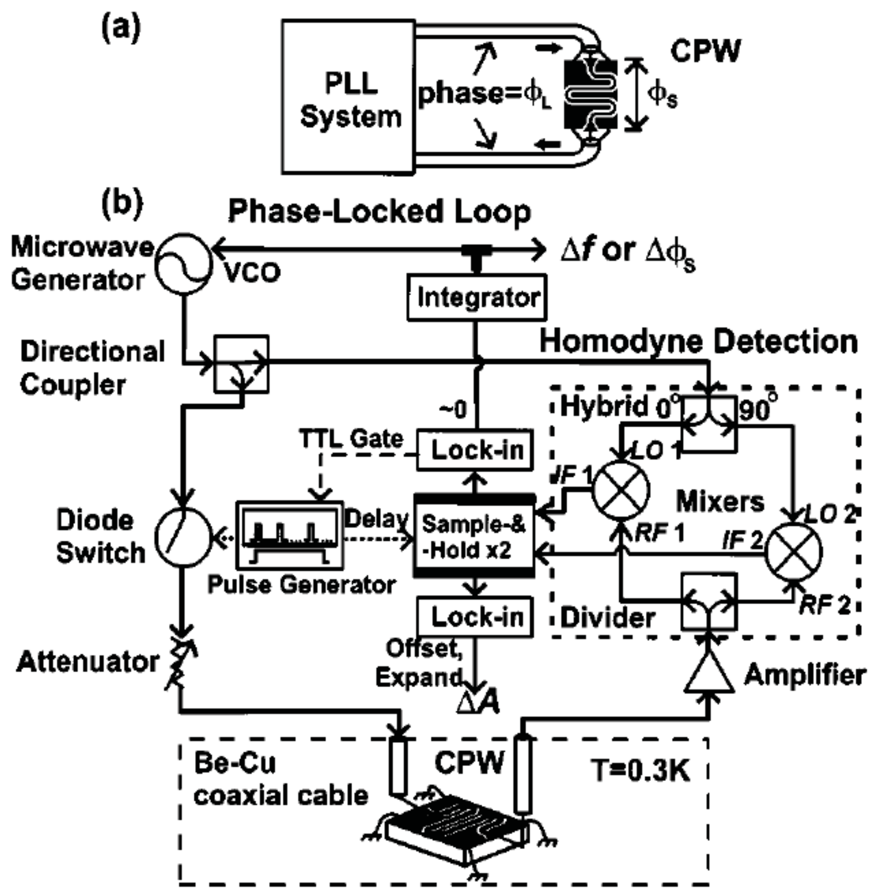
Microwave scattering studies on superconductive devices

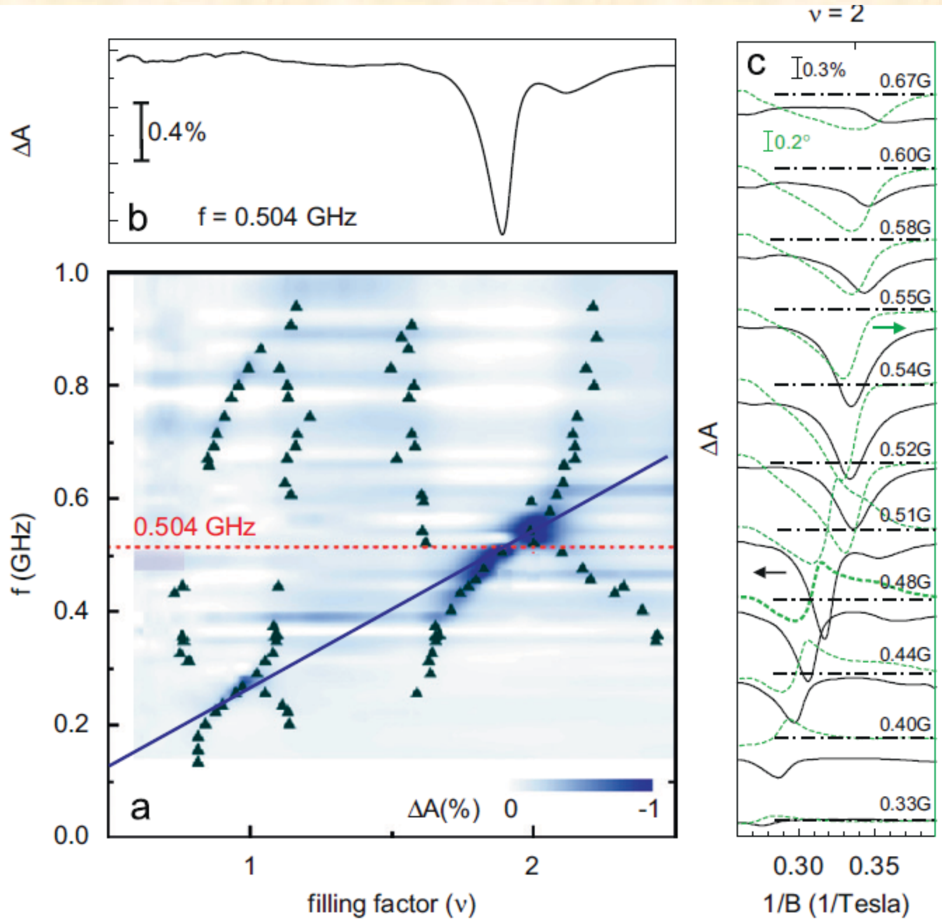
Watson Kuo
National Chung Hsing University

Taiwan-France joint school on Quantum Information Science
& Workshop on Quantum Measurement

What is
“microwave photoluminescence
on-a-chip”
?

Once upon a time….



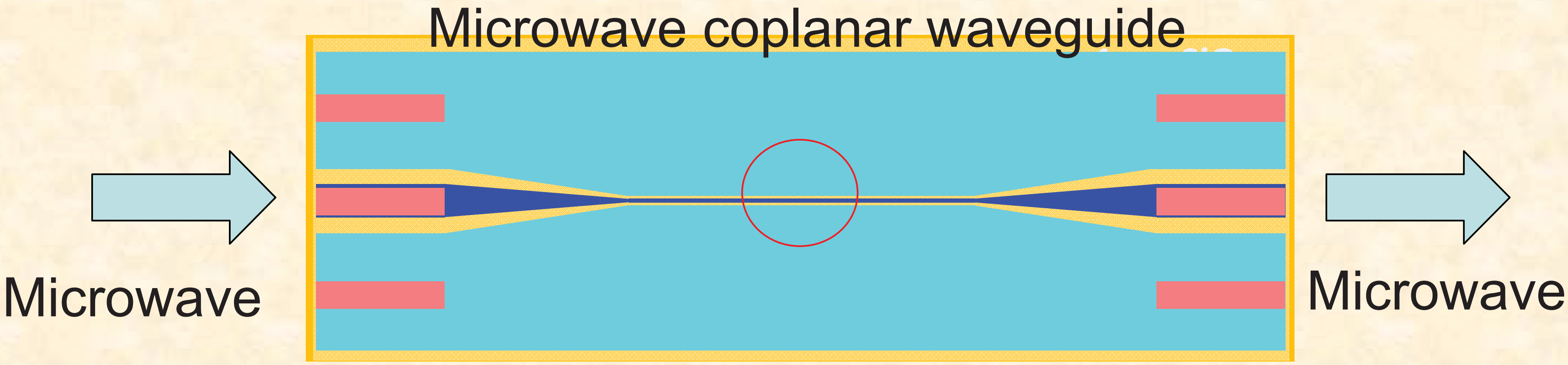


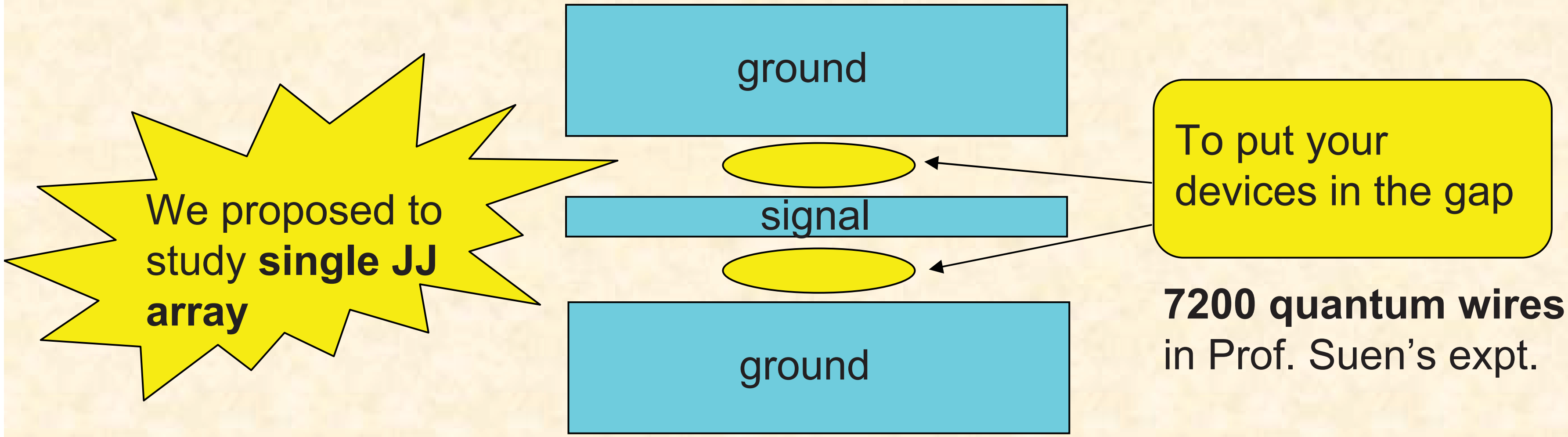
W. H. Hsieh et al APL85, 4196 (2004)

W. H. Hsieh et al Physica E 40,1681 (2008)

Edge magnetoplasma excitations in quantum wire arrays

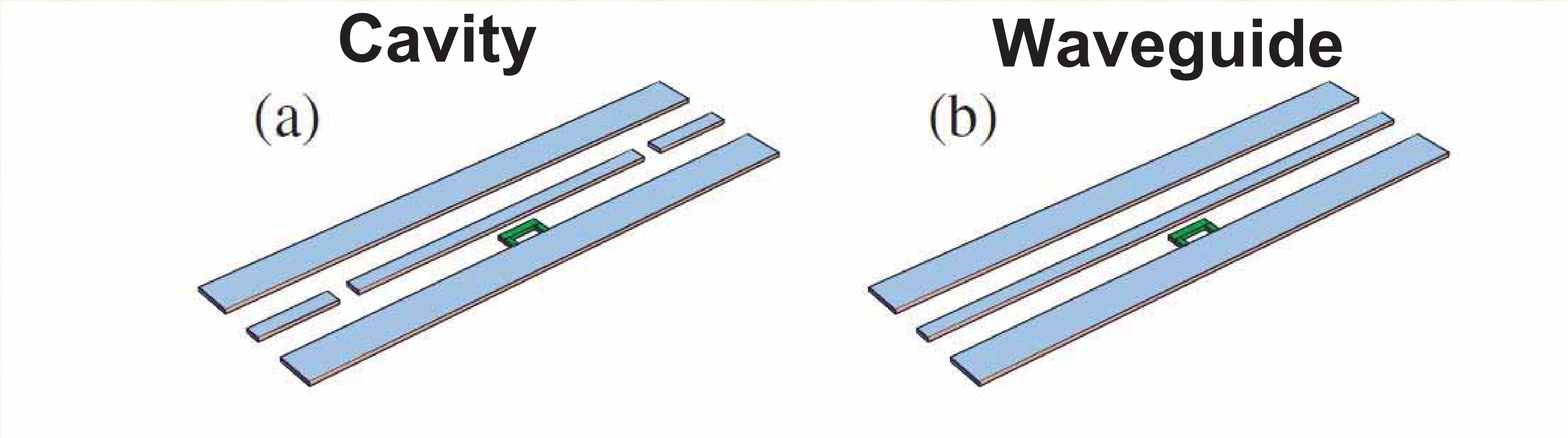
Concept





7200 quantum wires in Prof. Suen's expt.

Cavity vs. waveguide

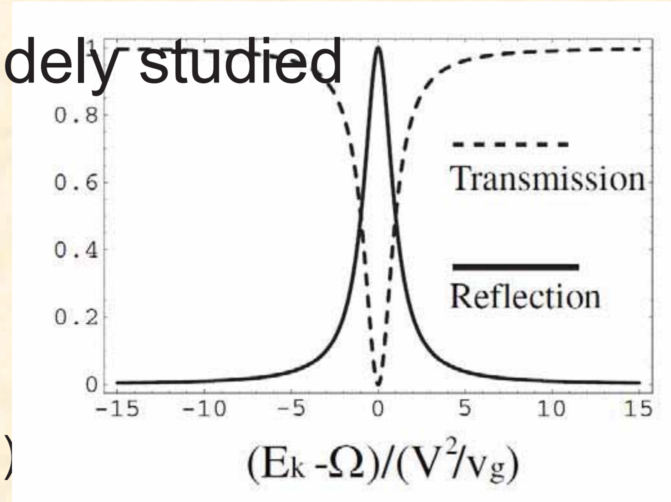


Continuum of photon modes

Single mode photon

Not widely studied

Enhanced coupling



Of great success

J.-T. Shen and S. Fan, **PRL 95**, 213001 (2005)

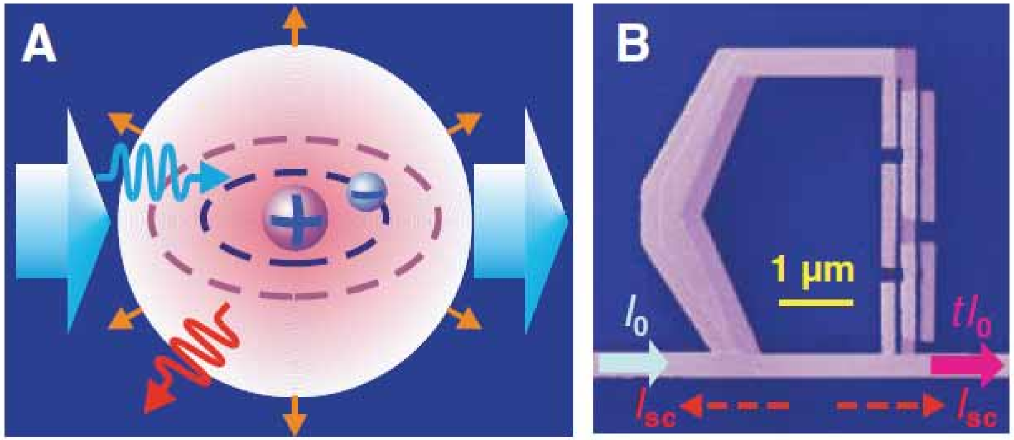
A recent breakthrough

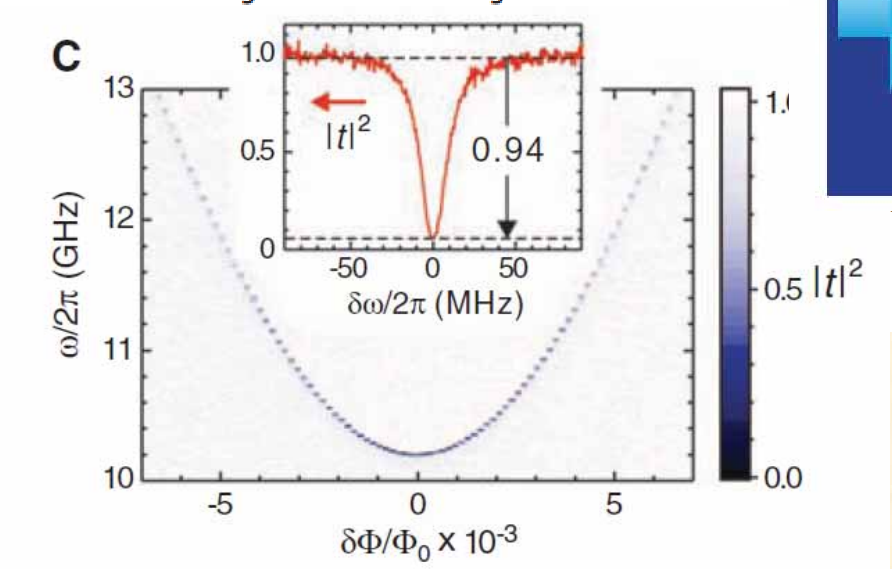
Resonance Fluorescence of a Single Artificial Atom

