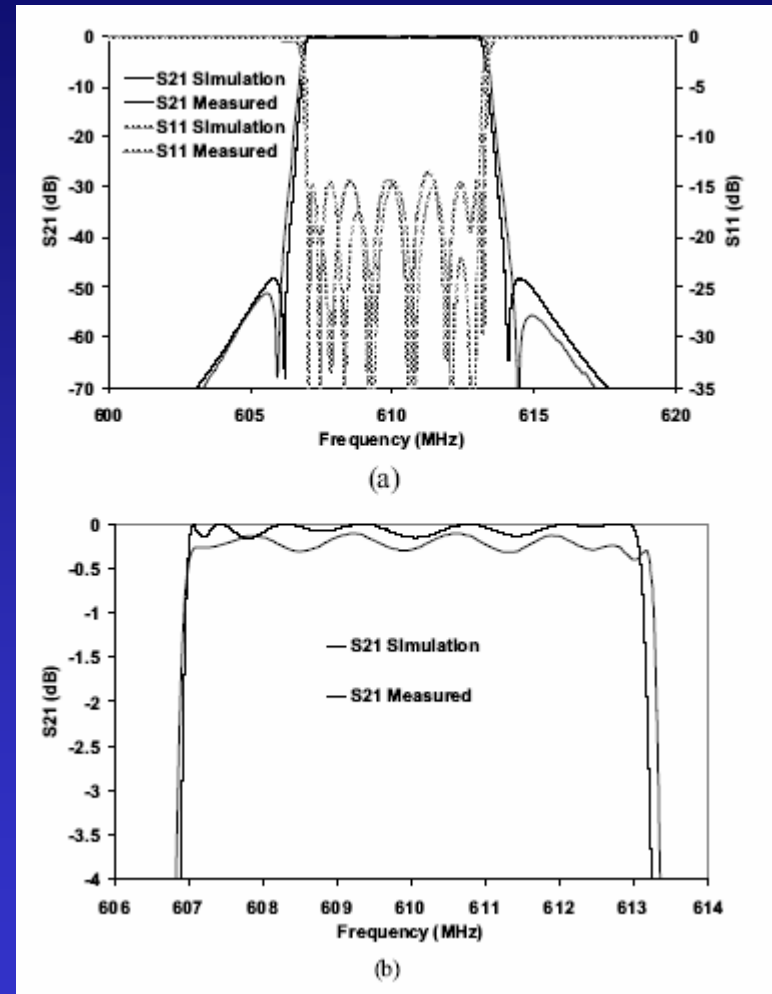


Fig. 4. Photographs of the packaging for the HTS filter.

Measured at 22K



# An Eight Pole Self-Equalised Quasi-Elliptic Superconductor Planar Filter For Satellite Applications

2005

J-F Seaux<sup>1</sup>, S. Courreges<sup>1</sup>, S. Bila<sup>1</sup>, V. Madrangeas<sup>1</sup>, M. Maignan<sup>2</sup>, C. Zanchi<sup>3</sup>

<sup>1</sup> IRCOM – UMR CNRS n°6615, University of LIMOGES, 123 Av Albert Thomas, 87060 Limoges Cedex – France

<sup>2</sup> ALCATEL SPACE – 26 Av Champollion – 31037 Toulouse Cedex – France

<sup>3</sup> CNES – 18 Av Edouard Belin – 31055 Toulouse - France

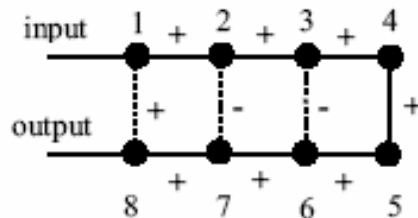
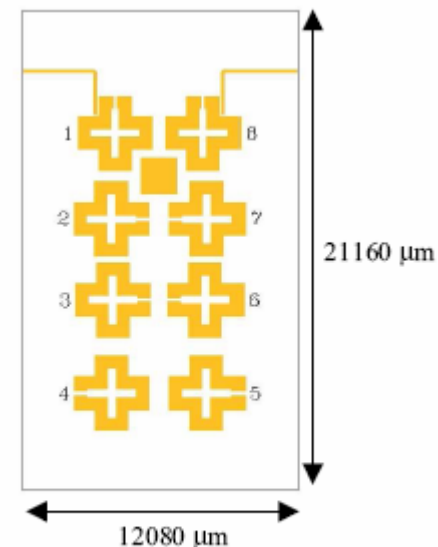


Fig. 1. Diagram of the self-equalised quasi-elliptic filter

Thus, the interest of the metallic patch square to annihilate the parasitic couplings is shown in simulation. The input channel filter is realised using double-sided superconductor YBaCuO thin film on LaAlO<sub>3</sub> substrate with thickness of 520  $\mu\text{m}$ .



