Microwave Photoluminescence Studies on Superconductive Devices

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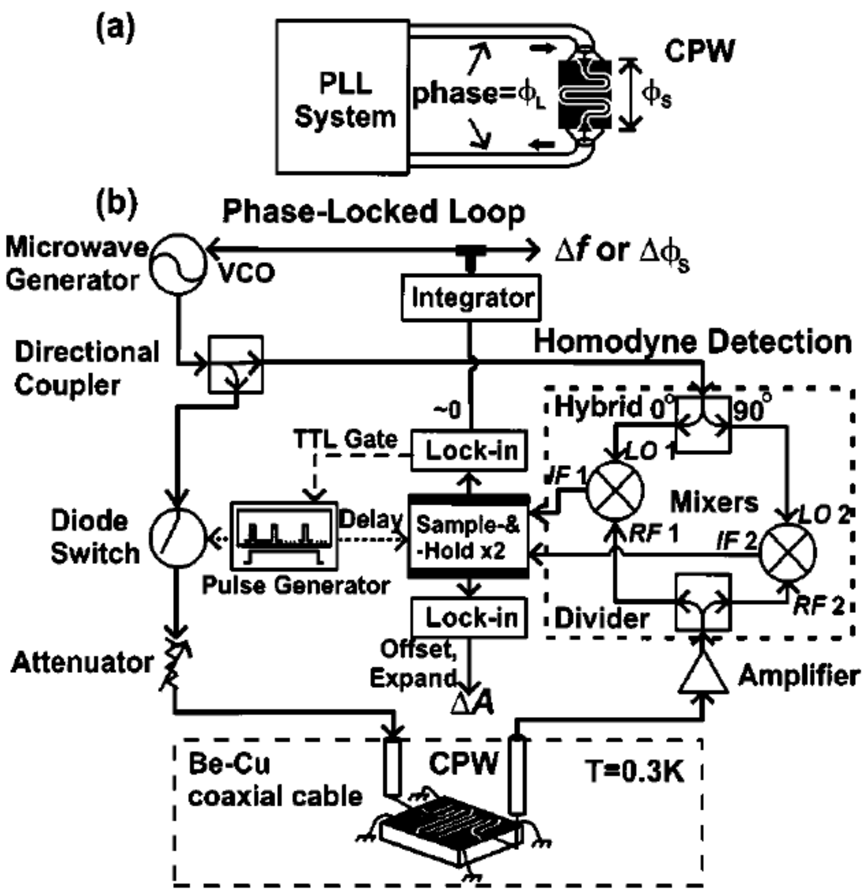
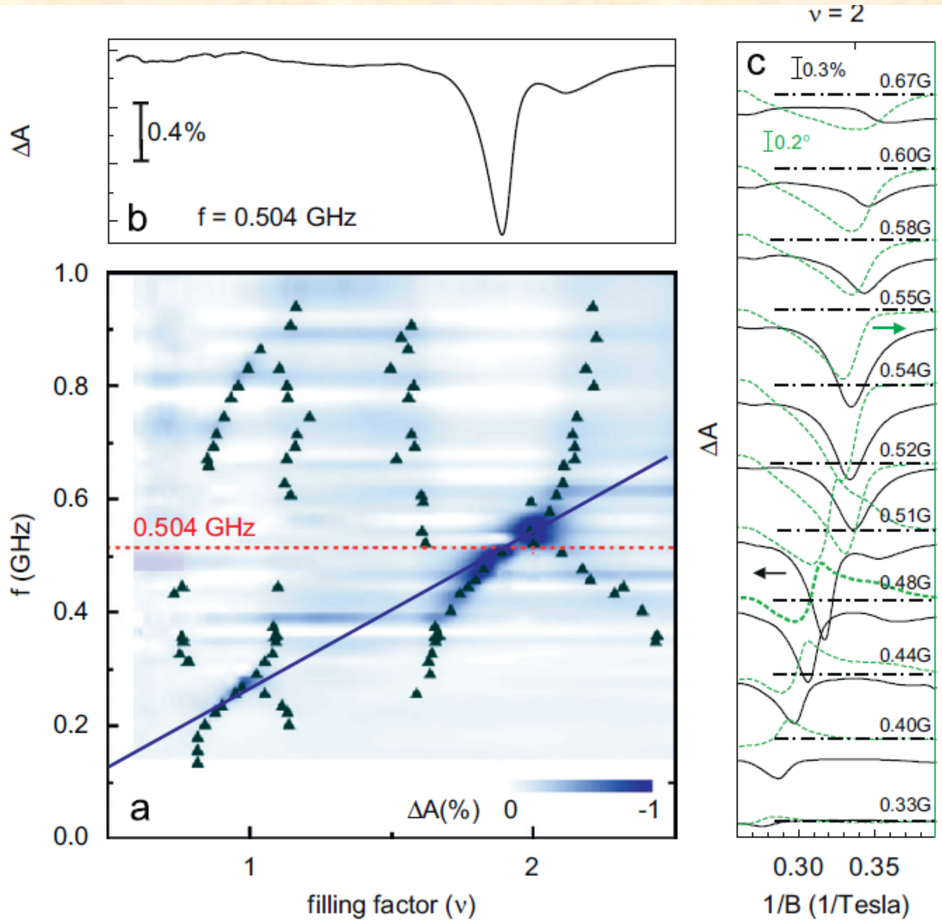
@ CYCU physics 2011/5/12

What is
“microwave photoluminescence”
?

Once upon a time….



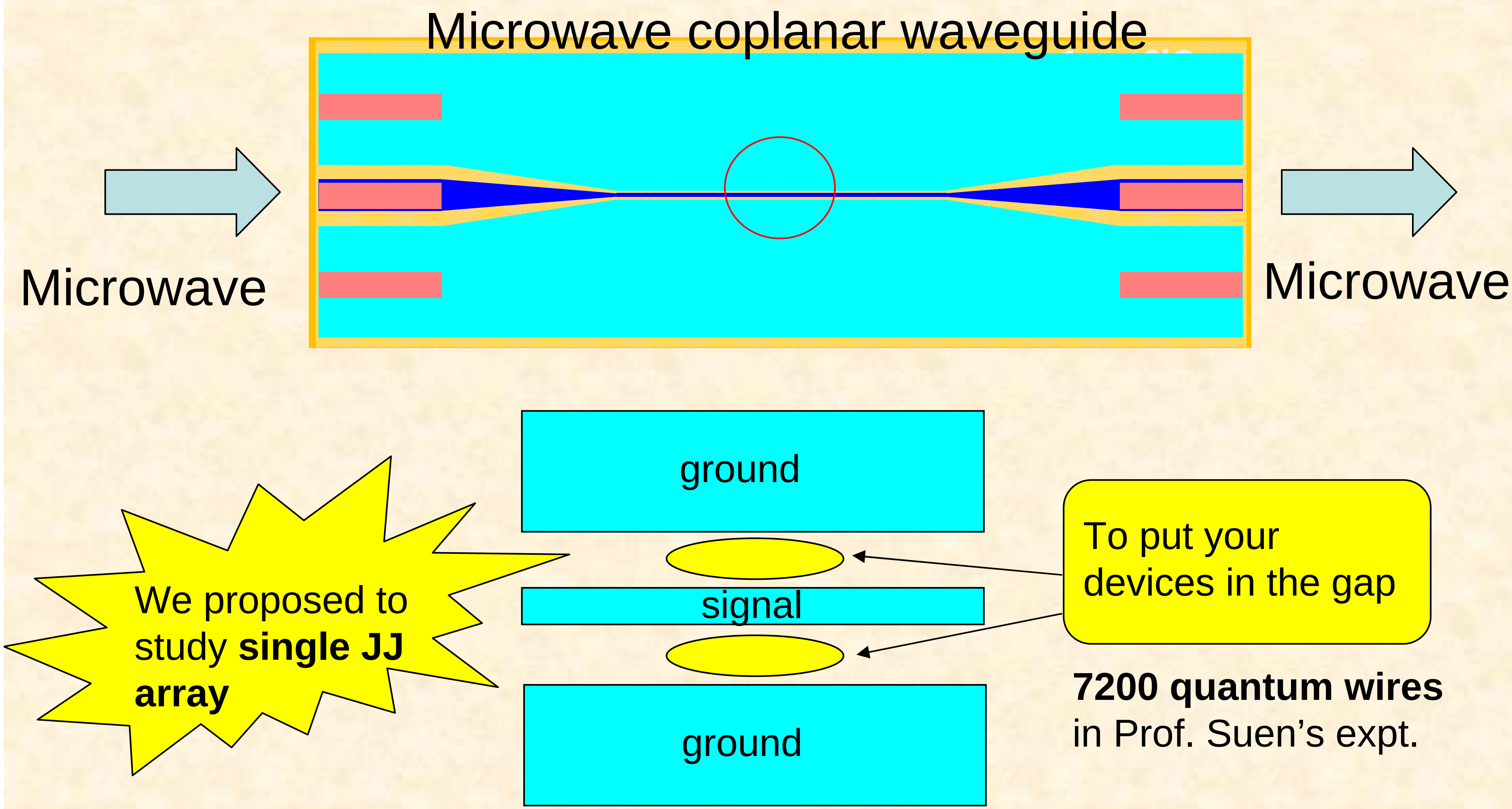


W. H. Hsieh et al APL85, 4196 (2004)

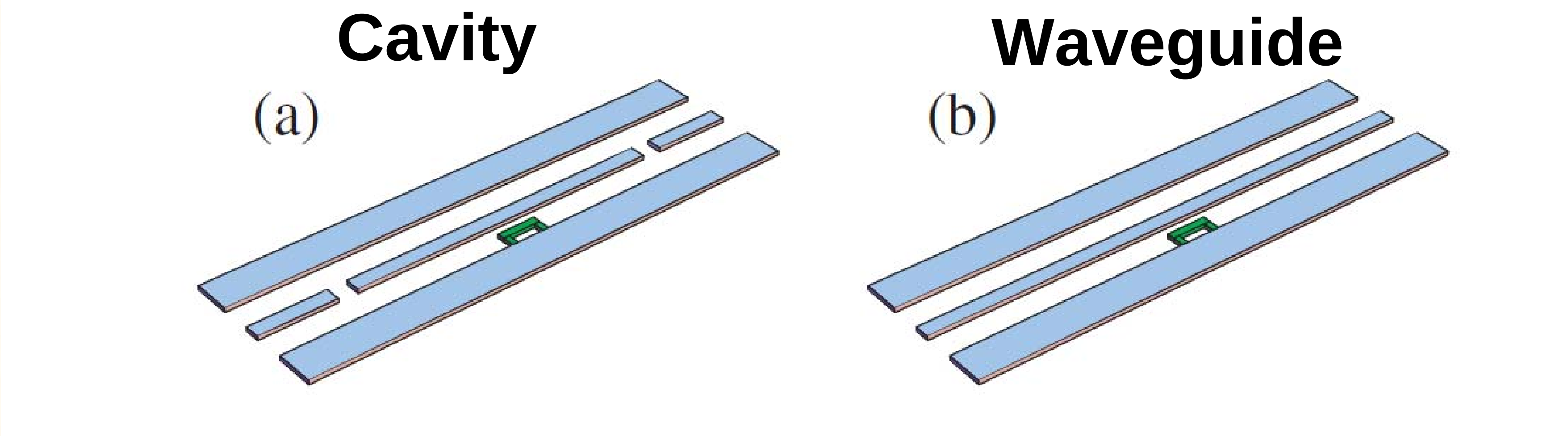
W. H. Hsieh et al Physica E 40,1681 (2008)

Edge magnetoplasma excitations in quantum wire arrays

Concept


Microwave coplanar waveguide
Microwave
Microwave
ground
signal
ground
We proposed to study **single JJ array**
To put your devices in the gap
7200 quantum wires in Prof. Suen’s expt.

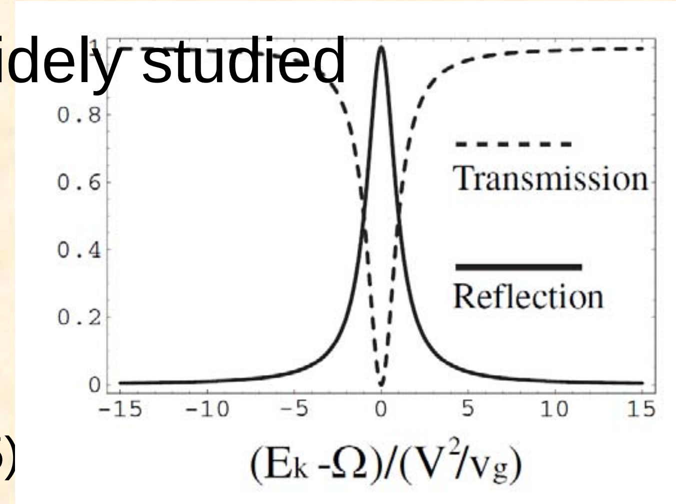
Cavity vs. waveguide



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)

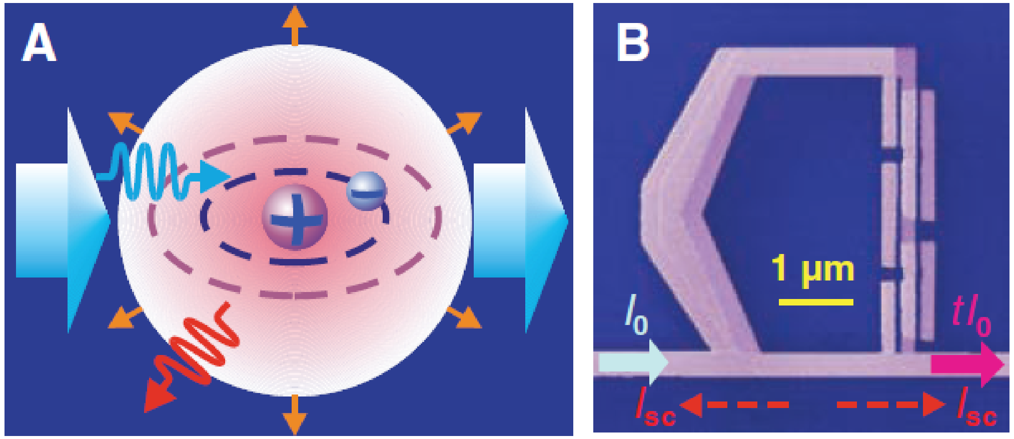
A recent breakthrough

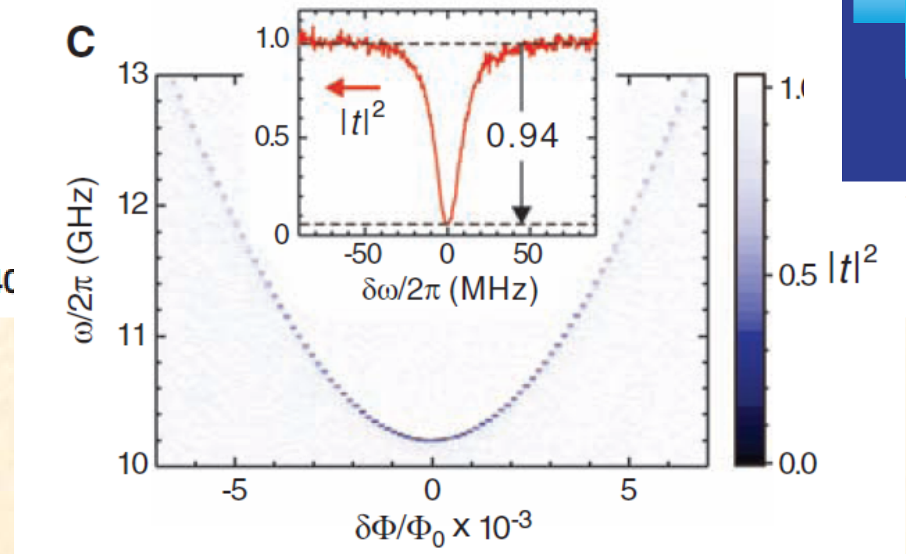
Resonance Fluorescence of a Single Artificial Atom