O. Astafiev,[1,2]* A. M. Zagoskin,[3] A. A. Abdumalikov Jr.,[2]† Yu. A. Pashkin,[1,2]‡ T. Yamamoto,[1,2] K. Inomata,[2] Y. Nakamura,[1,2] J. S. Tsai[1,2]

An atom in open space can be detected by means of resonant a
electromagnetic waves, known as resonance fluorescence, which
quantum optics. We report on the observation of scattering of p
artificial atom. The behavior of the artificial atom, a supercondu
system, is in a quantitative agreement with the predictions of qu
scatterer interacting with the electromagnetic field in one-dimer

for quantum electronics and quantum information processing. In three-dimensional (3D) space, however, although perfect coupling (with 100% extinction of transmitted power) is theoretically feasible (2), experimentally achieved extinction has not exceeded 12% (3–7) because of spatial mode mismatch between incident and scattered





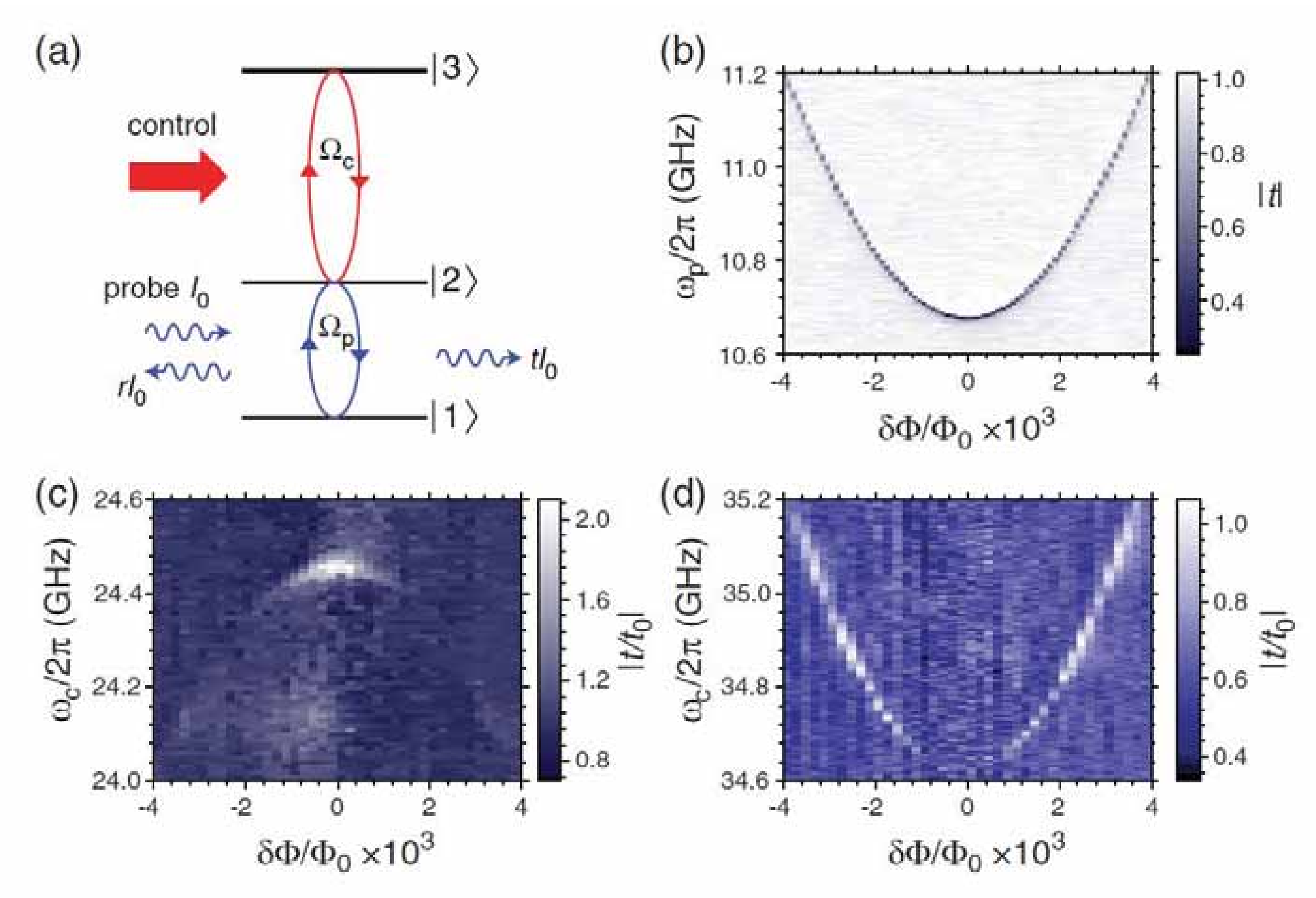
More optical ideas can be tested in this way…

PRL **104**, 193601 (2010) PHYSICAL REVIEW LETTERS week ending 14 MAY 2010

Electromagnetically Induced Transparency on a Single Artificial Atom

A. A. Abdum … S. Tsai[1,2]

[3]Depart… …dom



We… …le
macr… …a
trans… …is
revea… …d
almo… …ll
contr… …n
can b… …n
photo…

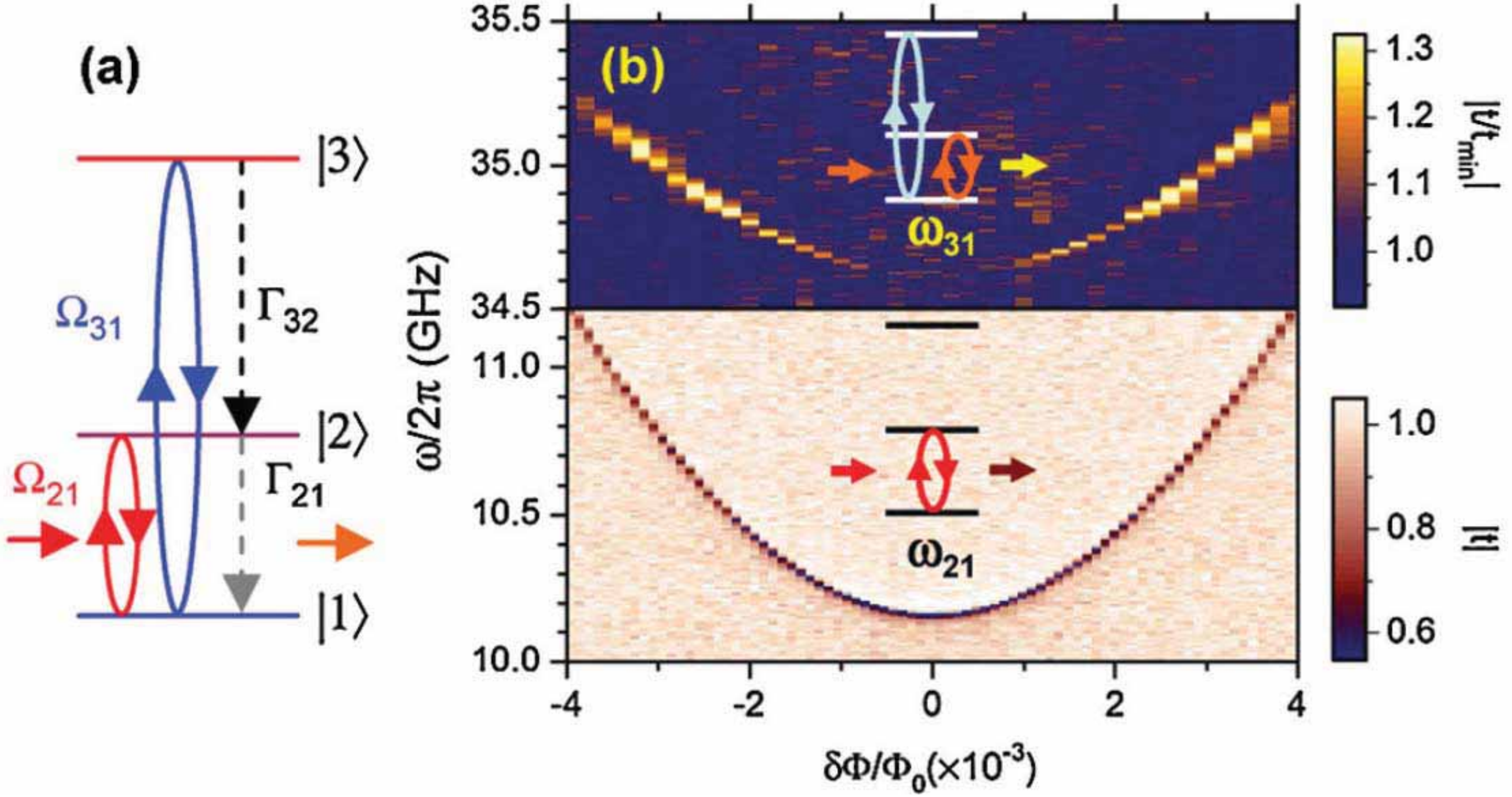
DOI: … …j

A broadband photon transistor can be demonstrated…

PRL **104,** 183603 (2010) PHYSICAL REVIEW LETTERS week ending 7 MAY 2010

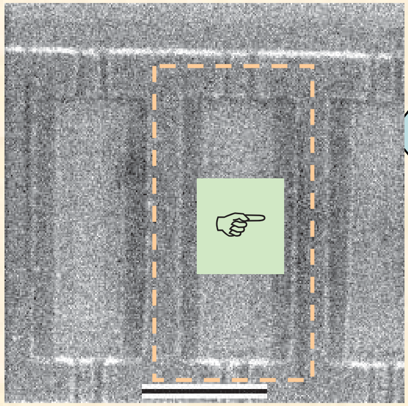
Ultimate On-Chip Quantum Amplifier

O. i[1]



Why 1D arrays?

Arrays with tunable Josephson coupling energy

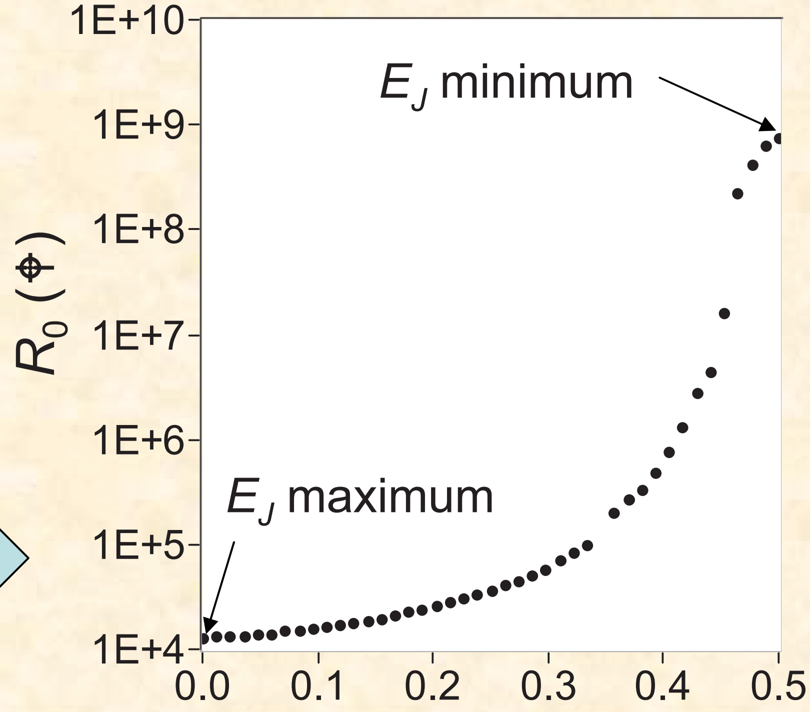


The SQUID structure renders a E_J-tunable 1D array

$$E_J = E_J^0 \cos\left|\frac{\pi\Phi}{\Phi_0}\right|$$

$E_J^0 = 325 \pm 20\,\mu\text{eV}$
$E_C = 45 \pm 5\,\mu\text{eV}$

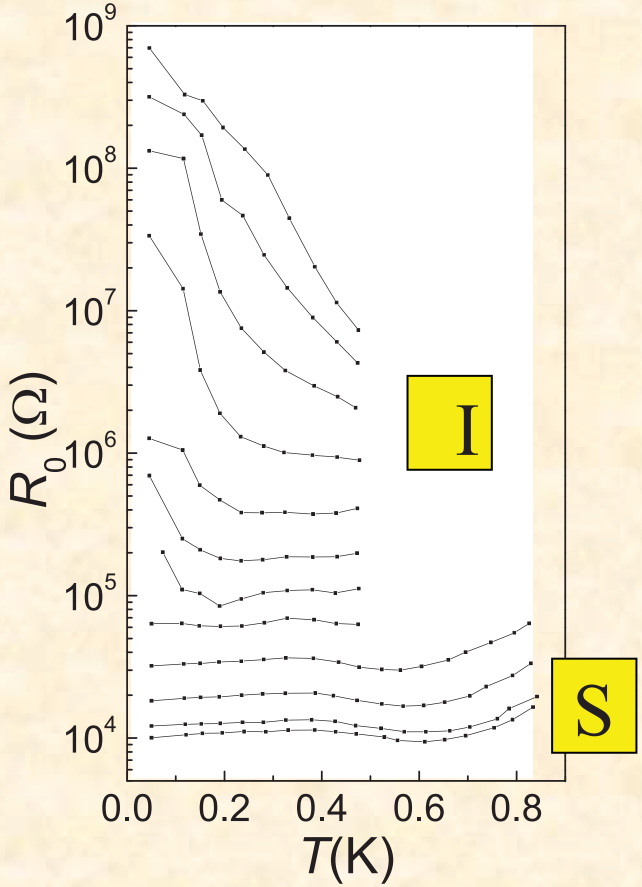
The zero-bias resistance becomes minimal when E_J is maximal.



