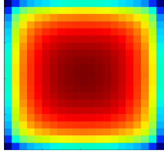
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 4-ND-I-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.



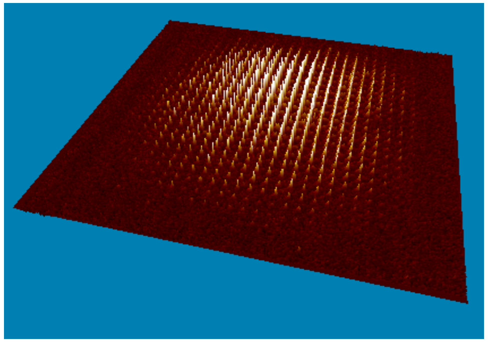
rf SQUID Metamaterials: A Rich Nonlinear Setting for Applications

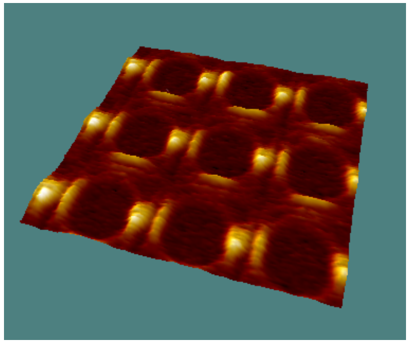
Jingnan Cai, Seokjin Bae, Steven M. Anlage

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)

ISEC2019
July 28 - August 1, 2019

International Superconducting Electronics Conference
28 July – 1 August, 2019
Riverside, CA USA





CNAM Center for Nanophysics and Advanced Materials

DEPARTMENT OF PHYSICS
UNIVERSITY OF MARYLAND

1 August, 2019

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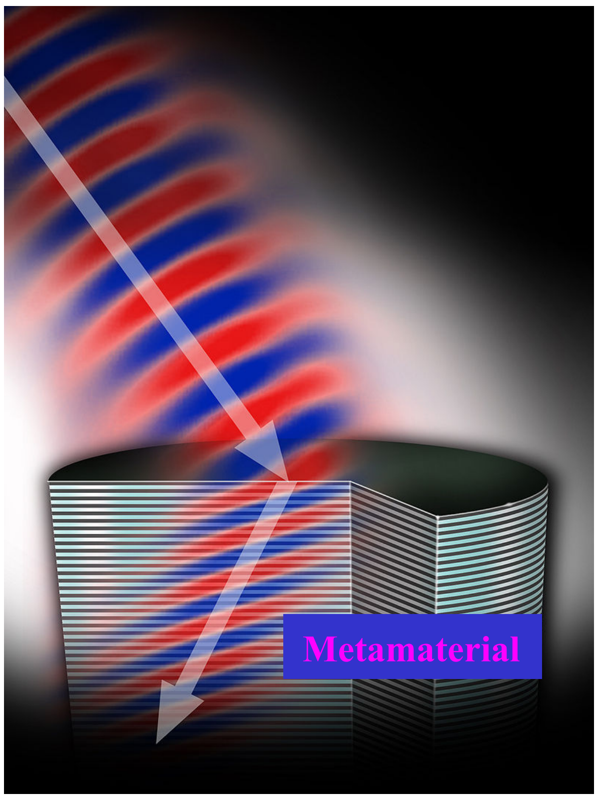
Motivation and Background

Metamaterials:

Artificial Structures with New or Extreme Properties

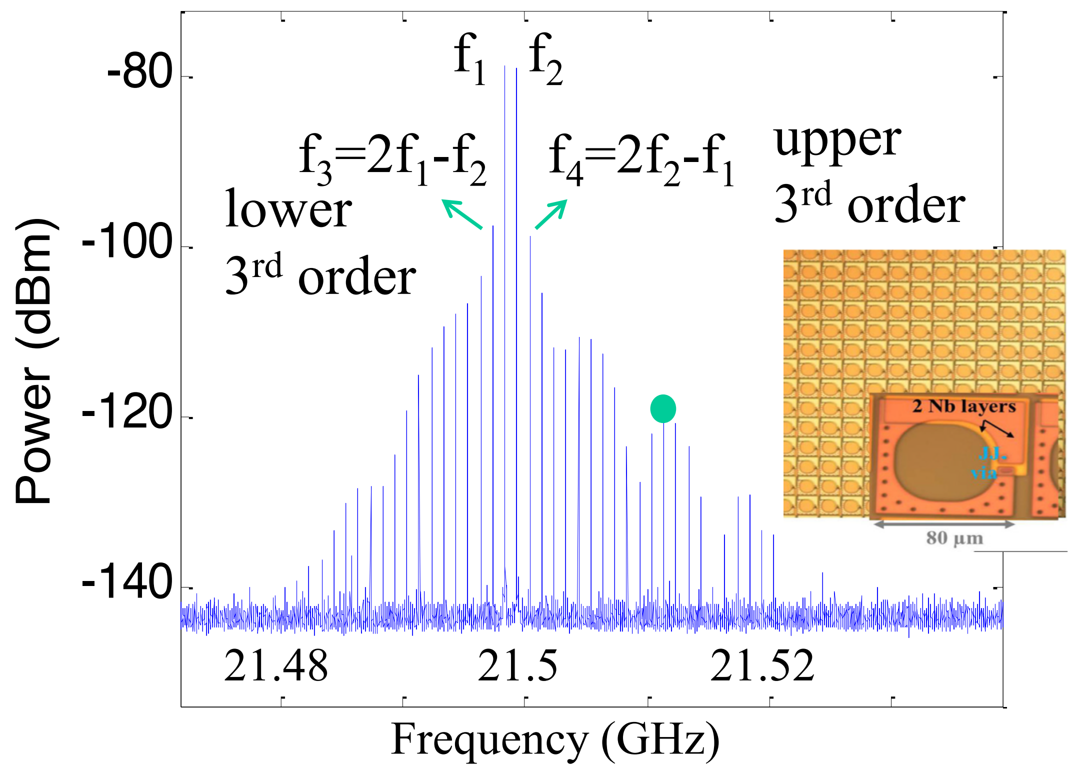
Negative Refraction



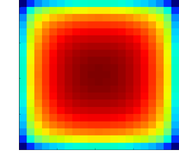
https://en.wikipedia.org/wiki/Negative-index_metamaterial

Extreme Nonlinearity

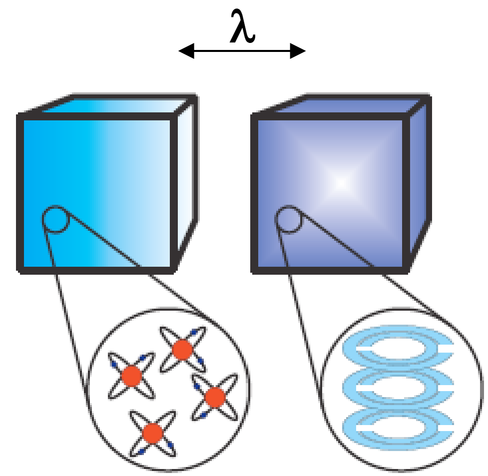
Intermodulation in a superconducting metamaterial



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. …

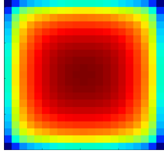
… have strict REQUIREMENTS on the metamaterials:

- 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)



Outline

Motivation and Background

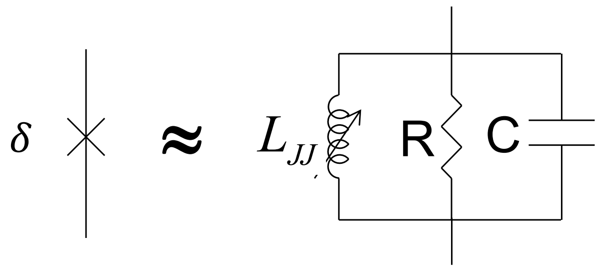
➡ **rf SQUID Metamaterials**

- **"Auto-cloaking"**
- **Intermodulation**
- **Imaging "Dark" Modes**

Conclusions

rf SQUID Meta-Atoms

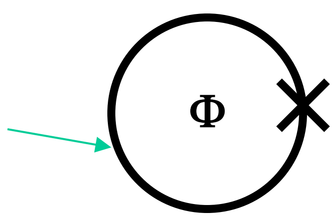
Josephson Inductance is large, tunable and nonlinear



Resistively and Capacitively Shunted Junction (RCSJ) Model

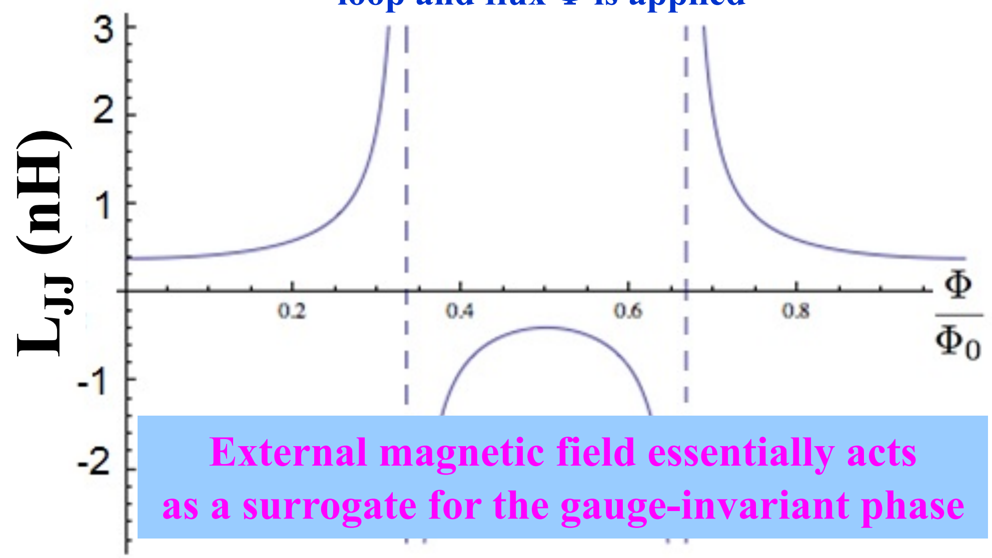
$$L_{JJ} = \frac{\Phi_0}{2\pi I_c \cos(\delta)}$$

The "third Josephson effect"



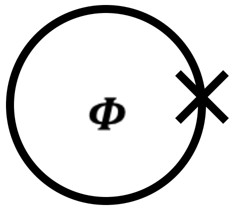
Combines the Josephson effects with flux quantization

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

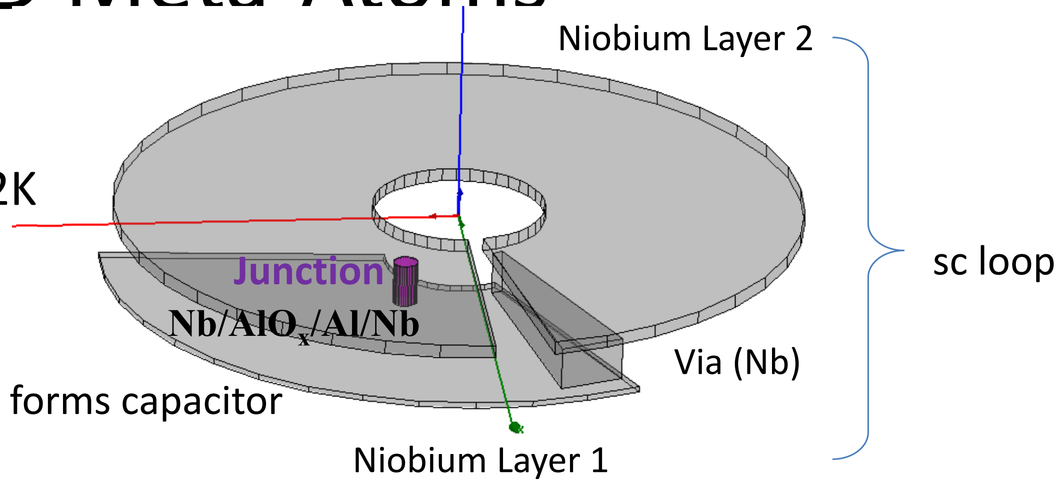


rf SQUID Meta-Atoms

rf SQUID

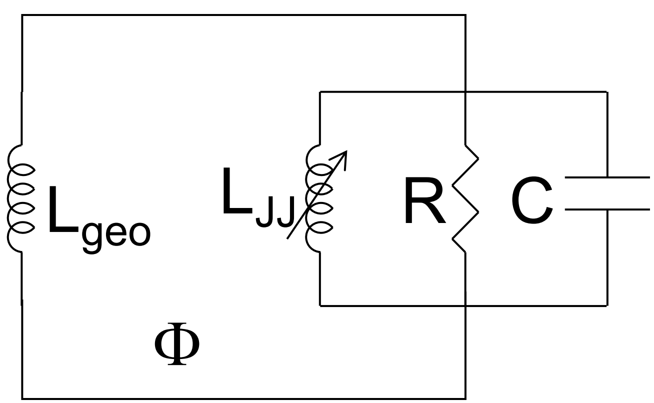


A 'Macroscopic Quantum' Split-Ring Resonator

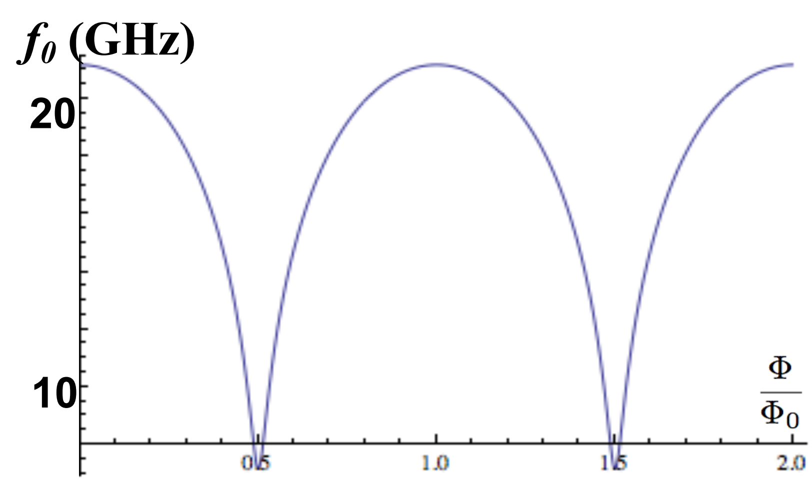


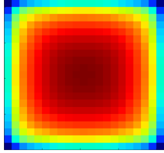
SQUID = **S**uperconducting **QU**antum **I**nterference **D**evice