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-dimen

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

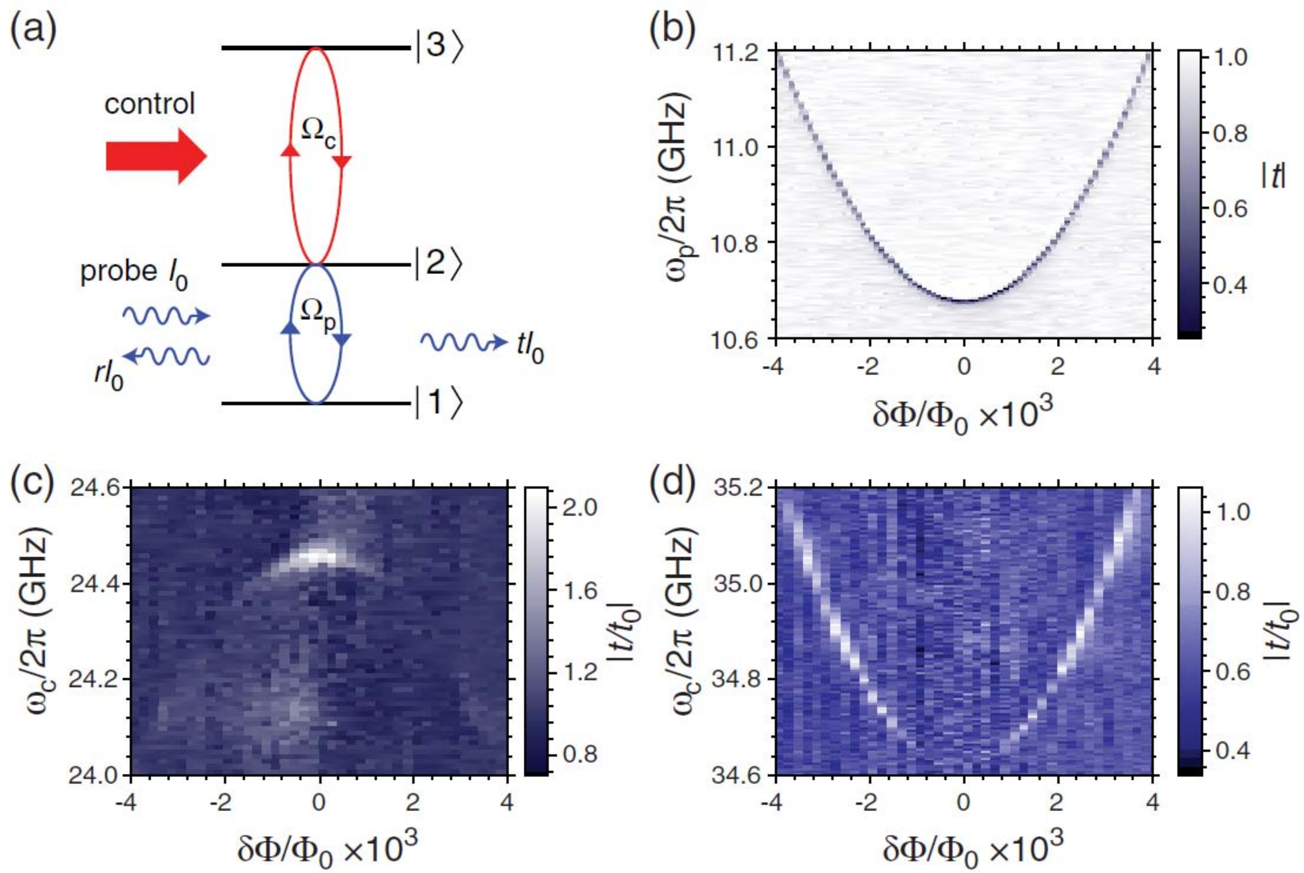
Electromagnetically Induced Transparency on a Single Artificial Atom

A. A. Abdum … S. Tsai[1,2]

[3]Departı … gdom

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

DOI: … -j

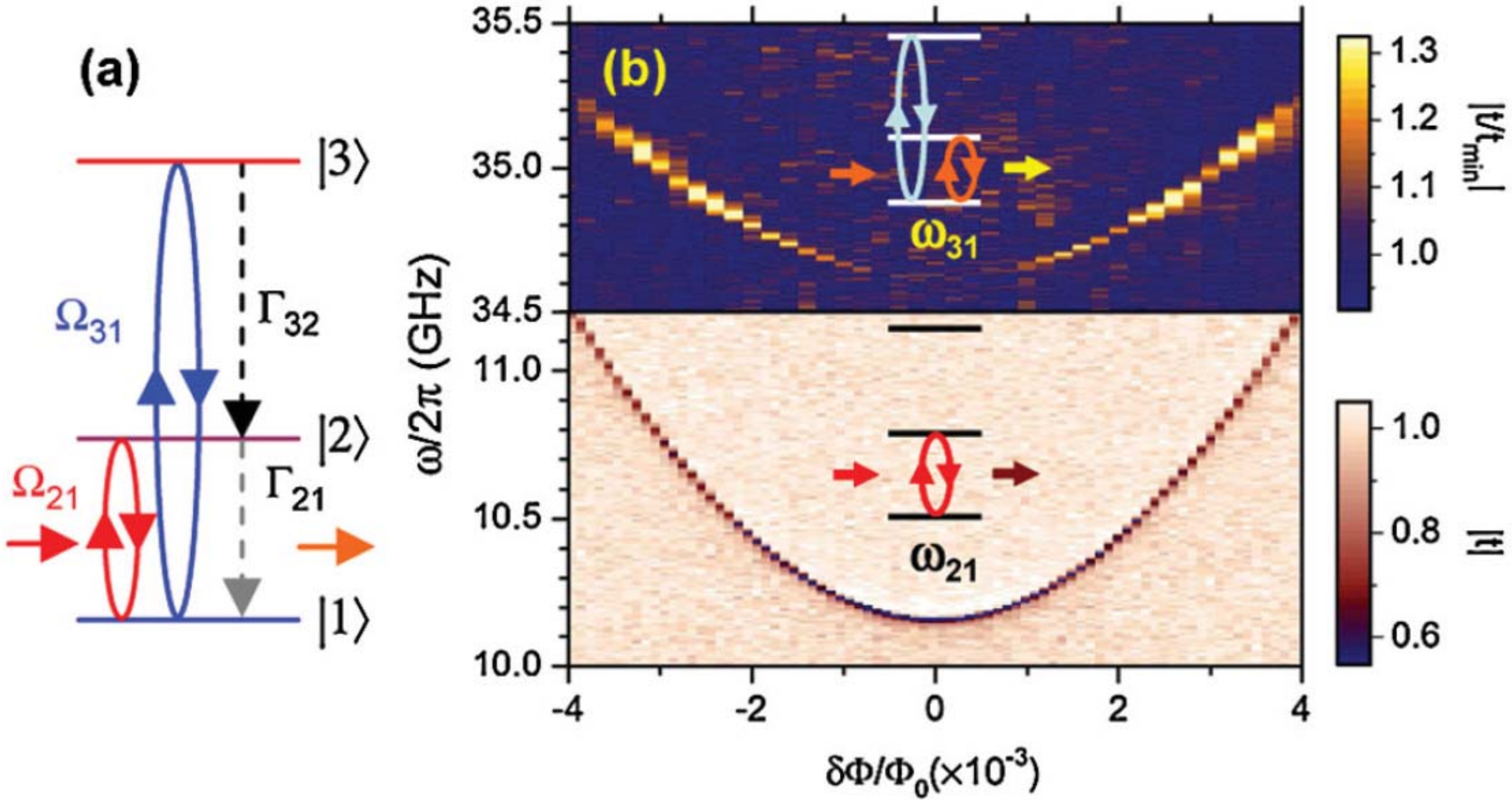


A broadband photon transistor can be demonstrated…

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

Ultimate On-Chip Quantum Amplifier

O. i[1]

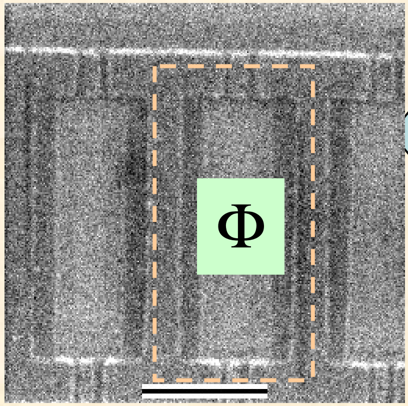


This work opened a new direction toward quantum optical study on artificial atoms.

But how about our progress?

Why 1D arrays?

Arrays with tunable Josephson coupling energy

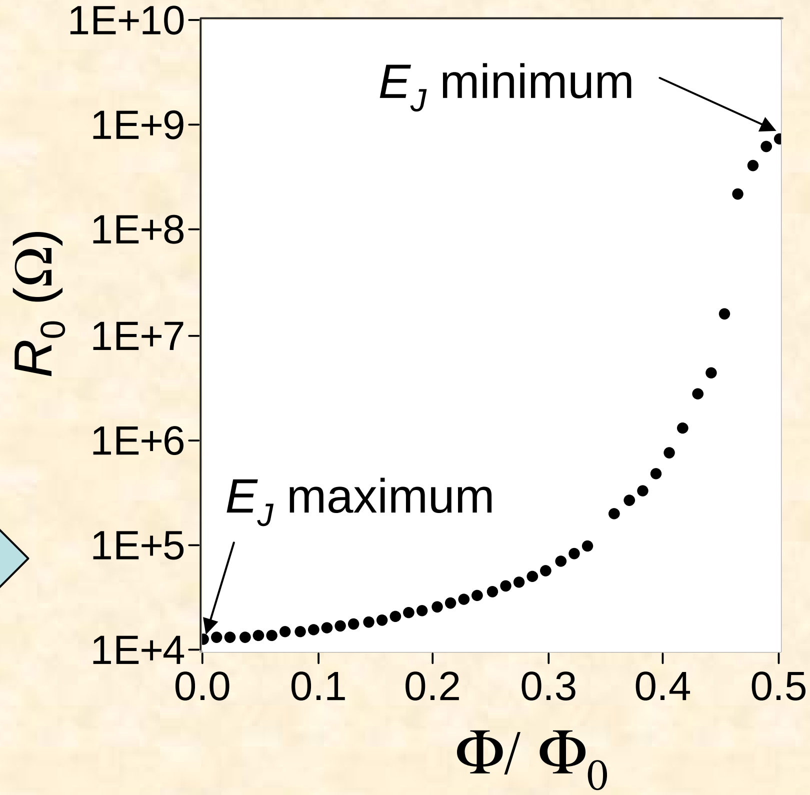


The SQUID structure renders a E_J-tunable 1D array

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

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

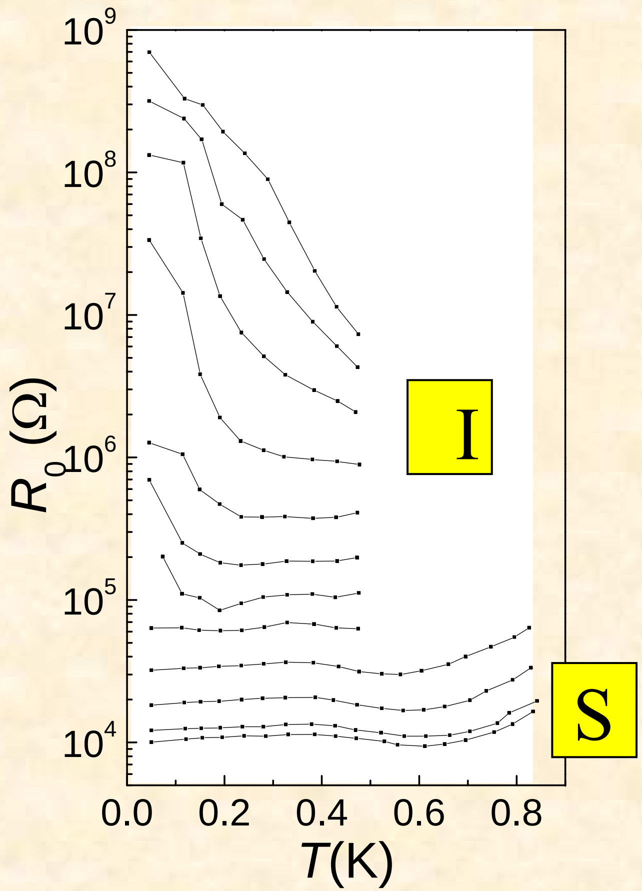
The zero-bias resistance becomes minimal when E_J is maximal.



Superconductor-insulator transition

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

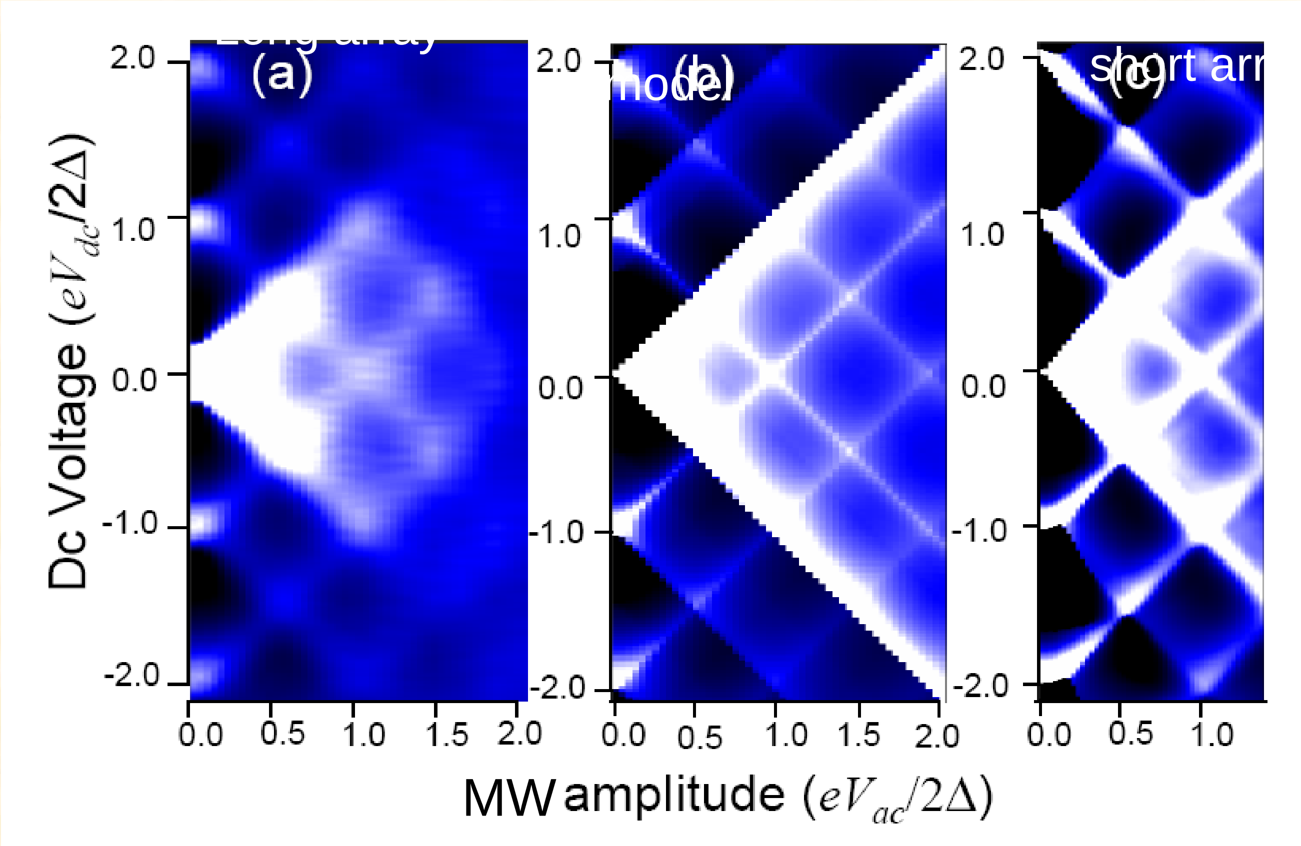
● Exhibiting Superconductor-insulator phase transition tuned by dissipation or E_J/E_C value



