Superconducting metamaterials for THz technology

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Industry Open Day, Southampton, 13 September 2012

Why superconductors?

0. Low resistance from Radio to THz frequencies
   [Low-loss metamaterials & high-Q resonances]

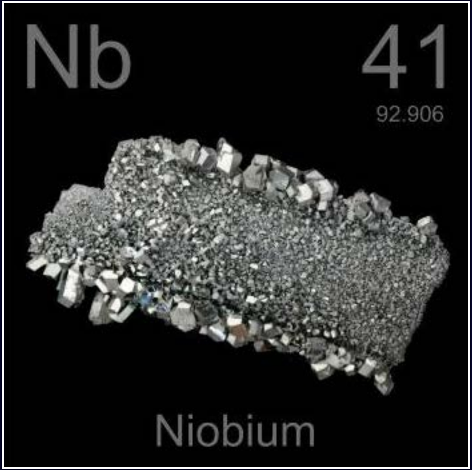
1. Inherently plasmonic media
   [THz plasmonics & compact metamaterials]

2. Sensitive to
   - *temperature* ⇐ [Tuning]
   - magnetic field
   - electric current
   - light

   } [Active control]

3. Macroscopically quantum behavior
   [Nonlinear and quantum metamaterials]

Niobium (Nb)



T_c = 9.2 K
2Δ ~ 0.7 THz

Normal state:
metallic

$YBa_2Cu_3O_7$ (YBCO)

T_c = 90 K
2Δ~ 5 THz

Normal state:
non-metallic

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Metamaterial fabrication

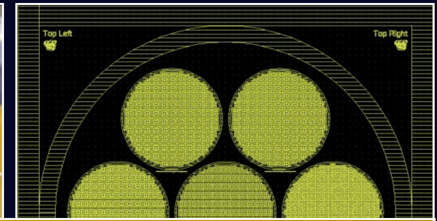
Standard planar techniques:

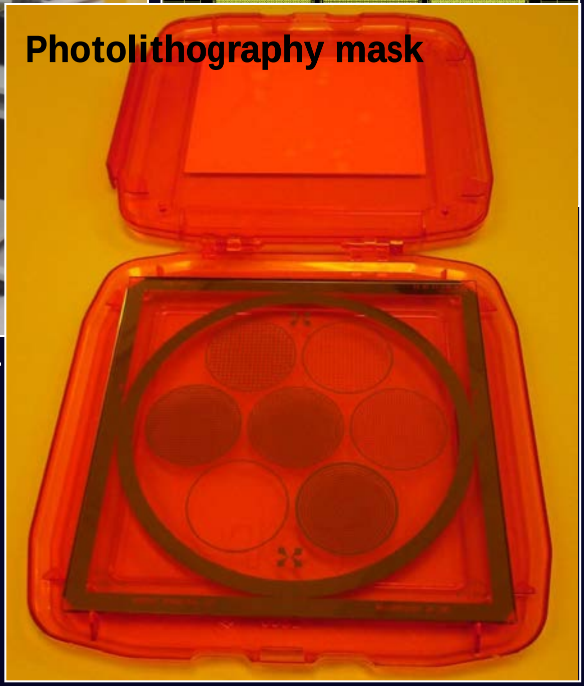
- Photolithography [area up to 7″, resolution 1-2 μm]
- Low-energy plasma etching [sharp features, vertical sidewalls]
- Ion bean milling & e-beam lithography [area tens of μm, resolution ~10 nm]

