IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
EUCAS 2015 plenary presentation PL-5. Not submitted to *IEEE Trans. Appl. Supercond.*

Superconducting Metamaterials

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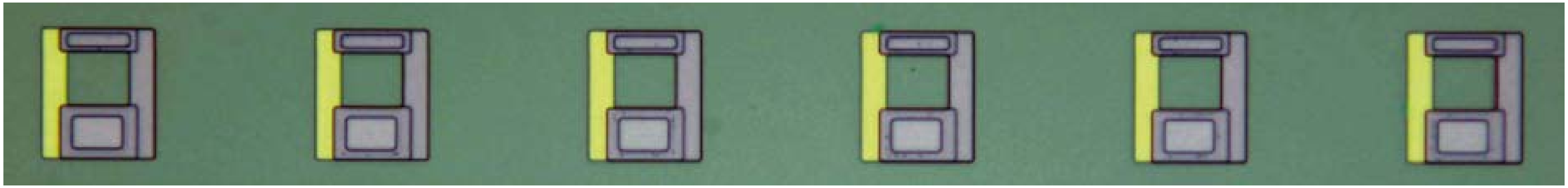
[3] **Russian Quantum Center (RQC), Moscow, Russia**
[4] **Kotel’nikov Institute of Radio Engineering and Electronics (IREE), Moscow, Russia**



Acknowledgements

Superconducting metamaterials:

S. M. Anlage

University of Maryland, College Park, Maryland, USA

A. P. Zhuravel

B. Verkin Low Temperature Physics Institute, Kharkov, Ukraine

Quantum metamaterials:

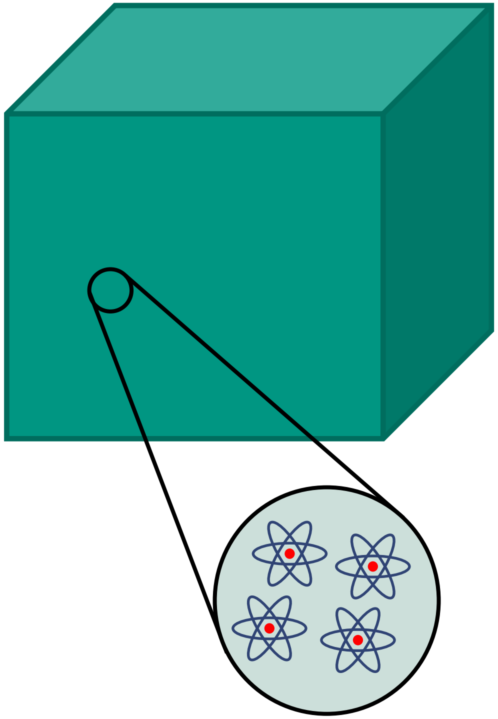
M. Jerger and A. Lukashenko

Physikalisches Institut, Karlsruhe Institute of Technology, Germany

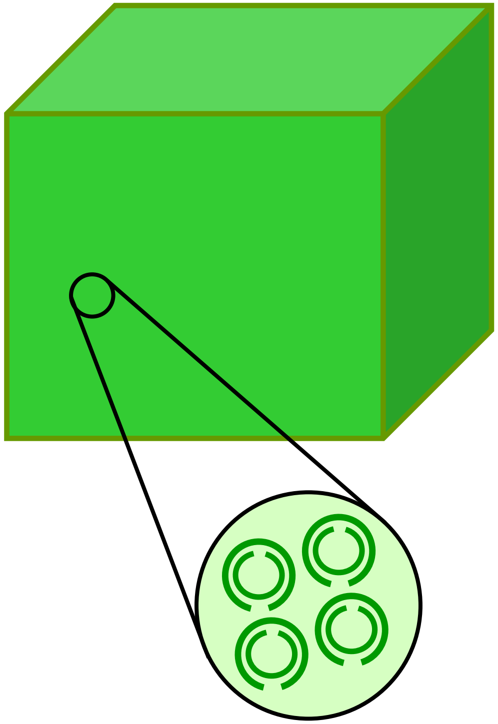
P. Macha, U. Hübner, and E. Il’ichev

Institute of Photonic Technology, Jena, Germany

Materials and Metamaterials



material is made
out of *atoms*



metamaterial is composed
out of *units* called *meta-atoms*

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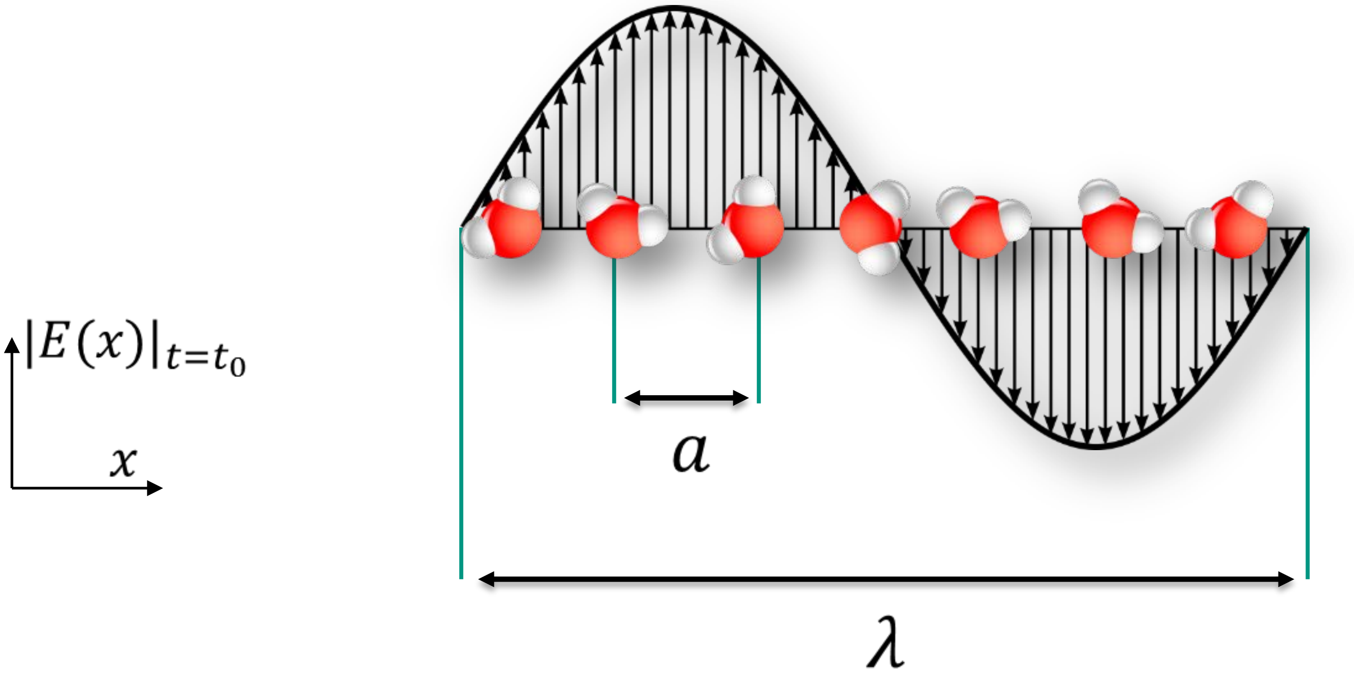
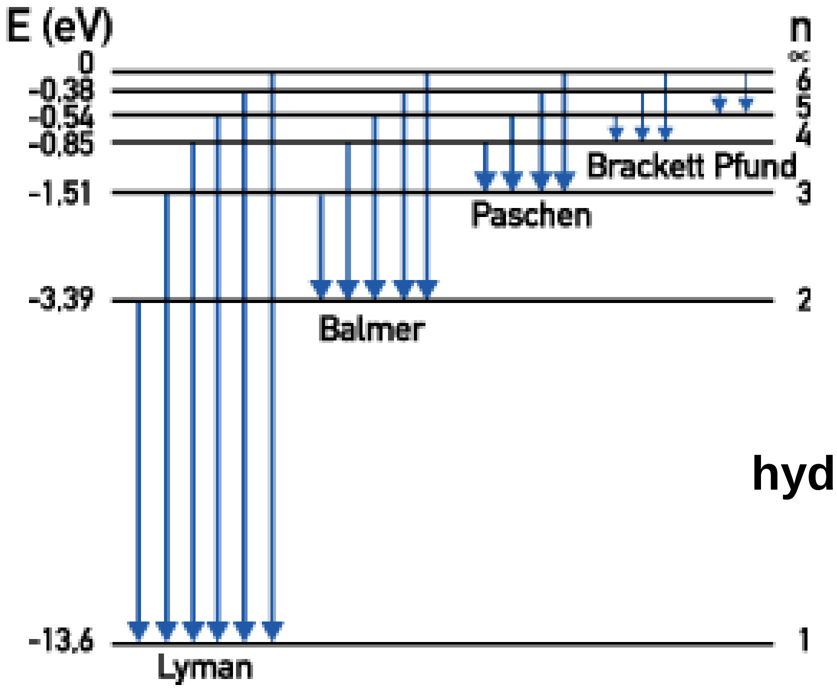
Electromagnetic wave in a material



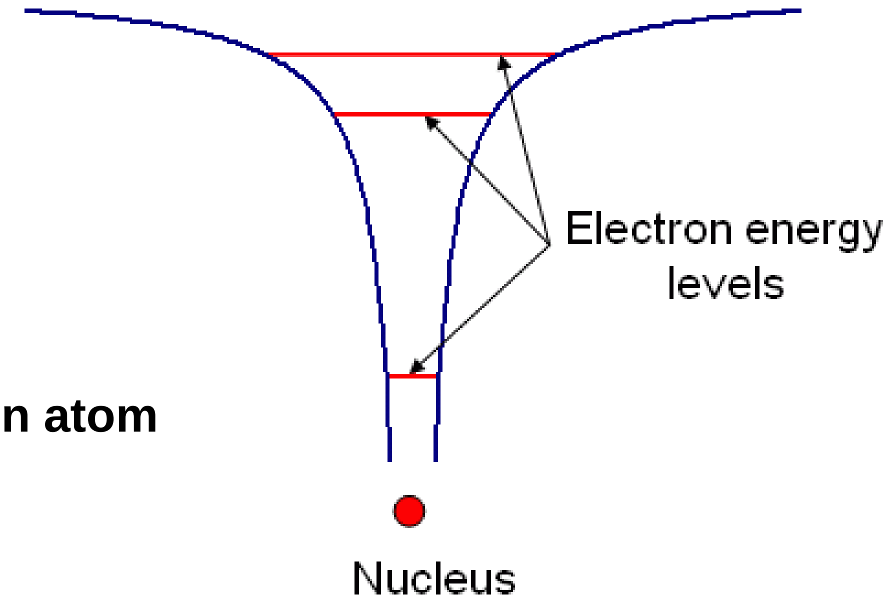
$\lambda \gg a$

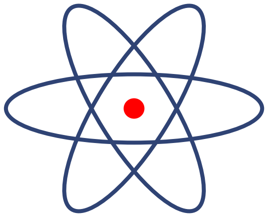
- Water: $a \cong 3\ \text{Å}$
- Visible light: $\lambda \cong 390\text{nm} - 700\text{nm}$

Materials are composed out of atoms – smallest resonators “made” by nature



hydrogen atom



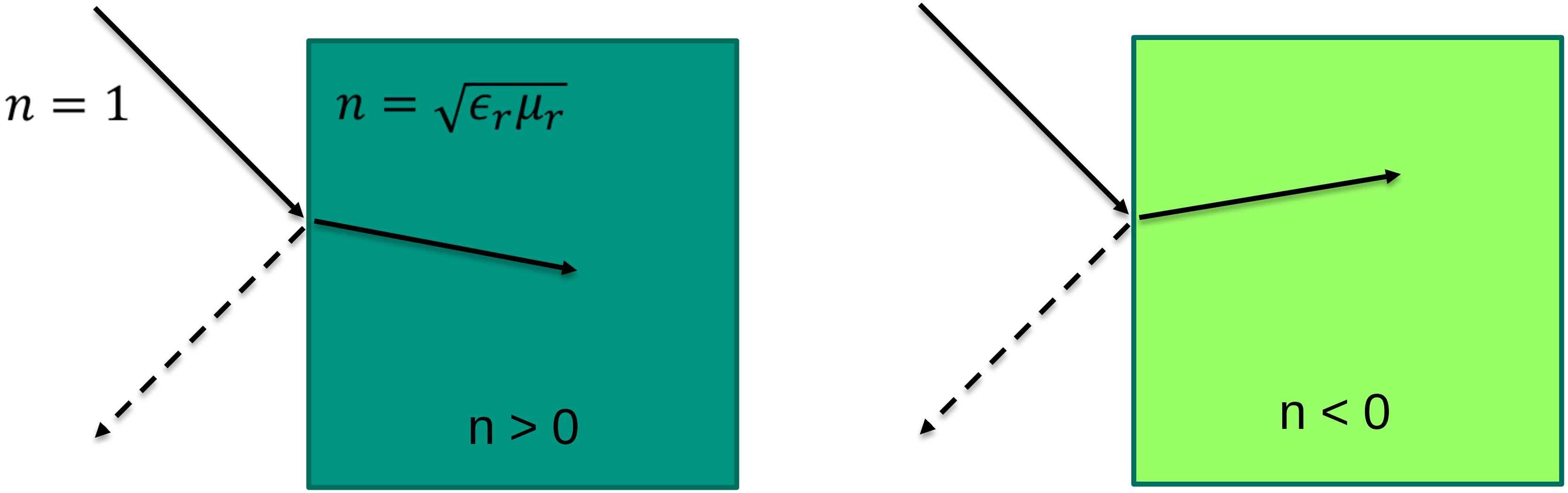


for the Lyman α–transition with wavelength λ = 122 nm
with the “resonator” size $d = 2r_B$ = 0.103 nm
one gets the ratio λ/d = **1150**