A self-resonant meta-atom with very nonlinear properties



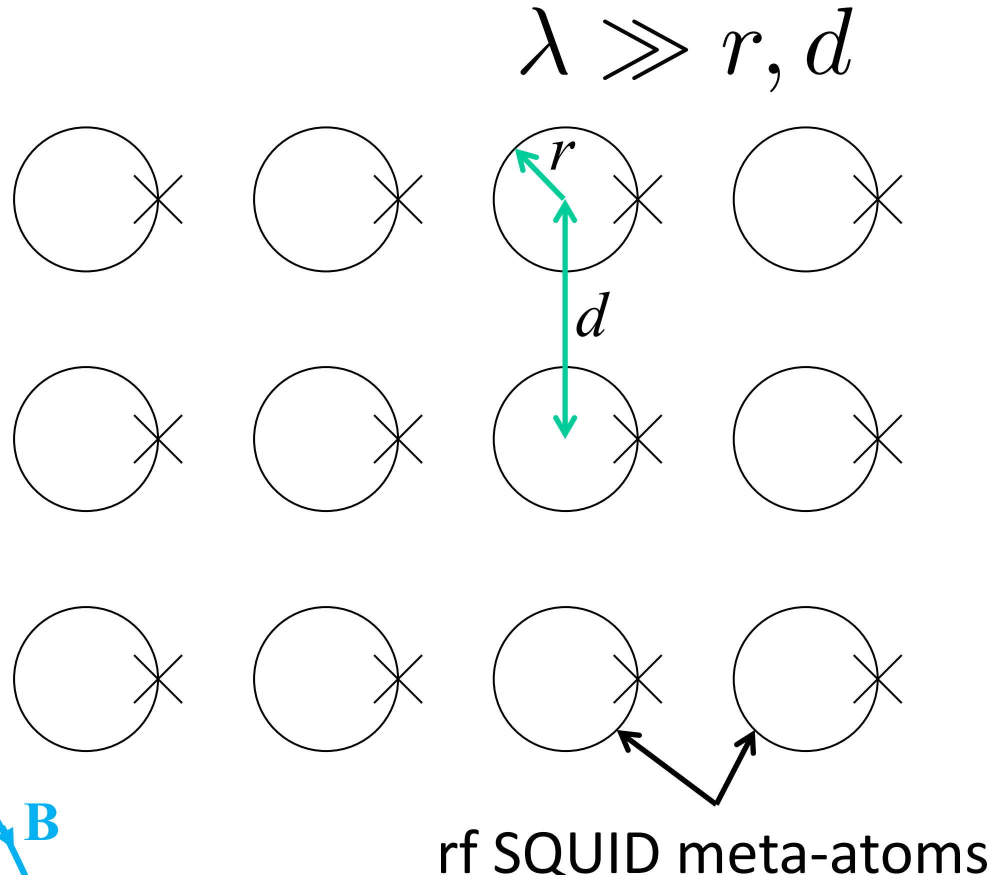
Resonant Frequency of rf SQUID

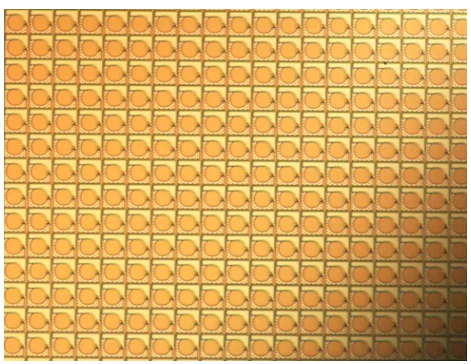


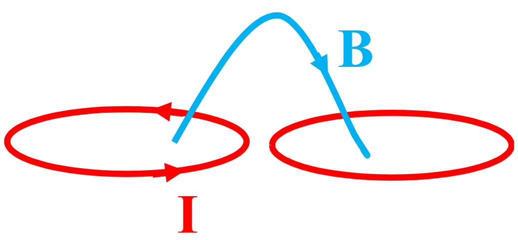


rf SQUID Superconducting Metamaterial

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







The SQUIDs interact by means of dipole – dipole coupling

→ Collective Behavior

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

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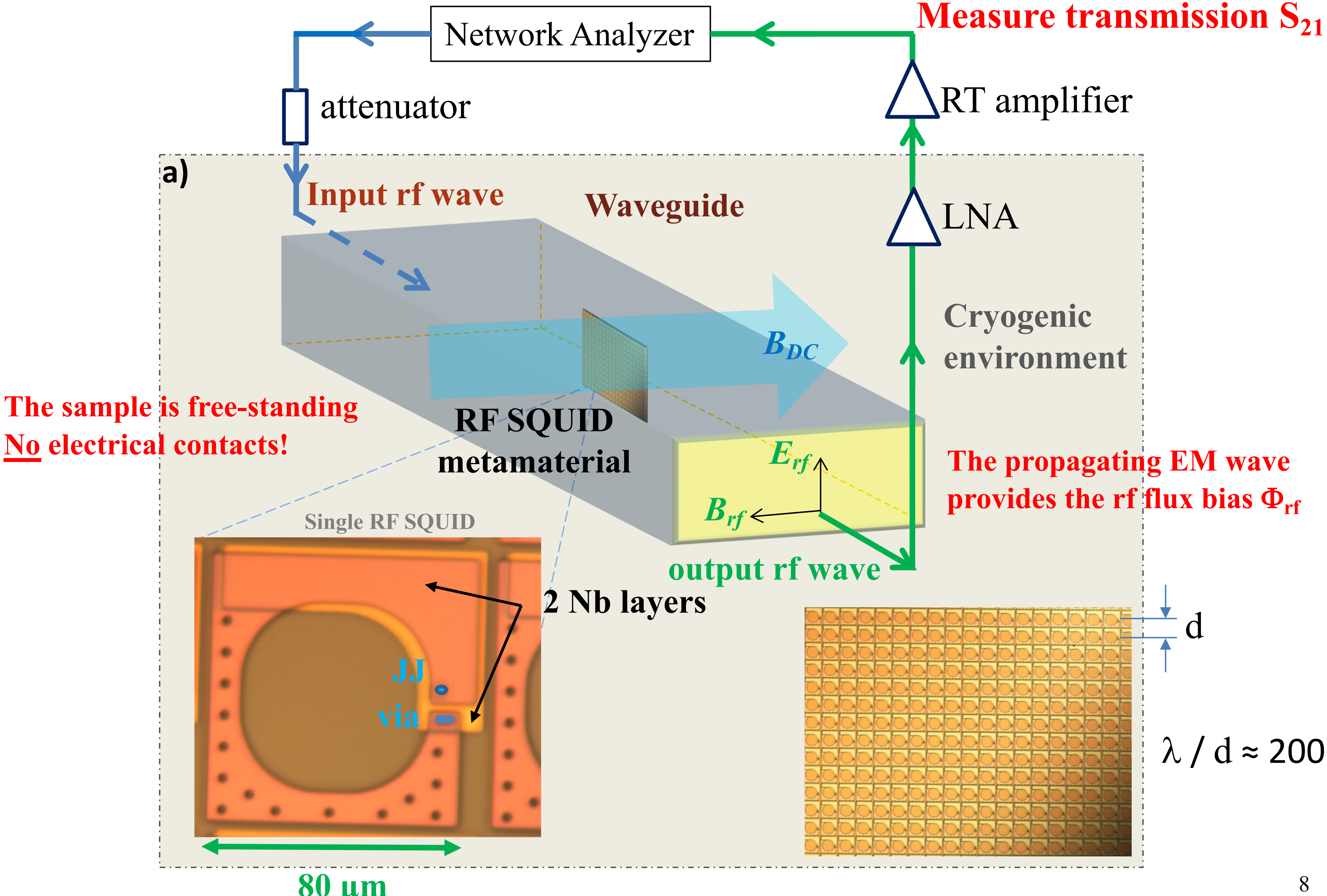
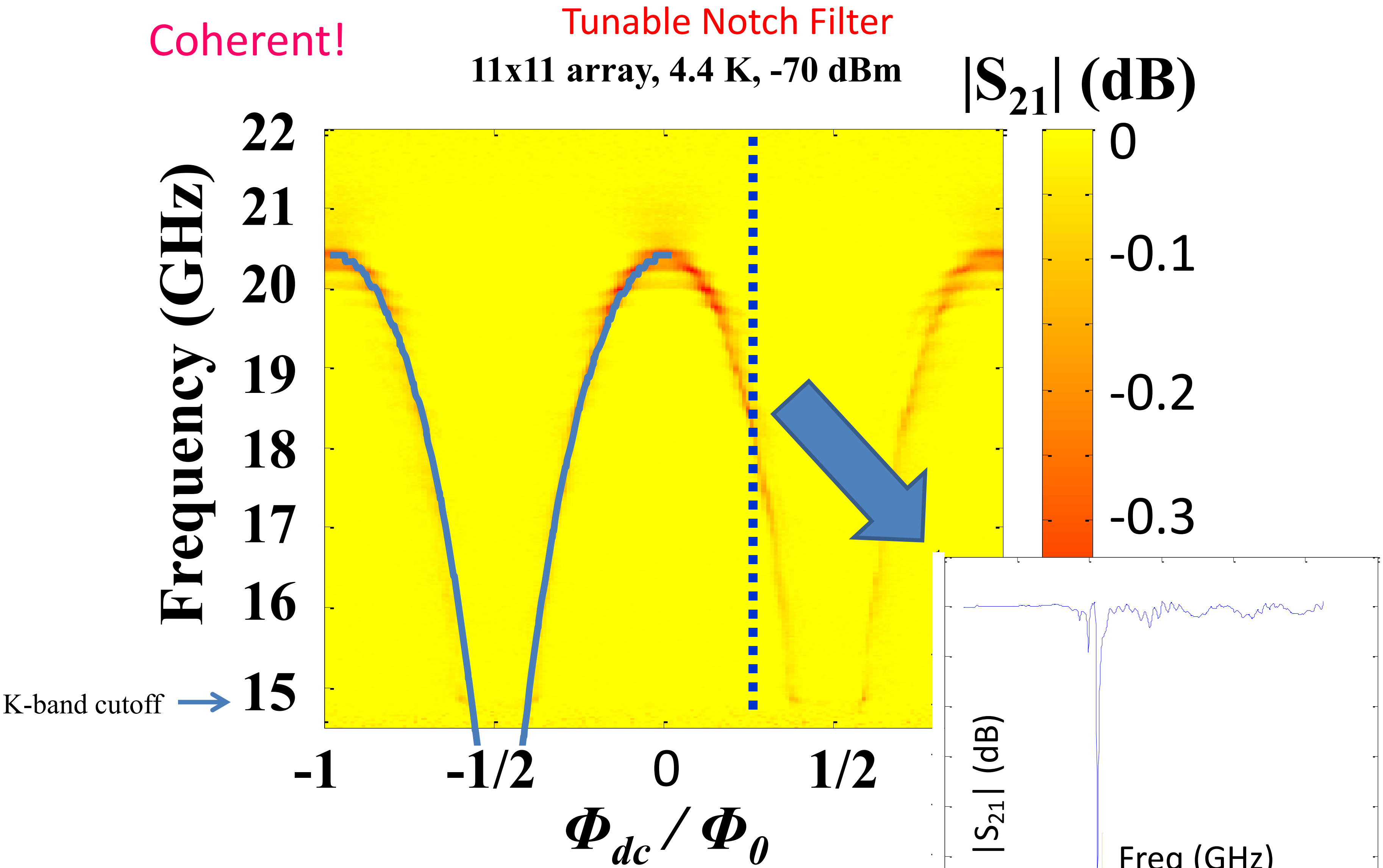
Measurement of rf SQUID Metamaterial



DC magnetic flux tuned resonance



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

Why Nonlinear Metamaterials?