New topology of the eight pole linear phase filter.

# An Eight Pole Self-Equalised Quasi-Elliptic Superconductor Planar Filter For Satellite Applications

2005

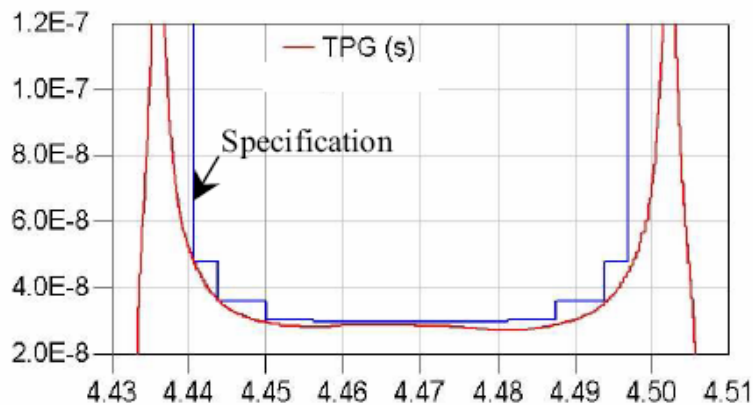
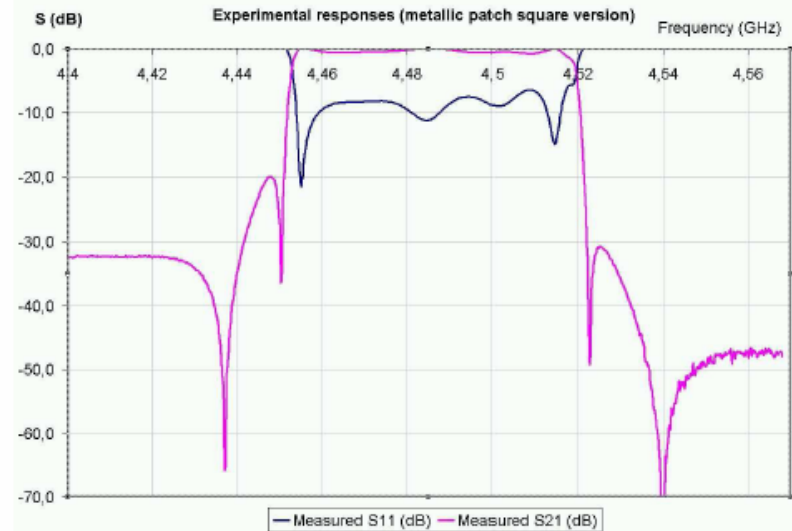


Fig. 11. Group delay performance of the new topology.



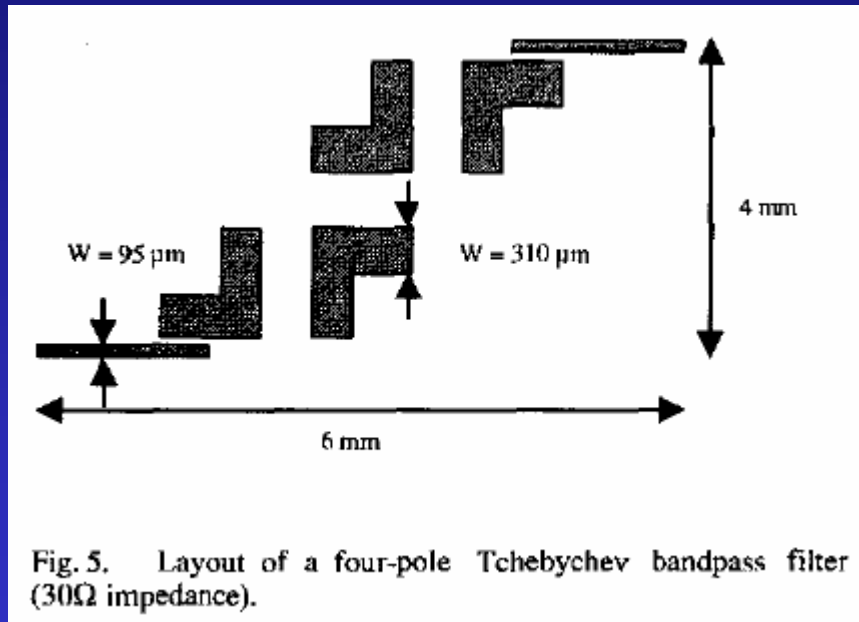
The experimental responses of the encapsulated eight pole self equalised without tuning quasi elliptic HTS microstrip filter at 77 K are presented on Fig. 12.

