Josephson-junction array masers

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In collaboration with:

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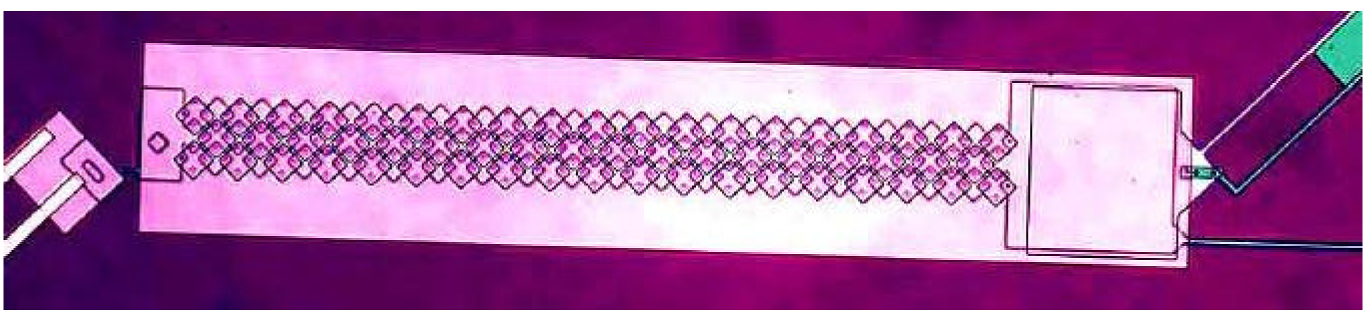
A. Nielsen	B. Vasilic

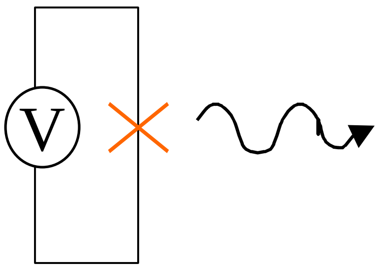


*After August 1: Georgetown University, Washington DC

Outline

- Introduction to Josephson-junction arrays
- Our arrays
- Resonances in discrete Josephson transmission lines
- Laser models
- Conclusions

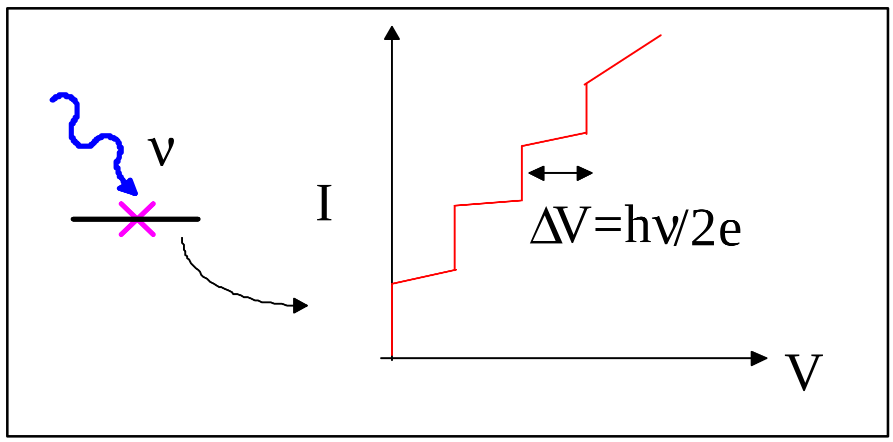
Why arrays?

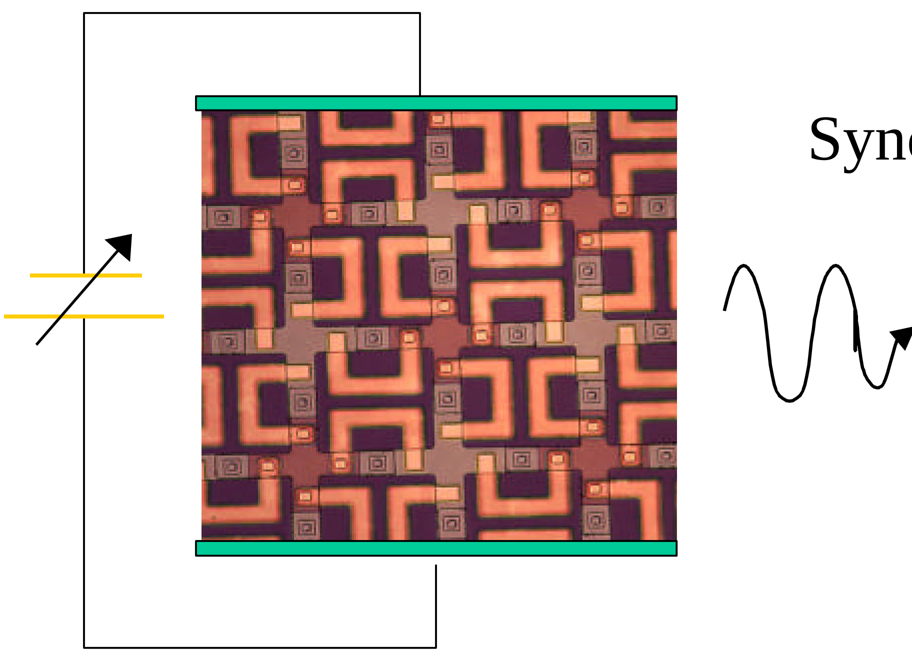


$\nu = 2eV/h$

$2e/h \sim 483\text{GHz/mV}$

$P \sim 1\ \text{nW}$



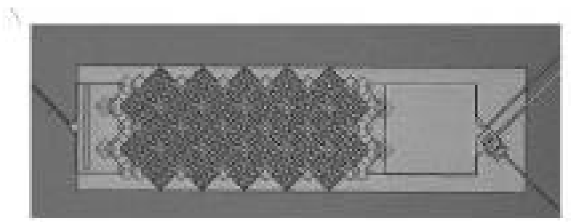


Synchronization?

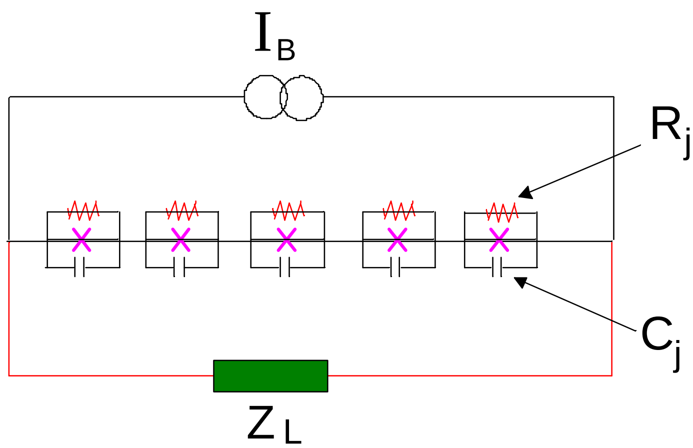
How do junctions synchronize?

