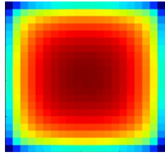
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March, 2024. Invited presentation given at ISS 2023, Nov. 2023, Wellington, New Zealand

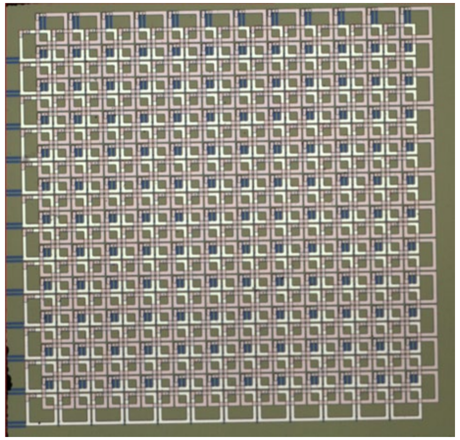


Effects of Strong Capacitive and Inductive Coupling on Hysteretic rf SQUID Metamaterials

Jingnan Cai, Steven M. Anlage

36th International Symposium on Superconductivity
I·S·S 2023
Tākina, WELLINGTON, NEW ZEALAND
November 28–30, 2023

Collaborators:
Thomas Antonsen, Edward Ott (Univ. of Maryland)
Alexander Zhuravel (Kharkov, Ukraine)
Alexey Ustinov (Karlsruhe, Germany)
Johanne Hizanidis, Nikos Lazarides and George Tsironis (Univ. of Crete, Greece)

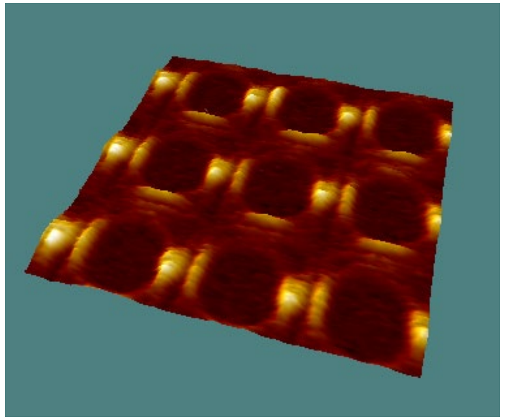


3D rf SQUID metamaterial

36th International Symposium on Superconductivity (ISS2023)
Presentation No: ED-6-2-INV
28-30 November, 2023
Wellington, New Zealand

Quantum Materials Center

DEPARTMENT OF PHYSICS
UNIVERSITY OF MARYLAND



LSM image of 2D rf SQUID metamaterial

https://doi.org/10.48550/arXiv.2402.07044

29 November, 2023

Research supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award DESC0018788

Outline

- **Brief Review of Superconducting Metamaterials**
- **rf SQUID Metamaterials**
  - **Tuning**
  - **Nonlinearity**
- **Collective Behavior of rf SQUID Metamaterials**
  - **Long-range Inductive Coupling**
  - **Laser Scanning Microscopy**
- **3D Stacked rf SQUID Metamaterials**
  - **The Role of Capacitive Coupling**
- **Current / Future Work**
- **Conclusions**

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Motivation and Background

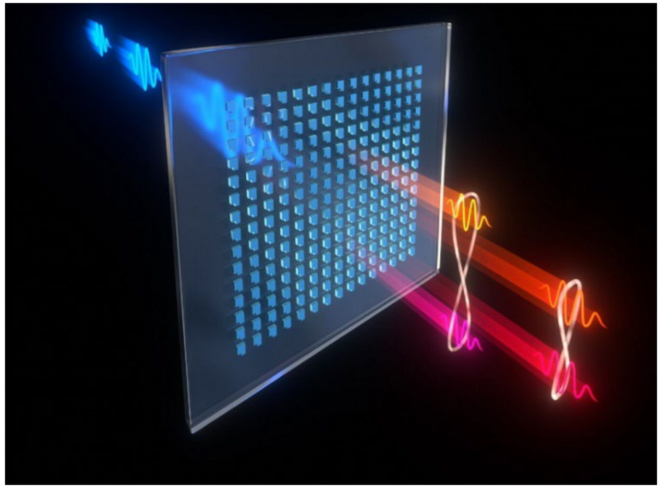
Metamaterials:

Artificial Structures made up of "meta-atoms" with new or extreme properties

Collections of sub-wavelength scatterers that create an effective medium with new functionality

Enhance light/matter interactions

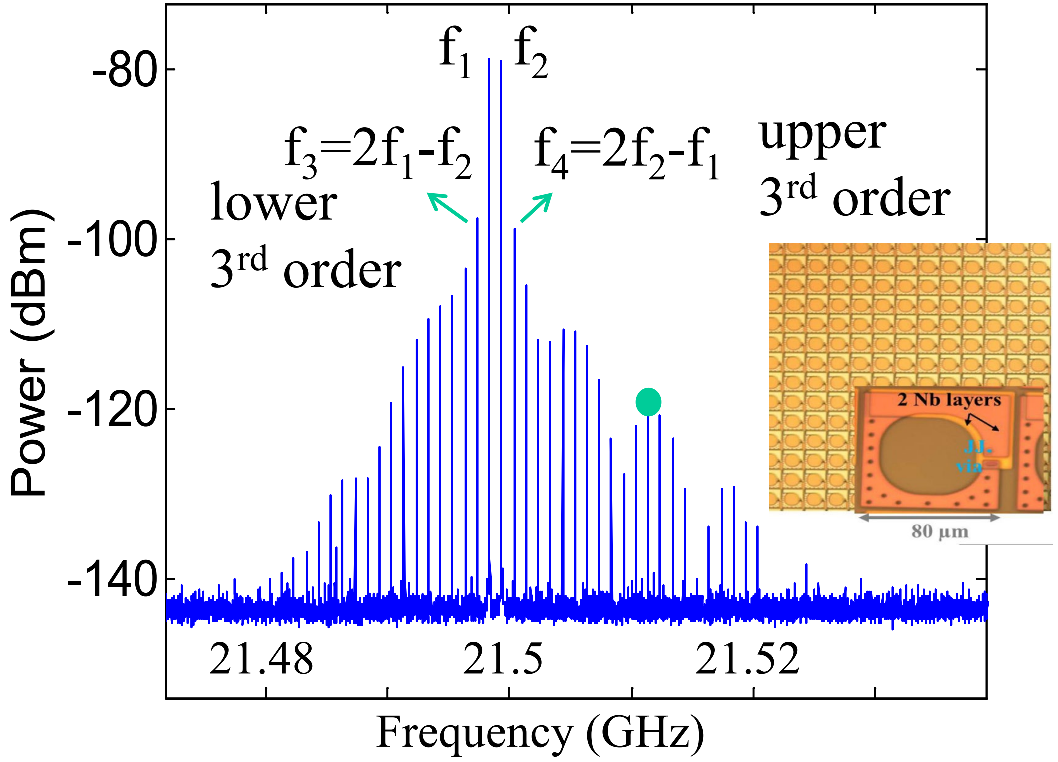
Functional Metasurfaces



https://www.photonics.com/Articles/Metasurfaces_Open_Up_Research_Paths_For_Quantum/a68324

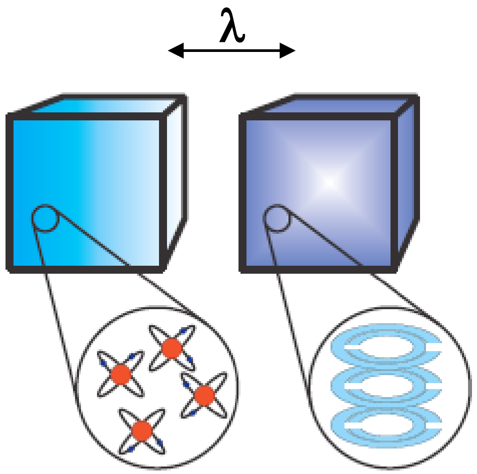
Extreme Nonlinearity

Intermodulation in a superconducting metamaterial



D. Zhang, *et al.*, Phys. Rev. B 94, 174507 (2016)

Why Superconducting Metamaterials?



Pendry (2004)

Many exciting applications of metamaterials:

- Metasurface optics
- Cloaking
- Super-resolution imaging, etc. …

… have strict REQUIREMENTS on the metamaterials:

- Ultra-Low Losses
- Ability to scale down in size (e.g. $\lambda/10^2$) and texture the “meta-atoms”
- **Nonlinearity with wide and fast tunability of the index of refraction *n***

… and superconductors bring these new features to the metamaterials field:

- Strong diamagnetism
- **Flux quantization and Josephson effects**
- Quantized energy states and quantum interactions with light

M. Ricci, N. Orloff, S.M.A., “**Superconducting Metamaterials**,” Appl. Phys. Lett. **87** , 034102 (2005)
S.M.A. "**The Physics and Applications of Superconducting Metamaterials**," J. Opt. **13**, 024001 (2011)
P. Jung, A. V. Ustinov, and S.M.A., “**Progress in Superconducting Metamaterials**,” Supercond. Sci. Technol. **27**, 073001 (2014)
N. Lazarides and G. P. Tsironis, "**Superconducting Metamaterials**," Physics Reports **752**, 1 (2018)

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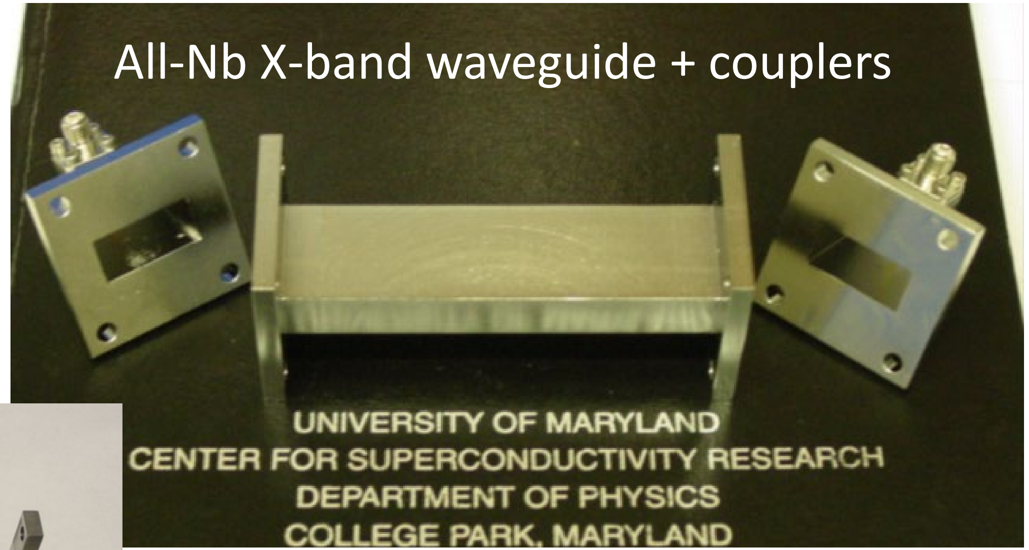
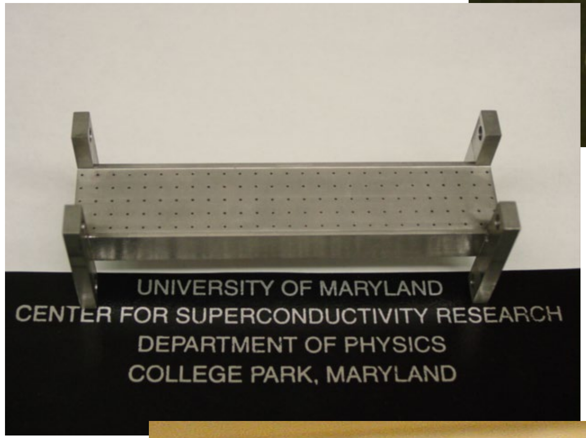
Negative Index Superconducting Metamaterials

How to make them: Step 1

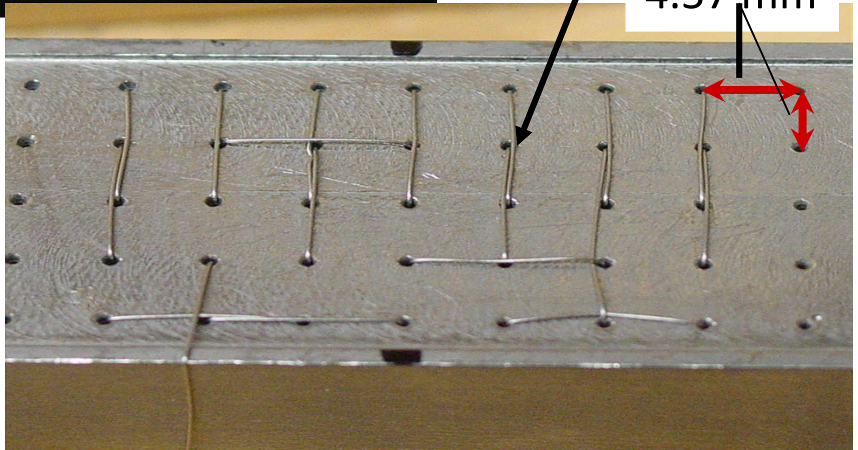
Nb X-band waveguide
($22.86 \times 10.16\ mm^2$)
$T_c = 9.25$ K

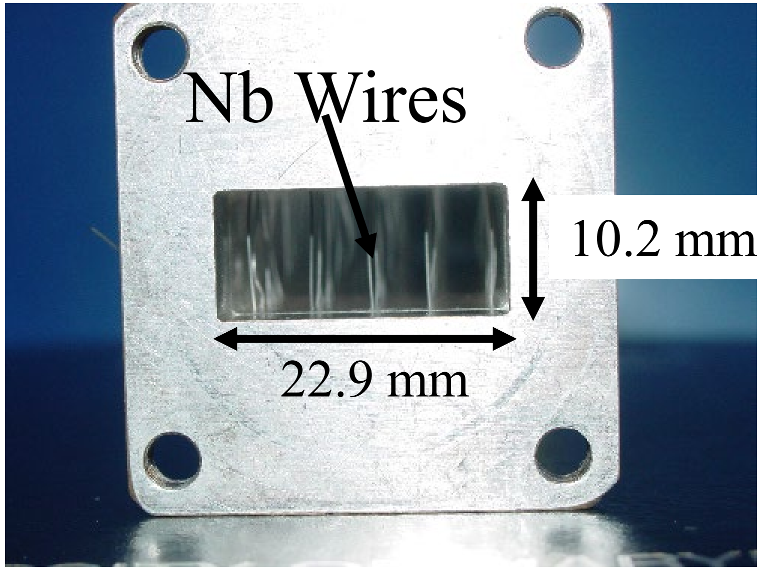


Thanks to
P. Kneisel
@ Jefferson Lab



Nb Wires
0.25 mm dia.
$T_c = 9.25$ K





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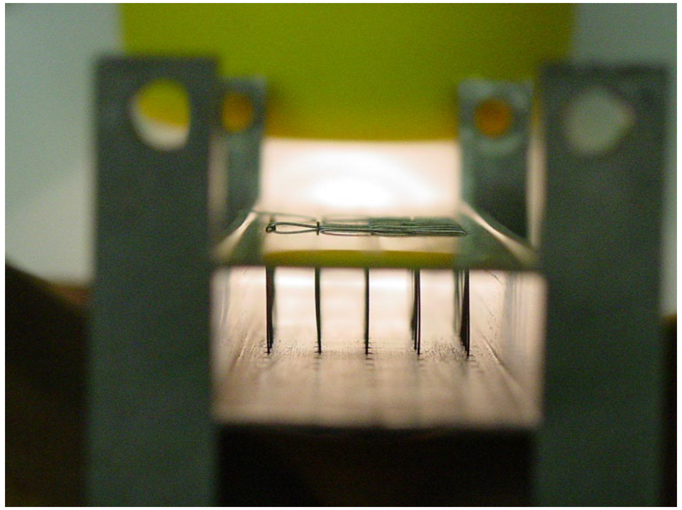
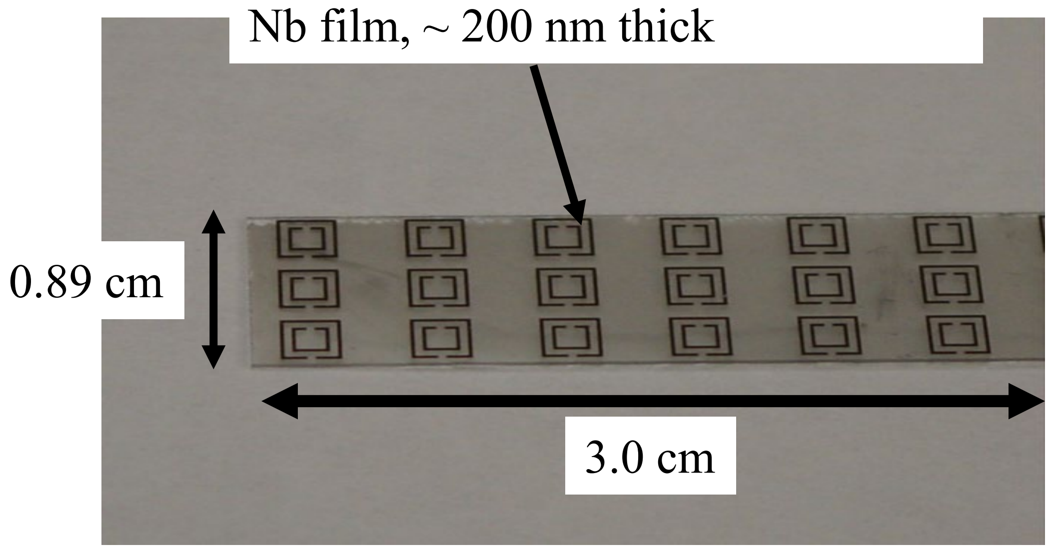
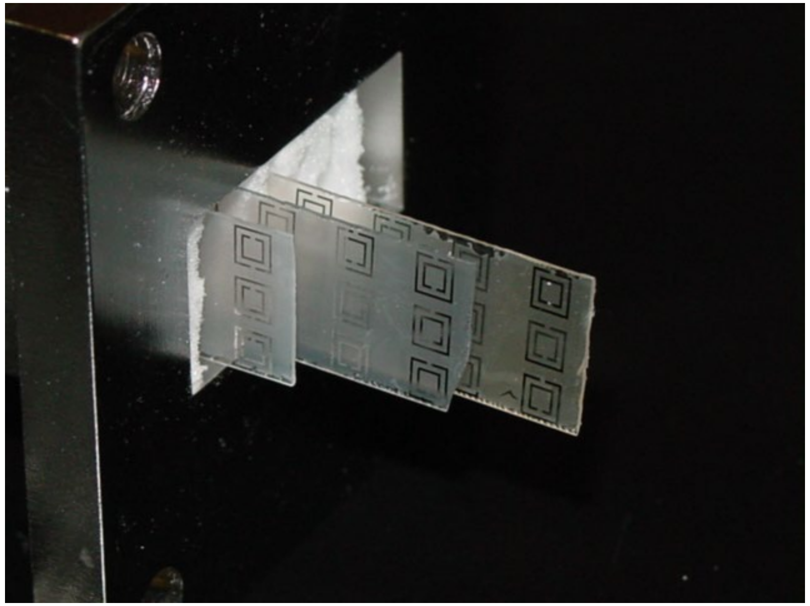
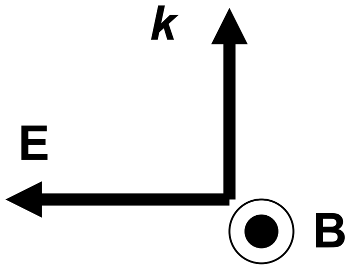
Negative Index Superconducting Metamaterials

