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A Thirty-Year History of Superconducting Microwave Devices and Fundamental Studies Thereof

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1. HTS films for microwave devices

The most important superconducting properties for microwave devices

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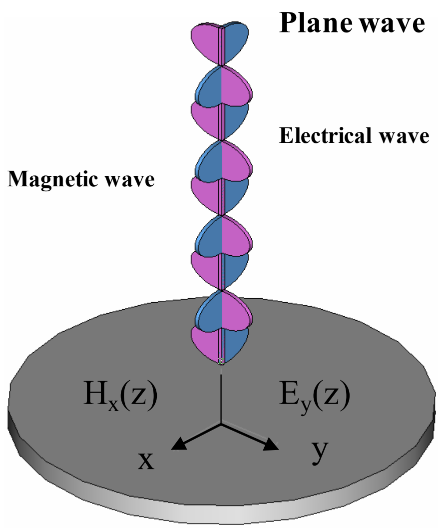
Surface resistance

Definition of surface resistance

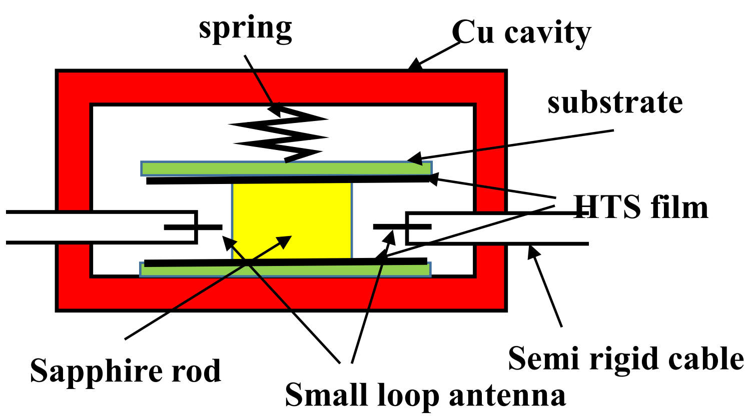
$$Z_S = \left. \frac{E_y(z)}{H_x(z)} \right|_{z=0}$$



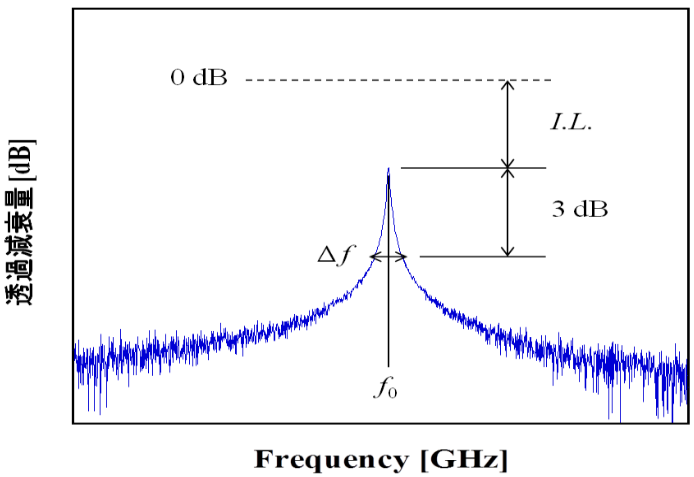
When a plane wave is irradiated on the superconductors, the magnetic field $H_x(z)$ and the electric field $E_y(z)$ are penetrated in it. The surface resistance is defined by E/H.

Measurement of surface resistance

Dielectric resonator method is standard for measurement of surface resistance; (IEC/TC90 61788-7)



Closed cavity of a dielectric resonator using quite small tand sapphire rod.



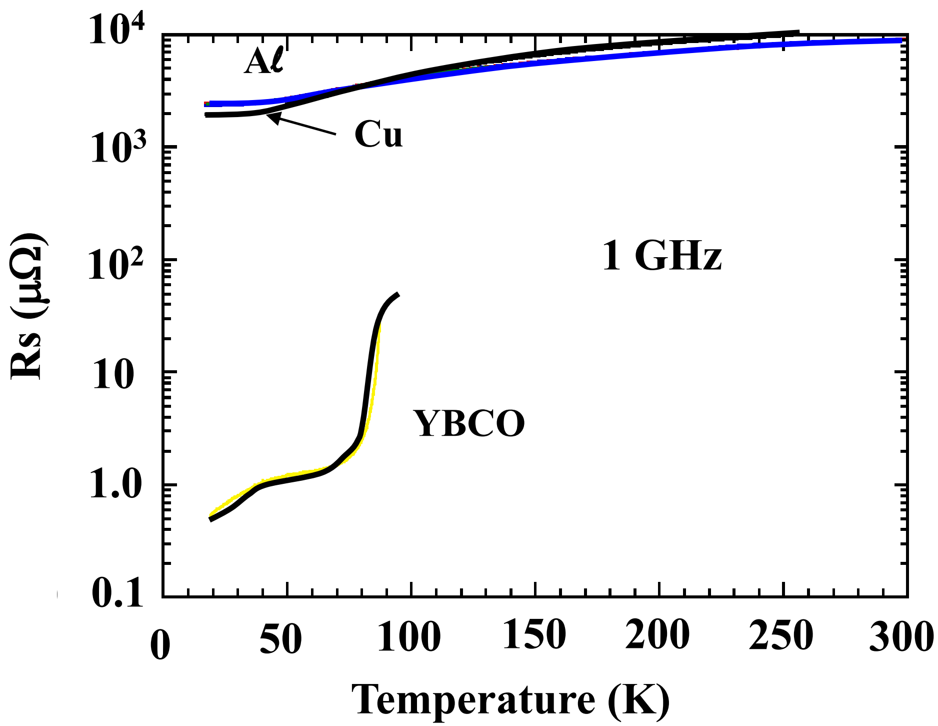
Frequency response of a cavity

$$R_s = \frac{1}{B}\left(\frac{A}{Q_u} - \tan\delta\right)$$

A,B; constant

$$Q_u = \frac{Q_L}{1 - A_t}, \quad A_t = 10^{-I.L[dB]/20}$$

Surface resistance of YBCO, Cu and Al films

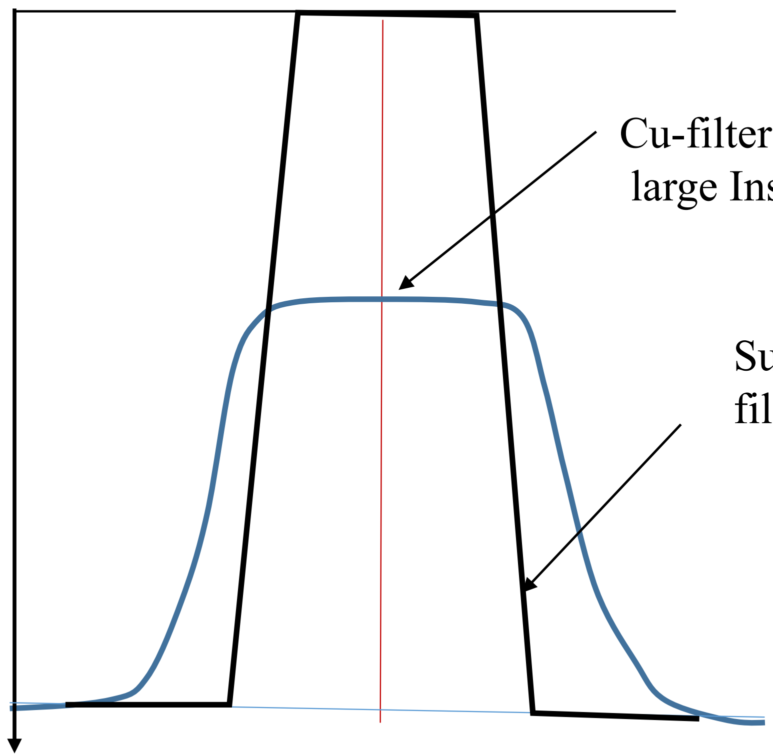


Temperature dependence of microwave surface resistance of Cu, Al and YBCO thin films measured at 1 GHz

Rs of YBCO films is 3-order magnitude smaller than that of Al, Cu films. This difference in surface resistance affects the characteristics of microwave devices

Example:

Difference of insertion loss between Cu and superconducting filter



Superconducting filter has quite small insertion loss and sweep skirt properties, however cu filter has large insertion loss.

How to reduce a surface resistance of superconducting films

The surface resistance of superconducting films is inversely proportional to the critical current density

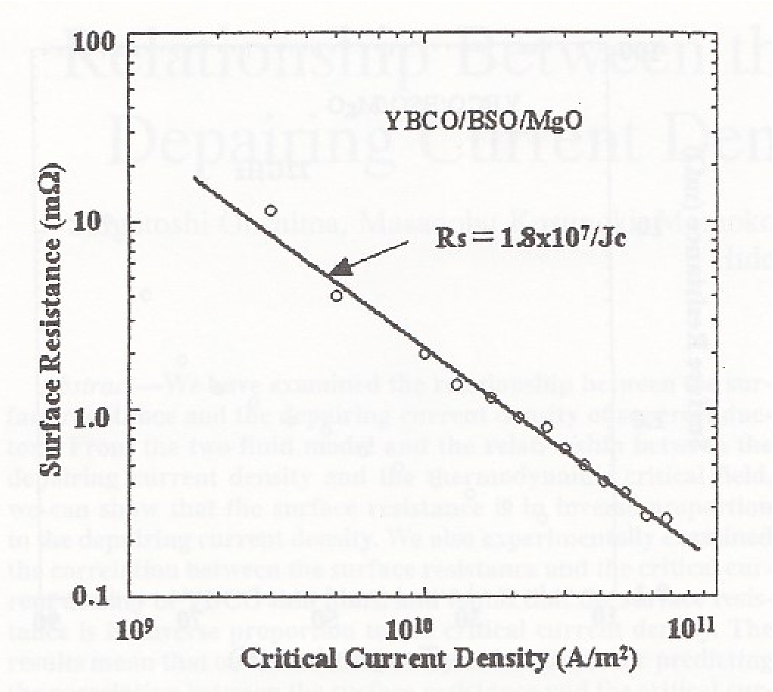
↓

Higher Jc films is lower Rs films

↓

In order to increase Jc of YBCO films. Reduction of grain boundary density is important.

Perfect C-plane oriented films
Single crystal films



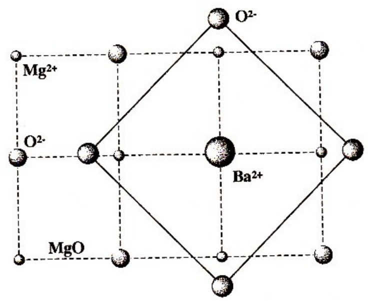
Relationship between a surface resistance and critical current density of YBCO film

S. Ohshima, et al: IEEE Trans. Applied Superconductivity, **13** (2003) 3578

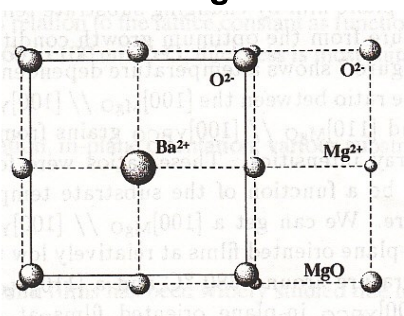
Grain boundary density vs surface resistance

Our group

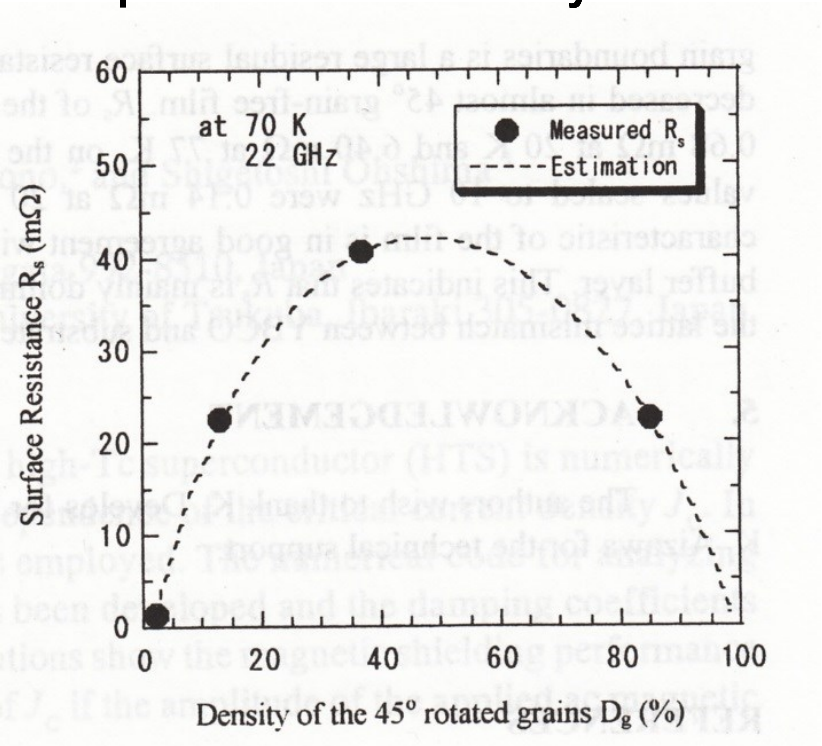
We could control the density of 45-degree tilt grain by template deposition method of laser deposition method and we examined the relationship between its density and surface resistance.