- Lumped arrays

$\lambda/2$

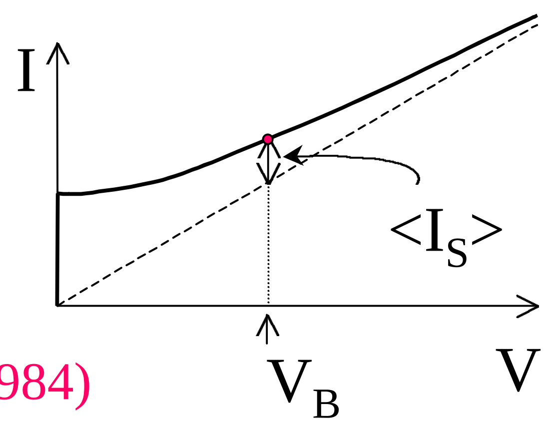


- Coupling through external load



- Overdamped junctions

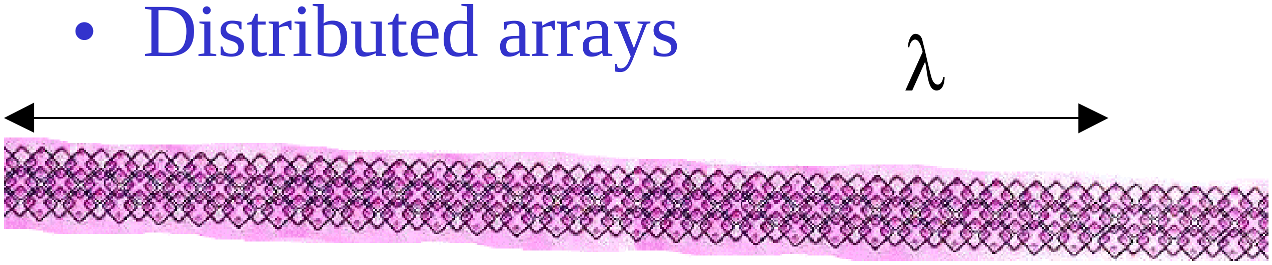
(efficiency 1-5%)



A. K. Jain et al. Phys. Rep. **109**, 310 (1984)
P. Hadley et al., Appl. Phys. Lett. **52**, 1619 (1988)
S. P. Benz et al., Appl. Phys. Lett. **58**, 2162 (1991)
K. Wiesenfeld et al., J. Appl. Phys. **76**, 3835 (1994)

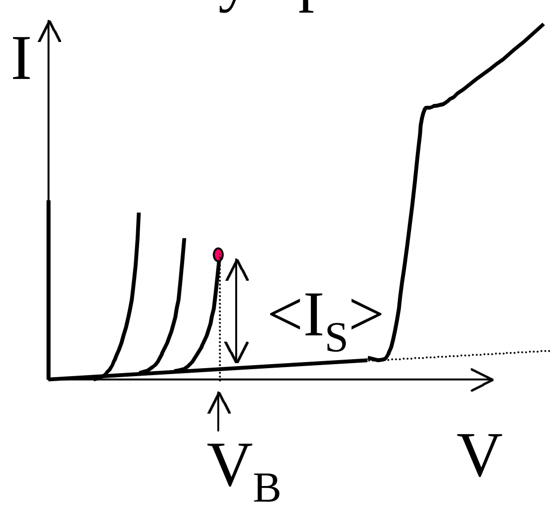
Our arrays: A puzzle for the standard synchronization picture

- Distributed arrays

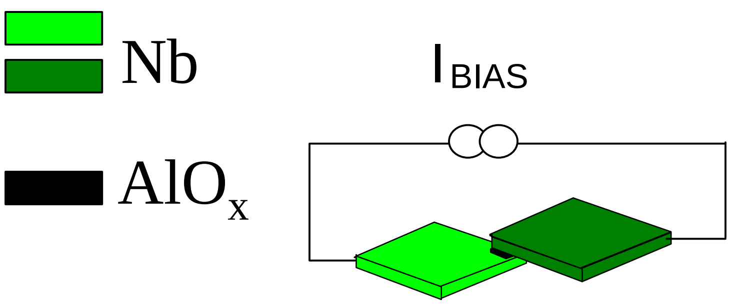


- Synchronization: analogies with lasers
  - threshold to coherent state
  - characteristics of steady state emission

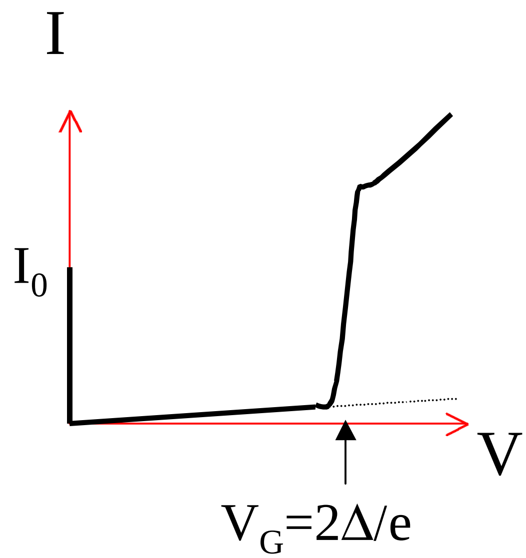
- Underdamped junctions
  - bonus: efficiency up to 33%!