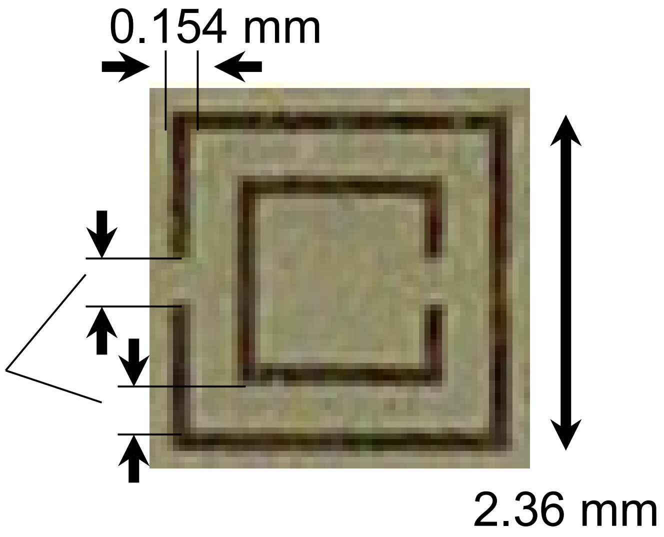
How to make them: Step 2







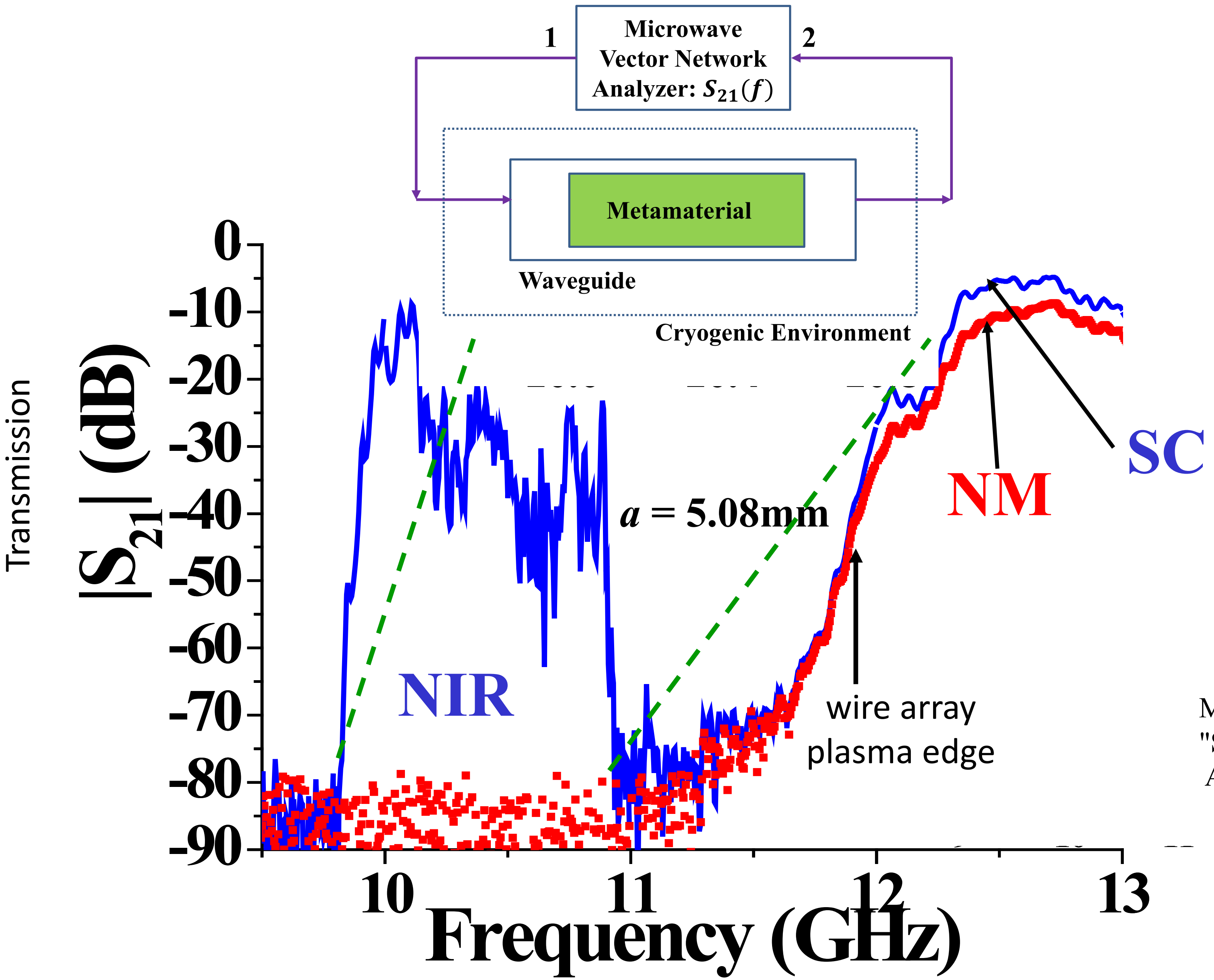




Nb SRR
200 nm thick
on Quartz (350 μm)
T_c = 8.65 K

Negative Index Passband in a Superconducting Metamaterial

216 Split Ring Resonators in a 12-cell wire array, 9 cm long



M. Ricci, N. Orloff , and S. M. A., "**Superconducting Metamaterials**,“ Appl. Phys. Lett. **87**, 034102 (2005)

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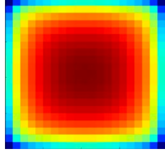

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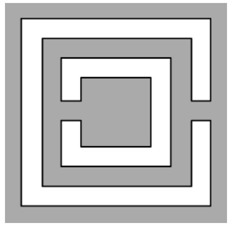
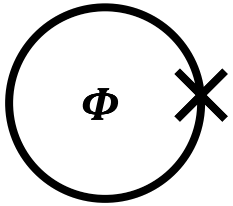
rf SQUID Meta-Atoms



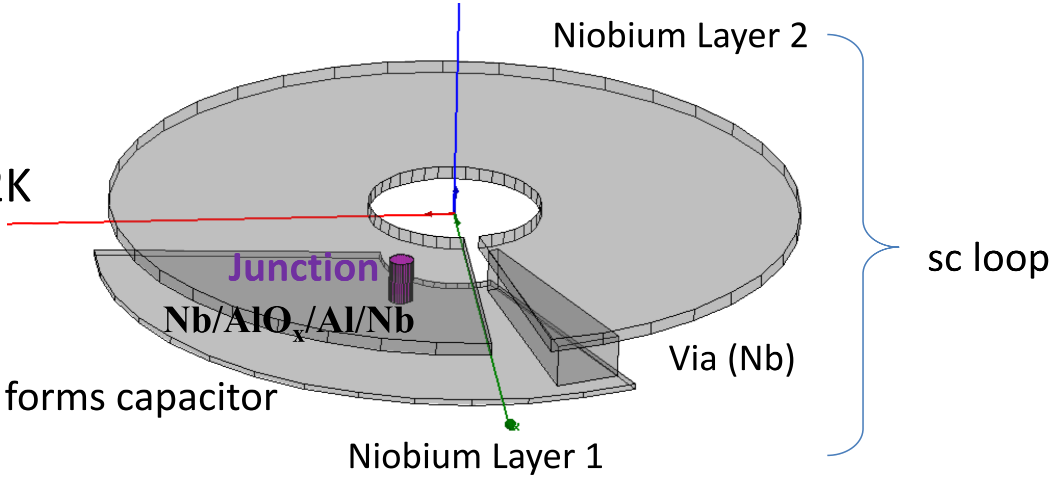
split-ring resonator (used to create 'optical magnetism')

rf SQUID



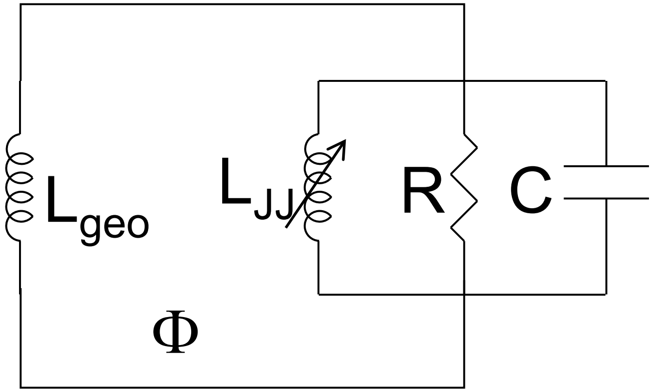
A 'Macroscopic Quantum' Split-Ring Resonator

Nb: T_c = 9.2K

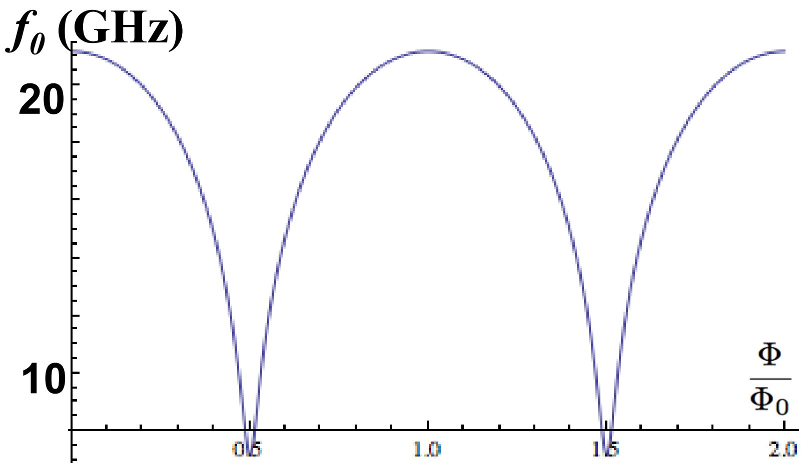


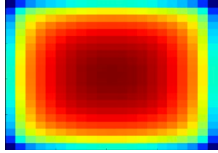
SQUID = **S**uperconducting **QU**antum **I**nterference **D**evice

A self-resonant meta-atom with very nonlinear properties



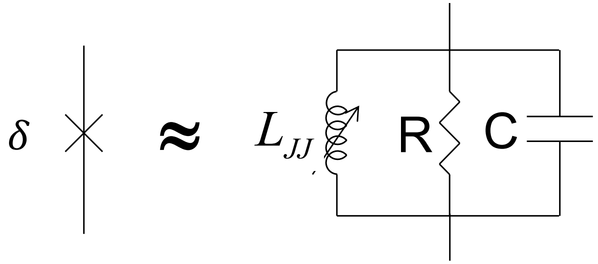
Resonant Frequency of rf SQUID





rf SQUID Meta-Atoms

Josephson Inductance is large, tunable and nonlinear

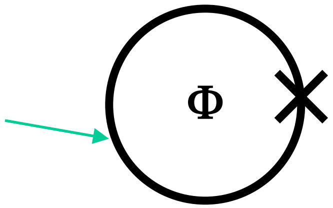


Resistively and Capacitively Shunted Junction (RCSJ) Model

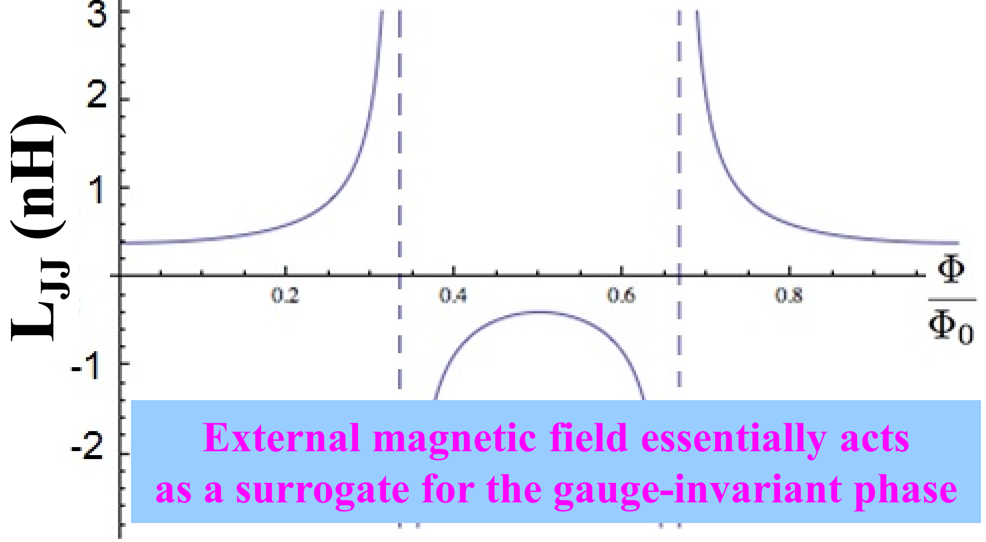
$$L_{JJ} = \frac{\Phi_0}{2\pi I_c \cos(\delta)}$$

The "third Josephson effect"

