Microwave Dynamics and Phase Locking in Spin Transfer Nanocontacts

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NIST OMP Office

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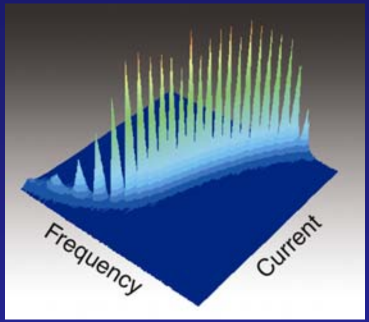
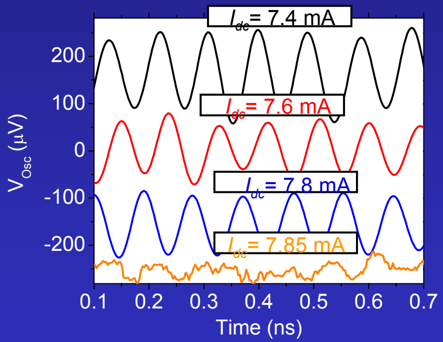
Outline

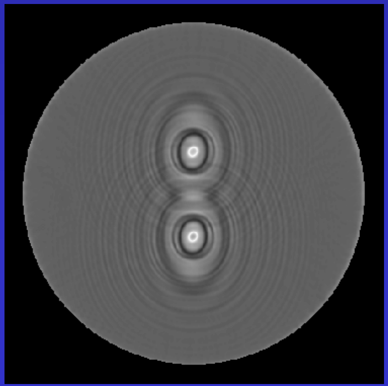
- **Introduction**
  - **Spin transfer effects**
  - **Device geometry**



- **Spin transfer induced dynamics**
  - **in plane fields**
  - **out of plane fields**



- **Phase locking of devices**
  - **Injection locking to source**
  - **Mutual synchronization of oscillators**



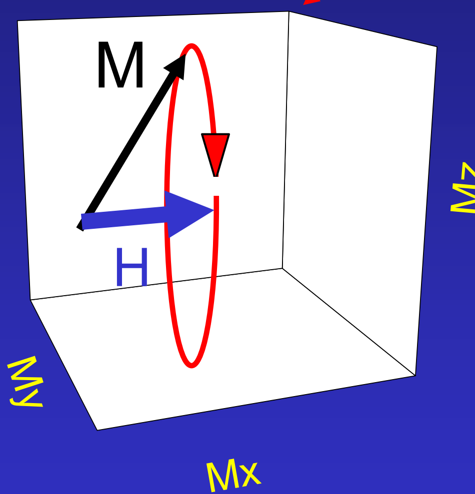
- **Summary**

Magnetodynamics

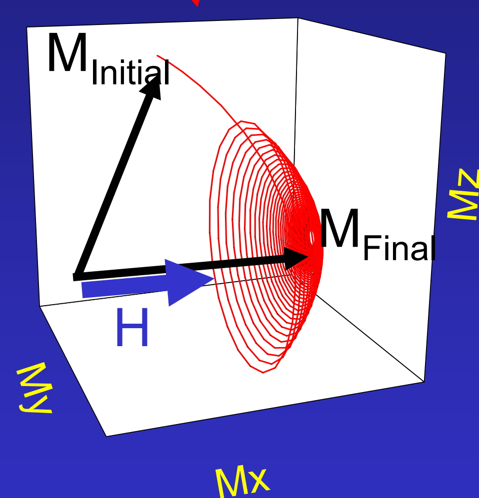
$$\frac{d\vec{m}_1}{dt} = T_{Larmor} + T_{Damping} + T_{SpinTransfer}$$

Slonczewski 1996

$$\frac{d\vec{m}_1}{dt} = -\mu_0\gamma\vec{m}_1 \times \vec{H}_{eff} - \mu_0\gamma\alpha\vec{m}_1 \times (\vec{m}_1 \times \vec{H}_{eff}) + \frac{\varepsilon J_{inj}\hbar}{el_z 2}\frac{\gamma}{M_{s1}}\vec{m}_1 \times (\vec{m}_1 \times \vec{m}_2)$$