45° rotated grain of YBCO on MgO substrate



Cube on cube grain of YBCO



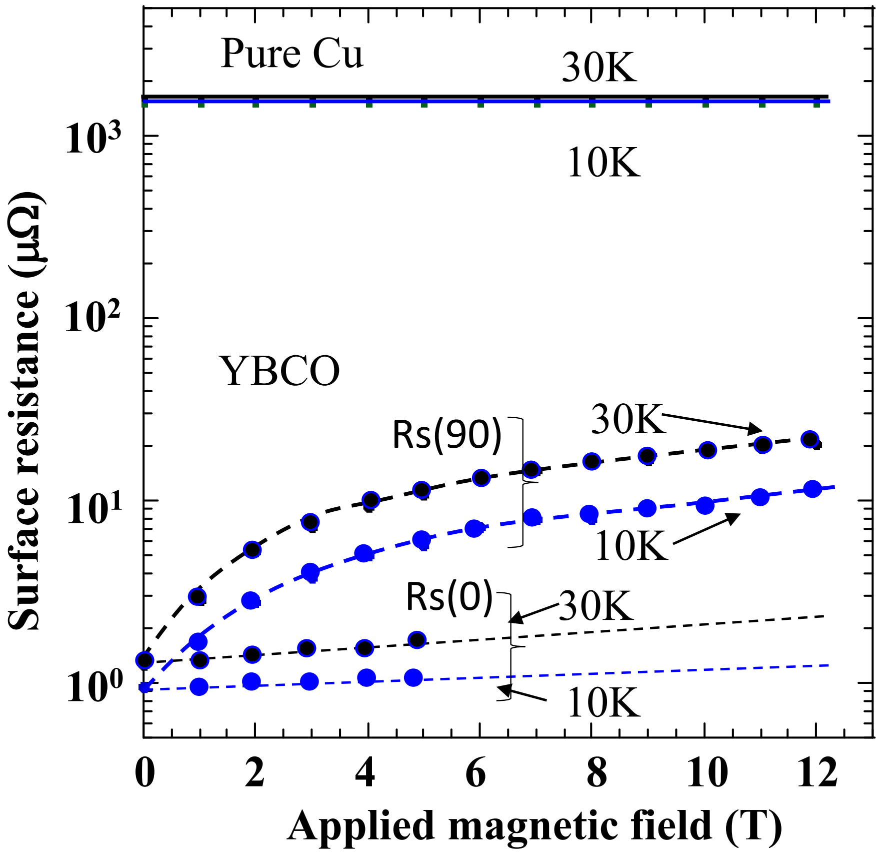
Surface resistance vs. 45° tilt grain density

M. Kusunoki, S. Ohshima et al; EUCAS 1999

We found that grain boundary increases the Rs of YBCO thin films. Therefore, it is important to make thin films with perfect c plane oriented film

Surface resistance of HTS films in High magnetic field

Our group



Magnetic field dependence of surface resistance of YBCO films

Surface resistance of YBCO films is smaller than Cu films in a high magnetic field

Rs(90); Applied magnetic field direction is normal to a film plane
Rs(0); Applied magnetic field direction is parallel to a film plane

T. Honma, S. Ohshima et al ISS 2011

We can use YBCO films for microwave devices worked in high magnetic field, for example, NMR pickup coils.

2. Some topic of superconducting microwave devices （1988～2017）

First topics; filter and antenna

Electrical small antennas

Helical and patch superconducting antennas

Small size and high quality HTS filters

Hairpin filter, cross-coupled filter

Second topics; HTS bandpass filter for mobile communication

GSM and IMT-2000 filters

Tunable and ultra wide-band filters

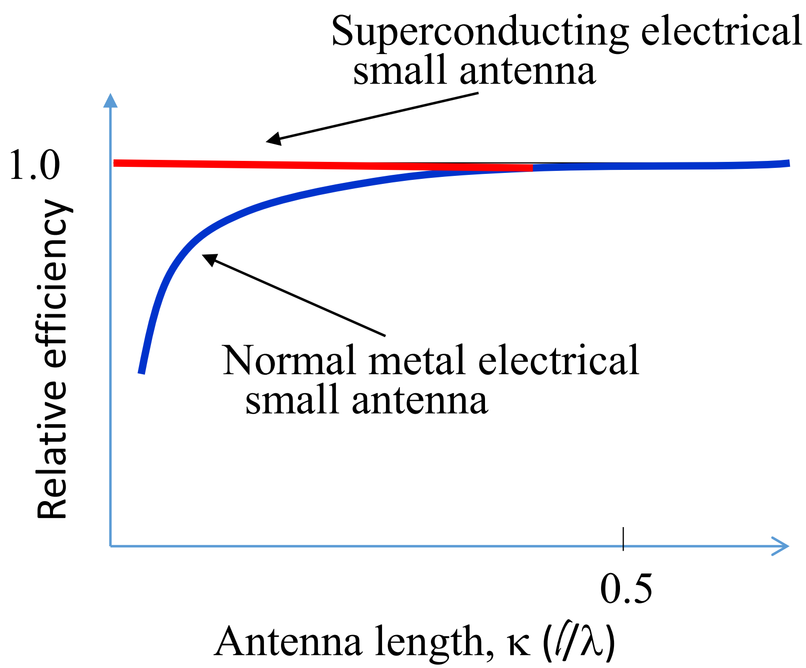
Third topics; detector and sensor

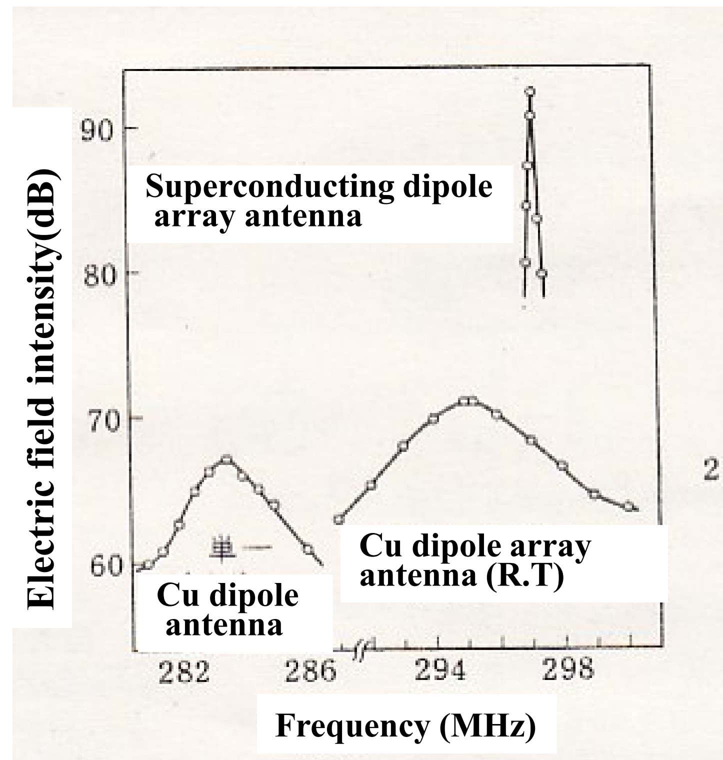
MKIDs,TES

2.1 Electrical small antennas

Half wave length antenna(Yagi antenna)

Normally, we cannot use a electrical small antenna, because efficiency is small. However the efficiency of superconducting electrical small antenna is large even in very small size. Therefore, the first focused microwave device was an electrical small antenna when HTS was discovered.





From Prof. Adachi (Tohoku Univ.) 1980

Helical antenna

Reported in ISS'92

NTT group

Bandwidths of Electrically Small Antennas Composed of High-T_c Superconducting Helical Radiators

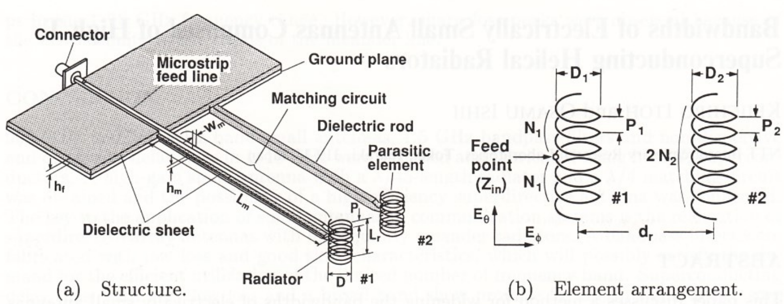
KEIICHIRO ITOH and OSAMU ISHII

NTT Interdisciplinary Research Laboratories, Tokai, Ibaraki, 319-11 Japan

Unfortunately, the HTS antennas could not be used for practical application, because of Cooling problem.

ABSTRACT

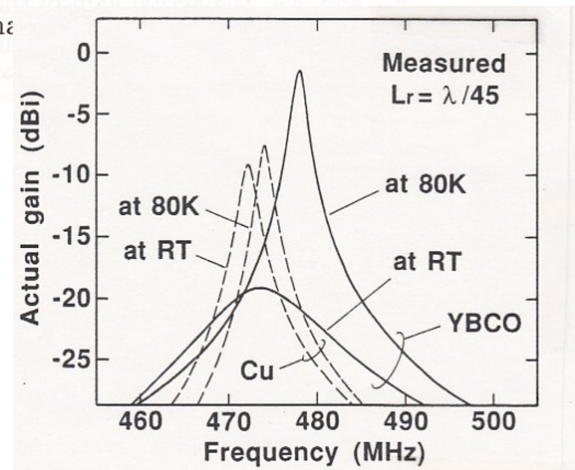
This paper discusses a method for widening the bandwidths of electrically small antennas with Ba(Pb)SrCaCuO helical radiators, and describes calculated and experimental results on their gain characteristics. As a result of numerical analysis, it was found that the bandwidth of a 500-MHz-band antenna with a $\lambda/30 \sim \lambda/40$ radiator was widened about 3 times by placing a parasitic helical element near the radiator, and this result agreed well with experimental results. Through this investigation, it is confirmed that parasitic elements are effective in widening bandwidths even in small antennas with very high-Q radiators.



(a) Structure. (b) Element arrangement.

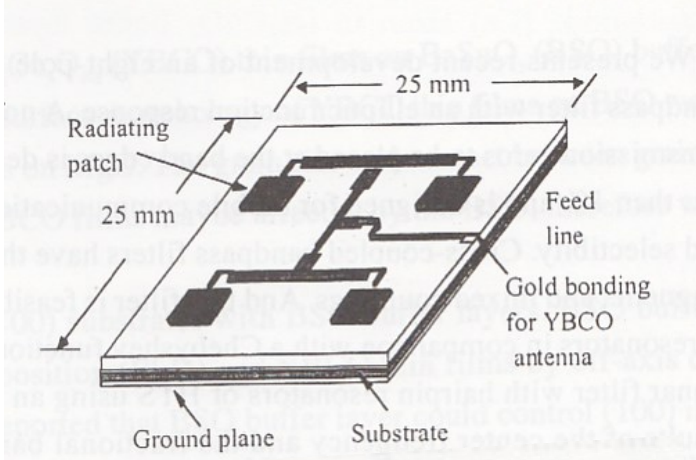
Fig. 1: Antenna structure and its element arrangement.