size/wavelength ≈ 10^{-3}

Electromagnetic metamaterials

Controlling the propagation of light through material parameters



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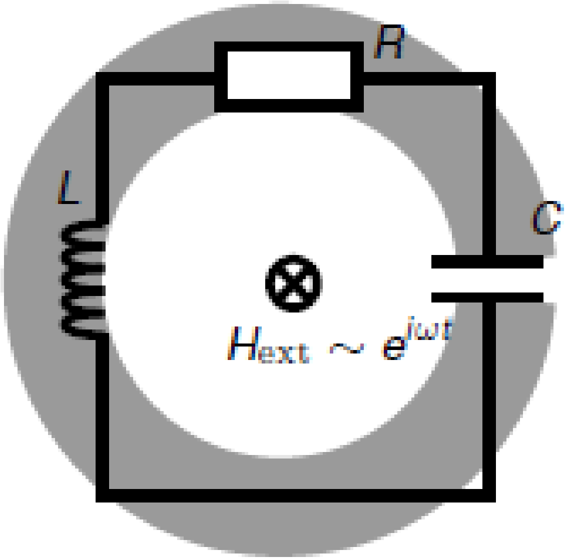
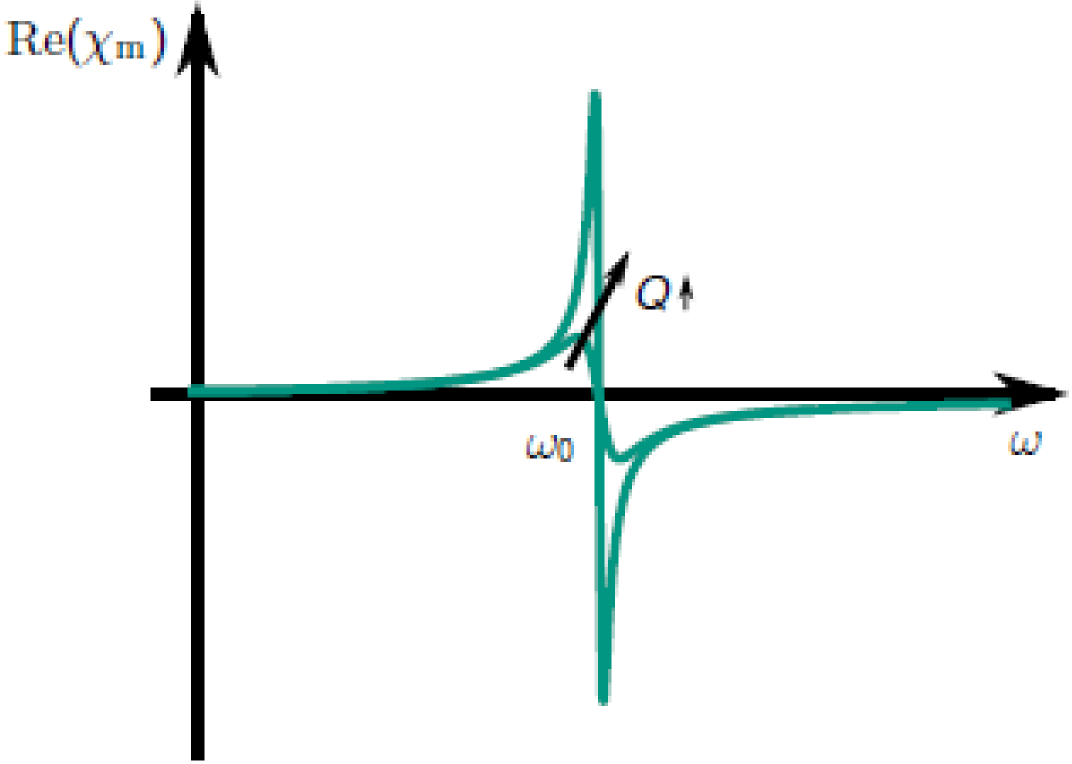
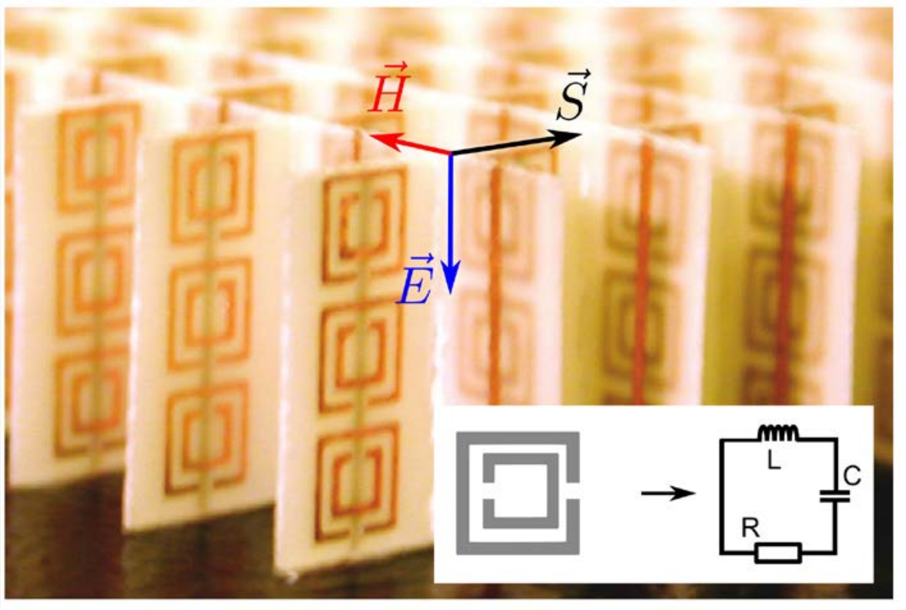
Magnetic Meta-Atoms





Microwave Metamaterials and Meta-Atoms

- $\lambda \gg a$ can be achieved for "macroscopic" dimensions



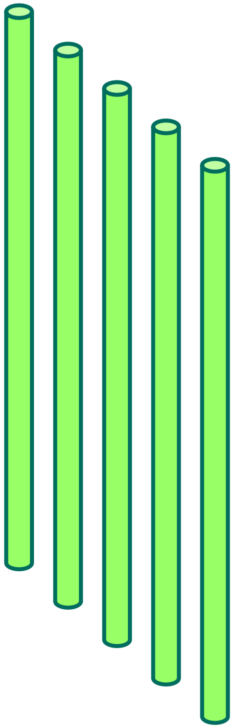
Shelby et al., *Science* **77** 292 (2001)

Problem:
losses increase with decreasing the size of meta-atoms

- Distance between meta-atoms: $a \cong 5\ \mathrm{mm}$
- Microwaves (X-band): $\lambda \cong 2.5\mathrm{cm} - 3.75\mathrm{cm}$

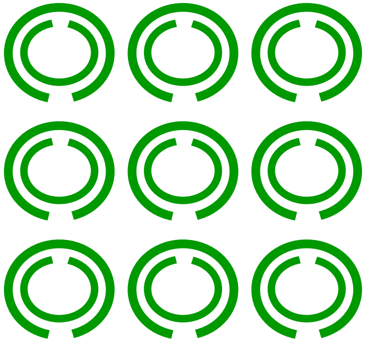
Modern history of metamaterials

V. G. Veselago
Usp. Fiz. Nauk
92, 517 (1967)



$\varepsilon < 0$
rods

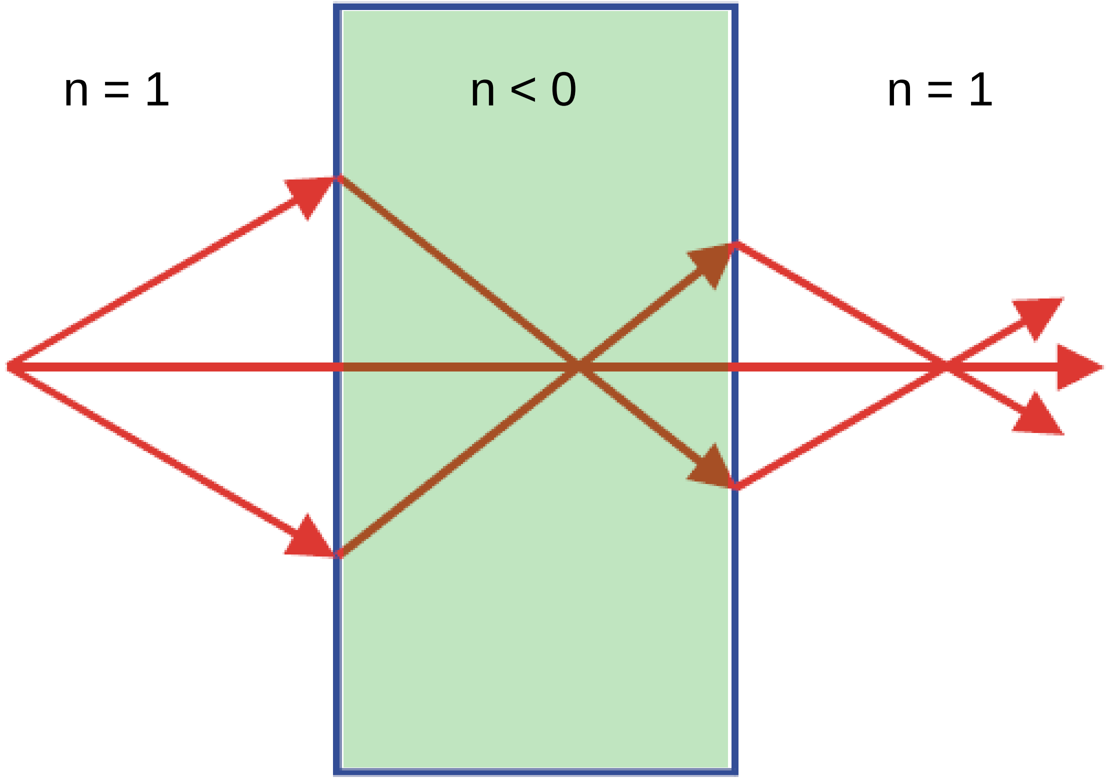
J. B. Pendry et al.
Phys. Rev. Lett.
76, 4773 (1996)



$\mu < 0$
split
rings

D. R. Smith et al.
Phys. Rev. Lett.
84, 4184 (2000)

Veselago-Pendry lens



J. B. Pendry, Negative Refraction Makes a Perfect Lens, *Phys. Rev. Lett.* **85**, 3966 (2000).

© J. Pendry

Not so modern history of metamaterials …

H. Lamb, *Proc. London Math. Soc.* **1**, 473 (1904)
(backward waves; mechanical systems)

A. Schuster, *An Introduction to the Theory of Optics*, pp. 313-318
Edw. Arnold, London (1904) (backward waves)

H. C. Pocklington, *Nature* **71**, 607 (1905)
(phase velocity opposite to the group velocity)

L. I. Mandel'shtam, *Zh. Eksp.Teor. Fiz.* **15**, 476 (1945) (in Russian);

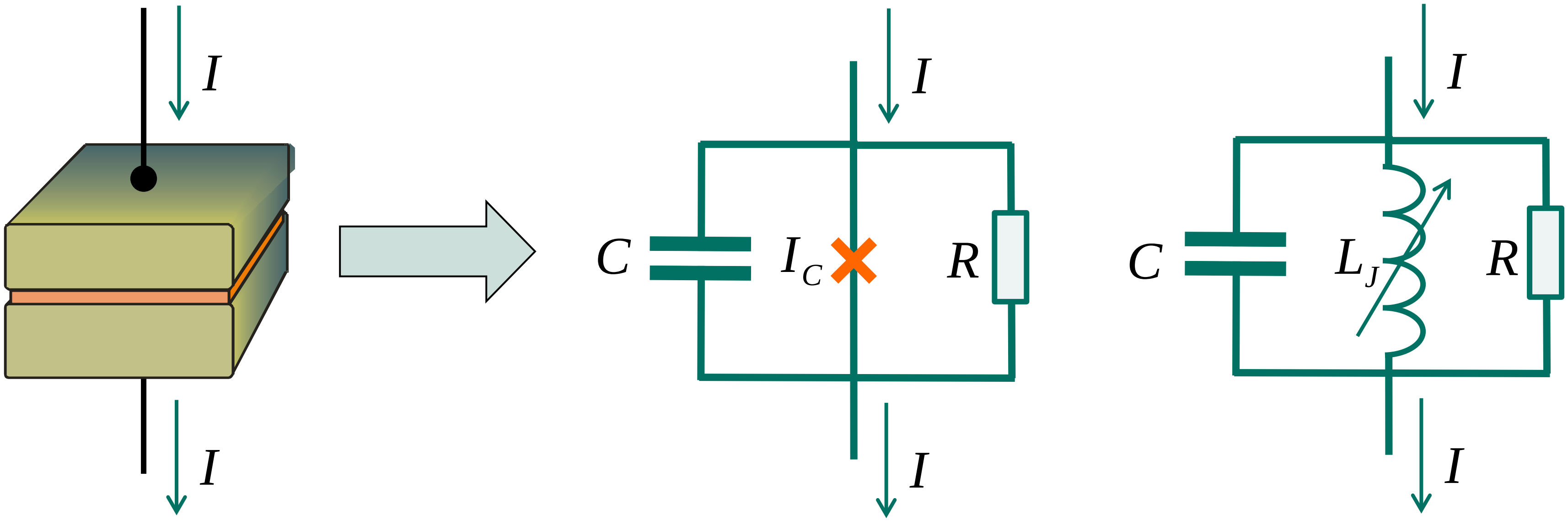
G. D. Malyuzhinets, *Zh. Tekh. Fiz.* **21**, 940 (1951) (in Russian)

D. V. Sivukhin, *Opt. Spektrosk.* **3**, 308 (1957) (in Russian) ($n < 0$)

Superconducting Metamaterials

- **Decreasing size** of meta-atoms without extra loss
- Easily **tunable frequency** (magnetic field, current, temperature)
- **Nonlinear**, multi-stable, and switchable
- **Ultra-compact** low-loss resonators
  - size/wavelength $< 10^{-4}$ is within reach
- **Quantum** metamaterials
  - arrays of superconducting qubits
  - quantum optics with artificial atoms

Equivalent circuit for a Josephson junction



RSCJ model

$$\begin{cases} I = I_C \sin\varphi + \dfrac{V}{R} + C\dfrac{dV}{dt} \\[2ex] V = \dfrac{\hbar}{2e}\dfrac{d\varphi}{dt} \end{cases}$$

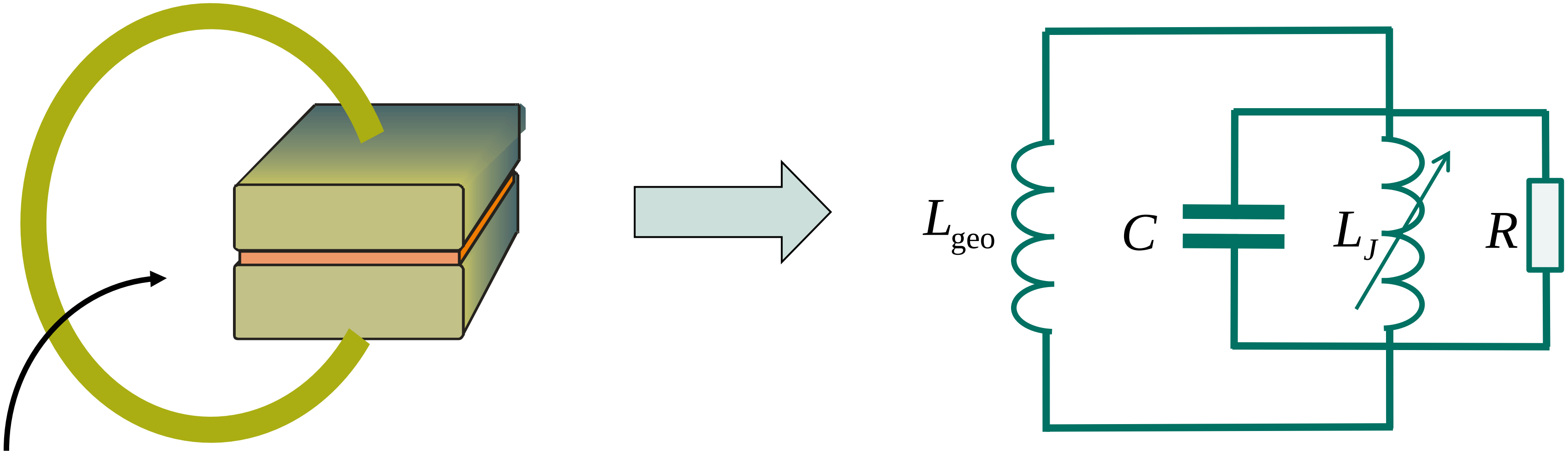
Josephson inductance

$$\Rightarrow \quad L_J = -V\frac{dI_S}{dt} = \frac{\hbar}{2e\,I_C\cos\varphi}$$

Superconducting quantum interference device (SQUID)