Mask-alignment + UV exposure

Plasma etcher

Plasma discharge

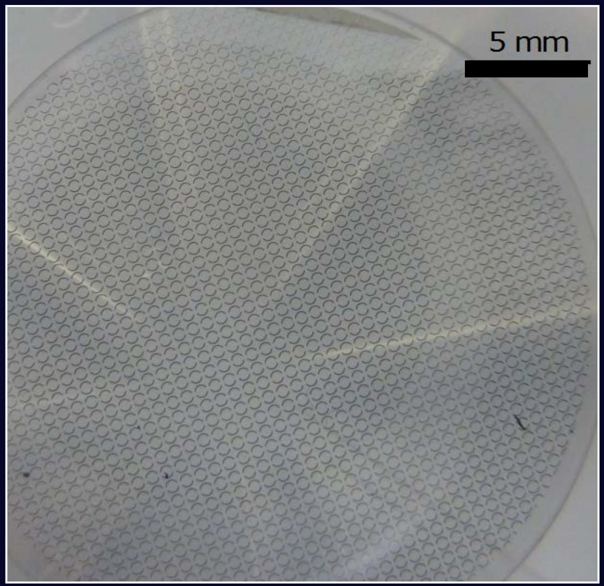


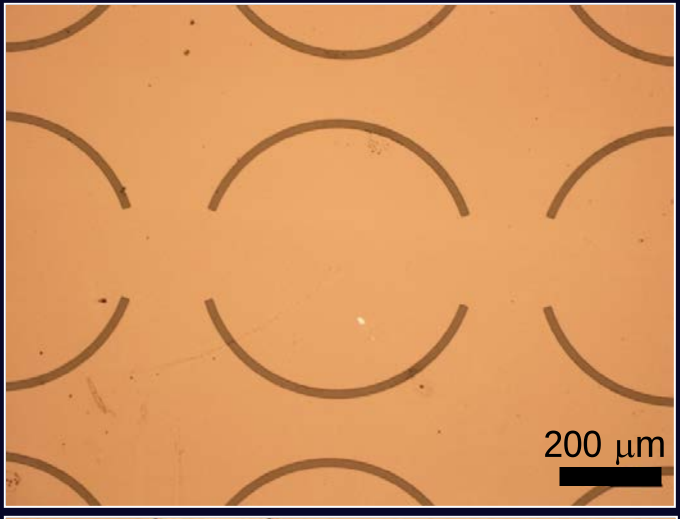


Photolithography mask

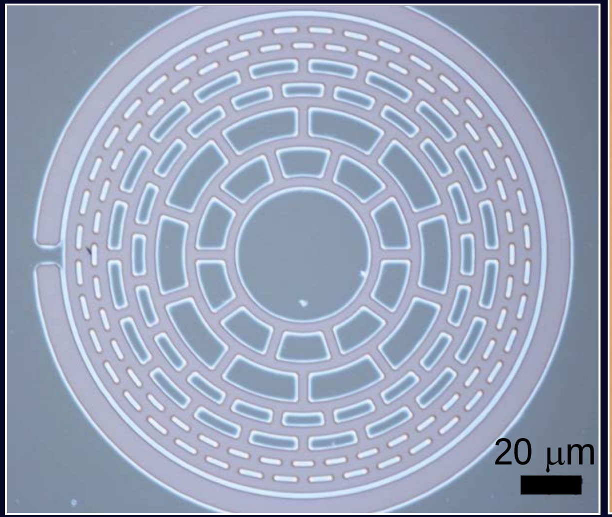
Metamaterial fabrication

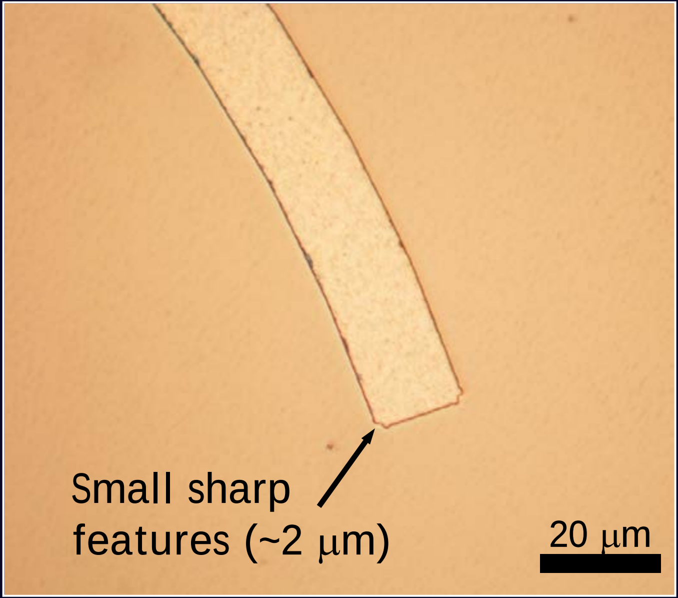
Superconducting metamaterial samples





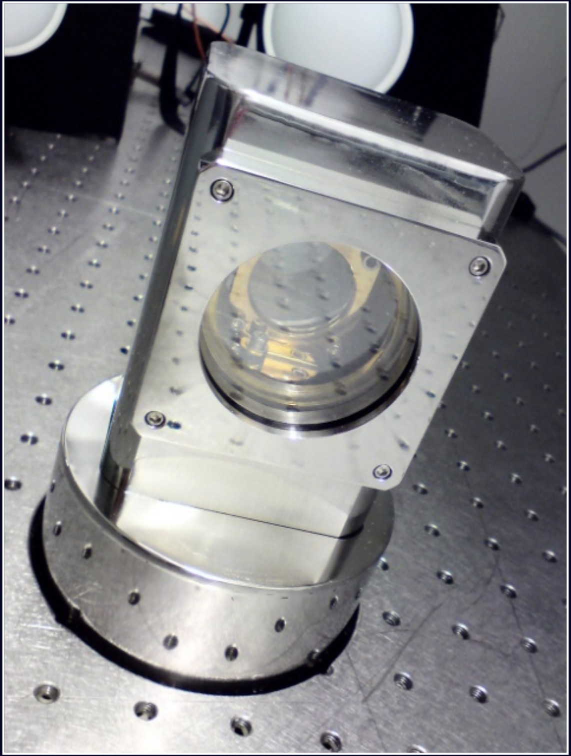
Micro-patterning does not affect superconducting transition