# Interest of the superconductivity at 30 GHz : Application to the HTS preselect receive filters for satellite communications

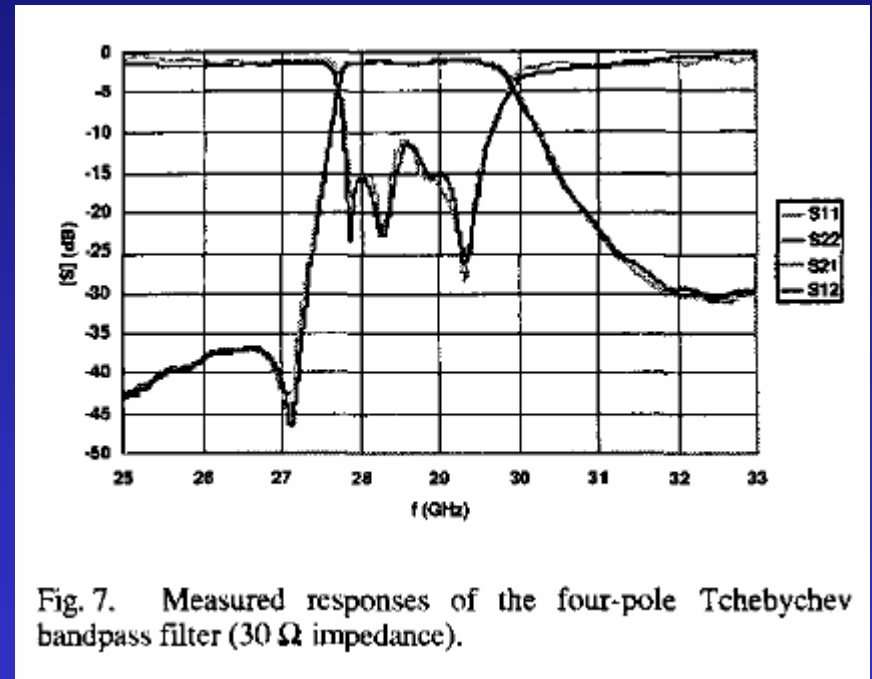
J. F. Seaux, C. Lascaux, V. Madrangeas, S. Bila, M. Maignan\*

