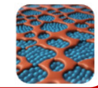
Absolute measurement of penetration depth of superconducting thin films using microstrip resonator

Arghya Dutta[1*], Ajeet Salunke[1*], Mahesh Poojary[2], Vivas C Bagwe[1], Sangita Bose[2] and **Pratap Raychaudhuri**[1]

[1]*Tata Institute Of Fundamental Research, Homi Bhabha Road, Mumbai- 400005,*

[2]*School of Physical Sciences, UM-DAE Centre for Excellence in Basic Sciences, University of Mumbai, Kalina Campus, Santacruz (E), Mumbai 400098, India*



Introduction & motivation

- In this quantum era, Microwave resonators are widely used both for basic science and high frequency application.
- Kinetic Inductance of superconducting resonator i.e. Penetration depth of the superconductor plays the crucial roles behind it.
- Finding the absolute value of Penetration depth (λ) *solely from high frequency measurements* is a major challenge.
- In this work, we present a novel method for *incorporating superconductivity* in the thin films and evaluating the ***Penetration depth*** (λ)
- We combine 2D cavity resonator measurement with *Finite Element simulation (FE)* in **COMSOL Multiphysics**

Measure $f_0\,(T)$ from experiment → Determine $\lambda(T)$ from FE simulation → Fit $\lambda(T)$ with theory

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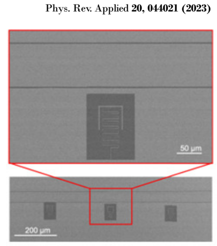

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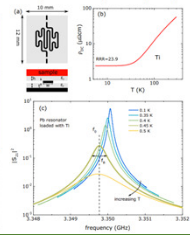
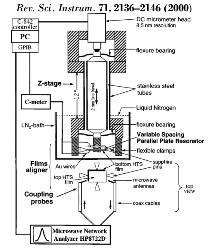


Rev. Sci. Instrum. **71, 2136–2146 (2000)**



Simulation setup

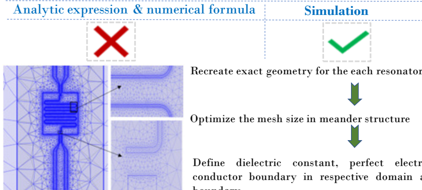
- For superconducting resonator, $f_{0n} = \frac{n}{2l}\left(\frac{c}{\sqrt{\epsilon_{eff}}}\right) \Rightarrow \frac{n}{2l}\frac{1}{\sqrt{C_G(L_G+L_k)}}$

  Where, $L_k = g\frac{\mu_0\lambda^2}{A}$; $L_G = \frac{Z_0\sqrt{\epsilon_{eff}}}{c}$

- In practical , various factors including the shape and structure of resonator influence the resonance -

Tools to tackle the problems:

Analytic expression & numerical formula	Simulation
✗	✓



Recreate exact geometry for the each resonator

Optimize the mesh size in meander structure

Define dielectric constant, perfect electrical conductor boundary in respective domain and boundary

Use **Transition Boundary Condition (TBC)** on the superconducting layer

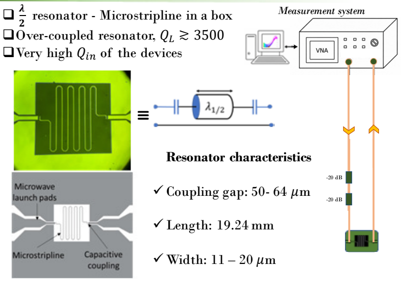
TBC allows $\sigma_{complex} = \sigma' - j\sigma''$ and thickness (t) for the layer $\left(\sigma'' = \frac{1}{\mu_0\omega\lambda^2}\right)$

Set up study for eigen frequency (f_0) for different values λ with constant σ'

For the flip-chip geometry, we define two TBC layer for two superconductors and set study for eigen frequency

Experimental Set up

- $\frac{\lambda}{2}$ resonator - Microstripline in a box
- Over-coupled resonator, $Q_L \gtrsim 3500$
- Very high Q_{in} of the devices

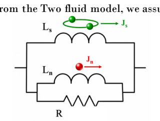


Resonator characteristics

- ✓ Coupling gap: 50- 64 μm
- ✓ Length: 19.24 mm
- ✓ Width: 11 – 20 μm

Theoretical part

From the Two fluid model, we assumes the current density in oscillating electric field, $J_T = J_n + J_s = (\sigma_{complex})E$

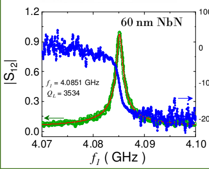


for a non zero frequency, $\omega \ll 10^{11}$ Hz ($\hbar\omega < 2\Delta$) Complex conductivity,

$$\sigma_c = \sigma' - j\sigma'' \approx \frac{n_n e^2\tau_e}{m} + \frac{-j}{\mu_0\omega\lambda_L^2(T)}$$

Real part of conductivity ⟶ Dissipated power loss

In the BCS dirty limit $\left(\lambda_L^{-2}(T)\right)_{l<\xi_0} = \lambda_L^{-2}(0)\frac{\Delta(T)}{\Delta(0)}\tanh\left(\frac{\Delta(T)}{2k_bT}\right)$