W. Kuo and C. D. Chen PRL87, 186804(2001)

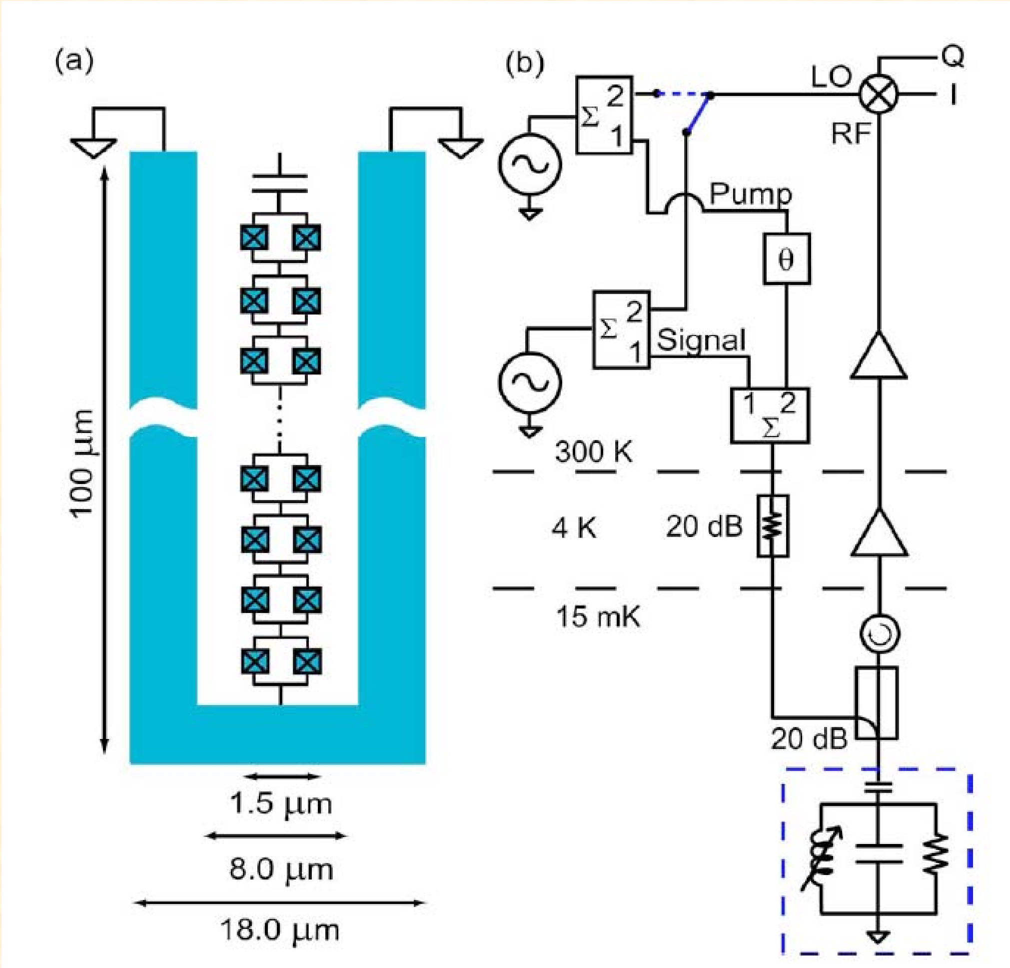
Direct detection in 1D arrays

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



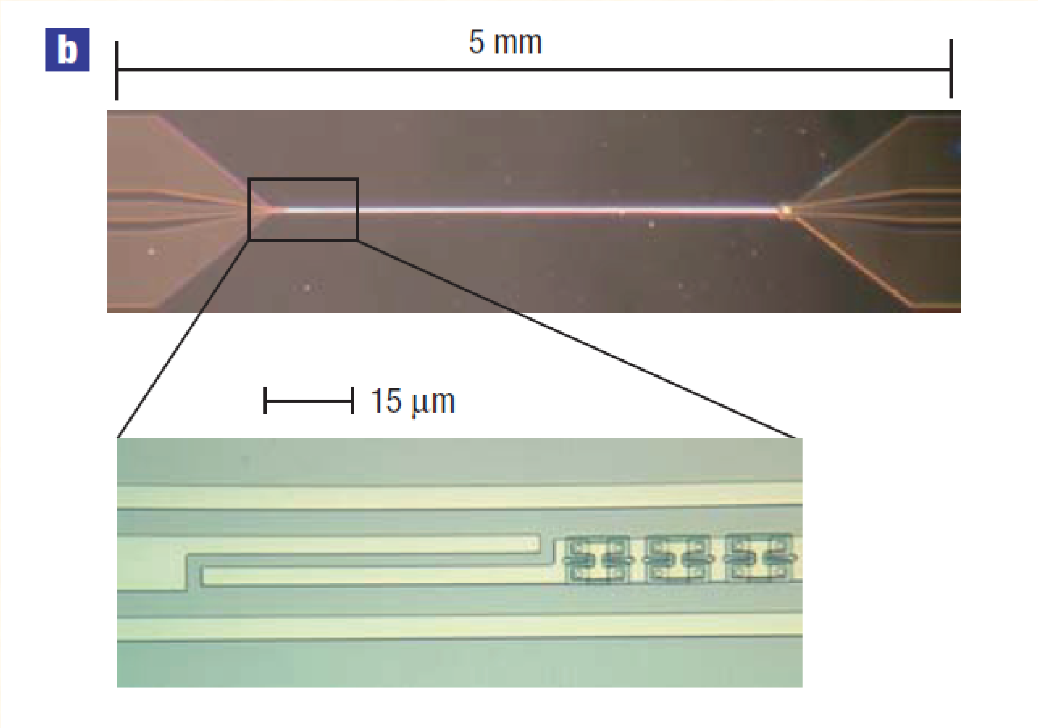
S. Liou, W. Kuo et al, NJP 10, 073025(2008)

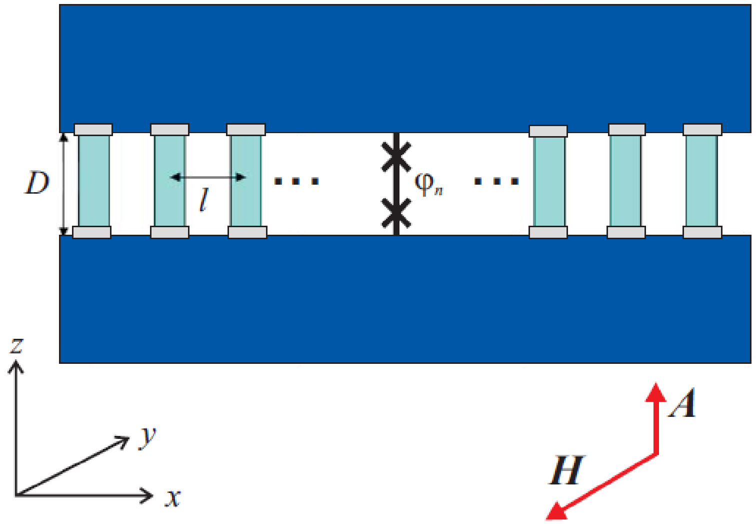
1D arrays as parametric amplifiers



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

1D arrays as meta-materials





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

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

Characteristic energy scales

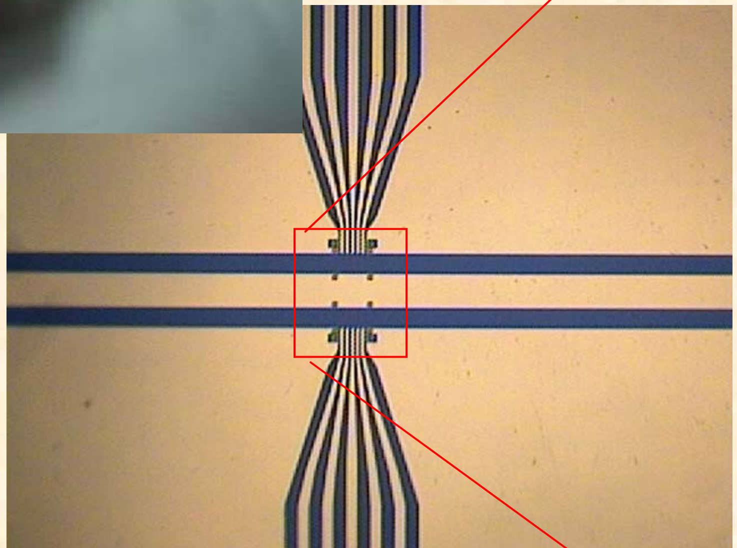
Josephson coupling energy (charge hopping) $E_J^0 \sim 100\mu\text{eV}$

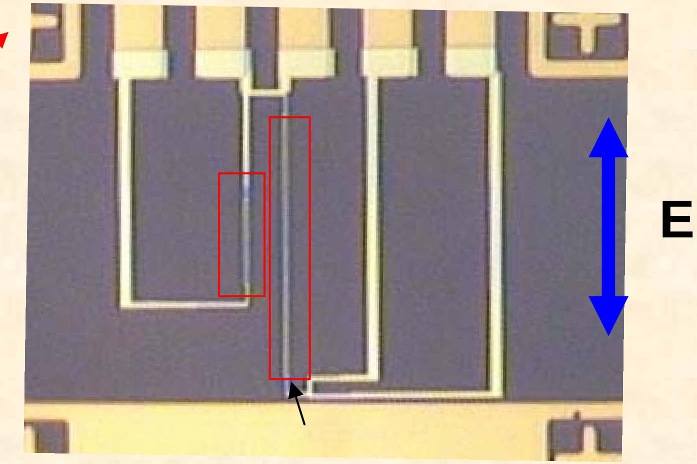
Charging energy (on-site repulsion) $E_C \sim 100\mu\text{eV}$