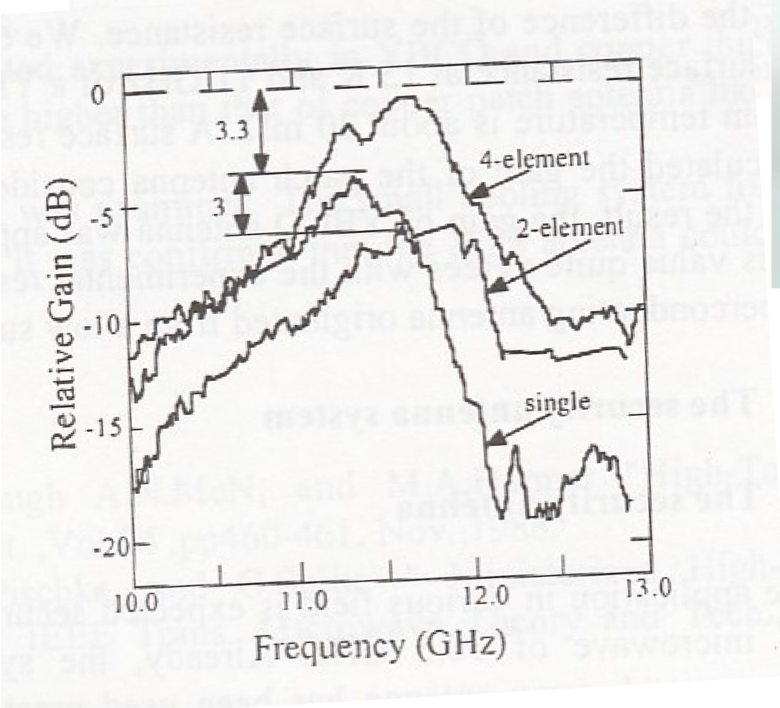
A helical antenna is one of the electrical small antenna, And they can reduce a size of 1/40 of the wave length



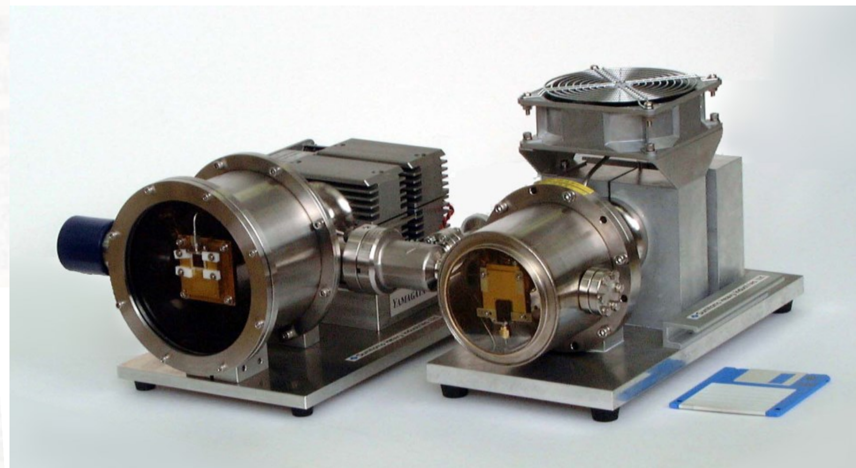
The gain of the HTS helical antenna is 5 dB or more as compared with that of copper antenna at 80K.

Patch array antenna





The helical antenna cannot be cooled by a small refrigerator, and that is a serious problem for practical use. However, patch antennas can be cooled by a small refrigerator, and easy to cool.



Mini cryocooler for a patch antenna

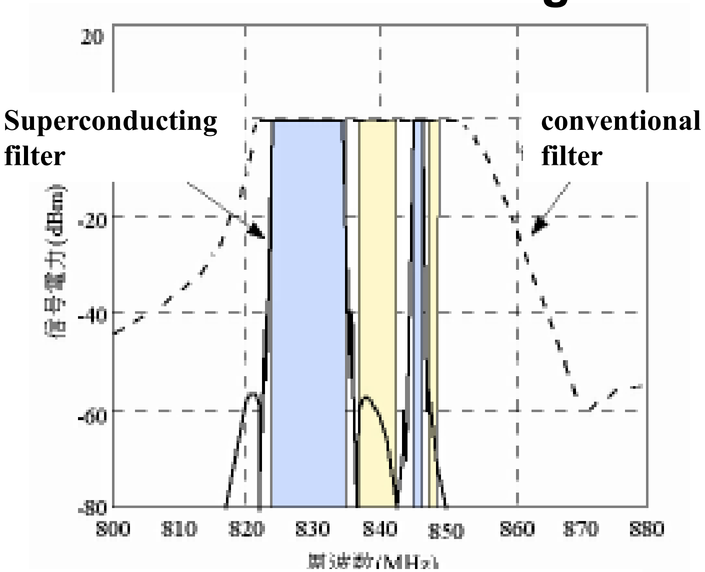
The superiority of the superconducting antenna could be demonstrated, but it could not be put into practical use. Superconducting antennas must be cooled to a low temperature, and that is large disadvantage.

2.2 Second topics; HTS filters for mobile communication

Merits of HTS bandpass filter

- Sharp skirt characteristics
- Low insertion loss
- High frequency selection

Superconducting bandpass filter systems have already been put to practical use for 2G wireless communication in the USA. In the 1990's troubles were continuing among users of two mobile phone companies.



Two-band filter for 2G wireless

A company
B company

STI group

The superconducting filters can separate the signals between Company A and B, but the conventional filter can not.

↓

More than 5000 systems were used for wireless communication base stations

Next researches

IMT-2000 filters
Tunable filters for software wireless communication

HTS filters for IMT-2000

ISS'97

AMTEL group

High Temperature Superconducting Filters for Receiver Front-end of Mobile Telecommunication Base Station

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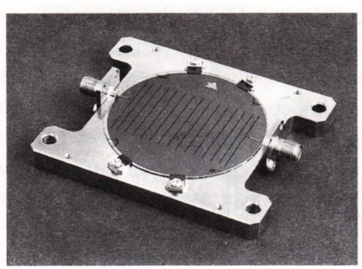
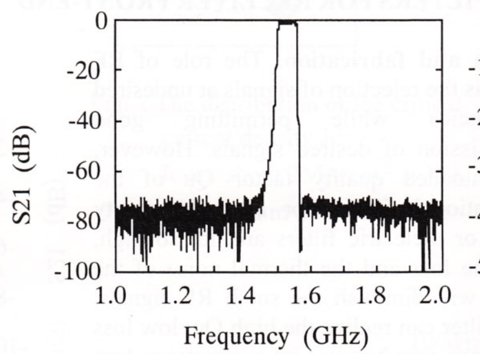
ABSTRACT

The performance of multi-pole microstrip filters with low insertion loss and sharp-skirt using $YBa_2Cu_3O_{7-\delta}$ high temperature superconducting thin films is presented. The HTS films were deposited on both sides of substrates by a DC sputtering method. The surface resistance of the films was about 0.35mΩ (at 70k and 10GHz). A 9-pole bandpass filter was designed at 2.6GHz center frequency with bandwidth 34MHz. The filter was fabricated using 40mm×25mm HTS films on a 0.5-mm thick MgO substrate. The insertion loss at 70 K was about 0.1dB with 0.1dB ripple and the minimum return loss was about 20 dB across the passband of the filter. In addition, a 15-pole bandpass filter whose center frequency and bandwidth were 1.53GHz and 60MHz respectively was fabricated using 50-mm diameter HTS film on 0.5-mm thick $LaAlO_3$ substrate. The insertion loss at 70K was less than 0.1dB and the rejection level was more than 70dB at the rejection band.

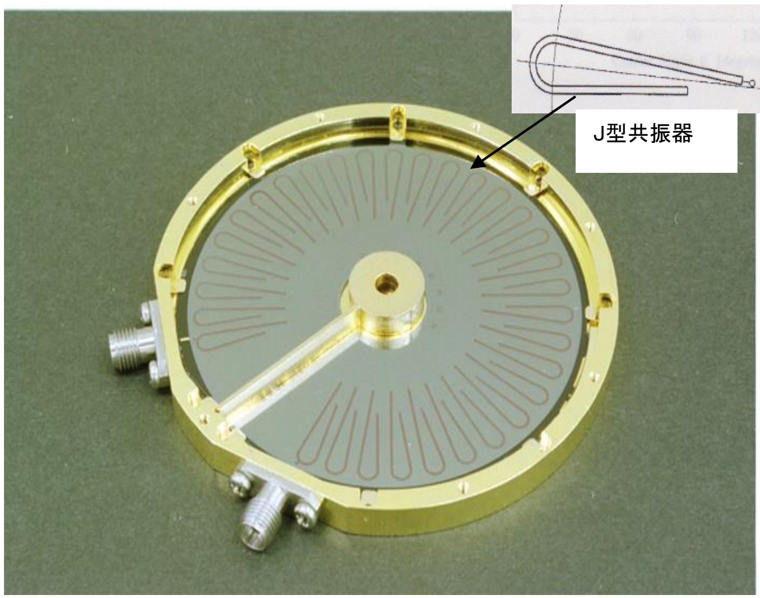
KEY WORDS: h

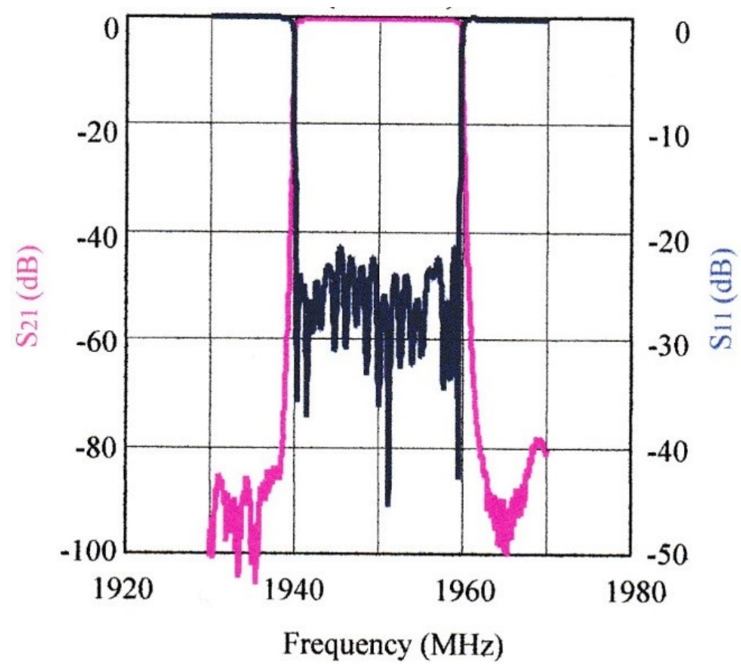




J-type resonator filter for IMT-2000

By Ueno, Tsuzuki and Sakakibara: AMTEL





Sharp skirt characteristics; > 20dB/1MHz
Low insertion loss; < 0.1dB
High frequency selection > -80dB at out of band

Superconducting filters didn't use for IMT-2000 because of high price and maintenance problem

Tunable filters

High-T_c superconducting tunable filter with steep attenuation

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Received 27 September 2001; accepted 19 November 2001

Toshiba group

Abstract

We developed a compact RF receiver front-end subsystem using a high-T_c superconducting sharp-skirt band-pass filter with a center frequency tuning function. The subsystem had two pairs of the tunable filter and an LNA on board. A 23-pole hairpin-type 2-GHz microstrip-line filter was fabricated with $YBa_2Cu_3O_y$ thin films deposited on a 35-mm-wide and 70-mm-long sapphire substrate. Attenuation characteristics were more than 40 dB at 1 MHz, apart from both the lower and the higher pass-band edges. For center frequency tuning, a 1-mm-thick dielectric sapphire plate was stacked on the filter, and the filtering characteristics were tuned by moving the plate using a piezoelectric bending actuator. The range of the center frequency modulation was more than 10 MHz with no significant degradation of the low-loss and sharp-skirt characteristics.

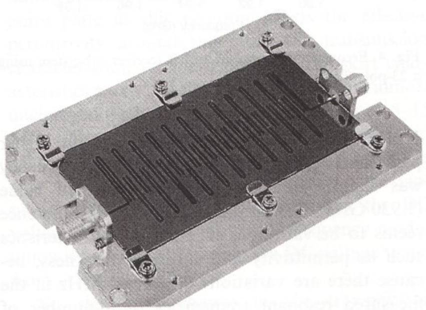


Fig. 1. Photograph of a 23-pole hairpin-type microstrip line filter using sapphire substrate.