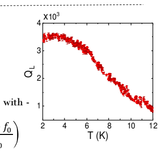


The Loaded Quality factor, Q_L

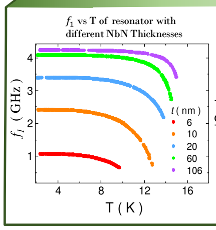
$$\frac{1}{Q_L} = \frac{1}{Q_{internal}} + \frac{1}{Q_{external}}$$

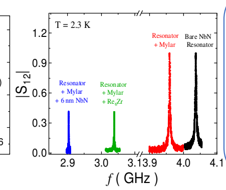
Fit the line shape of transmission spectra S_{12} with -

$$|S_{12}| = \frac{Q_L}{Q_e}\left(\frac{1}{1+4Q_L^2\delta^2}\right)^{1/2} \quad \left(\delta = \frac{f-f_0}{f_0}\right)$$

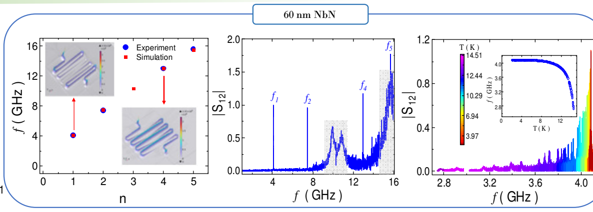


Basic data of resonators :

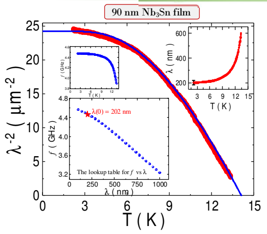


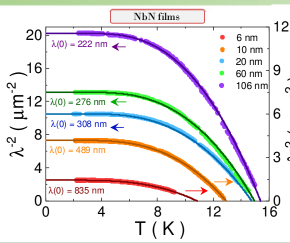


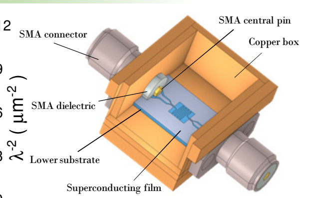
60 nm NbN



Experimental results : Bare resonators

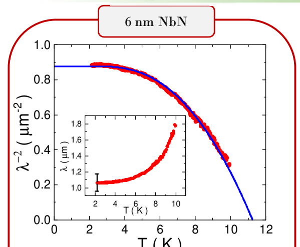


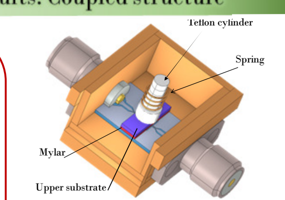




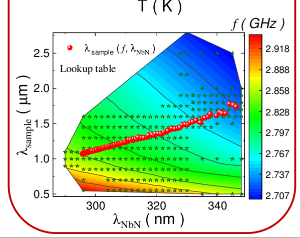
- Bare superconducting resonator

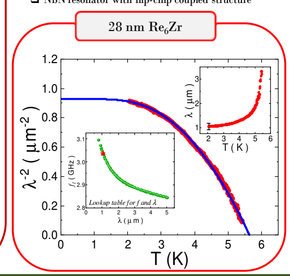
Experimental results: Coupled structure





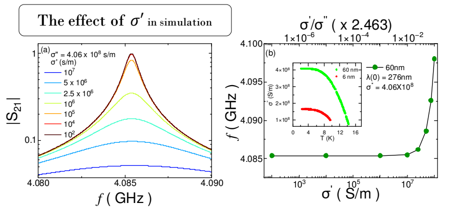
- NbN resonator with flip-chip coupled structure





Conclusion & Remarks

The effect of σ' in simulation



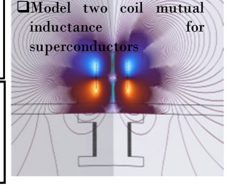
- This is a versatile technique to measure absolute penetration depth at high frequencies with any resonator structure
- The flip chip method provide quick way to characterize continuous samples at high frequency.
- This technique can also determine a superconducting film's surface resistance, R_s.

Future work

- Study the complete electrodynamics of different superconductors (BiPd, $FeSe_{0.5}Te_{0.5}$ etc.) with cavity resonator.
- Set up & Study on trapped vortices with the resonator.
- Discrepancy in λ(0) between high-frequency cavity resonator and low-frequency two-coil methods in very thin films requires further study.
- Dielectric material characterization and ESR studies

Questions ?

- Model two coil mutual inductance for superconductors



For more info- visit our lab website

https://www.tifr.res.in/~superconductivity/index.php

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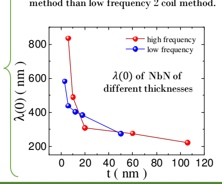
Error & Discussion

- We get $\lambda(0)$ **higher** in the cavity resonator method than low frequency 2 coil method.



- The sensitivity of the flip chip method is become lower with thickness of the flip sample

Error coming from	Error
Substrate and film thickness + ε_r(MgO) for bare resonator	8 %
Substrate and film thickness + ε_r(MgO)+ε_r(Mylar) for flip chip	12%

- Lookup table f *vs* λ of the flipped sample of different thicknesses