Superconductor-insulator transition

- Tunable 1D superconducting system Josephson coupling energy(E_J), charging energy(E_C) and dissipation

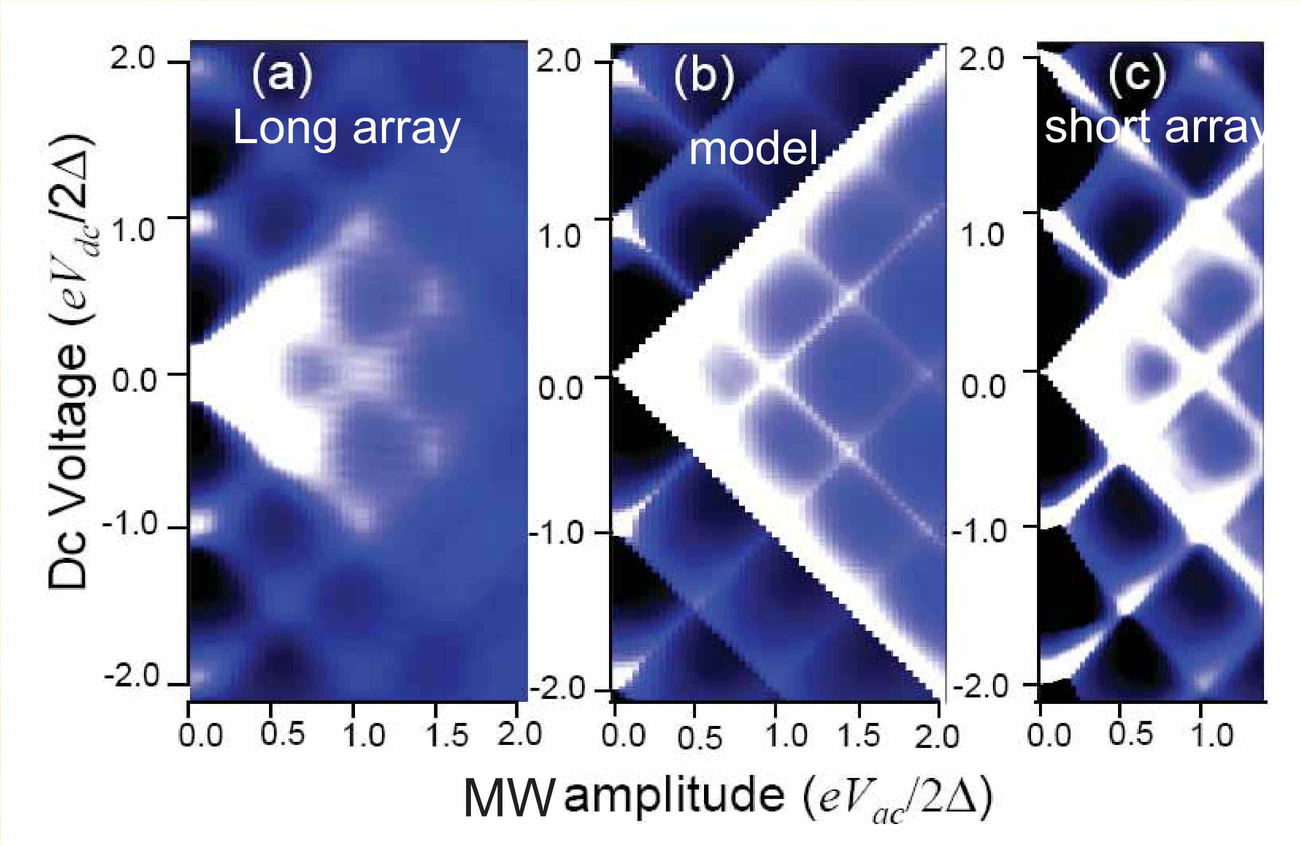
- Exhibiting Superconductor-insulator phase transition tuned by dissipation or E_J/E_C value



W. Kuo and C. D. Chen PRL**87**, 186804(2001)

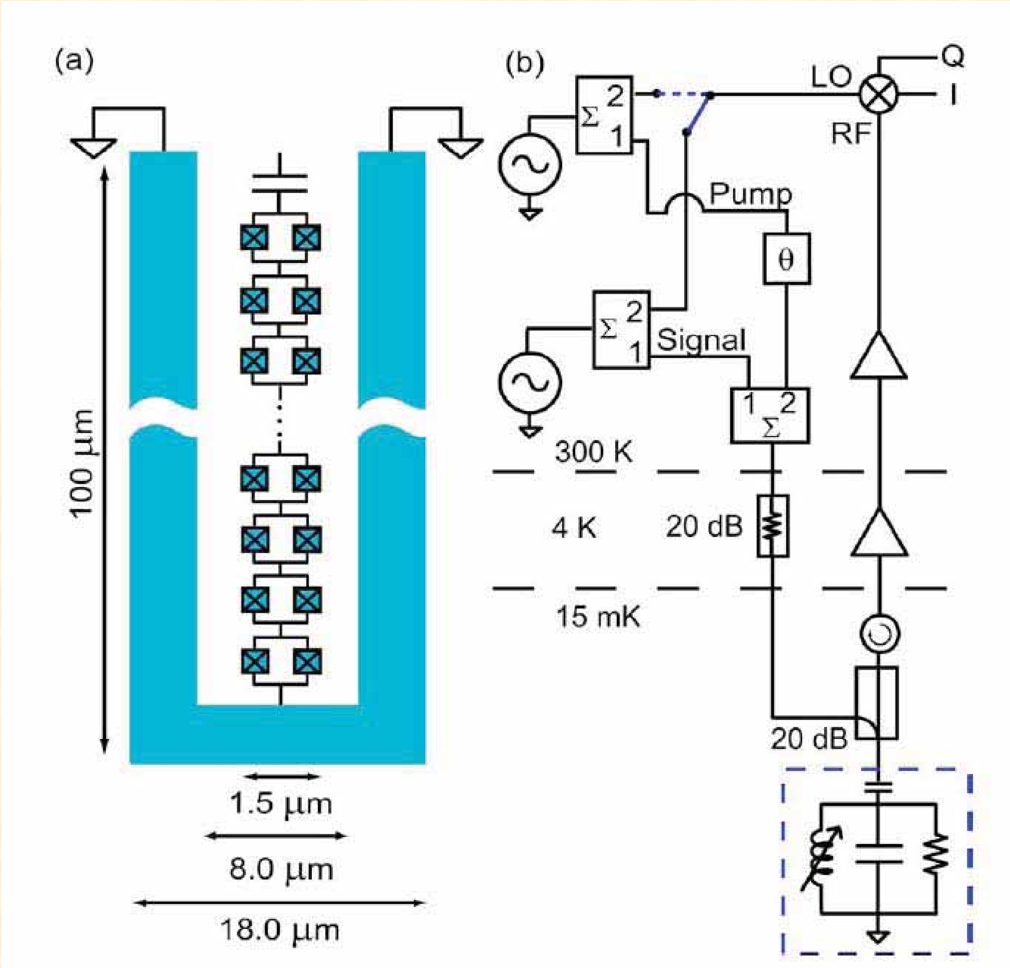
Direct detection using 1D arrays

Classical detector model $$G = (2\pi)^{-1} \int_0^{2\pi} G^0 (V_{dc} + V_{ac} \cos u) du$$



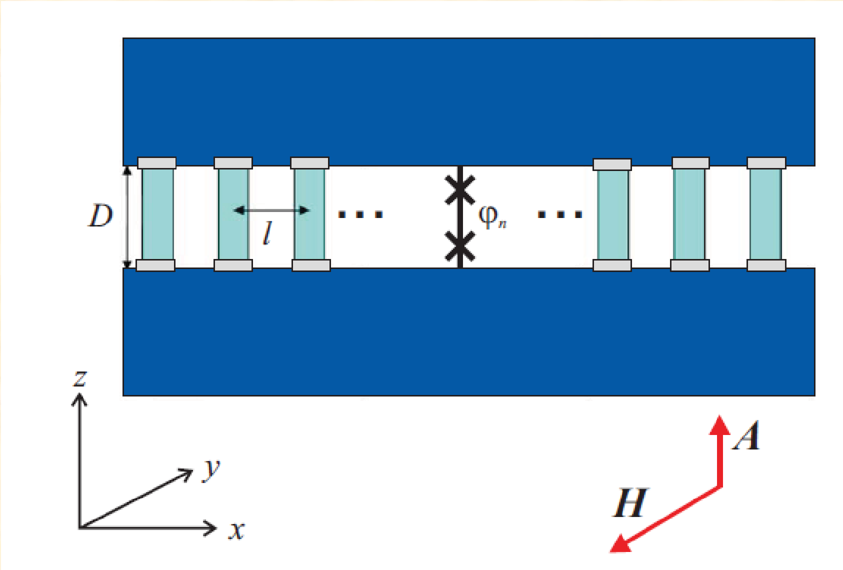
S. Liou, W. Kuo et al, NJP **10**, 073025(2008)

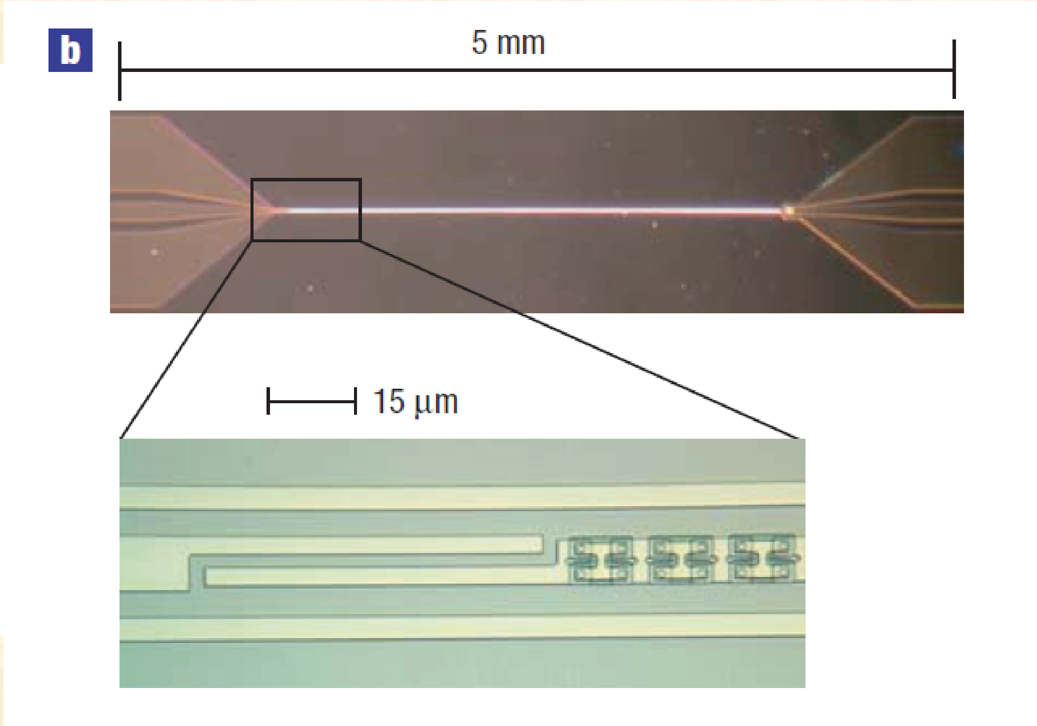
1D arrays as parametric amplifiers



M. Castellanos-Beltran and K. Lehnert, APL **91**, 083509 (2007).

1D arrays as meta-materials





A. Rakhmanov, A. Zagoskin, S. Savel'ev, and F. Nori, PRB **77**, 144507 (2008)

M. A. Castellanos-Beltran, K. D. Irwin, G. C. Hilton, L. R. Vale, and K. W. Lehnert, Nat Phys **4**, 929 (2008).

Characteristic energy scales

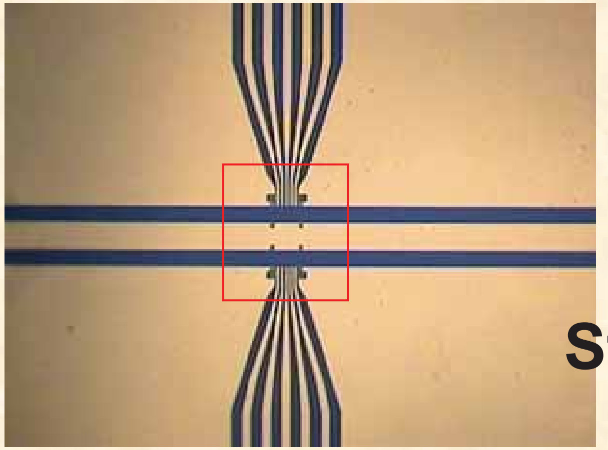
Josephson coupling energy (charge hopping) $E_J^0 \sim 100\mu eV$

