Thin Film SRF Applications beyond Accelerators

Norbert Klein
Forschungszentrum Jülich
Institut für Schichten und Grenzflächen
D-52425 Jülich
Germany
Outline:

• Introduction

• Electrodynamic properties of superconducting thin films: new results on MgB$_2$ and Nb

• Thin film based high-temperature superconducting resonators, filters and subsystems

• Cryogenic low-phase noise oscillators

• Millimetre wave / THz HTS Josephson devices: voltage standard and Hilbert transform spectroscopy

• Summary and outlook
Overview: Microwave to THz applications of superconducting films

- Cavities for particle accelerators (Nb, Nb$_3$Sn ?, NbN ?)
- Passive devices for wireless communications (YBCO, Tl and Hg ? based cuprates)
- Detectors for mm wave and THz radiation (Nb, NbN, YBCO, MgB$_2$ ?)
- Josephson voltage standards (Nb, YBCO ?)
- Josephson digital circuits (Nb, YBCO ?, MgB$_2$ ?)
T-ray specs

Radiation from a previously unexploited region of the electromagnetic spectrum could hold the key to a new generation of security devices. Catherine Zandonella investigates.

Suicide bombers, plastic explosives strapped to their bodies, approach the turnstiles at a packed football stadium. The security guards don’t have time to search every spectator, and even if a metal detector were installed, it would miss the terrorists’ deadly cargo. But a novel device that can see through the bombers’ clothing succeeds were other systems fail. Security personnel are alerted, and surround the attackers before they can strike.

Such is the potential power of a new imaging technology, Terahertz device, so named because they detect electromagnetic radiation in the terahertz frequency range (1 THz is $10^{12}$ Hz), promise to peer through clothing, revealing concealed weapons and explosives. The technique could also be used to seek out structural defects in materials, to detect skin cancer or to provide new information about astronomical objects.

For years, radiation with a frequency of between 0.1 THz and 10 THz languished unexplored. But recent advances in generating and analysing such radiation, together with an avalanche of research funding for antiterror applications, are now helping researchers to examine its applications.

Terahertz radiation, often called T-rays, lies between microwaves and infrared light in the electromagnetic spectrum. It can sail through paper and clothing, but not very far through skin or biological molecules, so objects hidden beneath clothing can be

Caught: this terahertz image clearly shows an object (blue) concealed beneath the person’s clothing.
Millimeter wave surface resistance of epitaxially grown YBa$_2$Cu$_3$O$_{7-x}$ thin films

N. Klein, G. Müller, and H. Piel
Fachbereich Physik, Bergische Universität, Gesamthochschule Wuppertal, D-5600 Wuppertal 1, West Germany
B. Roas$^{10}$ and L. Schultz
Siemens AG, Research Laboratories, D-8520 Erlangen, West Germany
U. Klein and M. Pfeiffer
Intasatom GmbH, D-3500 Bergisch Gladbach 1, West Germany

(Received 10 November 1988; accepted for publication 22 December 1988)

We have measured the surface resistance of two c-axis oriented YBa$_2$Cu$_3$O$_{7-x}$ thin-film samples in a copper host cavity at 86.7 GHz between 4.2 and 300 K. High quality films of 0.6 and 0.4 µm thickness have been grown epitaxially on SrTiO$_3$, by pulsed excimer laser ablation. Their millimeter wave absorption drops sharply at a transition temperature of 86 and 88 K to a corresponding surface resistance at 77 K of 18 mΩ and less than 8 mΩ, respectively. These values exceed the best results on polycrystalline samples and come close to the expectation from classical superconductors. Therefore, applications of high T$_c$ superconductors up to THz frequencies can be envisaged now.
Thin films for high-frequency applications

REBa$_2$Cu$_3$O$_7$ ($T_c \approx 90$ K)

- Thin film technology is mature
- Large area thin films commercially available, global market leader is THEVA in Germany

from http://www.theva.com
d-wave nature of oxide high-temperature superconductors forbids exponential slope of $R_s$ below $T_c/2$ 

$\Rightarrow$ no chance for accelerator applications

Nonlinearities extremely sensitive to film quality because of short coherence length
Magnesium Diboride - new hope?

Jun Nagamatsu et al., Nature 410, 63 (2001)
clear exponential dependences, but BCS fit to $\lambda(T)$ reveals $\Delta/kT_c$ between 0.7 and 1

local limit: extract dynamic conductivity $\sigma_1(T)$ from $R_s(T)$ and $\lambda(T)$ employing

$$R_s(T) \approx \frac{1}{2} \omega^2 \mu_0^2 \sigma_1(T) \lambda^3(T)$$

Consequence of two-gap BCS model: coherence peak shifted to lower temperatures

B.B. Jin et al., accepted for Phys. Rev. Letters
High-precision $\lambda(T)$ measurements on ultrathin niobium films

\[ \lambda_0(d) = \frac{\lambda_{L,0} \left[ \frac{\xi_0(d)}{l(d)} \right]^{1/2}}{\left[ 1 - \frac{4l(d)}{\pi^2 \xi_0(d)} \right] \ln \left[ \pi \xi_0(d)/l(d) \right]} \]

