Time-Reversal Symmetry Breaking in the Nonlinear Electrodynamics of $Tl_2BaCa_2Cu_2O_8$ Superconductors

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Why Superconductors?

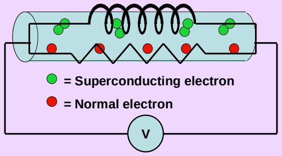
High-temperature superconductors, HTS, such as the TBBCO samples used in this experimentation, conduct direct current with zero resistance at temperatures below the material's *critical temperature*, T_c.

$$\sigma = \frac{1}{\rho} + \frac{i}{\omega L_k}$$

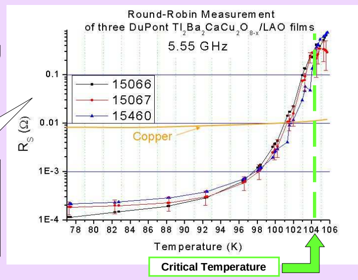
Superconductor's Conductivity

Resistivity of the Normal Electrons

Even superconducting electrons are impeded at high frequencies due to the *kinetic inductance* of free charges.



The *two-fluid model* dictates how a non-zero surface resistance, R_S, arises for alternating currents with microwave frequencies.

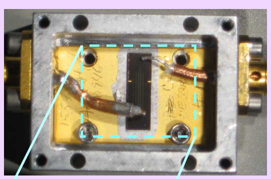


Three samples exhibit superconductivity below T_c, but at 5.55 GHz their surface resistance is still measurable.

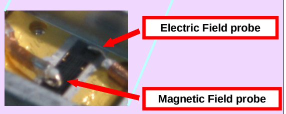
Graph from Bradley Dober and S.K. Remillard, "Harmonic and Intermodulation Distortion in a Superconducting Microwave Resonator", American Physical Society March Meeting, Pittsburgh, PA, March 13-20, 2009

Superconducting Resonators

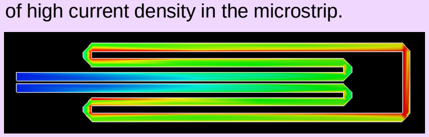
- A $Tl_2BaCa_2Cu_2O_8$ microstrip line is mounted on a substrate of lanthanum aluminate (LAO).



- Probes induce current in the resonator.



- Input signals with certain *resonant frequencies* set up "hot spots" of high current density in the microstrip.



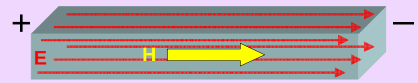
Map of Current Density in a Resonator at the 1st-Order Resonance
(Simulation produced with IE3D EM Design System; *Zeeland Software Inc.*)

- Surface resistance, R_S, is measured at various input powers, revealing…

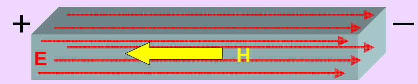
Nonlinearity: Resistance depends on current

Time-Reversal Symmetry (TRS) and Distortion

Superconducting microstrip with time going ***forward***…



Superconducting microstrip with time going ***backwards***…



E → = Electric field — ***Even* TRS**

H → = Surface current — ***Odd* TRS**

Conventionally: $E = -L\frac{dH}{dt}$ (if resistance is zero)

Even TRS; Constant, so Even TRS; Time derivative of Odd TRS, so Even TRS

Superconductor with nonlinear L: $L = L_0 + \Delta L_1(H) + \Delta L_2(H)^2 + \ldots$

Odd; Breaks TRS of L

Driver: $H = H_0 \sin(\omega t)$

Response: $E = -L\frac{dH}{dt} = E_0 + E_1\cos(\omega t) + E_2\cos(2\omega t) + E_3\cos(3\omega t) + \ldots$

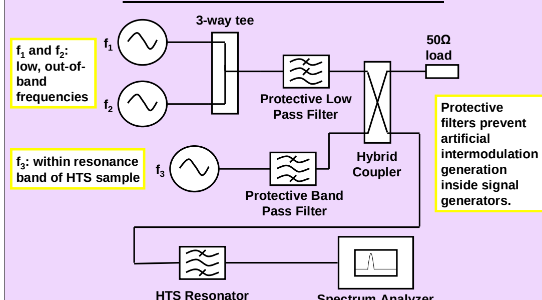
2nd Order Distortion; 3rd Order Distortion

If 2nd Order Distortion is measurable, then $E_2 \neq 0$. (Predicted by S.C. Lee)

The measurement of 2nd Order Distortion will show TRS is broken.

Theory of Sheng-Chiang Lee, et al., "Doping dependent nonlinear Meissner effect and spontaneous currents in high-T_c superconductors," Phys. Rev. B, **71**, 014507 (2005).

Three-Tone Intermodulation



With three input tones, HTS resonators produce **Intermodulation (IM) Distortion** in the pass band. 2nd and 3rd order IM distortion appears at mixing frequencies:

2nd Order	3rd Order
$(f_3 + f_1)$, $(f_3 - f_1)$, $(f_3 + f_2)$, $(f_3 - f_2)$	$[f_3 + (f_1 - f_2)]$, $[f_3 - (f_1 - f_2)]$

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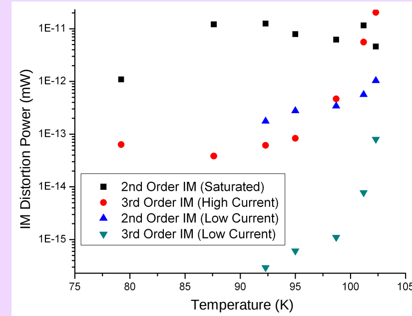
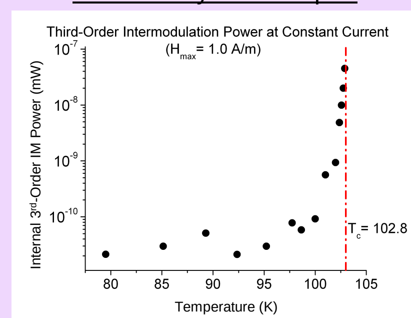
Results of Three-Tone IM Testing

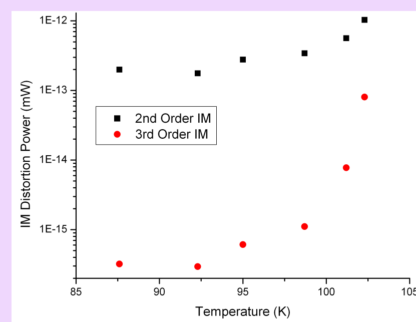


- 2nd order IM distortion was measured, confirming TRS is broken in high-temperature superconductors.
- 3rd order IM distortion was much weaker than 2nd order, and 2nd order IM appeared to saturate at high current levels
- To improve and further clarify these results, new probe locations and a third probe to introduce the two out-of-band carriers separately will be added.

Nonlinearity Catastrophe



- First observed in two-tone measurements
- An explosion of more than 3 orders of magnitude in 3rd order IM distortion as $T \rightarrow T_c$
- Consistent with the nonlinear Meissner effect



- Observed again in three-tone measurements
- Much less catastrophic explosion in 2nd Order IM distortion suggests a higher order of TRS in conduction near T_c