IRCOM UMR CNRS 6615, 123 avenue Albert Thomas, 87060 Limoges Cédex, France

\*ALCATEL SPACE INDUSTRIES, 26 avenue Champollion, 31037 Toulouse Cédex, France



**Qu ~ 4000 at 77K**



**1.5 dB insertion loss at 77K**

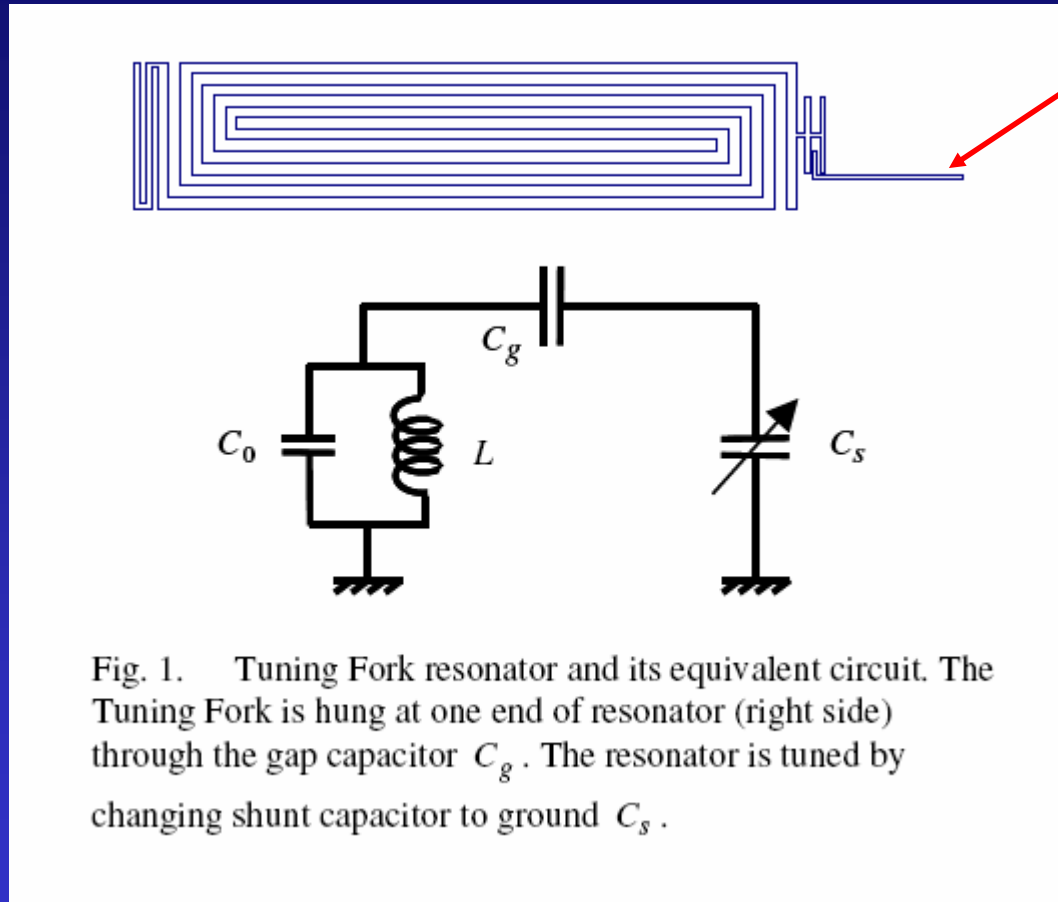
# Tuning Fork Filter Design for Hand Scribe Tuning

Genichi Tsuzuki, Matthew P. Hernandez and Balam A. Willemsen  
Superconductor Technologies, Santa Barbara, CA  
IEEE MTT-S 2005

## Tuning HTS filters:

- Mechanical tuning (e.g. tuning screws)
- Laser trimming
- Thin dielectric layer deposition
- Hand scribe tuning ->

# Tuning Fork Filter Design for Hand Scribe Tuning



Scribing here  
So as not to  
damage HTS  
resonator

Fig. 1. Tuning Fork resonator and its equivalent circuit. The Tuning Fork is hung at one end of resonator (right side) through the gap capacitor  $C_g$ . The resonator is tuned by changing shunt capacitor to ground  $C_s$ .

# Tuning Fork Filter Design for Hand Scribe Tuning

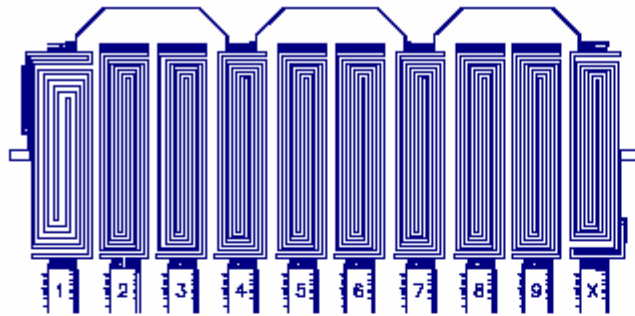


Fig. 3. A layout of 10-pole AMPS-B band filter. Two tuning Forks, those give different tuning ranges, are hung at the bottom of each resonator. Numbers and scales beside tuning forks allows hand scribing easier.

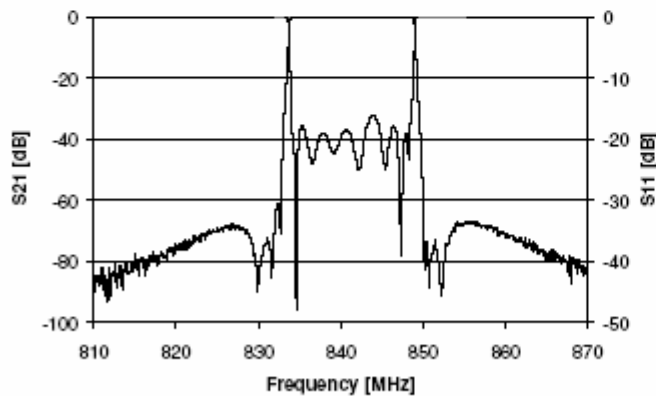


Fig. 4. Initial measurement data before the tuning process.