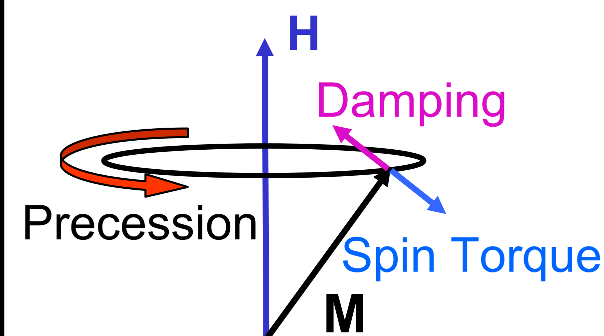


Larmor term: precession



Damping term: aligns M with H_{EFF}

Spin Torque Term

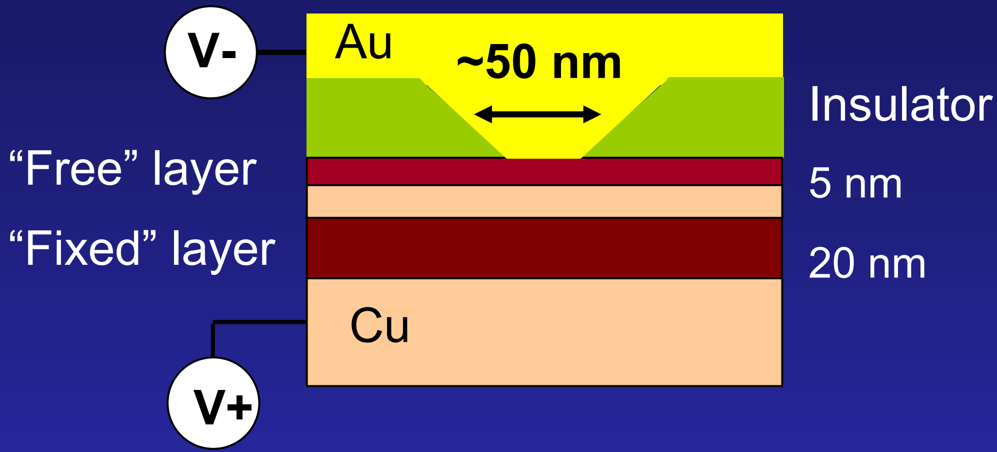


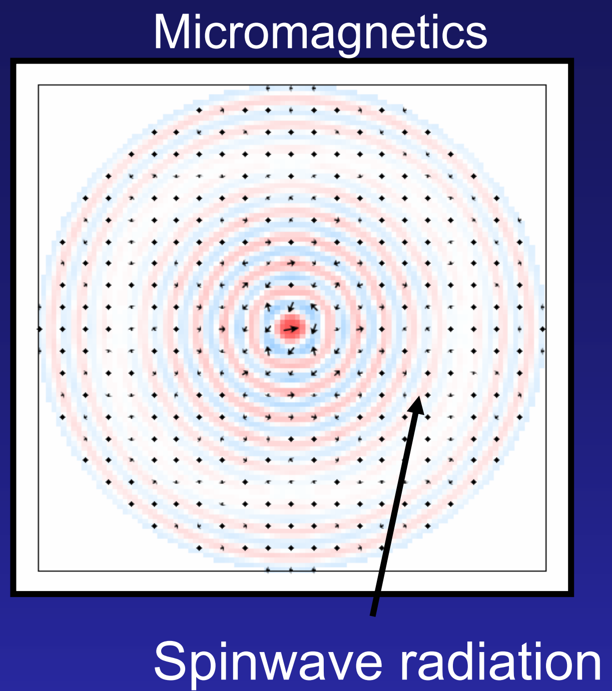
Spin torque can counteract damping

$$T_{Spin\ Transfer} \cong T_{Damping}$$

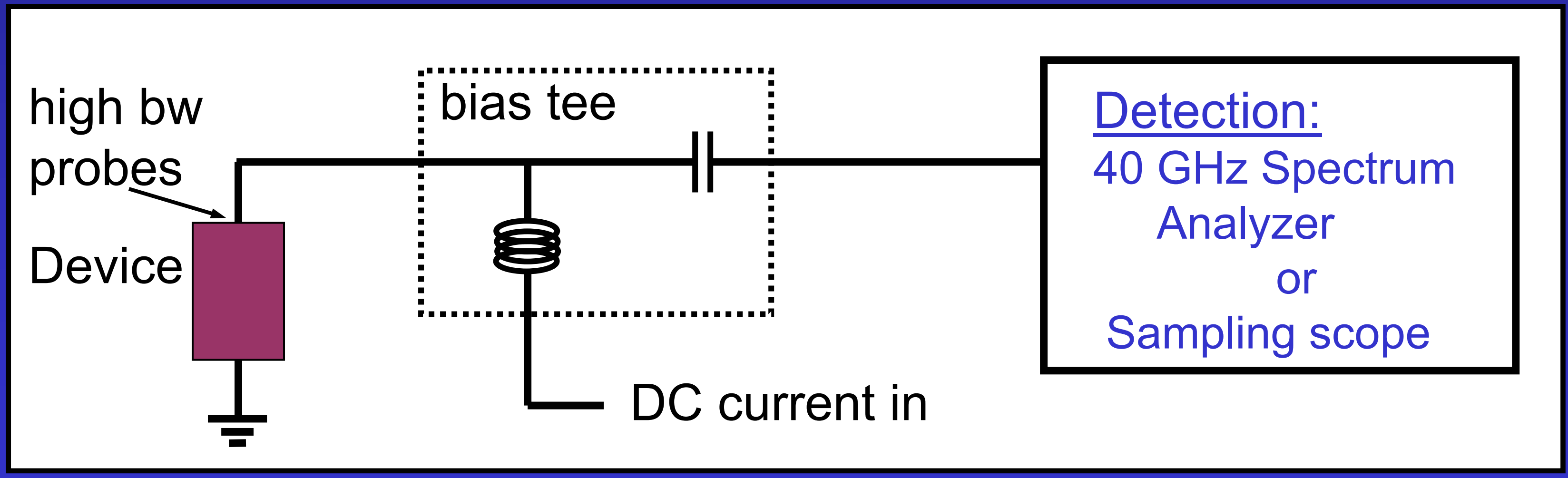