When the JJ is incorporated into a loop and flux Φ is applied



Combines the Josephson effects with flux quantization



10

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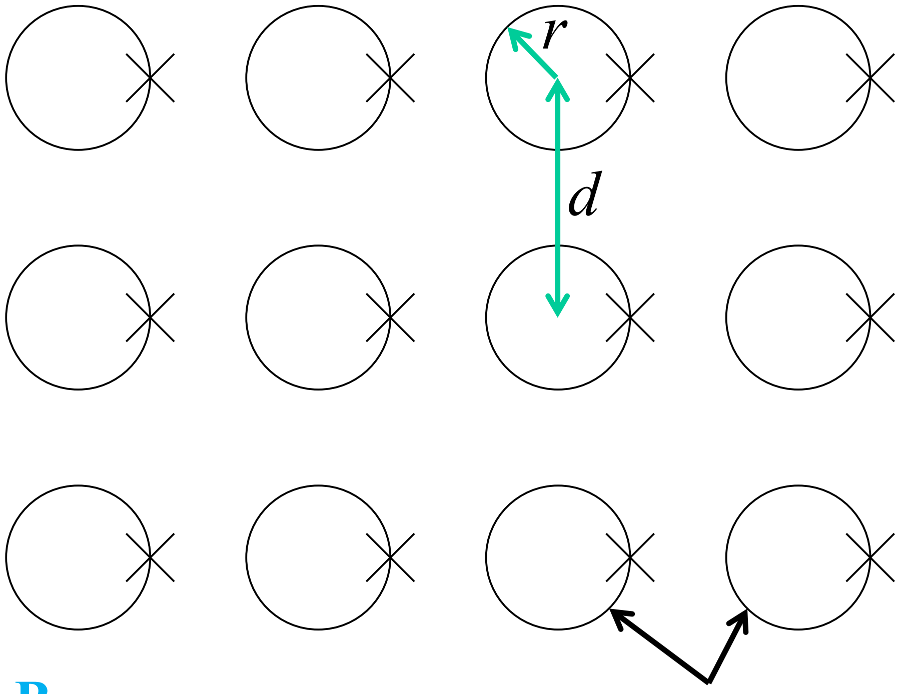
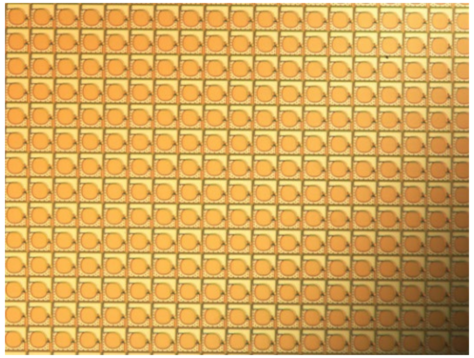
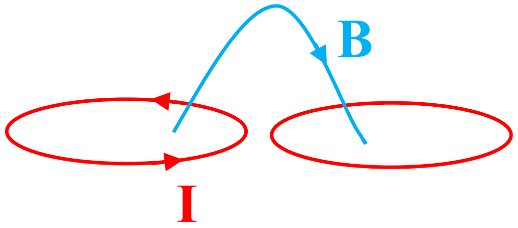
rf SQUID Superconducting Metamaterial

$$\lambda \gg r, d$$

- Low loss
- Small Size
  - λ ~ 3 cm (~ 10 GHz)
  - $2r$ = 20 ~ 800 μm





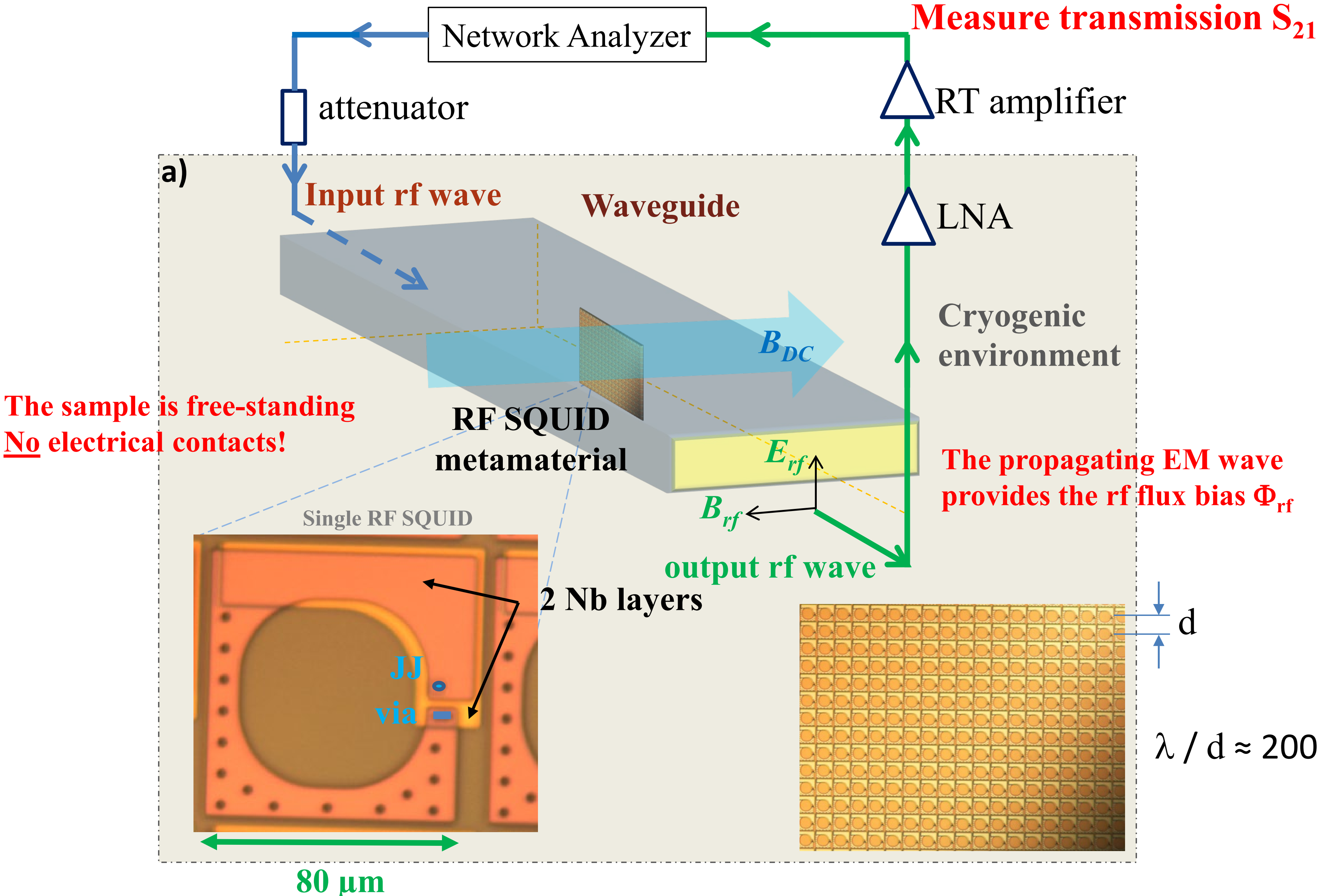


The SQUIDs interact by means of dipole – dipole coupling

→ Collective Behavior

Original theory proposals:
C. Du, H. Chen, and S. Li, PRB 74, 113105 (2006)
N. Lazarides and G. P. Tsironis, APL 90, 163501 (2007)

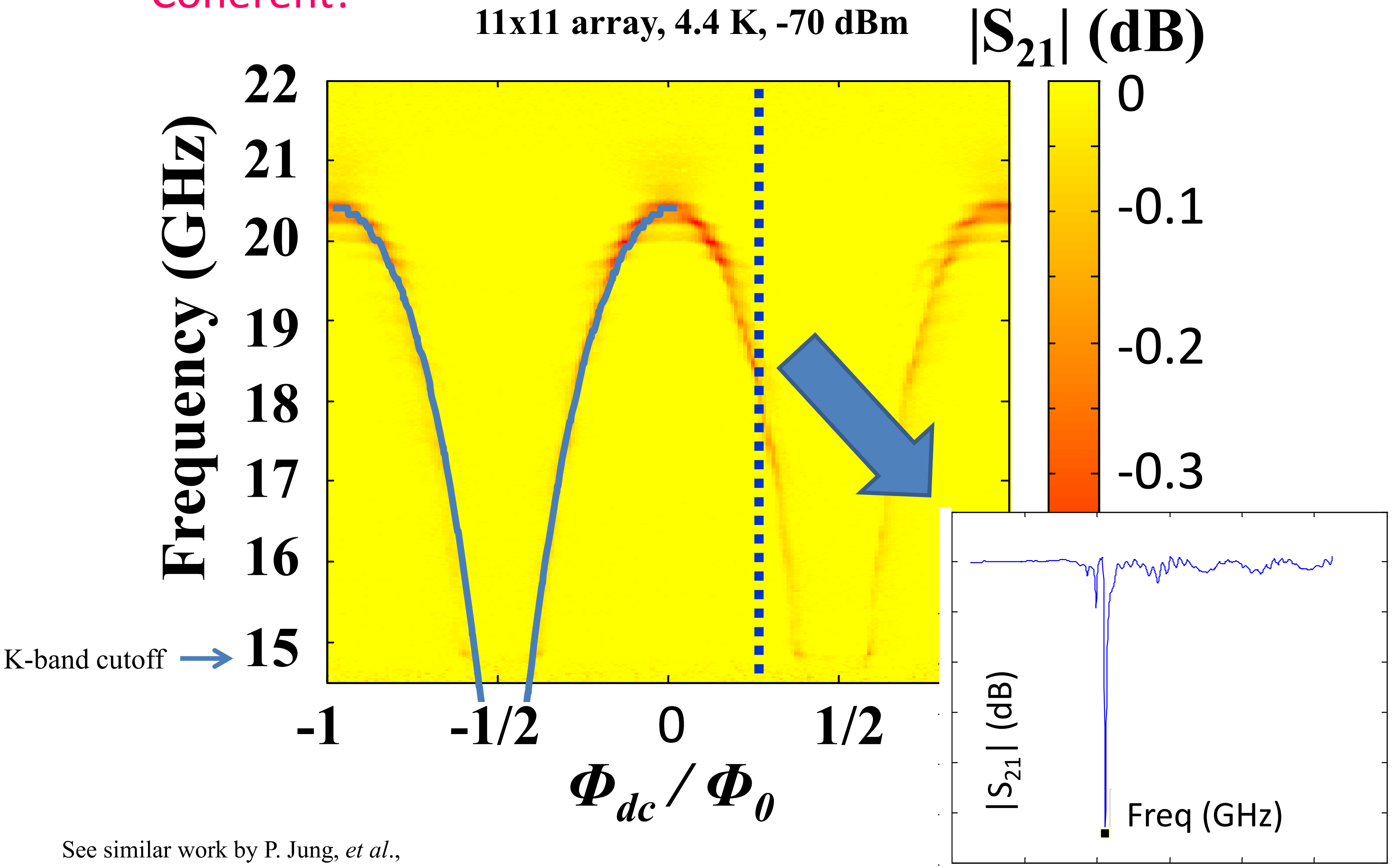
Measurement of rf SQUID Metamaterial



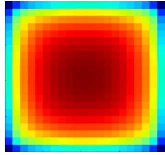
DC magnetic flux tuned resonance

Tunable Notch Filter

Coherent!

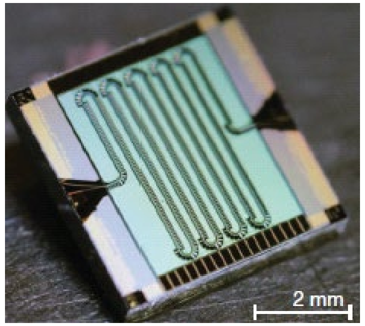


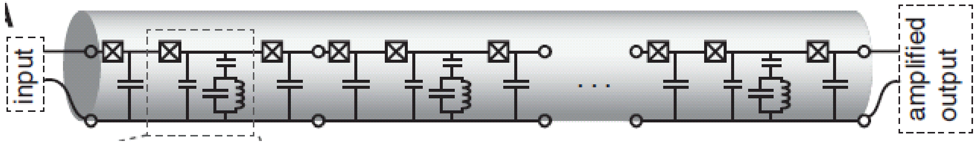
See similar work by P. Jung, *et al.*, Appl. Phys. Lett. 102, 062601 (2013)



Applications of Nonlinear SQUID Metamaterials

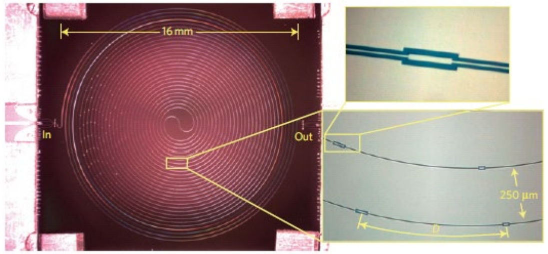
Quantum-Limited Amplifiers





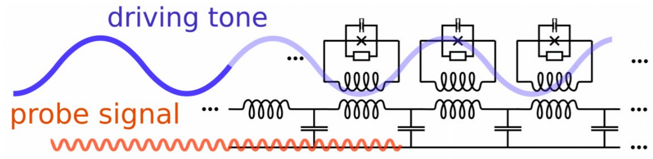
A near-quantum-limited Josephson traveling-wave parametric amplifier

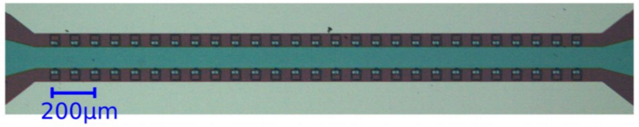
C. Macklin,[1,2*] K. O'Brien,[3] D. Hover,[4] M. E. Schwartz,[1] V. Bolkhovsky,[4] X. Zhang,[3,5] W. D. Oliver,[4,7] I. Siddiqi[1]



A wideband, low-noise superconducting amplifier with high dynamic range

Byeong Ho Eom[1], Peter K. Day[2*], Henry G. LeDuc[2] and Jonas Zmuidzinas[1,2]





Two-tone spectroscopy of a SQUID metamaterial in the nonlinear regime

E. I. Kiselev,[1,2] A. S. Averkin,[3] M. V. Fistul,[4,3,5] V. P. Koshelets,[6] and A. V. Ustinov[2,3,5]

Phys. Rev. Research 1, 033096 (2019)

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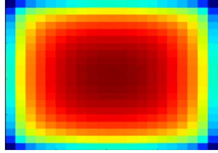

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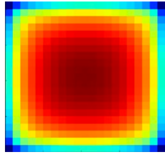
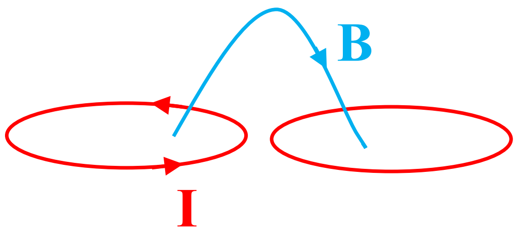


Long-Range Inductive Coupling in rf SQUID metamaterials

Side-by-side SQUIDs have mutual inductance M that falls off like a dipole-dipole interaction:

$$\boldsymbol{M < 0}, \textbf{ with } |\boldsymbol{M}| \sim \frac{\mathbf{1}}{\boldsymbol{r^3}}$$



Sample edges are also a large perturbation

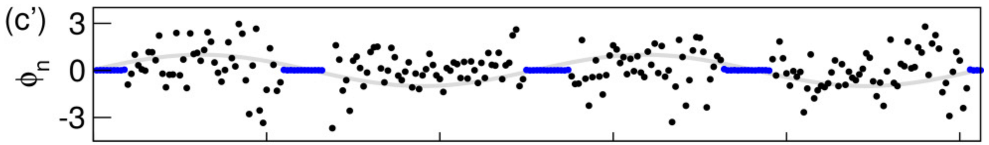
Chimera: coexistence of synchronous and asynchronous groups of oscillations in a material, even for uniform constituent atoms and symmetric couplings

PHYSICAL REVIEW E **94**, 032219 (2016)

Robust chimera states in SQUID metamaterials with local interactions

J. Hizanidis, N. Lazarides, and G. P. Tsironis

1D rf SQUID metamaterial

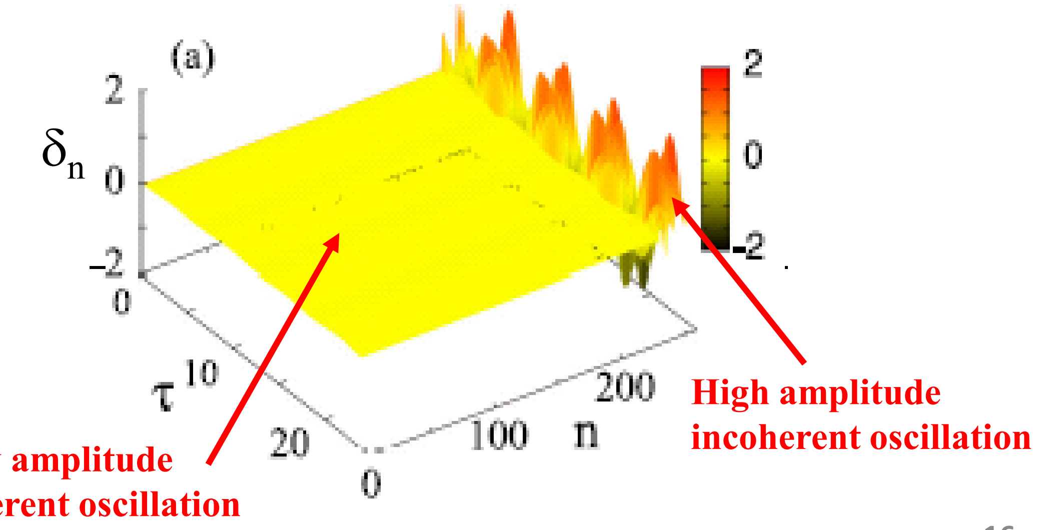


SQUID index n

PHYSICAL REVIEW B **91**, 054303 (2015)

Chimeras in SQUID metamaterials

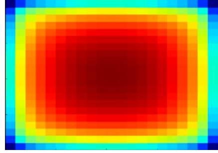
N. Lazarides,[1,2] G. Neofotistos,[1] and G. P. Tsironis[1,2,3]