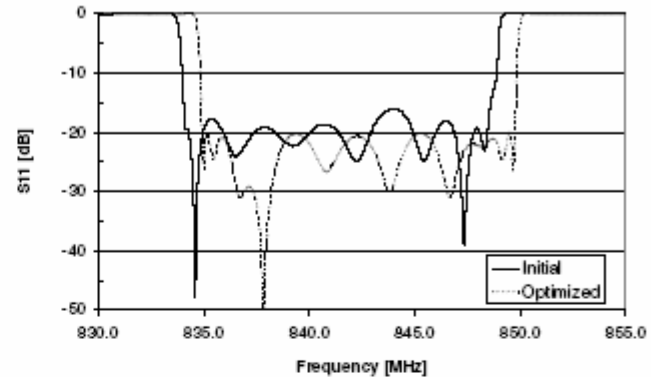


Fig. 5. Initial measured and optimized return loss.

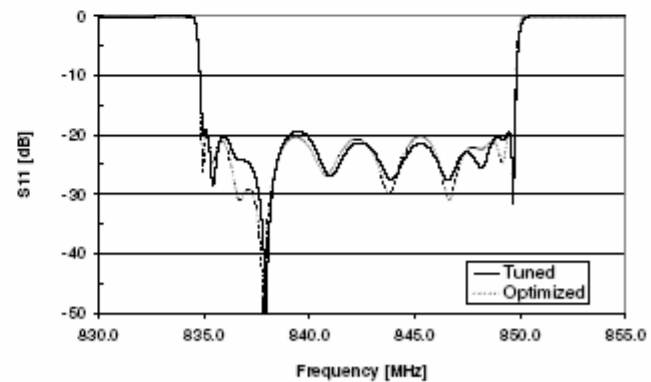


Fig. 6. Tuned and Optimized return loss.



# Highly-Selective **Electronically-Tunable** Cryogenic Filters Using Monolithic, Discretely-Switchable MEMS Capacitor Arrays

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

E. M. Prophet, J. Musolf, B. F. Zuck, S. Jimenez, and B. A. Willemssen are with Superconductor Technologies Inc., Santa Barbara, CA 93111 USA (e-mail: [balamw@suptech.com](mailto:balamw@suptech.com)).

K. E. Kihlstrom is with the Physics Department of Westmont College, Santa Barbara, CA 93108 USA, and also with the Superconductor Technologies Inc., Santa Barbara, CA 93111 USA.

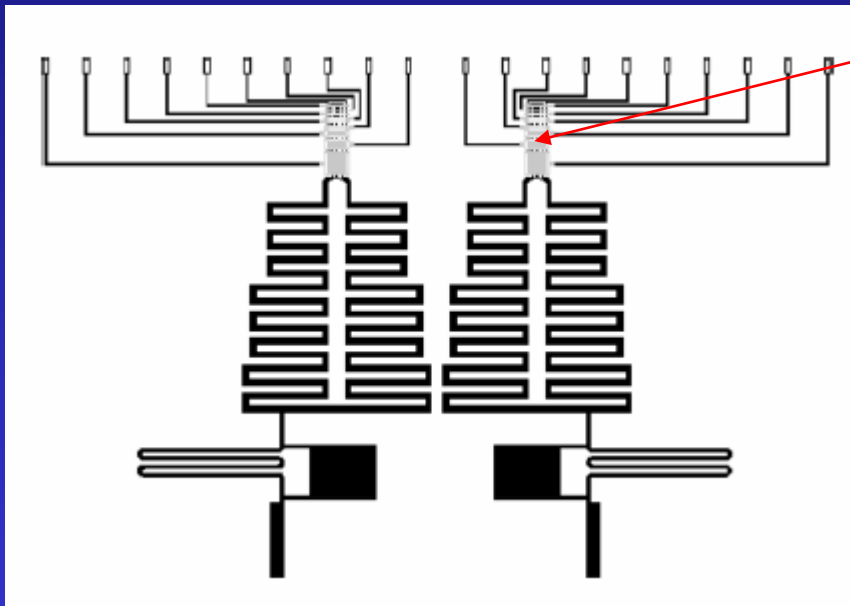
**The use of Micro Electromechanical Systems (MEMS) with High Temperature Superconductors (HTS) has enabled a new class of highly-selective tunable filters. HTS microstrip filters are generally planar, and are thus very well suited to subsequent monolithic processing such as MEMS technology.**