Photon energy 1GHz ~ $4\mu\text{eV}$

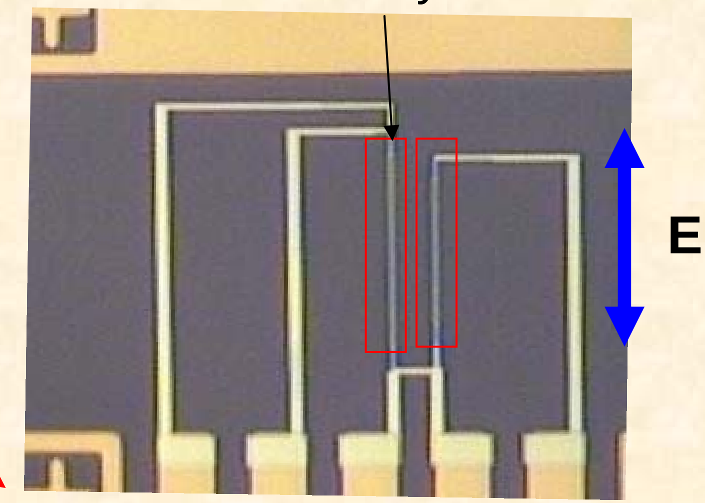
Temperature 50mK ~ $4\mu\text{eV}$

Experimental setup—
weak coupling



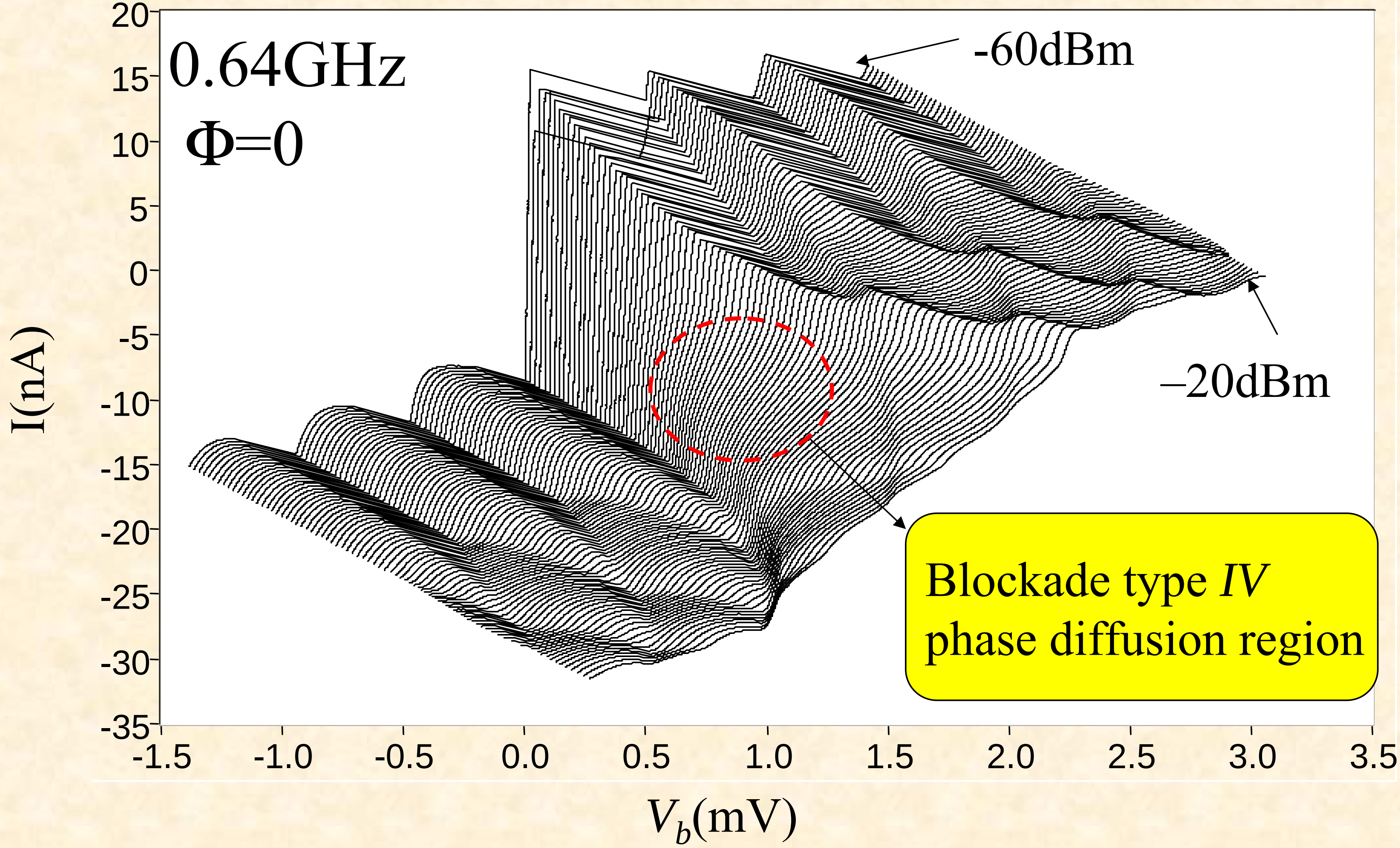


1D arrays

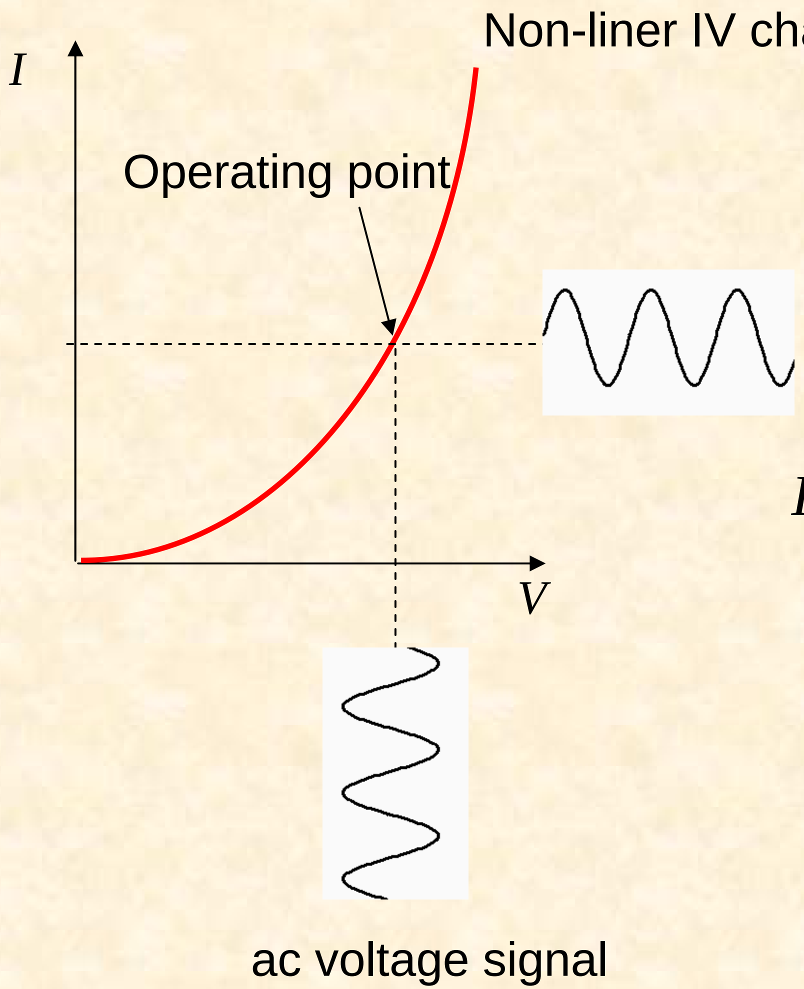


Polarization, frequency dependence
Better microwave power control

Phase diffusion due to microwave excitation



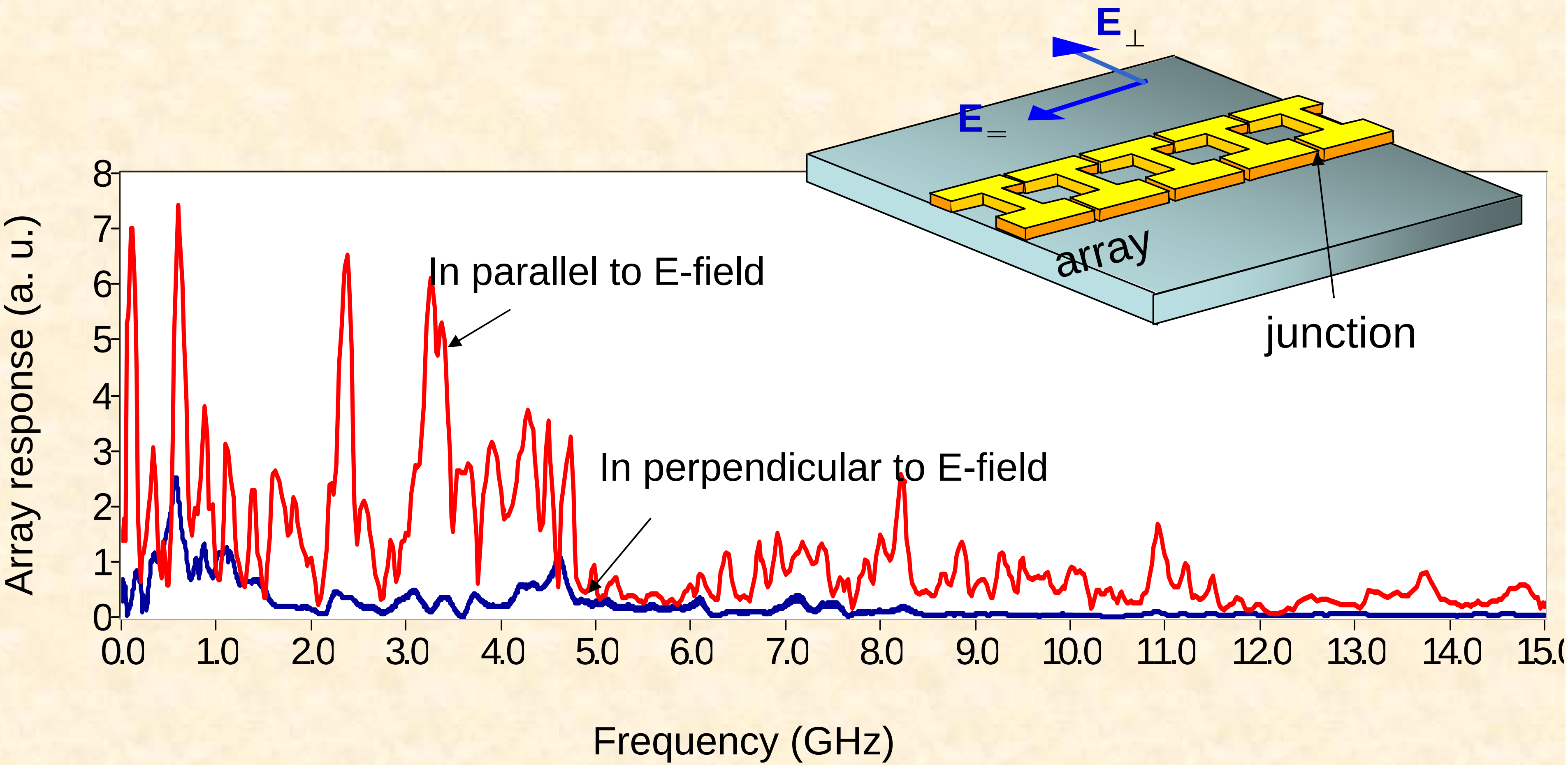
Direct (square-law) detection

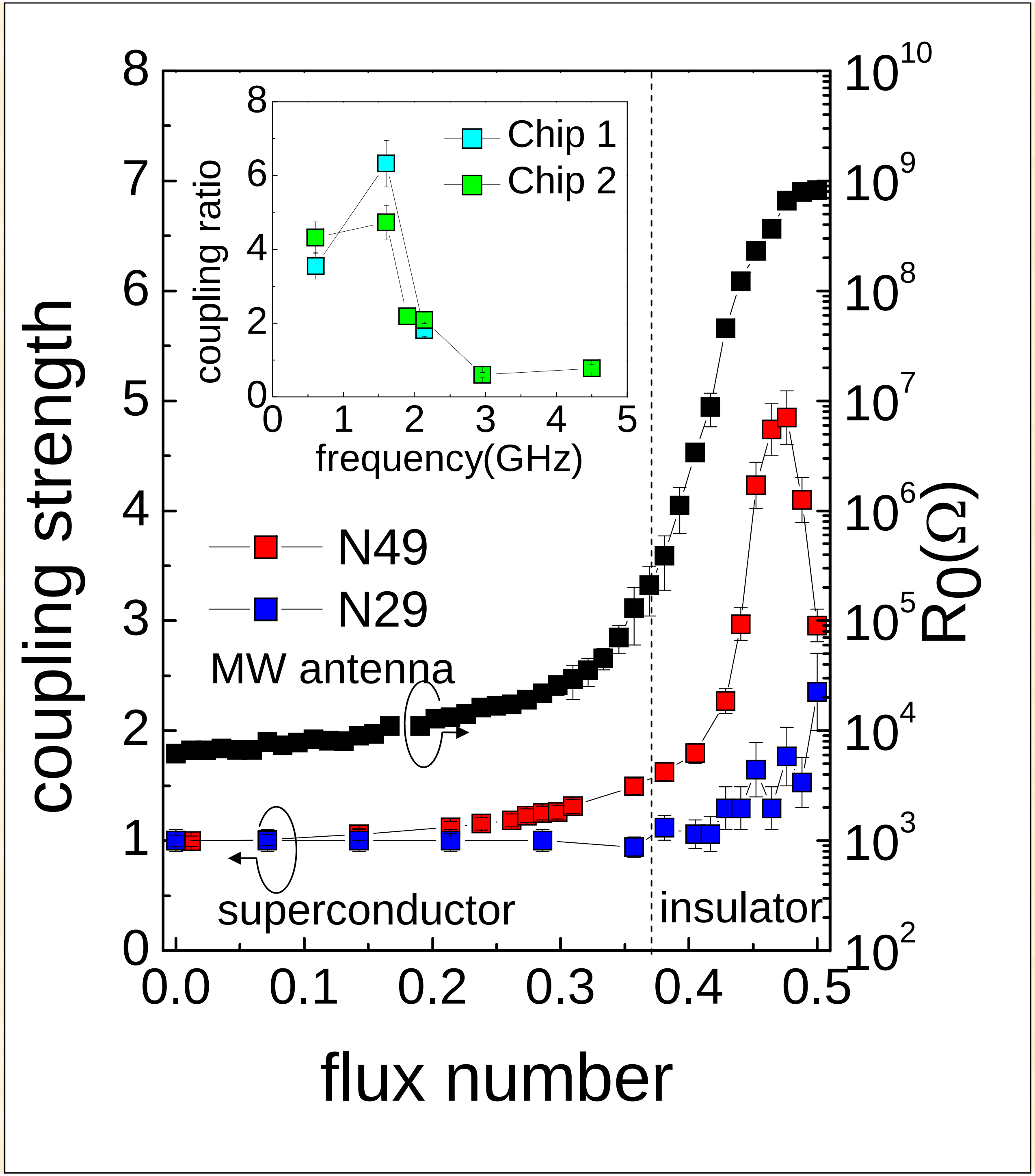


$$I_{dc} = (2\pi)^{-1} \int_0^{2\pi} I^0 (V_{dc} + V_{ac} \cos u) du$$

When V_{ac} is small $\quad \Delta I_{dc} \propto V_{ac}^2$

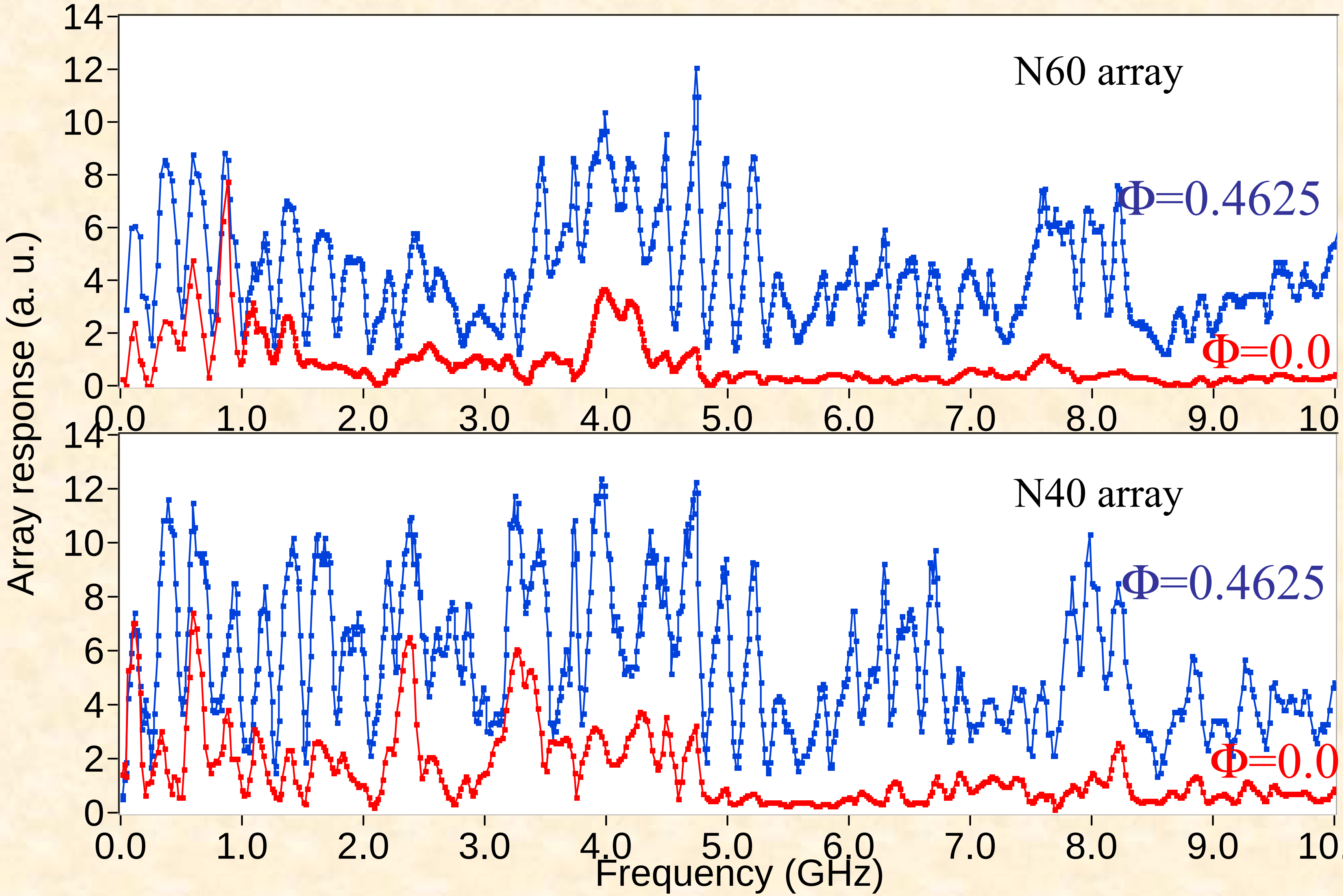
Polarization dependence



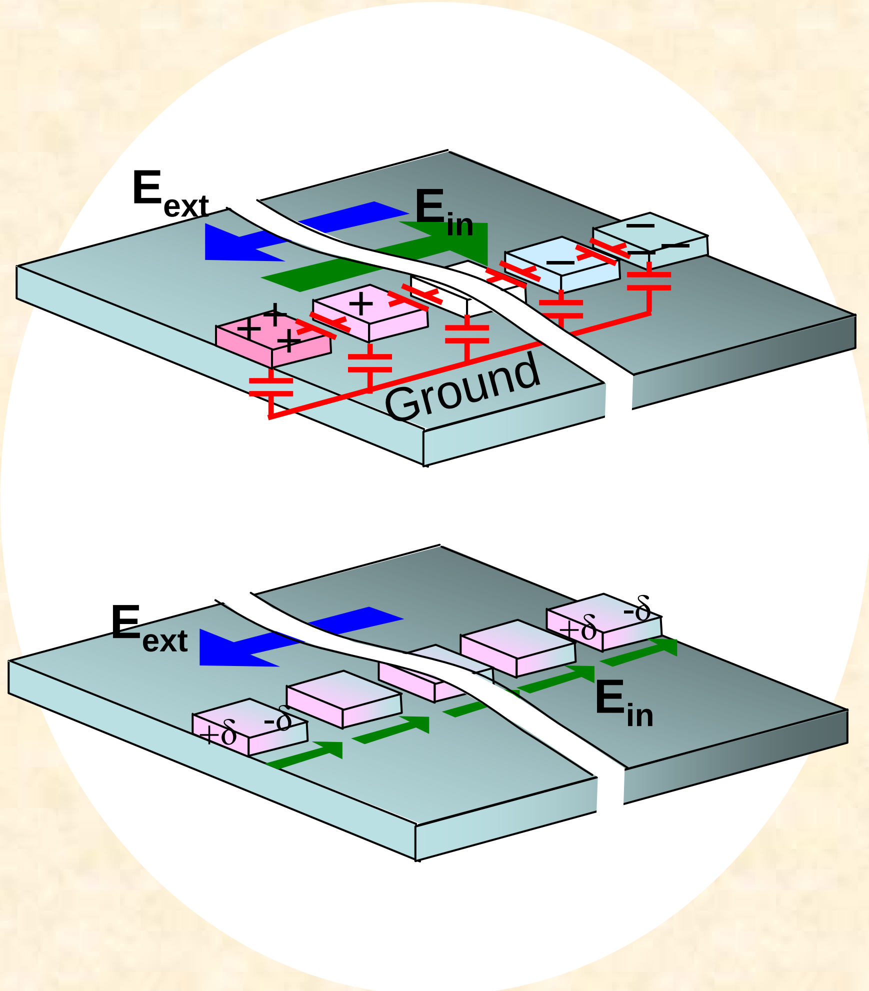


coupling strength
flux number
R0(Ω)
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
6
7
8
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
N49
N29
MW antenna
superconductor
insulator
coupling ratio
frequency(GHz)
Chip 1
Chip 2