Charging energy (on-site repulsion) $E_C \sim 100\mu eV$

Photon energy 1GHz ~ $4\mu eV$

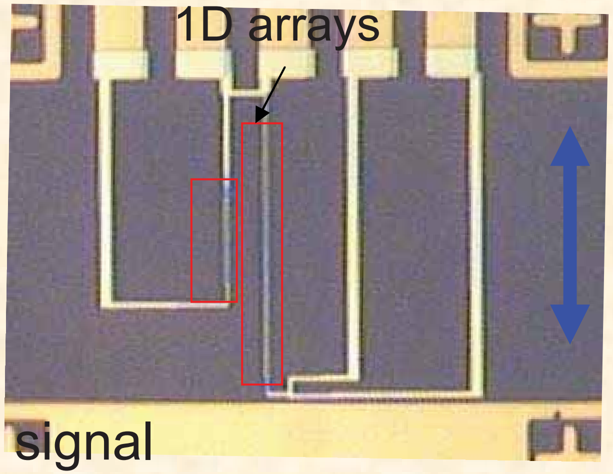
Temperature 50mK ~ $4\mu eV$

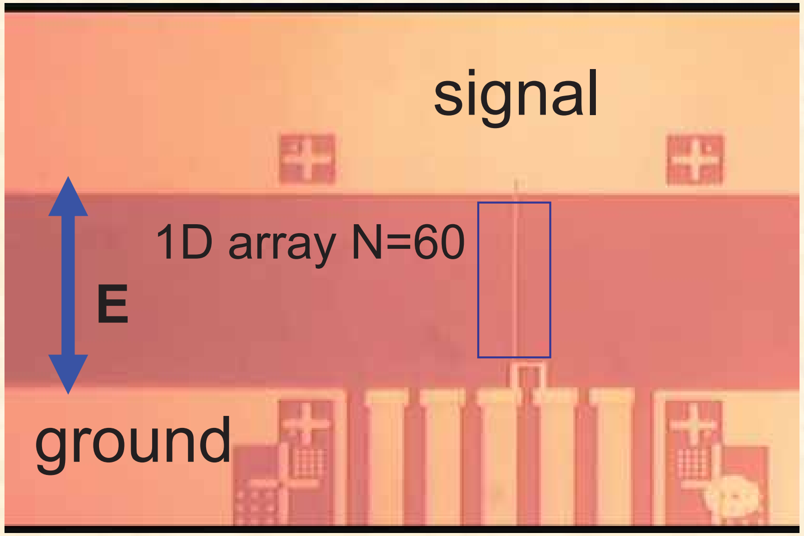
Experimental setup



weak coupling

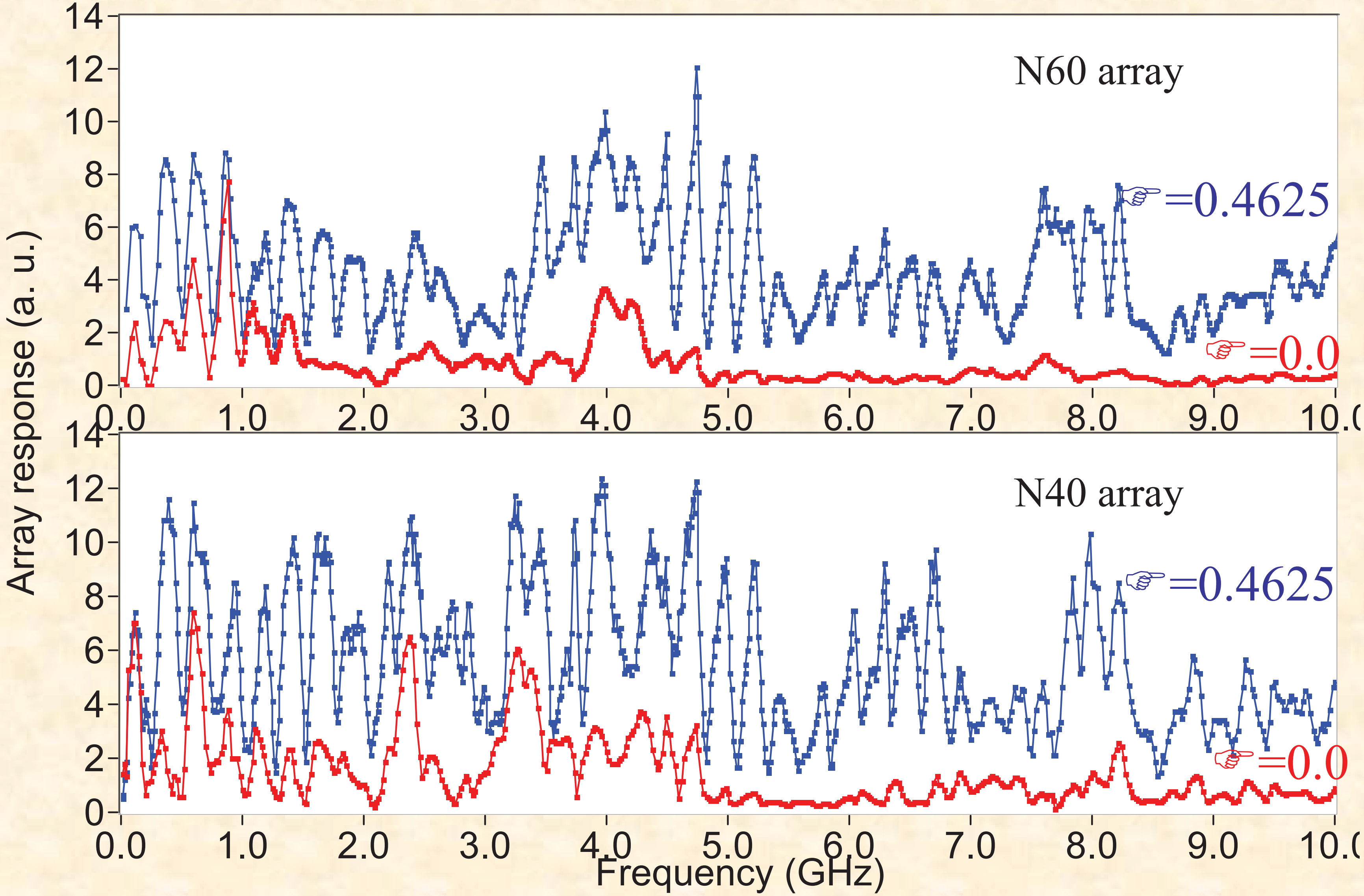
Strong coupling



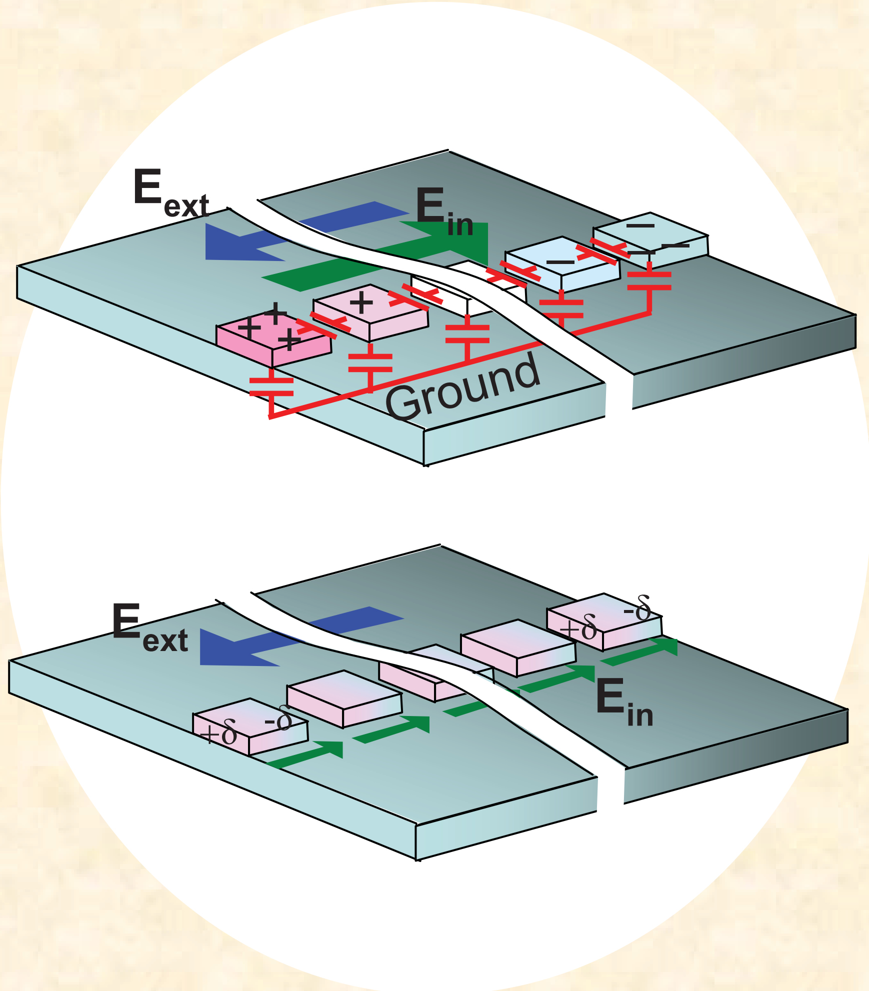


To probe photon coupling strength…

1D array as a on-chip MW detector



The screening interpretation



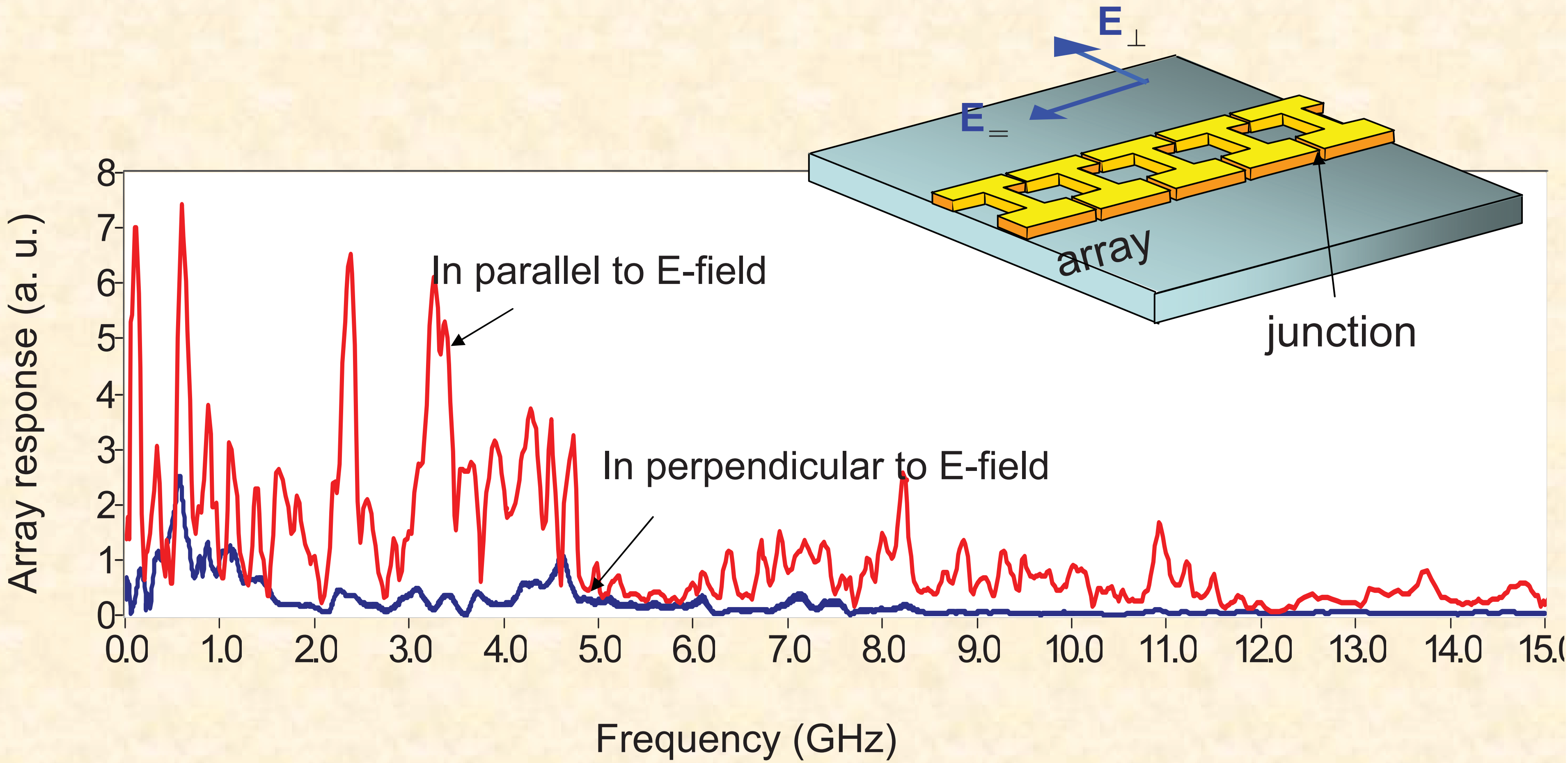
Superconducting state

Charges are mobile so as to screen the external electric field

Insulating state

The charge screening is weak

Polarization dependence



Effective coupling strength

Size-dependence:

For the long array the effective coupling is significantly larger than that of the short array

Flux-dependence:

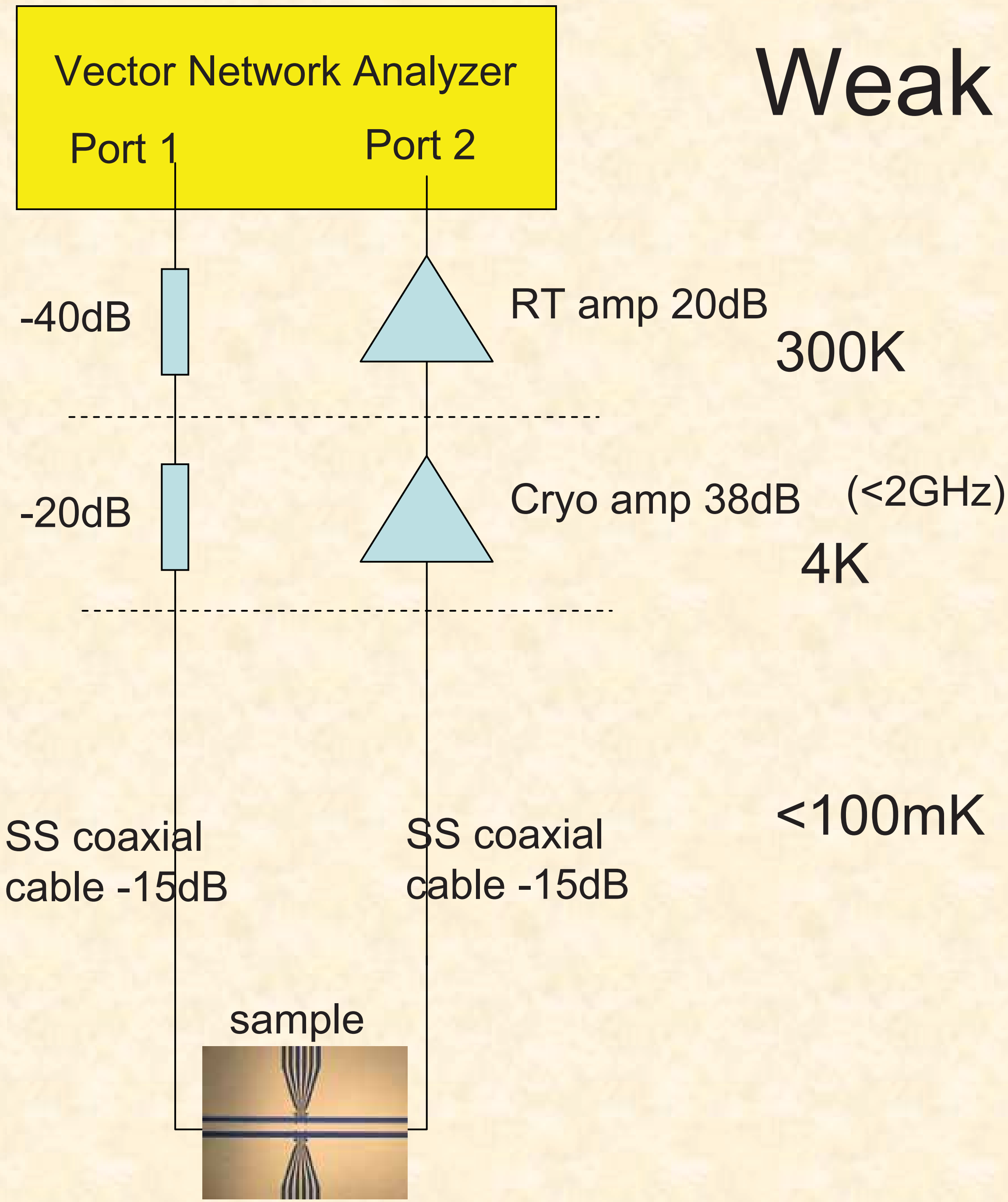
The coupling strength is related to the ground state properties of the array
Obviously beyond the scope of impedance matching

Frequency-dependence:

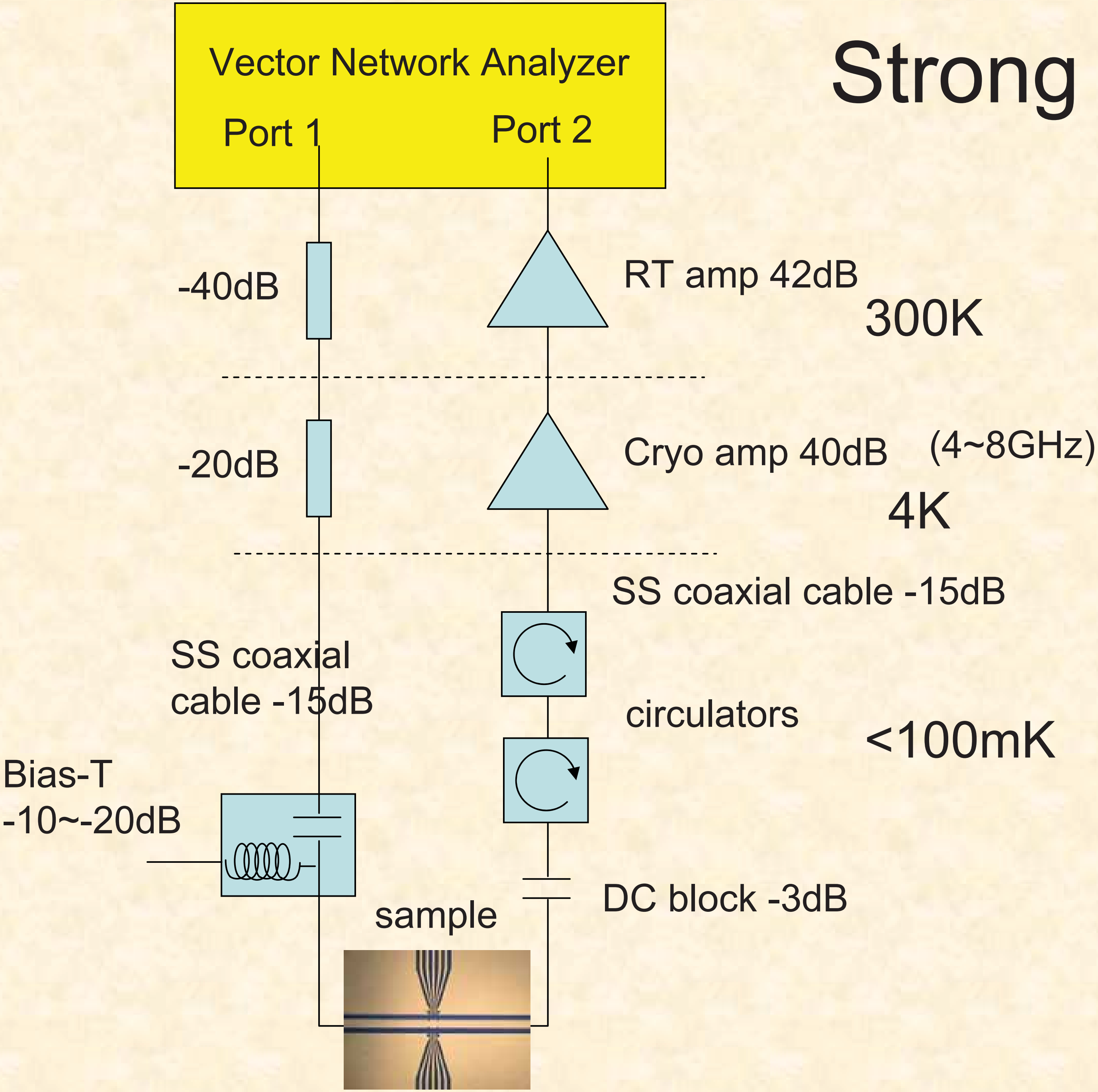
Reflects the standing waves in the waveguides, but also indicates specific absorption bands for arrays