# Highly-Selective Electronically-Tunable Cryogenic Filters Using Monolithic, Discretely-Switchable MEMS Capacitor Arrays

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

E. M. Prophet, J. Musolf, B. F. Zuck, S. Jimenez, and B. A. Willemssen are with Superconductor Technologies Inc., Santa Barbara, CA 93111 USA (e-mail: balamw@suptech.com).

K. E. Kihlstrom is with the Physics Department of Westmont College, Santa Barbara, CA 93108 USA, and also with the Superconductor Technologies Inc., Santa Barbara, CA 93111 USA.



MEMS switches

A low loss electronically tunable filter was demonstrated using HTS/Au MEMS switched capacitor arrays. The two-pole filter was tuned by simultaneously varying the capacitance of each resonator by equal amounts. The total tuning range was about 25% with an average Q of 7,000 at 77 K.

# Improvement of Power Handling Capability

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 52, NO. 12, DECEMBER 2004

A research team at NTT (Nippon Telegraph and Telephone) Corporation has focussed on improving power handling of HTS filters and found that

- IP3 is enhanced by increasing HTS thin film thickness  $t$ . For YBCO filters, IP3 at 70 K increased from 53 to 65 dBm as  $t$  increased from 620 nm to 800 nm.
- Different materials and deposition methods can affect the power handling.
- A possible trade-off between the passband insertion loss, i.e.  $|S_{21}|$ , and power handling capability in HTS bandpass filters.

2005

# New Method to Improve Power Handling Capability for Coplanar Waveguide High-Temperature Superconducting Filter

Kei Satoh, Daisuke Koizumi, and Shoichi Narahashi

NTT DoCoMo, Inc., Wireless Laboratories

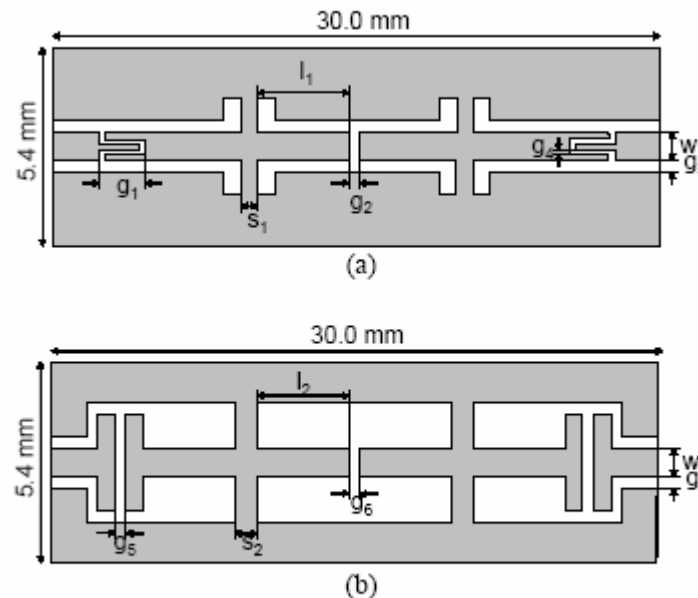


Fig. 2. Circuit pattern and dimensions of CPW-HTSFs employing line characteristic impedance of (a)  $50 \Omega$  and (b)  $100 \Omega$ .

High impedance line would result in a smaller  $Q_u$ , but can reduce maximum current density so as to increase the power handling.

# Improvement of Power Handling Capability

NTT, 2005



Fig. 5. Photograph of fabricated 100-Ω CPW HTSF.