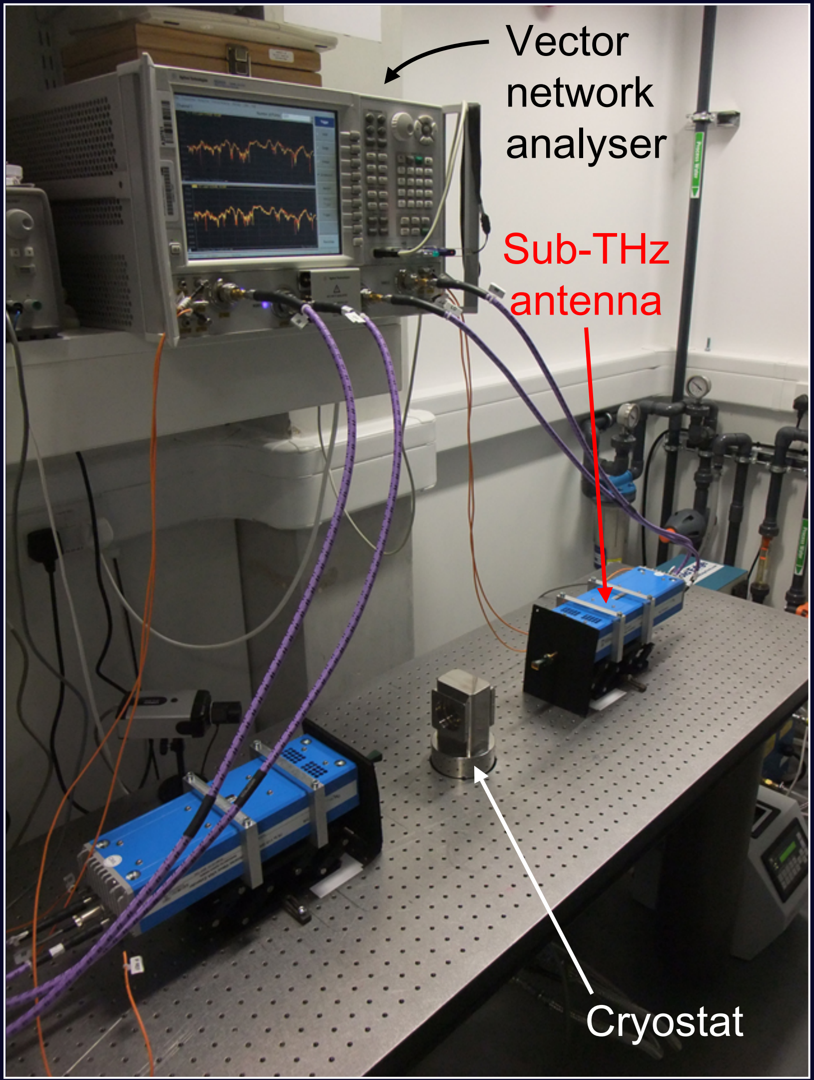


Sample handling and characterization

Cryogenic cooling is no longer technical limitation



Standard optical cryostat:
- very compact
- temperature 4 – 300K (mid-range model)