Microwave scattering parameters…

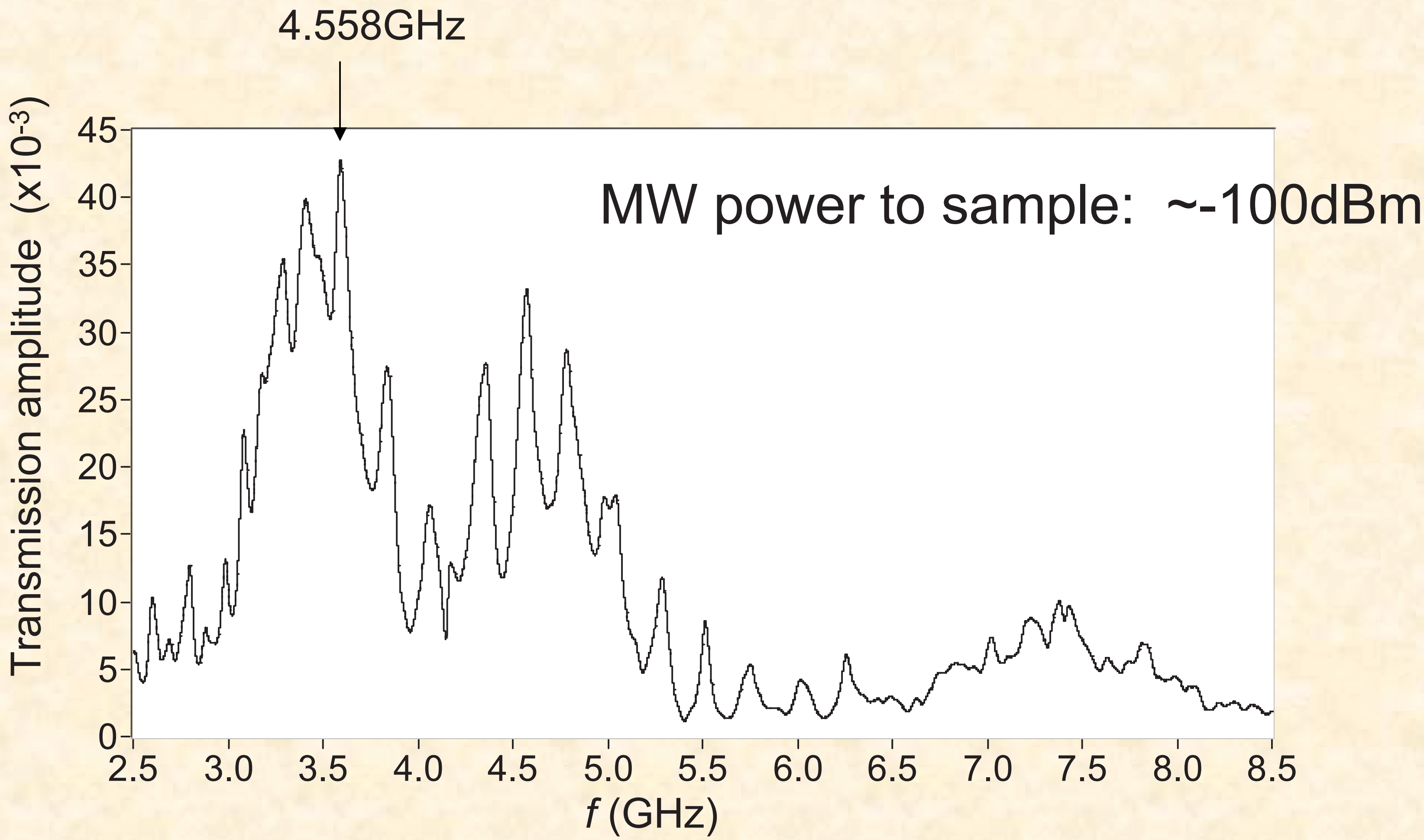
Weak coupling



Strong coupling

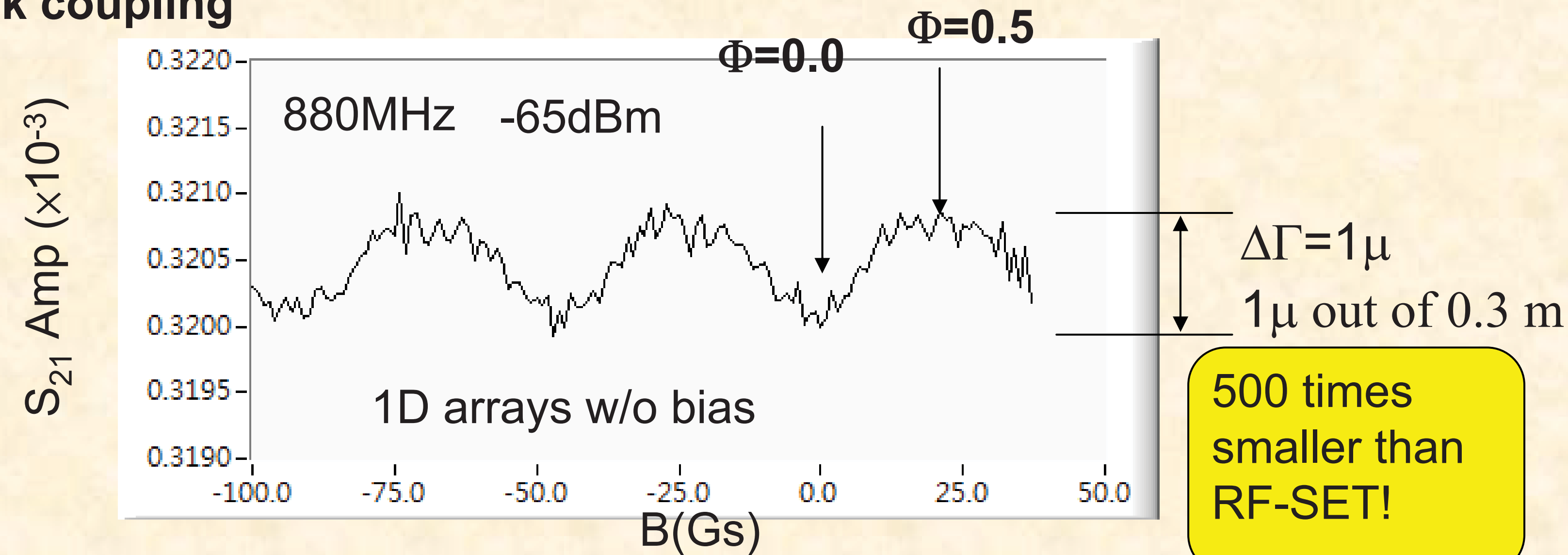


MW Transmission (strong)



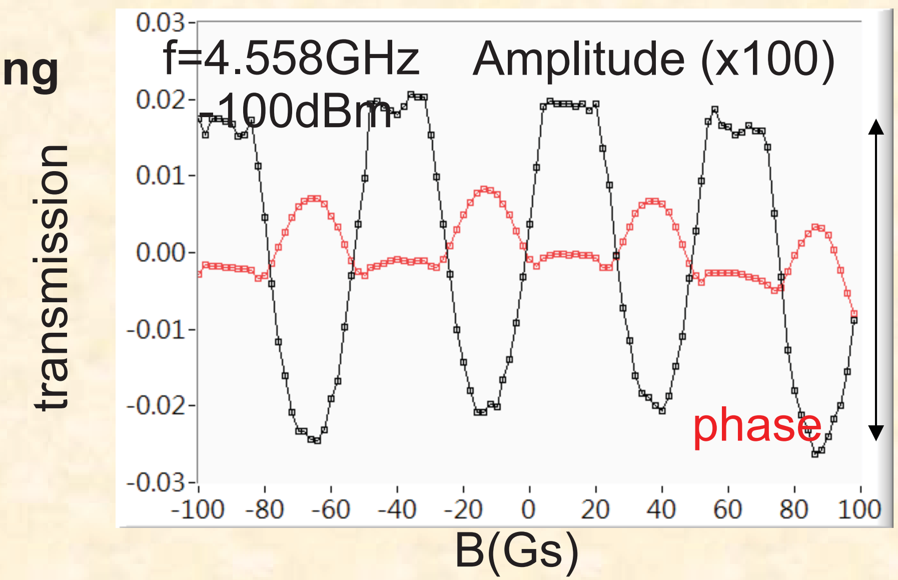
RF/MW transmission

Weak coupling

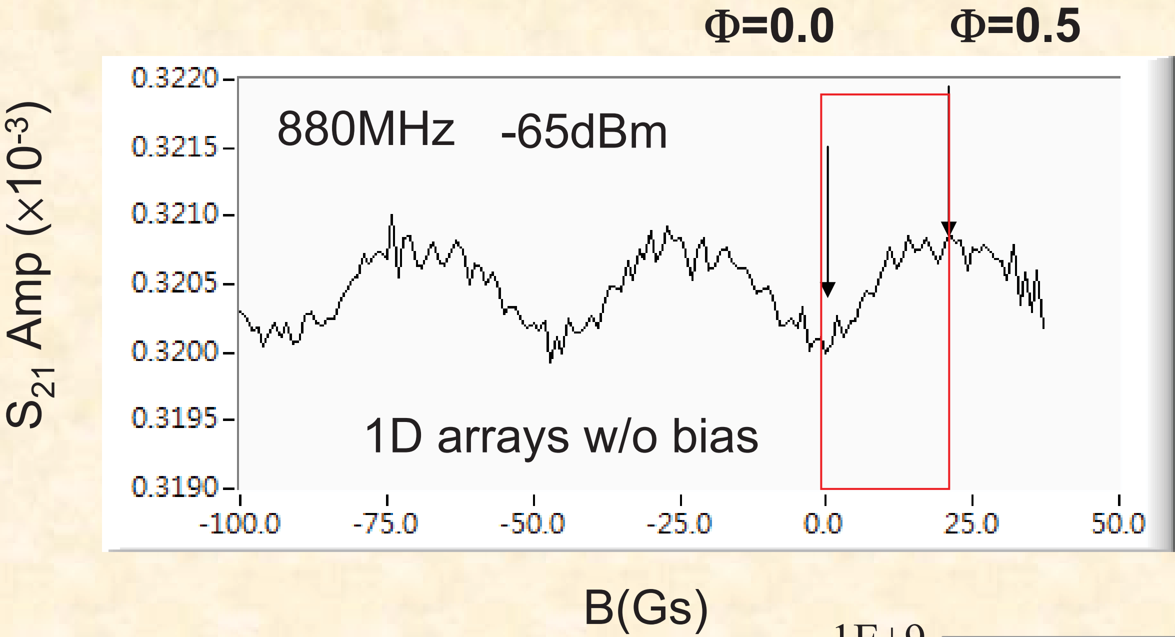


500 times smaller than RF-SET!