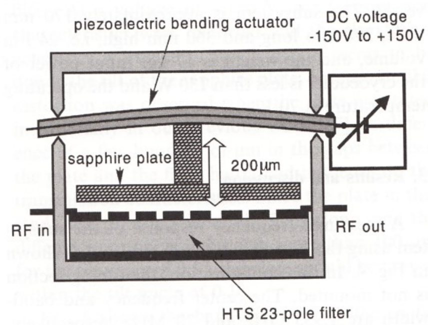
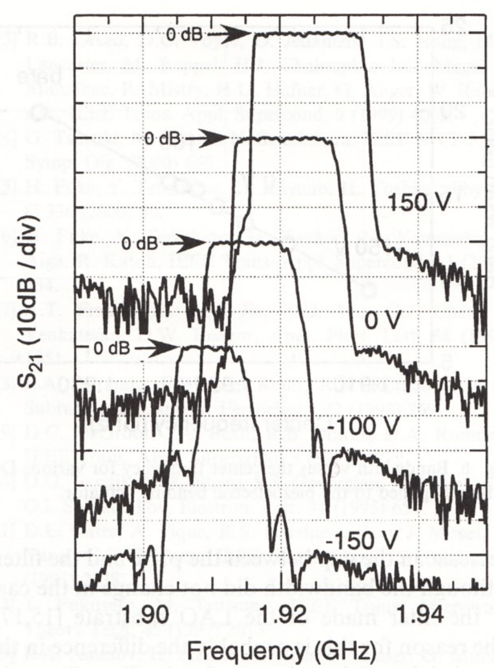


Fig. 2. Cross-sectional schematic illustration of the proposed tunable filter.



By moving a sapphire plate up and down by a piezo element, center frequency of the filter can shift more than 10 MHz.

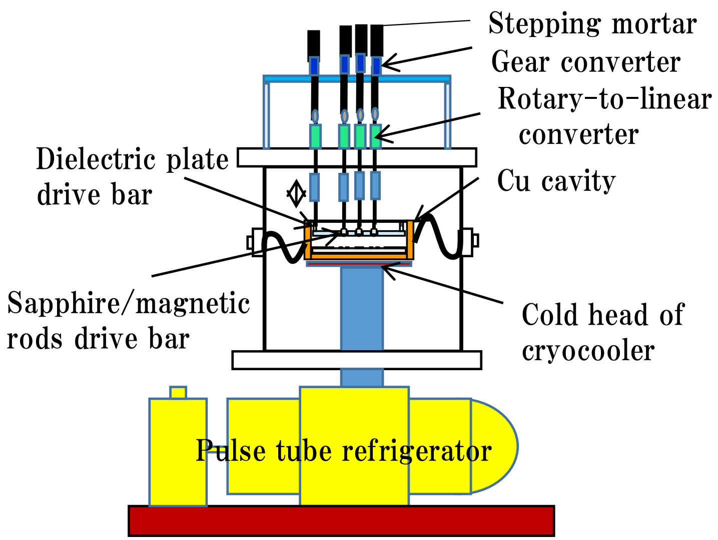
INVITED PAPER *Special Section on Recent Progress in Superconducting Analog Devices and Their Applications*

Automatic Trimming Technique for Superconducting Band-Pass Filters Using a Trimming Library

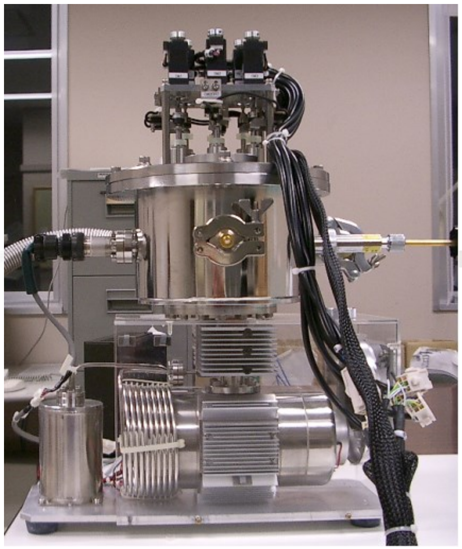
Shigetoshi OHSHIMA[†a)], *Member*, **Takuro KANEKO**[†], **Jae-Hun LEE**[†], **Maya OSAKA**[†], **Satoshi ONO**[†], *Nonmembers, and* **Atsushi SAITO**[†], *Member*

SUMMARY The superconducting band-pass filter has small insertion loss and excellent out-of-band rejection properties. It has been put to practical use in a number of applications. However, in order to expand its range of application, a tuning technique that can restore the filter characteristics is needed. We propose an automatic tuning system using a trimming library and checked the feasibility of the system by tuning a forward-coupled filter with three resonators. The results show that the trimming library method is an effective way of automatically improving the filter characteristics.

key words: HTS band-pass filter, automatic tuning, trimming library microwave device



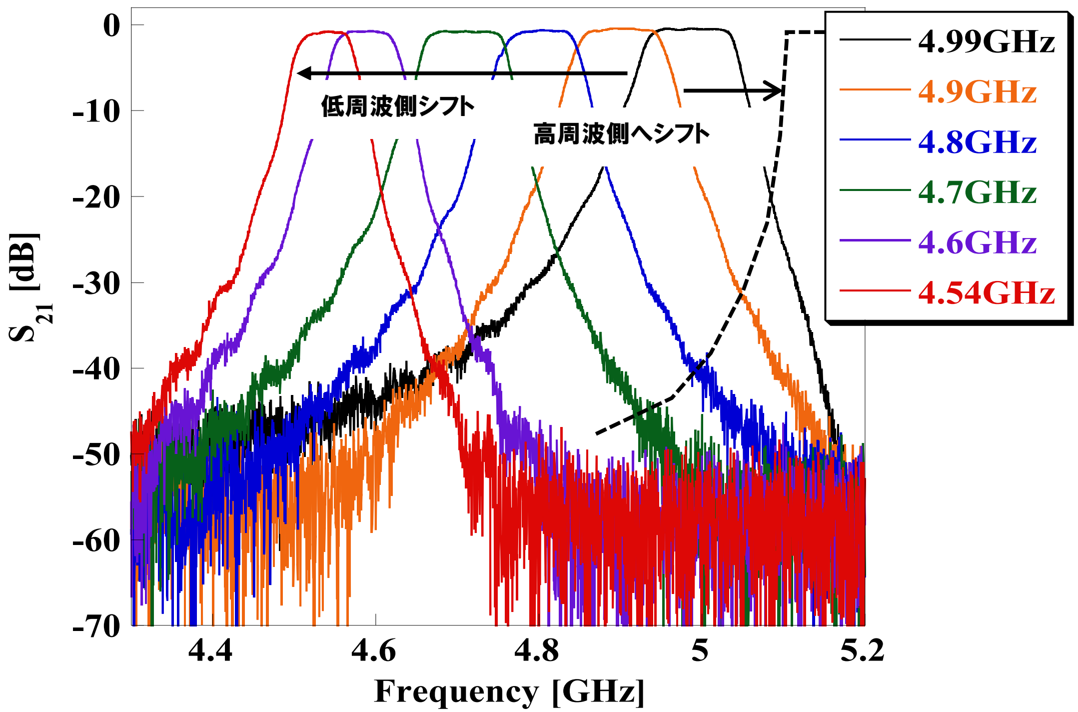
Schematic diagram of automatic tuning system



Picture of automatic tuning system

Achieve 500MHz shift with automatic tuning system,

Our group

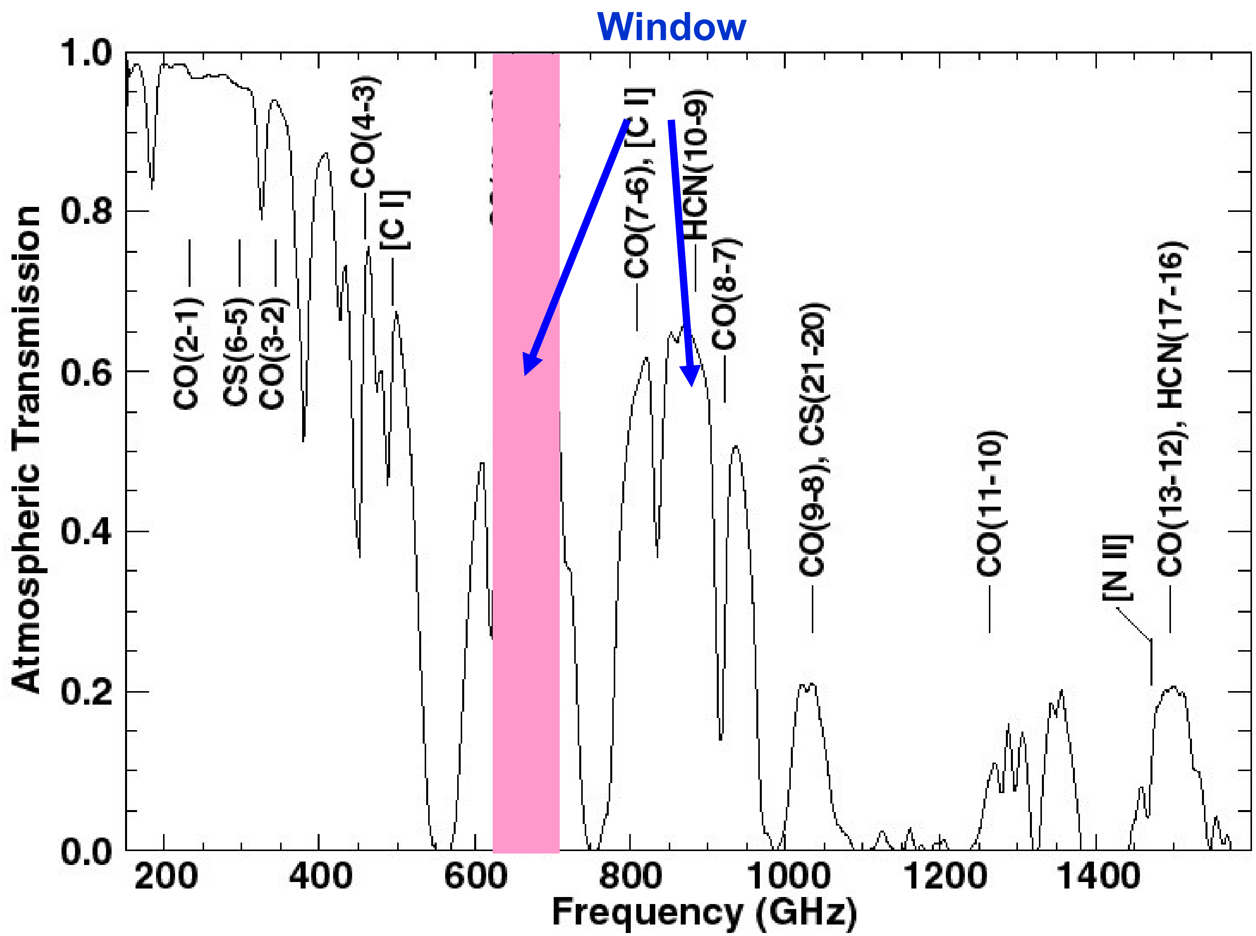


By moving a sapphire rod by a stepping mortar, center frequency of the filter can be shifted more than 500 MHz and the time required for the shift is less than 0.5 seconds.

2.3 Third topics

When observing cosmic radio waves on the ground, it is necessary to use electromagnetic waves with a low absorption in the air.

600 to 900 GHz band is useful to observe radio wave



Relationship between frequency and absorptivity of air

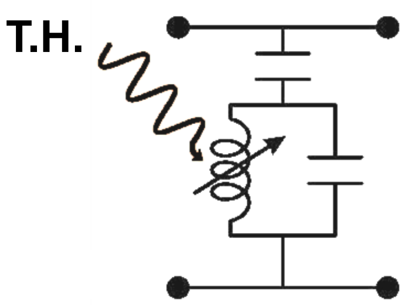
Matsushita *et al.*(1999)

MKIDs

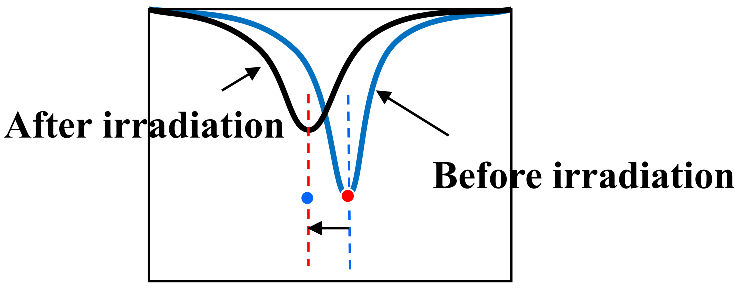
MKID is an excellent element for detecting Terahertz waves. Principle of MKIDs: When Terahertz waves are irradiated to superconducting LC resonators, resonance frequency is shifted to lower side, because cooper pairs are broken. That is, we can detect Terahertz wave by using ~GHz resonator.