Quasi-optical measurements

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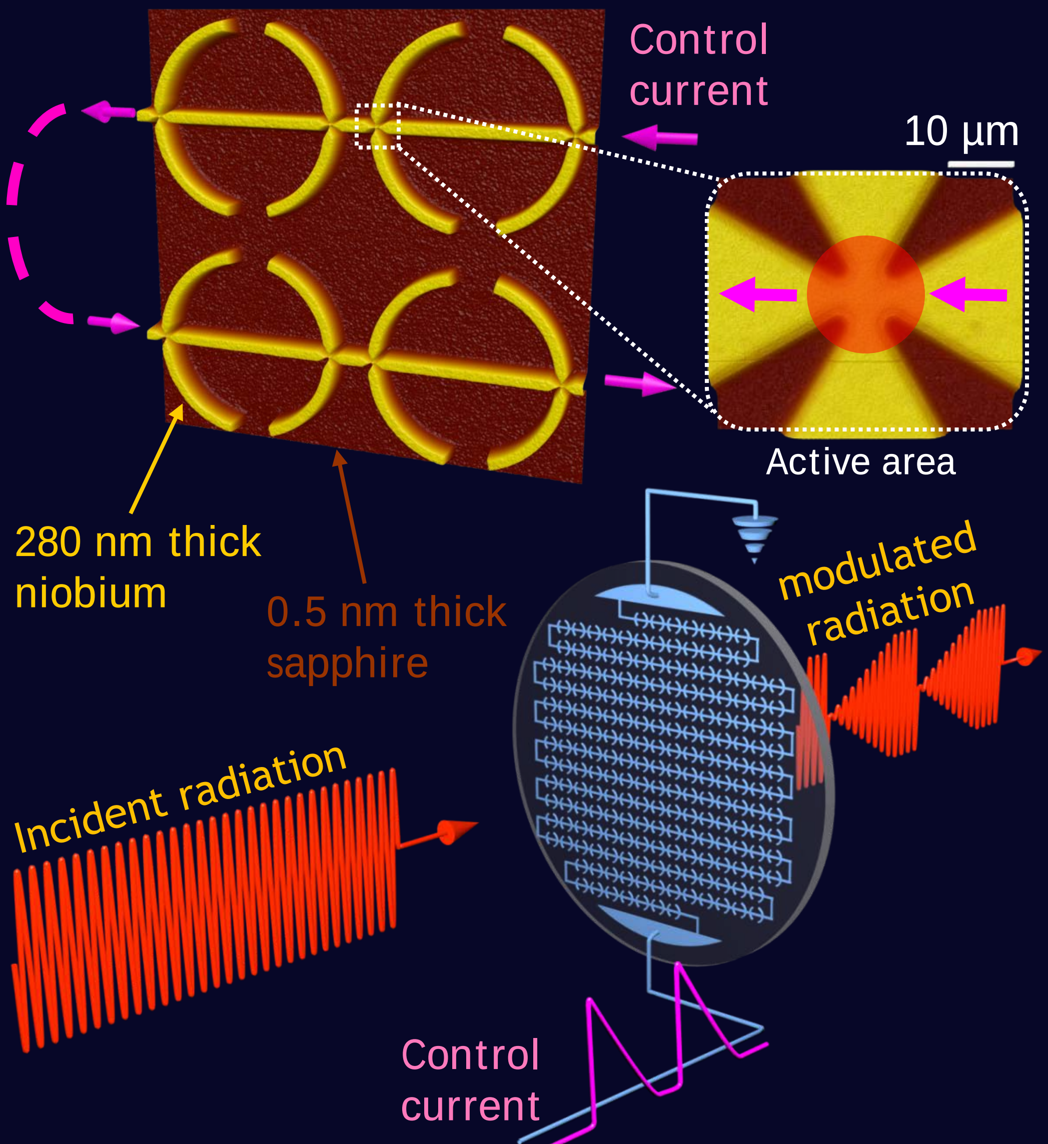
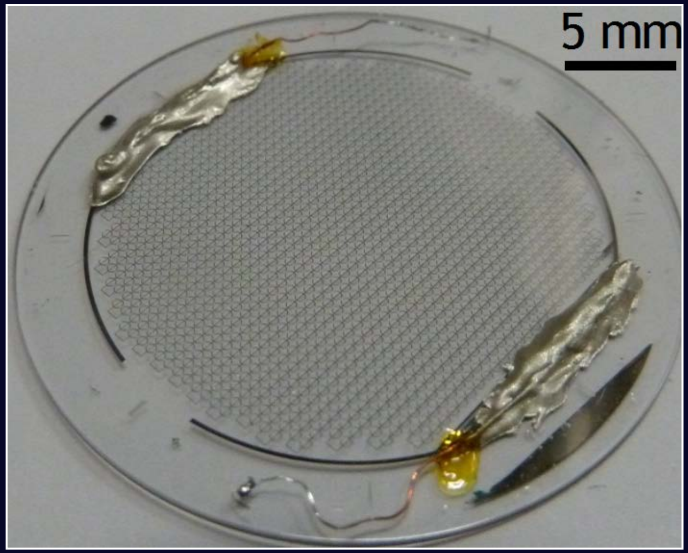
Superconducting electro-optical modulator