SQUID

equivalent circuit



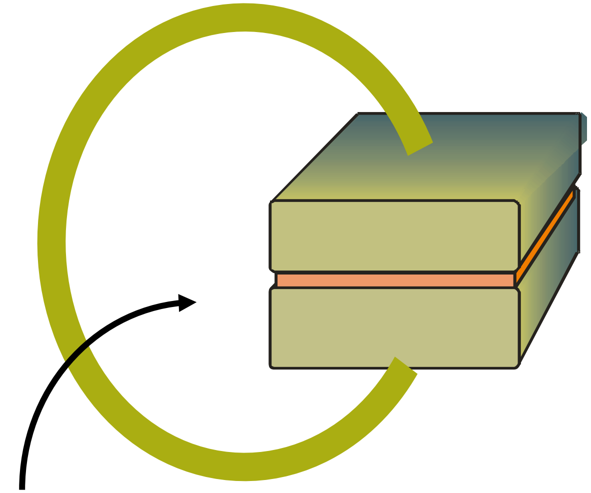
$$\Phi_{ext} = \Phi_{DC} + \Phi_{RF}$$

magnetic flux

L_J is tunable by Φ_{ext}

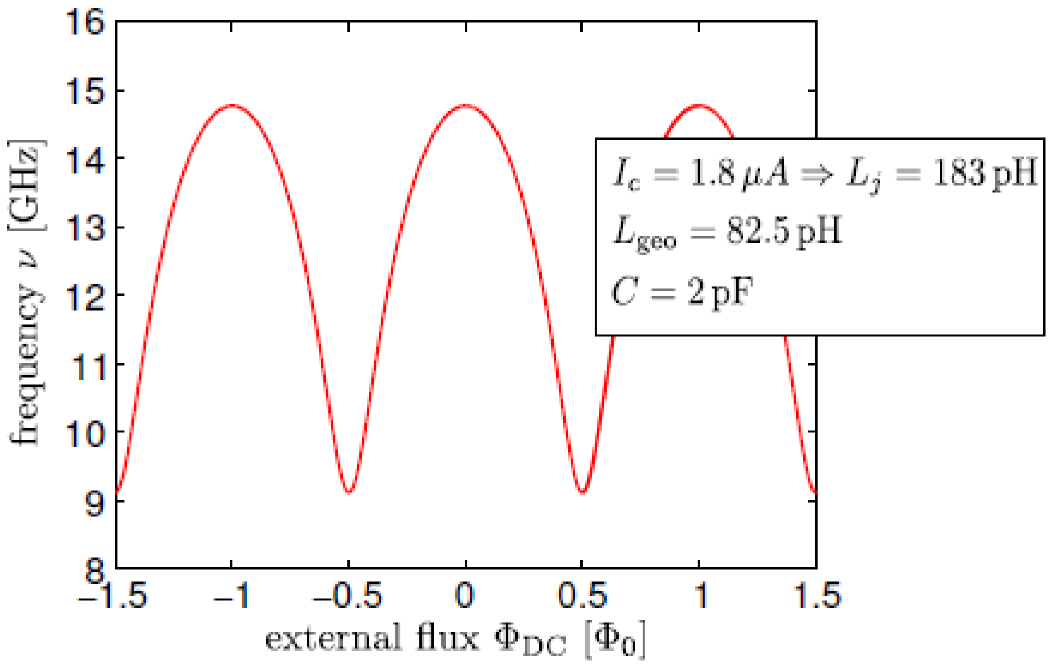
Tunable resonance frequency of a SQUID

SQUID



$$\Phi_{ext} = \Phi_{DC} + \Phi_{RF}$$

calculation



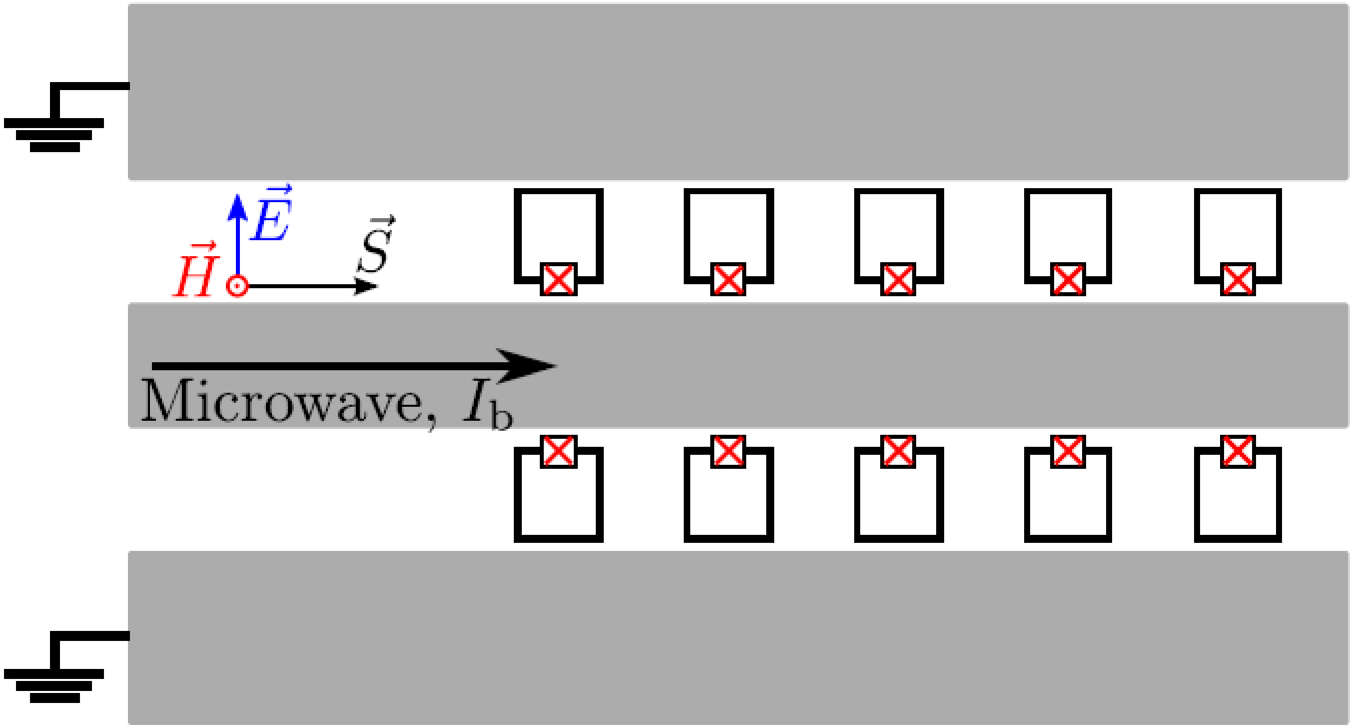
for $\Phi_{RF} \ll \Phi_0$

$$L_J(\Phi_{DC}) = \frac{h}{2e\, I_C \cos\varphi}$$

$$\nu_{res} = \frac{1}{2\pi\sqrt{L_{tot}C}}$$

1D SQUID metamaterial

- 1D coplanar transmission line
- coupling to magnetic component of the field
- Central conductor is used for both Φ_{DC} and Φ_{RF}



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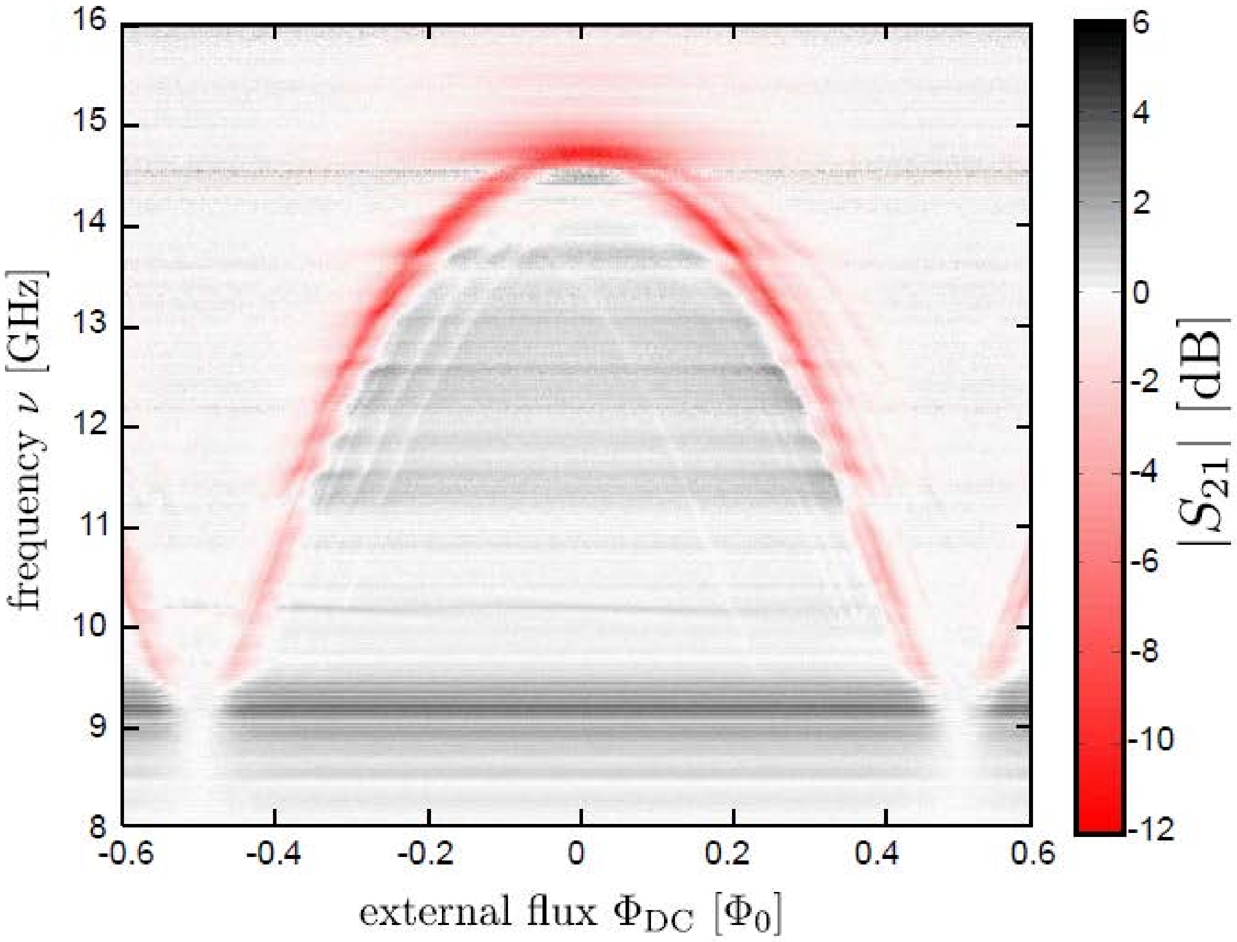
SQUID-based 1D metamaterial

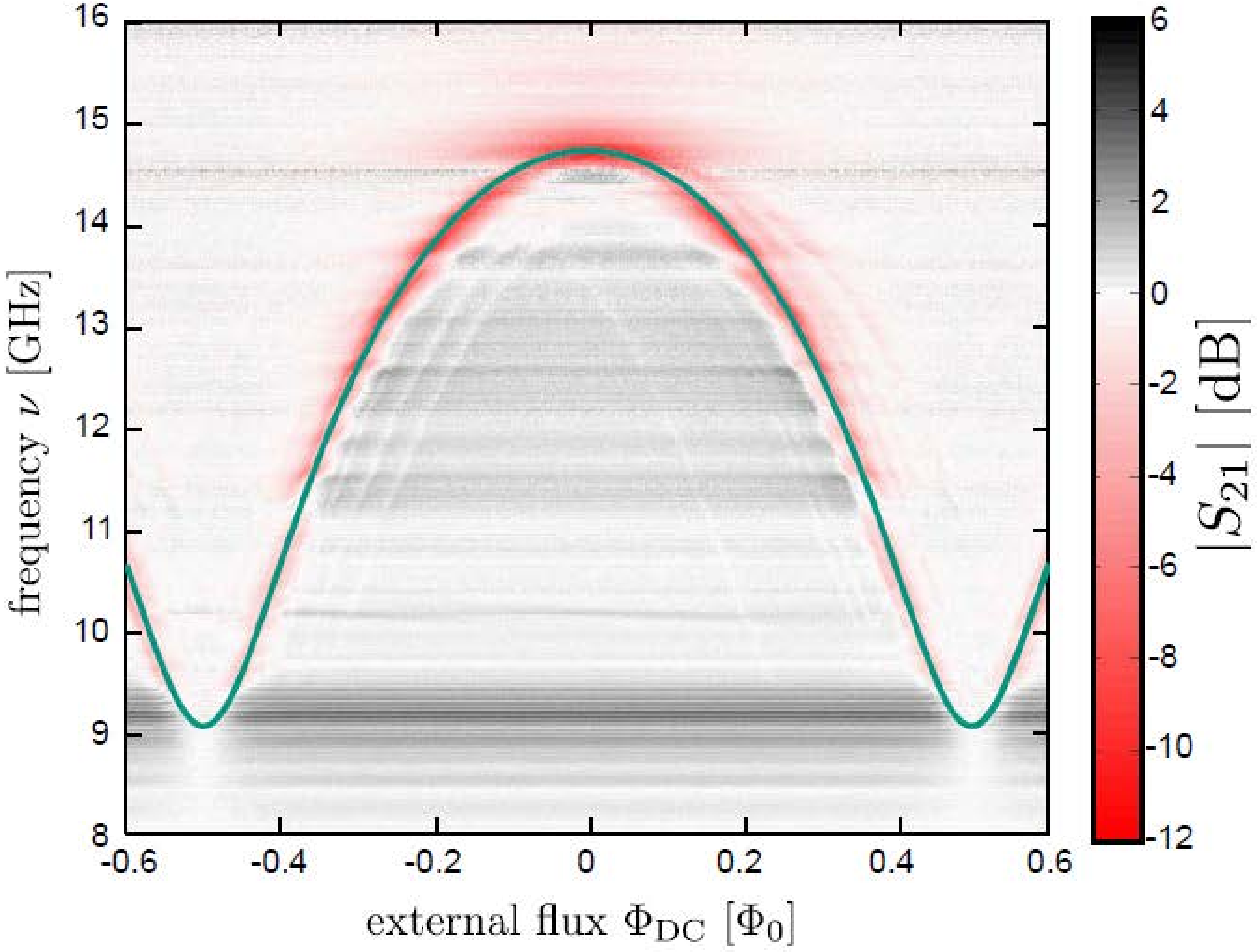
Results for 54 SQUIDs: tuning the transmission S_{21} by magnetic flux