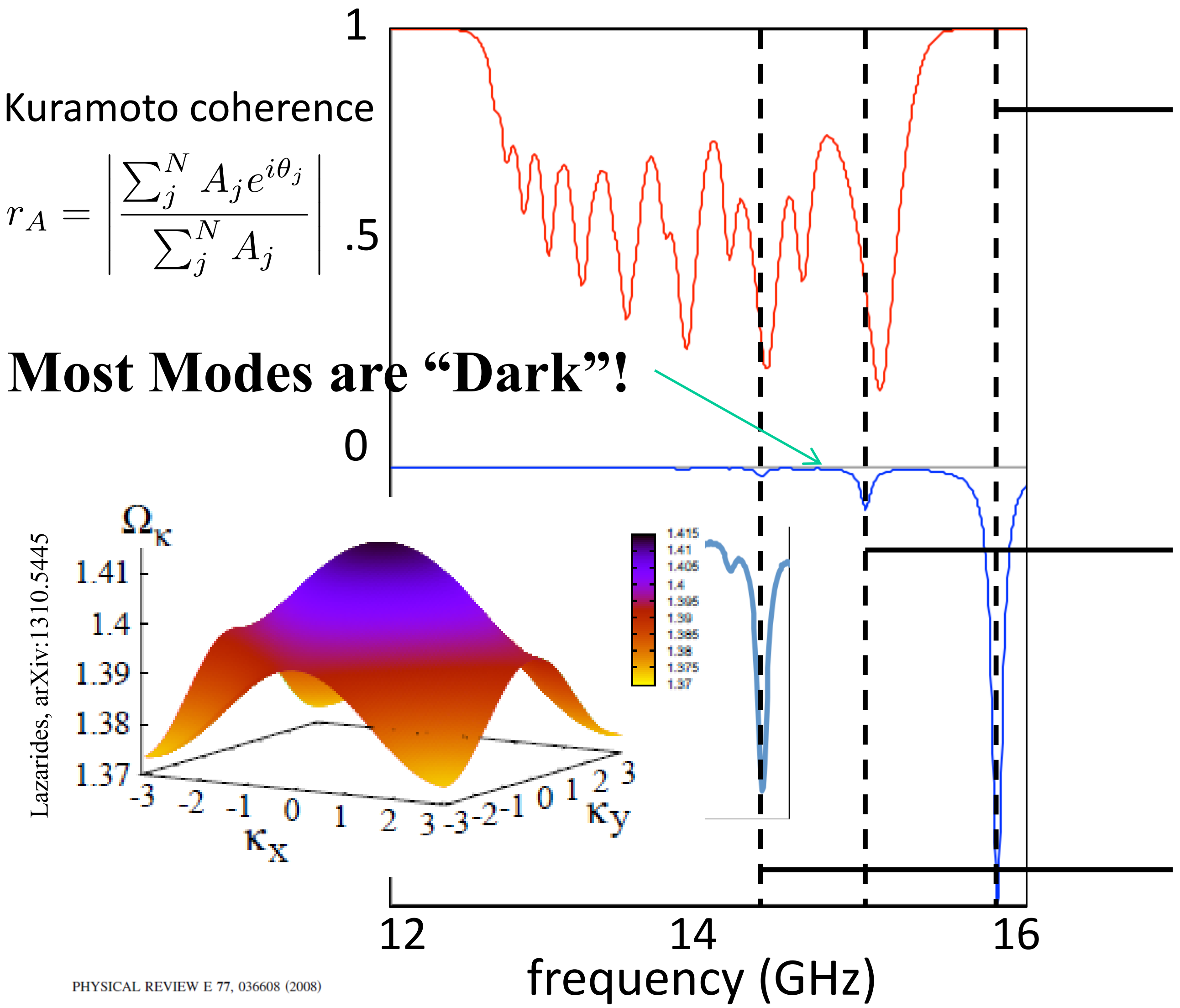
Other theory papers motivated by our rf SQUID metamaterials:

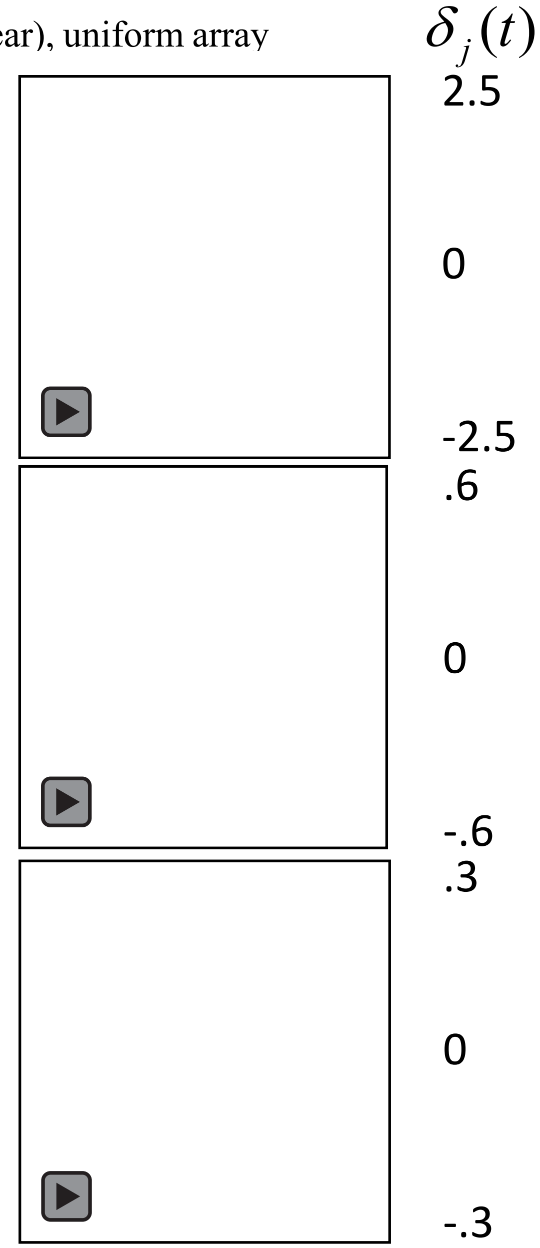
A. Banerjee and D. Sikder, Phys Rev E 98, 032220 (2018).
N. Lazarides and G. P. Tsironis, Physics Reports 752, 1 (2018).
J. Hizanidis, Front. Appl. Math. Stat. 5, 33 (2019).
N. Lazarides, Chaos, Solitons and Fractals 130, 109413 (2020)
J. Shena, Chaos 30, 123127 (2020)
J. Shena, Chaos 31, 093102 (2021)

Coupling Between SQUIDs Introduces Magneto-Inductive Modes



Simulation results for strong coupling (21 x 21 array), low power (linear), uniform array





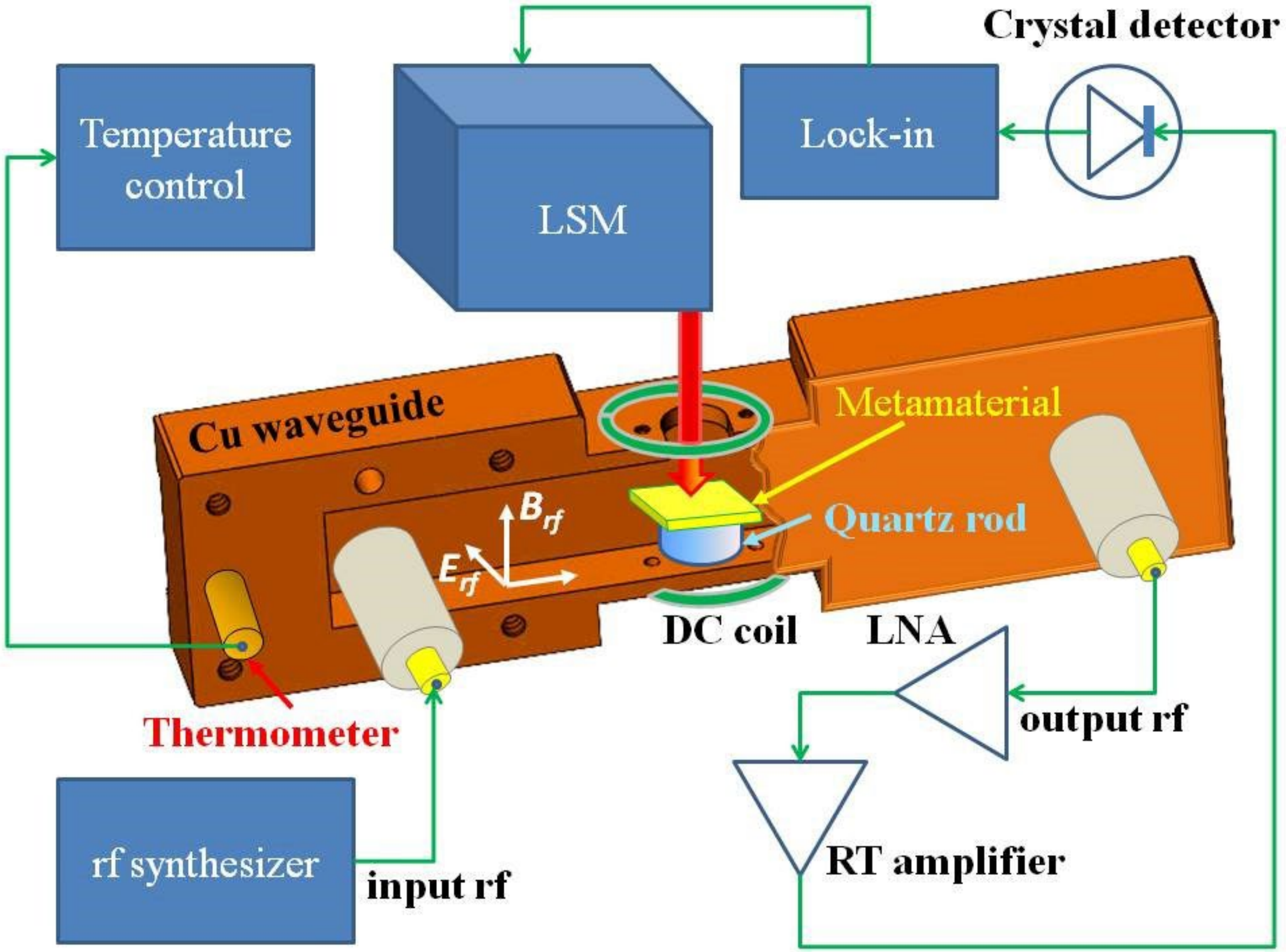
PHYSICAL REVIEW E 77, 036608 (2008)

Magnetoinductive breathers in metamaterials

M. Eleftheriou,[1,2] N. Lazarides,[1,3] and G. P. Tsironis[1]

Image rf SQUID Collective Response

Laser Scanning Microscope Imaging



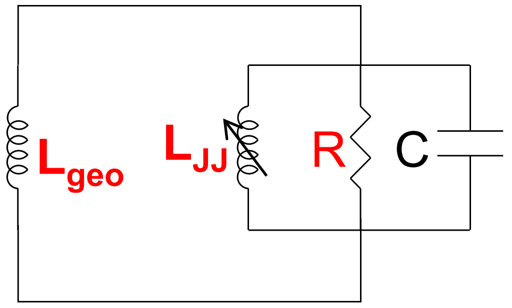
Variables:
- Temperature
- dc magnetic flux
- rf magnetic flux
- rf frequency

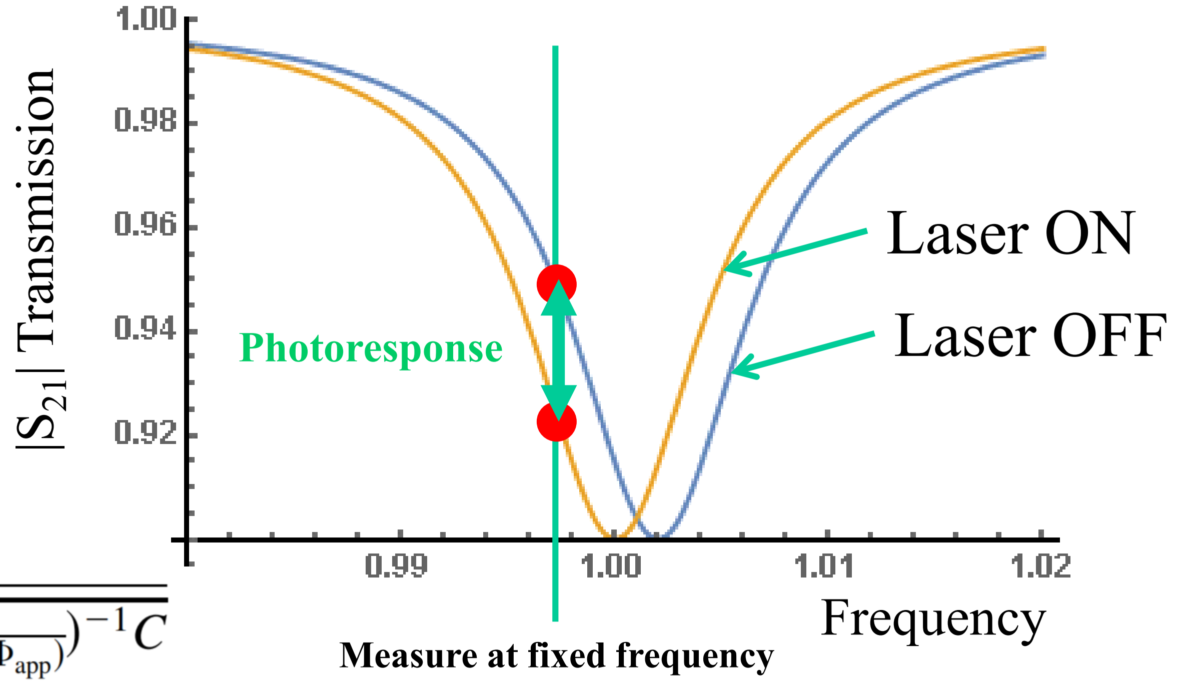
Imaging experiments done by: A. P. Zhuravel in laboratory of A. Ustinov, KIT, Germany
Also Seokjin Bae and Jingnan Cai at UMD

Origins of rf Photoresponse

Contrast mechanisms

Laser heating





$$f_0(T, \Phi_{app}) = \frac{1}{2\pi\sqrt{\left(\frac{1}{L_{geo}} + \frac{1}{L_{JJ}(T,\Phi_{app})}\right)^{-1} C}}$$

Heating of JJ leads to decrease of critical current and shift of resonance

$$L_{JJ} = \frac{\Phi_0}{2\pi\, I_c(T)\cos\delta}$$

Photoresponse ~ $|I_{rf}|^2$ in junction

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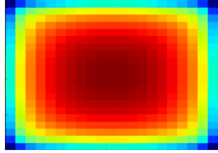
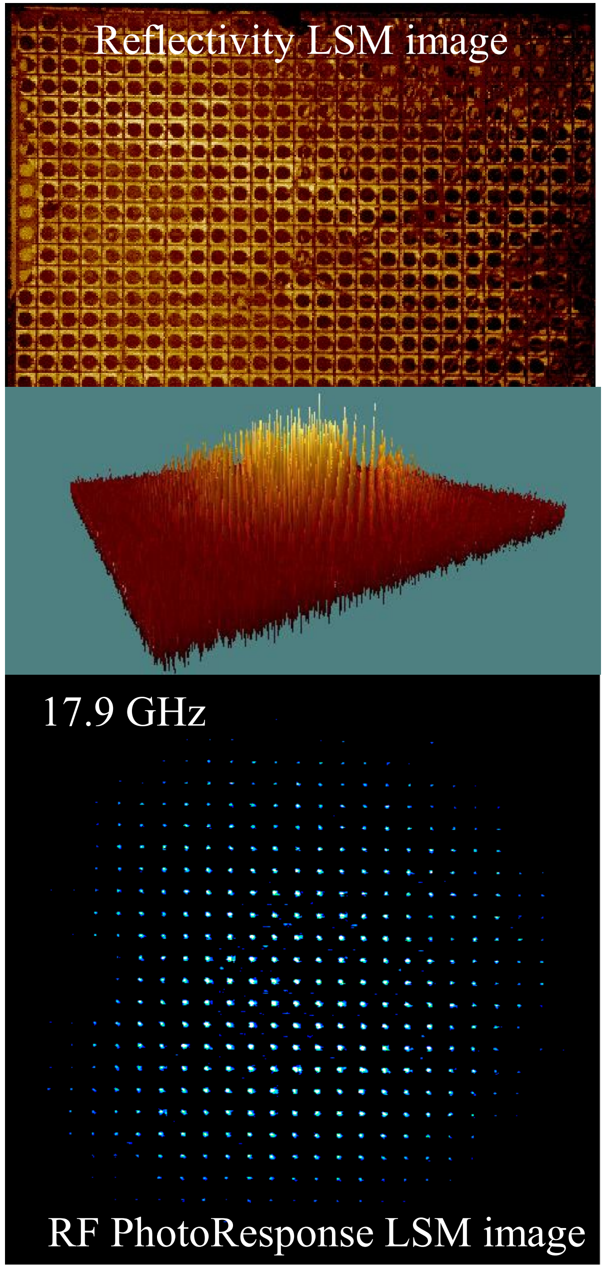
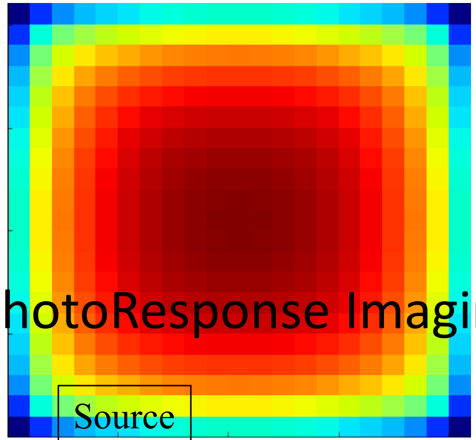
Imaging rf SQUID Metamaterial High-Power Coherent Mode







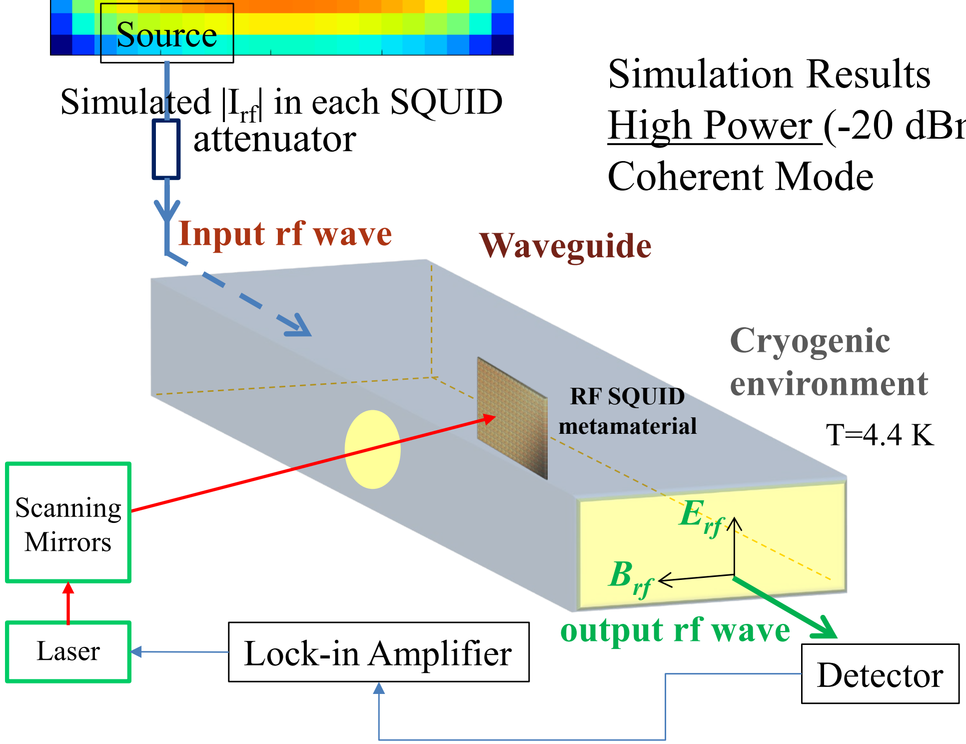
27 x 27 rf SQUID metamaterial

Photoresponse ~ $|I_{rf}|^2$

PhotoResponse Imaging of rf SQUID Metamaterial

Simulated $|I_{rf}|$ in each SQUID

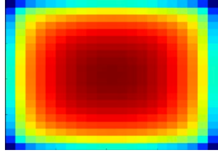
Simulation Results
High Power (-20 dBm)
Coherent Mode



A. P. Zhuravel, P. Jung, S. Anlage, A. Ustinov, KIT, Germany

Imaging rf SQUID Metamaterial

The "Dark Modes" are now visible!