Tunability – Change the properties of the metamaterial after it has been fabricated – improved design flexibility

Nonlinear response – the metamaterial 'looks' different when probed at different intensity/power, frequency, direction, etc.

Engineer enhanced coupling to EM fields

Self-induced nonlinear response

Some examples:

Tunable band-pass filter

Power limiters

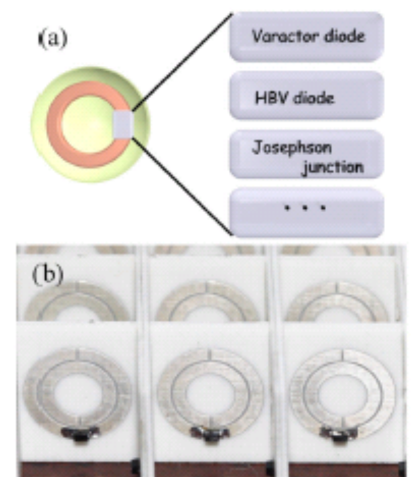
Nonlinear gain media

Colloquium: Nonlinear metamaterials

Mikhail Lapine

Rev. Mod. Phys., Vol. 86, No. 3, July–September 2014

Ilya V. Shadrivov and Yuri S. Kivshar



Outline

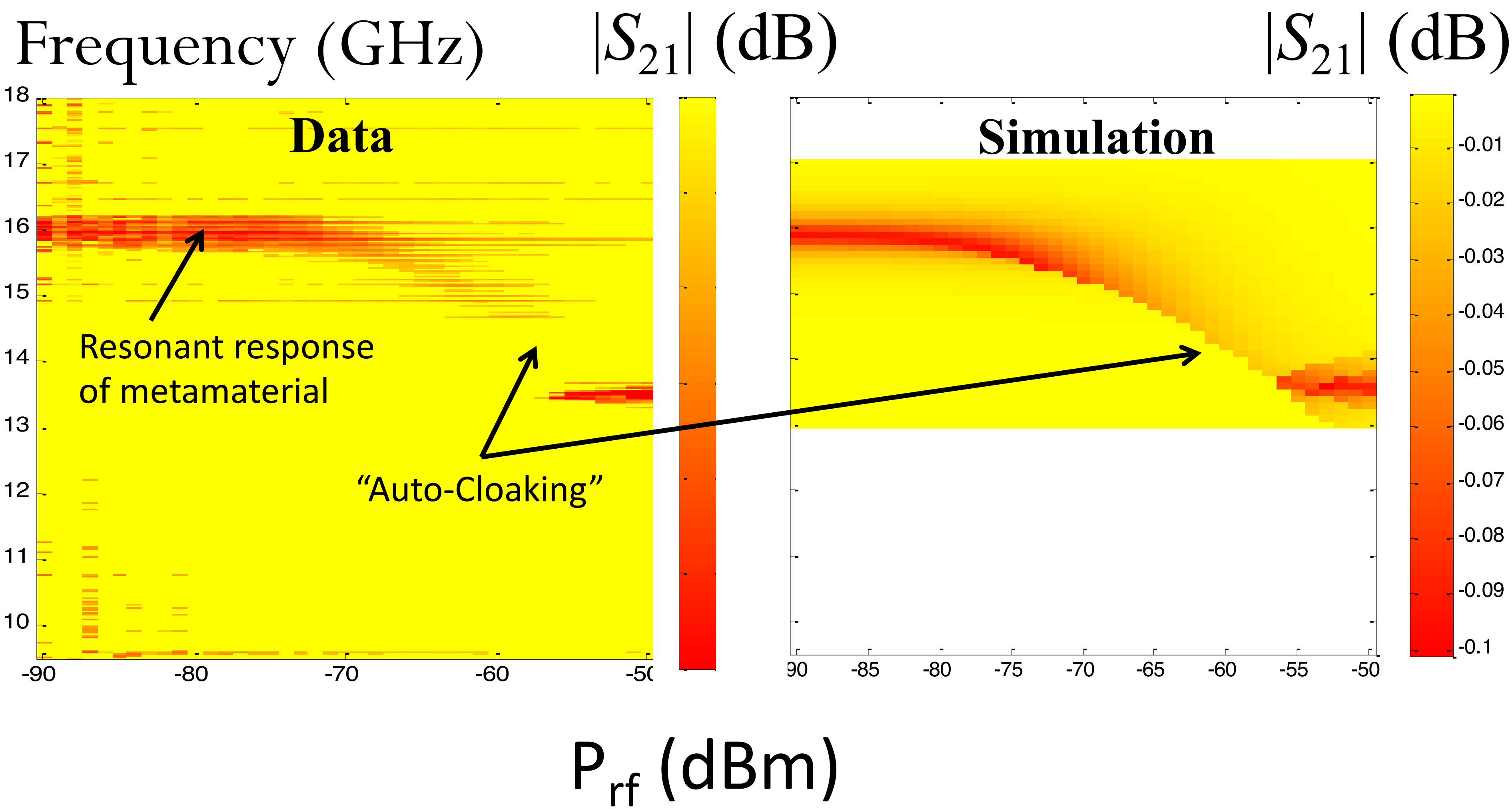
Motivation and Background

rf SQUID Metamaterials

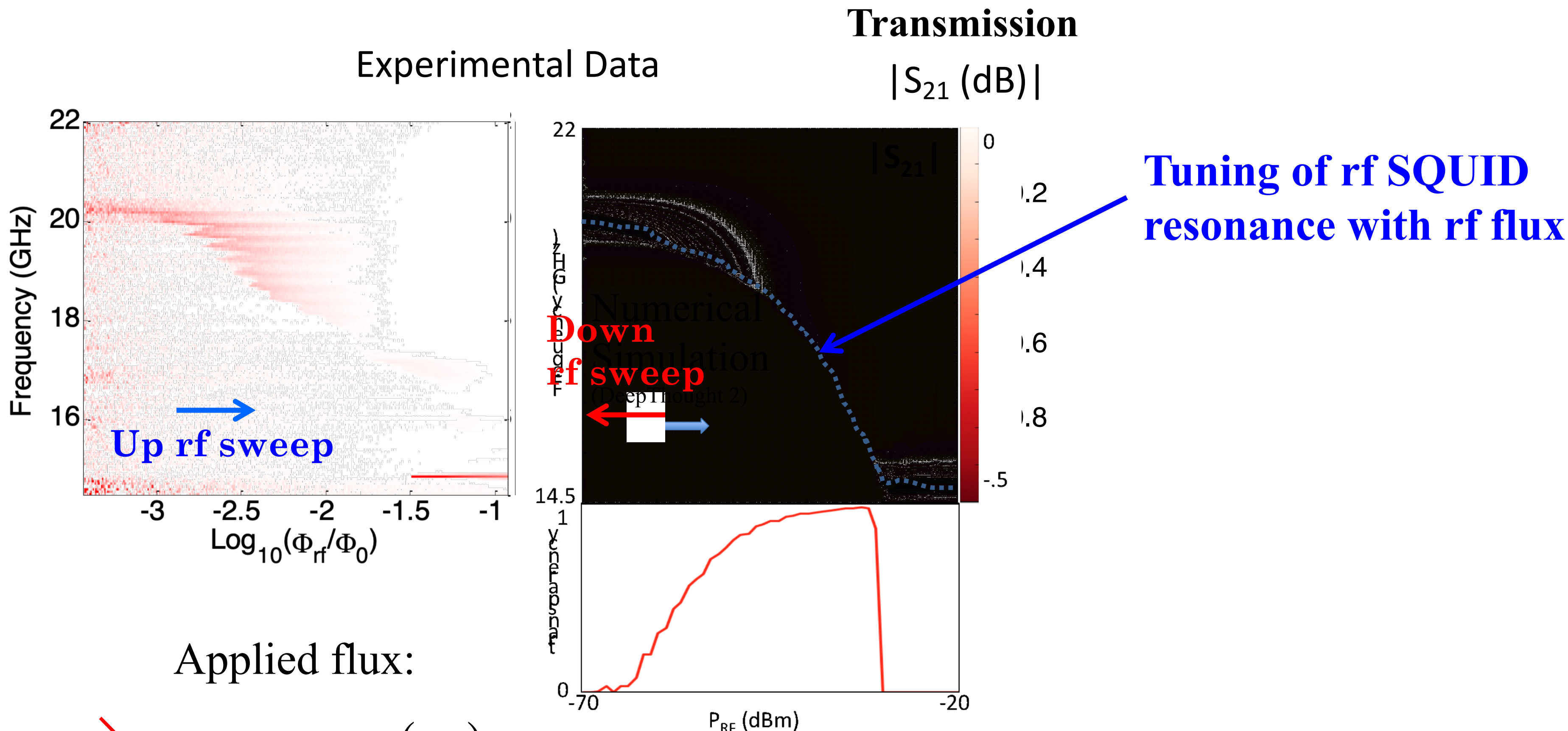
- **"Auto-cloaking"**
- **Intermodulation**
- **Imaging "Dark" Modes**

Conclusions

Observation of Near-Transparency for a single rf-SQUID



Tuning of Resonant Response with rf Flux: 11x11 SQUID array Metamaterial



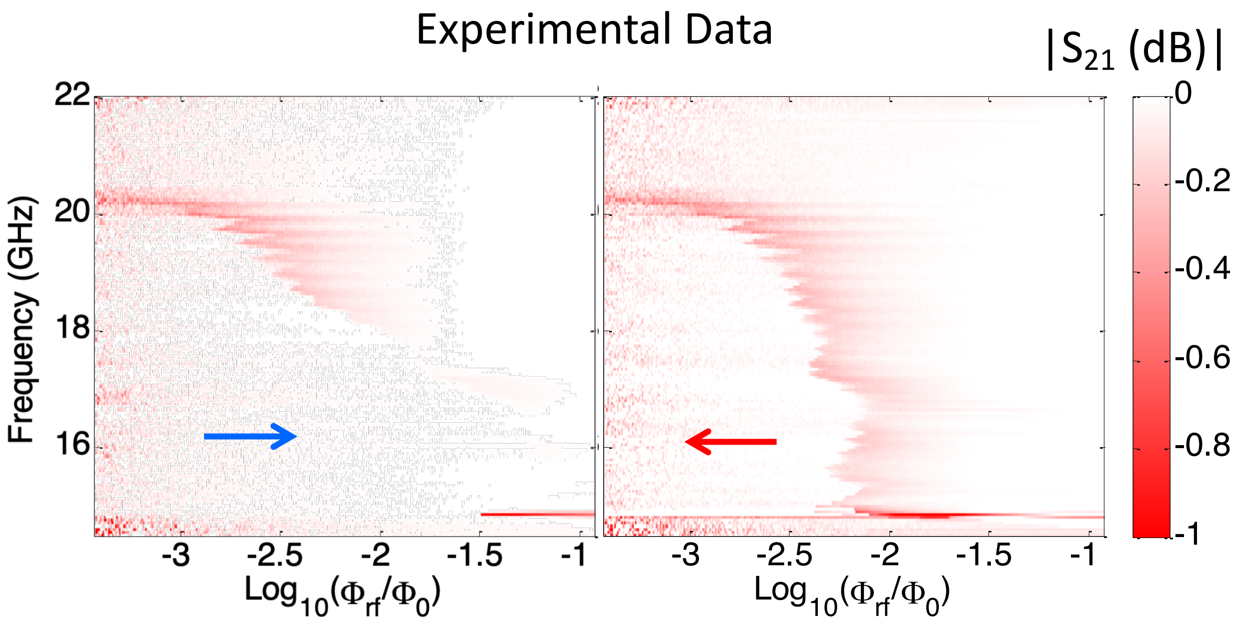
Applied flux:

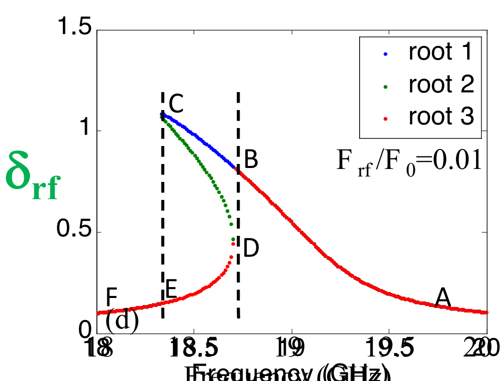
$$\Phi_{DC} + \Phi_{rf}\sin(\omega t)$$

≈ 0

D. Zhang, *et al.*, Phys. Rev. X 5, 041045 (2015)

Bi-Stability of Transparency of an 11x11 SQUID array Metamaterial



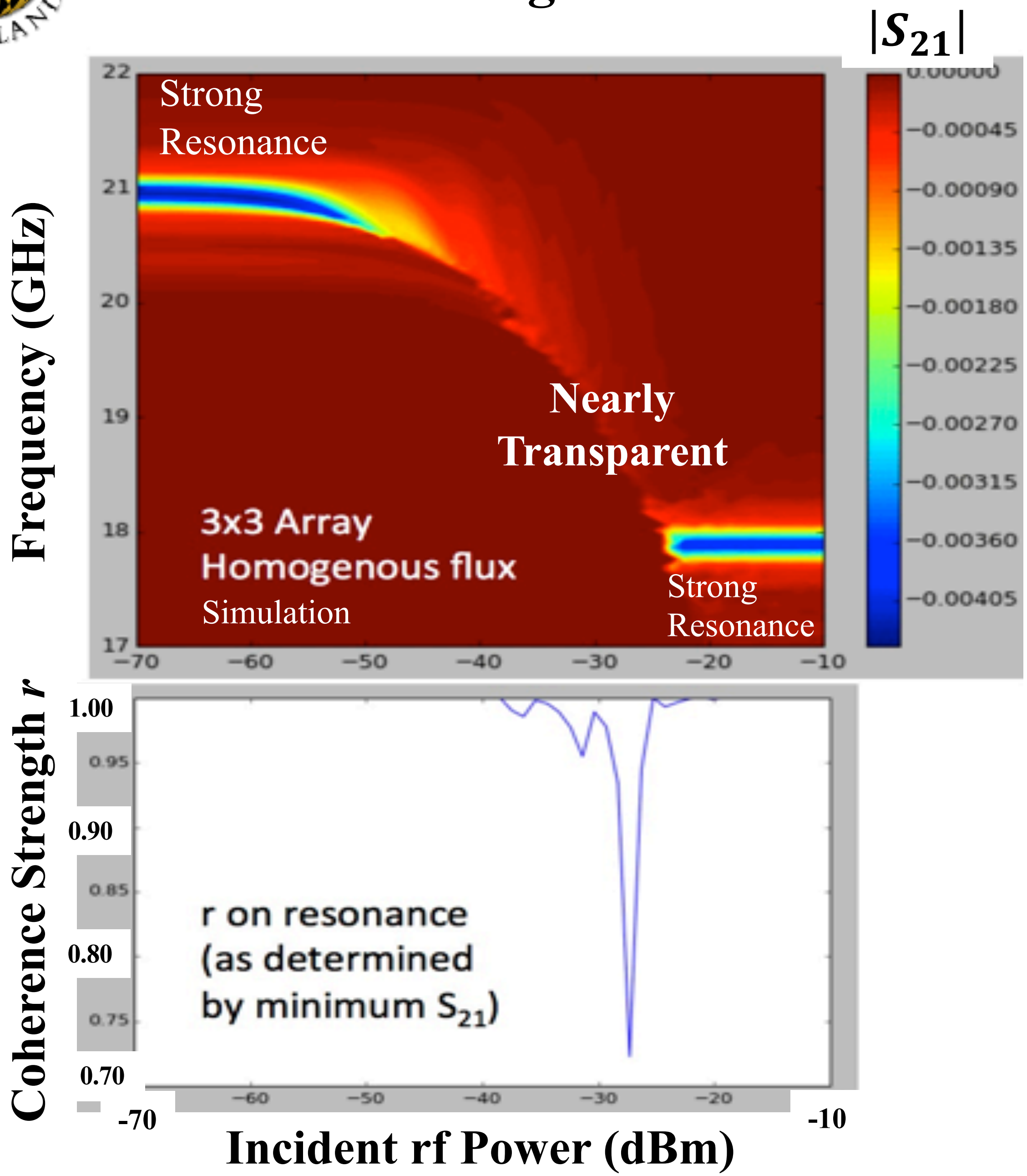


D. Zhang, *et al*., Phys. Rev. X 5, 041045 (2015)

$$\sin\delta \cong \delta - \delta^3/3!$$

Transparency shows up when bistability begins. → Evident from Duffing Oscillator

"Auto-Cloaking" and Loss of Coherence



The rf SQUID metamaterial shows incoherent oscillations and "disappears" at intermediate incident power levels!

Outline

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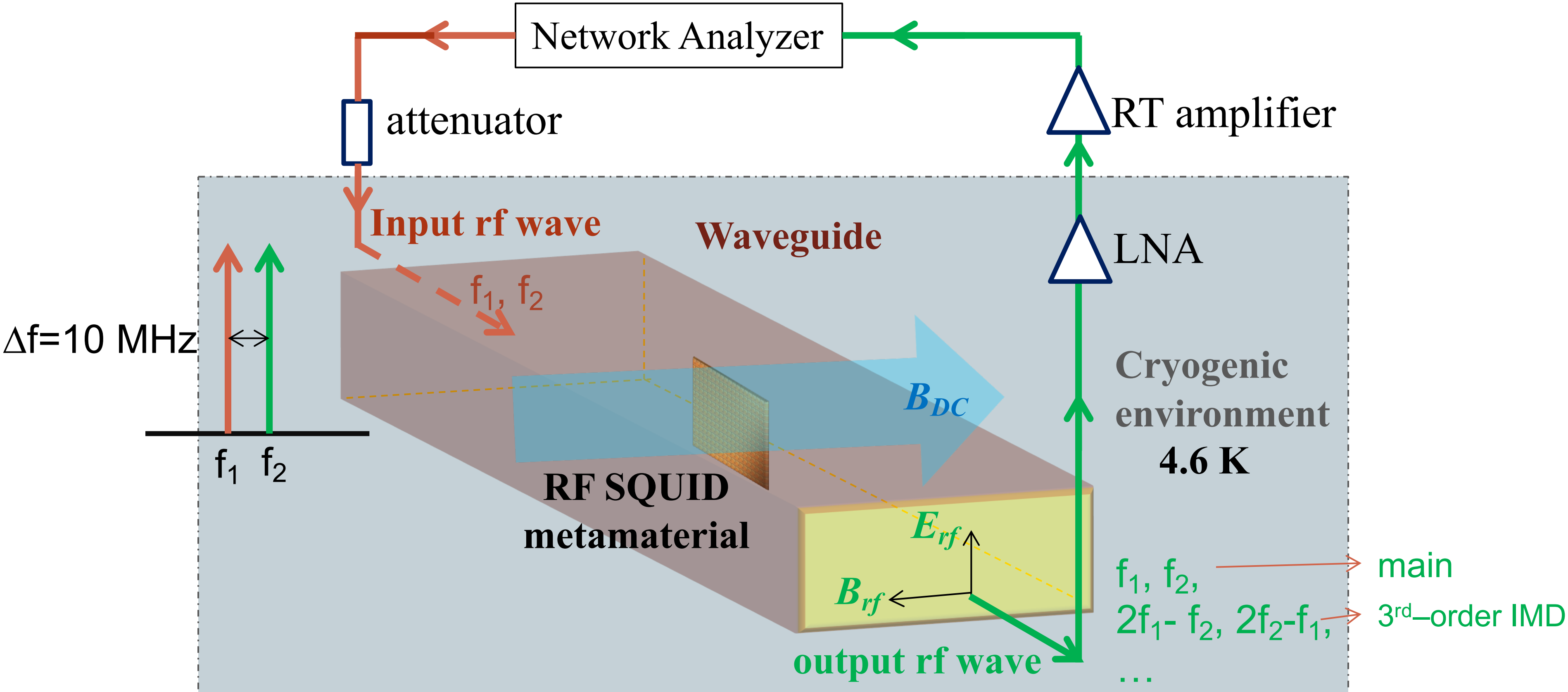
rf SQUID Metamaterials

- "Auto-cloaking"
- Intermodulation
- Imaging "Dark" Modes

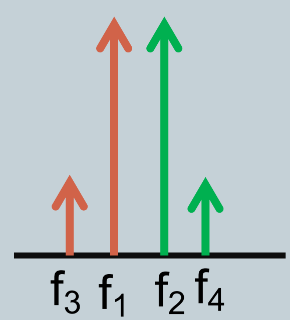
Conclusions

Measurement of Intermodulation in rf SQUID Metamaterials



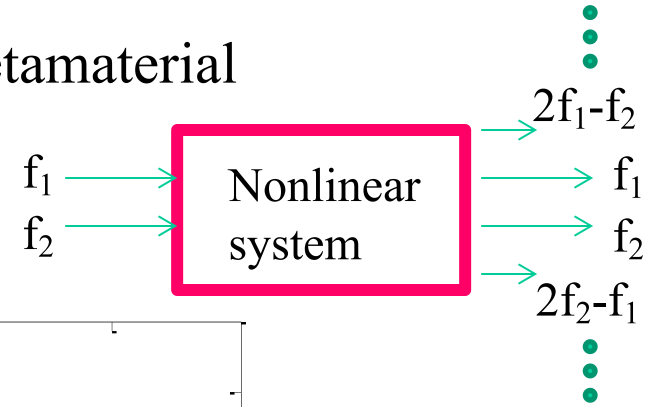
Why measure IMD?

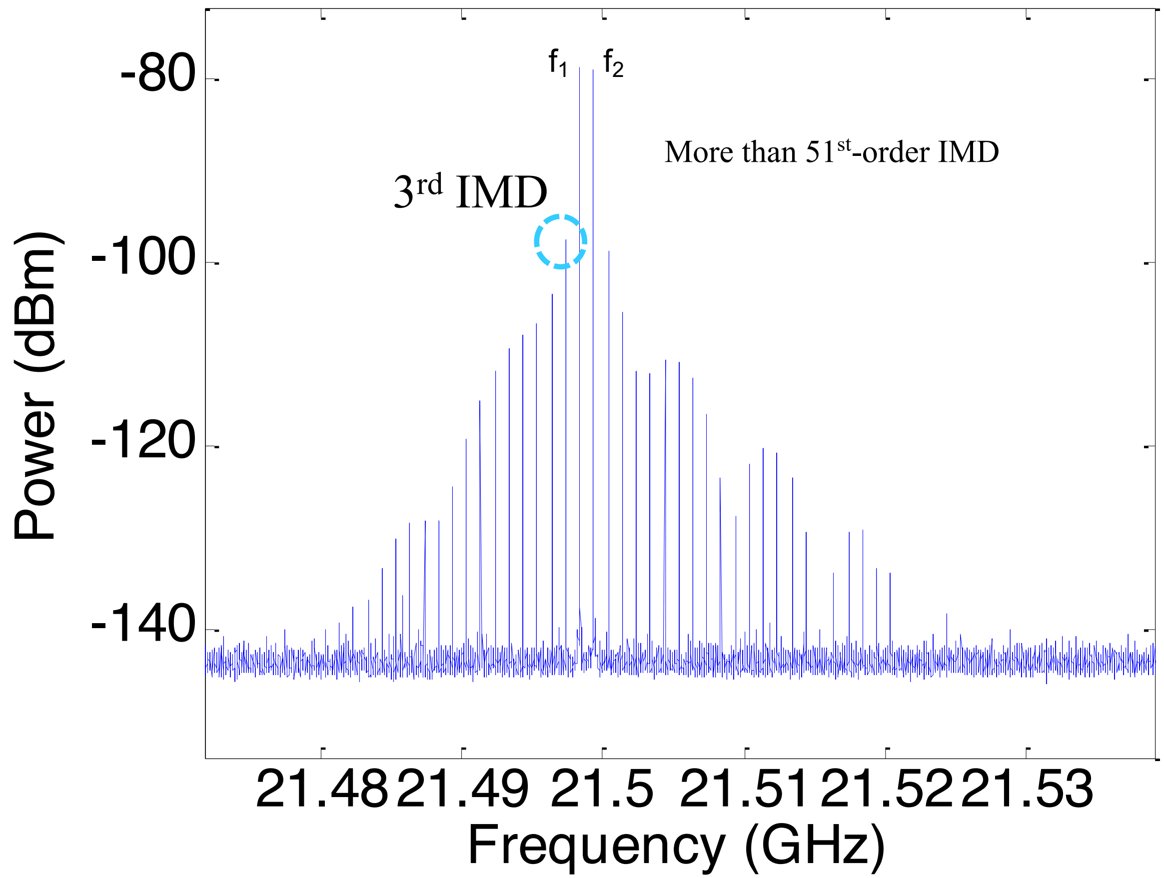
- Gives insight into metamaterial dynamics
- "zero" background (large S/N)
  - large dynamic range
- Related to engineering specs for wireless communications