- 54 SQUIDs
- pitch 92 μm
- MW power @ sample $P \approx -90$dBm

P. Jung, S. Butz, S. V. Shitov, and A. V. Ustinov, *Appl. Phys. Lett.* **102**, 062601 (2013)

Fitting experiment to theory



fit results:

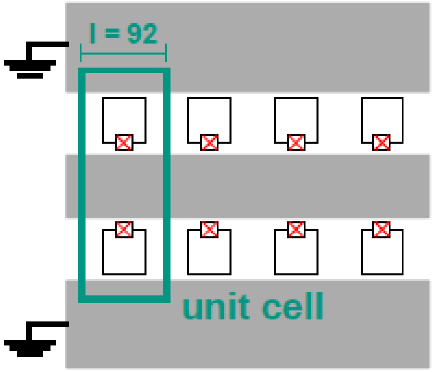
- $I_c = 1.8\,\mu A$
- $C = 2.0\,pF$
- $L_{geo} = 82.5\,pH$ (fixed)

design values:

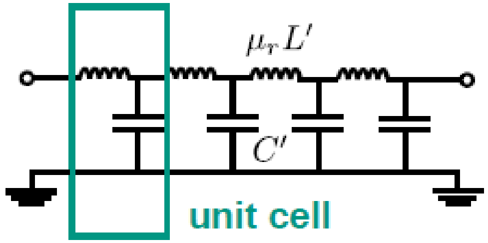
- $I_c = 2\,\mu A$
- $C = 2\,pF$
- $L_{geo} = 82.5\,pH$

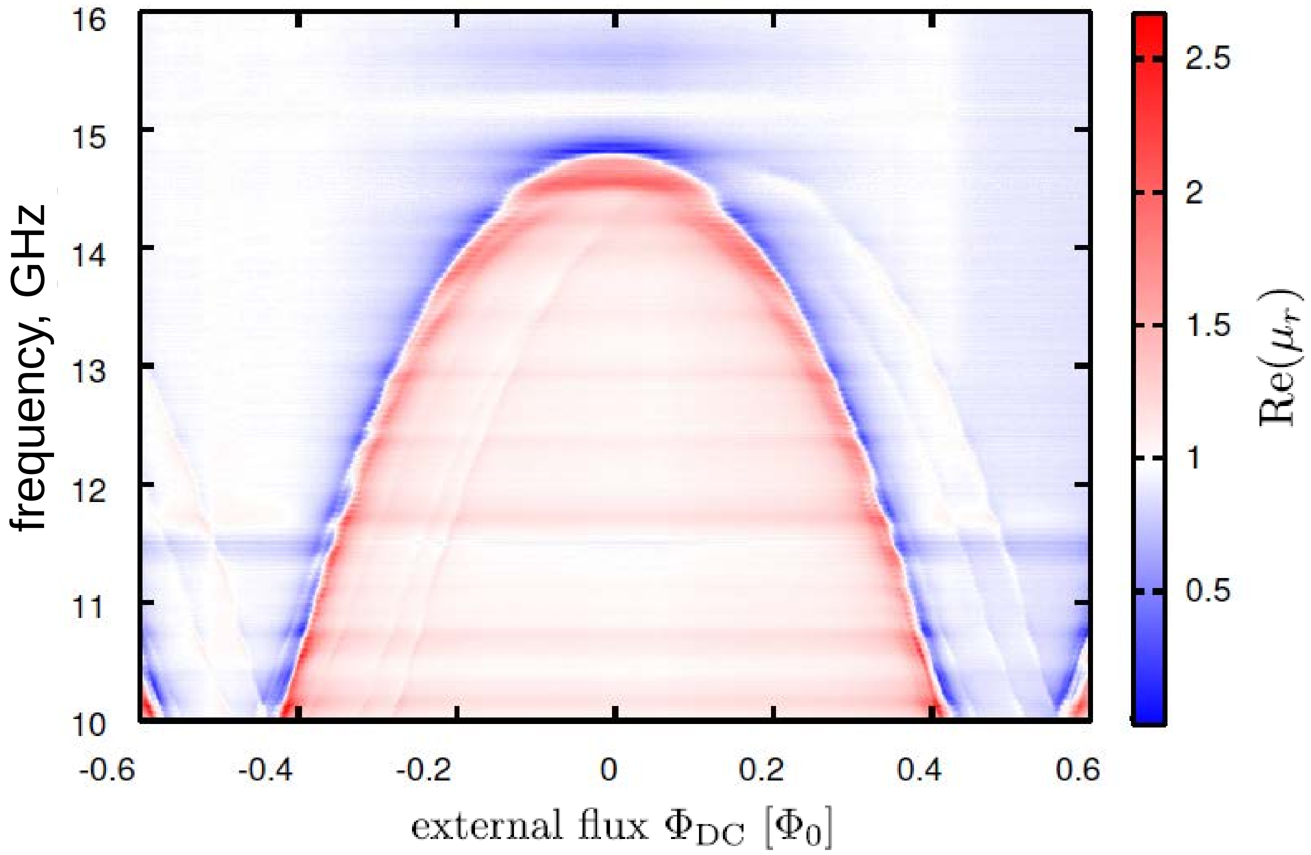
Extracting effective μ_r

sketch:



transmission line model:

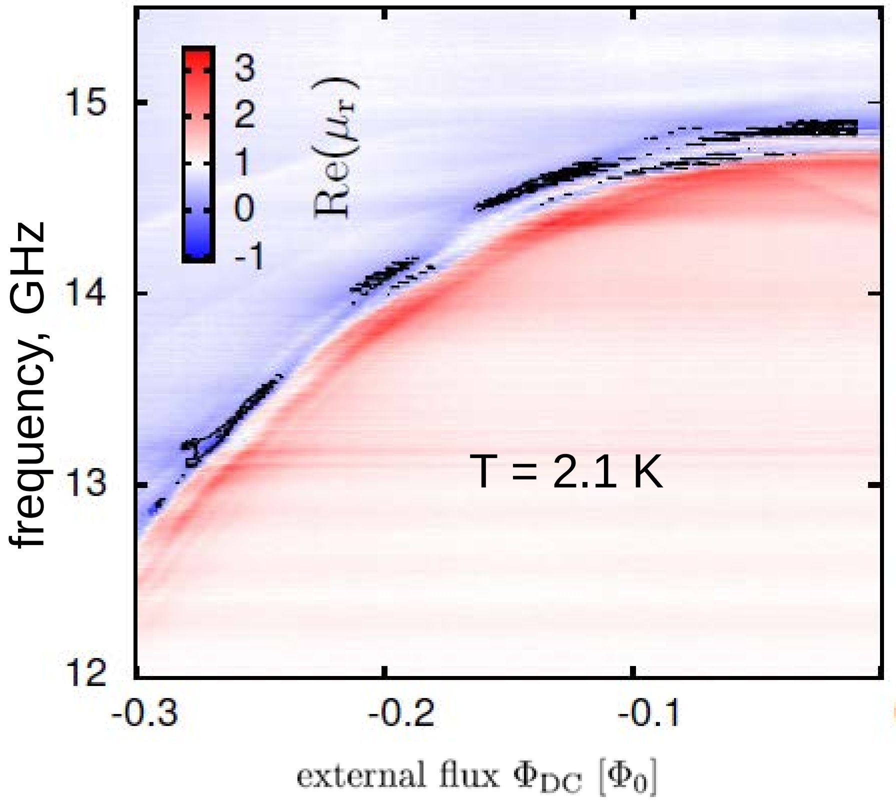


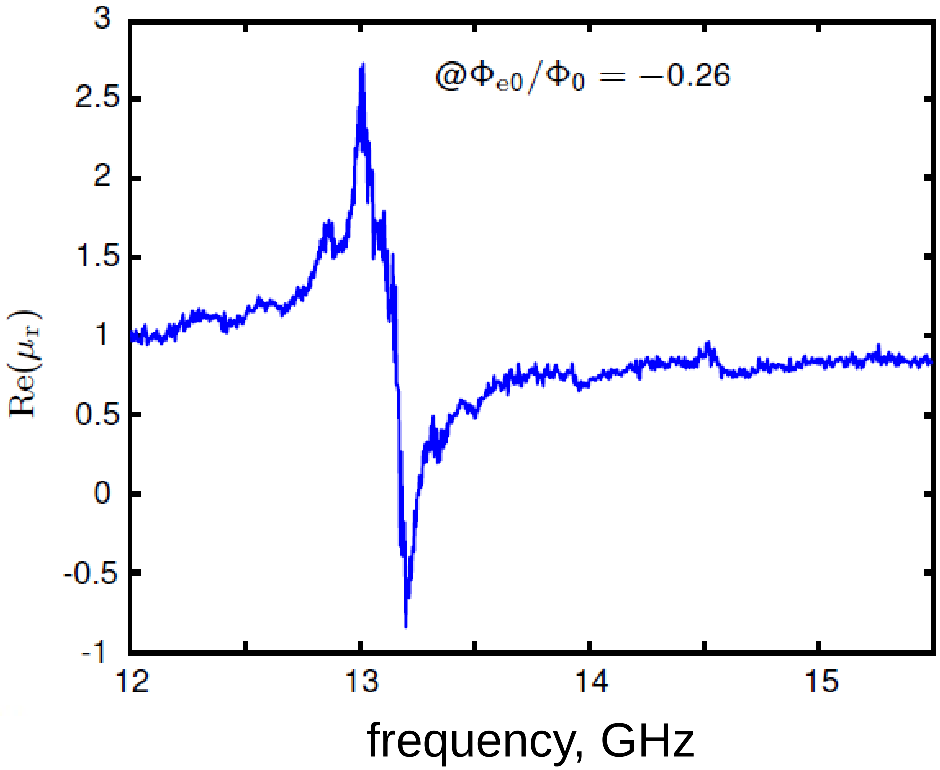


S. Butz, P. Jung, L.V. Filippenko, V.P. Koshelets, and A. V. Ustinov, Opt. Express **21**, 22540 (2013)

Tuning effective μ_r by magnetic flux

real part of magnetic permeability

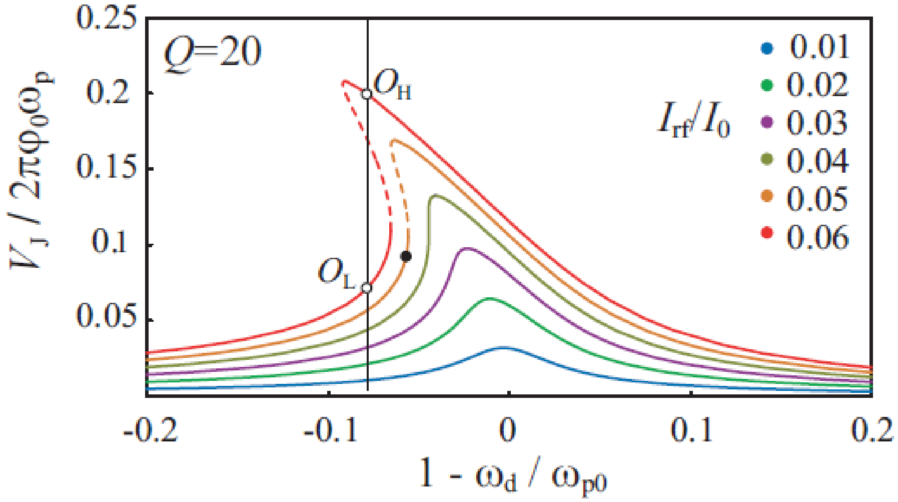


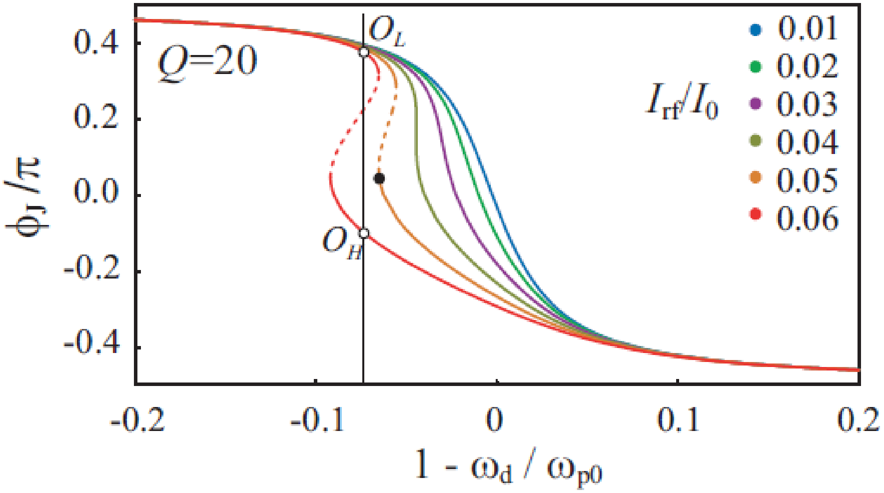


S. Butz, P. Jung, L.V. Filippenko, V.P. Koshelets, and A. V. Ustinov, Opt. Express **21**, 22540 (2013)

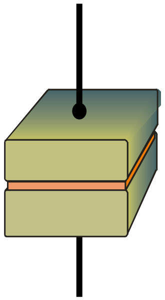
Nonlinear and multi-stable superconducting metamaterials