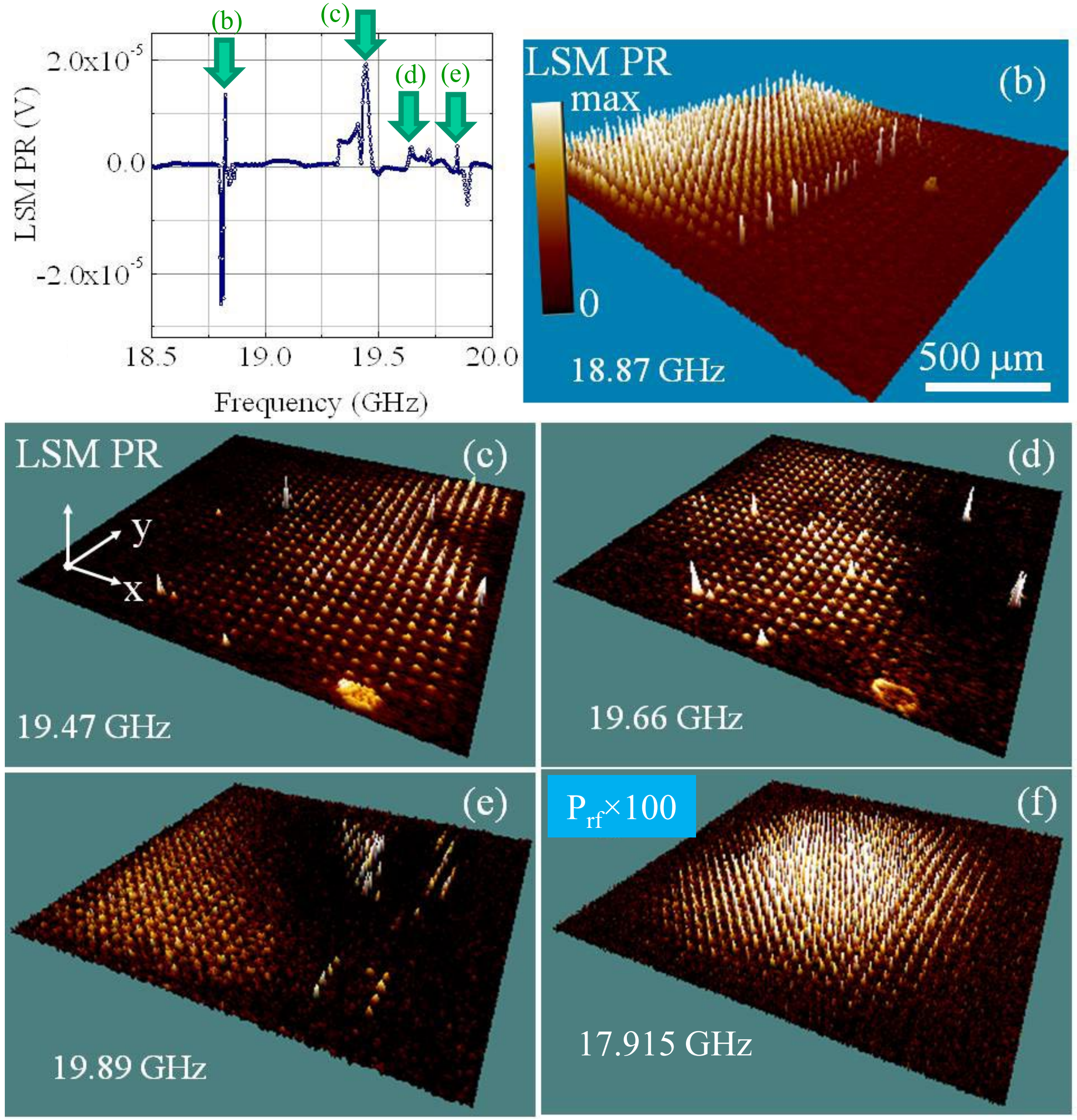
A weak global driving field reveals strong disorder of the sample

T = 4.8 K

$\Phi_{dc} = 0\ \Phi_0$

$\Phi_{rf} = 10^{-4}\ \Phi_0$

27 x 27 array
rf SQUID (12, 14)



Images taken at low rf flux amplitude
$\boldsymbol{\Phi_{rf} = 10^{-4}\ \Phi_0}$

$\boldsymbol{\Phi_{rf} = 10^{-3}\ \Phi_0}$

Stronger global rf flux creates a coherent mode

A. Zhuravel, S. Bae, SMA, Appl. Phys. Lett. 114, 082601 (2019).

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Outline

- Brief Review of Superconducting Metamaterials
- rf SQUID Metamaterials
  - Tuning
  - Nonlinearity
- Collective Behavior of rf SQUID Metamaterials
  - Long-range Inductive Coupling
  - Laser Scanning Microscopy
- 3D Stacked rf SQUID Metamaterials
  - The Role of Capacitive Coupling
- Current / Future Work
- Conclusions

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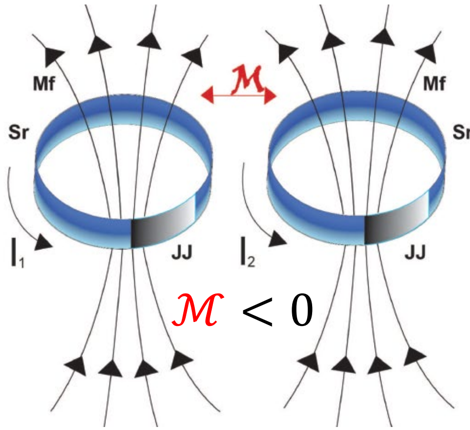
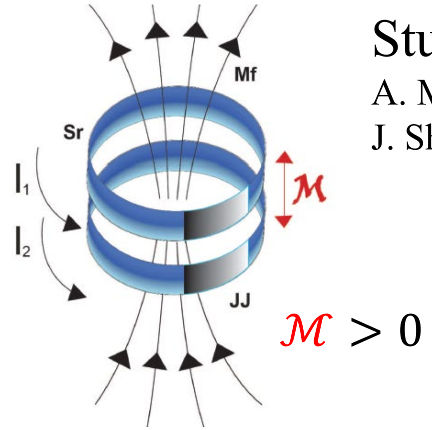
Next-Generation rf SQUID Metamaterials

Move into the third dimension



side-coupled
rf SQUIDs



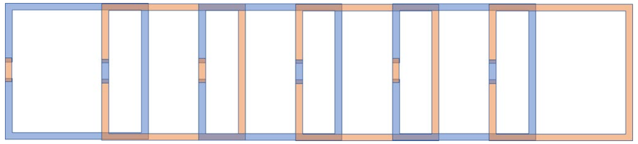
Study 3D "stacked metamaterials"

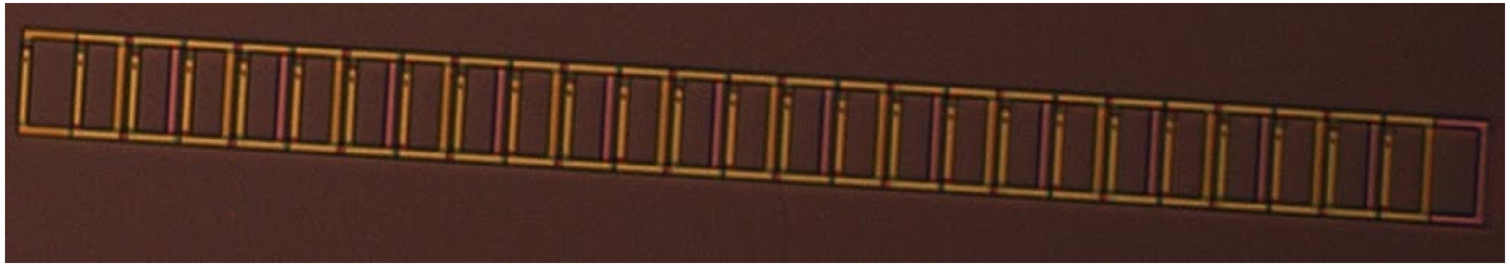
A. M. Zagoskin J. Optics 14, 114011 (2012)

J. Shena, *et al.*, Chaos 30, 123127 (2020)

Positive (Ferromagnetic) Coupling between meta-atoms

(M/L → -0.2 to 0 to +0.70 as overlap increases)





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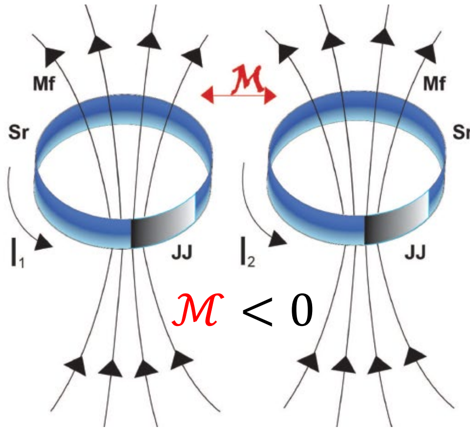
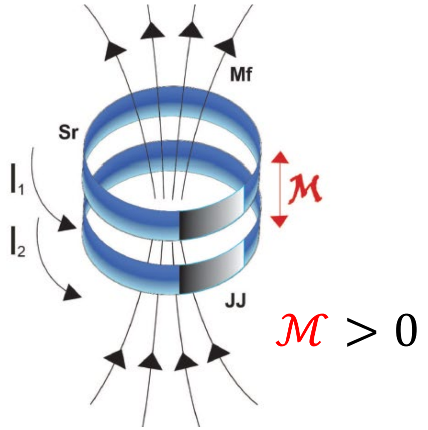
Next-Generation rf SQUID Metamaterials

Move into the third dimension

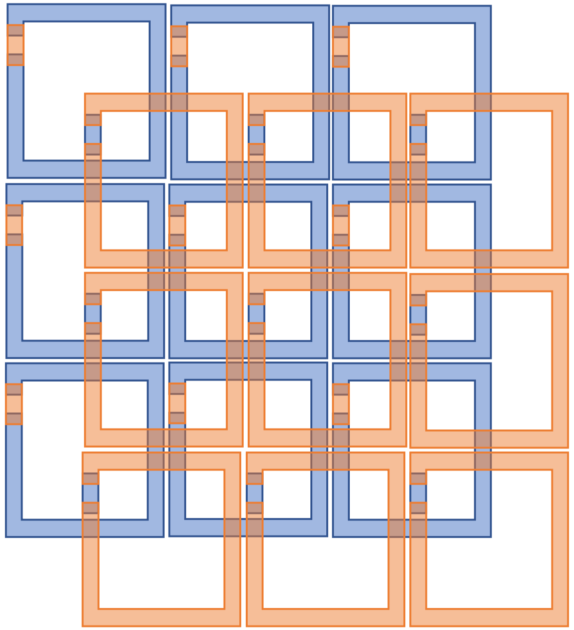


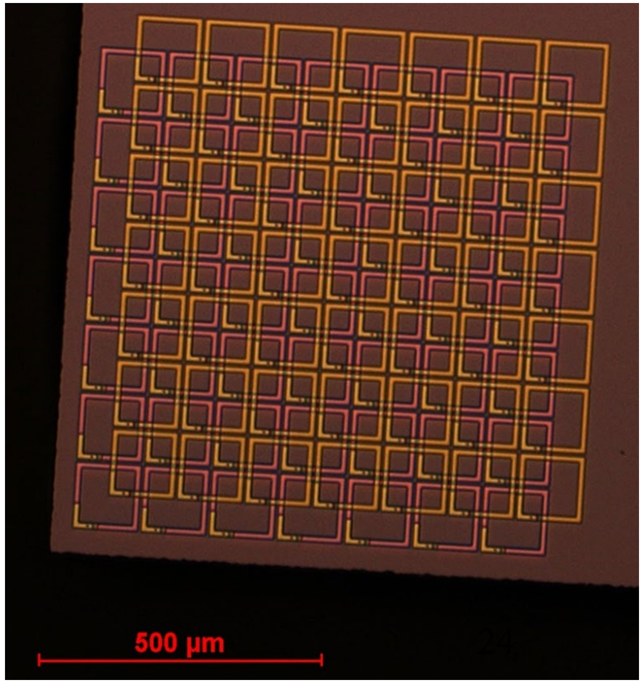
side-coupled
rf SQUIDs



7x7x2
rf SQUID
metamaterial

2D metamaterial with mixed ferromagnetic and anti-ferromagnetic coupling





Thanks to Robin Cantor
@StarCryoelectronics

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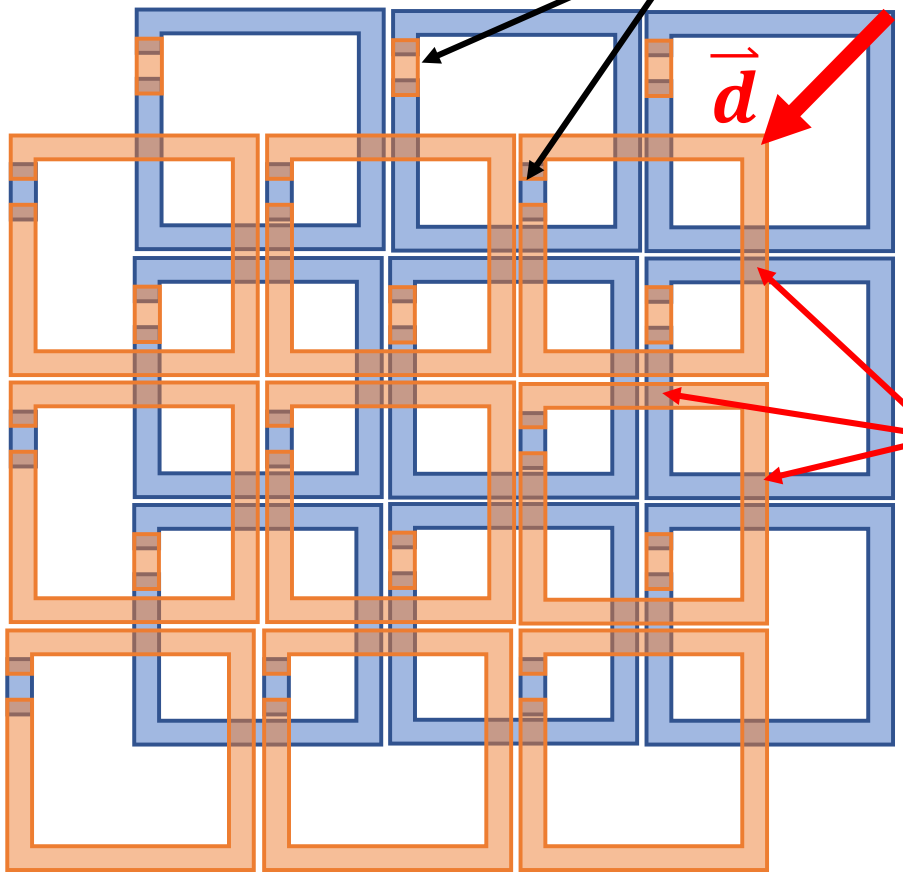
Josephson Junction Fabrication is Highly Constrained!