Proof-of-concept demonstration



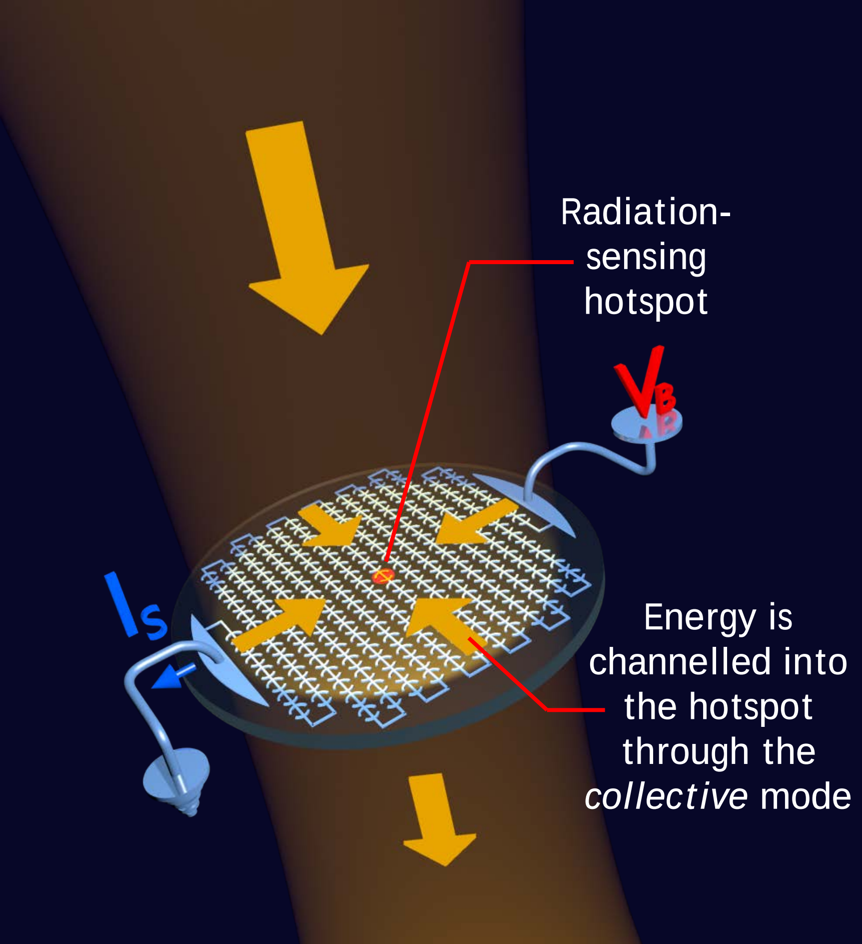
Metamaterial sample

- Operation frequency ~ 0.1 THz
- Diameter = 20 mm
- Number of meta-molecules = 1000+