Nonlinear effects: Multi-stability

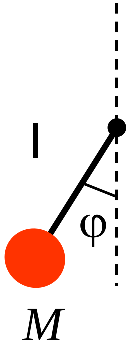




Josephson junction

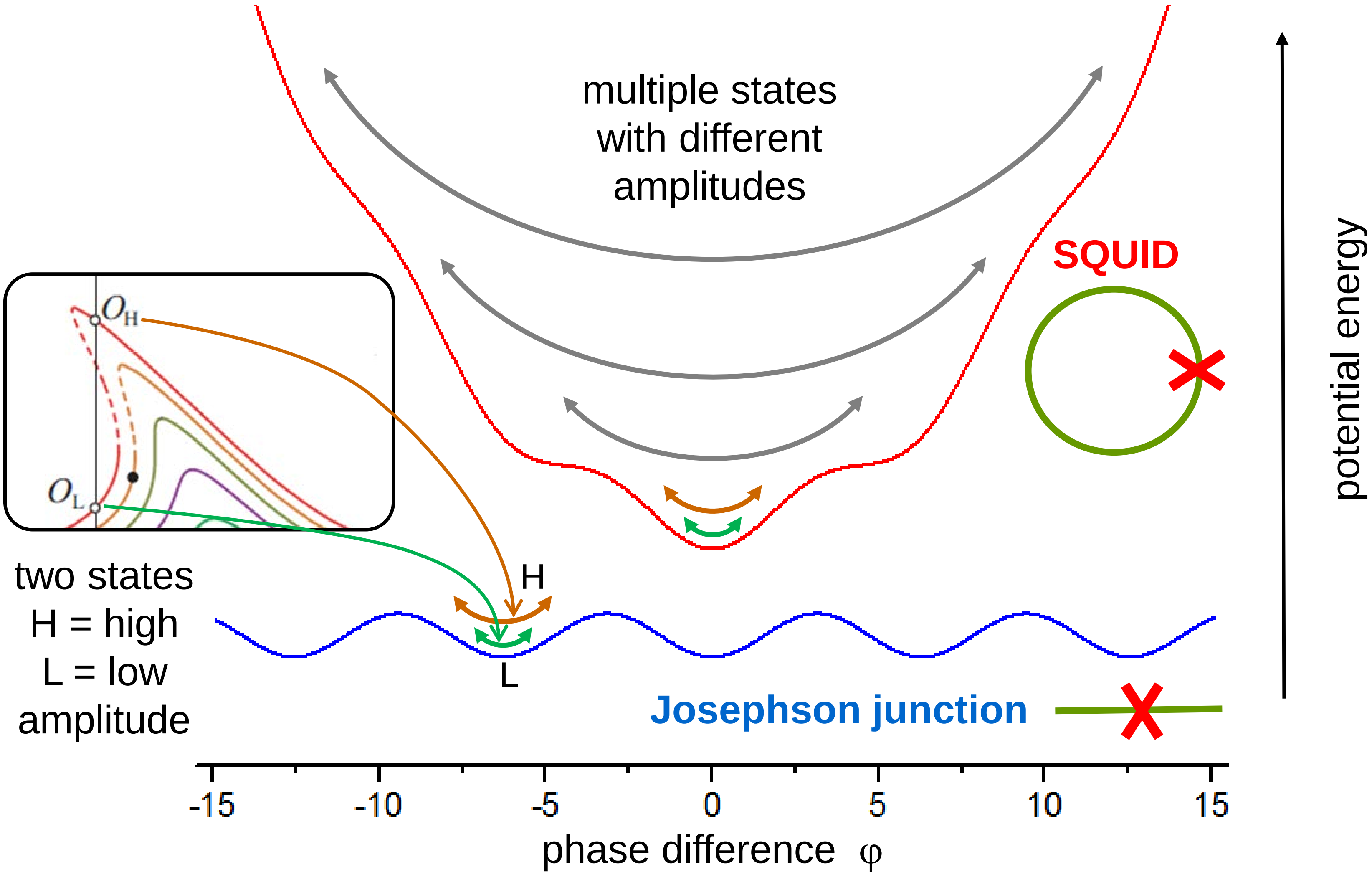


or pendulum



R. Vijay, M. H. Devoret, and I. Siddiqi
Rev.Sci.Intr. **80**, 111101 (2009)

Potential energy of junction and SQUID



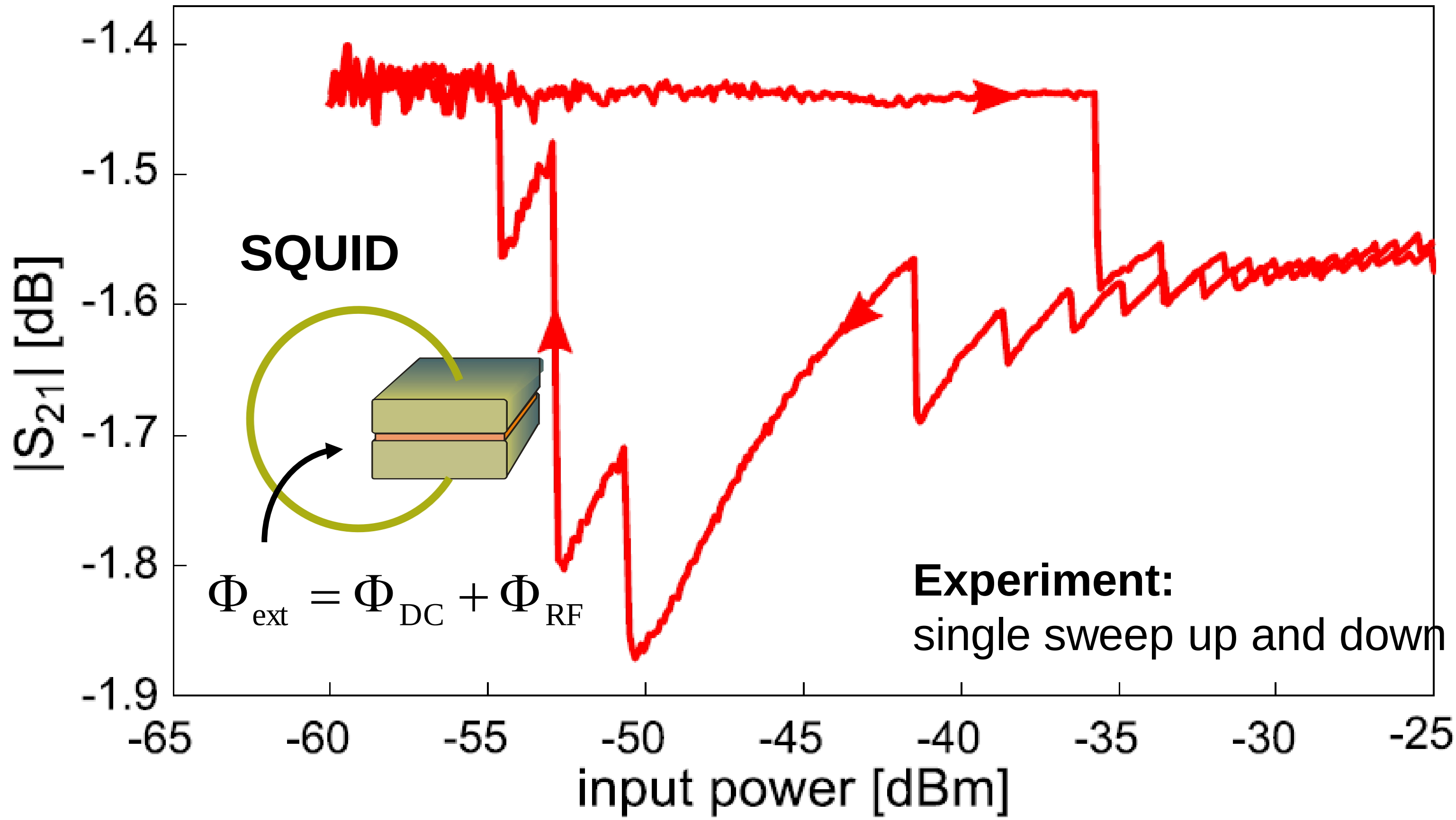
multiple states
with different
amplitudes

SQUID

two states
H = high
L = low
amplitude

Josephson junction

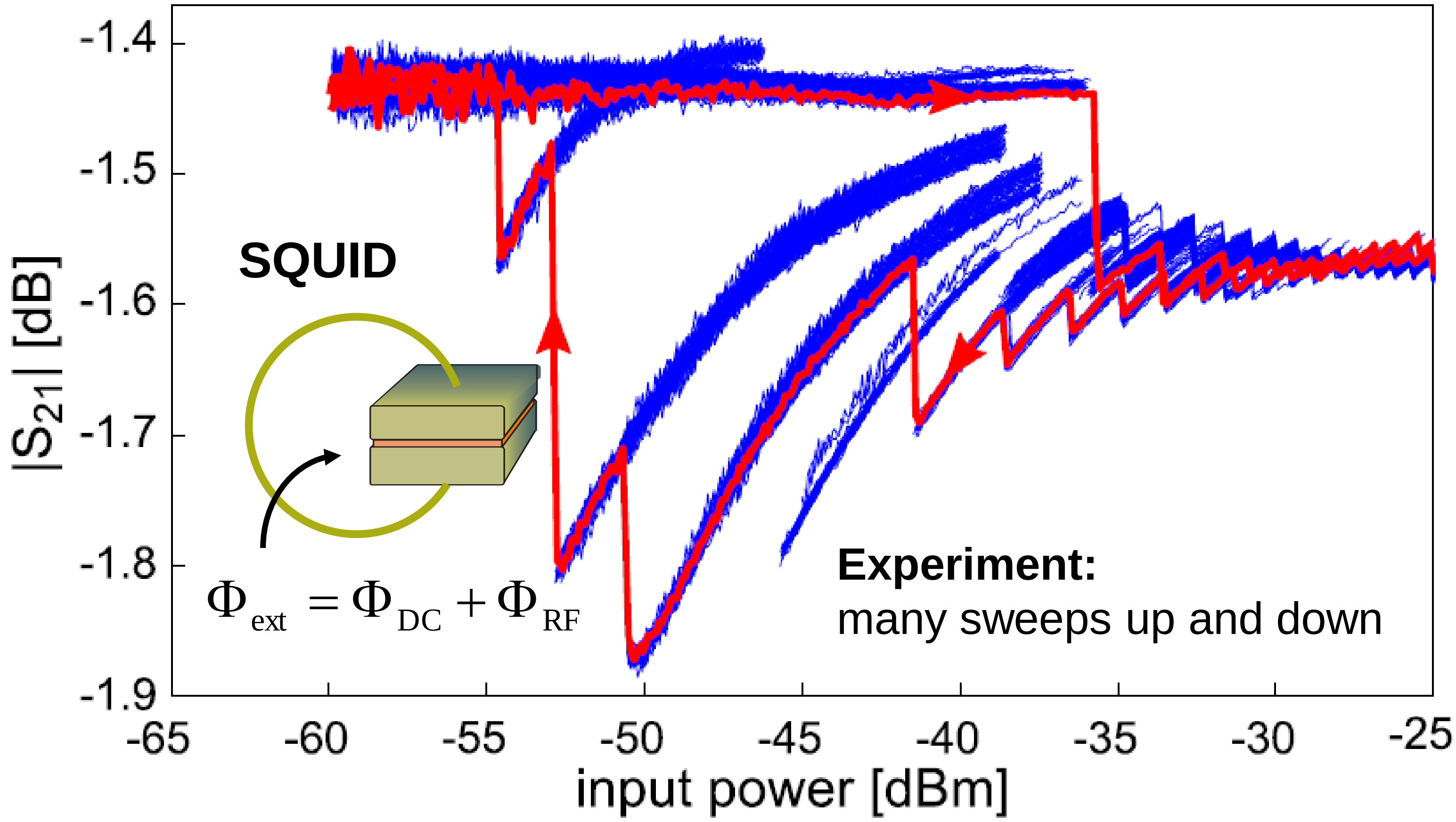
Nonlinear effects: Multi-stable metamaterial



Experiment:
single sweep up and down

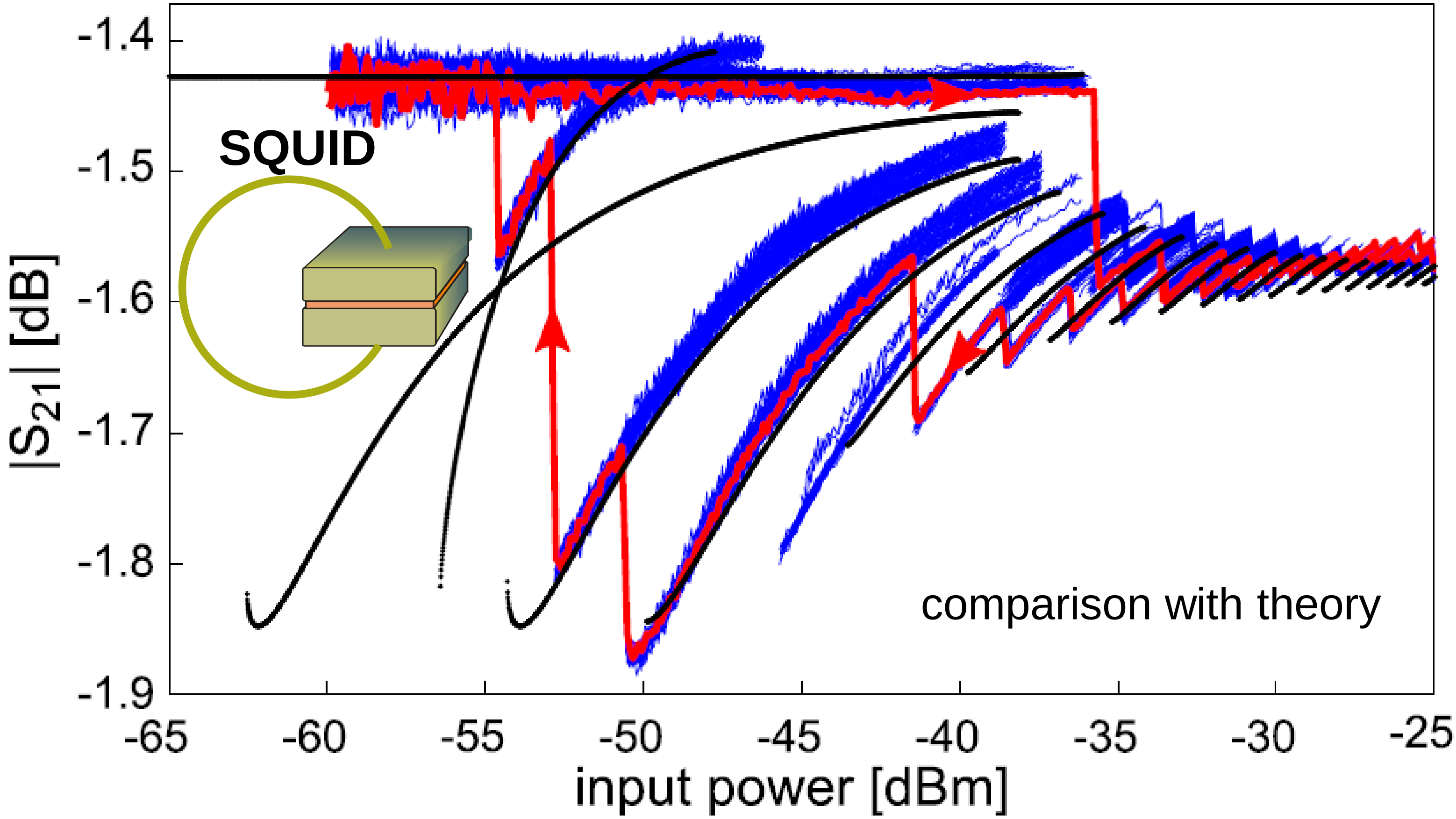
P. Jung, S. Butz, M. Marthaler, M.V. Fistul, J. Leppäkangas, V.P. Koshelets, and A.V. Ustinov, Nature Commun. **5**, 3730 (2014)