All JJs are fabricated on the base (orange) layer



The blue layer wiring is on top of the orange layer wiring

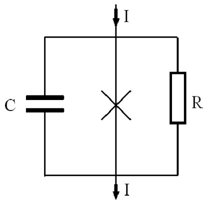
Note that large capacitors are formed where the blue layer wiring crosses the orange layer wiring

$$C_{ov}$$

Note that *dc currents* only flow through the blue or orange loops

***rf currents* can also flow <u>between</u> the blue and orange loops**

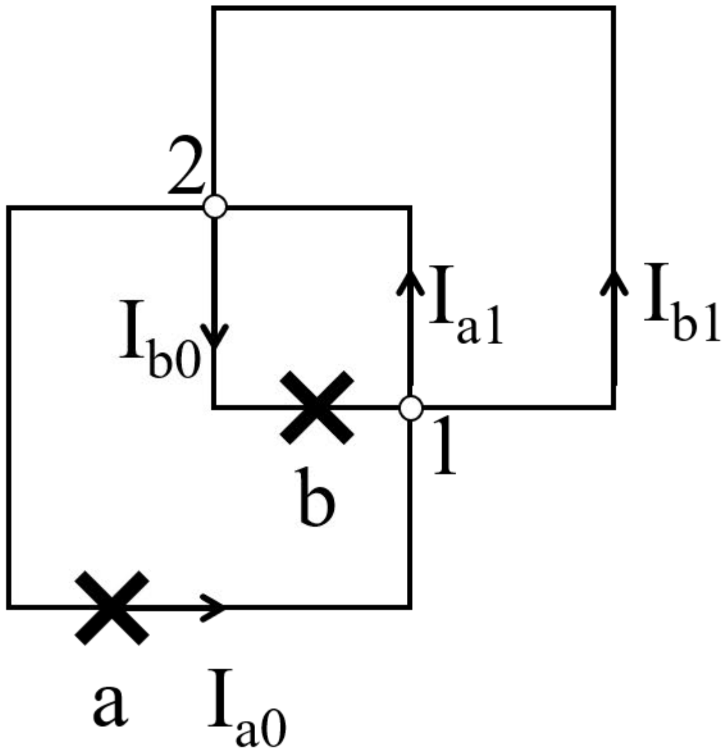
RCSJ

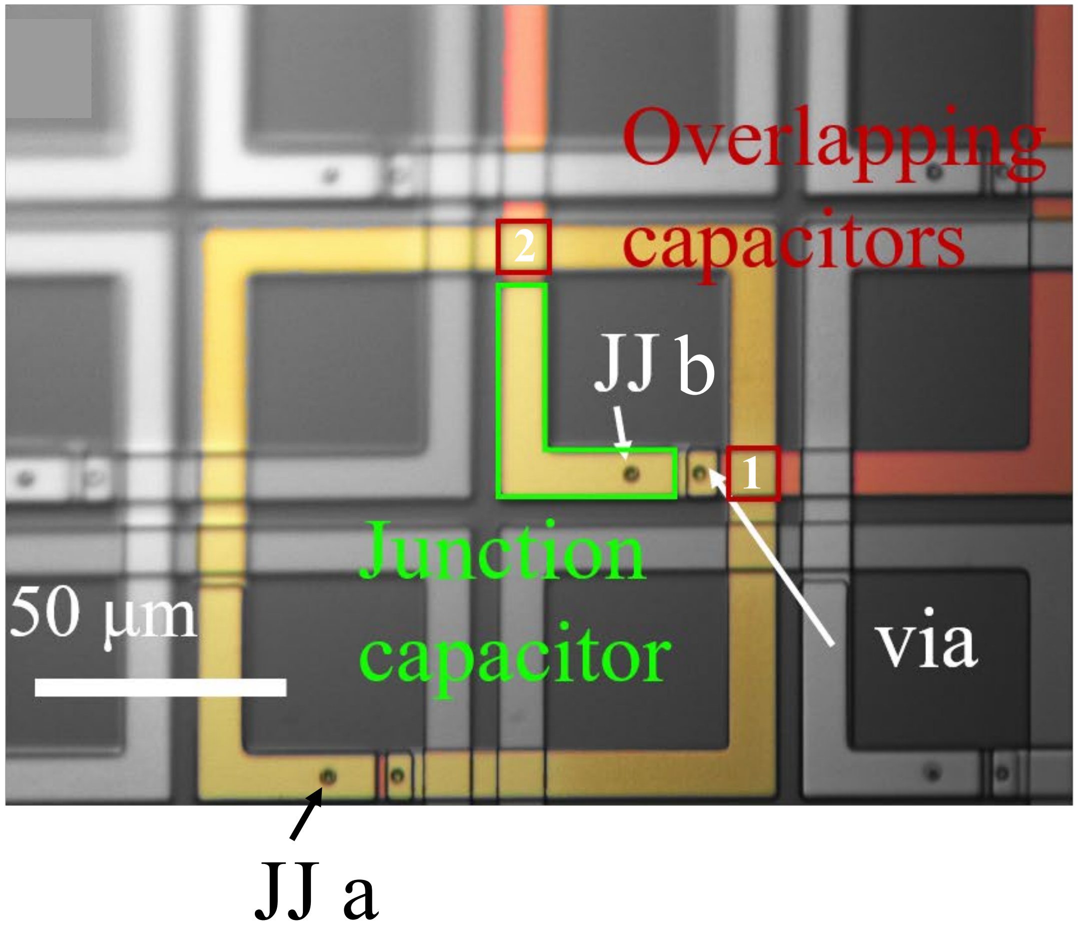


$C_{ov} \approx C$, **so the metamaterial dynamics are strongly altered!**

Overlapping SQUID geometry

Focus on a Corner-Coupled SQUID Pair





The JJs can only be fabricated on the base layer

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Single SQUID Equations for $\delta(t)$

Flux Quantization vs. Faraday's Law Approach

rf SQUID equation utilizing
flux quantization and RCSJ model for current

$$\Phi = \Phi_{app} + \Phi_{ind}$$

Total flux quantization: $2\pi n = \delta + \frac{2e}{\hbar}\Phi,$

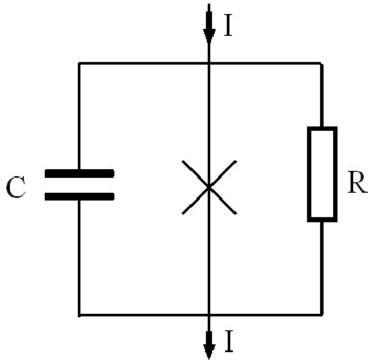
Combine and use the RCSJ model for $\Phi_{ind} = LI$:

$$\Phi_{dc} + \Phi_{rf}\sin\omega t = \frac{\Phi_0}{2\pi}\,\delta + L\left(I_c\ \sin\delta + \frac{\Phi_0}{2\pi}\frac{\dot{\delta}}{R} + C\frac{\Phi_0}{2\pi}\ddot{\delta}\right)$$

Second-order nonlinear differential equation for δ(t)

Voltage on the junction:

$$V = \frac{\Phi_0}{2\pi}\dot{\delta}$$

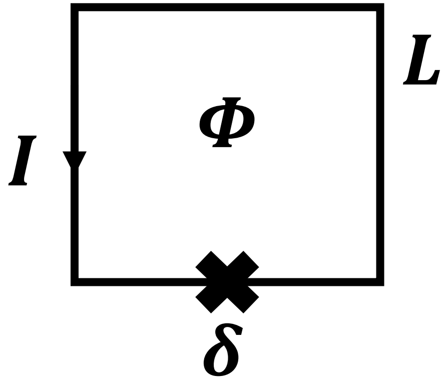


rf SQUID equation utilizing **Faraday's law**

$$V = \frac{d}{dt}\left(\Phi_{app} + \Phi_{ind}\right)$$

Faraday's law applied to a single SQUID results in the time-derivative of the rf SQUID equation

$$\frac{d}{dt}\left[\Phi_{dc} + \Phi_{rf}\sin\omega t\right] = \frac{d}{dt}\left[\frac{\Phi_0}{2\pi}\,\delta + L\left(I_c\ \sin\delta + \frac{\Phi_0}{2\pi}\frac{\dot{\delta}}{R} + C\frac{\Phi_0}{2\pi}\ddot{\delta}\right)\right]$$



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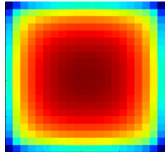


Two Corner-Coupled SQUID Equations

Faraday's Law / Voltage Approach

Now there are voltage drops in the SQUID loops that are not simply related to $\dot{\delta}$

2-SQUID flux relation: $\begin{pmatrix} \Phi_a^{app} \\ \Phi_b^{app} \end{pmatrix} = \frac{\Phi_0}{2\pi} \begin{pmatrix} \delta_a \\ \delta_b \end{pmatrix} + \begin{pmatrix} \Phi_a^{ind} \\ \Phi_b^{ind} \end{pmatrix}$

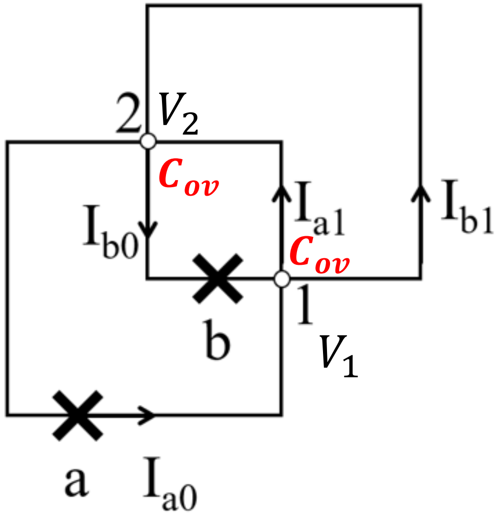
Apply Faraday's law to the central loop:

$$V_b - V_1 + V_2 = \frac{d}{dt}\left(\Phi_{cen}^{app} - \Phi_{cen}^{ind}\right)$$

where V_1 and V_2 are the voltages across the capacitors,
V_b is the voltage across junction b

Conservation of current through the overlap capacitors:

$$I_{a0} + I_{b0} = I_{a1} + I_{b1}$$
$$\dot{V}_1 = -\dot{V}_2$$



The flux relations become:

$$\begin{pmatrix} \Phi_{dc} + \Phi_{rf}\sin(\omega t) \\ \Phi_{dc} + \Phi_{rf}\sin(\omega t) \end{pmatrix} = \frac{\Phi_0}{2\pi}\begin{pmatrix} \delta_a \\ \delta_b \end{pmatrix} + \begin{pmatrix} L_{geo} & M \\ M & L_{geo} \end{pmatrix}\begin{pmatrix} I_{a0} \\ I_{b0} \end{pmatrix} + C_{ov}\begin{pmatrix} -L_{\delta a}\dot{V}_1 \\ L_{\delta b}\dot{V}_1 \end{pmatrix}$$

with

$$\dot{V}_1 = [(1+\kappa_{vb})\dot{V}_b + \kappa_{va}\dot{V}_a + L_{Ib}\ddot{I}_b + L_{Ia}\ddot{I}_a - \ddot{\Phi}_{cen}^{app} - \kappa_{va}\ddot{\Phi}_a^{app} - \kappa_{vb}\ddot{\Phi}_b^{app}]/2$$

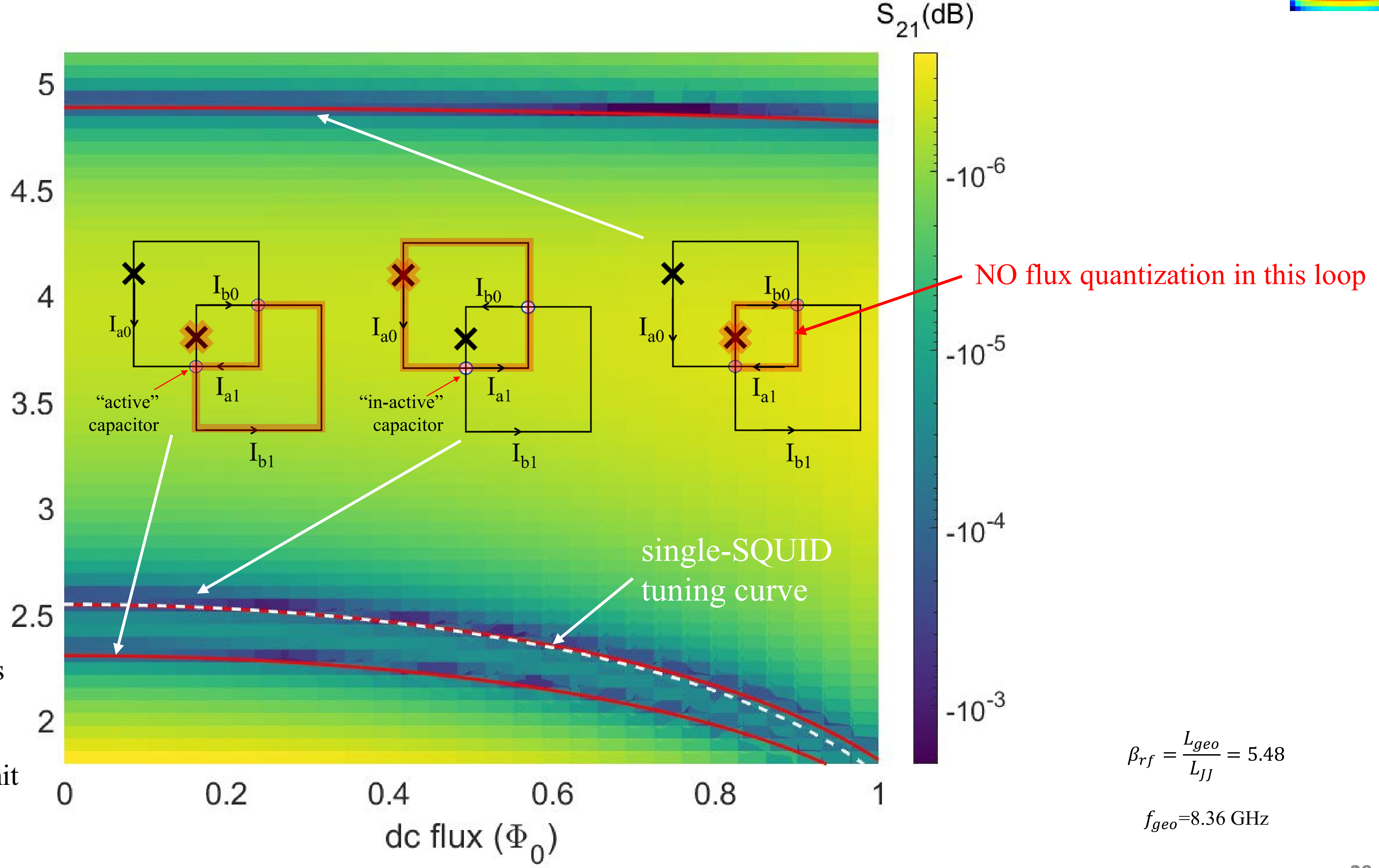
and $L_{\delta a}, L_{\delta b}$ are partial inductances

This is a pair of coupled 4th-order nonlinear equations for δ_a, δ_b.
These can be reduced to a set of 6 first-order equations (utilizing constraints)

Write $\delta = \delta_{dc} + \delta_{rf}\, e^{i\omega t}$, and linearize by assuming $|\delta_{rf}| \ll 1$, results in a characteristic equation for ω of 6th order, yielding 3 positive and 3 negative frequency solutions.