IMD Spectrum of a 27x27 SQUID Metamaterial

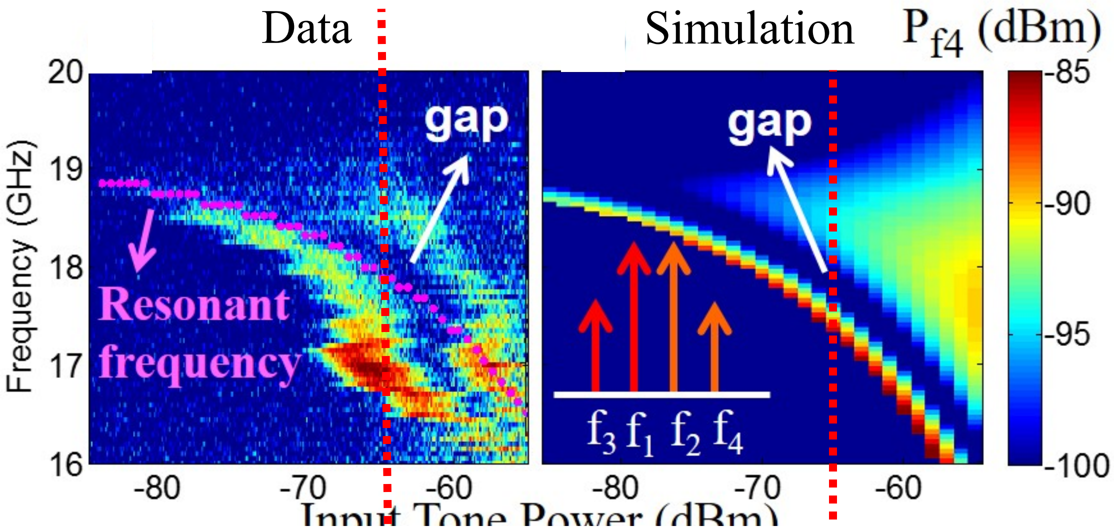
- very rich generation of IMD





Fixed input power, fixed center frequency for the two tones

Intermodulation in a Single rf SQUID



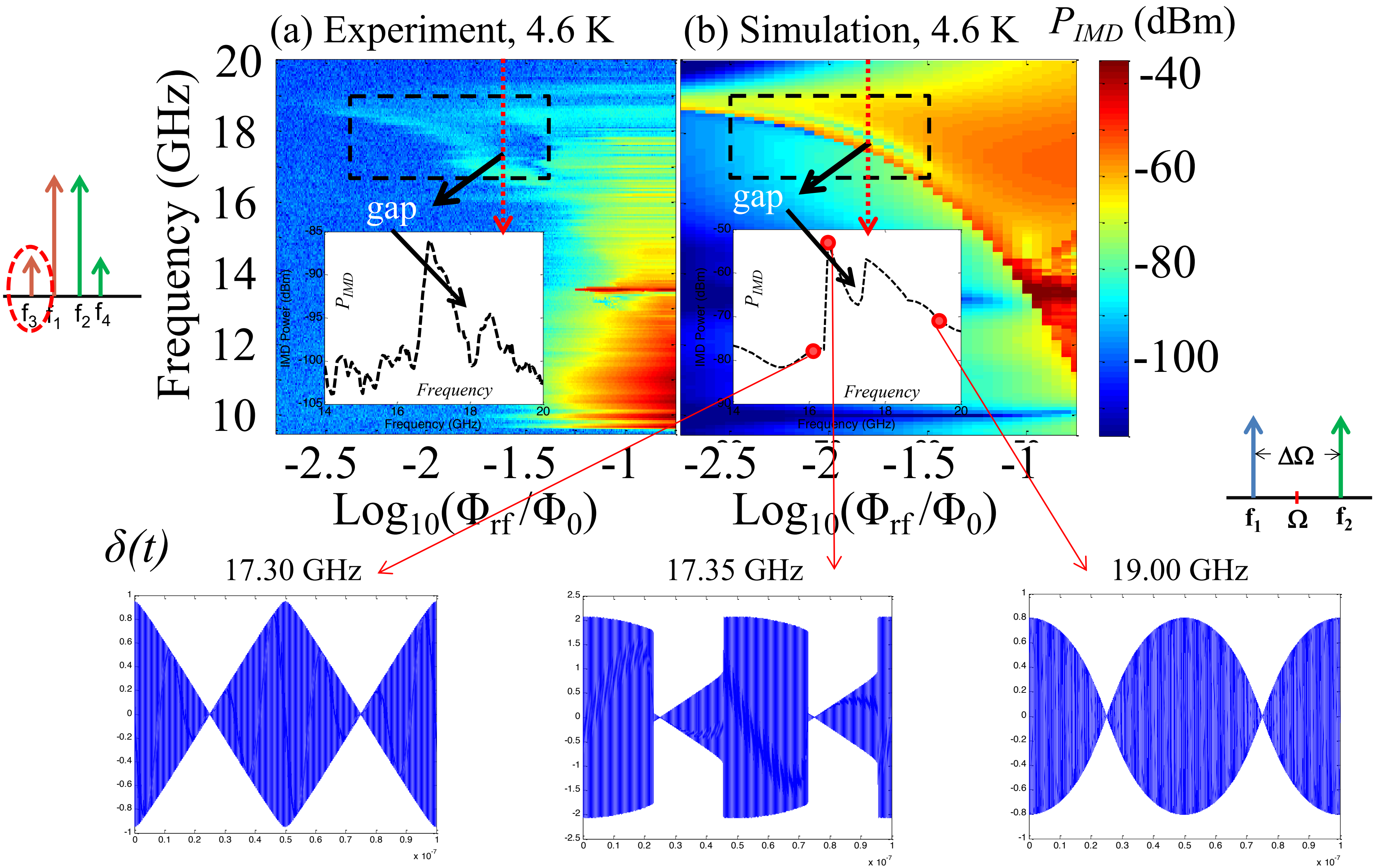
Line cuts at
-65 dBm
rf flux

Input Tone Center Frequency (GHz)

Nb/AlO_x/Nb JJ
4.6 K
Δf = 10 MHz

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

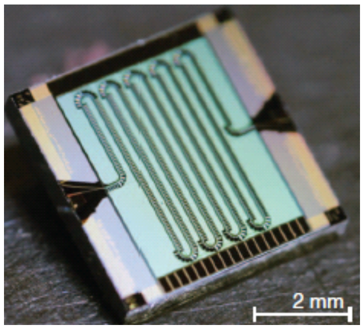
P_{IMD} Generation : Experiment and Simulation

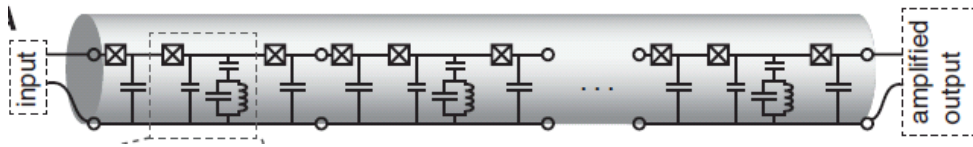


D. Zhang, *et al.*, Phys. Rev. B 94, 174507 (2016)

Why Nonlinear Metamaterials?

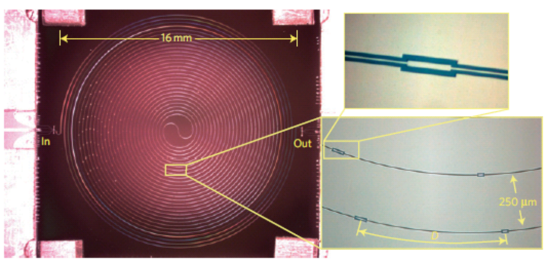
Quantum-Limited Amplifiers





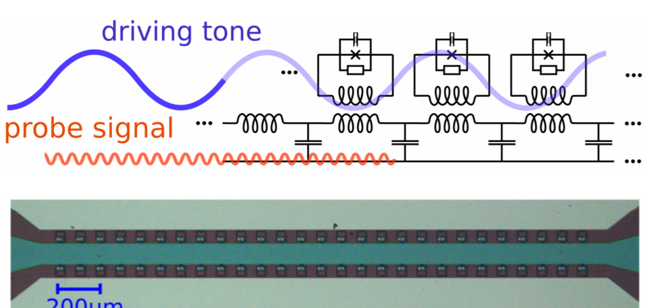
A near-quantum-limited Josephson traveling-wave parametric amplifier

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[3,4,5], V. P. Koshelets[6], A. V. Ustinov[2,3,5]

arXiv:1905.01511

Outline

Motivation and Background

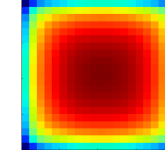
rf SQUID Metamaterials

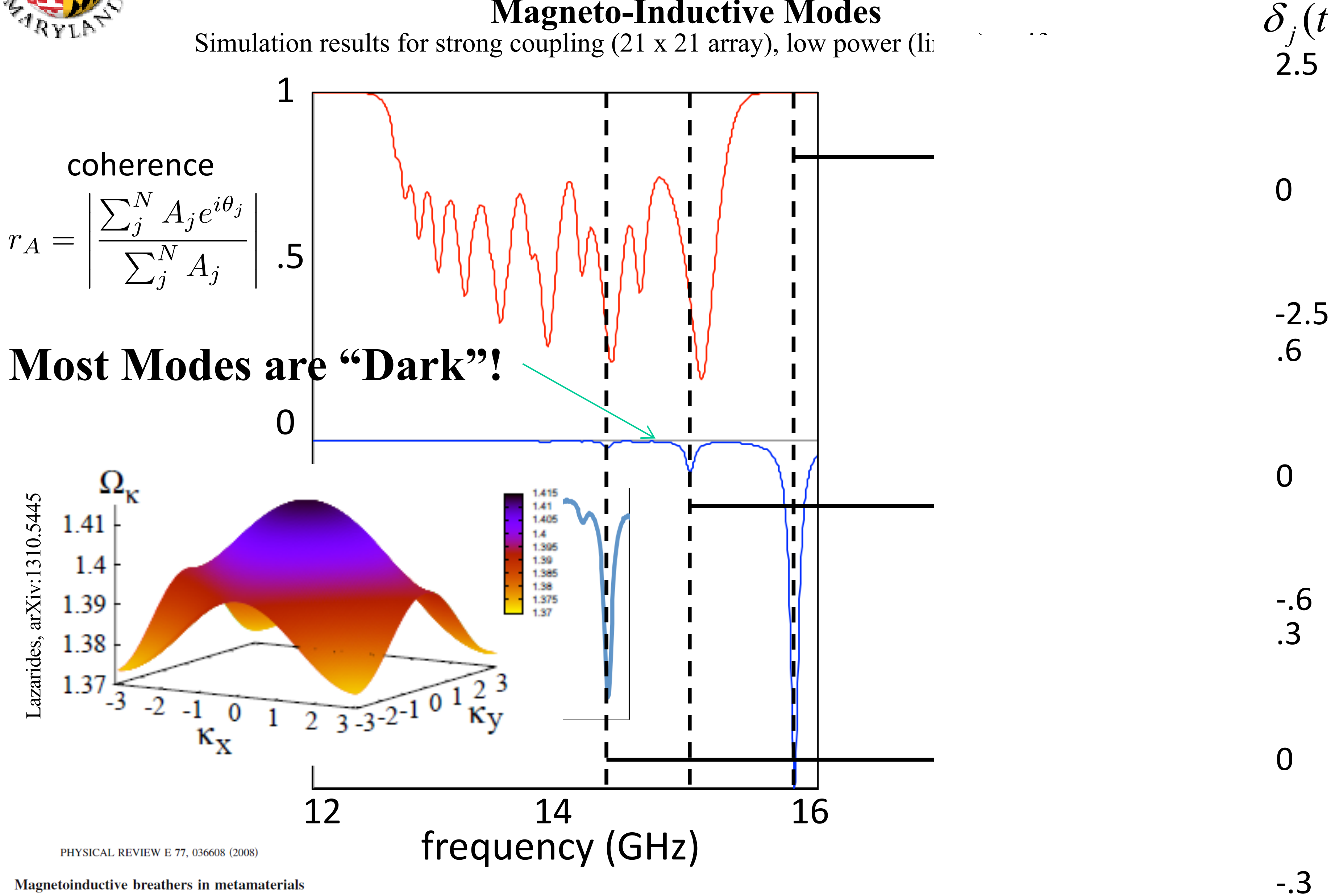
- "Auto-cloaking"
- Intermodulation
- ➡ Imaging "Dark" Modes