Frequency and field dependence



The screening interpretation



Superconducting state

Charges are mobile so as to screen the external electric field

Insulating state

The charge screening is weak

Effective coupling strength

Size-dependence:

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

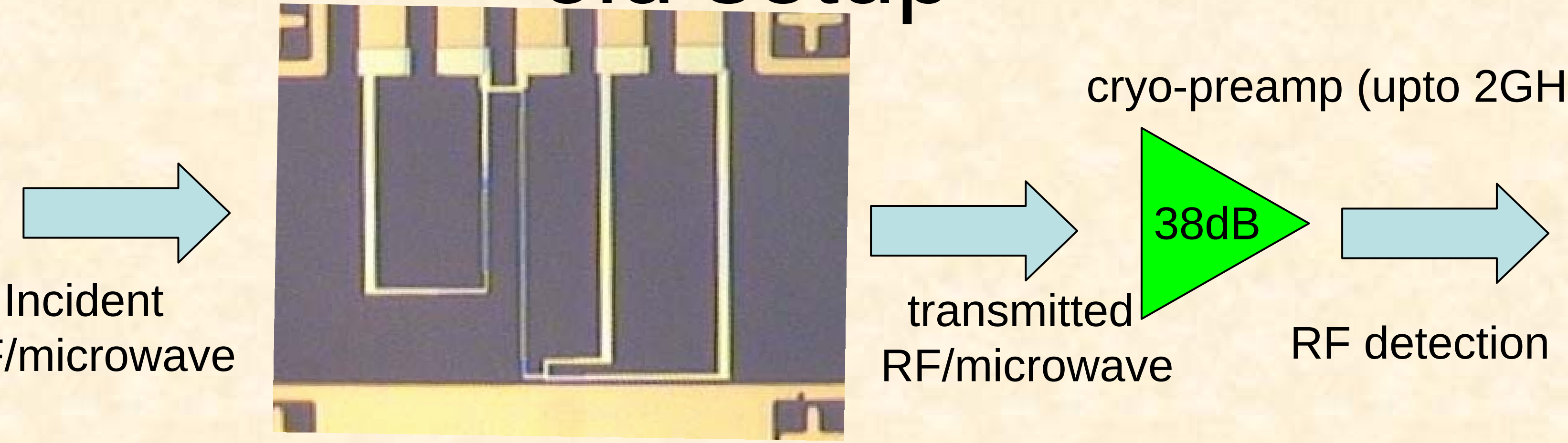
Flux-dependence:

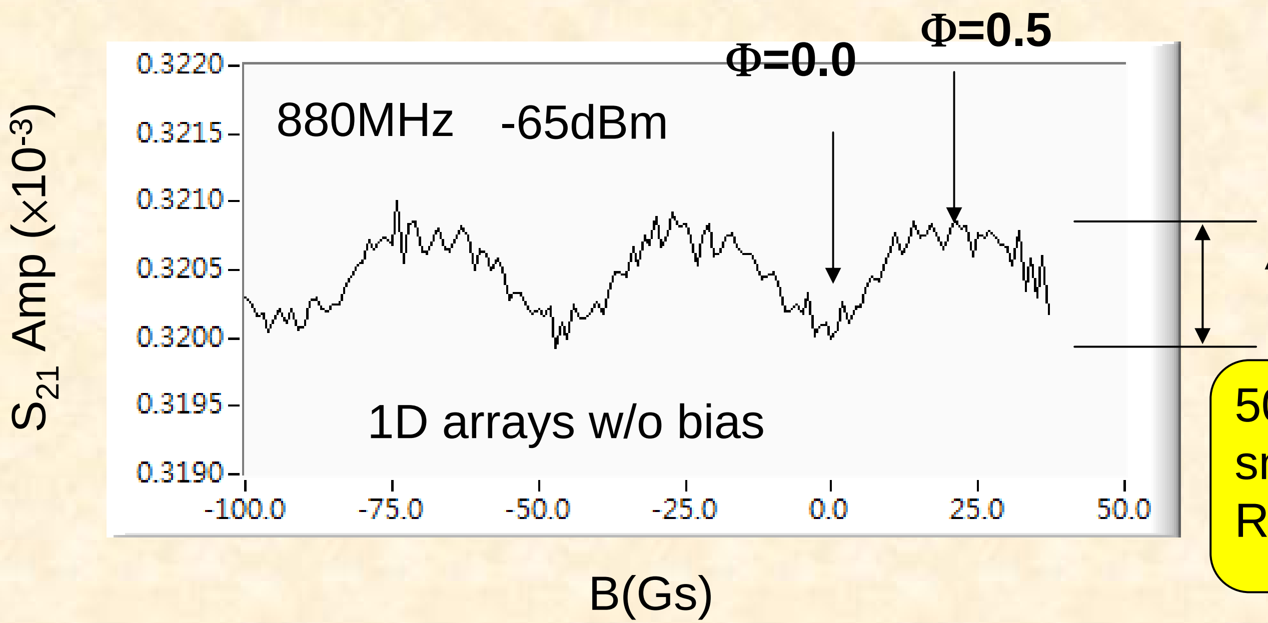
The coupling strength is related to the ground state properties of the array
Obviously beyond the scope of impedance matching

Frequency-dependence:

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

RF/MW transmission—old setup

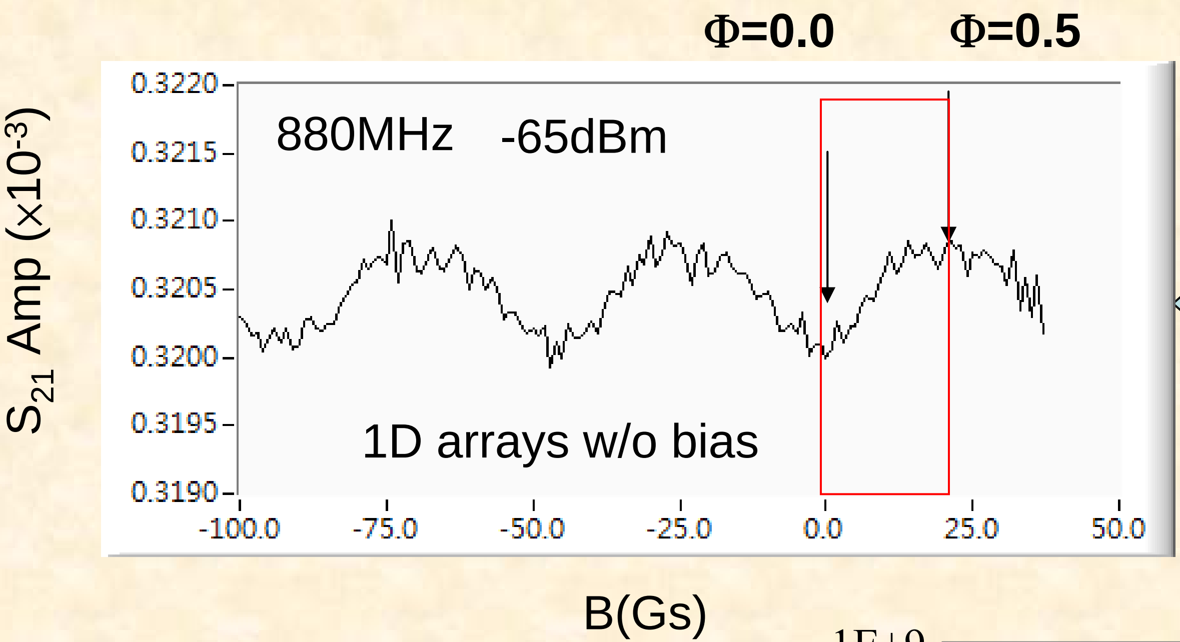




$\Delta\Gamma$=1μ

1μ out of 0.3 m

500 times smaller than RF-SET!

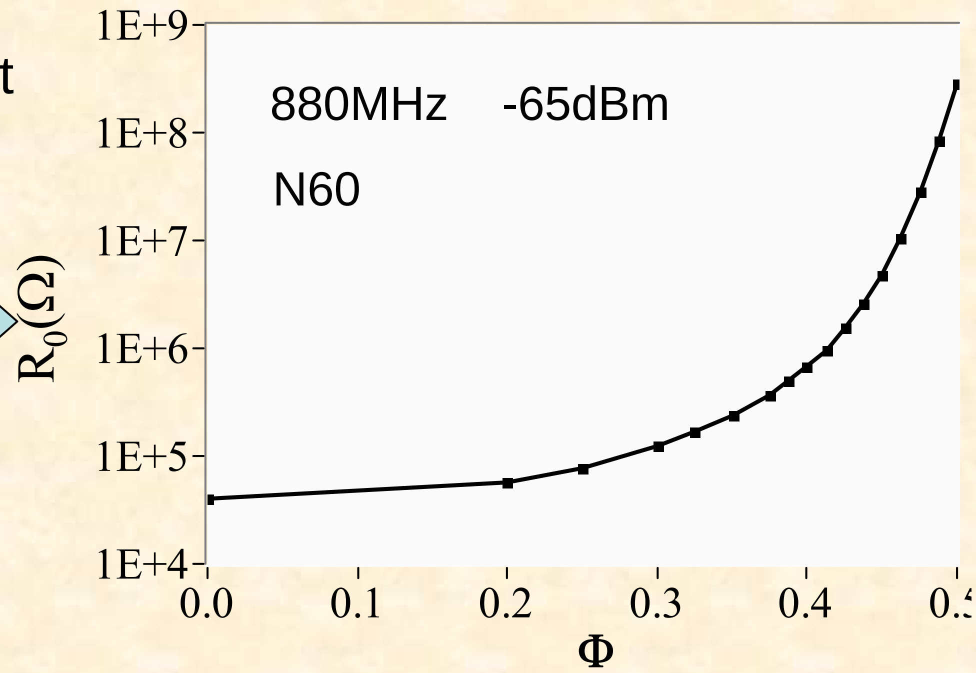


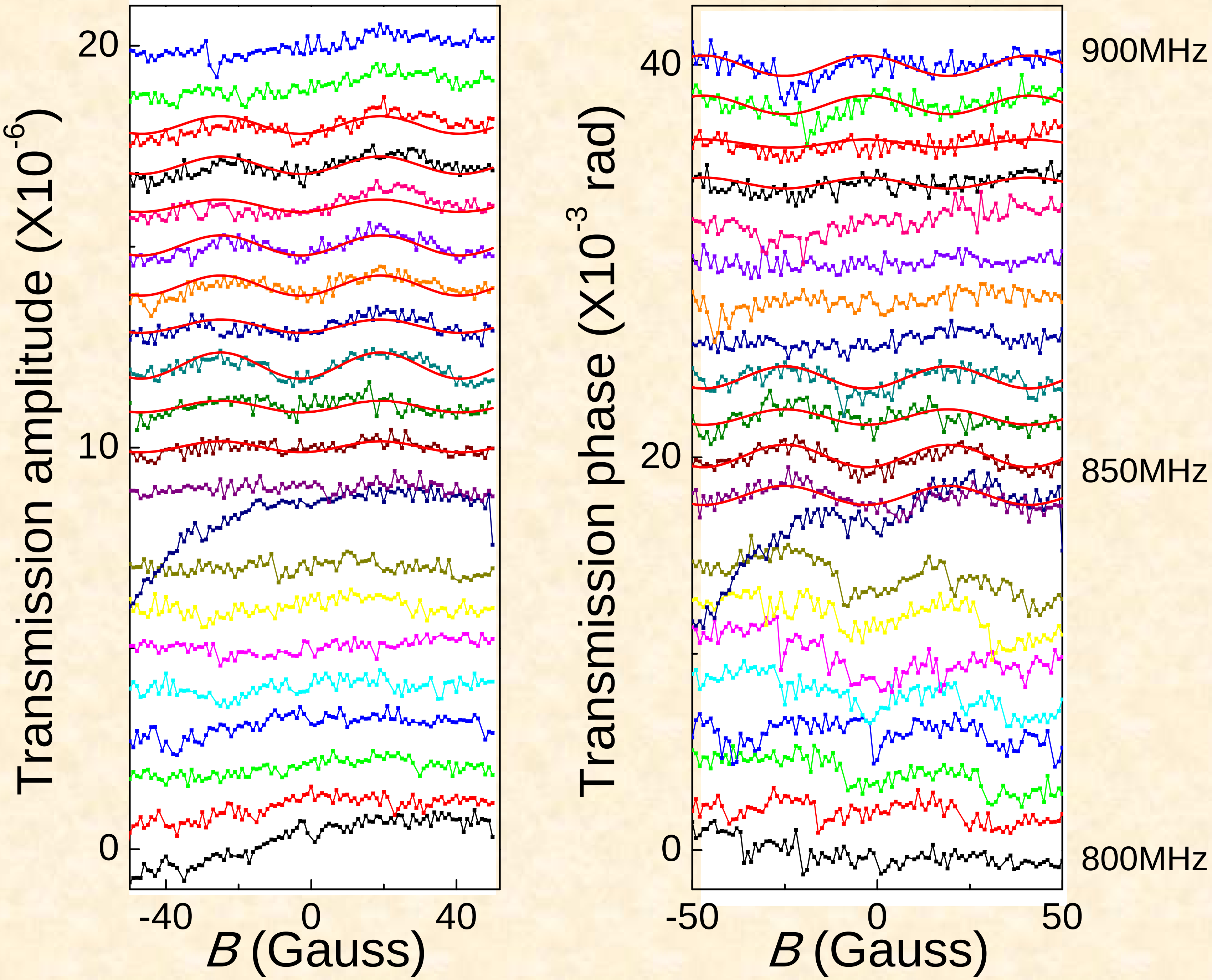
The RF power -65dBm gives a coupling energy of about 500μeV