Resonant Modes of Two Corner-Coupled rf SQUIDs

$$\Omega = \frac{\omega}{\omega_{geo}}$$



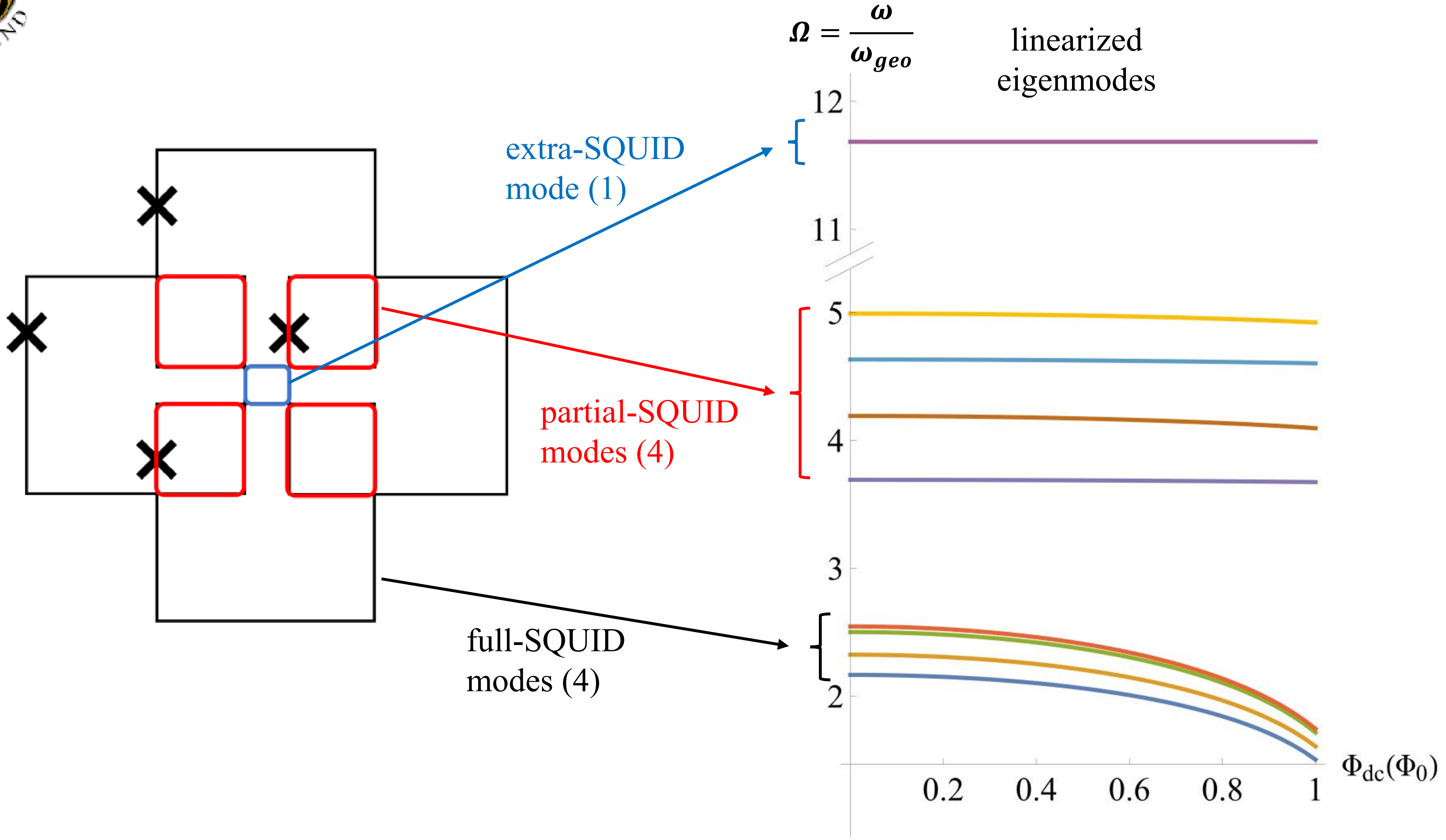
Red line: linearized solutions

Dark features: full nonlinear solution in the $\Phi_{rf} \ll 1$ limit

$\beta_{rf} = \frac{L_{geo}}{L_{JJ}} = 5.48$

f_{geo}=8.36 GHz

Resonant Modes of Four Corner-Coupled rf SQUIDs



https://doi.org/10.48550/arXiv.2402.07044

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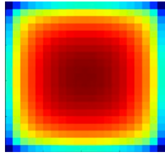
Resonant Modes of $N \times N \times 2$ Corner-Coupled rf SQUIDs



$2N^2$ SQUID loops

$(2N-1)^2$ partial loops

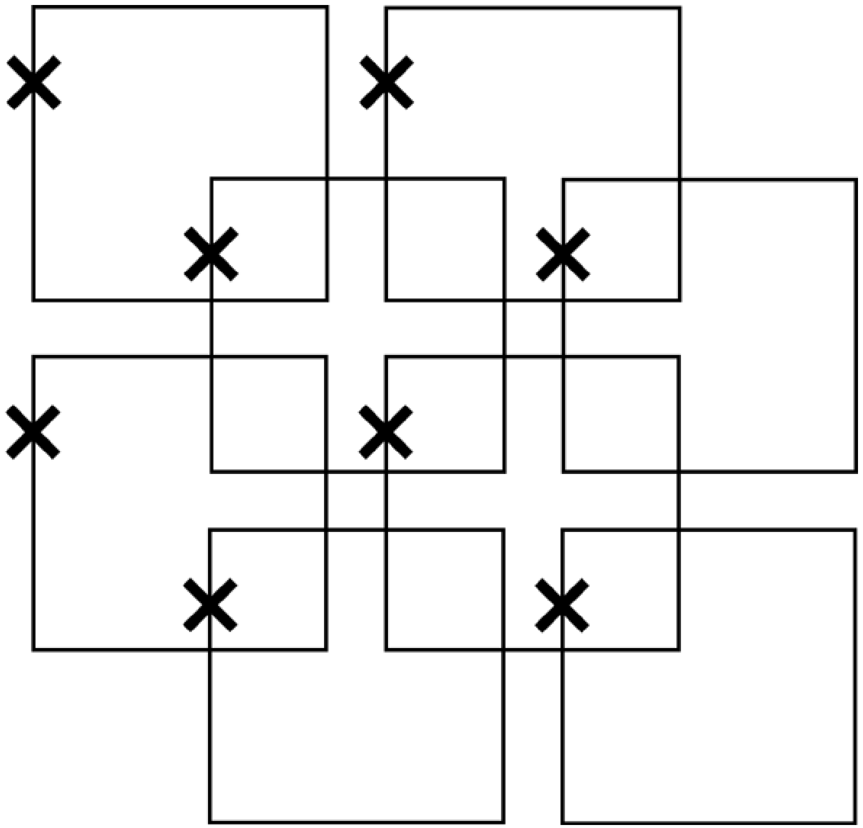
$2(N-1)^2$ extra SQUID loops

Total: $8N^2 - 8N + 3$

Gauge-invariant phase differences δ: $2N^2$

Each loop contributes one equation, giving a total number of equations: $8N^2 - 8N + 3$

There are a total of $8N^2 - 8N + 3$ unknowns, resulting in a **total number of modes**: $8N^2 - 8N + 3$

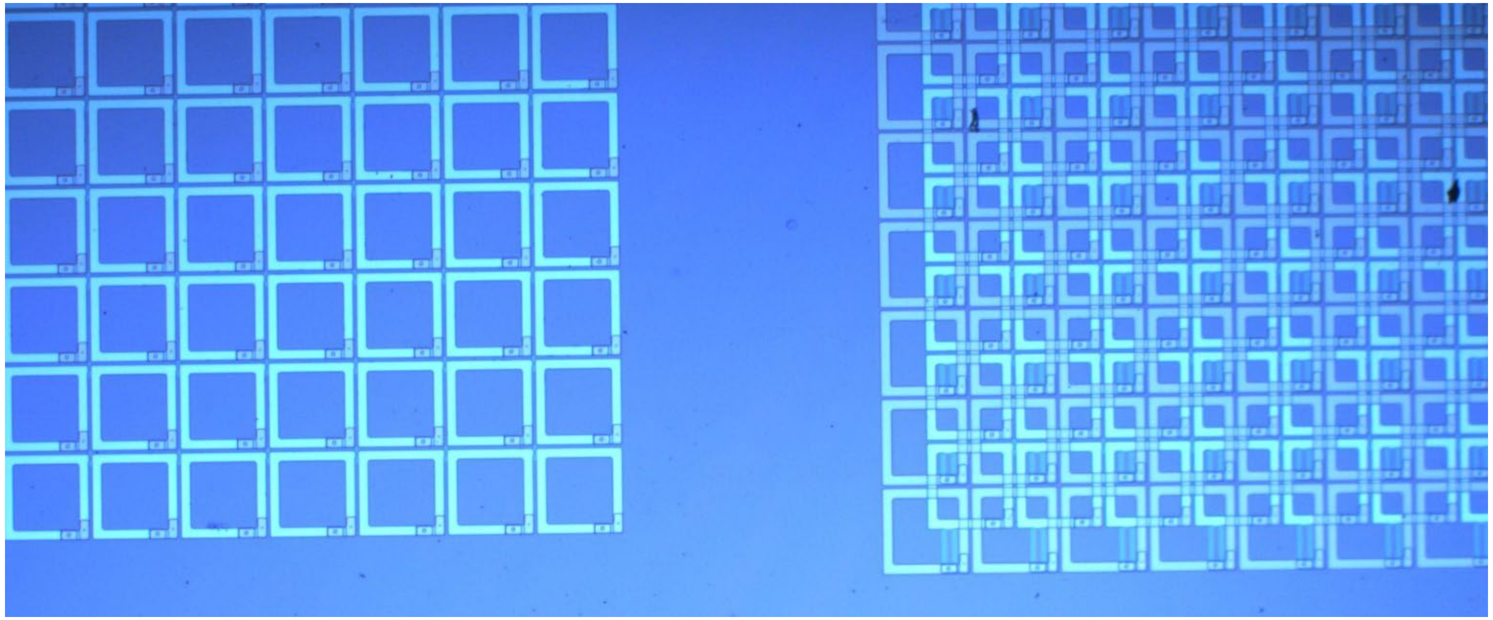


$N = 2$ case
19 modes

$N = 12$ case
1,059 modes

Next-Generation rf SQUID Metamaterials

Compare 2D and 3D samples made up of the same rf SQUIDs



Left: SNAP161D

12×12×1 rf SQUID array

β_{rf} = **5.48** @ 4.6K

f_{geo} = 8.82 GHz (for single SQUID)

f_{max} = 21.45 GHz (for single SQUID)

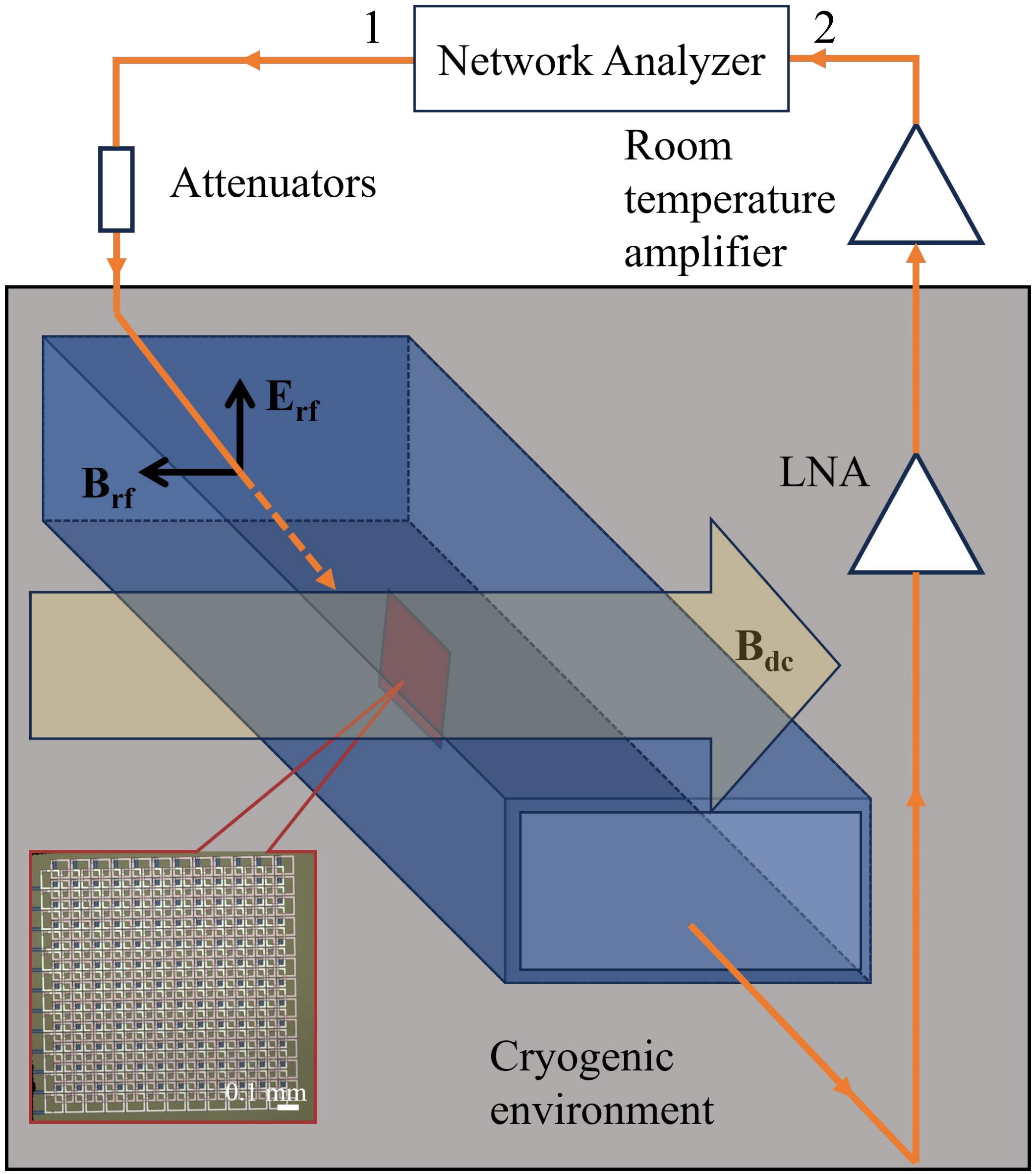
Right: SNAP161A

12×12×2 rf SQUID array

with the same SQUIDs as the one-layer sample

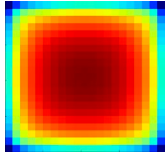
3D rf SQUID Metamaterial Transmission Measurement

The passing microwave signal provides the rf flux $\boldsymbol{\Phi_{rf}}$



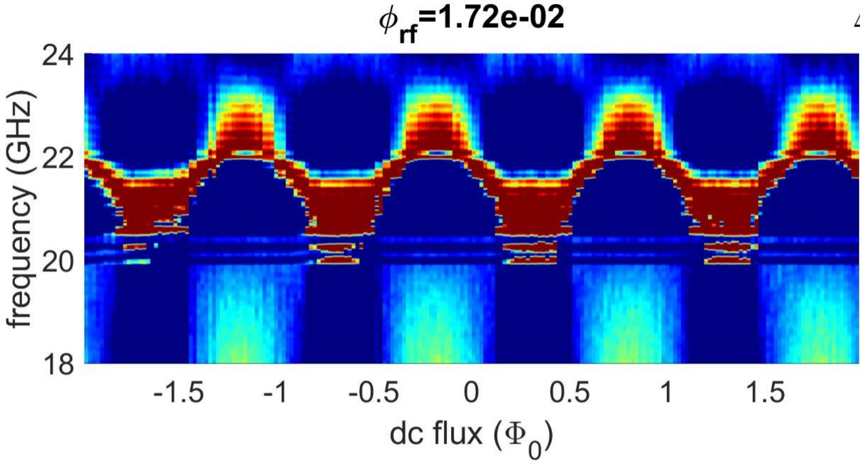
Measured quantity:
Transmission $\boldsymbol{S_{21}}$ vs $\boldsymbol{f}$

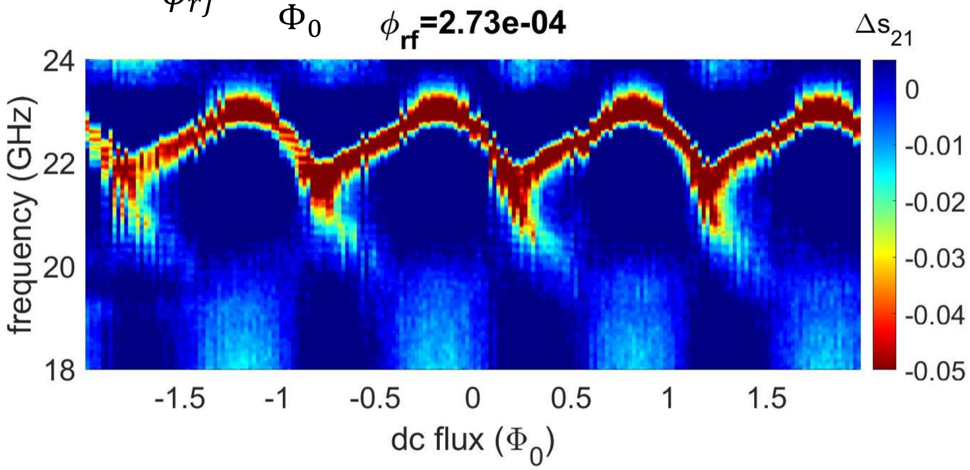
Variables:
dc magnetic flux $\boldsymbol{\Phi_{dc}}$
rf magnetic flux amplitude $\boldsymbol{\Phi_{rf}}$
Frequency of rf flux, $\boldsymbol{f}$
Temperature, $\boldsymbol{T}$

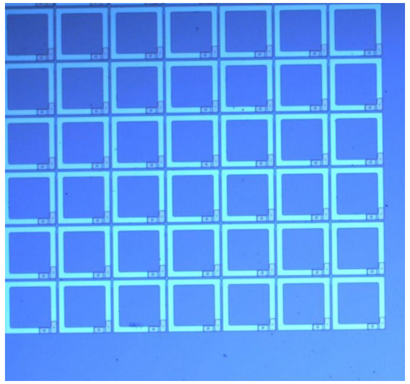


Single-layer SNAP161D rf Power Dependence

$$\phi_{rf} = \frac{\Phi_{rf}}{\Phi_0}$$







At low rf-flux we see the top of the tuning curve
- Asymmetric and hysteretic response with dc flux
- Simulations show loss of coherence on lower frequency branches

With increasing rf-flux
- Tuning curve pushed down toward f_{geo} = 8.82 GHz
- Increasingly symmetric and less hysteretic response with dc flux

β_{rf} = 5.48 @ 4.6K

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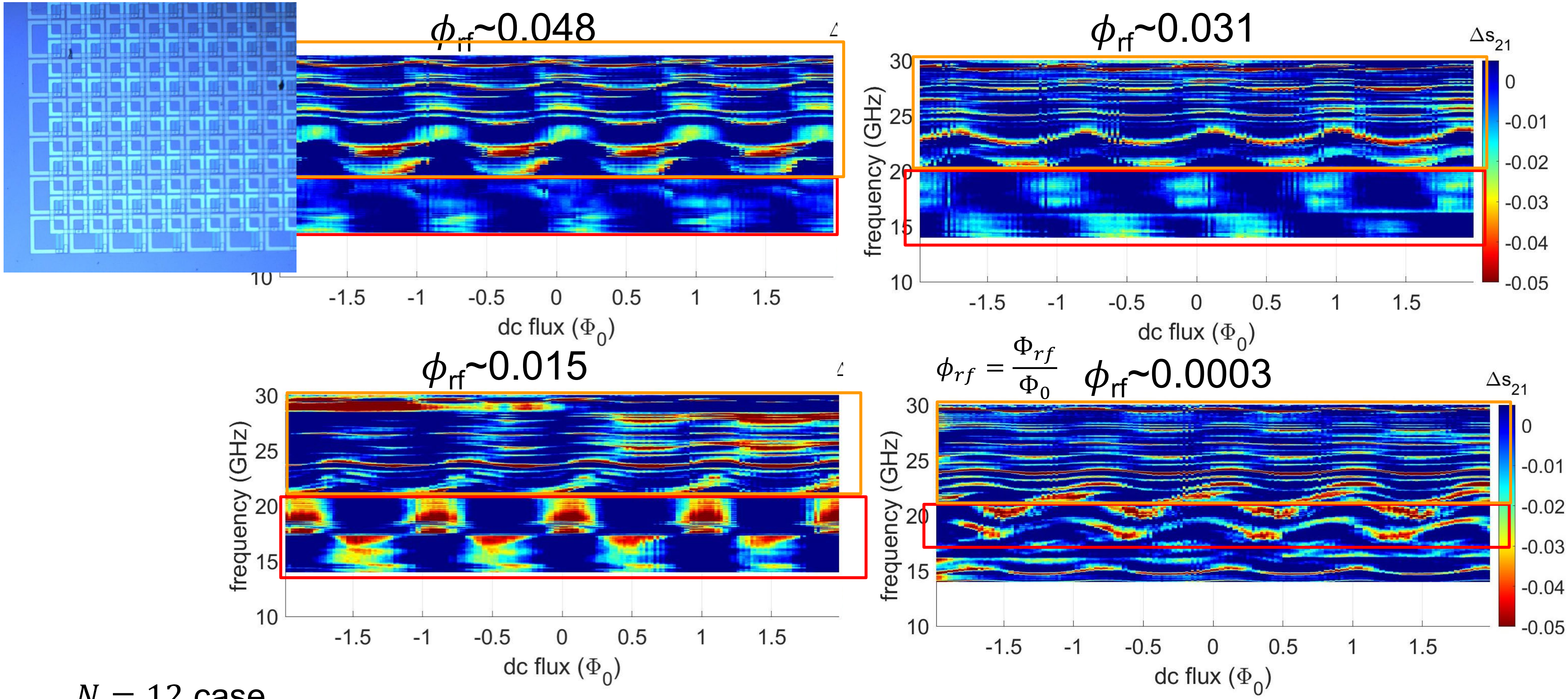
Two-layer 12×12×2 SNAP161A rf Power Dependence

Something qualitatively new happens!