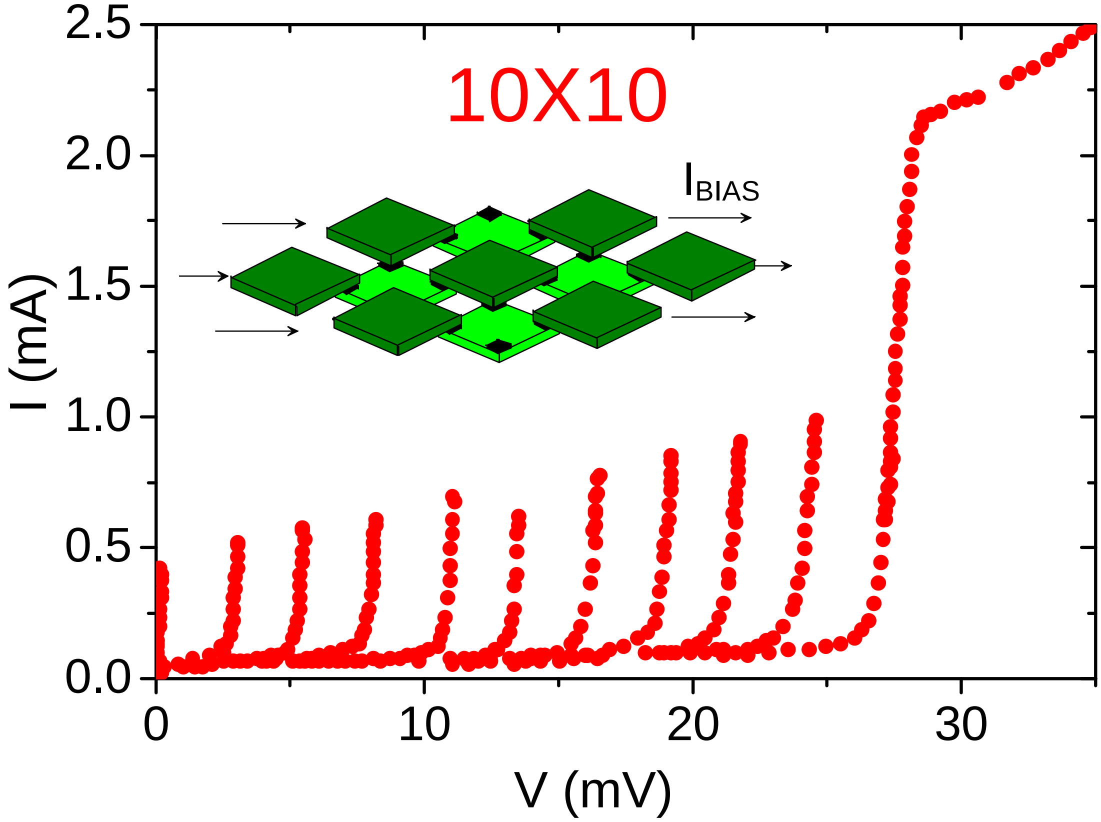
Underdamped junctions



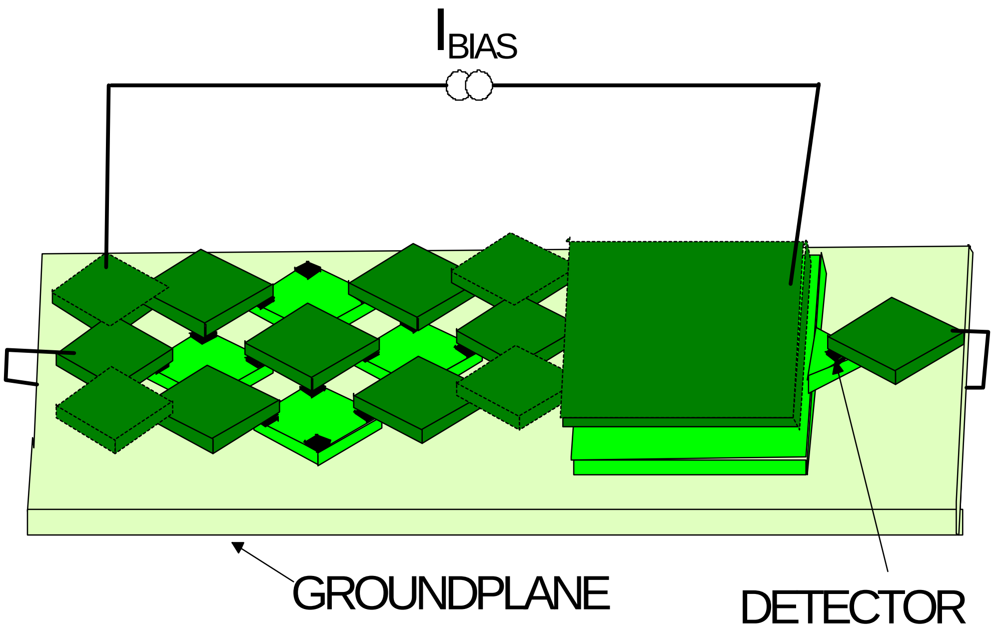
$I_0 \sim 100\ \mu A$
$V_G \sim 2.7\ mV$