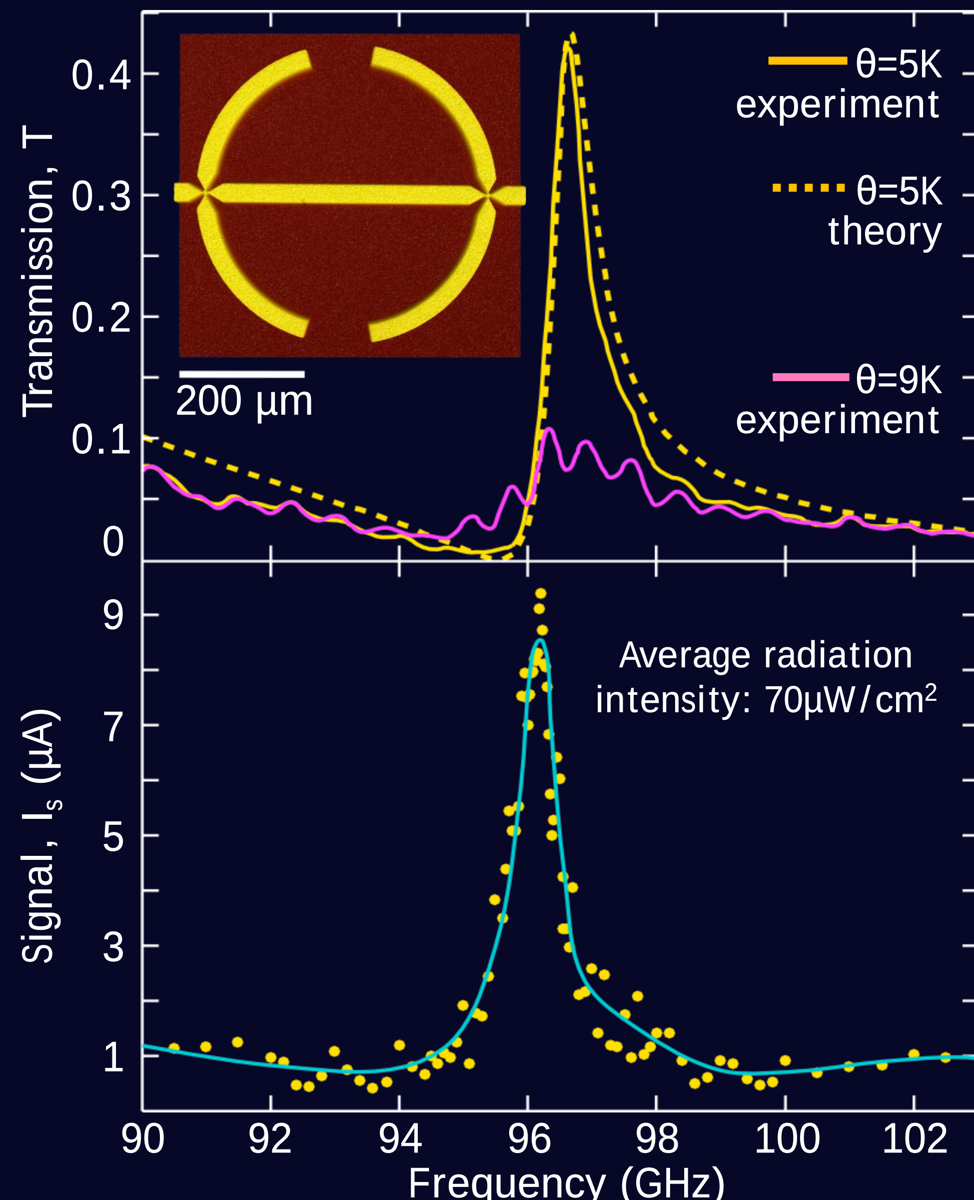
Electro-optical modulator

- Efficient: up to 50%
- Low insertion losses: ~ -3 dB
- Very fast: up to few GHz
- Spectral range: RF → 5 THz

Metamaterial Bolometer

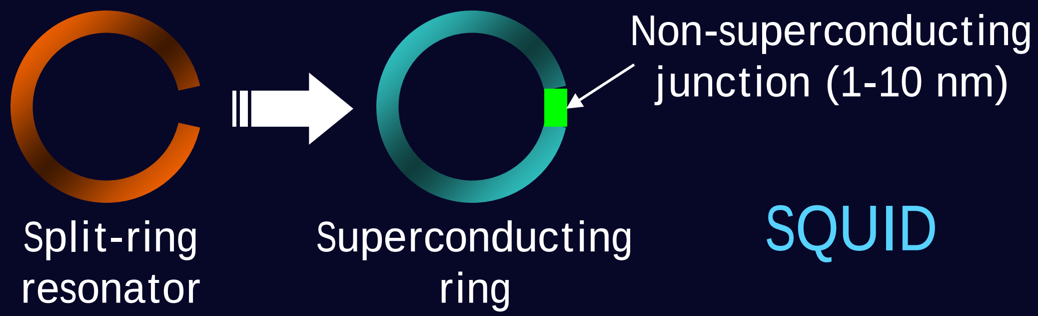


- Bias voltage creates stable hotspot
- Size (and resistance) of the spot is controlled by radiation absorption
- Absorption is enhanced by metamaterial narrow-band resonance
- Change of current is proportional to absorbed energy