Conclusions

Coupling Between SQUIDs Introduces Magneto-Inductive Modes

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



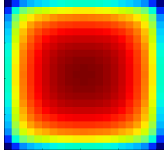


PHYSICAL REVIEW E 77, 036608 (2008)

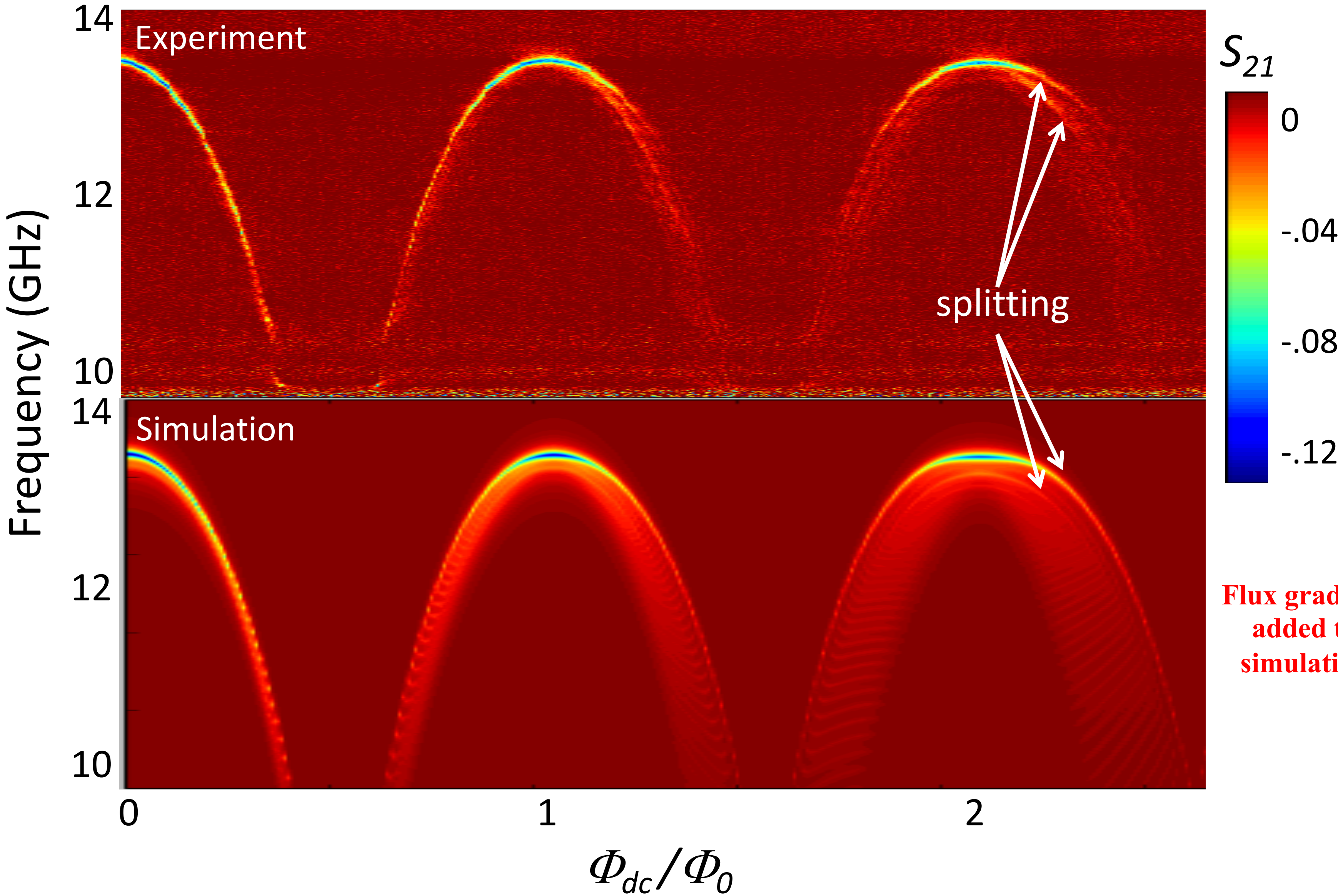
Magnetoinductive breathers in metamaterials

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

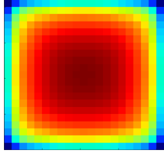
Indirect Experimental Evidence for MI Modes



21 x 21 rf SQUID metamaterial (M/L = -.02 [n.n. coupling], linear response limit)



Flux gradient added to simulation



Predictions for Interesting Collective Properties of rf SQUID Metamaterials

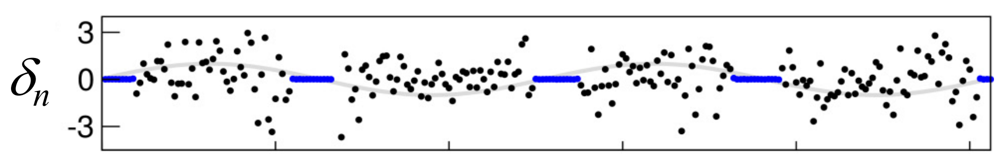
Chimera: coexistence of synchronous and asynchronous groups of oscillations in a material, even for uniform constituent atoms and symmetric couplings

PHYSICAL REVIEW E 94, 032219 (2016)

Robust chimera states in SQUID metamaterials with local interactions

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

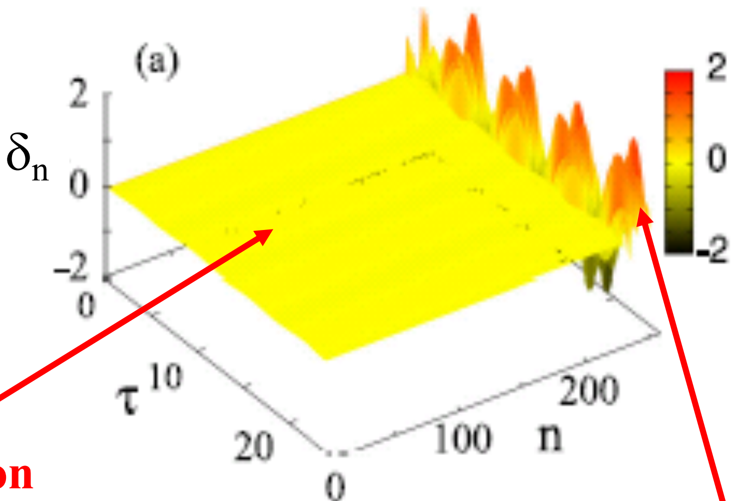
1D rf SQUID metamaterial



PHYSICAL REVIEW B 91, 054303 (2015)

Chimeras in SQUID metamaterials

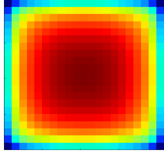
N. Lazarides,[1,2] G. Neofotistos,[1] and G. P. Tsironis[1,2,3]



Low amplitude coherent oscillation

High amplitude incoherent oscillation

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, arXiv:1902.02158
N. Lazarides, arXiv:1902.01711



Our Global Transmission Measurements are Largely Insensitive to Chimeras

coherence

$$r_A = \left| \frac{\sum_j^N A_j e^{i\theta_j}}{\sum_j^N A_j} \right|$$

Most Modes are "Dark"!

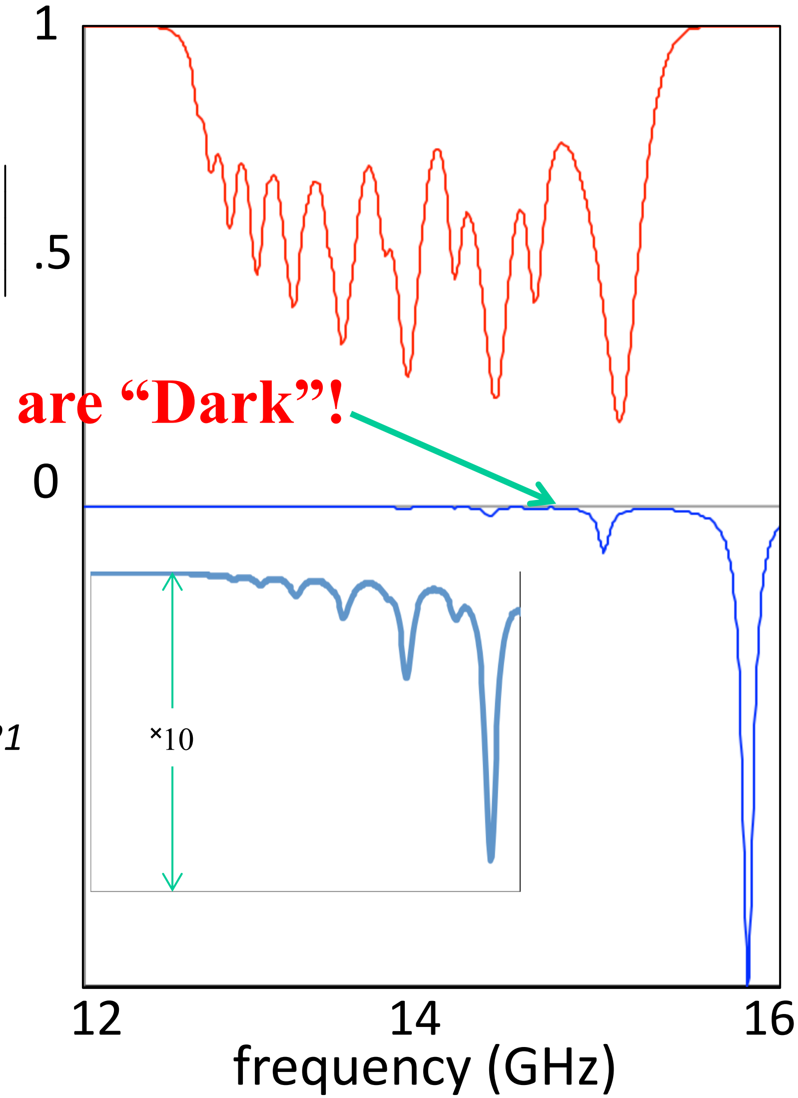
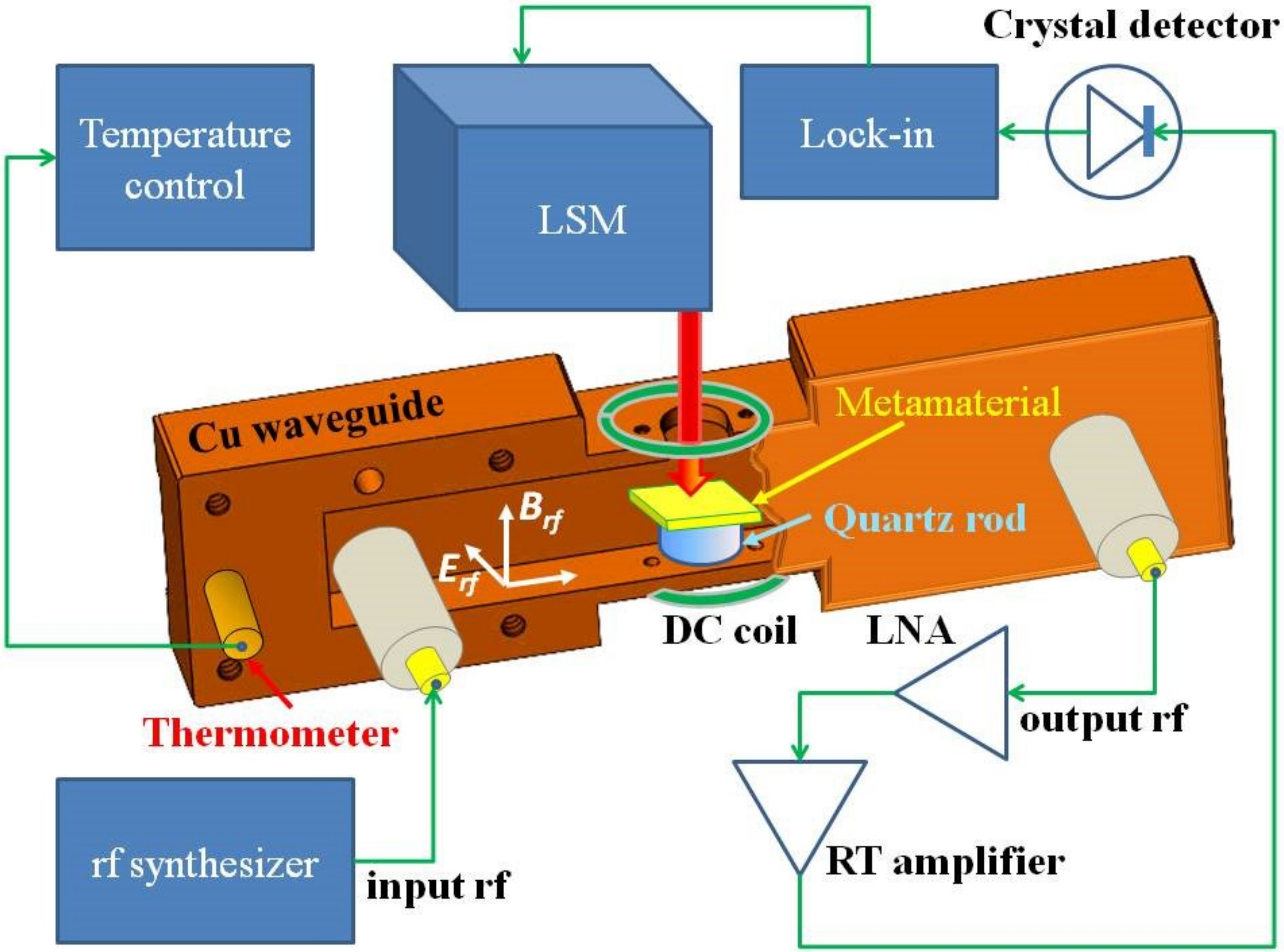