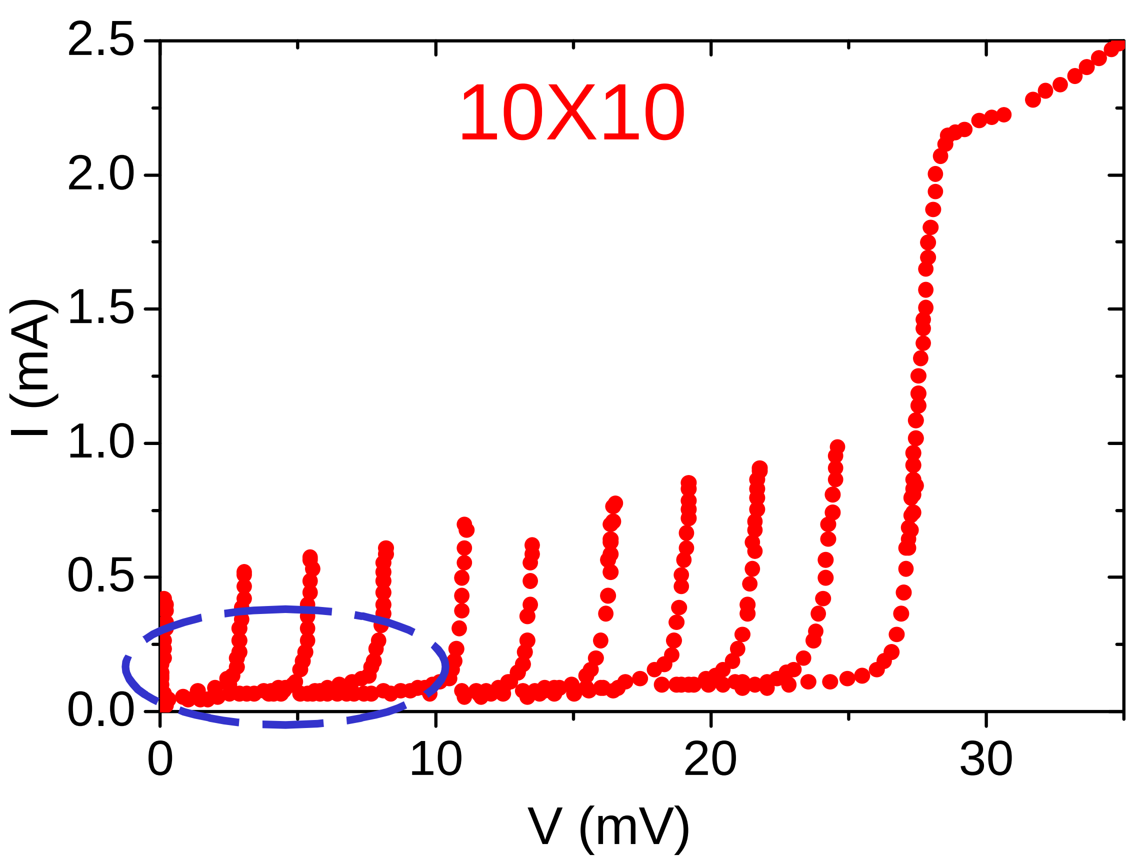


Underdamped arrays

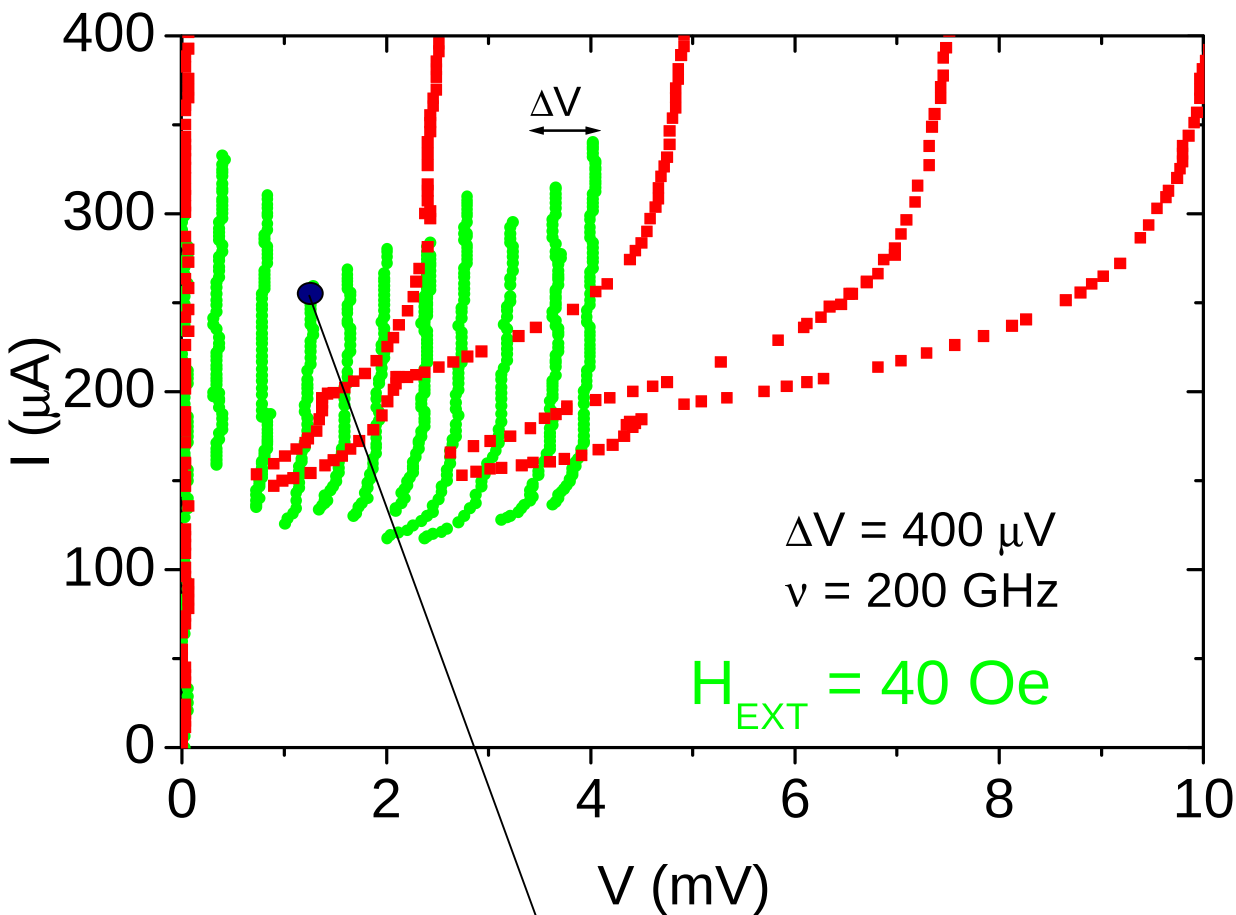


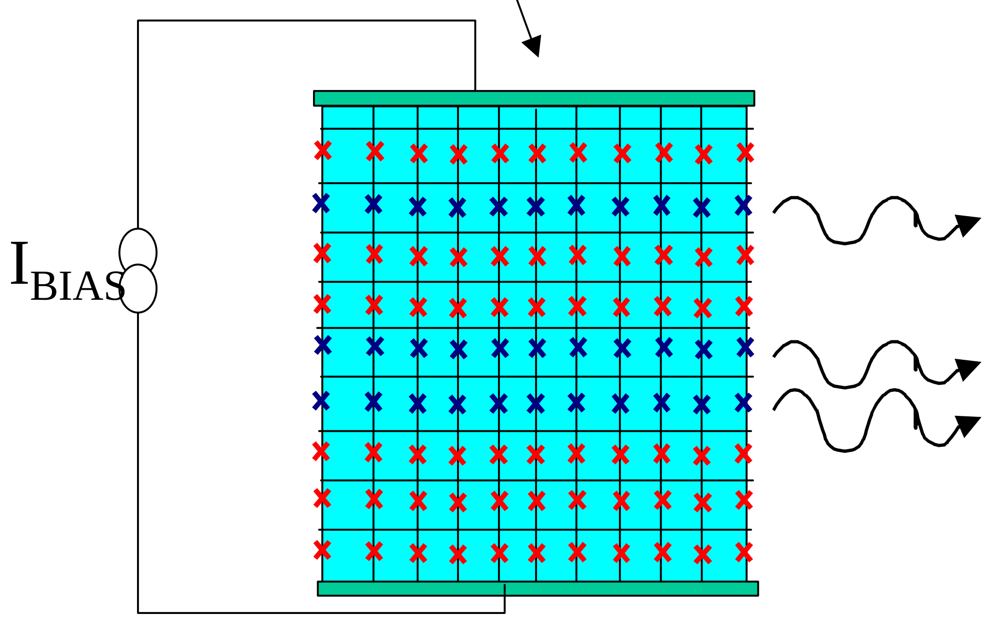
Our Arrays


I BIAS
GROUNDPLANE
DETECTOR

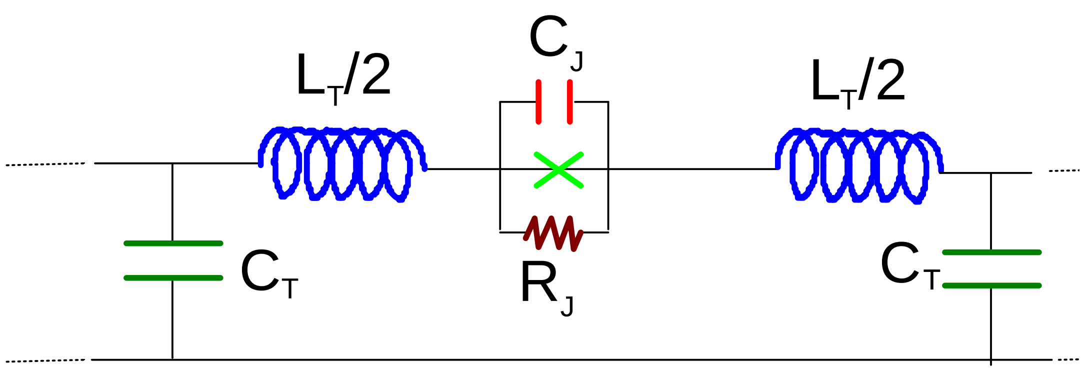

10X10
I (mA)
V (mV)
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30

Resonances

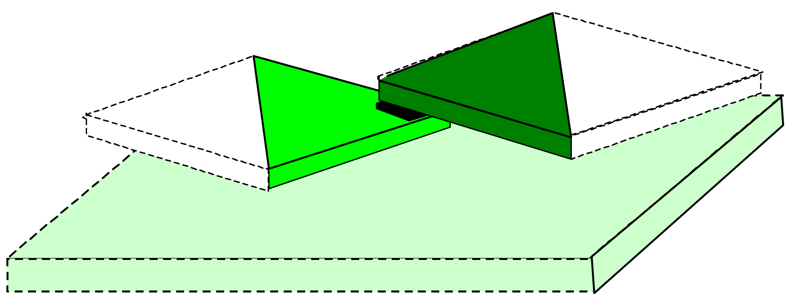

400
300
200
100
0
I (μA)
0
2
4
6
8
10
V (mV)
ΔV
ΔV = 400 μV
ν = 200 GHz
H_EXT = 40 Oe


I_BIAS

Where does the resonance come from?



Circuit model for 1 column*

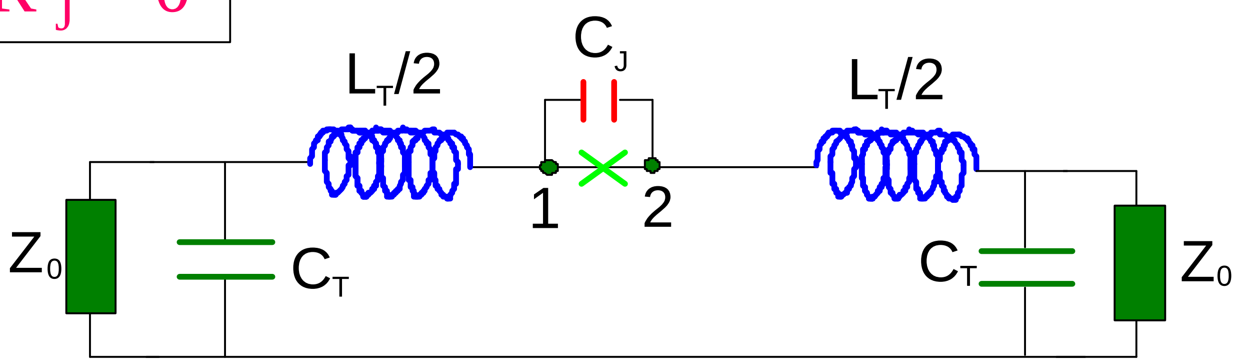


L_T = 2.1 pH; C_T = 11 fF;
C_J = 0.6 pF; R_J= 300 Ω (sub-gap)

* A. B. Cawthorne et al., PRB **60**, 7575 (1999)

