Superconducting Metamaterials

P. Jung\(^1\), S. Butz\(^1\), N. Maleeva\(^1,2\), A. Averkin\(^2\), N. Abramov\(^2\), K. Shulga\(^2,3\)
V. P. Koshelets\(^2,4\), L. V. Filippenko\(^2,4\), V. Chichkov\(^2\)
A. Karpov\(^2\), S. V. Shitov\(^2,4\), V. V. Ryazanov\(^2,3\), and A. V. Ustinov\(^1,2,3\)

\(^1\) Karlsruhe Institute of Technology (KIT), Germany
\(^2\) National University of Science and Technology (MISiS), Moscow, Russia
\(^3\) Russian Quantum Center (RQC), Moscow, Russia
\(^4\) Kotel’nikov Institute of Radio Engineering and Electronics (IREE), Moscow, Russia
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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
Electromagnetic wave in a material

Water: $a \approx 3 \text{ Å}$

Visible light: $\lambda \approx 390\text{nm} - 700\text{nm}$
Materials are composed out of atoms – smallest resonators “made” by nature

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

size/wavelength $\approx 10^{-3}$
Electromagnetic metamaterials

Controlling the propagation of light through material parameters

\[ n = \sqrt{\varepsilon_r \mu_r} \]

\( n > 0 \)

\( n < 0 \)
Magnetic Meta-Atoms

\[ H_{\text{ext}} \sim e^{i\omega t} \]

\[ \operatorname{Re}(\chi_m) \]

\[ Q_\uparrow \]

\[ \omega_0 \]
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: $a \approx 5$ mm

- Microwaves (X-band): $\lambda \approx 2.5\text{cm} - 3.75\text{cm}$
Modern history of metamaterials

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

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

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

ε < 0
rods

µ < 0
split rings

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Veselago-Pendry lens

Not so modern history of metamaterials ...

(backward waves; mechanical systems)

Edw. Arnold, London (1904) (backward waves)

(phase velocity opposite to the group velocity)


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

\[ I = I_C \sin \varphi + \frac{V}{R} + C \frac{dV}{dt} \]

Josephson inductance

\[ L_J = -V \frac{dI_s}{dt} = \frac{h}{2e I_C \cos \varphi} \]
Superconducting quantum interference device (SQUID)

\[ \Phi_{\text{ext}} = \Phi_{\text{DC}} + \Phi_{\text{RF}} \]

magnetic flux

\[ L_J \text{ is tunable by } \Phi_{\text{ext}} \]
Tunable resonance frequency of a SQUID

\[ \Phi_{\text{ext}} = \Phi_{\text{DC}} + \Phi_{\text{RF}} \]

for \( \Phi_{\text{RF}} \ll \Phi_0 \)

\[ L_j(\Phi_{\text{DC}}) = \frac{h}{2e I_c \cos \varphi} \]

\[ \nu_{\text{res}} = \frac{1}{2\pi \sqrt{L_{\text{tot}} C}} \]

\( I_c = 1.8 \mu A \Rightarrow L_j = 183 \text{ pH} \)

\( L_{\text{geo}} = 82.5 \text{ pH} \)

\( C = 2 \text{ pF} \)
1D SQUID metamaterial

- 1D coplanar transmission line
- Coupling to magnetic component of the field
- Central conductor is used for both $\Phi_{DC}$ and $\Phi_{RF}$

Microwave, $I_b$
SQUID-based 1D metamaterial
Results for 54 SQUIDs:
tuning the transmission $S_{21}$ by magnetic flux

Fitting experiment to theory

**fit results:**
- $I_c = 1.8 \mu A$
- $C = 2.0 \text{ pF}$
- $L_{geo} = 82.5 \text{ pH (fixed)}$

**design values:**
- $I_c = 2 \mu A$
- $C = 2 \text{ pF}$
- $L_{geo} = 82.5 \text{ pH}$
Extracting effective $\mu_r$

Tuning effective $\mu_r$ by magnetic flux

Nonlinear and multi-stable superconducting metamaterials
Nonlinear effects: Multi-stability

R. Vijay, M. H. Devoret, and I. Siddiqi
Potential energy of junction and SQUID

- Two states: H = high, L = low amplitude
- Multiple states with different amplitudes

Phase difference $\varphi$

Josephson junction

SQUID
Nonlinear effects: Multi-stable metamaterial

\[ \Phi_{\text{ext}} = \Phi_{\text{DC}} + \Phi_{\text{RF}} \]

Experiment: single sweep up and down

Nonlinear effects: Multi-stable metamaterial

\[ \Phi_{\text{ext}} = \Phi_{\text{DC}} + \Phi_{\text{RF}} \]

Experiment:
many sweeps up and down

Multi-stability: Comparison with theory

“All-optical” switching between stable states

Ultra-compact low-loss resonators
Superconducting spiral resonator

Superconducting spiral resonator

Imaging resonant modes in a superconducting spiral resonator

Ultra-compact superconducting spiral resonators

\[ f_0 = \frac{1}{2\pi \sqrt{(L_g + L_k)C}} \]

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

Spiral resonator of 100 nm wide NbN wire

Spiral resonator of 100 nm wide NbN wire

1st resonance frequency \( f_1 = 193 \text{ MHz} \)

wavelength \( \lambda = 1.5 \text{ m} \)
resonator size \( d = 100 \text{ \mu m} \)
yields \( \lambda/d = 15000 \)
=> size/wavelength \( \approx 10^{-4} \)

A. Karpov et al., unpublished
Quantum metamaterials
Superconducting flux qubit

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

effective 2D potential:

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

Van der Wal et al. Science 290, 1140 (2000)
Superconducting flux qubit as a quantum two-level system

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

persistent current states \( \pm I_p \)


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Superconducting quantum metamaterial: array of flux qubits

Collective coupling of 8 qubits out of 20

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 occurring materials.

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


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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

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