Towards quantum nonlinear THz metamaterials

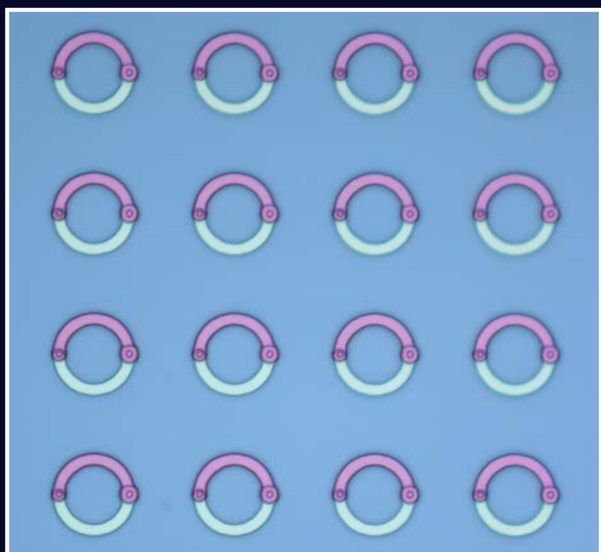
Nonlinear SQUID metamaterial



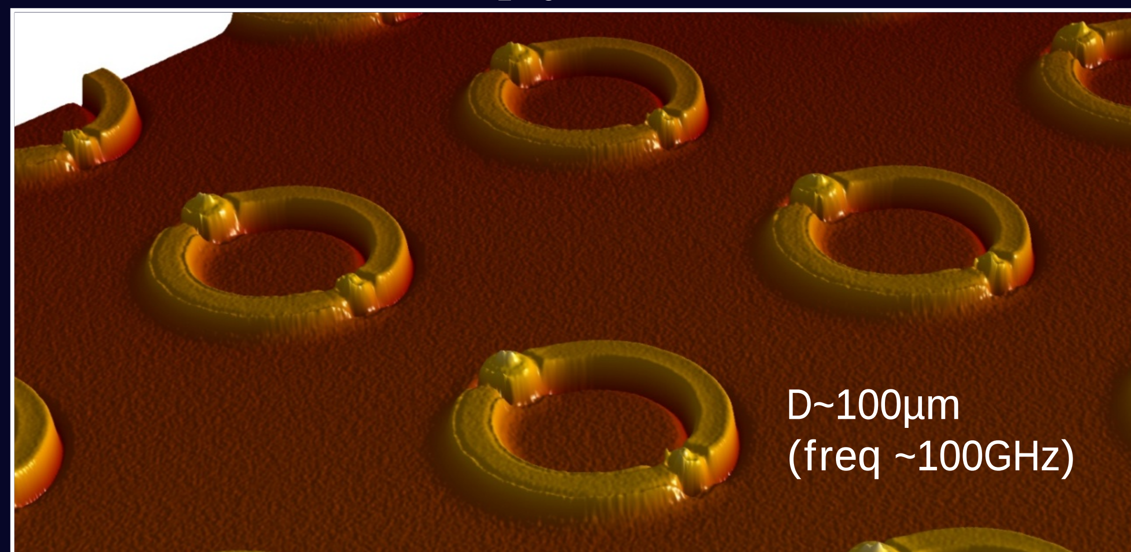
SQUID

- Quantum interference circuit
- Discrete energy levels [like hydrogen atom]
- Nonlinearity is 100,000 times stronger than p-n junction of an electronic diode

1[st] realization of SQUID metamaterial (Southampton): $Nb/Al_2O_3/Nb$ superconducting ring array



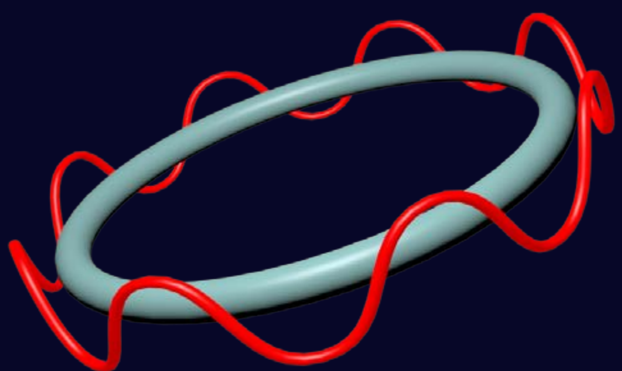
Optical micrograph



Profile

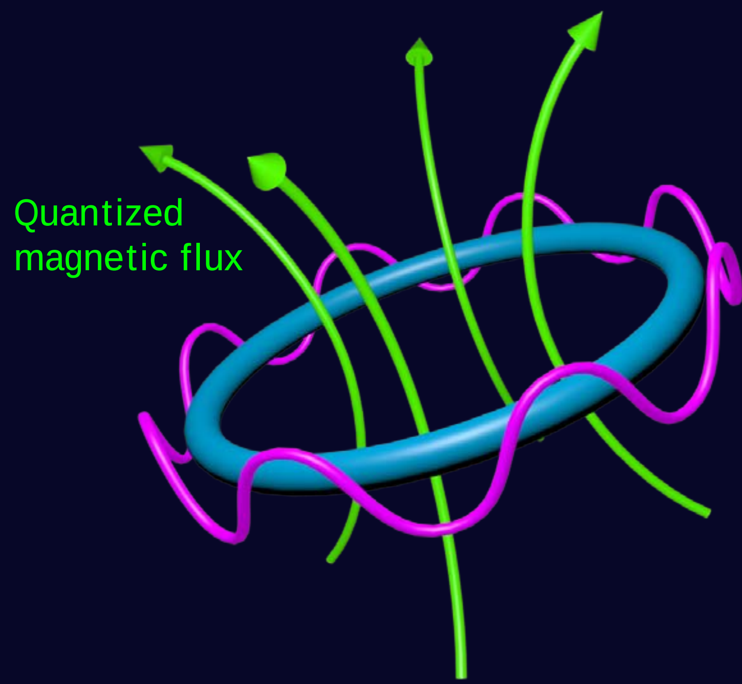
Flux quantization in closed superconducting loop