Where does the resonance come from? II

$1/R_J = 0$

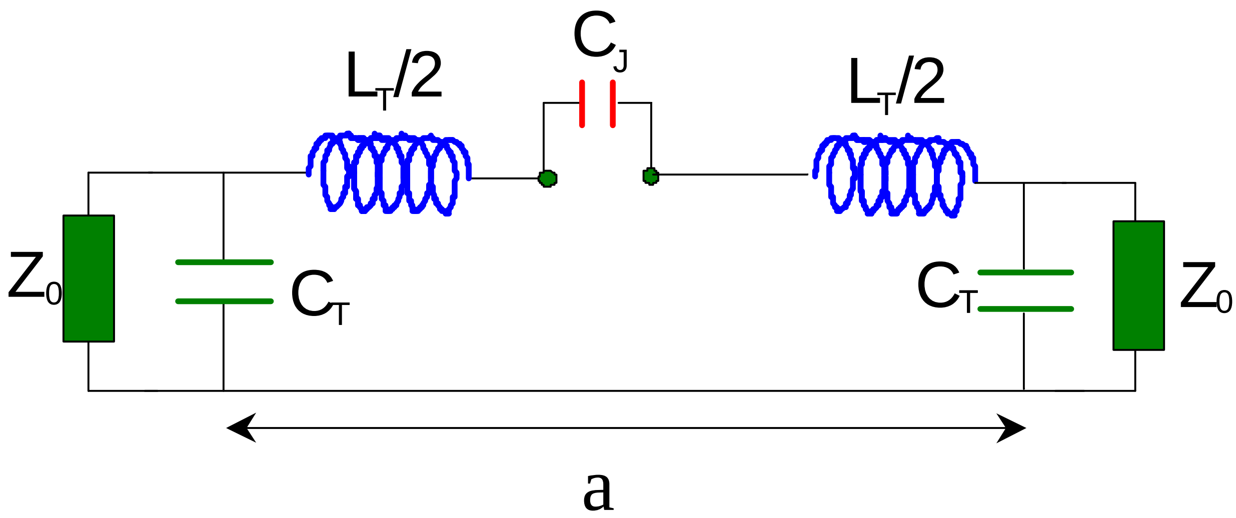


$$2Z_0 = \frac{1-\omega^2 L_T C_J}{i\omega C_J} + \left[\frac{(1-\omega^2 L_T C_J)^2}{\omega^2 C_J^2} - 4\frac{(1-\omega^2 L_T C_J)}{\omega^2 C_J C_T} \right]^{1/2}$$

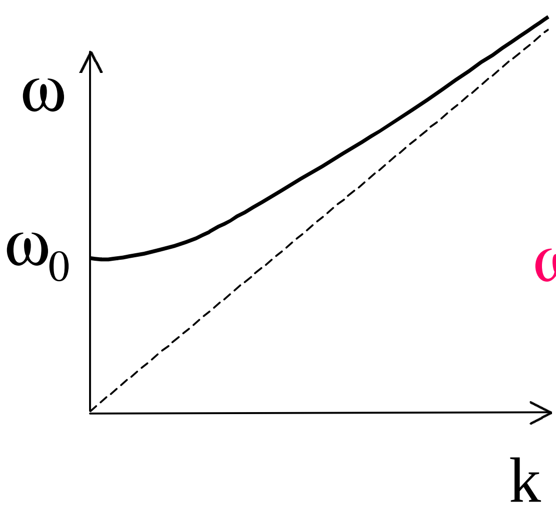
$$\omega^2 = \frac{1}{L_T C_J} \Rightarrow \left\{ \begin{array}{c} Z_0 = 0 \\ \mathrm{Im}(Y_{1,2} = 0) \end{array} \right\}$$