Merits of MKIDs

(1) Easy to array (can be more than 10000 pixels)
(2) Only Two lines of input / output (coplanar shape)
(3) High sensitivity



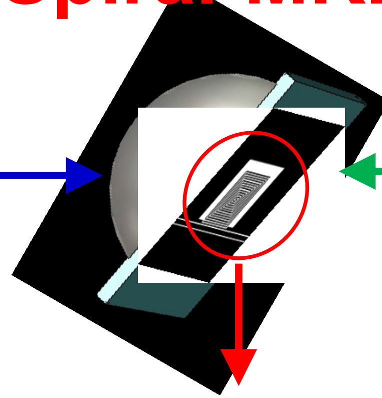
LC resonator



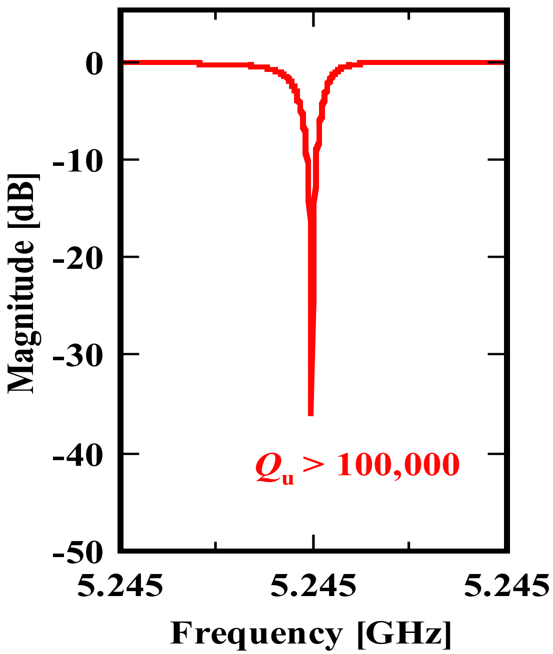
Frequency shift

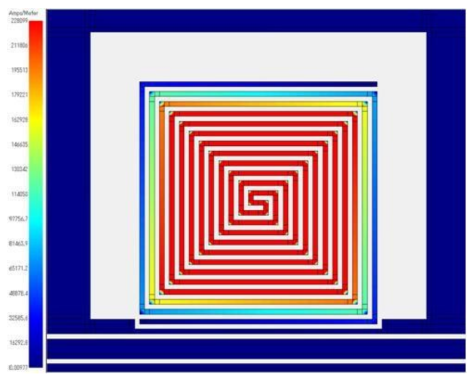
~ Spiral-MKIDs ~

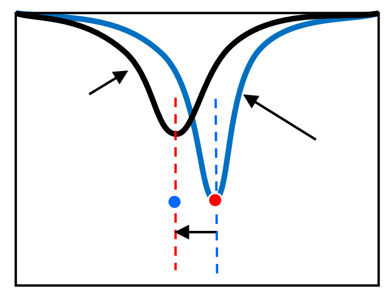
Small sized microwave resonator with high Q_u



THz antenna for wide band





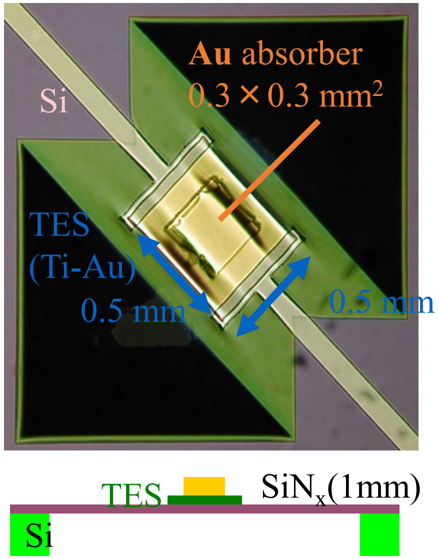


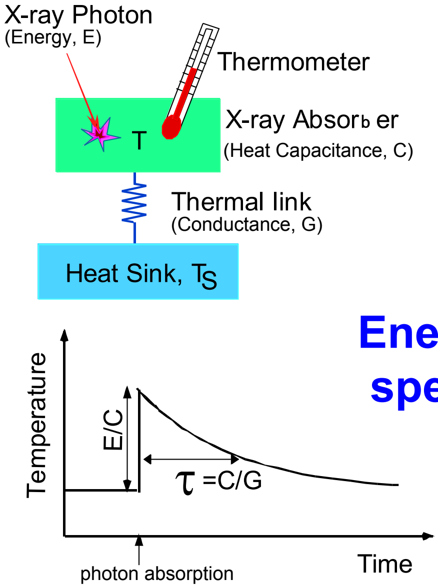
TES

TES X-ray microcalorimeters for X-ray astronomy and material analysis

Kazuhisa Mitsuda **JAXA group**

TES X-ray microcalorimeter arrays provide not only high-energy resolution (FWHM < 10eV) in X-ray spectroscopy but also imaging and high-counting-rate capabilities. They are very promising spectrometer for X-ray astronomy and material analysis. In this paper, we report our recent progress. For material analysis, we have fabricated 8 x 8 format array with a fast signal response (40 mu s) and proved the energy resolution of 5.8 eV FWHM at 5.9 keV. We developed common biasing scheme to reduce number of wirings from room temperature to the cryogenic stage. From measurements using the newly-designed common-bias SQUID array amplifier chips, and from numerical simulations, we demonstrated that signal cross talks due to the common bias is enough small. For space applications, we are developing frequency-division signal multiplexing system. We have fabricated a baseband feedback system and demonstrated that the noise added by the feedback system is about 4 eV FWHM equivalent for 16 ch multiplexing system. The digital to analog converter (DAC) dominates the noise, and needs be reduced by a factor of four for future astronomy missions.





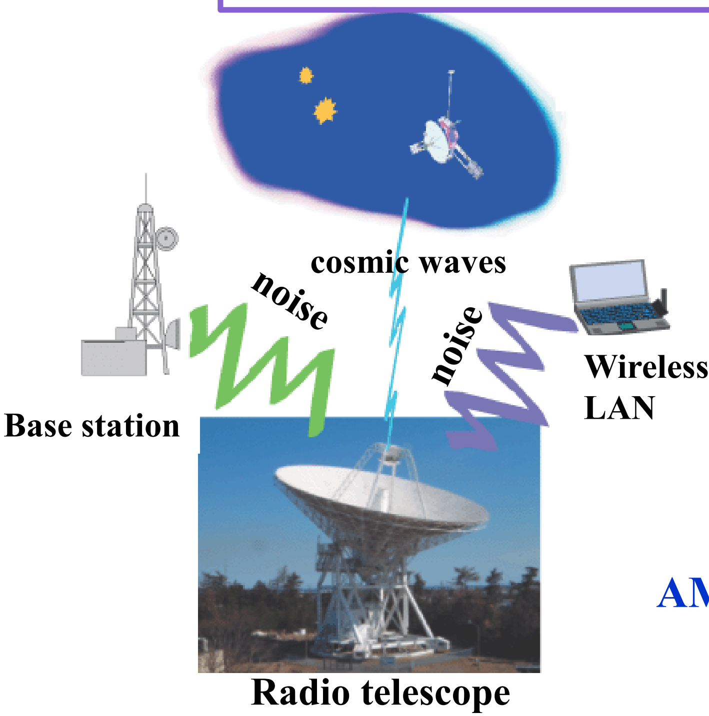
Energy resolution in X-ray spectroscopy; < 4eV

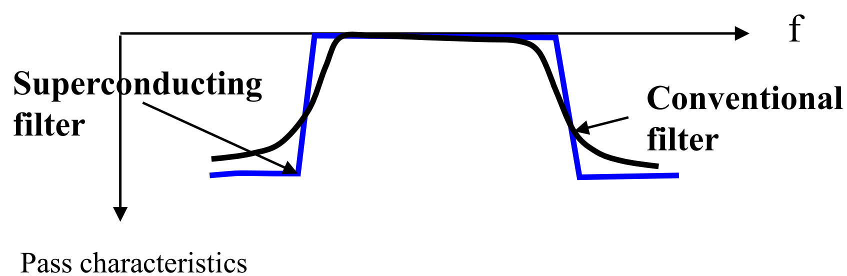
Contents

3.1 City noise reduction for radio astronomy

As wireless communication becomes popular, city noises are superimposed on the radio telescope on Kashima 34m radio telescope and weak cosmic electromagnetic waves can not be observed.

Require broadband bandpass filter with excellent out-of-band rejection



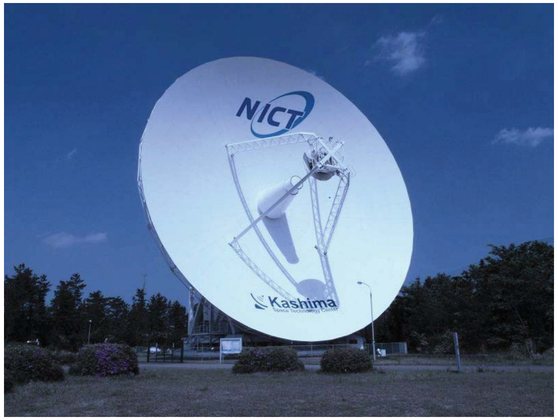


Frequency response of bandpass filters for radio telescope

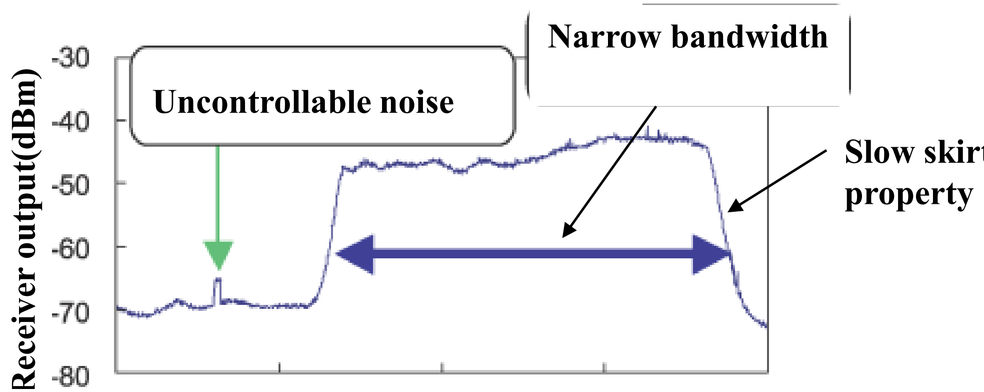
AMTEL group

Actual filter characteristics

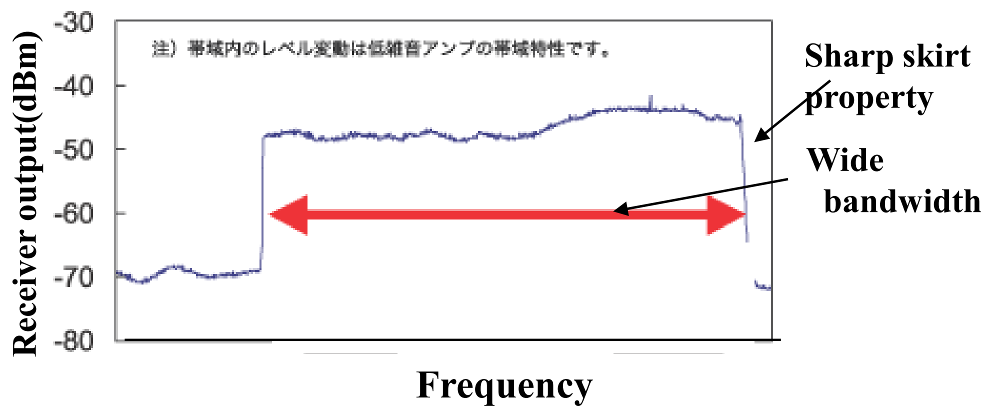
AMTEL group



Conventional filter (19 stage cavity filter)