Strong coupling



0.4 m out of 40 m

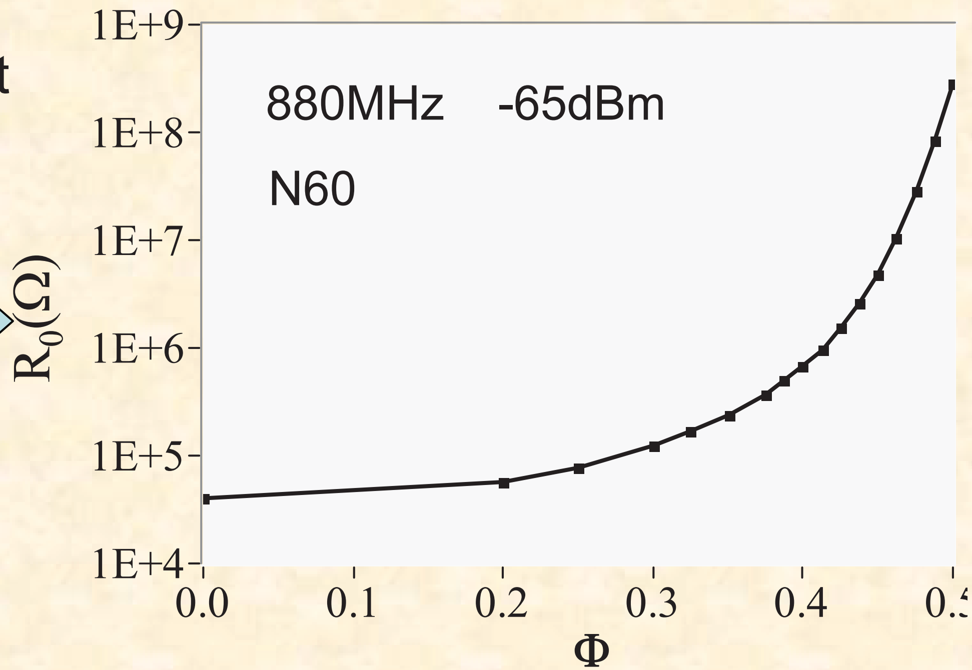


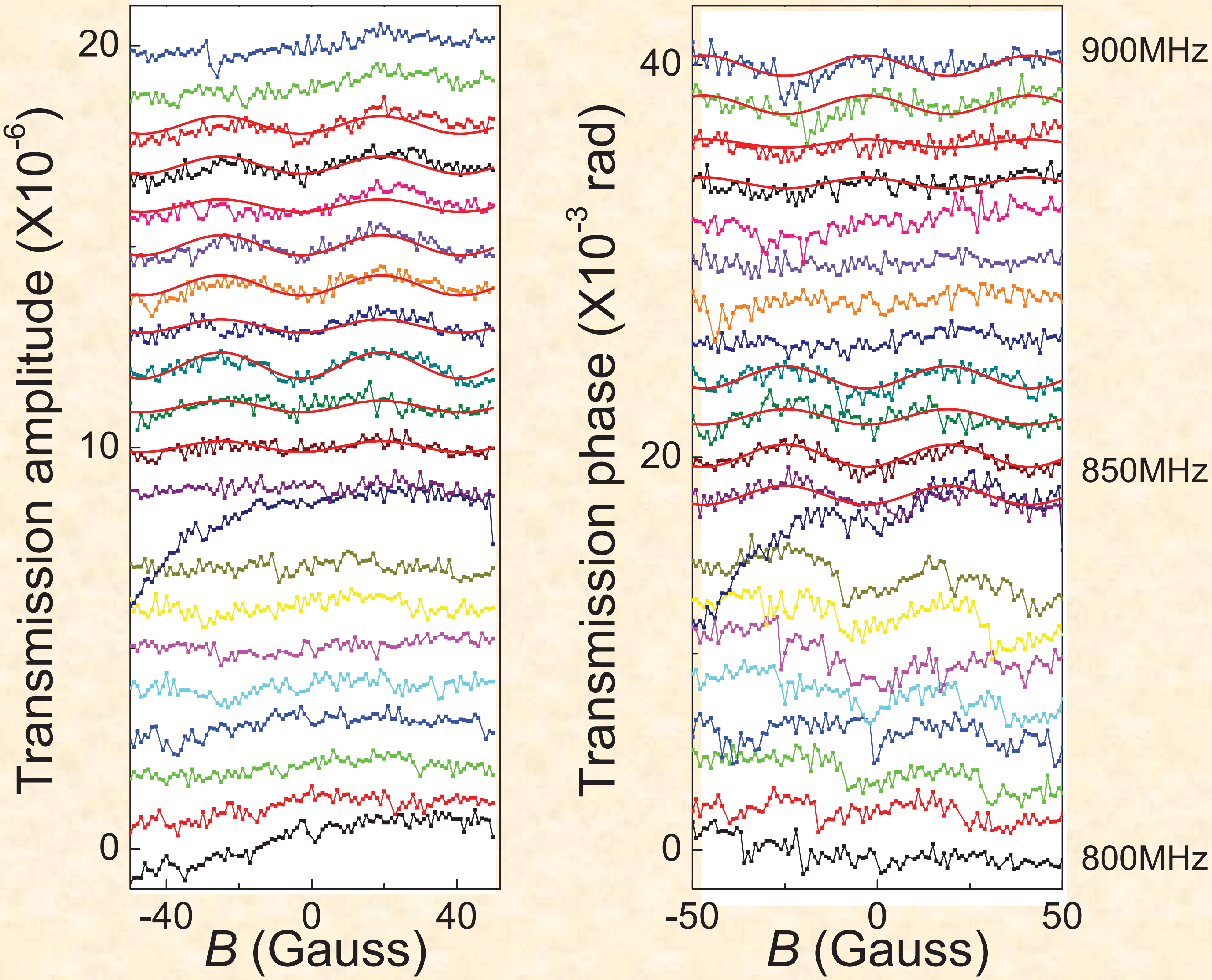
The RF power -65dBm gives a coupling energy of about 500μeV

AC result

The RF transmission is lowest when the array impedance is lowest.

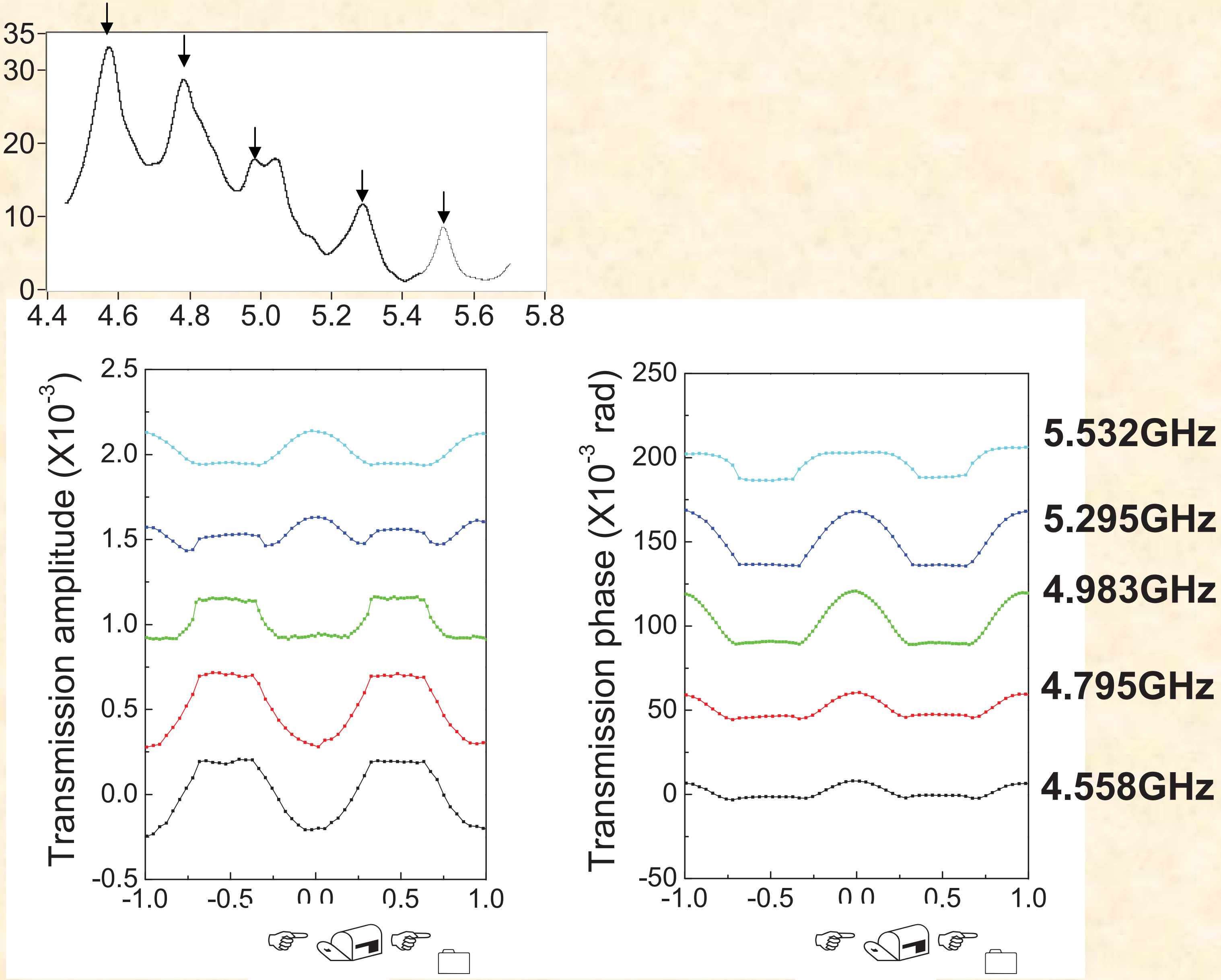
DC result



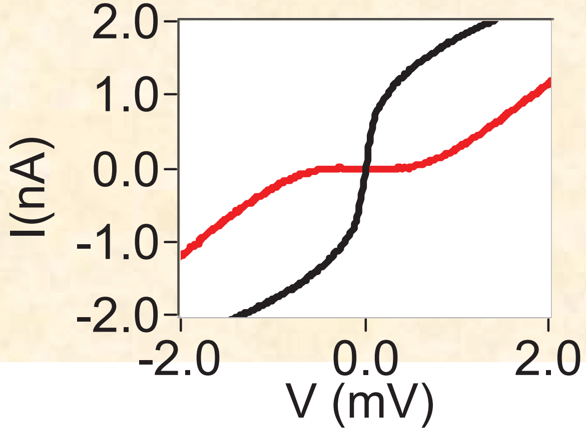


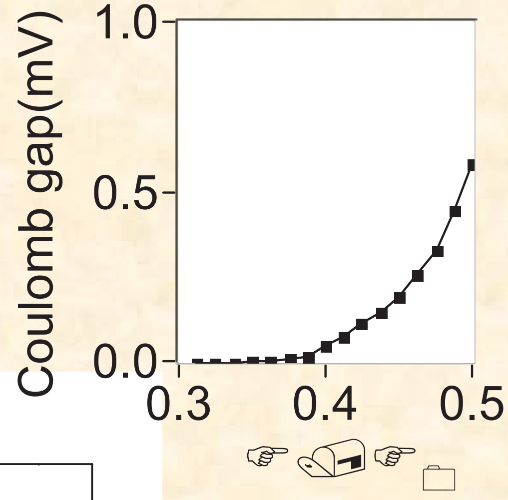
Transmission amplitude (X10^{-6})
20
10
0
-40
0
40
B (Gauss)
Transmission phase (X10^{-3} rad)
40
20
0
-50
0
50
B (Gauss)
900MHz
850MHz
800MHz

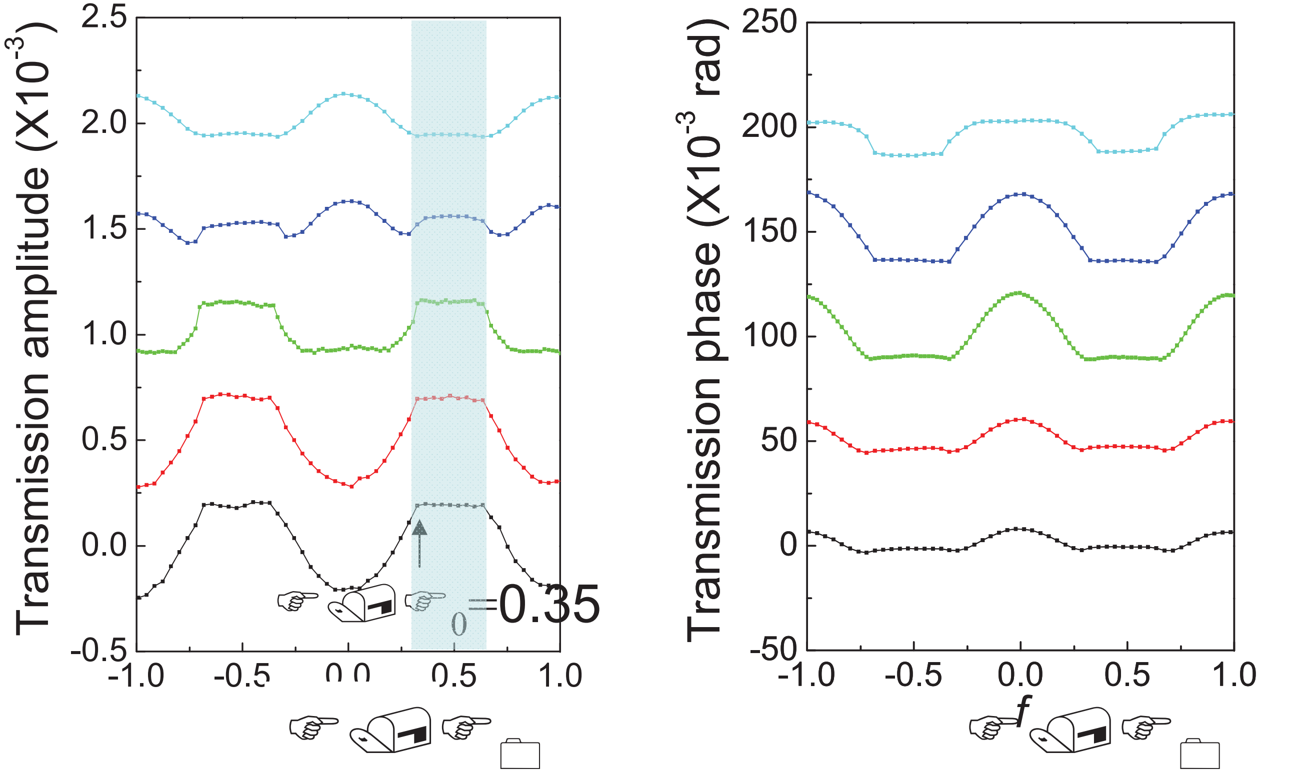
Frequency dependence (strong)



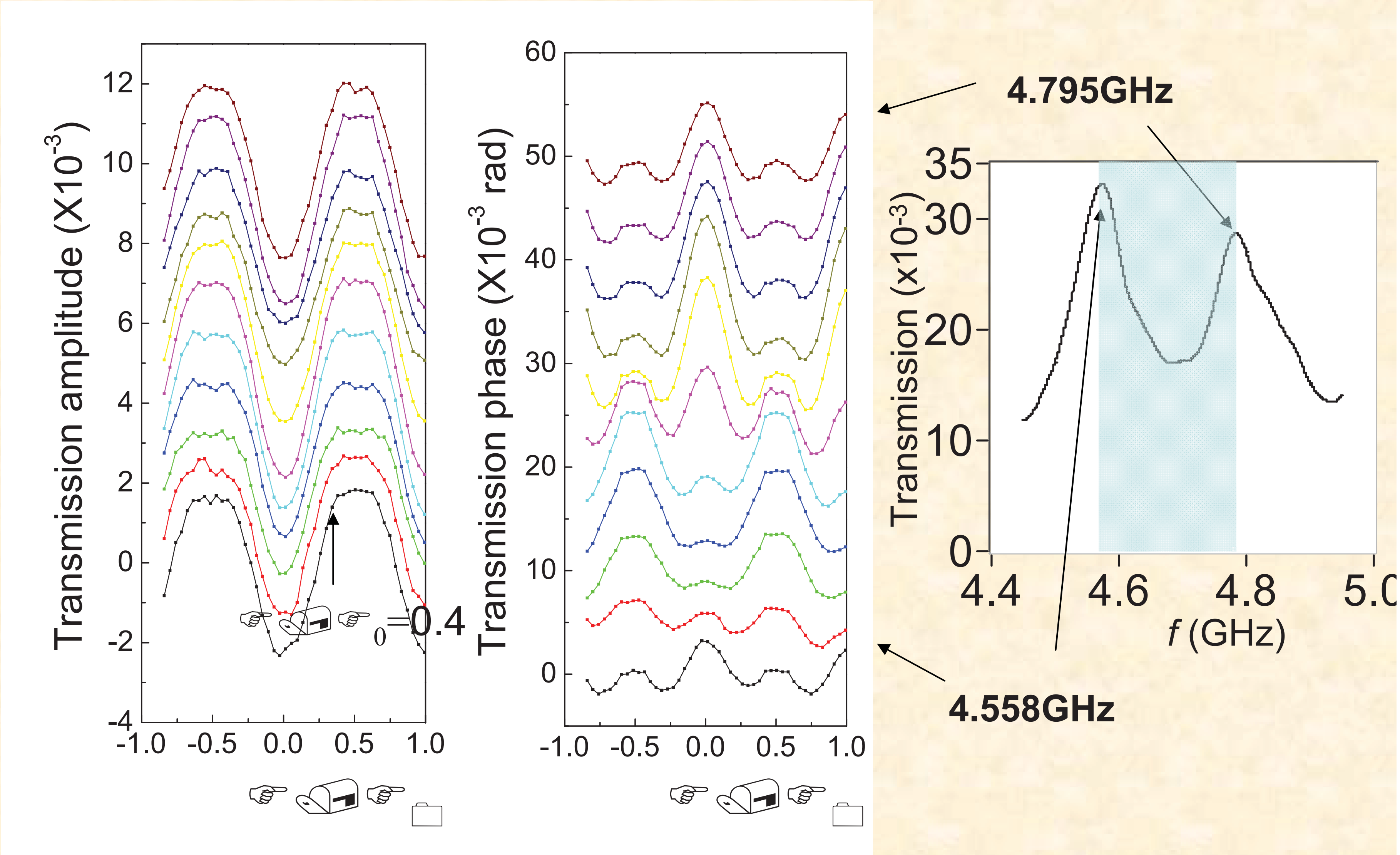
Frequency dependence (strong)