TABLE III  
SPECIFICATIONS FOR SUPERCONDUCTOR FILM AND DIELECTRIC  
SUBSTRATE

Superconductor film	
Material	YBCO
Thickness	0.5 $\mu\text{m}$
Critical temperature	86 K
Dielectric Substrate	
Material	MgO
Thickness	0.5 mm
Dielectric constant	9.68 (@ 77 K)
Loss tangent ( $\tan \delta$ )	$< 10^{-5}$

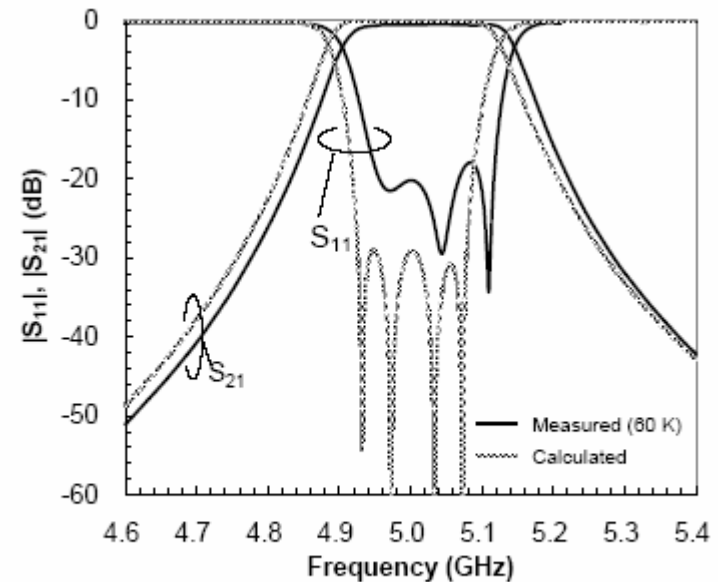
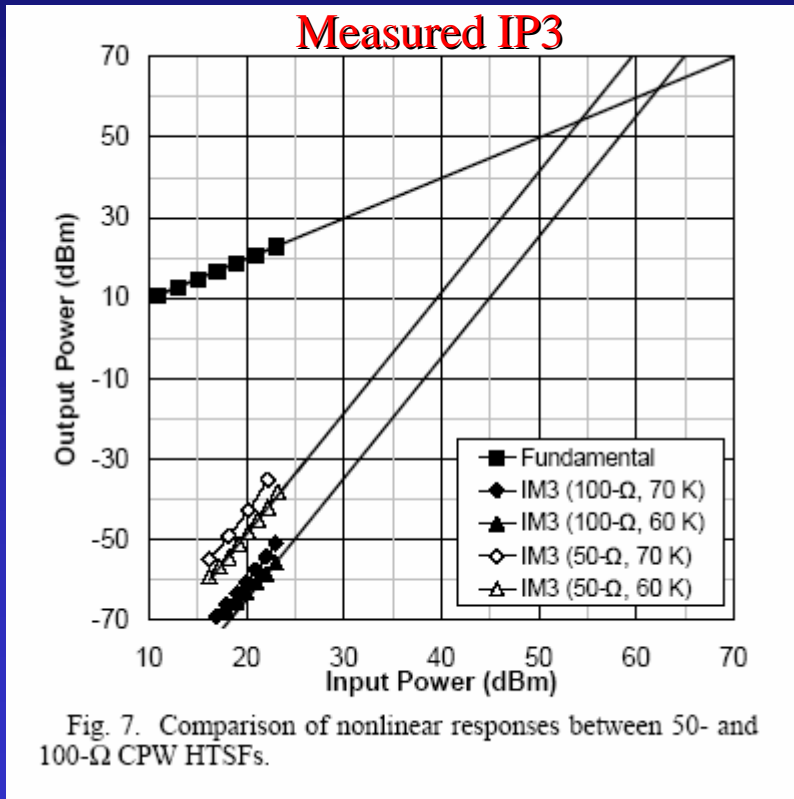


Fig. 6. Frequency responses of 100-Ω CPW HTSF.

# Improvement of Power Handling Capability

NTT, 2005



The IP3 of the 100-ohm CPW HTS filter is 62 dBm at 60K, while the IP3 of the 50-ohm CPW HTS filter is 54 dBm.

This means that the former can handle over 6 times as much power as that of the latter.

# Summary

- Some recent developments of HTS filters have been reviewed, including miniature high performances HTS filters for wireless and satellite communications as well as radio astronomy applications.
- There is also a new trend to develop electronically tunable HTS filters using RF MEMS and ferroelectric devices.
- Power handling capability can be improved through designs, fabrications processes and materials.
- Superconducting filter R&D will certainly continue at least for niche applications.