Resonance frequency: $\nu = \omega/2\pi \sim 142$ GHz

Propagation properties



$$\omega^2 = \frac{1}{C_J L_T} + k^2 \frac{a^2}{C_T L_T}$$

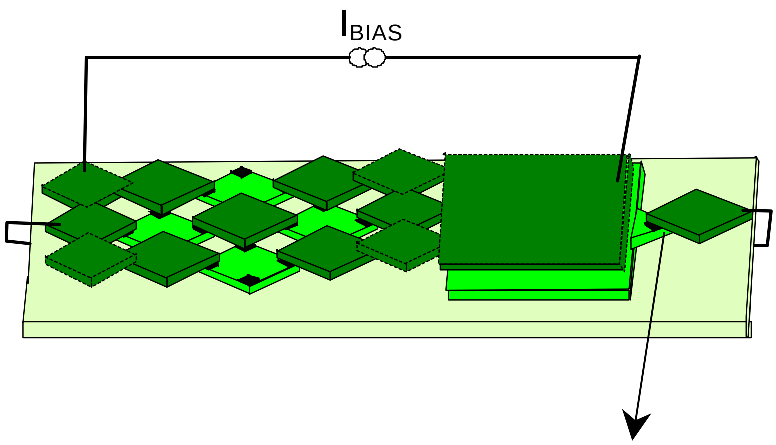


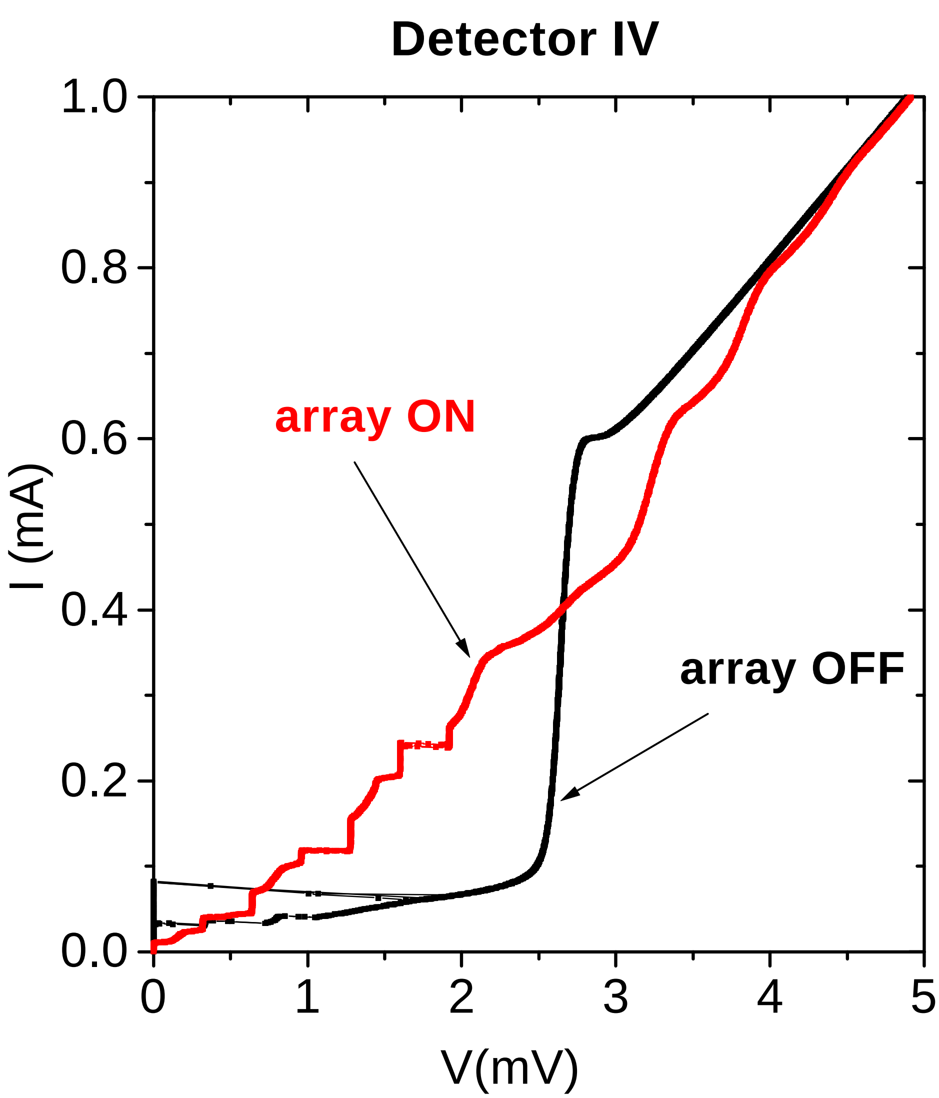
$\omega_0 = 1/(C_J\, L_T)^{1/2}$

Experimental facts

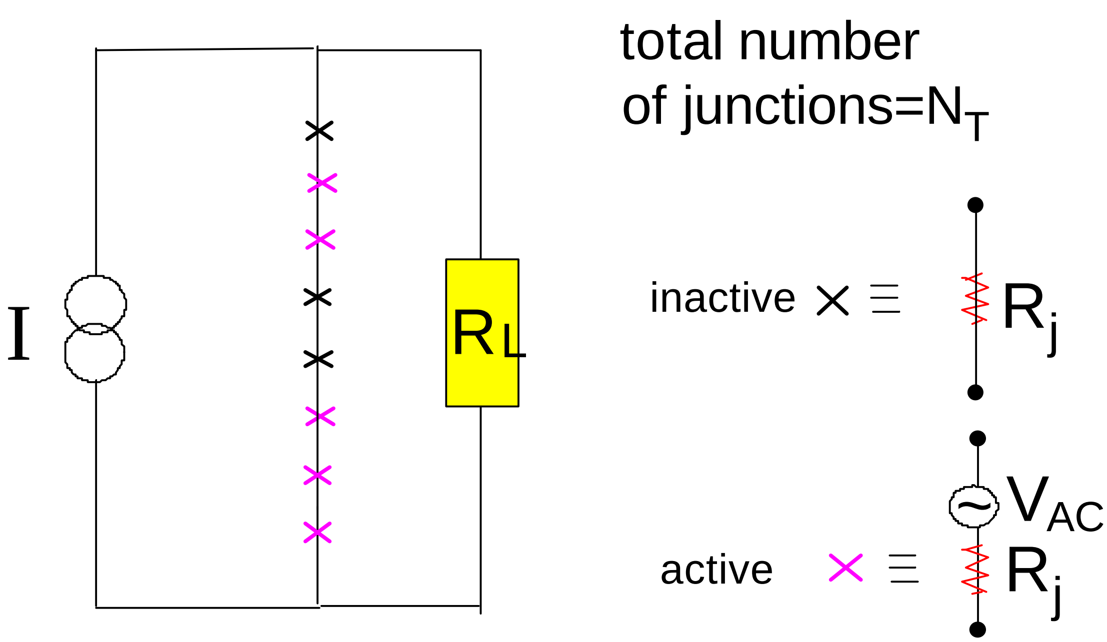
- 2D arrays show a resonance at k = 0
- the resonance frequency does not depend on array length or external load
- no resonance could be measured in 1D arrays
- no resonance could be measured in arrays with shorted horizontal junctions

Detector


IBIAS


Detector IV
1.0
0.8
0.6
0.4
0.2
0.0
I (mA)
0
1
2
3
4
5
V(mV)
array ON
array OFF

Power dissipated in the load

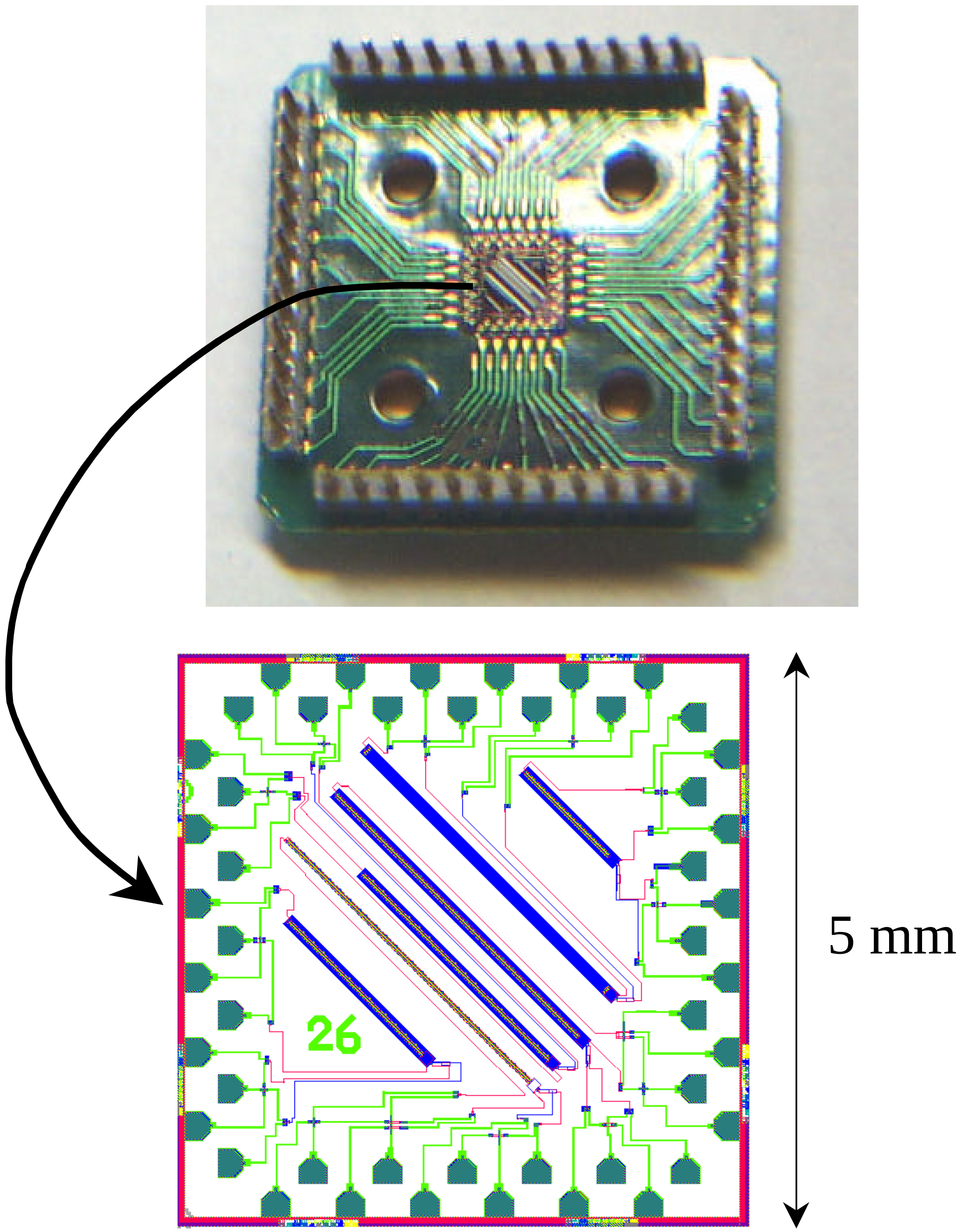


If all the junctions are synchronized:

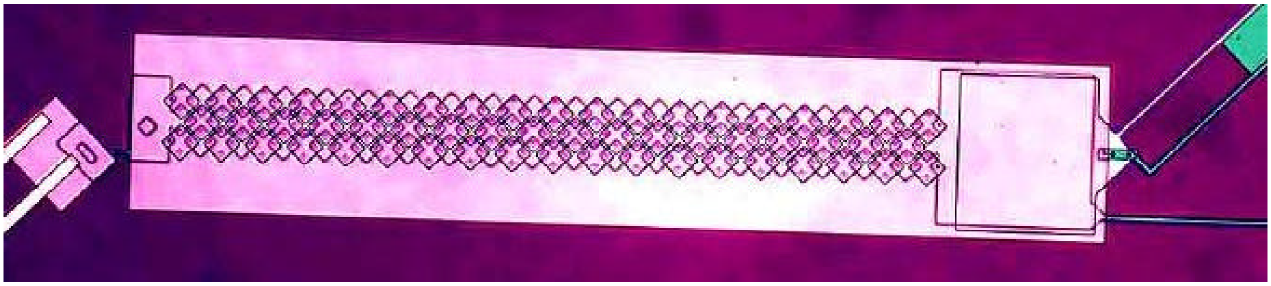
$$P_L = \frac{<(N_A V_{AC})^2>}{(N_T R_J + R_L)^2} R_L$$

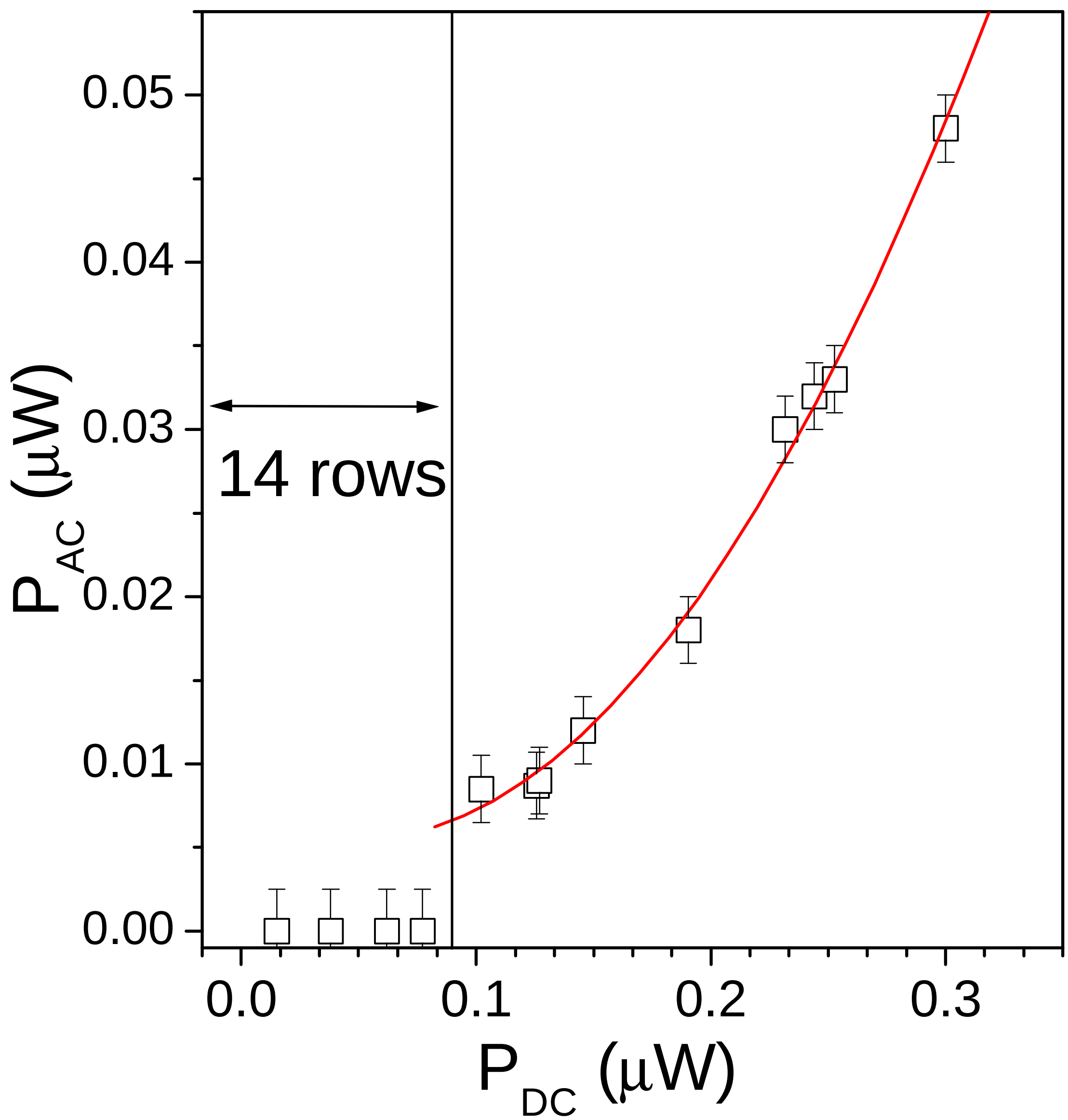
For $R_L = N_T R_J \quad \Rightarrow \quad P_L = \dfrac{N_A^2 < V_{AC}{}^2 >}{4 N_T R_J}$