Image rf SQUID Collective Response

Laser Scanning Microscope Imaging



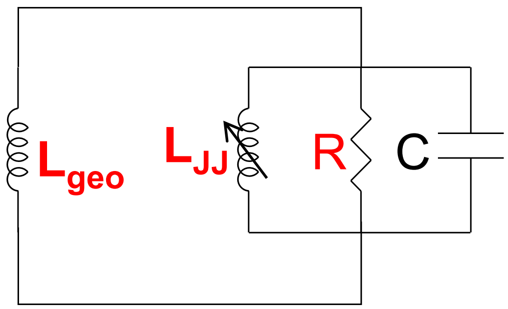
Variables:
- Temperature
- dc magnetic flux
- rf magnetic flux
- rf frequency

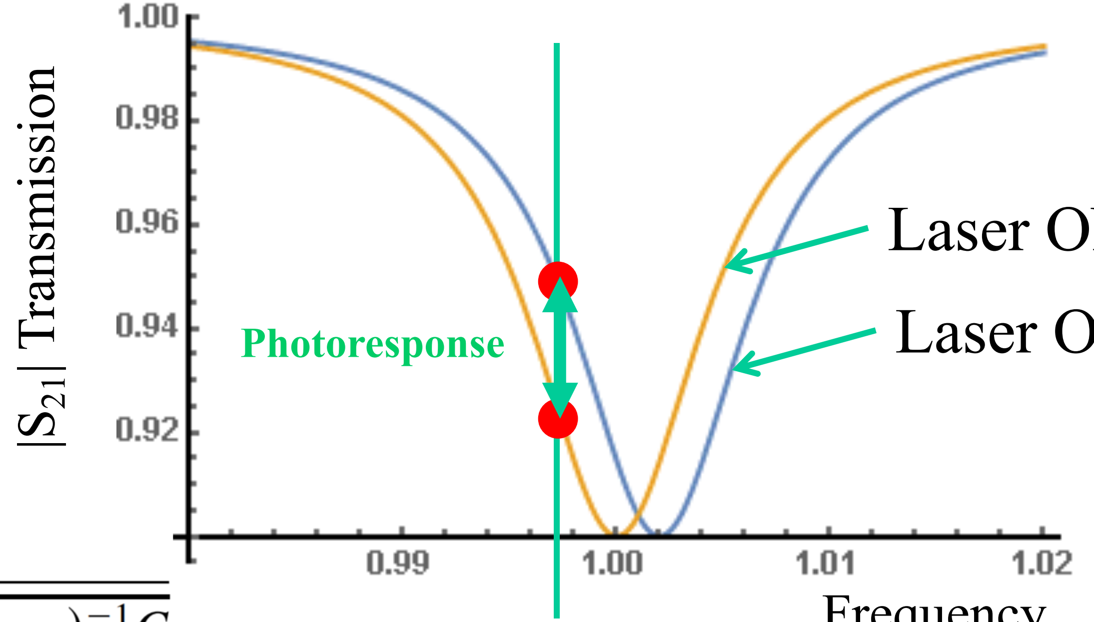
Imaging experiments done by: A. P. Zhuravel in laboratory of A. Ustinov, KIT, Germany
Seokjin Bae at UMD

Origins of rf Photoresponse

Contrast mechanisms

Laser heating





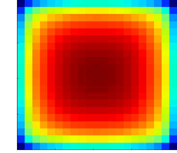
$$f_0(T, \Phi_{app}) = \frac{1}{2\pi\sqrt{\left(\frac{1}{L_{geo}} + \frac{1}{L_{JJ}(T,\Phi_{app})}\right)^{-1} C}}$$

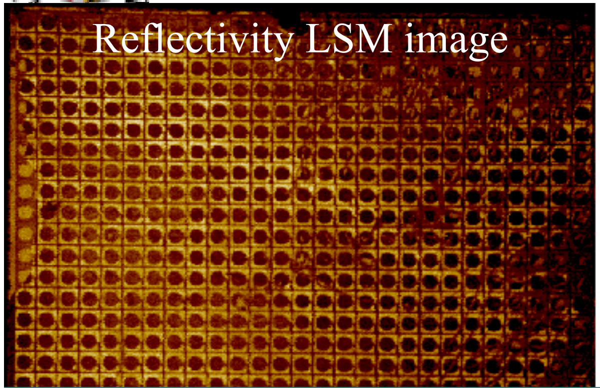
Heating of JJ leads to decrease of critical current and shift of resonance

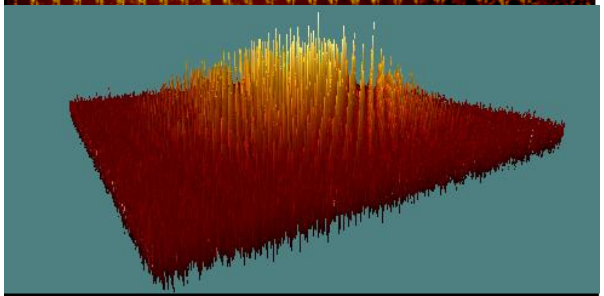
$$L_{JJ} = \frac{\Phi_0}{2\pi\, I_c(T) \cos\delta}$$

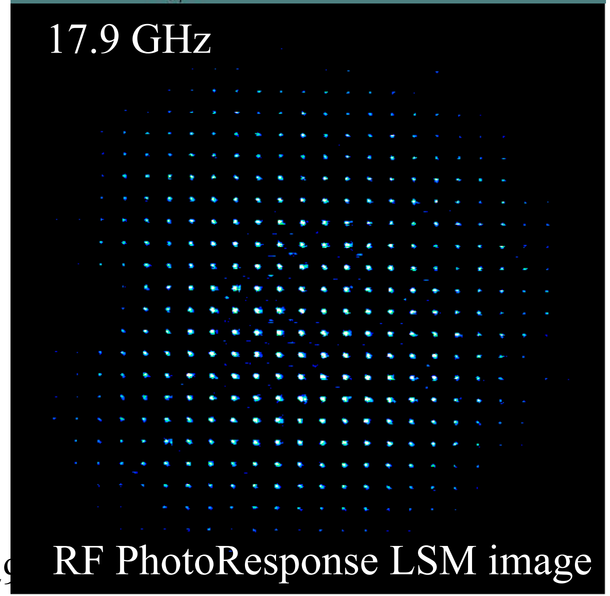
Photoresponse ~ $|I_{rf}|^2$ in junction

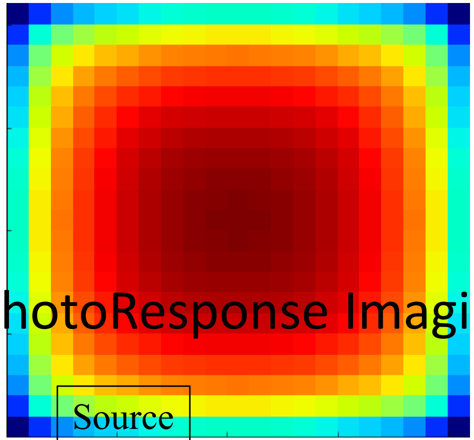
Imaging rf SQUID Metamaterial High-Power Coherent Mode











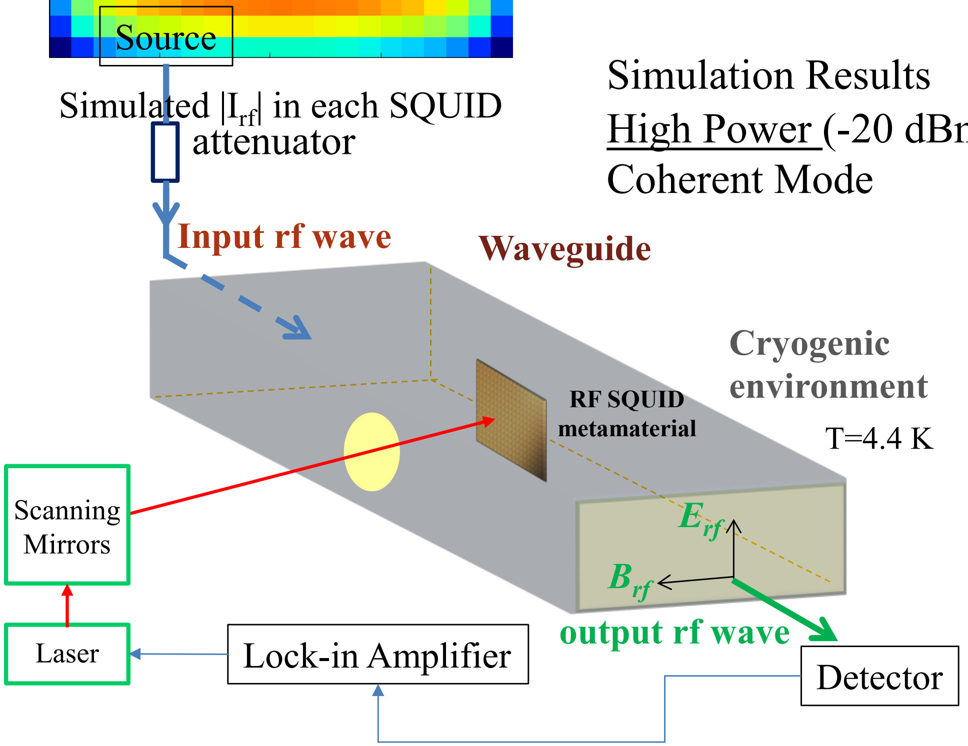
27 x 27 rf SQUID metamaterial

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

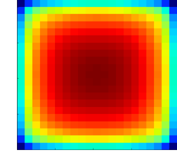
PhotoResponse Imaging of rf SQUID Metamaterial

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

What happens at low rf flux?

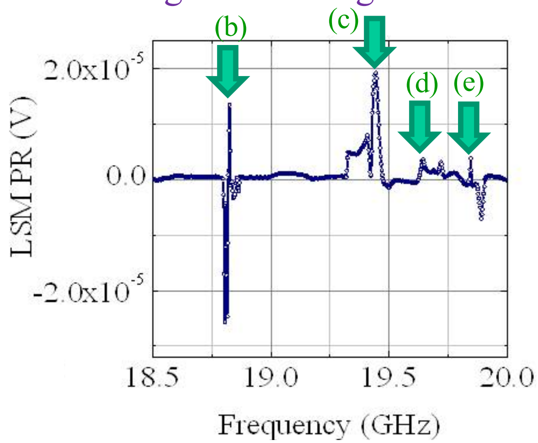
A weak global driving field reveals strong disorder of the sample

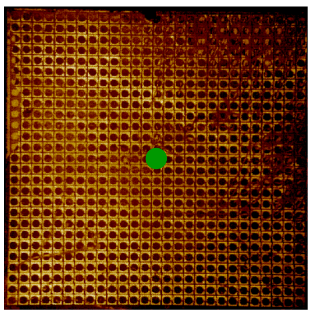
T = 4.8 K

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

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

27 x 27 array
rf SQUID (12, 14)
Multiple modes!