AC result

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

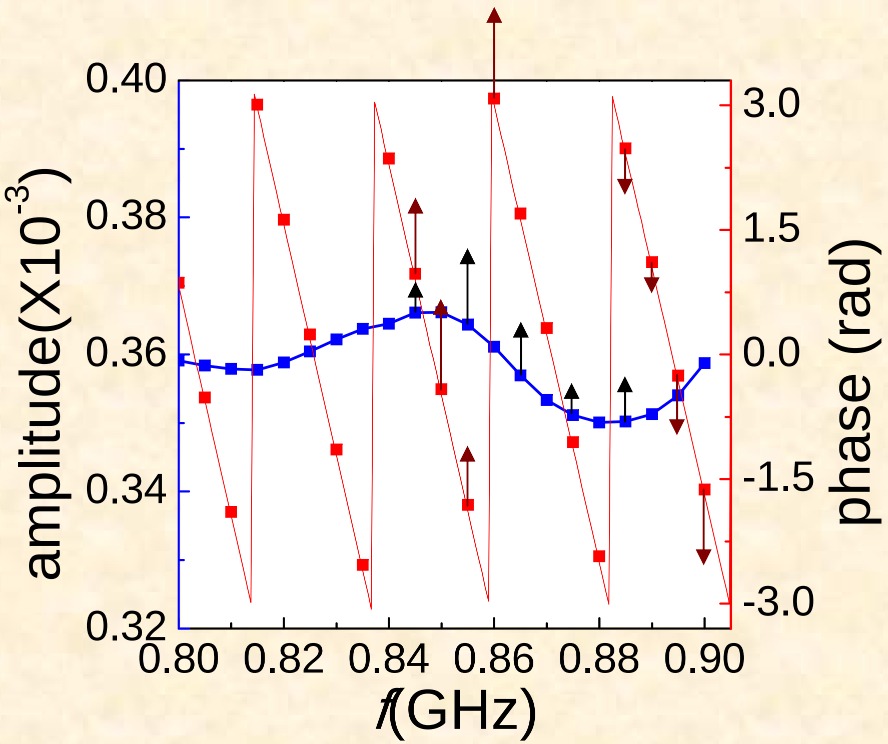
DC result

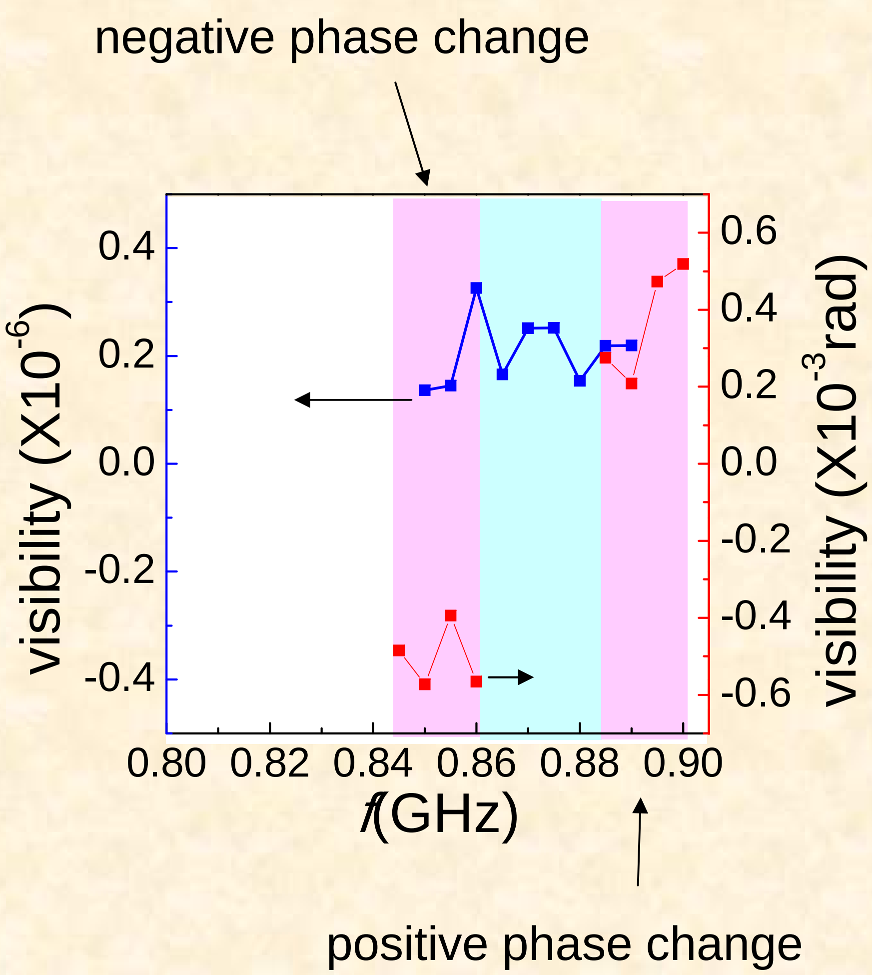




Transmission amplitude (X10^-6)
20
10
0
-40
0
40
B (Gauss)
Transmission phase (X10^-3 rad)
40
20
0
-50
0
50
B (Gauss)
900MHz
850MHz
800MHz

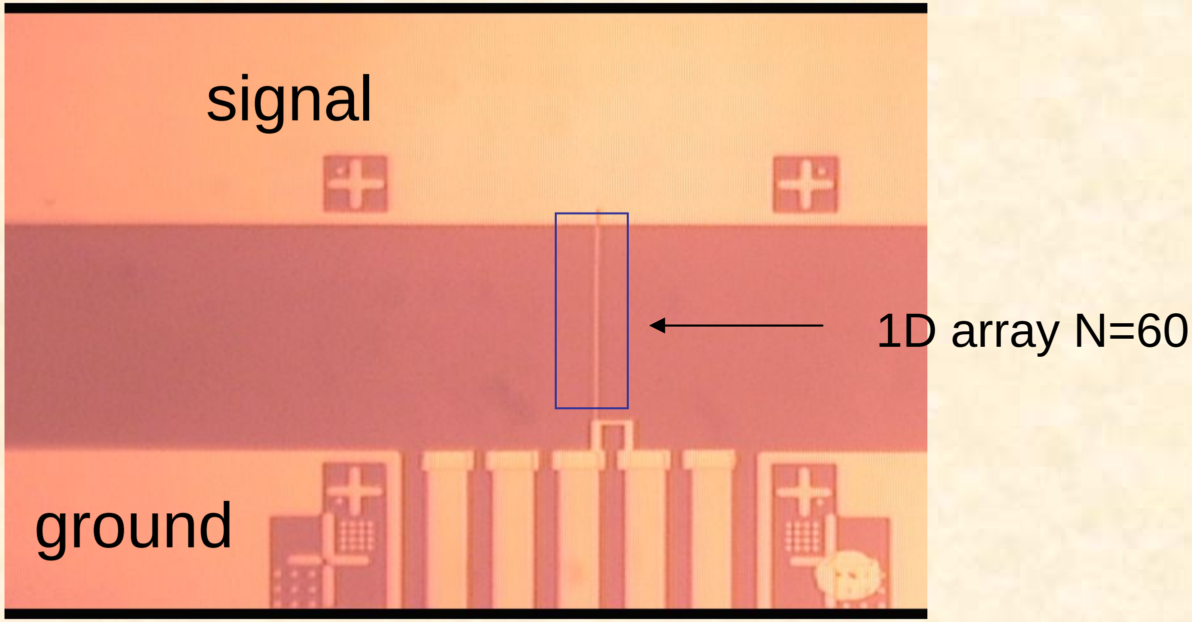
Visibility of the photon luminescence



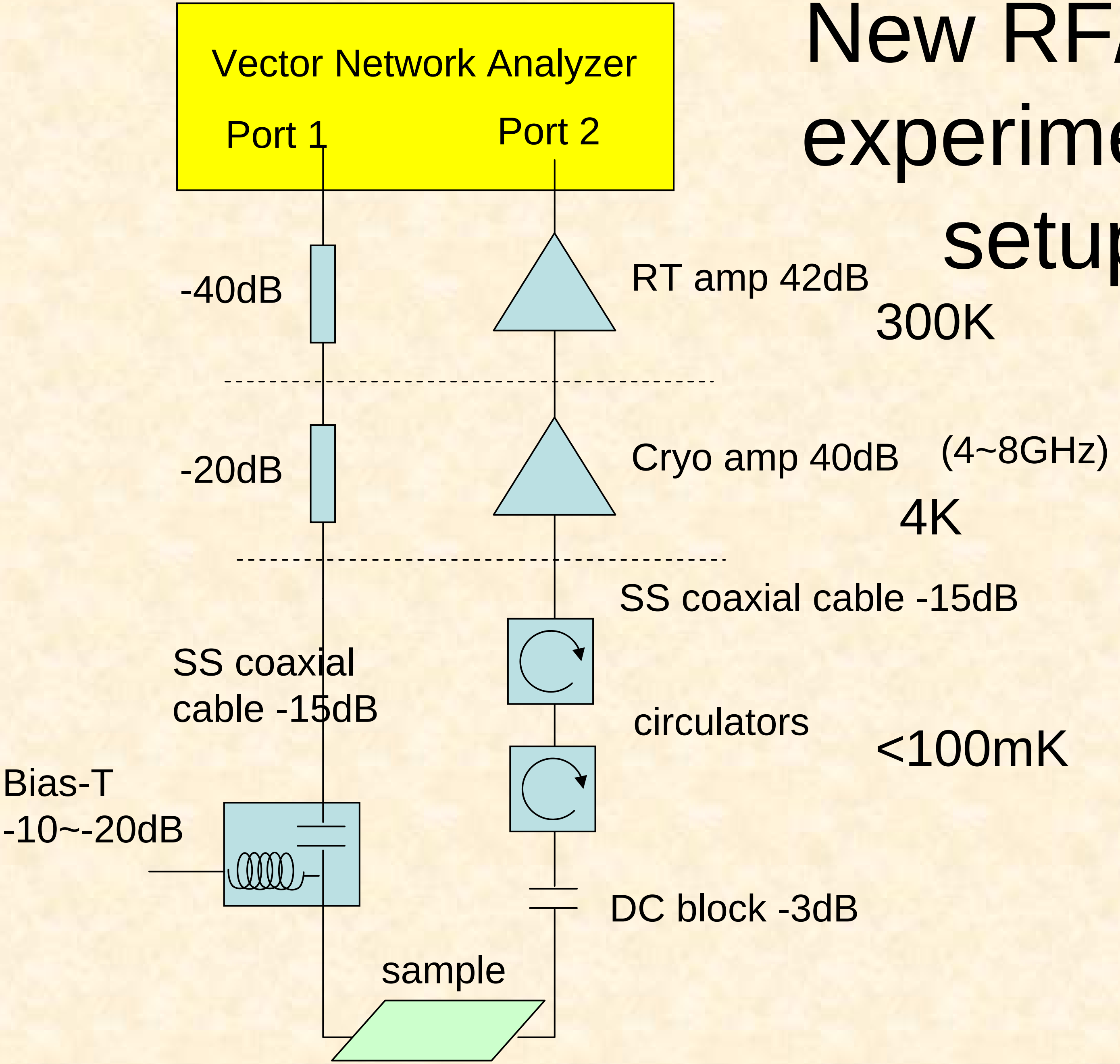


Experimental setup—Strong coupling

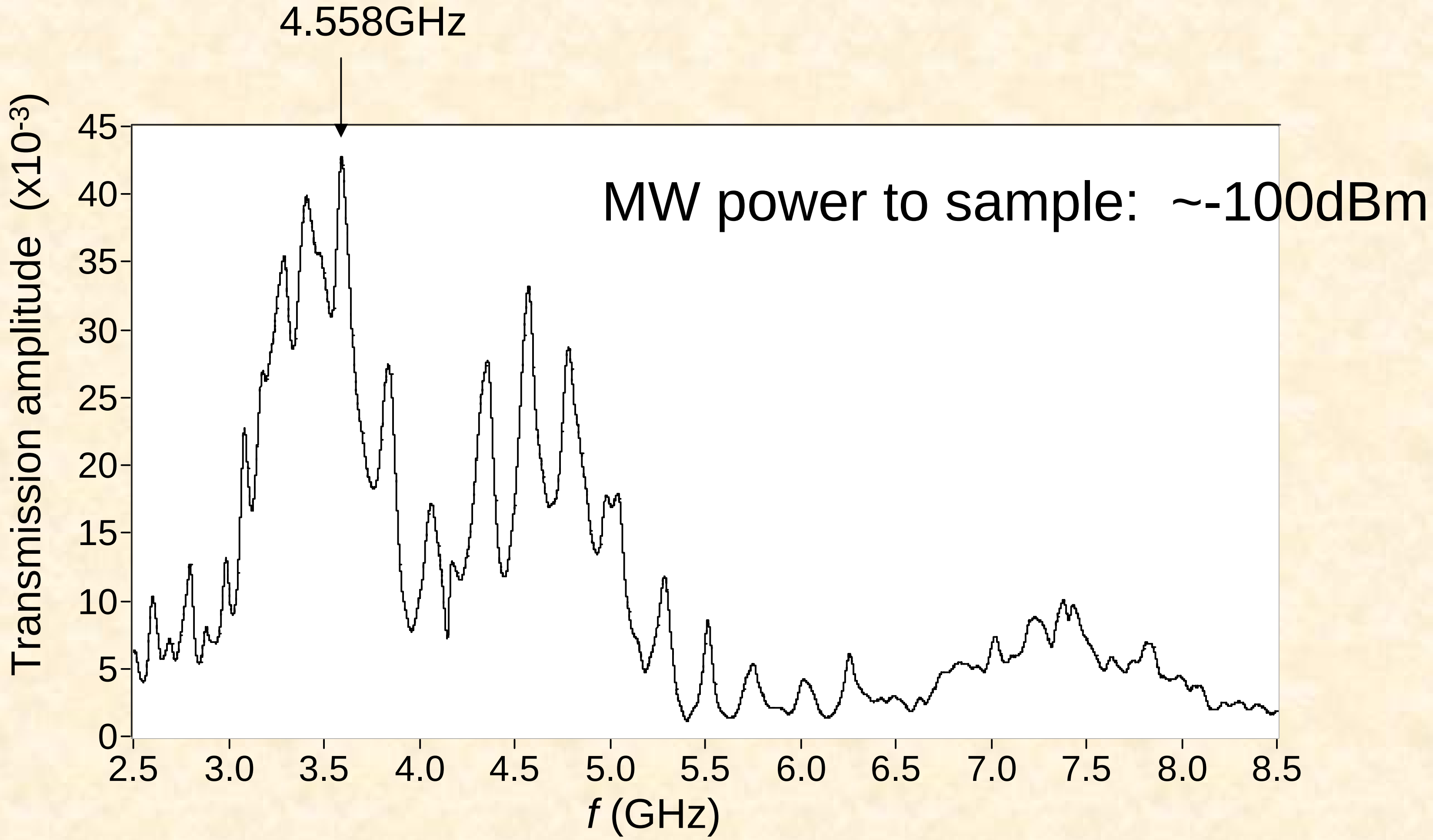
Single 1D array connected to signal and ground