Superconducting filter (32 stage HTS filter)

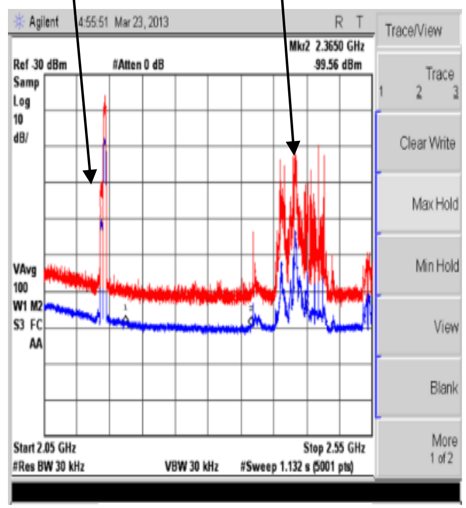


From A. Kawai; CR News March, 2004, No336

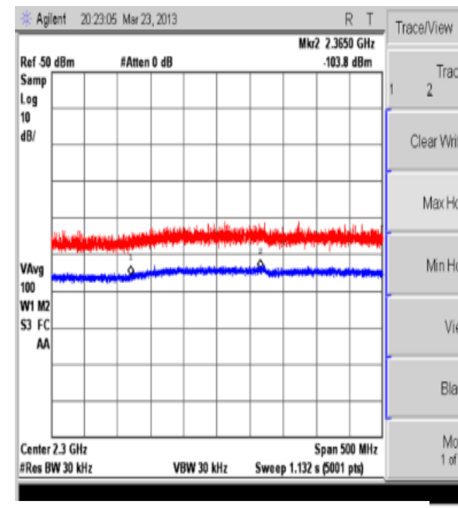
Similar research was done in China

Mobile phone noise WiFi noise

Superconducting bandpass filter system



Conventional filter



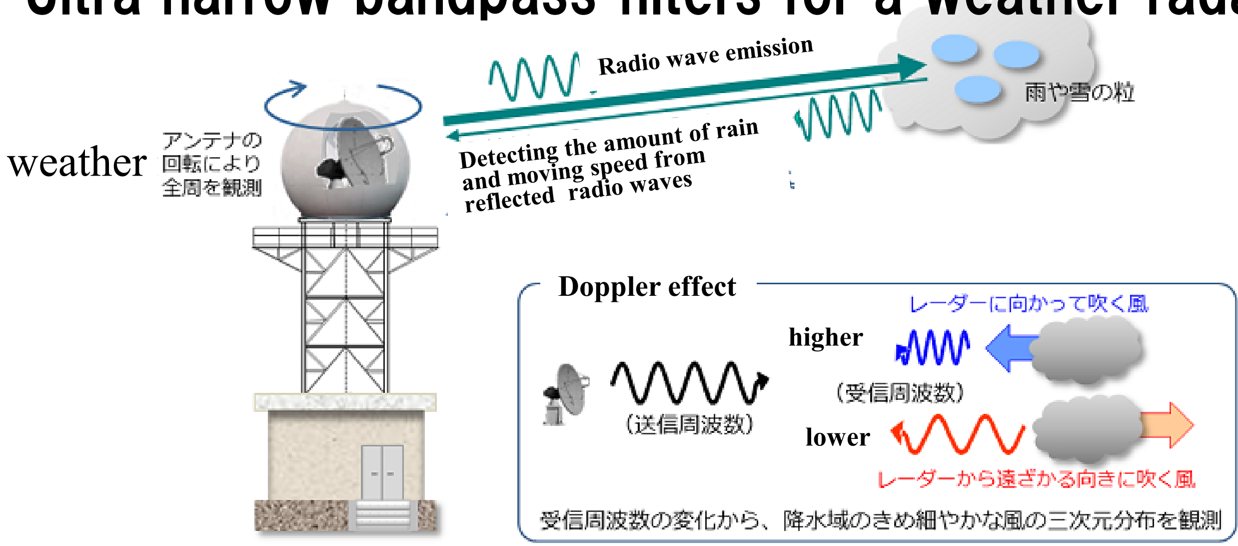
Superconducting filter

Picture of Radio Telescope in Beijing

We can eliminate mobile phones and WiFi Noise by using superconducting filters

From Prof. B.S Cao of Tsinghua Univ. China

3.2 Ultra narrow bandpass filters for a weather radar



Weather radar is important to detect the density and moving speed of rain clouds, however used wide frequency band is trouble to other system. It is necessary to narrow the band width.

The MIAC policy

Some 5GHz-band is released for wireless communication, so we need narrower the bandwidth of the weather radar.

18.8MHz ⟶ 8.8MHz

Required of superconducting narrow band filter

MIAC: Ministry of Internal Affairs and Communications

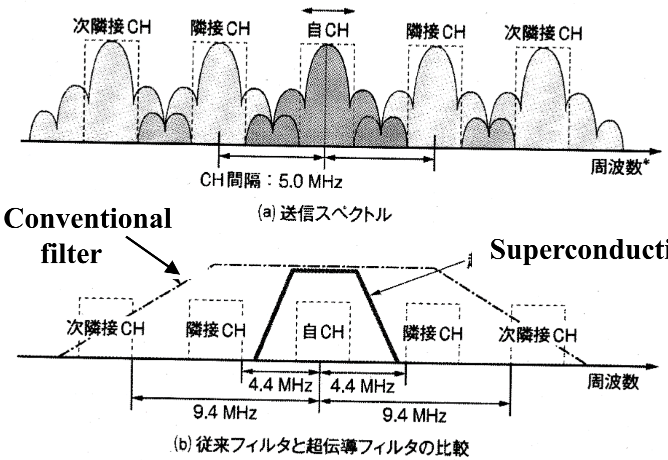
2.14

Required performance for band pass filter for weather radar

Toshiba group

(a) Ultra-narrow band
(b) High rejection at out of band
(c) High power durability

Weather radar channel



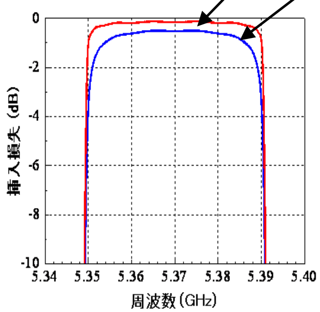
Conventional filter

Superconducting filter

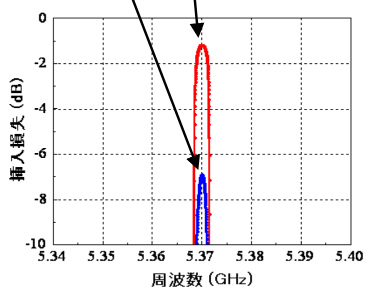
From Dr. Kayano of Toshiba

Superconducting filter

Ceramics filter



Wide-band filter



Narrow-band filter

In the case of a narrow band filter, the insertion loss increases when we use large surface resistance materials.

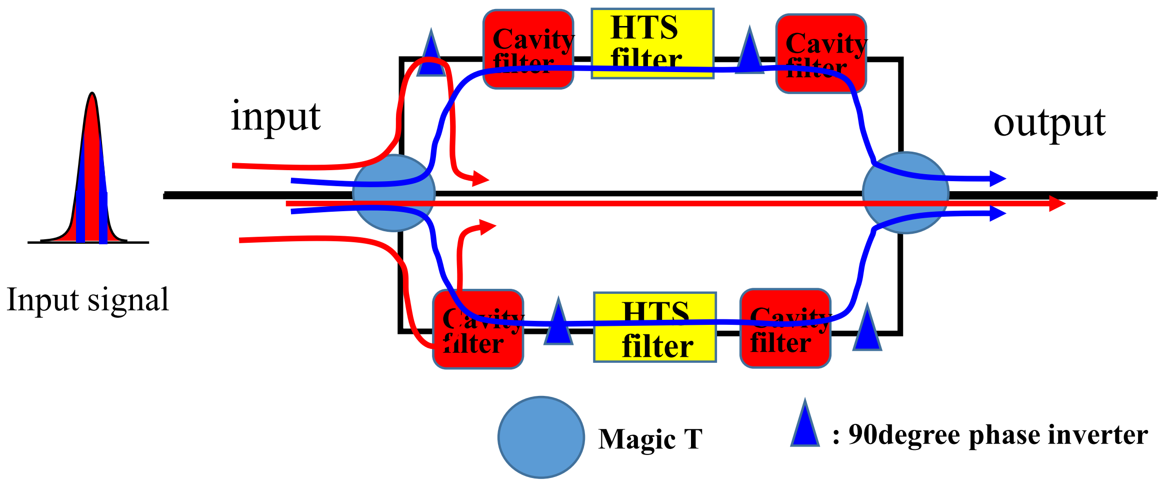
For superconducting bandpass filters, insertion loss is quite small and skirt property is quite sharp. Therefore, it is suitable for weather radar filter

High power durability is not easy for superconducting filter

2.15

Weather radar bandpass filter system designed by Toshiba group

Toshiba group



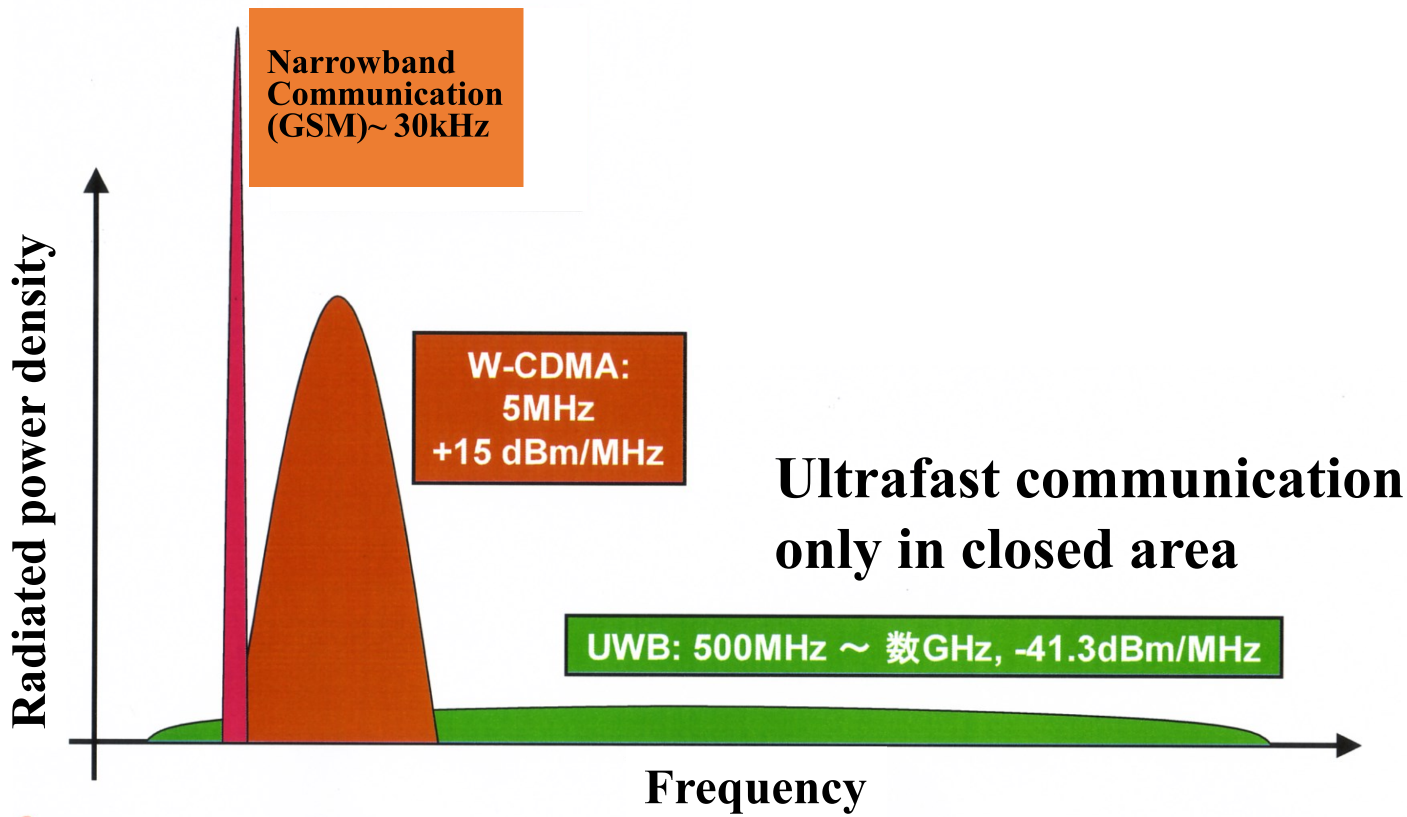
Schematic diagram of a weather radar system

From Dr. Kayano of Toshiba

They designed hybrid filters of cavity resonators and superconducting resonators. High power electromagnetic go directly to output or go to the cavity resonators by magic T and phase inverter. Only weak signals go to superconducting filters.