$\Rightarrow$ sensitive test of proximity effect generated by normal conducting surface of interface layers

B.B. Jin et al., publication in progress
Q factor of a resonator composed of dielectrics and metall wall segments:

\[
\frac{1}{Q_0} = \frac{R_s}{G} + \kappa \tan \delta
\]

\(G [\Omega] \propto \frac{V}{\lambda_0^3}\) : geometric factor

\(\kappa\): filling factor of electric field energy in dielectric material \((0 \leq \kappa \leq 1)\)

microstrip resonator: \(\kappa \approx 1, \ G = 1 - 10 \ \Omega\)

dielectric resonator: \(\kappa \approx 1, \ G = 100 - 10000 \ \Omega\)
Technology for planar HTS resonators and filters

Epitaxially grown HTS thin film:
- YBCO ($T_c = 90$ K),
- TBCCO ($T_c = 108$-$127$ K)

Compatible single-crystalline, low-loss substrate:
- LAO ($\varepsilon_r = 24$), MgO,
- sapphire ($\varepsilon_r = 10$) with buffer

from IMS_2002, Seattle, tutorial workshops
Planar HTS resonators

(a) quasi-lumped element
(b) micro strip
(c) coplanar waveguide
(d) folded microstrip with integrated capacitors
(e) 2D disk resonator

$Q \approx 10^4 - 10^5$: attractive for filters (< 5 GHz)

from N. Klein and H. Chaloupka, Encyclopedia of Materials, Elsevier
Properties of HTS disk resonator

Current distribution of TM$_{010}$ mode

Measured temperature dependence of $Q_0$ (TM$_{010}$ mode)

from IMS_2002, Seattle, tutorial workshops
Puck $\text{TE}_{01\delta}$ resonator with two HTS endplates

$Q \approx 10^5 - 10^6$: attractive for surface impedance measurements of HTS films and low phase noise oscillators (5 to 30 GHz)
High-sensitivity microwave surface impedance measurement system for 7 to 20 GHz based on a sapphire dielectric resonator

- measure $Q(T)$ and $f(T)$ of high Q resonance
- calculate surface impedance $Z_s(T) = R_s(T) + i\omega\lambda(T)$ of sample from $Q(T)$ and $f(T)$
- $R_s$: surface resistance, determines losses

Whispering gallery mode in a dielectric puck

\[ Q \approx 10^6 - 10^7 \]: very attractive for mm wave low-phase noise oscillators (10 to 70 GHz)
Filters: resonator coupling schemes

- Microwave resonator (resonant mode) with unloaded $Q$
- Coupling only between adjacent resonators $\Rightarrow$ Chebyshev-type characteristic
- Additional coupling between non-adjacent resonators $\Rightarrow$ quasielliptic characteristic: damping poles at the passband edges $\Rightarrow$ steeper skirts
Filters: steepness of skirts

⇒ high number of poles required for high performance filters

Filters: steepness of skirts

Q requirement to avoid rounding effects:

\[ Q_{0,\text{min}} \approx \beta \frac{L_s[\text{dB}]}{\delta f[\text{MHz}]} \frac{f_0[\text{GHz}]}{\delta L[\text{dB}]} \]

Chebyshev: \( \beta = 750 \)
Elliptic: \( \beta = 250 \)

example:

\[ \delta L = 1 \text{ dB} \quad L_S = 100\text{dB} \quad \delta f = 1\text{MHz} \Rightarrow Q_{0,\text{min}} = 50.000 \text{ for elliptic filter} \]

High Performance HTS Bandpass Filter

34mm X 18mm Die
10 HTS Resonators
Qu = 80,000
6 Cross Couplings
6 Tx Zeros
High Yield Production

from IMS_2002, Seattle, tutorial workshops
Extreme Selectivity: Measured Performance

![Graph showing SuperFilter and Typical Conventional performance in dB vs Frequency (MHz)]
from Cryoelectra GmbH, Wuppertal

from IMS_2002, Seattle, tutorial workshops
Sector of a basestation receiver frontend

antenna preselect LNA mixer IF filter

Advantages of HTS / cryogenics

• higher receiver sensitivity due to reduction of filter insertion loss and lower noise temperature of LNA (rural areas)

• higher selectivity due to steeper filter skirts (crowded areas with strong interference problems)
Enabling technology: cryocoolers

Compact, high-efficient, reliable, and low-cost cryocoolers required for most of the high-frequency applications
HTS subsystem developed by Cryoelectra GmbH, Germany with Stirling cooler developed at Leybold, Germany
Cryogenic oscillators

- Doppler radar
- Passive microwave frequency standard
- High purity reference sources
Leeson model: phase noise of a feedback oscillator


\[
L_{osc} = 10 \cdot \log \left[ 1 + \frac{f_0^2}{4Q_L^2 f_m^2} \right] + 10 \cdot \log \left[ \frac{\alpha}{f_m} + \frac{G F k T}{P} \right]
\]
tuneable cryogenic WG – resonator for $f = 23$ GHz