Typical chip

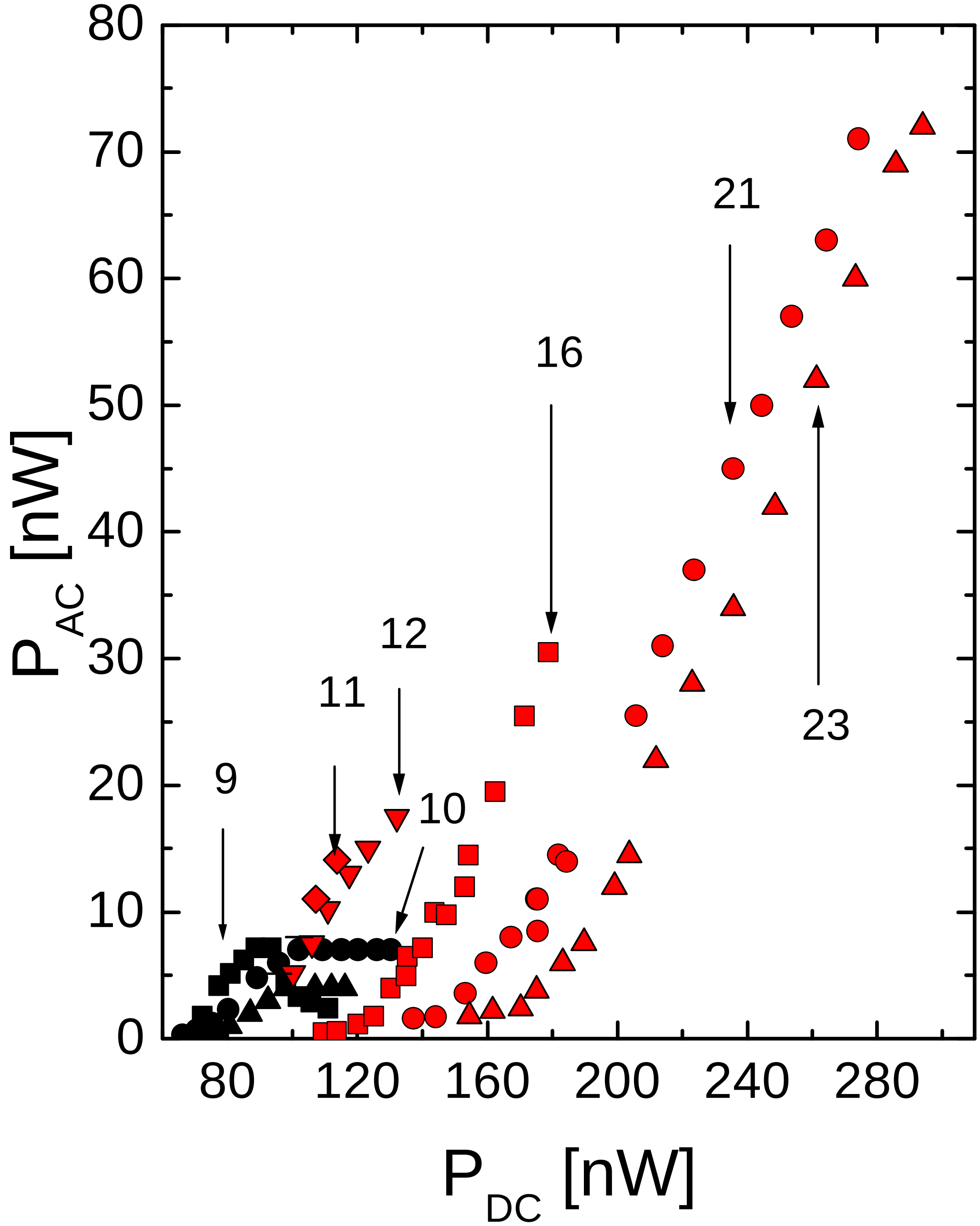


Array 3X36





Array 4X36



B. Vasilic: poster session

Our Best results at 150 GHz

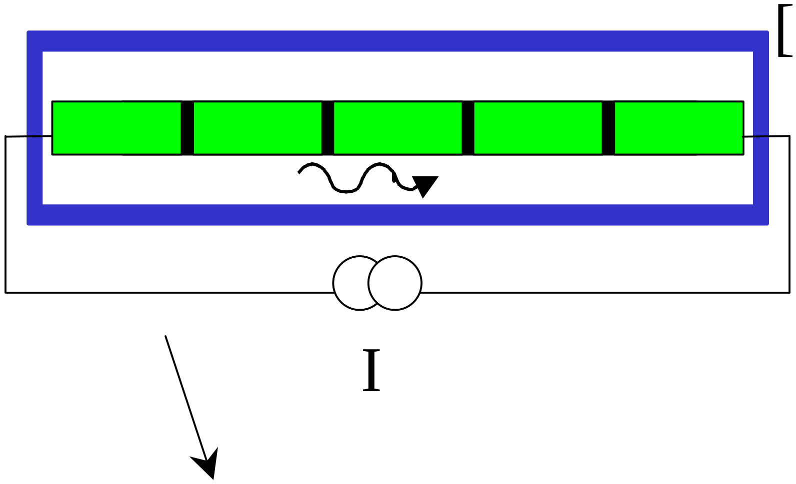
Maximum detected power:

Array 3x131
P_{AC} = 0.4 μW
DC-AC efficiency= 11%

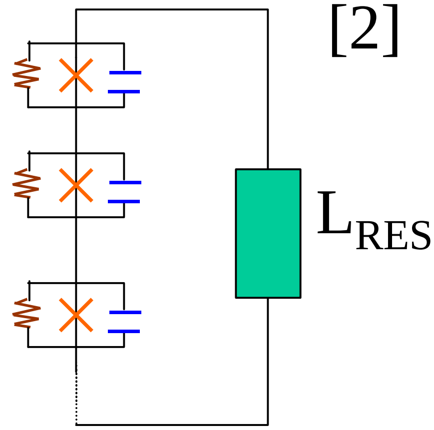
Maximum DC-AC efficiency:

Array 4x6
P_{AC} = 0.25 μW
DC-AC efficiency= 32%

Models for the coherent state



[1]



[2]

For an array of M junctions:

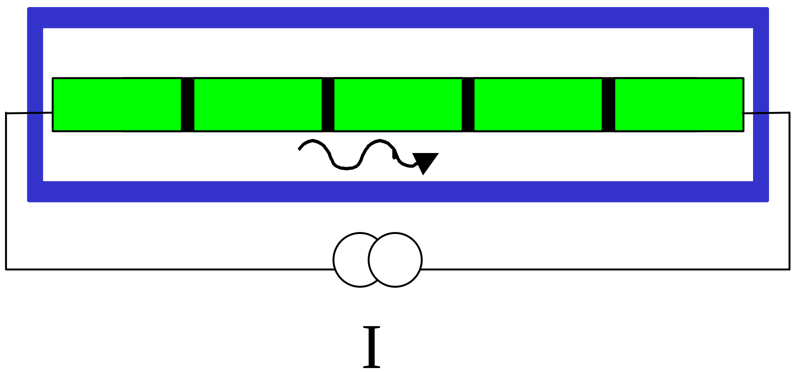
$H = \hbar\Omega n$ free-field energy for n photons

$+\hbar\omega\,\Sigma_m N_m$ electrostatic energy due to pair imbalance N_m, $\hbar\omega = 2eV$

$-2\hbar n^{1/2}\,\Sigma_m g_m \cos(\phi_m - \alpha_m)$ interaction of supercurrents with radiation field

[1] D. R. Tilley, Phys. Lett. **33A**, 205 (1970)
[2] G. Filatrella et al. Phys. Rev. E, **61**, 2513 (2000)

Tilley's predictions



$$H = \hbar\Omega + \hbar\omega \sum_m N_m - 2\hbar n^{1/2} \sum_m g_m \cos(\phi_m - \alpha_m)$$

in steady-state $\Rightarrow \frac{\partial n}{\partial t} = 0$

$n \propto P_{DC}$ for fixed M

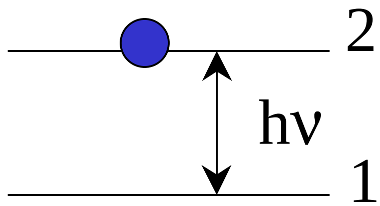
$n \propto M^2$ at the top of the steps

Analogy with lasers

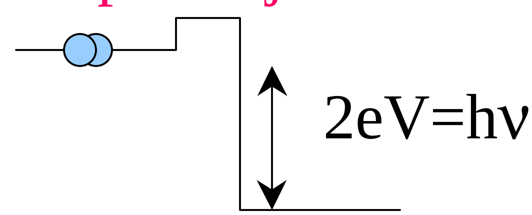
D. Rogovin and M. Scully, Phys. Rep. 25C, 175 (1976)

R. Bonifacio, F. Casagrande, and M. Milani, Lettere al Nuovo Cimento, 34, 520 (1982).

Two-level atoms



Josephson junctions



$N_2 > N_{Threshold}$

$N_A > N_{Threshold}$

in steady state

$n \propto P_{INPUT}$

$n \propto P_{DC}$

$n \propto (Pressure)^2$

$n \propto M^2$

density of atoms

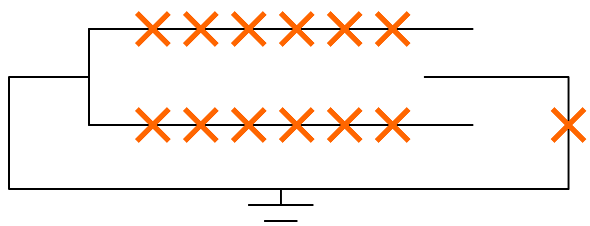
density of active junctions

Conclusions

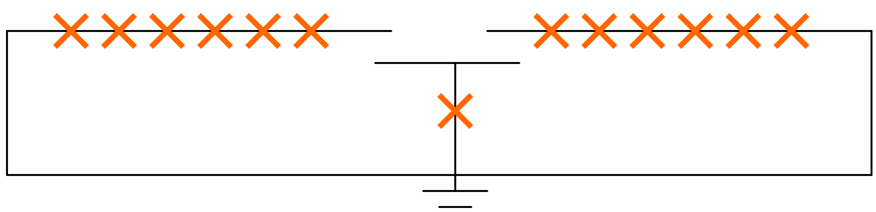
- very high DC-AC efficiency (32% !)
- maser behavior (threshold, steady-state coherent emission)

Future work

- Increase output power



- Linewidth measurements



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