$N = 12$ case
1.059 modes

The low-frequency bands show 1-Φ_0 tuning
Higher frequency bands show 0.93-Φ_0 tuning

https://doi.org/10.48550/arXiv.2402.07044

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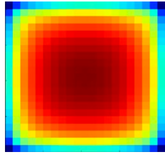
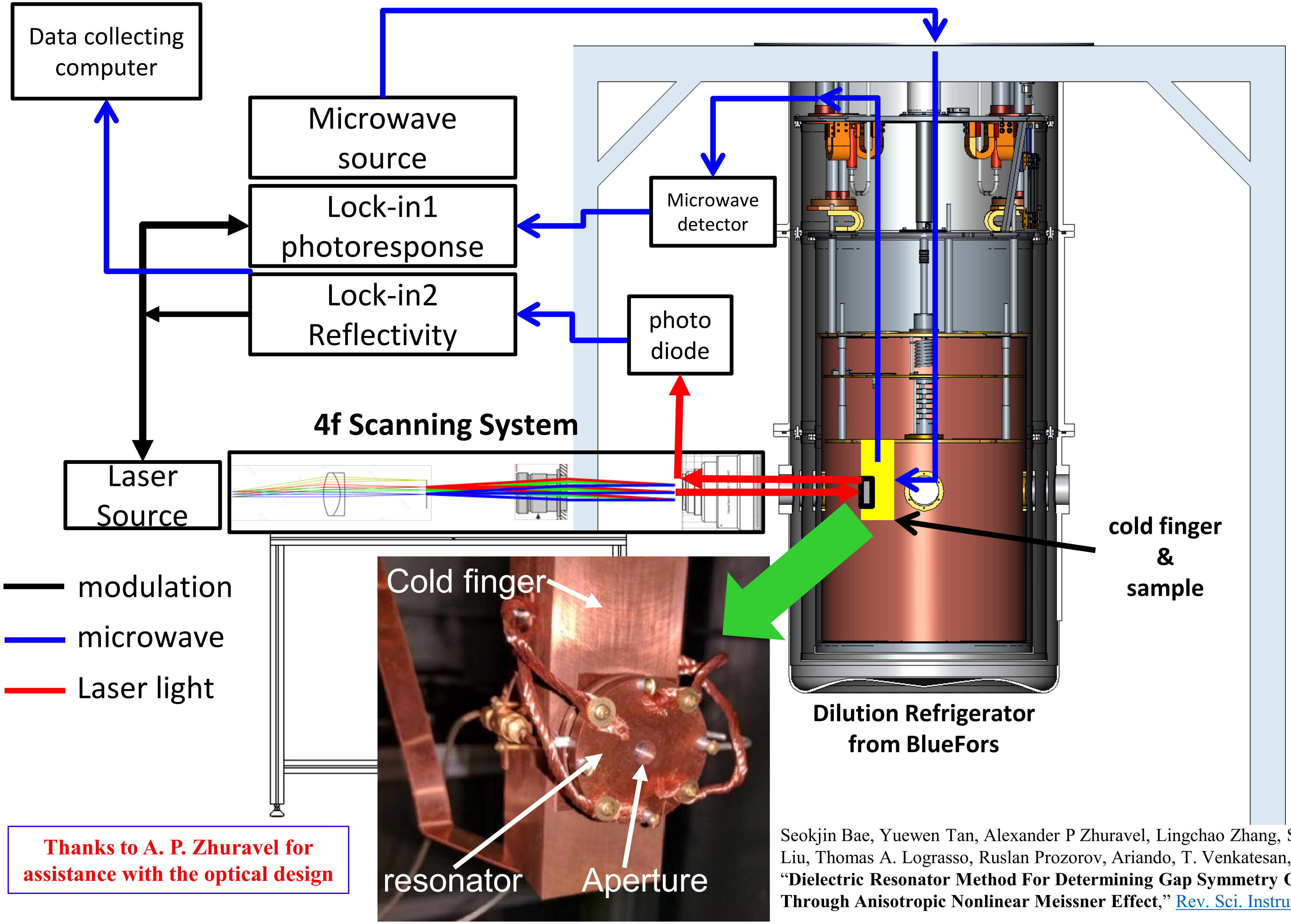
- 3D Stacked rf SQUID Metamaterials
    - The Role of Capacitive Coupling
- Current / Future Work
- Conclusions

Laser scanning microscope combined with dilution fridge





Thanks to A. P. Zhuravel for assistance with the optical design

Seokjin Bae, Yuewen Tan, Alexander P Zhuravel, Lingchao Zhang, Shengwei Zeng, Yong Liu, Thomas A. Lograsso, Ruslan Prozorov, Ariando, T. Venkatesan, Steven M. Anlage, "**Dielectric Resonator Method For Determining Gap Symmetry Of Superconductors Through Anisotropic Nonlinear Meissner Effect**," Rev. Sci. Instrum. 90, 043901 (2019)

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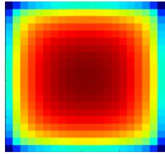


Phase-Sensitive LSM Imaging

A. P. Zhuravel, Verkin ILTPE Kharkiv, Ukraine

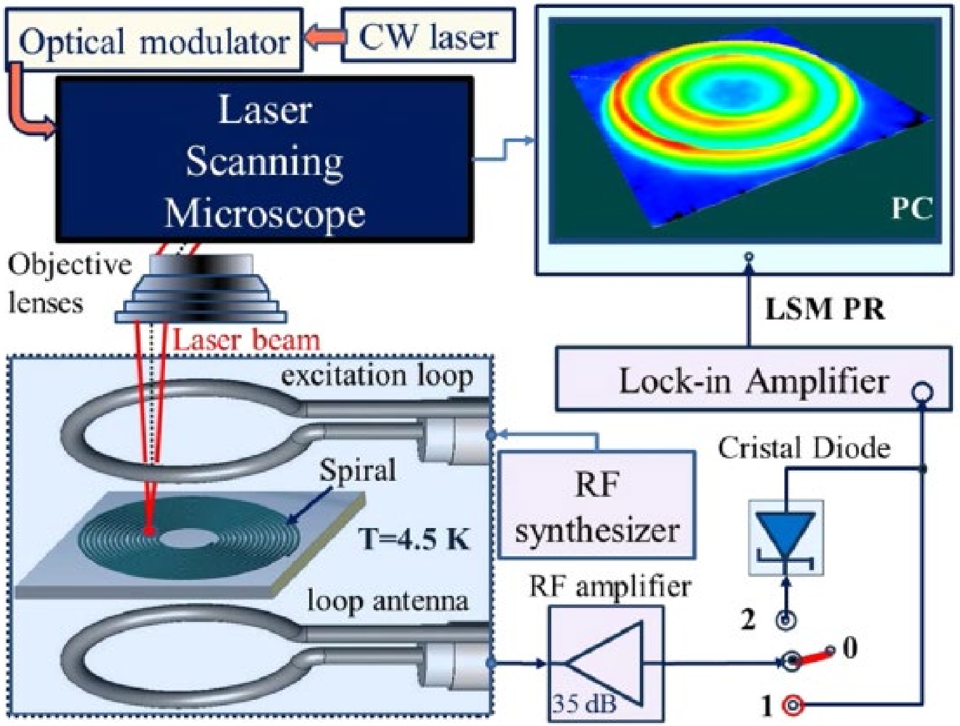
Low Temperature Physics ARTICLE scitation.org/journal/ltp

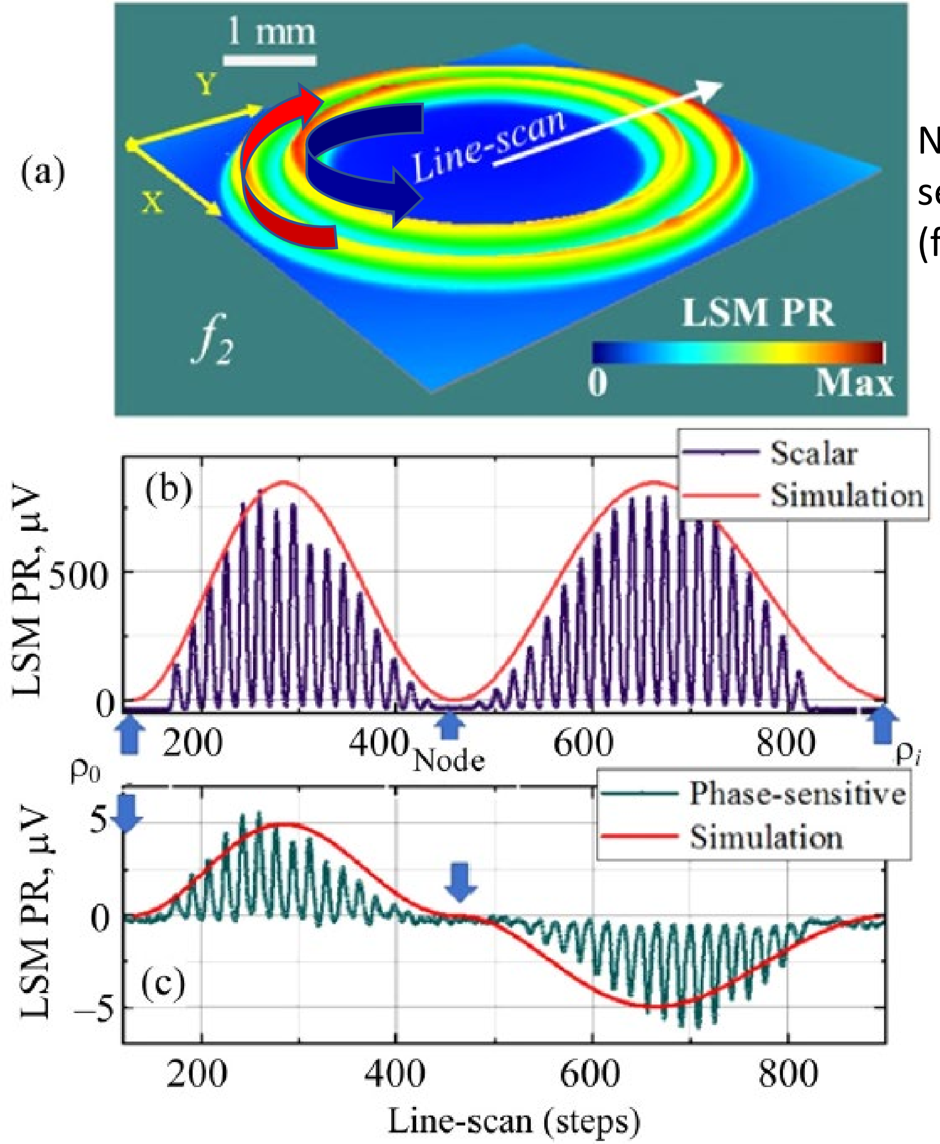
Phase-resolved visualization of radio-frequency standing waves in superconducting spiral resonator for metamaterial applications

Cite as: Fiz. Nizk. Temp. **48**, 119–128 (February 2022); doi: 10.1063/10.0009288
Submitted: 21 December 2021

View Online Export Citation

A. A. Leha,[1] A. P. Zhuravel,[1,a)] A. Karpov,[2] A. V. Lukashenko,[3] and A. V. Ustinov[2,3]



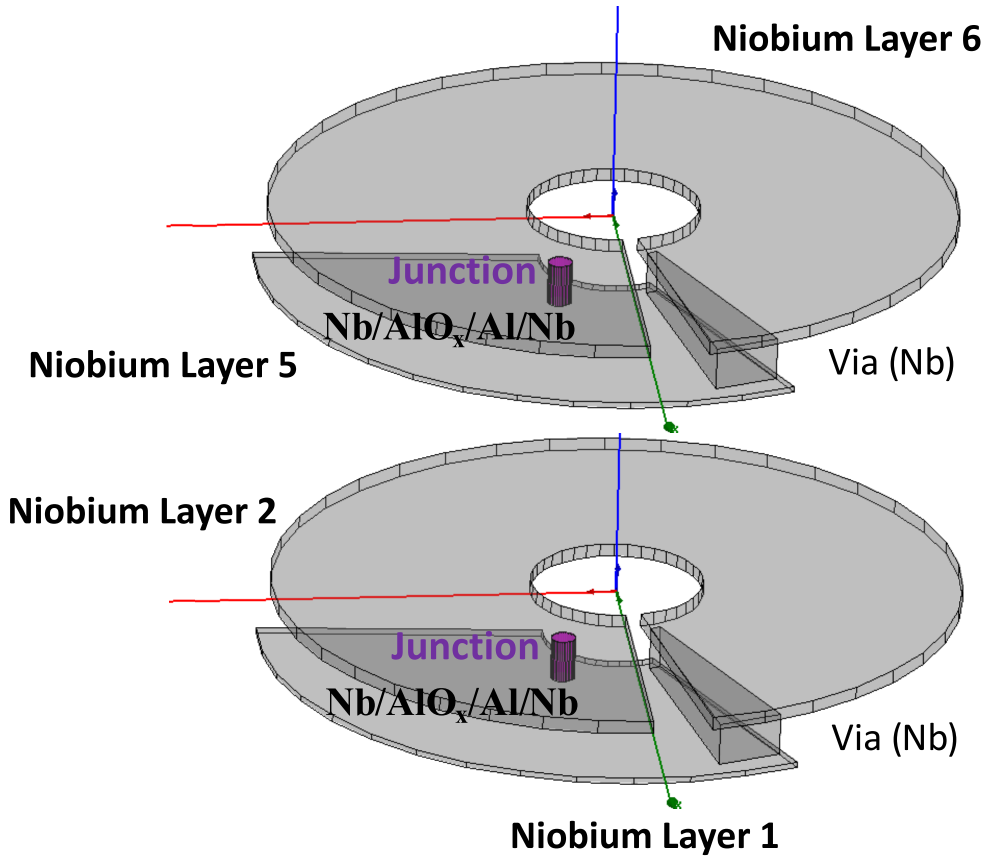


Nb spiral at 4.5 K second harmonic (f_2 = 220 MHz)

Extend to the 1-20 GHz range and apply to rf SQUID metamaterials

Question for the Audience

Can any fabrication process in the world create Josephson junctions on completely independent layers?



Conclusions

- Macroscopic Quantum rf SQUID meta-atoms and metamaterials show transparency, bi-stability, intermodulation, strongly nonlinear response
- Coherence of rf SQUID metamaterials is enhanced by strong coupling and nonlinearity
- Imaging “dark modes” and the suppression of disorder to recover coherent response
- Next-generation 3D rf SQUID metamaterials have a large number of modes!
- rf SQUID metamaterials are a rich nonlinear medium

Thanks for your attention!

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In Memoriam

Alexander P. Zhuravel

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(1953-2023)

1998 NATO Collaborative Linkage grant

The Co-PIs, Prof. Steven Anlage of the University of Maryland (left) and Dr. Alexander Zhuravel' of the Verkin Institute of Low Temperature Physics and Engineering, Kharkov, Ukraine (right). The picture is taken in Prof. Anlage's laboratory at the University of Maryland, Center for Superconductivity Research, and Physics Department. The scanning laser microscope is to the right of Dr. Zhuravel', while the equipment racks are behind him.

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