Project with Bosch SatCom (Tesat-Spacecom), German Patent

- mechanical tuning range: 50 MHz
- piezoelectric tuning range 50 KHz @ 60 V

Extremely high $Q_0 \geq 5 \cdot 10^6$ @ $T = 77$ K

Cryogenic 23 GHz „near“ space qualified oscillator

- WG-resonator
- HEMT amplifier
- Signal output
- HTS 2-pole dual-mode filter: $BW \approx 0.5\%$, $IL \approx -1\ dB$

Cryogenic 23 GHz space qualified oscillator: phase noise far below that of conventional oscillators

AC Josephson effect in HTS bicrystal junctions

• Employ 1st Shapiro step to represent a dc/ac voltage with quantum accuracy ⇒ towards an HTS voltage standard

• Employ differential IV characteristic to deconvolute the spectral response of incident THz radiation ⇒ Hilbert transform spectroscopy
Novel approach: quantum voltage standard in HTS technology

YBCO bicrystal junction with in-situ gold shunt: RSJ like I/V characterisitic with small (5%) spread of $R_n$

Fabrication of an array of bicrystal junctions by submicrometer lithography
Novel approach: quantum voltage standard in HTS technology

Irradiation of microwaves by a coplanar waveguide
First experimental demonstration for a giant Shapiro step in an HTS bicrystal array of 136 JJ with metrologically relevant accuracy

Laboratory prototype of an HTS voltage calibrator
Hilbert Transform Spectroscopy

dc Response of Josephson Junction to Weak Monochromatic Radiation*

\[
\frac{V(t)}{R_n} + I_c \cdot \sin \left[ 2\pi \frac{2e}{\hbar} \int_0^t V(t) dt \right] = I + I_s \sin 2\pi f t
\]

\[I_s \ll I_c\]

\[\Delta I(V) = \left( \frac{2e}{\hbar} \right)^2 \frac{I_c^2 R_n^2}{4 I(V)} \left( f_j^2 - f_i^2 \right)\]

Response \(\Delta I(V)\):
- resonance near \(hf/2e\)
- square-law detection
- additivity

*H. Kantor, V.L. Vernon. J. Appl. Phys. 43, 3174 (1972)
Hilbert Transform Spectroscopy

Response of Josephson junction to signal with arbitrary spectrum $S_{\Delta I}(f)$:

$$\Delta I(V) = -\frac{(2e)^2 \pi I_c^2 R_n}{\hbar} \cdot \frac{1}{I(V) \cdot V} \cdot P \int_{-\infty}^{\infty} S_{\Delta I}(f) \cdot df \cdot \frac{f_f-\frac{1}{f_f}}{f_f-\frac{f}{f_f}}$$

$$H(V) = \left(\frac{8}{\pi}\right) \cdot \left(\frac{h}{2e}\right) \cdot \frac{I(V) \cdot V \cdot \Delta I(V)}{I_c^2 R_n}$$

$$S_{\Delta I}(f) = \left(\frac{1}{\pi}\right) \cdot P \int_{-\infty}^{\infty} H(f_f) \cdot df_f$$

Hilbert Transform Spectroscopy

\[ \text{Ag/YBa}_2\text{Cu}_3\text{O}_{7-x} \]

\[ \text{NdGaO}_3 \]

\[ \text{NdGaO}_3 \]

50 \( \mu \text{m} \)

\[ \frac{\Delta I(V)}{\Delta I_c} \]

\[ 1.15 \text{ GHz}, 1.61 \text{ THz} \]

\[ 693 \text{ GHz} \]

\[ 404 \text{ GHz} \]

\[ 4.25 \text{ THz} \]

\[ 3.10 \text{ THz} \]

\[ 2.25 \text{ THz} \]

\[ T = 34 \text{ K} \]

Graph showing response versus voltage with marked frequencies.

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft
Hilbert-Transform Spectrometers

HT Spectrum Analyzer Integrated into a Stirling Cooler

HT Spectrometer for Pulsed Subterahertz Radiation

Quasioptical HT Spectrometer with LHe/LN Cryostat
Hilbert Spectroscopy of Coherent Transition Radiation in TESLA Test Facility Linear Accelerator at DESY

First measurements at DESY, 1997
- Thermoionic gun, N = 2.3 \times 10^8 \text{ electrons}
- Macrobunch averaging
- Bunch length measured by HTS: \sigma_z = 0.4 \text{ mm}

Measurements at DESY, 1999, 2001
- New Photoinjector, N = 1.6 \times 10^{10} \text{ electrons}
- Pulse response detection from a single bunch

Control room of the linac

Pulse response from HT spectrometer

Window

Al-foil

Transition radiation

bunch of N electrons


Summary and Outlook

• Passive filters have found a niche market in mobile communication

• Extremely narrowband and tuneable (MEMS) HTS filters are considered to be relevant for military applications

• Superconducting detectors are dominant for the THz range:
  Nb SIS mixers: < 700 GHz
  NbN Hot electron bolometers: < 1.5 THz

• HTS grain boundary Josephson junctions have a huge potential for millimetre wave and THz applications