Light in a fibre loop



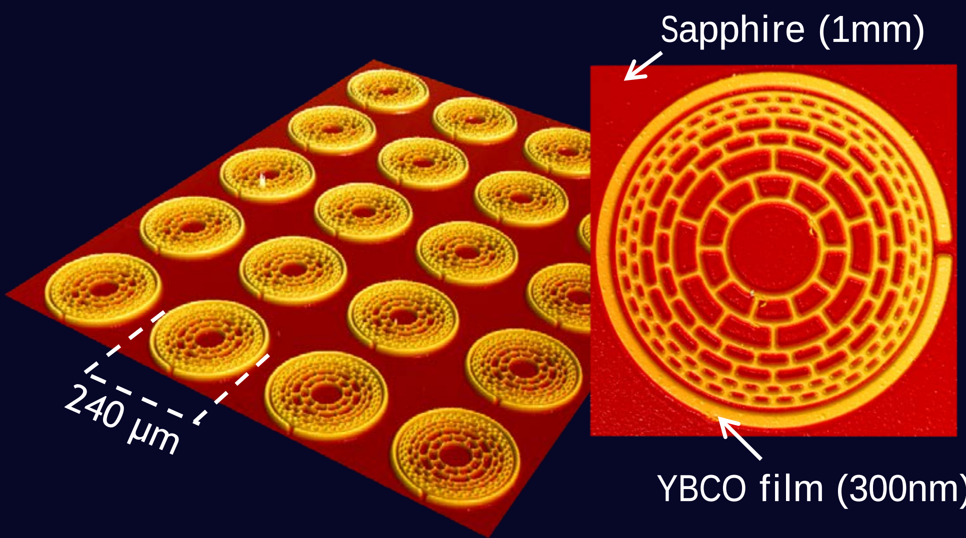
Quantized wavelength → Quantized momentum

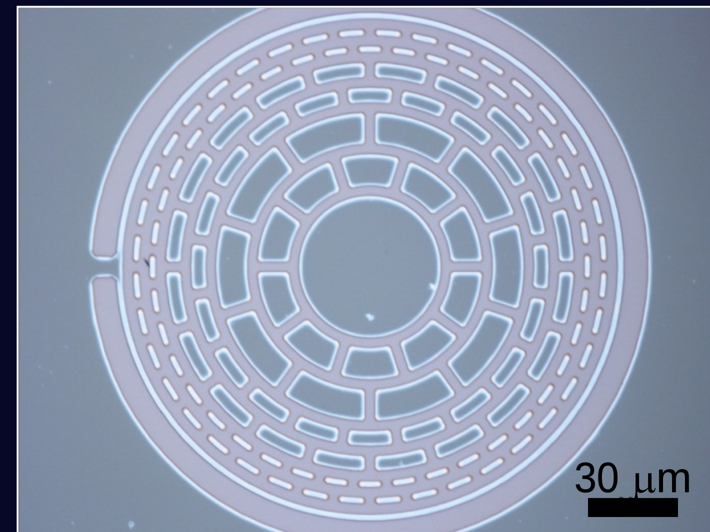
Superconducting “fluid” in a wire loop

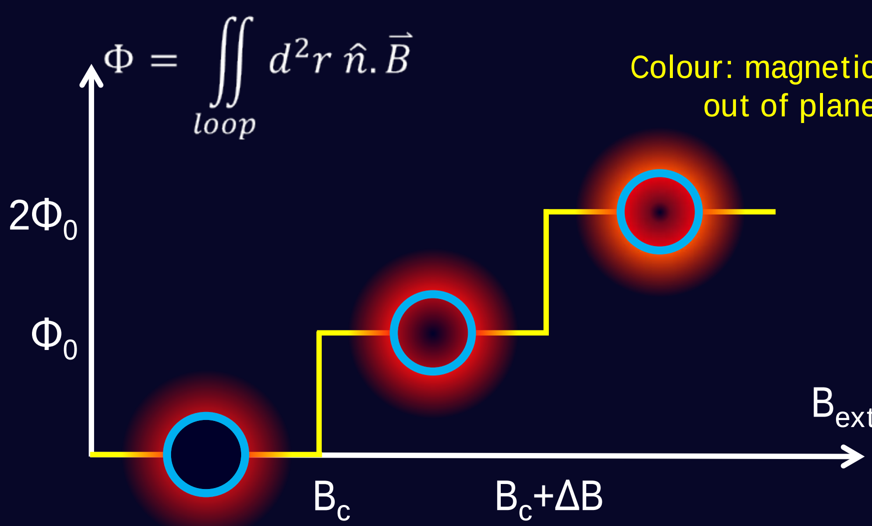


Quantized momentum → Quantized magnetic flux (because “fluid” is charged)

Quantum flux exclusion metamaterial







- Split-ring resonator produces magnetic field
- Superconducting currents in loops will screen induced magnetic field in steps (quanta)
- Superconducting loops + split-ring resonator → non-linear meta-molecule

What to take home…

Superconducting metamaterials/waveguides:

- viable platform for steering, controlling and switching THz radiation
- extreme confinement of THz fields > 1:1000 (μm $\rightarrow$ nm)
- cryogenic cooling is no longer a technical limitation

More details during posters session and lab tours today…

Vassili Savinov

Project team:

Anagnostis Tsiatmas
Roger Buckingham
Peter de Groot
Nikolay Zheludev

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THE ROYAL SOCIETY

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