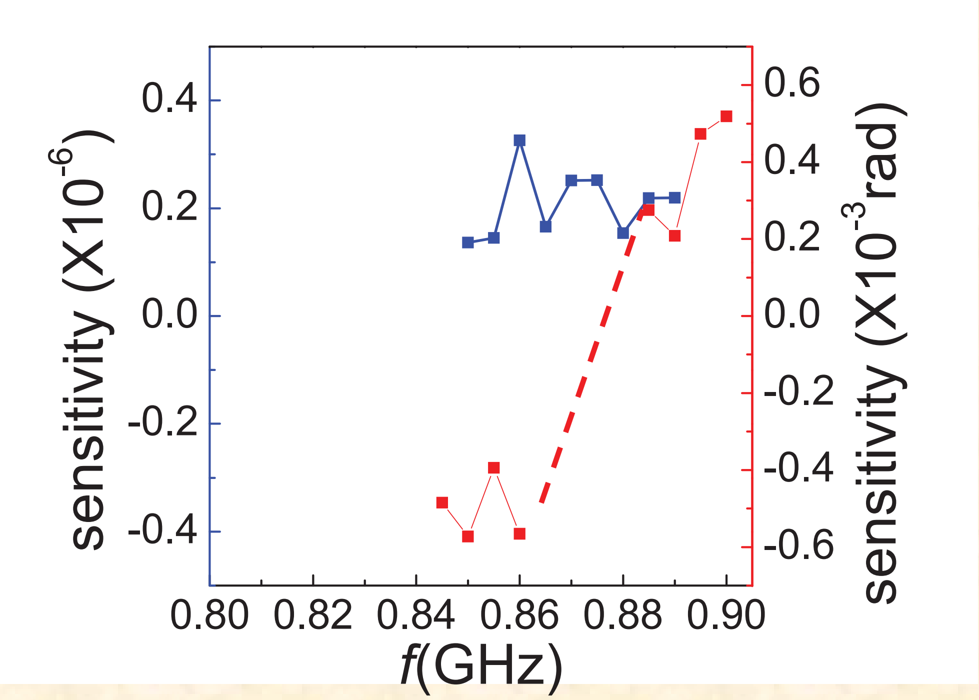


Frequency dependence (strong)—effect of standing wave

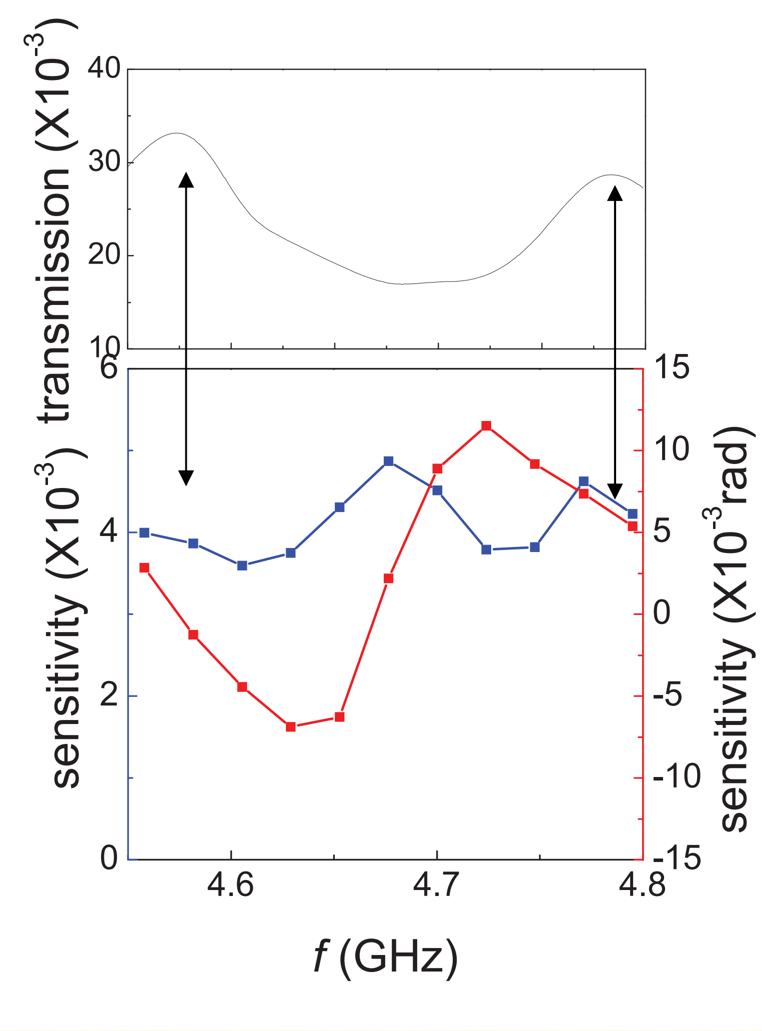


Sensitivity

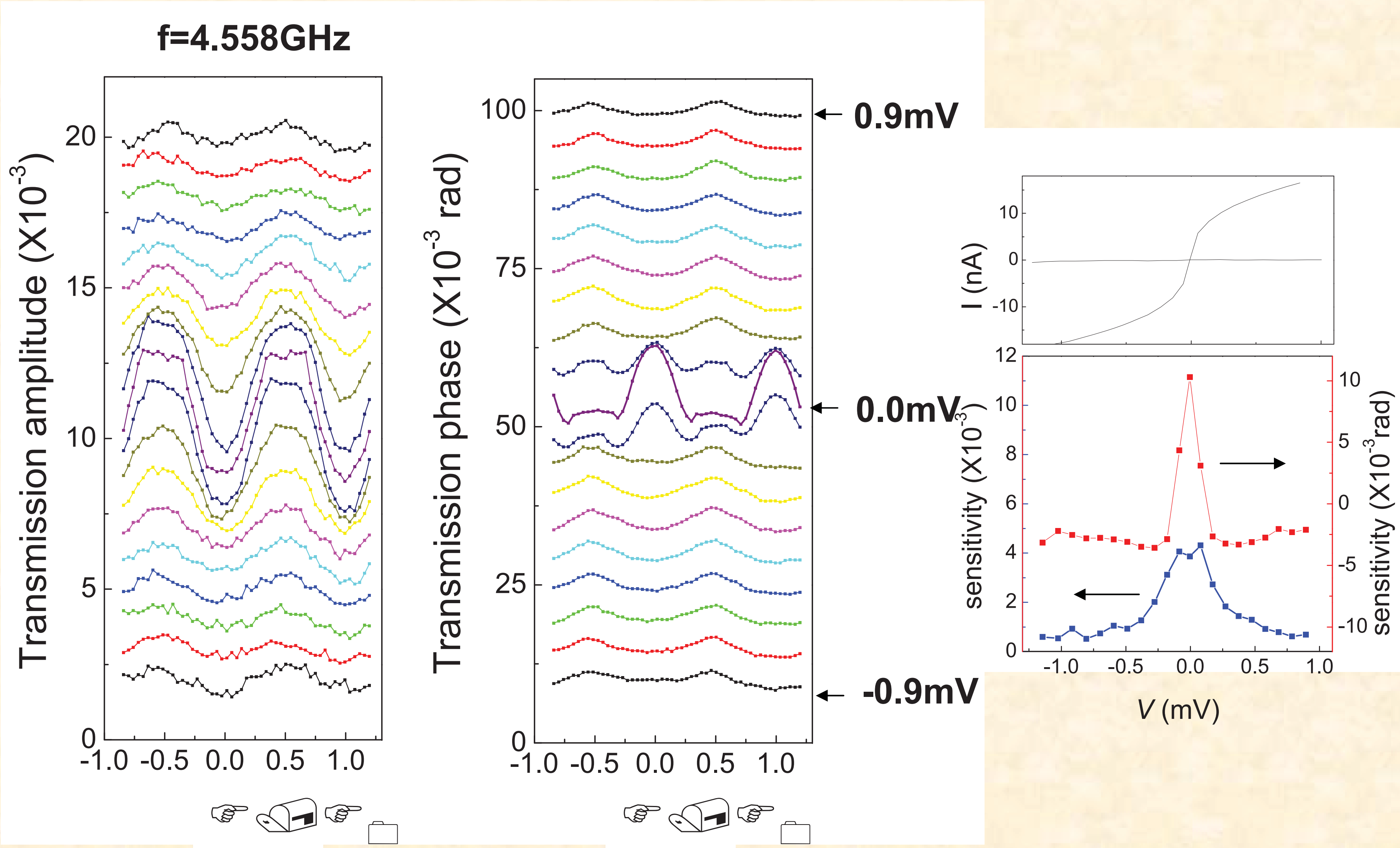
weak coupling



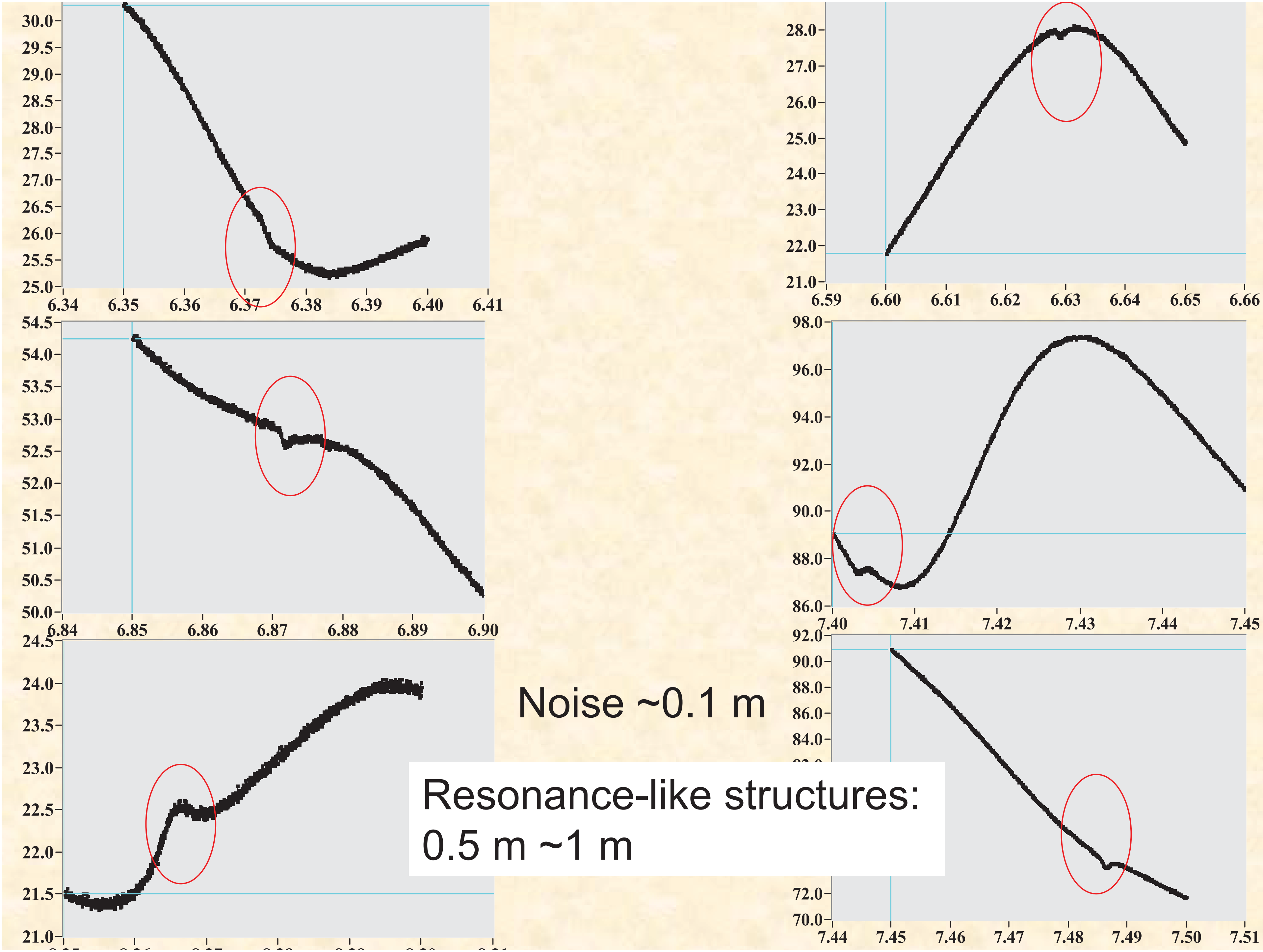
Strong coupling



Bias dependence (strong)