New RF/MW experimental setup

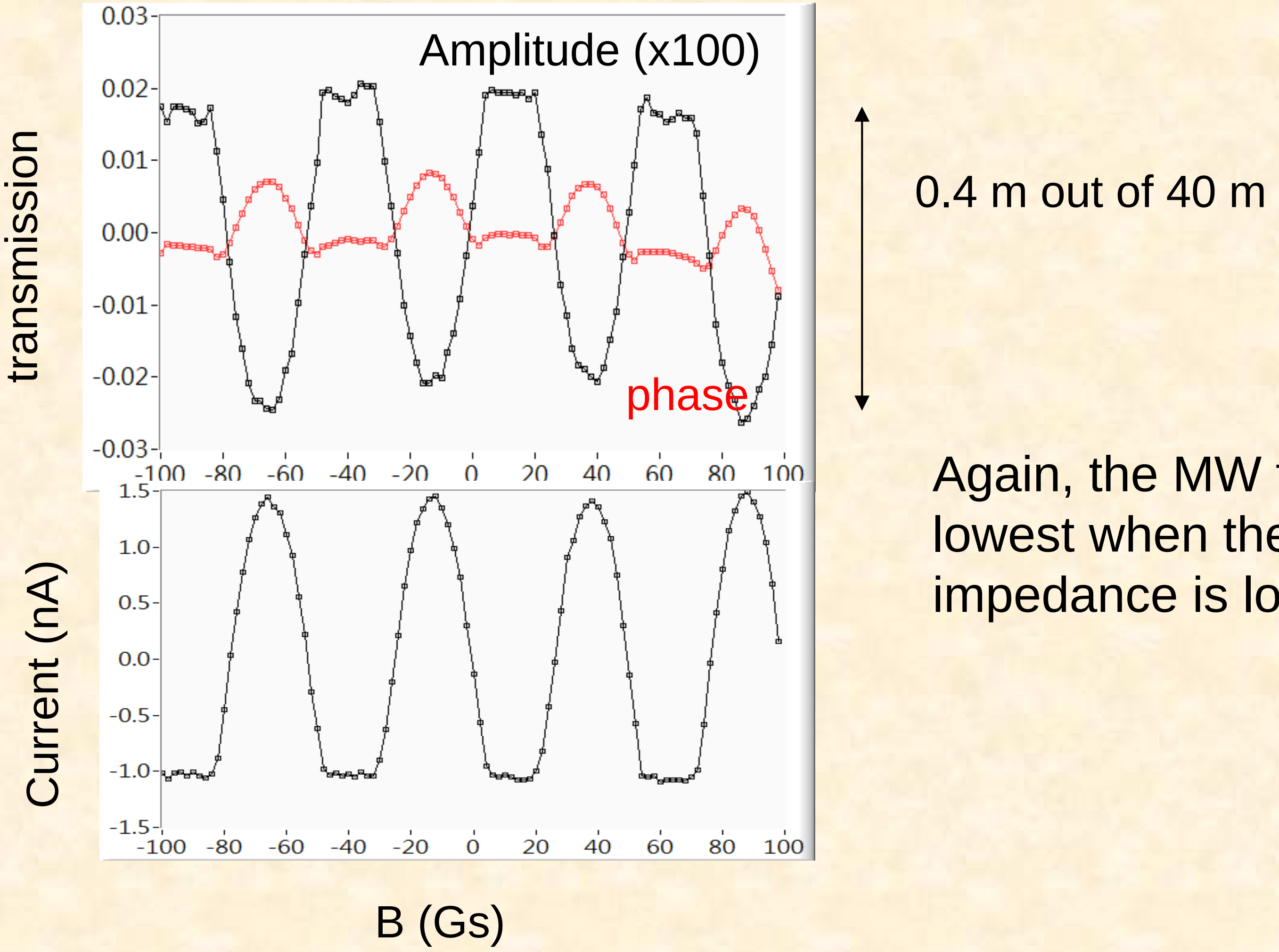


MW Transmission



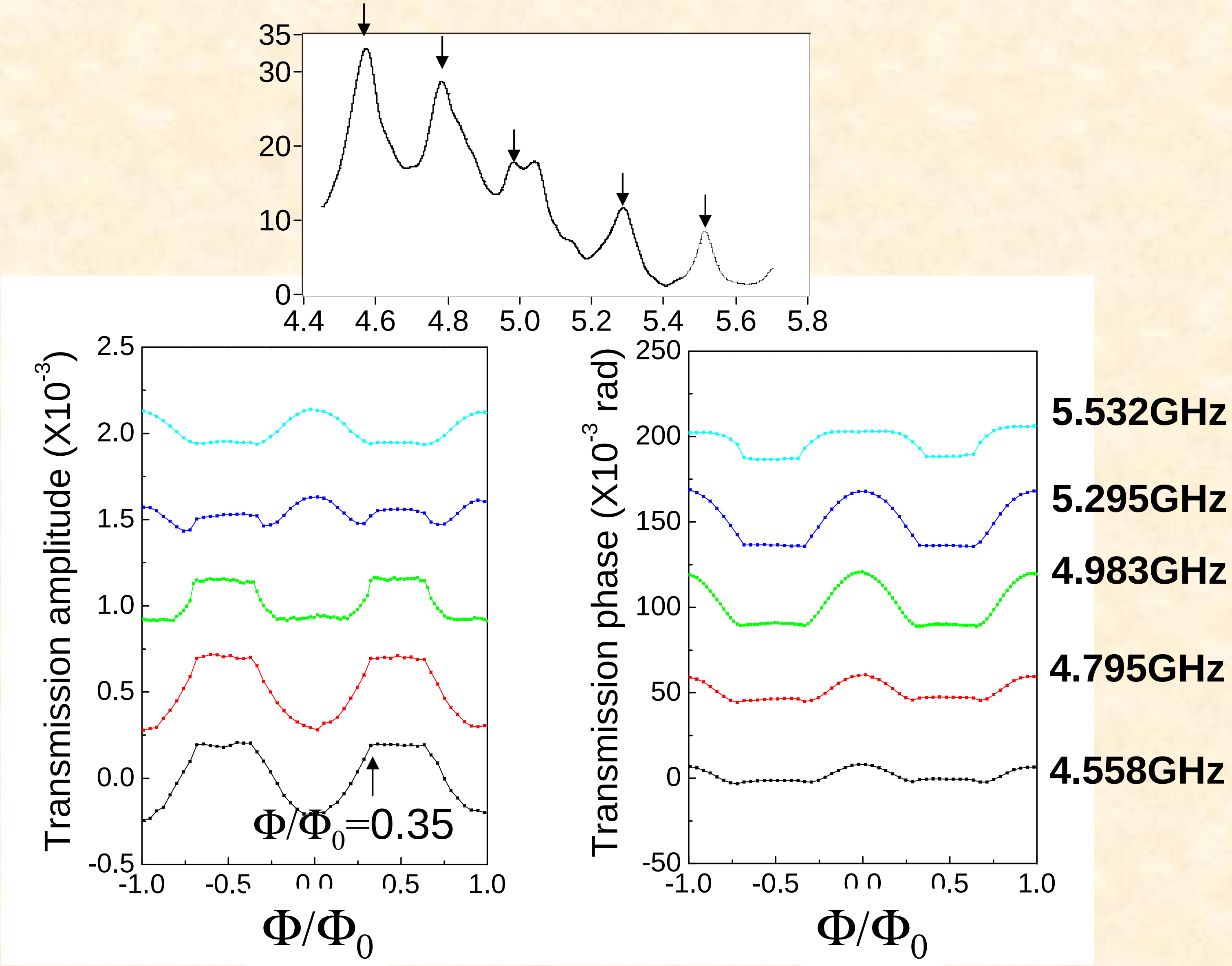
Field dependence

f=4.558GHz

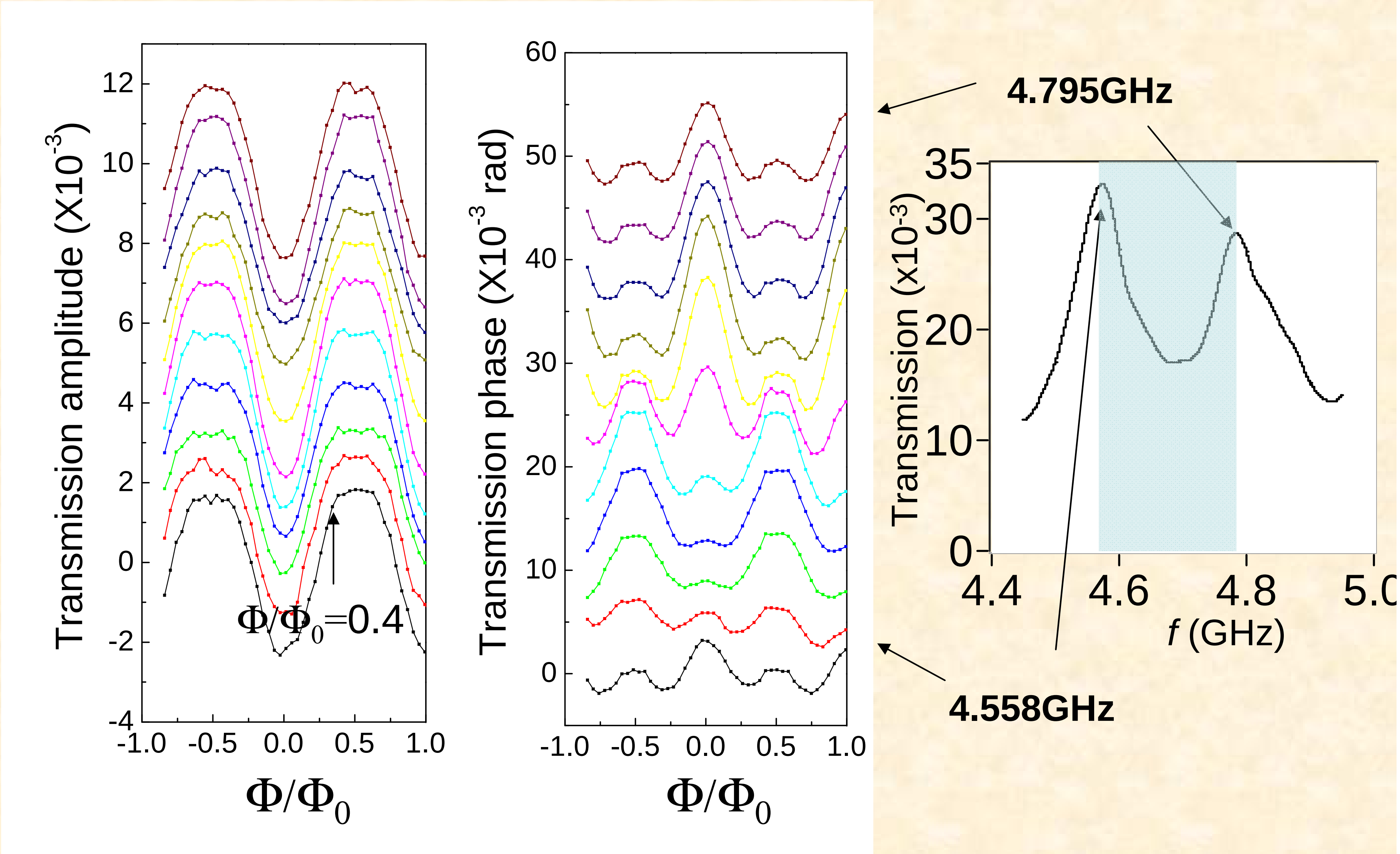


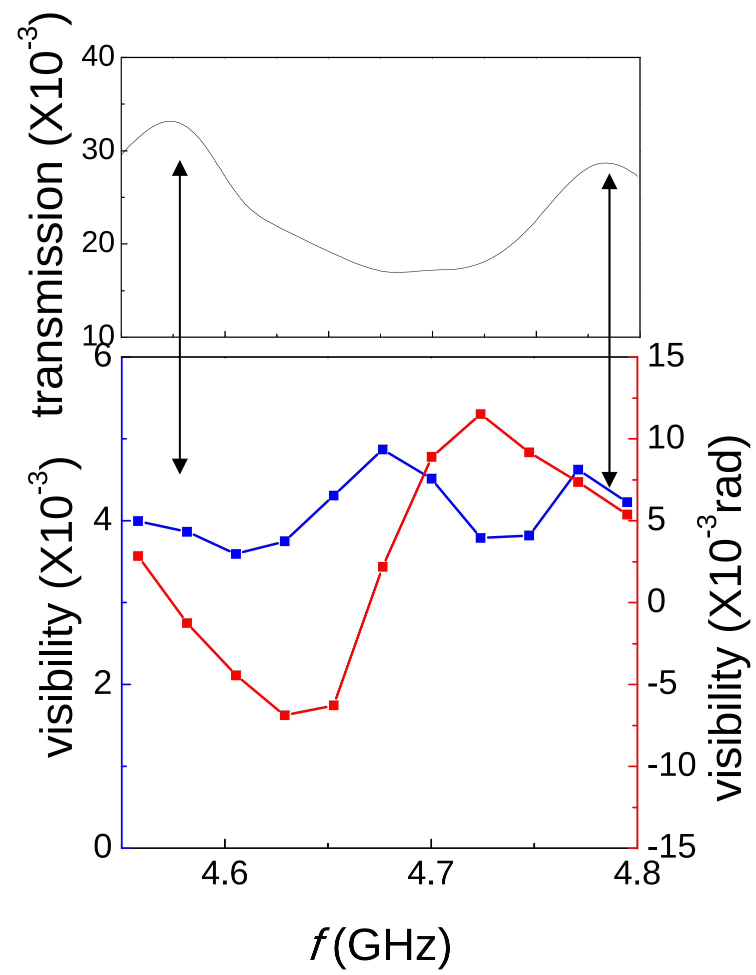
Again, the MW transmission is lowest when the array impedance is lowest.