Nonlinear effects: Multi-stable metamaterial



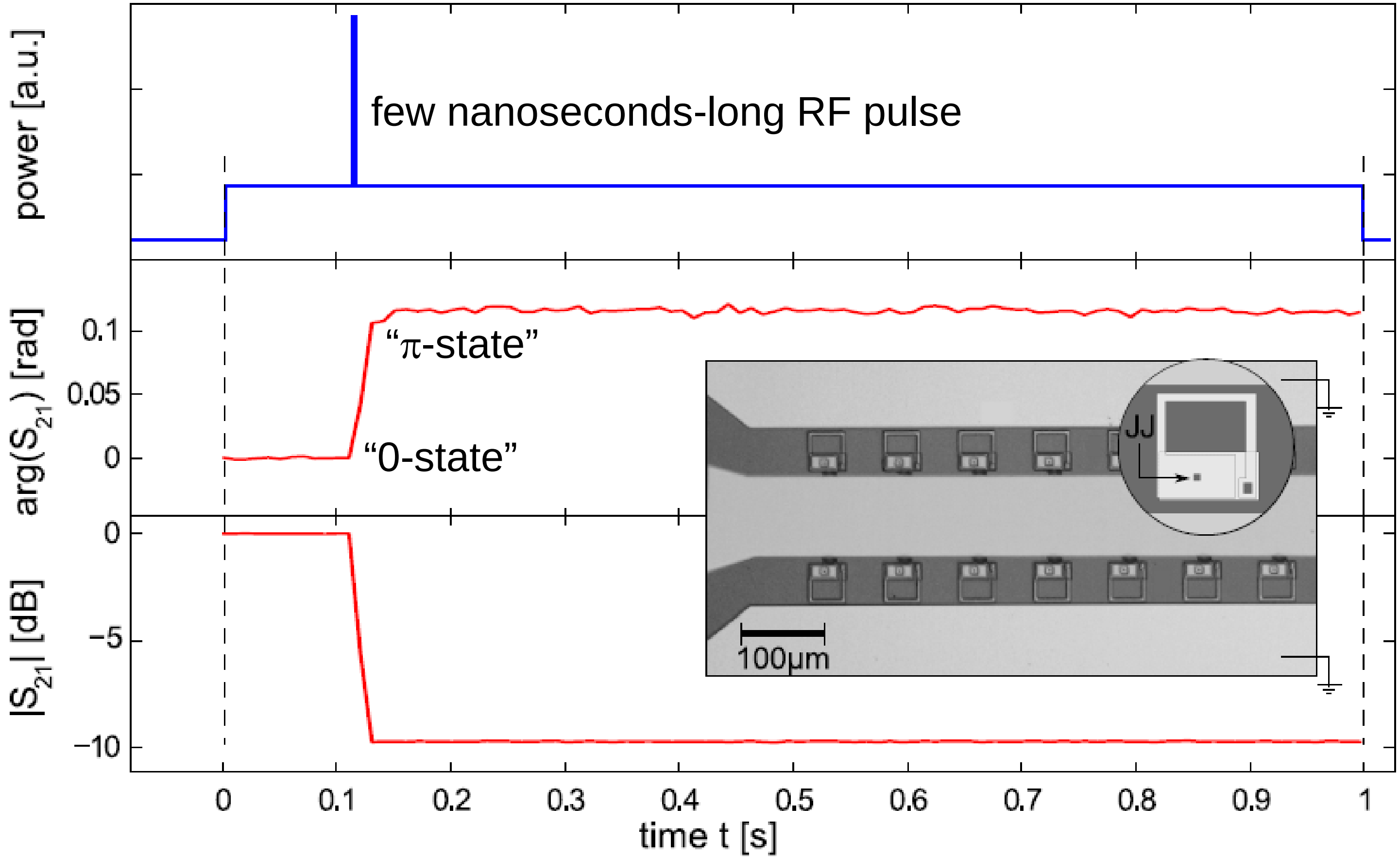
P. Jung, S. Butz, M. Marthaler, M.V. Fistul, J. Leppäkangas, V.P. Koshelets and A.V. Ustinov, Nature Commun. **5**, 3730 (2014)

Multi-stability: Comparison with theory



P. Jung, S. Butz, M. Marthaler, M.V. Fistul, J. Leppäkangas, V.P. Koshelets and A.V. Ustinov, Nature Commun. **5**, 3730 (2014)

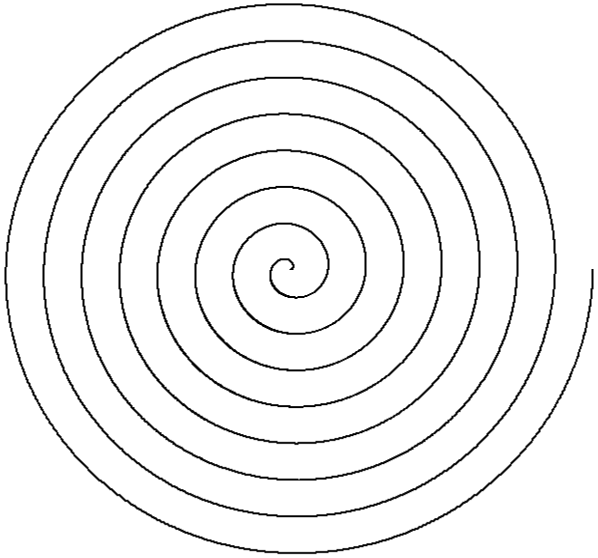
“All-optical” switching between stable states



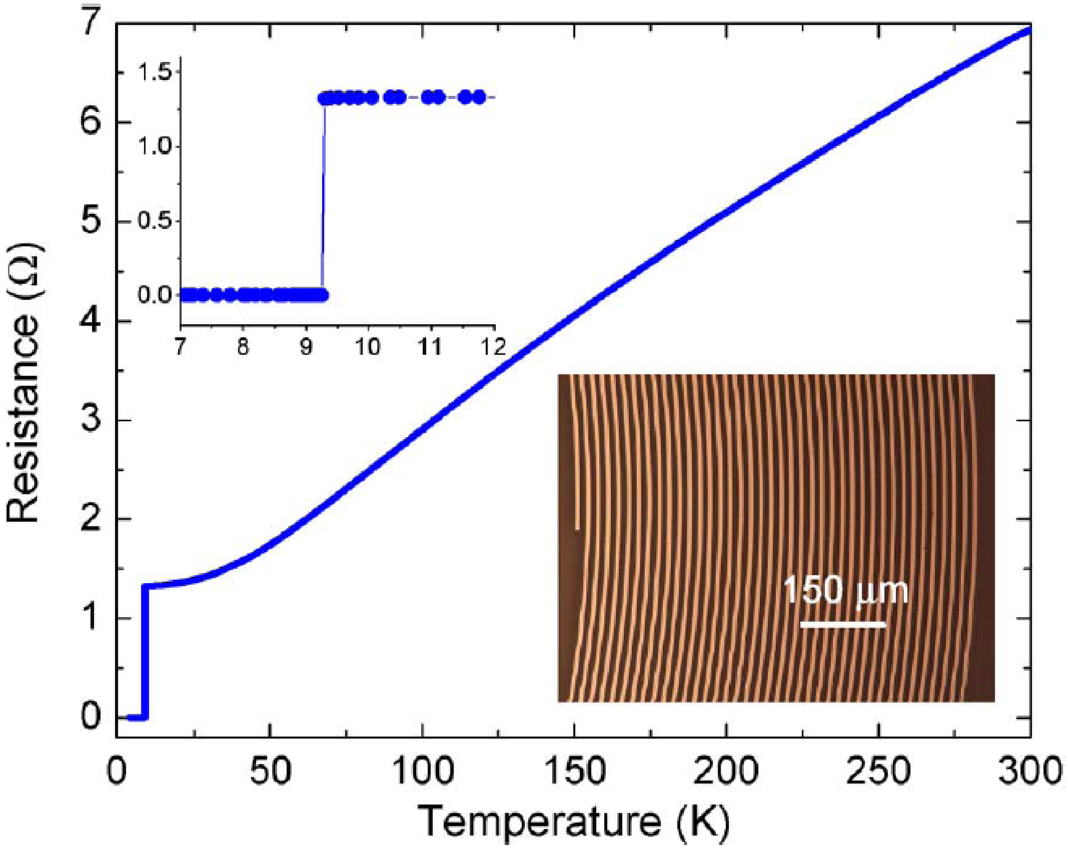
P. Jung, S. Butz, M. Marthaler, M.V. Fistul, J. Leppäkangas, V.P. Koshelets and A.V. Ustinov, Nature Commun. **5**, 3730 (2014)

Ultra-compact low-loss resonators

Superconducting spiral resonator

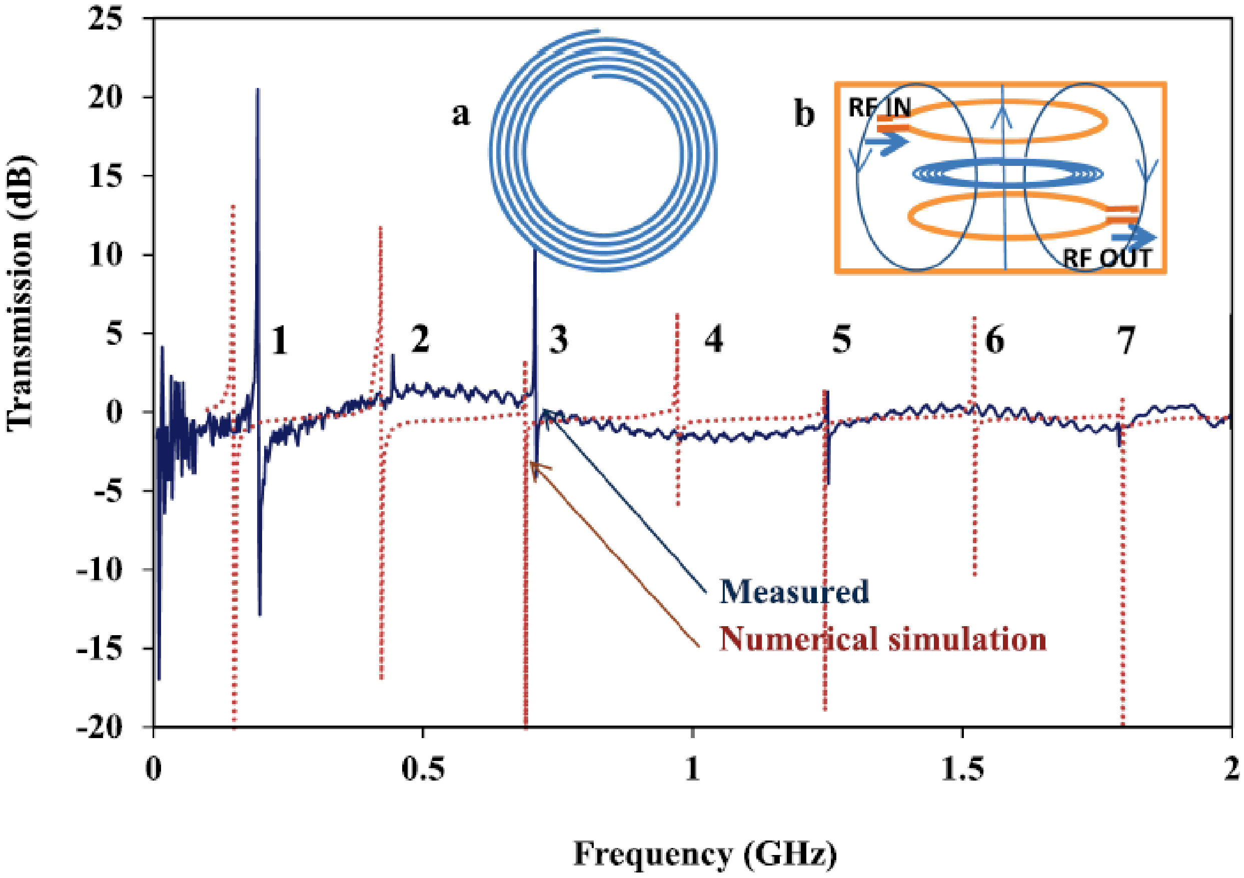


compact monofilar
Archimedean spiral resonator



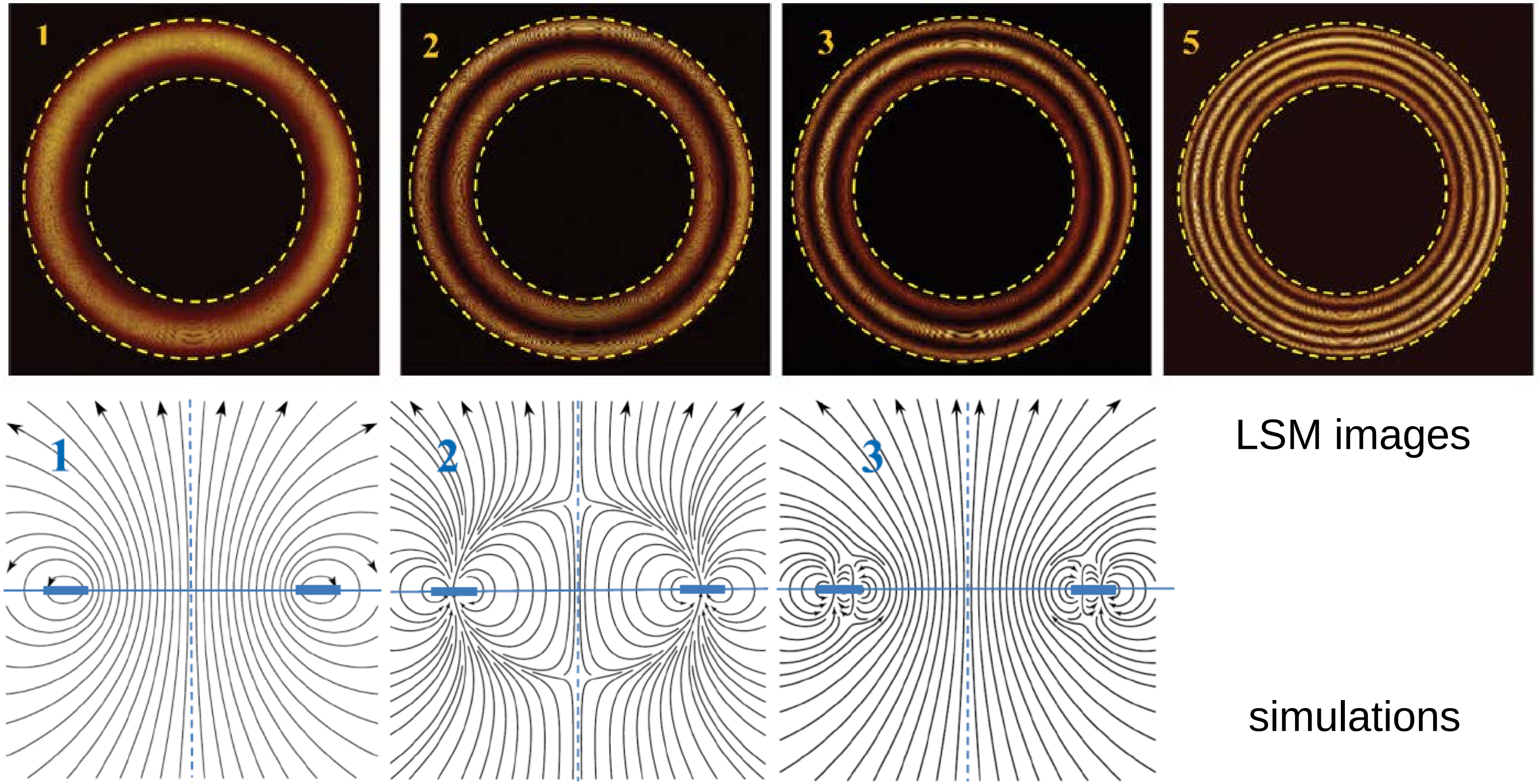
C. Kurter, A.P. Zhuravel, J. Abrahams, C.L. Bennett, A.V. Ustinov, and S.M. Anlage, IEEE Trans. Appl. Supercond. **21**, 709 (2011)