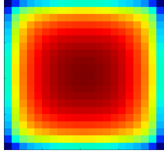


Images taken at low rf flux amplitude $\boldsymbol{\Phi_{rf} = 10^{-4}\ \Phi_0}$

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

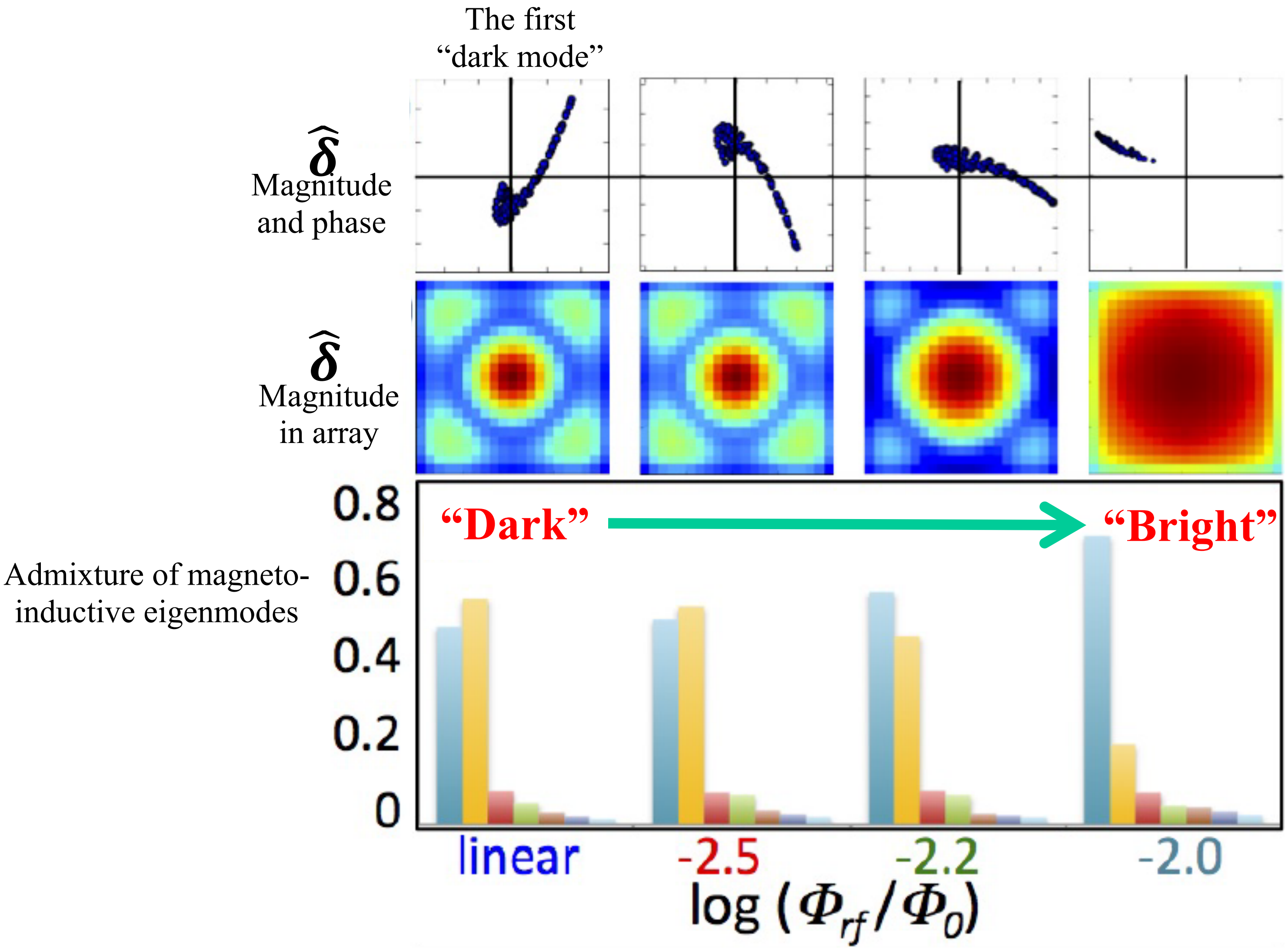
Stronger global rf flux creates a coherent mode

A. Zhuravel, *et al.*, Appl. Phys. Lett. 114, 082601 (2019).

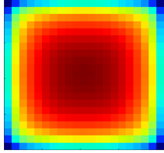


Simulation of Nonlinear 21 × 21 rf SQUID Array

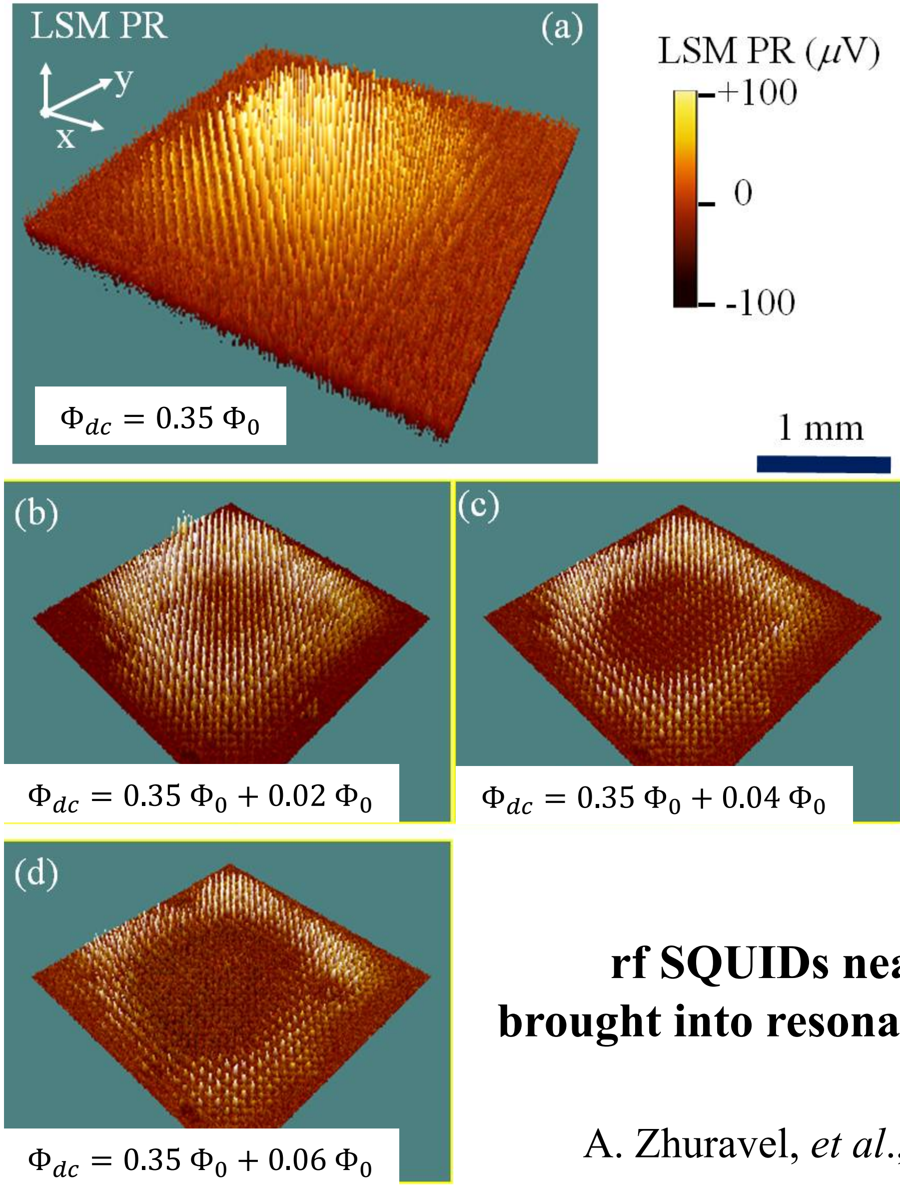
Fundamental Mode Emerges with Increased rf Flux Amplitude



Melissa Trepanier Ph.D. thesis, UMD, 2015, p. 83. http://hdl.handle.net/1903/17290



How is the coherent state destroyed with dc flux?

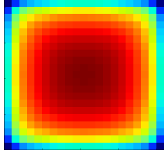


Starting from a coherent state at $\Phi_{dc} = 0.35\Phi_0$, add small dc flux offset

f = 14.4 GHz, T = 4.8 K

rf SQUIDs near the edge are brought into resonance at higher dc flux

A. Zhuravel, *et al.*, Appl. Phys. Lett. 114, 082601 (2019).

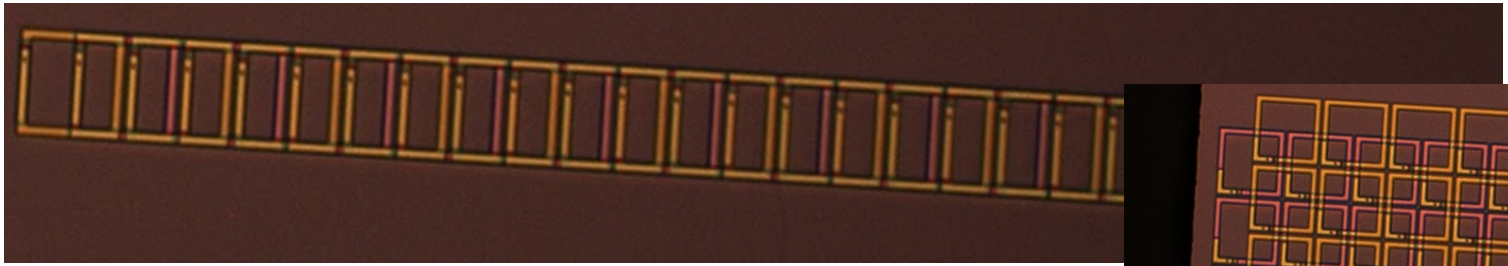


Next-Generation rf SQUID Metamaterials

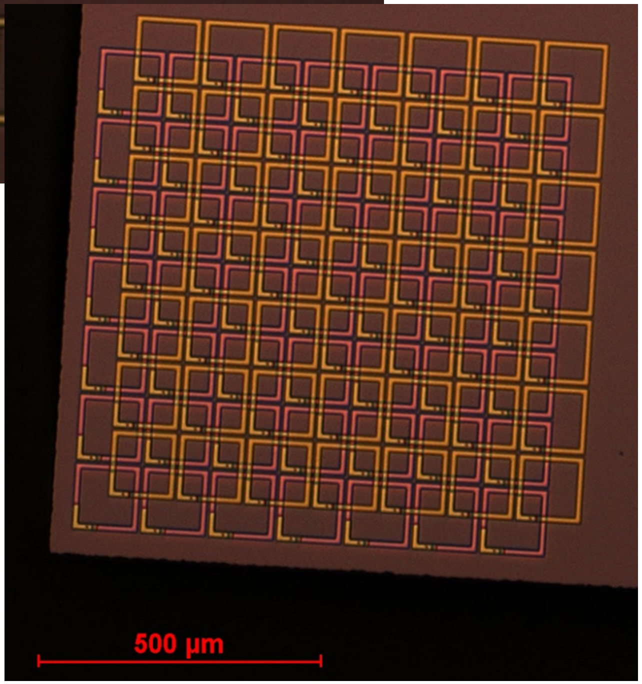
Now being measured

Stronger Coupling between meta-atoms (M/L = -0.06 → -0.18)

Positive (Ferromagnetic) Coupling between meta-atoms (M/L → +0.50)



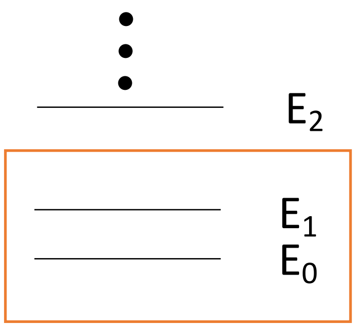
2D metamaterial with mixed ferromagnetic and anti-ferromagnetic coupling



IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 4-ND-I-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.

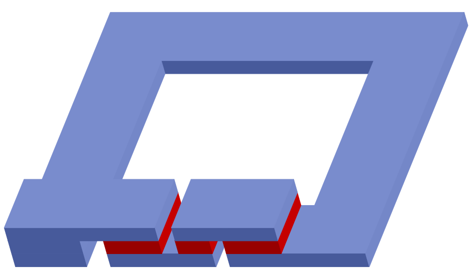
Superconducting Qubits as "meta-atoms"

- What makes a two-level quantum system?
  - Low temperature $k_B T \ll E_1 - E_0$ (T ~ 0.01K)
  - E_0 and E_1 well separated from the rest
  - Utilize Josephson nonlinearity



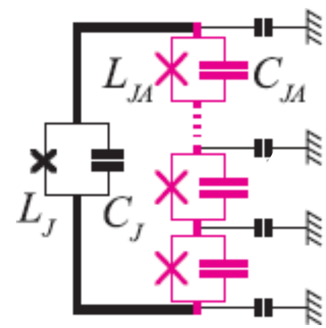
- To study interaction with external fields (photons):
  - $E_1 - E_0$ matches photon frequency (GHz)

- Superconductor based qubit: flux qubit, transmon qubit, fluxonium, etc.



3-Junction Flux Qubit

Transmon
Koch, PRA 76, 042319 (2007)



Fluxonium
Manucharyan, Science 326, 113 (2009)

Quantum Metamaterials

- Focus on the coherent (collective) effect of qubits on a resonating mode.

- Methods to establish existence of coherent behavior:
  - Cavity-QED: AC-Zeeman shift, qubit dispersive shift, super-radiance transition ...

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
- rf SQUID metamaterials are a rich nonlinear medium

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Thanks for your attention!

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