They realized a narrowband superconducting bandpass filter system for high power weather radar.

3.3 Ultra-wideband bandpass filter for UWB communication

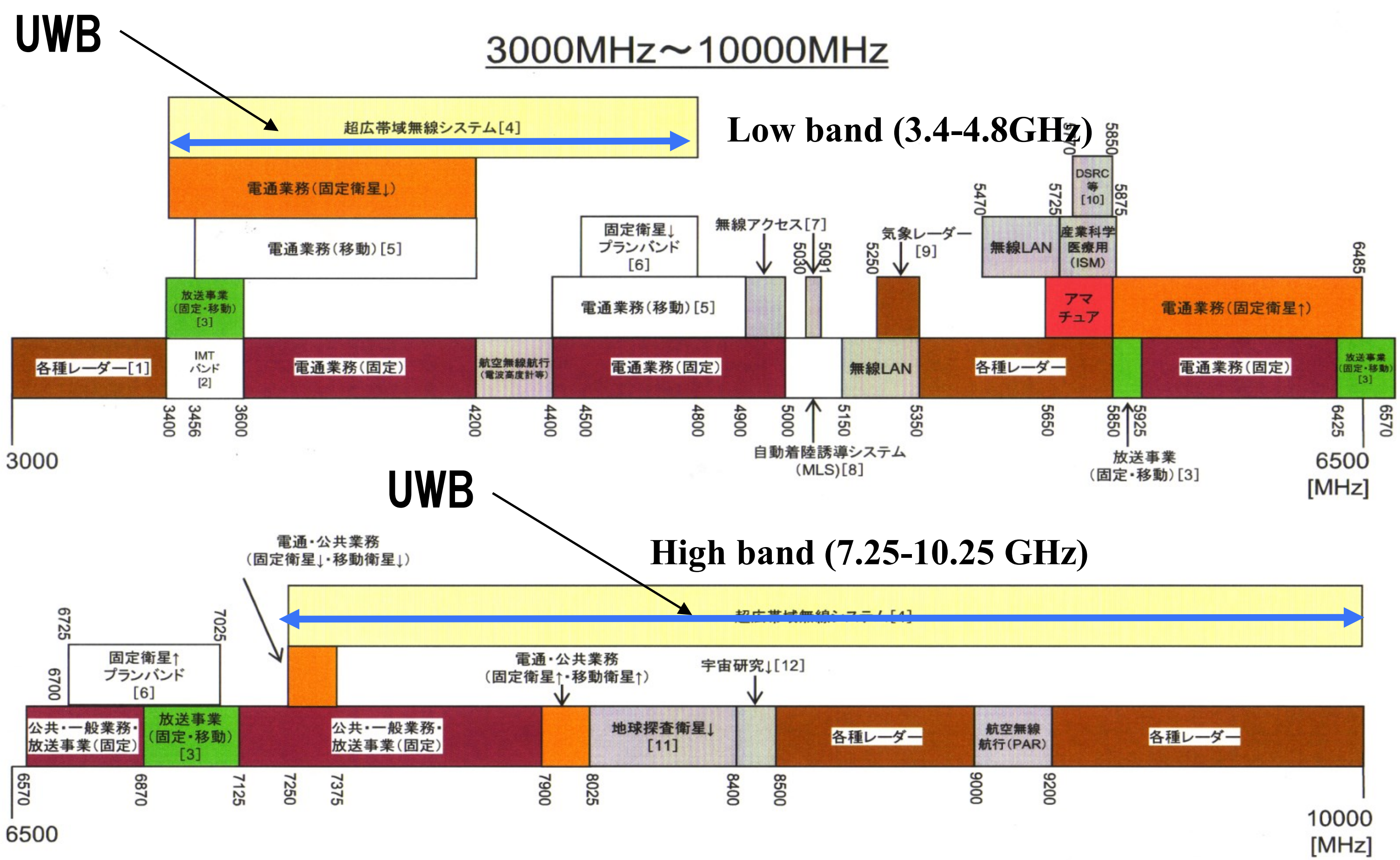


Schematic figure of frequency band and radiation power of W-CDM, GSM and UWB communication

UWB communication is useful for ultrafast communication and local area communication, however the used frequency band is quite wide

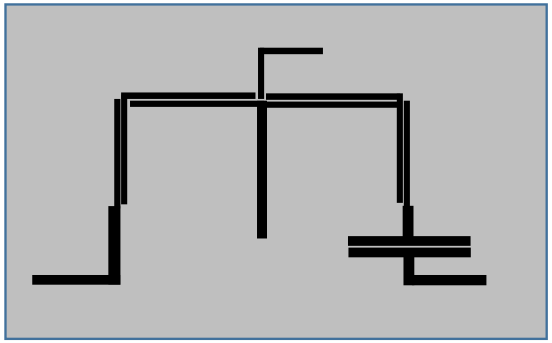
2.20

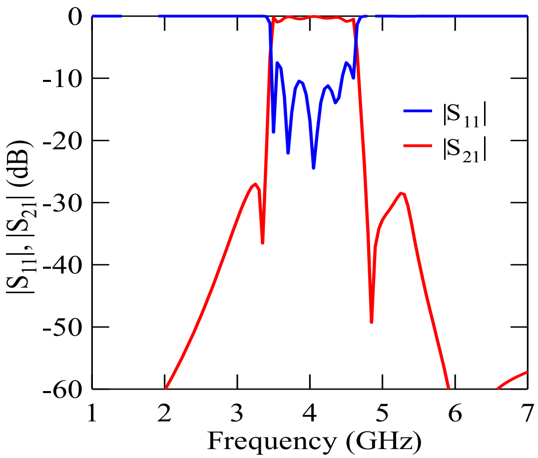
UWB frequency band in Japan



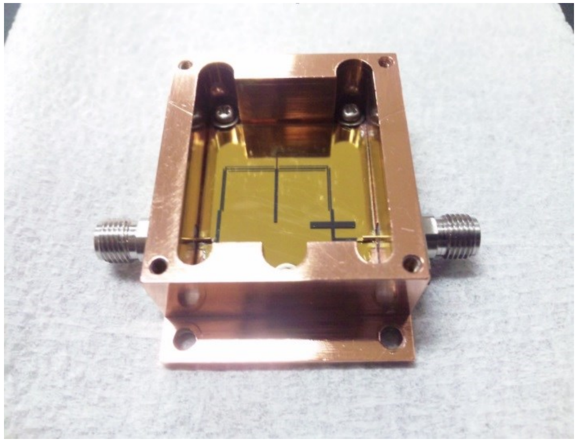
The frequency band used for UWB communication has already been used for other wireless communication. Therefore, the UWB communication filter is required to have a very sharp skirt characteristic

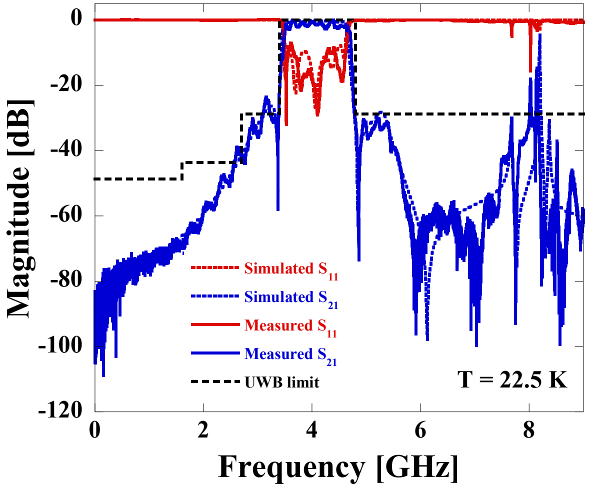
HTS filer for UWB communication





Our group



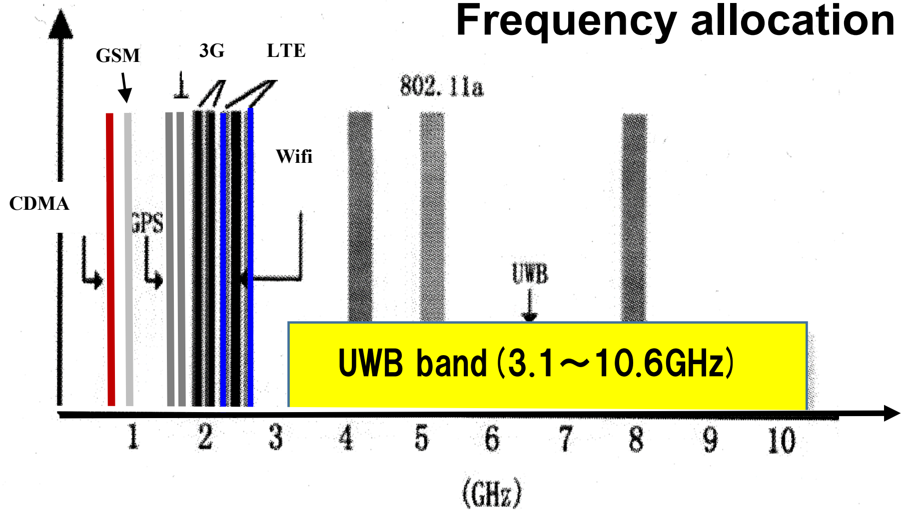


H. Ishii and S. Ohshima; Development of UWB HTS Bandpass Filters with Microstrip Stubs –Loaded Three-Mode Resonator, IEEE. Trans. Applied Superconductivity. Vol 23 (2013) 1500204

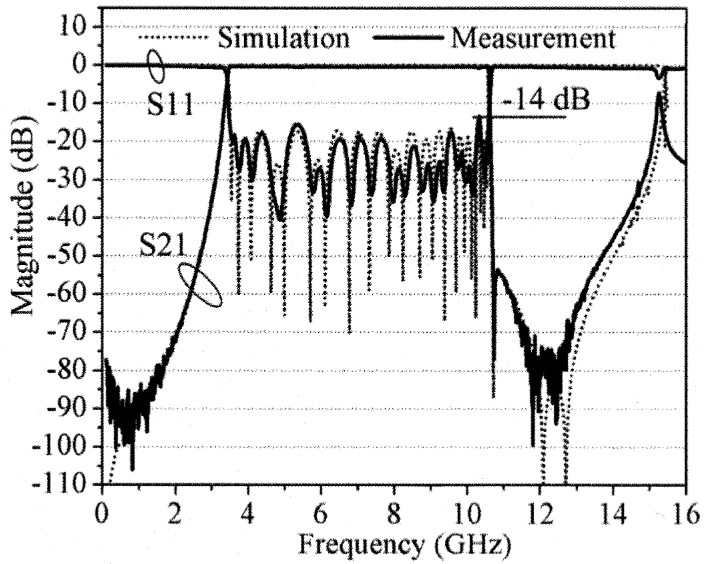
2.21

UWB HTS filter in China

Frequency allocation for UWB in China



BS Cao group



Frequency response of UWB filter of

Lu X, Wei B, Xu Z, et al. *IEEE Trans. Microw. Theory Techn.*, Apr. 2015, 63(4):1281-1