Superconducting spiral resonator



N. Maleeva, M.V. Fistul, A. Karpov, A.P. Zhuravel, A. Averkin, P. Jung, and A. V. Ustinov,
J. Appl. Phys. **115**, 064910 (2014)

Imaging resonant modes in a superconducting spiral resonator

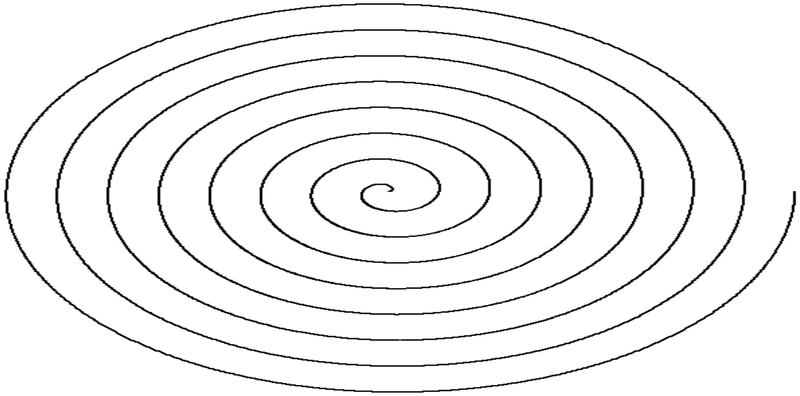


LSM images

simulations

N. Maleeva, M.V. Fistul, A. Karpov, A.P. Zhuravel, A. Averkin, P. Jung, and A. V. Ustinov, J. Appl. Phys. **115**, 064910 (2014)

Ultra-compact superconducting spiral resonators

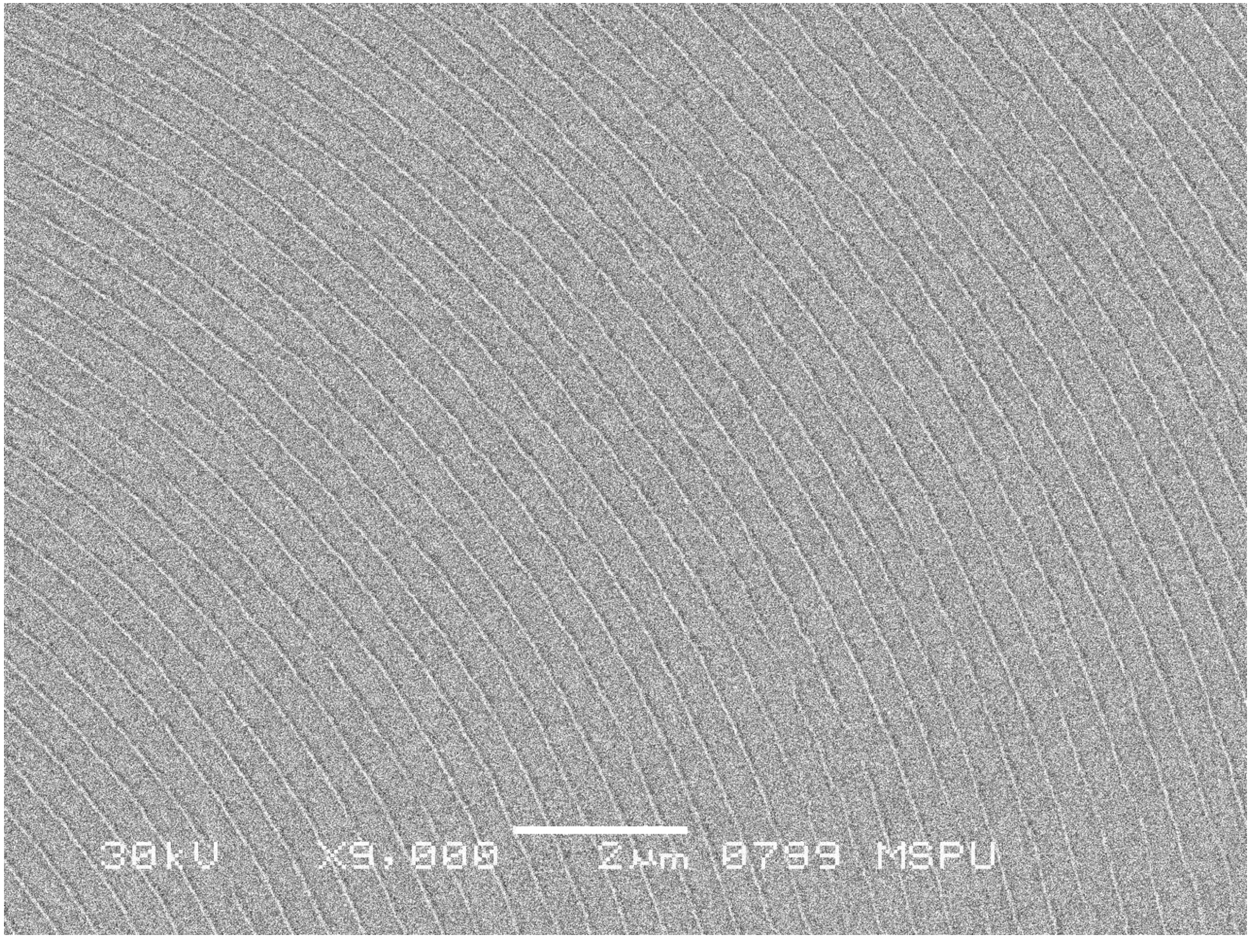


$$f_0 = 1/(2\pi\sqrt{(L_g + L_k)C}$$

In a superconducting 100-nm wide 5 nm thick NbN nanowire
the kinetic inductance L_k can be dominating the geometric inductance L_g
by a factor > 100

G. Goltsman et al., IEEE Trans. Appl. Supercond. **17**, 246 (2007)
A. J. Annunziata et al., Nanotechnology **21**, 445202 (2010)

Spiral resonator of 100 nm wide NbN wire



G. Goltsman et al., IEEE Trans. Appl. Supercond. **17**, 246 (2007)

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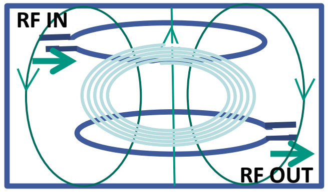
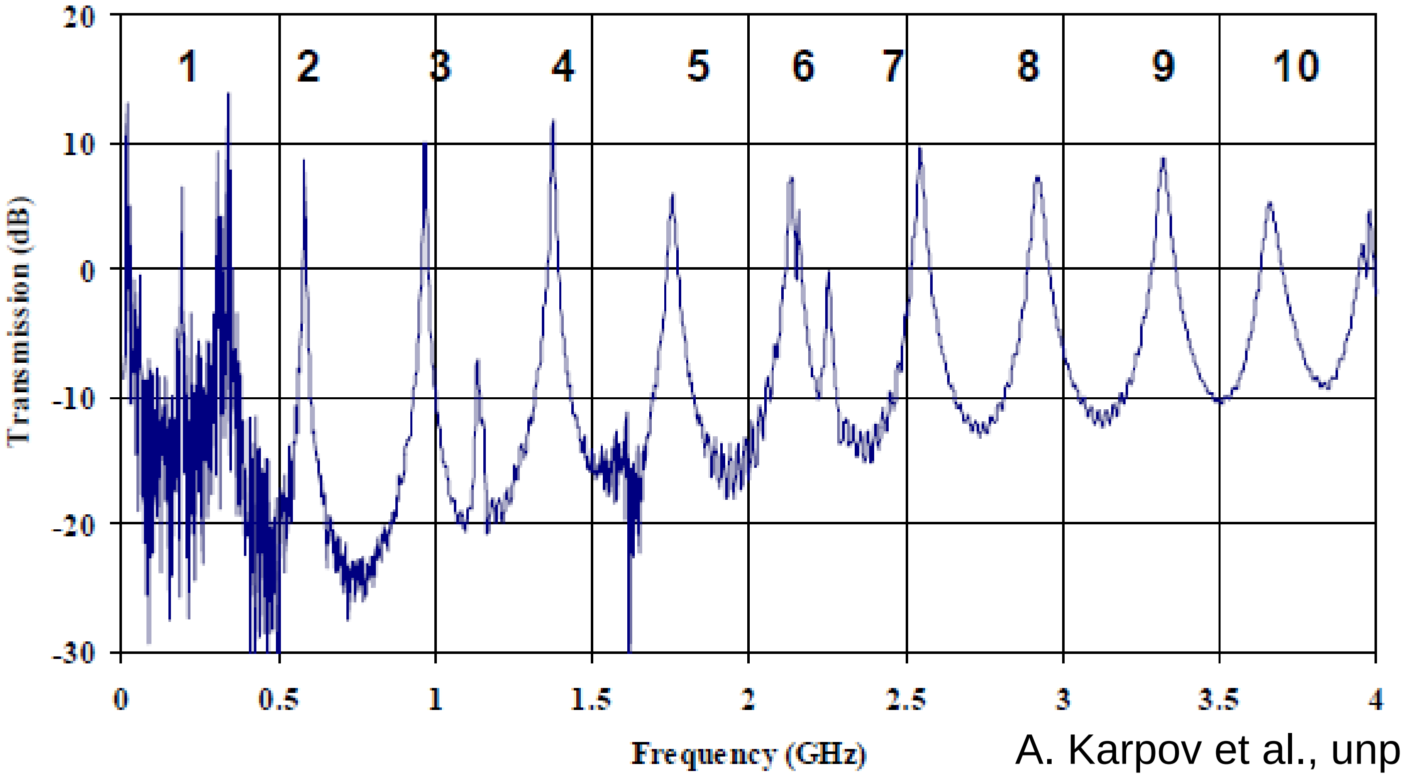
Spiral resonator of 100 nm wide NbN wire



1st resonance frequency
f_1 =193 MHz

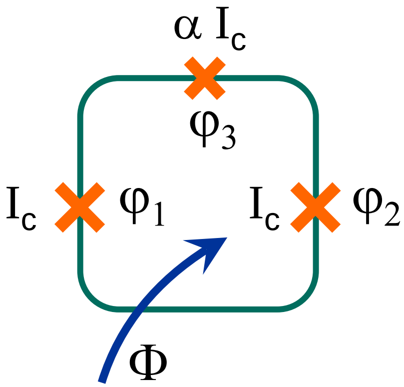
wavelength λ = 1.5 m
resonator size d = 100 μm
yields λ/d = **15000**
=> size/wavelength ≈ 10^{-4}



A. Karpov et al., unpublished

Quantum metamaterials

Superconducting flux qubit



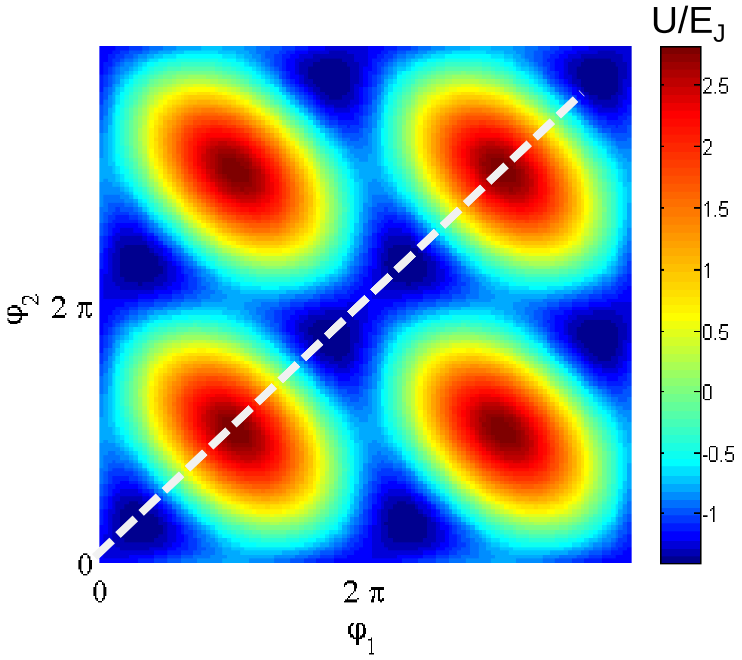
flux quantization:

$$\varphi_1+\varphi_2+\varphi_3+2\pi\frac{\Phi}{\Phi_0}=2\pi n$$

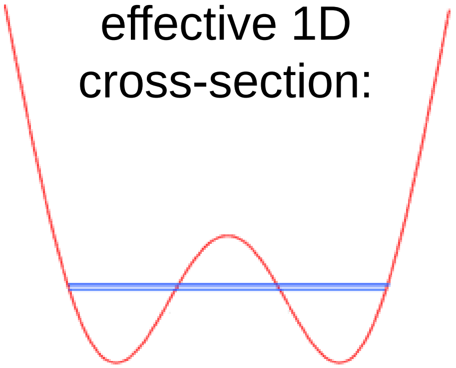
effective 2D potential:

$$\frac{U}{E_J}=\cos\varphi_1+\cos\varphi_2+\alpha\cos\left(-\varphi_1-\varphi_2-2\pi\frac{\Phi_{ext}}{\Phi_0}\right)$$

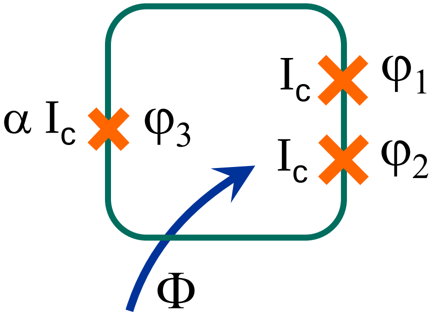
Mooij et al. Science **285**, 1036 (1999)
Van der Wal et al. Science **290**,1140 (2000)

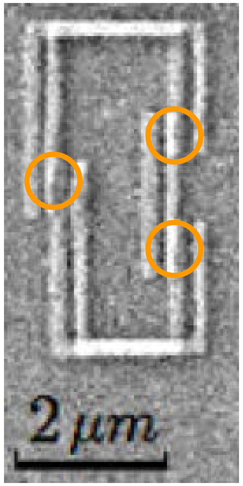


effective 1D cross-section:



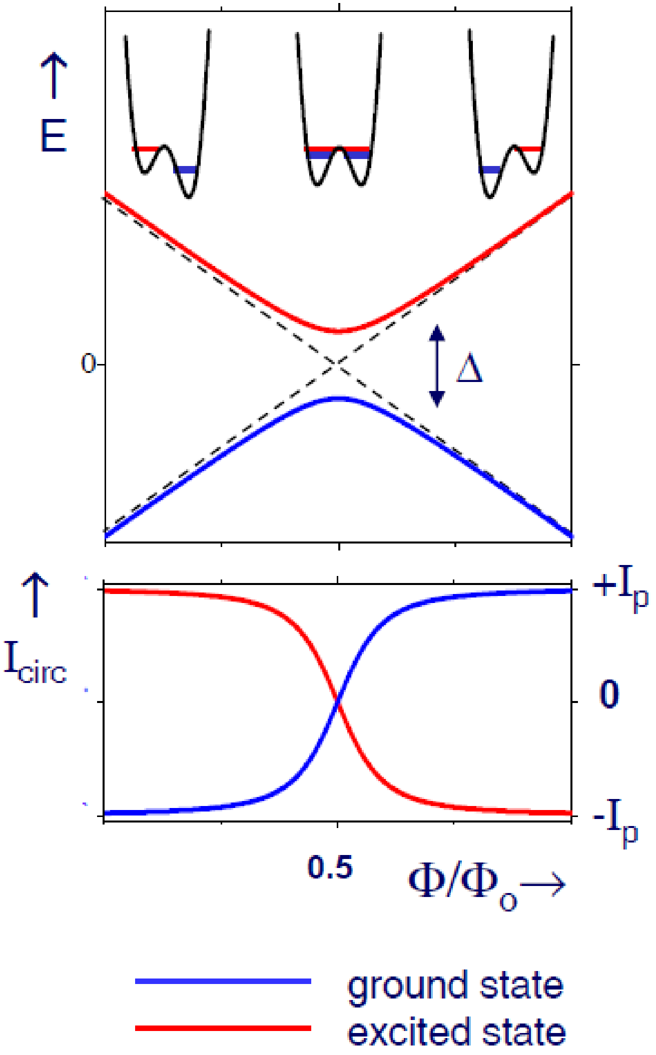
Superconducting flux qubit as a quantum two-level system



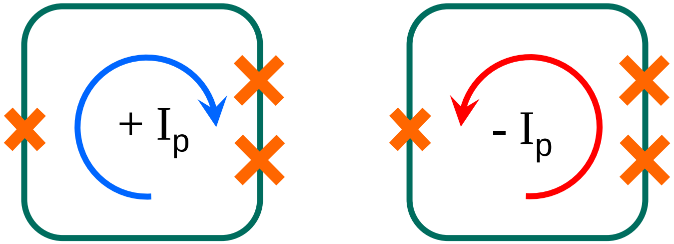


magnetic flux bias $\Phi \sim \Phi_0/2$

$$H = \frac{1}{2}(\varepsilon\sigma_z + \Delta\sigma_x)$$



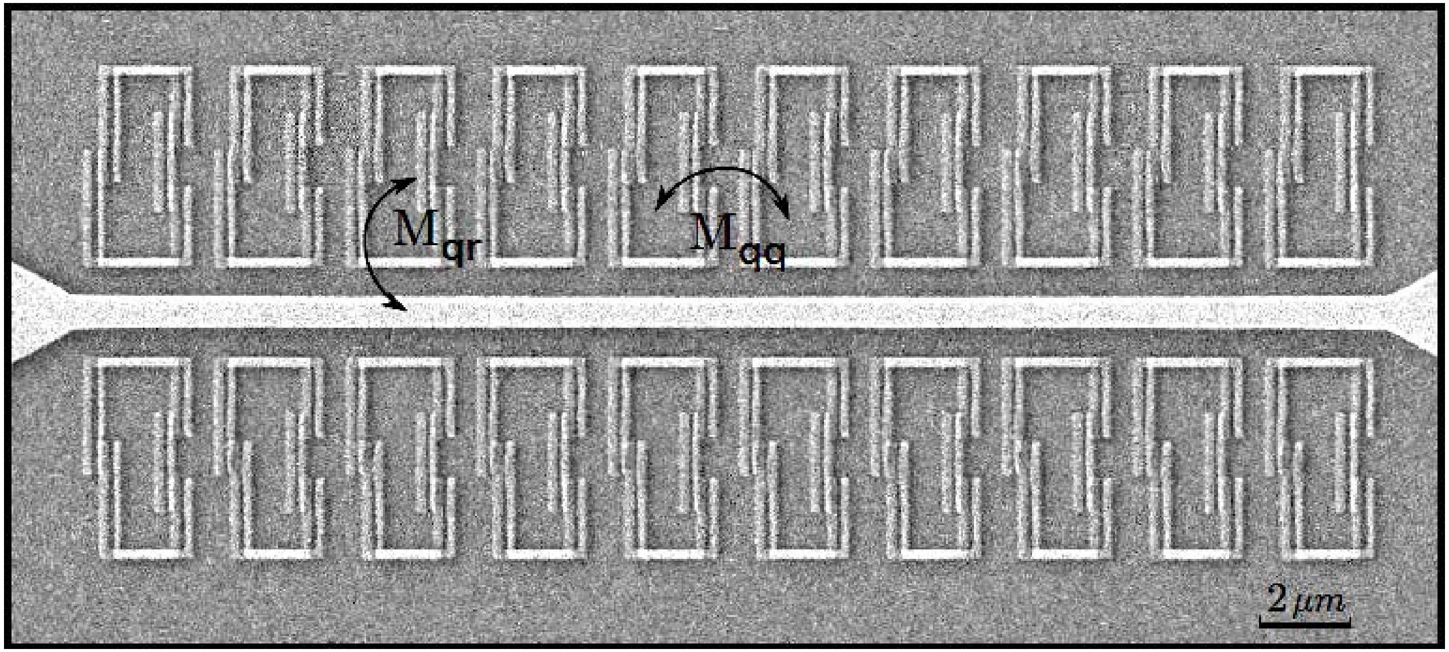
persistent current states ± I$_p$



J. Clarke and F. K. Wilhelm, *Nature* **453**, 1031 (2008)

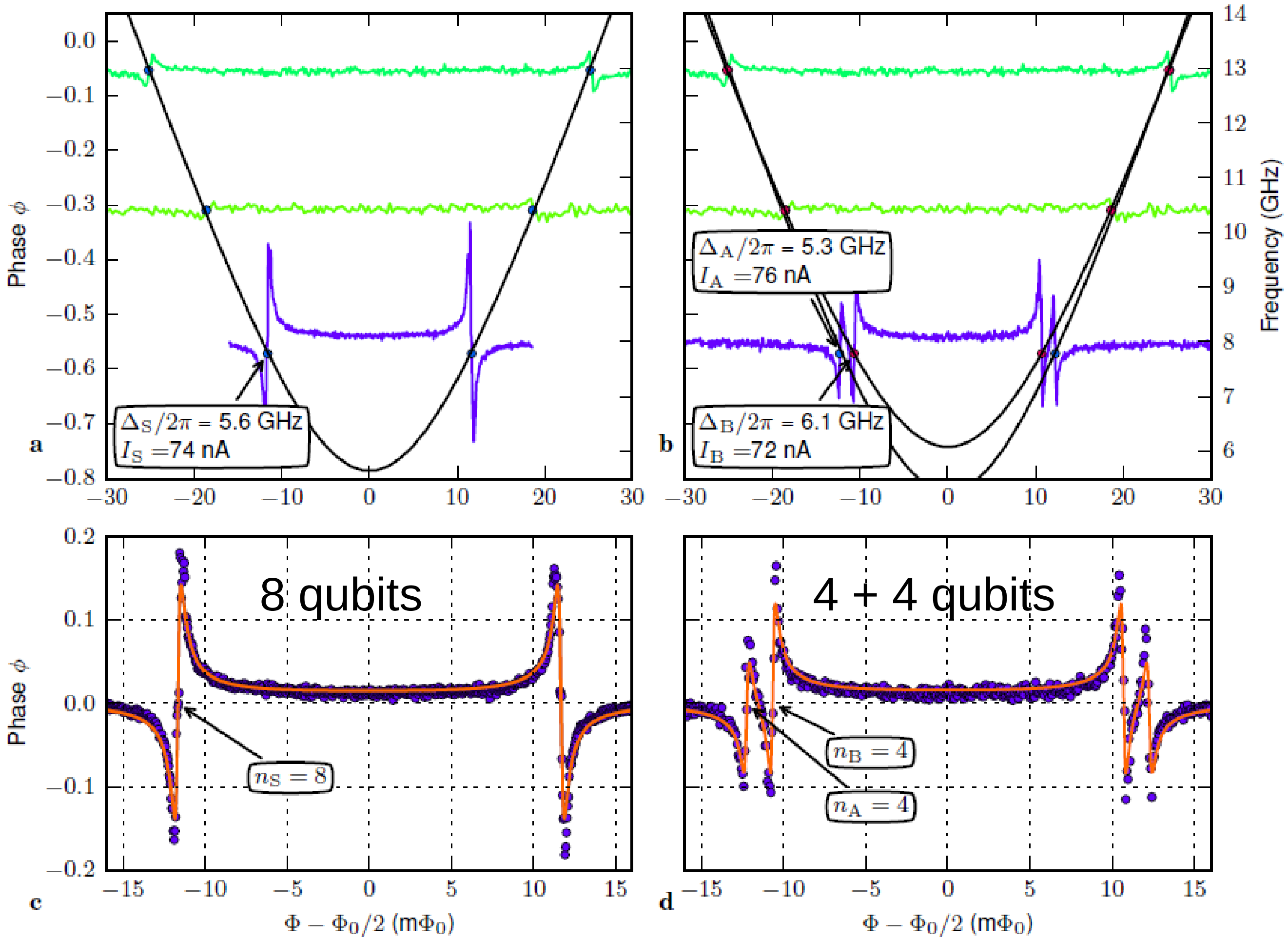
Superconducting quantum metamaterial: array of flux qubits

20 flux qubits



P. Macha, G. Oelsner, J.-M. Reiner, M. Marthaler, S. André, G. Schön, U. Huebner, H.-G. Meyer, E. Il'ichev, and A. V. Ustinov, *Nature Commun.* **5**, 5146 (2014)

Collective coupling of 8 qubits out of 20



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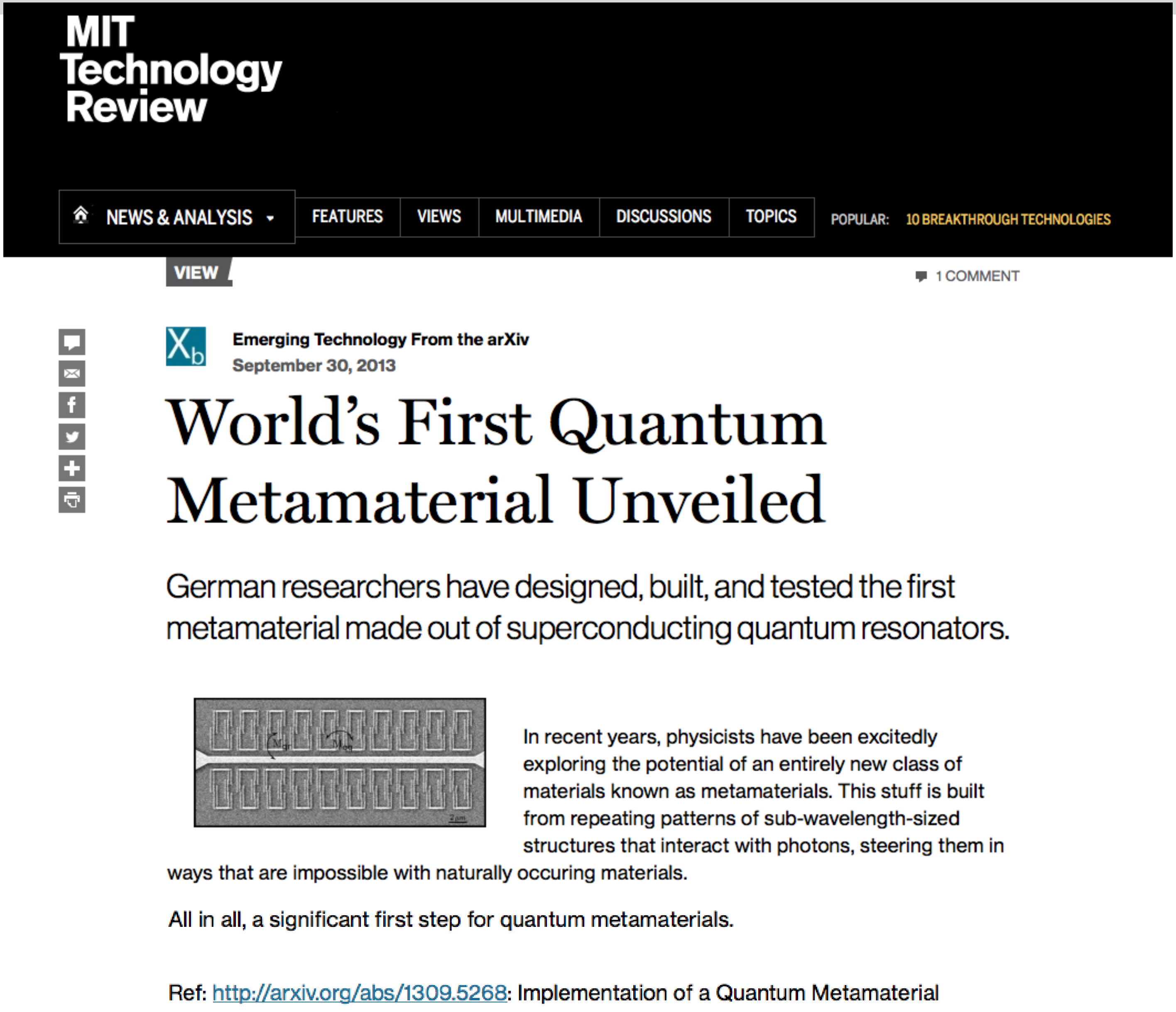

Emerging Technology From the arXiv
September 30, 2013

World's First Quantum Metamaterial Unveiled

German researchers have designed, built, and tested the first metamaterial made out of superconducting quantum resonators.

In recent years, physicists have been excitedly exploring the potential of an entirely new class of materials known as metamaterials. This stuff is built from repeating patterns of sub-wavelength-sized structures that interact with photons, steering them in ways that are impossible with naturally occuring materials.

All in all, a significant first step for quantum metamaterials.

Ref: http://arxiv.org/abs/1309.5268: Implementation of a Quantum Metamaterial

Summary

- **Tunable and switchable SQUID based metamaterials**
  - **decreasing size of meta-atoms without extra loss**
  - **easily tunable frequency (magnetic field, current, temperature)**
  - **strong nonlinearity (if needed, e.g. for parametric gain)**
- **Ultra-compact low-loss resonators**
  - **size/wavelength $< 10^{-4}$ is within reach**
- **Quantum metamaterials**
  - **arrays of superconducting qubits**
  - **quantum optics with artificial atoms**
- **Applications**
  - **MRI imaging**
  - **tunable antennas**
  - **ultra-compact filters**
  - **reflective back planes, metasurfaces**

Review: P. Jung, A. V. Ustinov, S.M. Anlage, Supercond. Sci. Techn. **27**, 073001 (2014)