As a next step, to probe quantum levels…

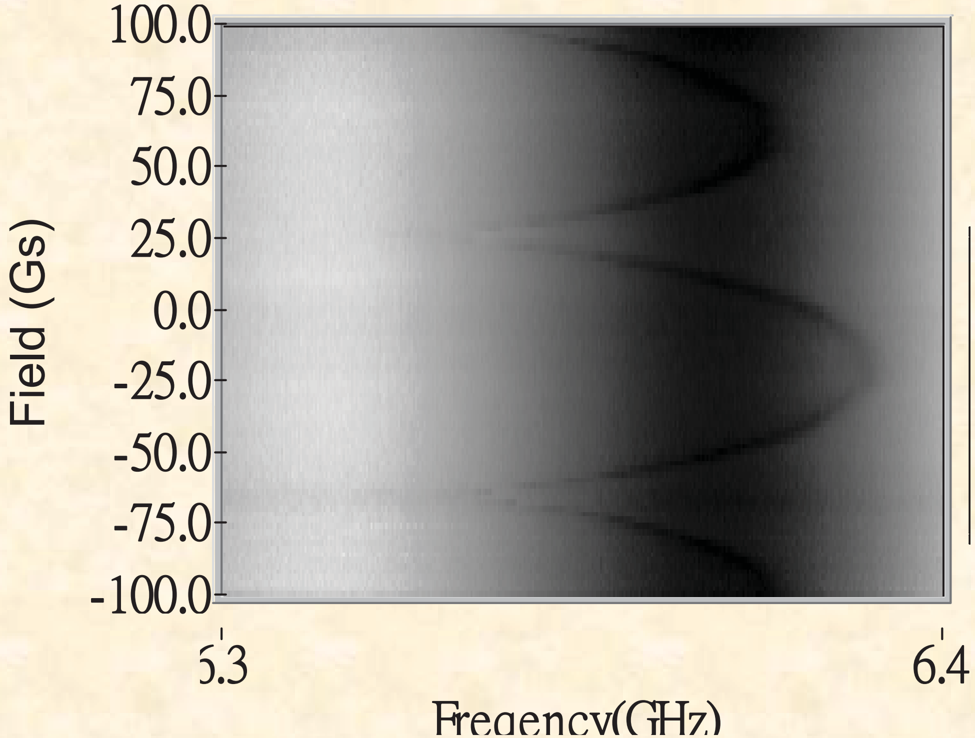


Noise ~0.1 m

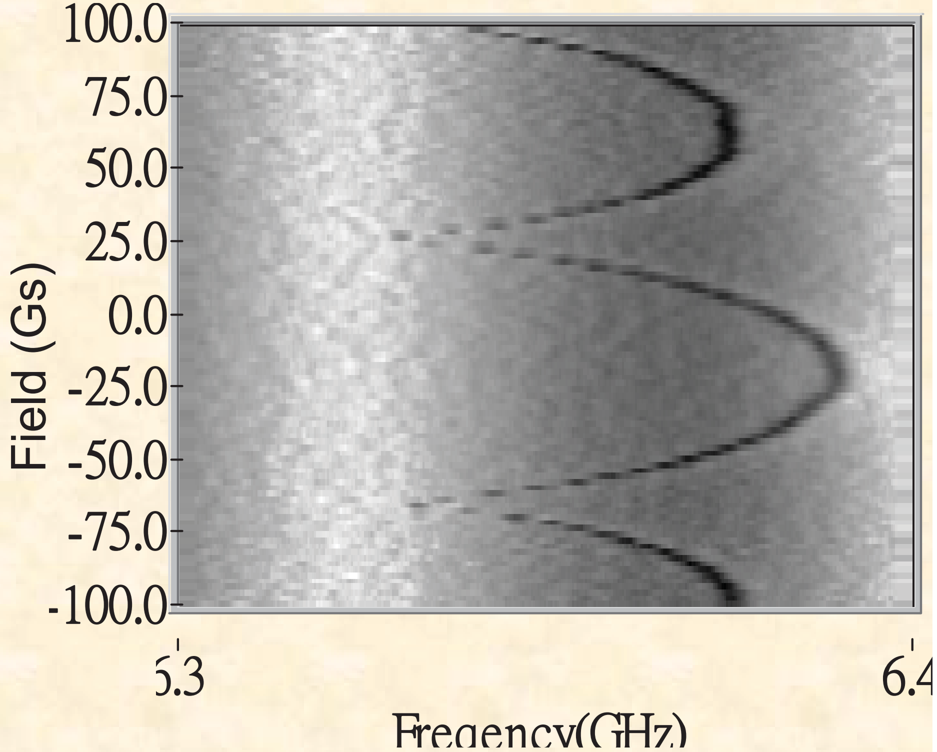
Resonance-like structures:
0.5 m ~1 m

Resonance structure--field scan

amplitude

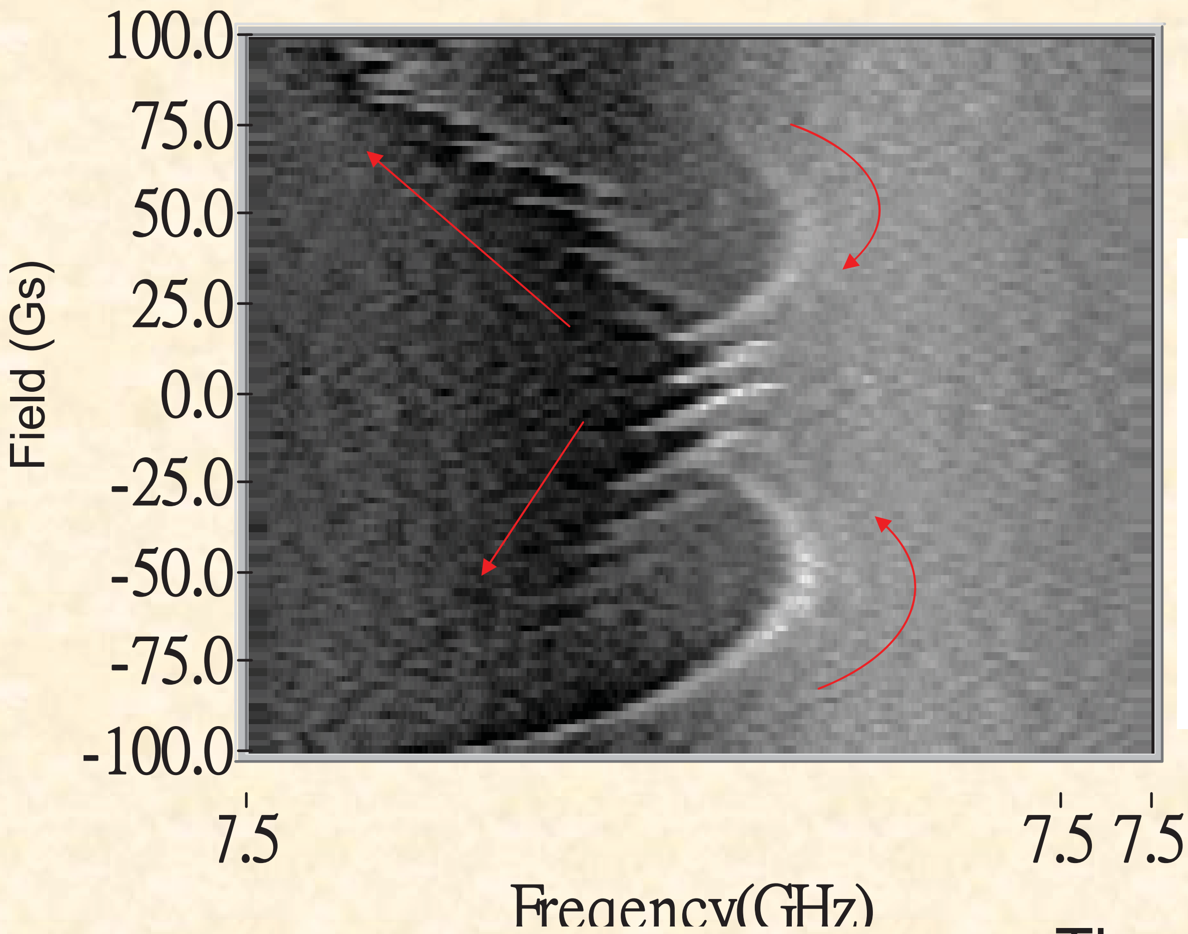


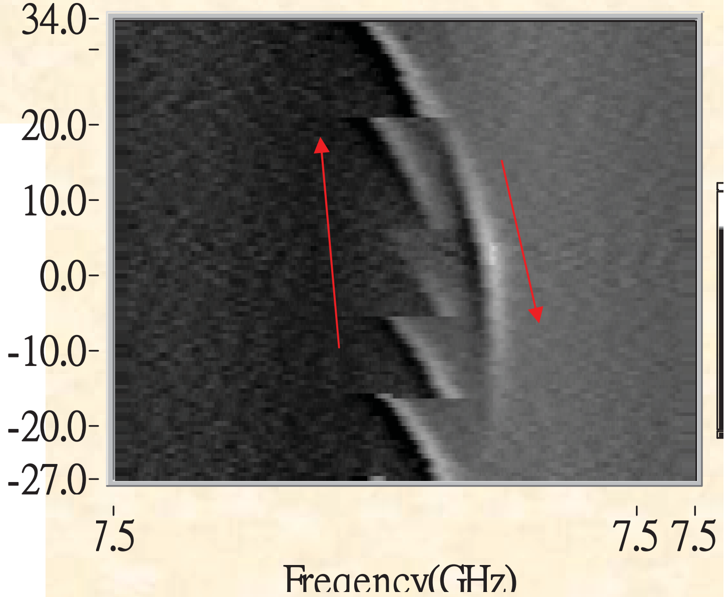
phase



The structure at 6.37GHz

Hysteretic behavior



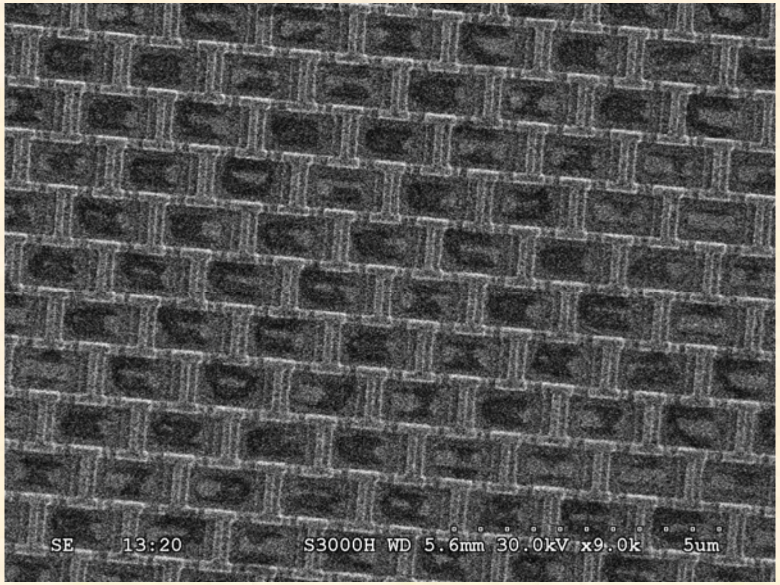


The structure at 7.48GHz

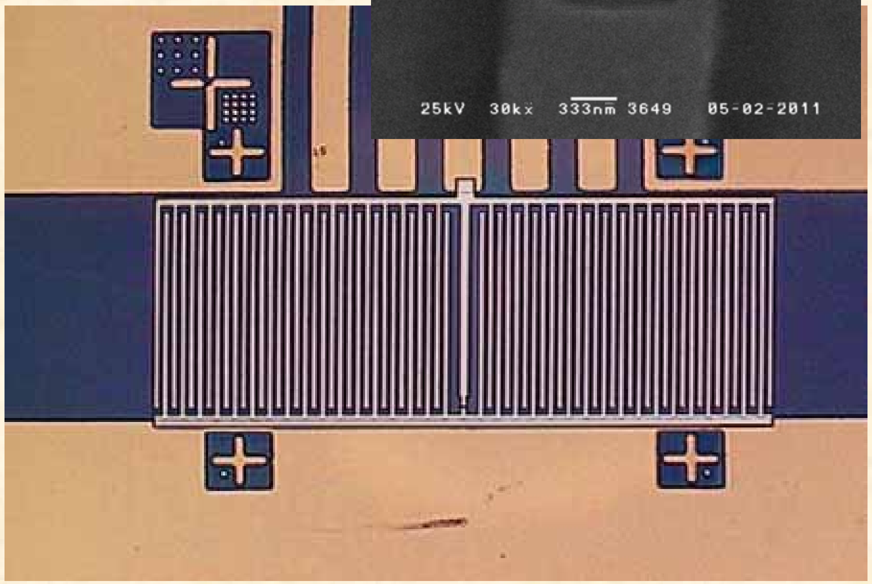
Summary

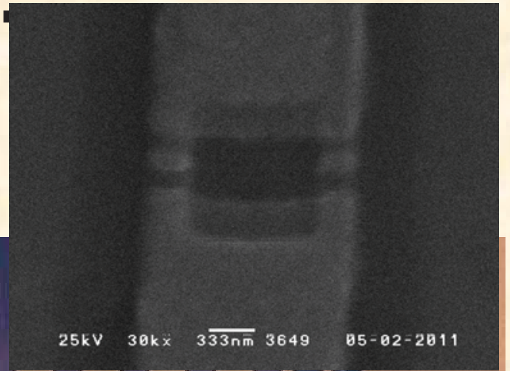
- 1D array can be used as a tool for studying microwave photon coupling strength.
- Microwave PL is an ideal approach for investigating the quantum levels of superconducting devices
- Photon absorption may be used to probe quantum phase transition

More devices are ready for cooled down….



2D JJ arrays



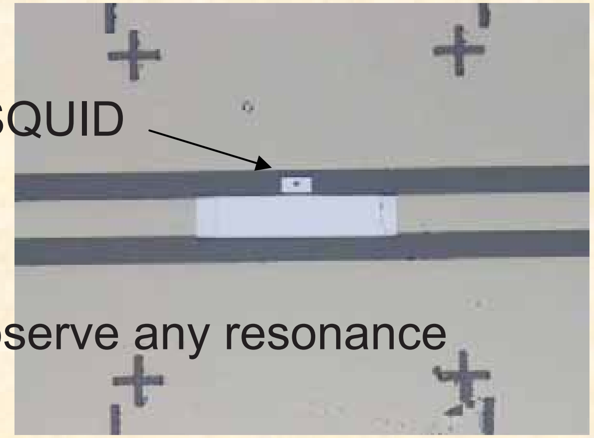


Single SQUID

Ongoing projects

In cooperation with Academia Sinica and NCUE

- A microwave PL study on single SQUID.
- Microwave cavity for single artificial atom detection
- Microwave meta-materials engineered from 1D arrays, Slow light, EIT etc



Collaborators

NCHU Physics

Prof. Y. W. Suen

Prof. C. C. Chang

Mr. Saxon Liou (PhD student)

Mr. W. C. Jian (PhD student)

IOP Academia Sinica

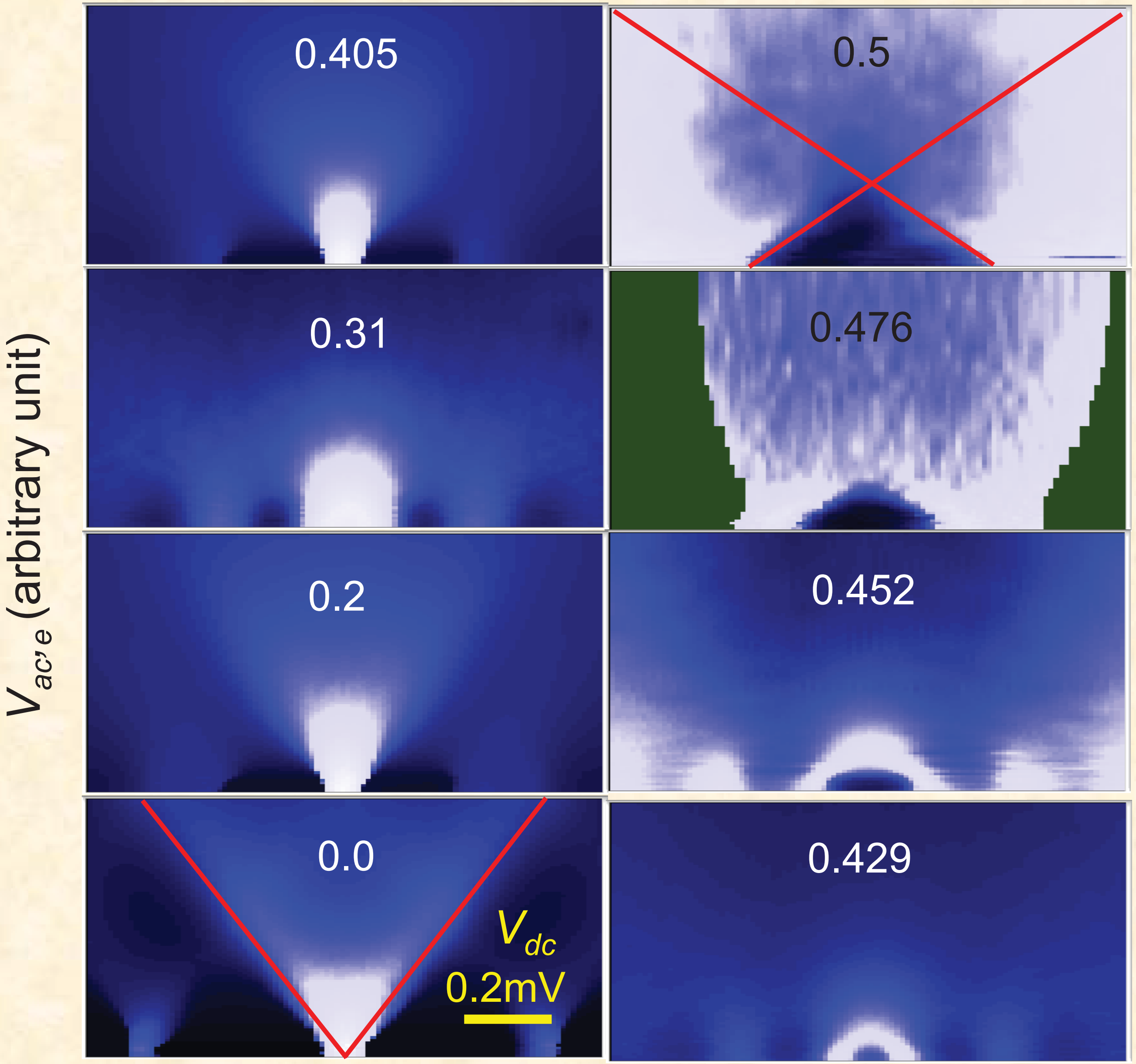
Prof. C. D. Chen

NCUE Physics

Prof. C. S. Wu

Thanks for your attention

DC and AC bias-dependent conductance



Theoretical modeling

Large charging energy → Large on-site Coulomb repulsion

low energy physics of the hard-core model can be treated by using an effective soft-core boson model with a 2-particle running coupling constant

Introduce the long-wavelength external excitation

↓

The total field is reduced by the induced field by the non-uniform charge density

↓

Evaluate the induction field by single particle Coulomb potential

↓

The coupling strength is obtained

In cooperation with Prof. C C Chang

Visibility of the photon luminescence