B.Wei提供 2.22

Contents

4.1 Development of high sensitivity NMR pickup coil

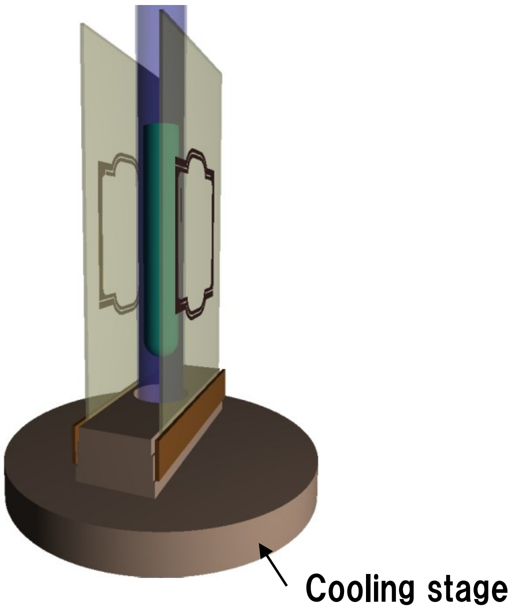
Sensitivity of NMR due to NMR pickup coil

$$\frac{S}{N}|_{NMR} \propto \sqrt{\frac{\eta Q_L}{T_{eff}+T_{am.}}}, \quad Q_L \propto \frac{1}{R_s}$$

η : *Filling factor,*
Q_L : *Quality facter of coil*
T_{eff} : *Effective sample temperature*
$T_{am.}$: *Temperature of pre-amplifier*

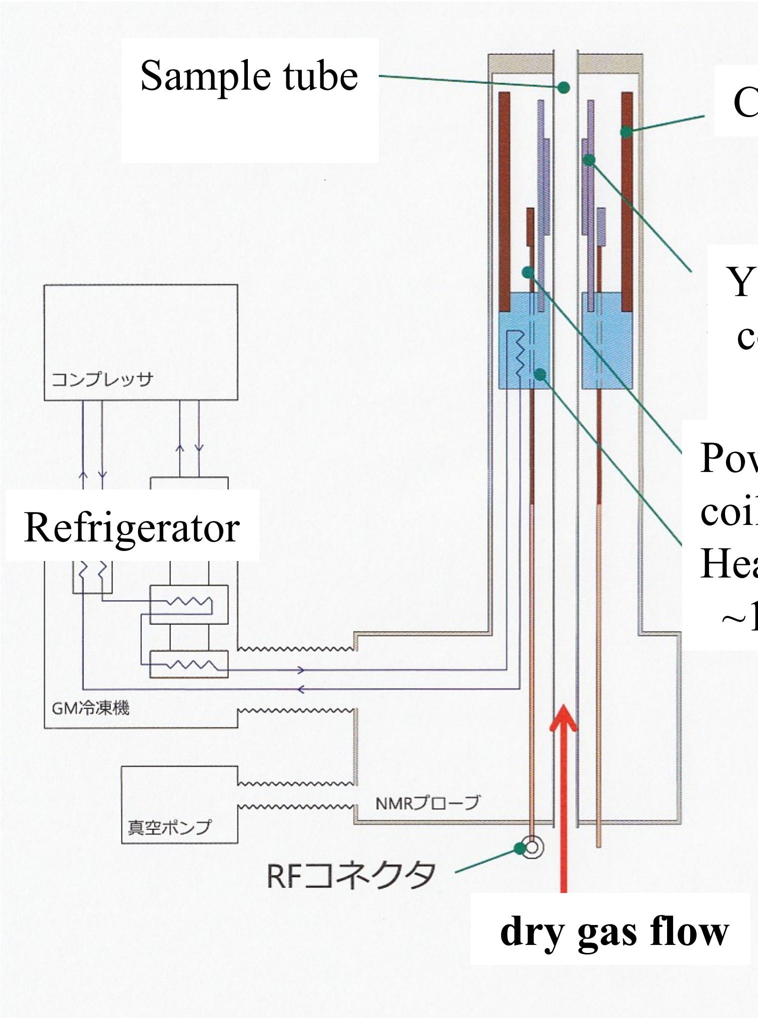
$$\frac{\left[S/N\right]_{YBCO\ coil}}{\left[S/N\right]_{Cu\ coil}} = \frac{\left(\eta_{YBCO\ coil} / 7.2\text{x}10^{-7}(100+20)\right)^{0.5}}{\left(\eta_{Cu\ coil} / 8.4\text{x}10^{-3}(300+300)\right)^{0.5}} \simeq$$

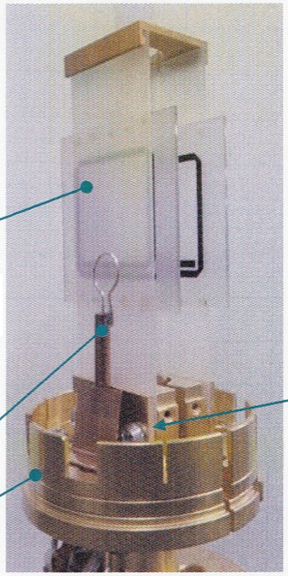
Superconducting NMR pickup coil improves the sensitivity more than 100 times, when copper pickup coil is used.



Pickup coil for NMR

Cooling system of a superconducting pickup coil

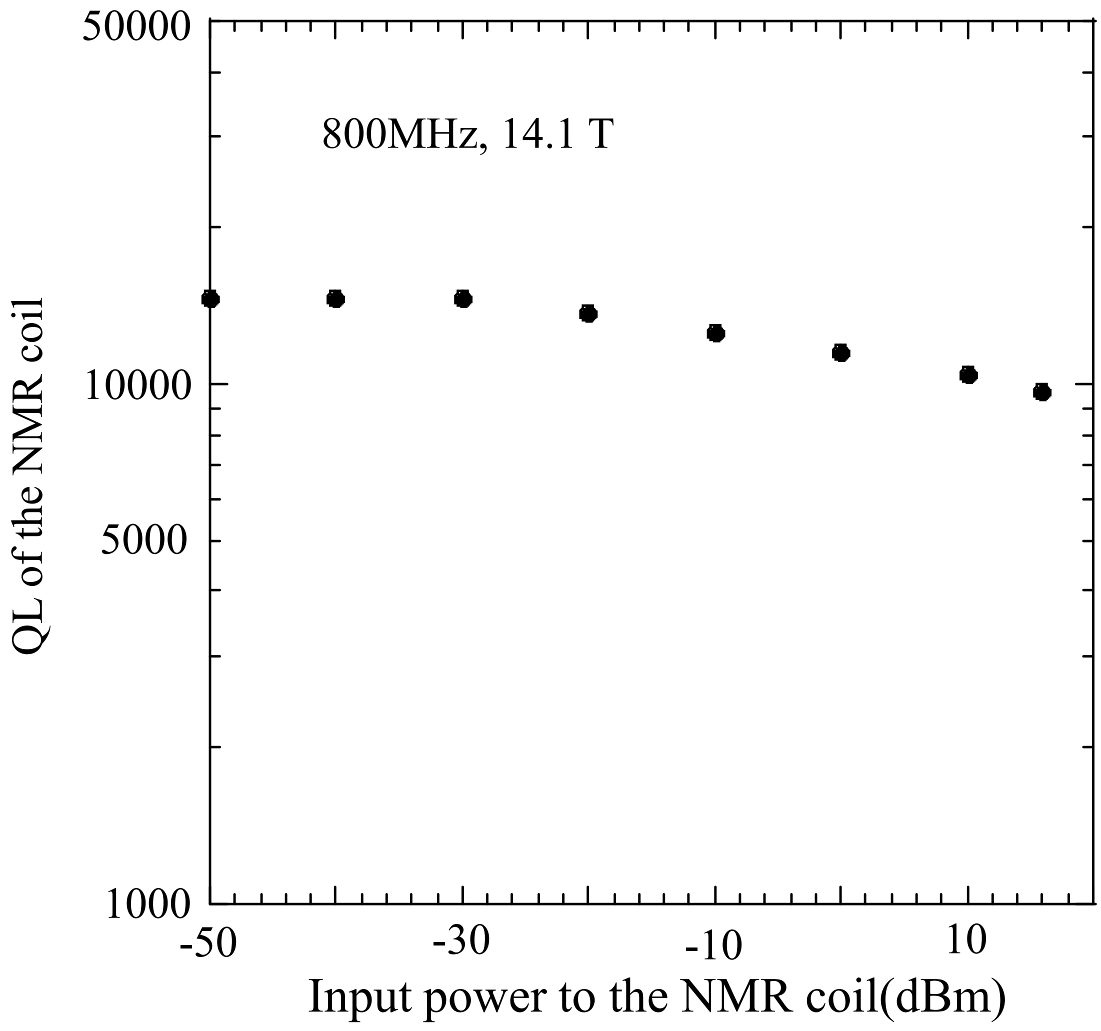




Picture of NMR pickup coil

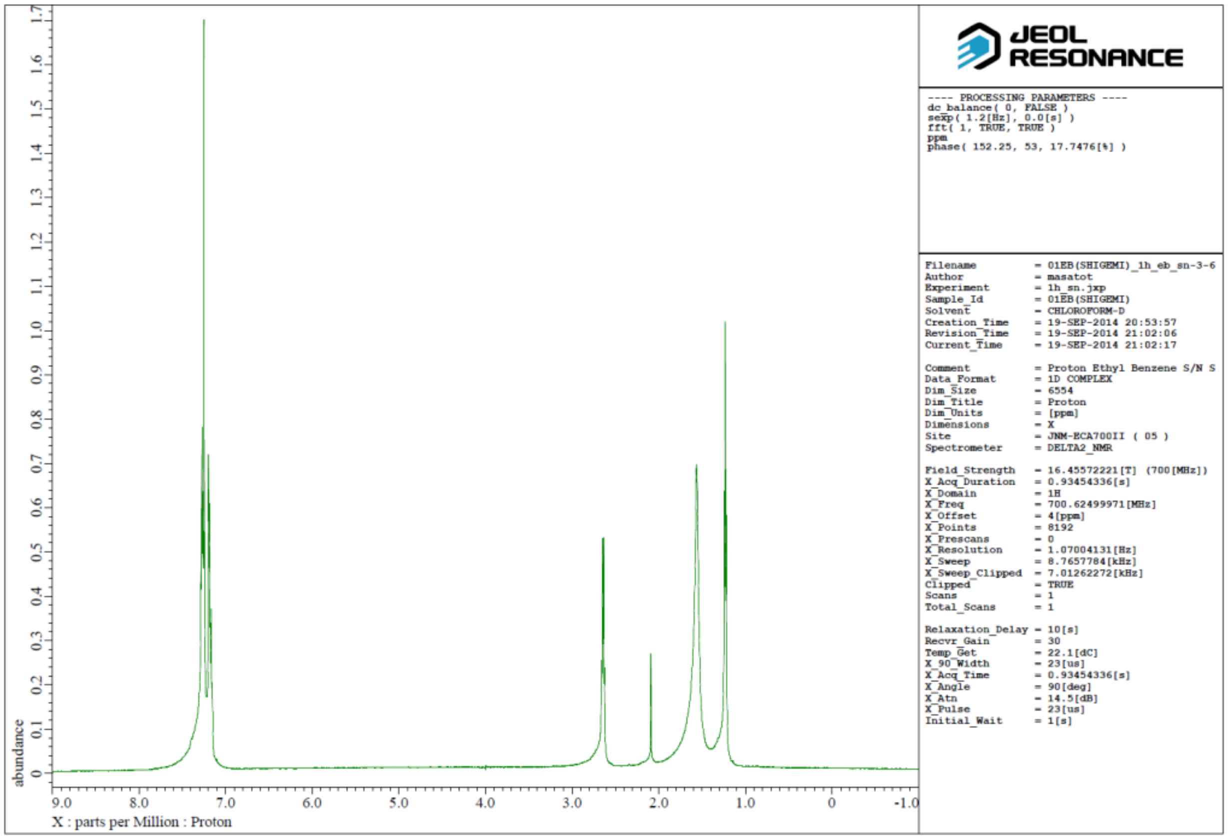
JEOL and our group

Supported by JEOL RESONANCE


800MHz, 14.1 T
50000
10000
5000
1000
QL of the NMR coil
-50
-30
-10
10
Input power to the NMR coil(dBm)

NMR signals using YBCO pickup coil

JEOL and our group



$$\frac{[S/N]_{YBCO}}{[S/N]_{Cu}} \simeq 50$$

5. Summary

Looking back on the 30 years of superconducting microwave devices, we can see that the research has greatly evolved from basic research into practical application research.
For example, the superconducting bandpass filters are used not only in the field of mobile communication but also for radio astronomy field and weather radar. Microwave and Terahertz detector of high sensitivity also evolve from the security field to receiving weak radio waves from space. As a new development in the future, I think that the development of composite device is important, for example, with semiconductors and magnetic materials. I am expecting future development

Thank you for your attention