Frequency dependence

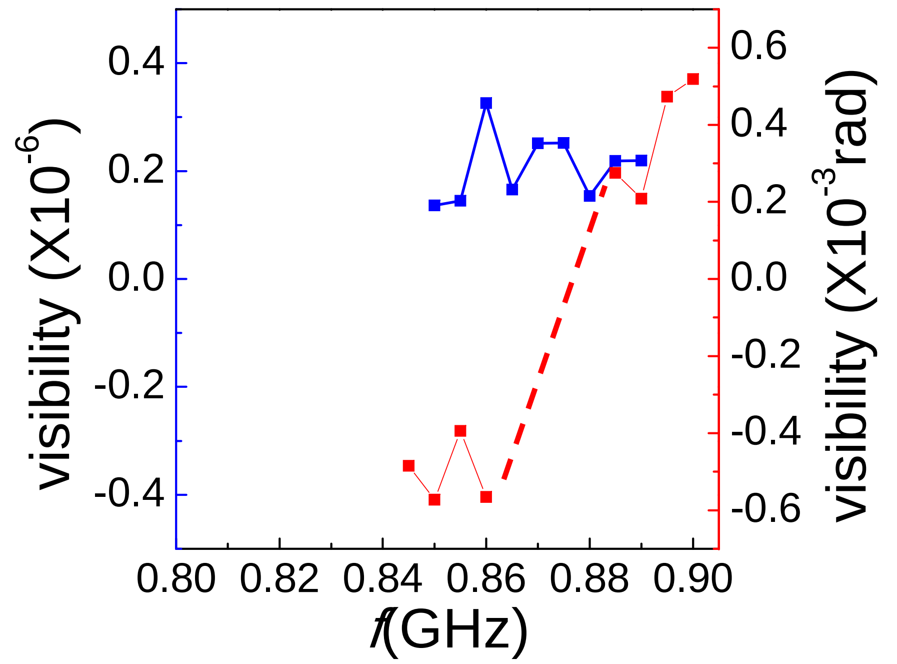


Within a standing wave



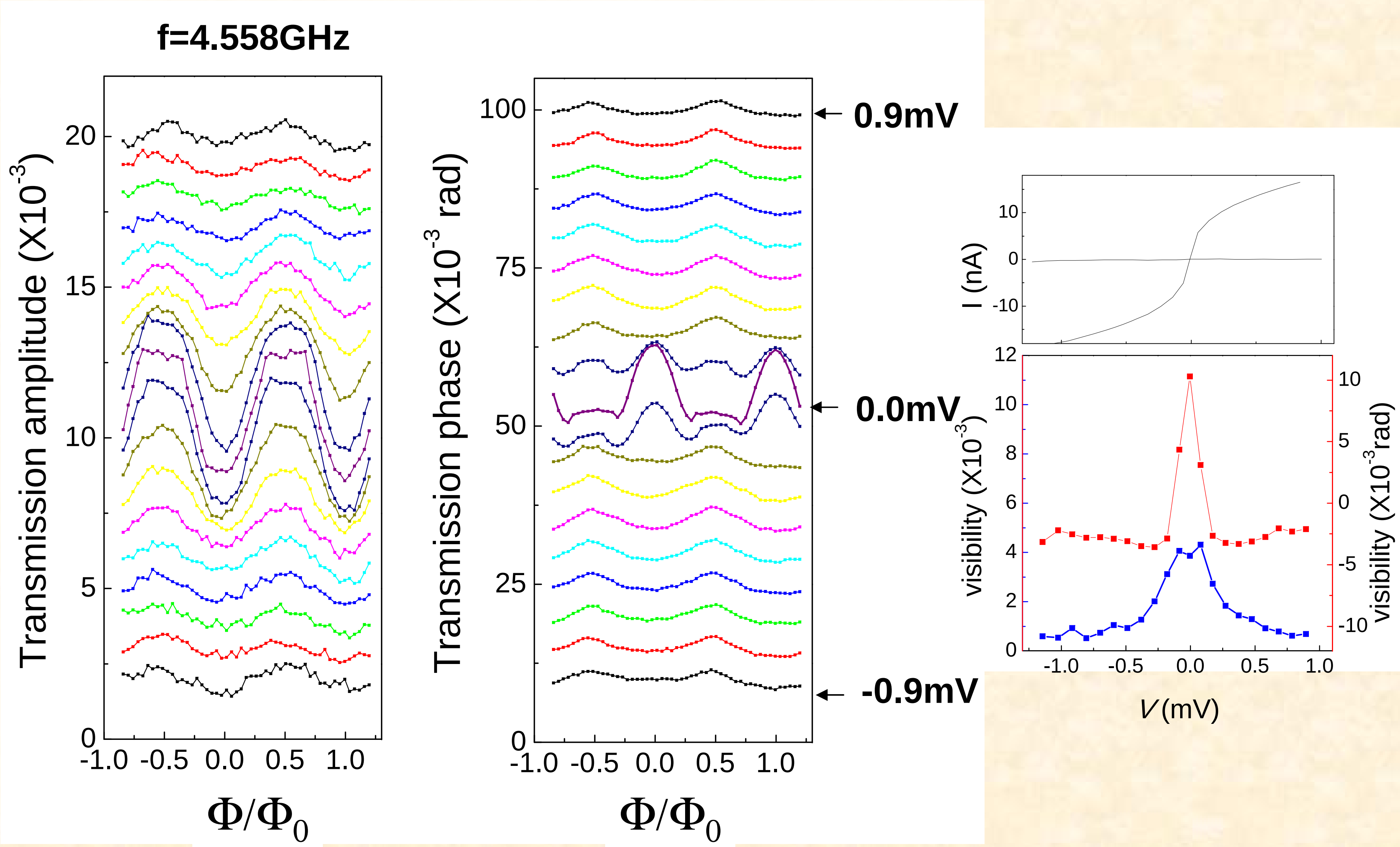


transmission (X10^-3)
40
30
20
10
6
4
2
0
15
10
5
0
-5
-10
-15
visibility (X10^-3)
visibility (X10^-3 rad)
4.6
4.7
4.8
f (GHz)

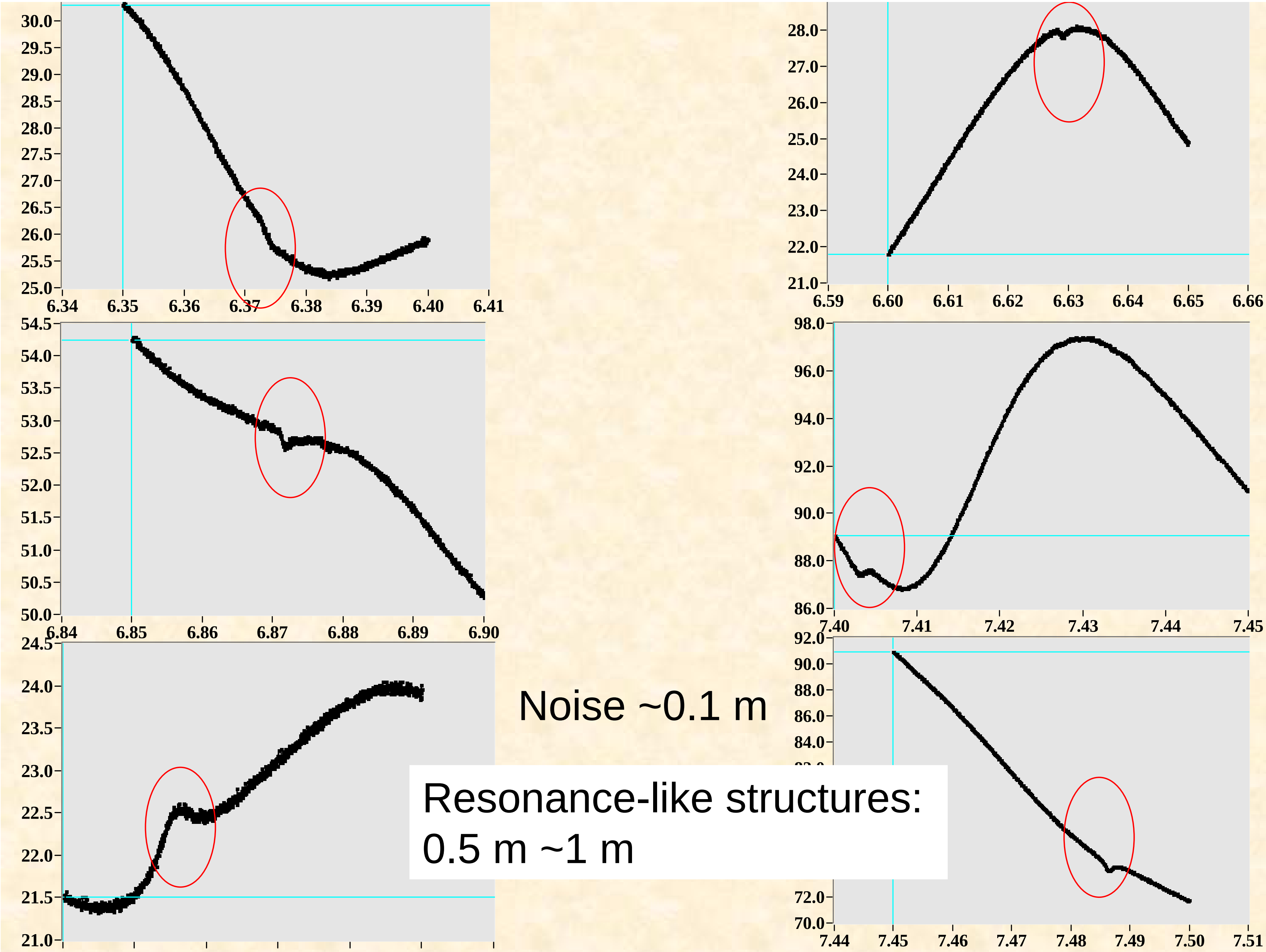


visibility (X10^-6)
0.4
0.2
0.0
-0.2
-0.4
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
visibility (X10^-3 rad)
0.80
0.82
0.84
0.86
0.88
0.90
f(GHz)

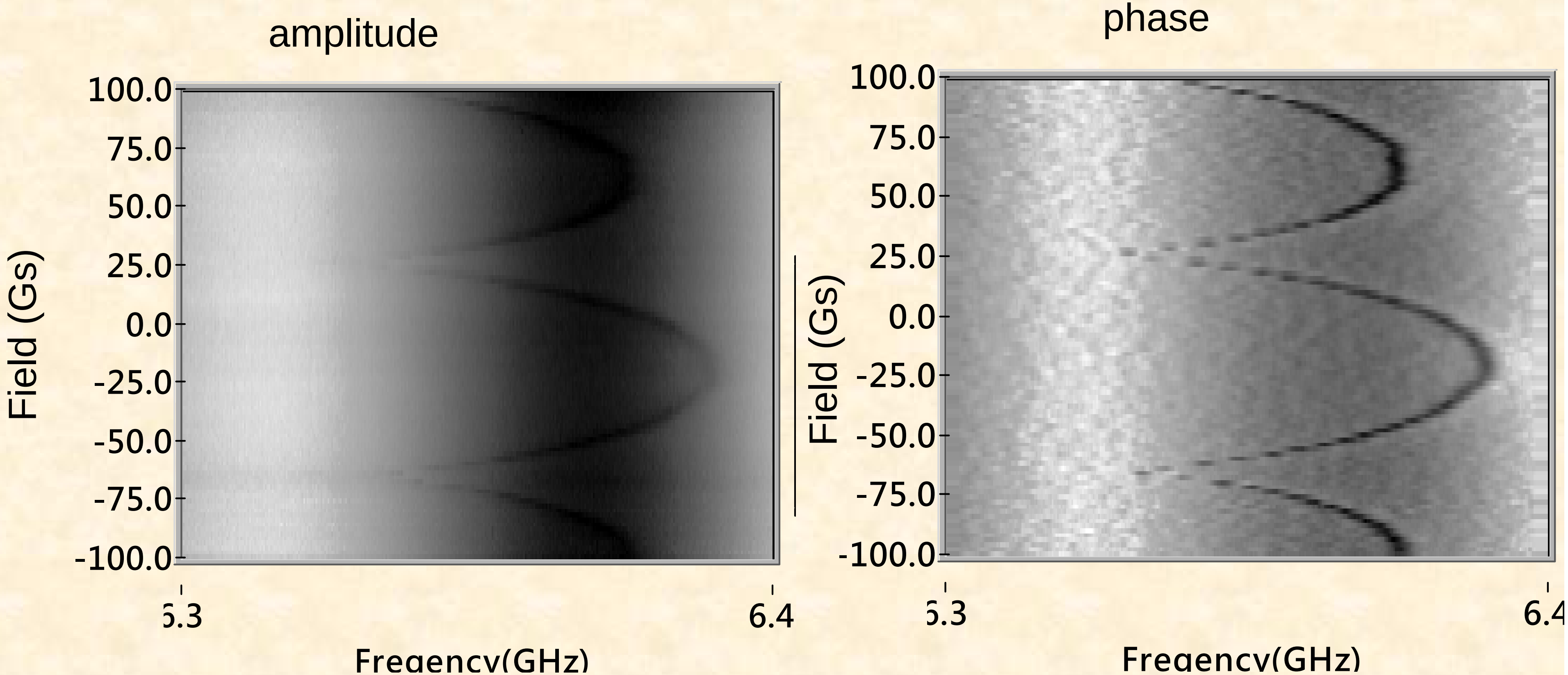
Bias dependence



As a next step, to probe quantum levels…

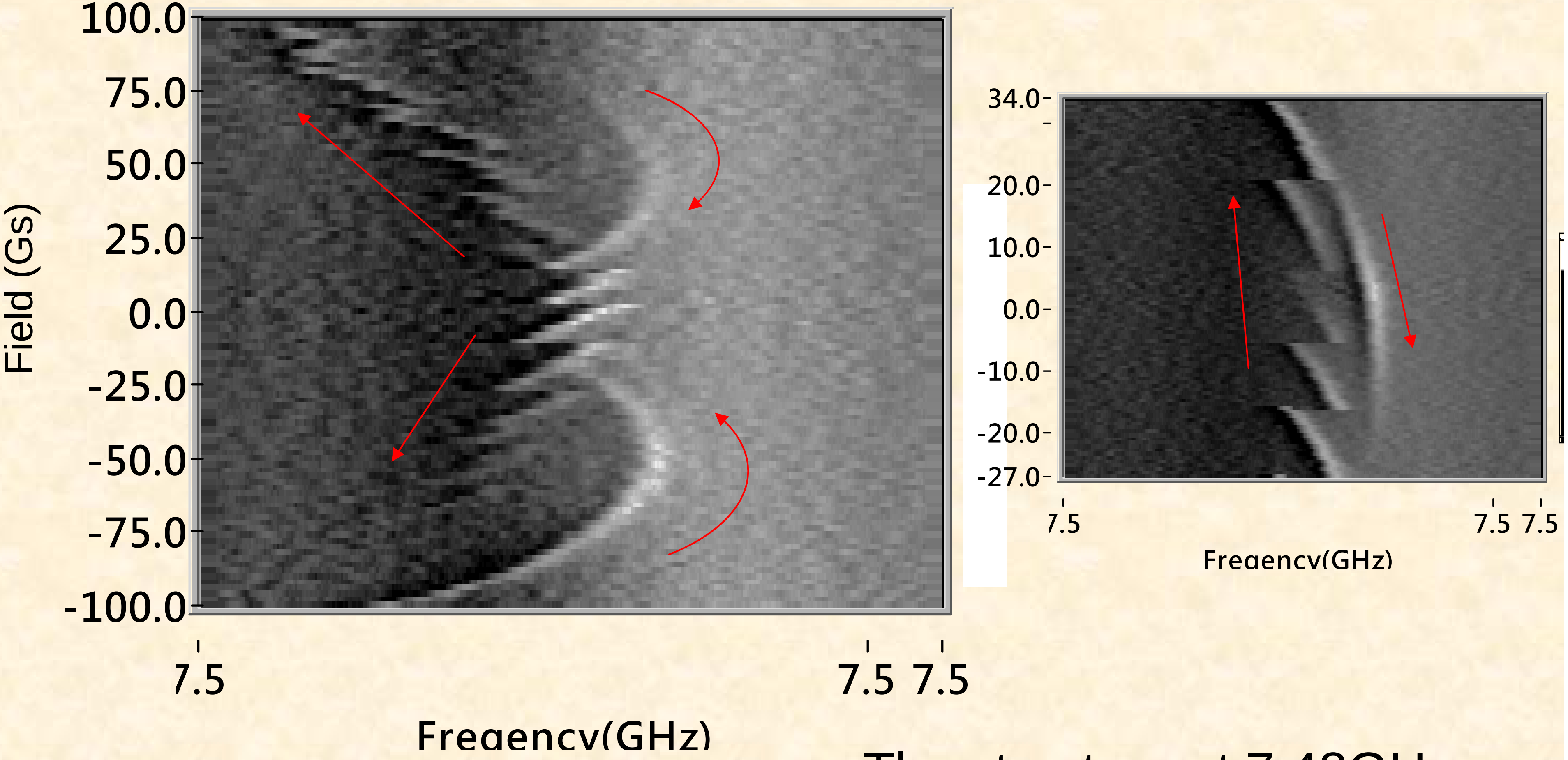

Noise ~0.1 m
Resonance-like structures:
0.5 m ~1 m

Resonance structure--field scan



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

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