$$J \sim 10^7 A/cm^2$$

Device Schematic





Measurement setup



Measured signal results from I_{DC} and GMR effect

Nanocontact Dynamics

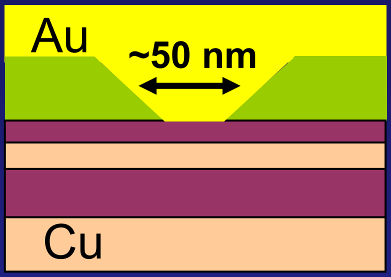
- Step DC current
- Measure DC *R*, microwave power output

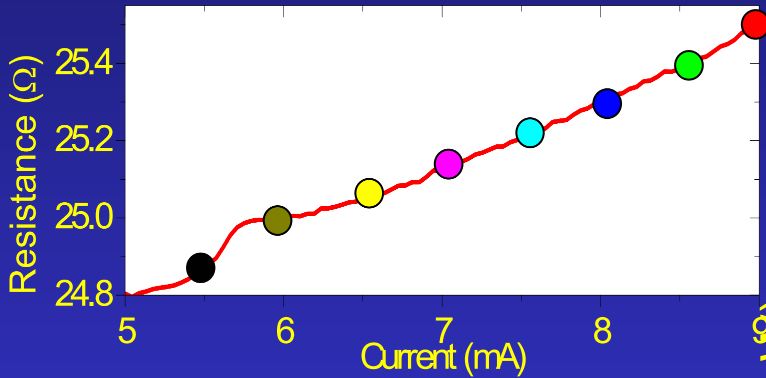
Device Schematic

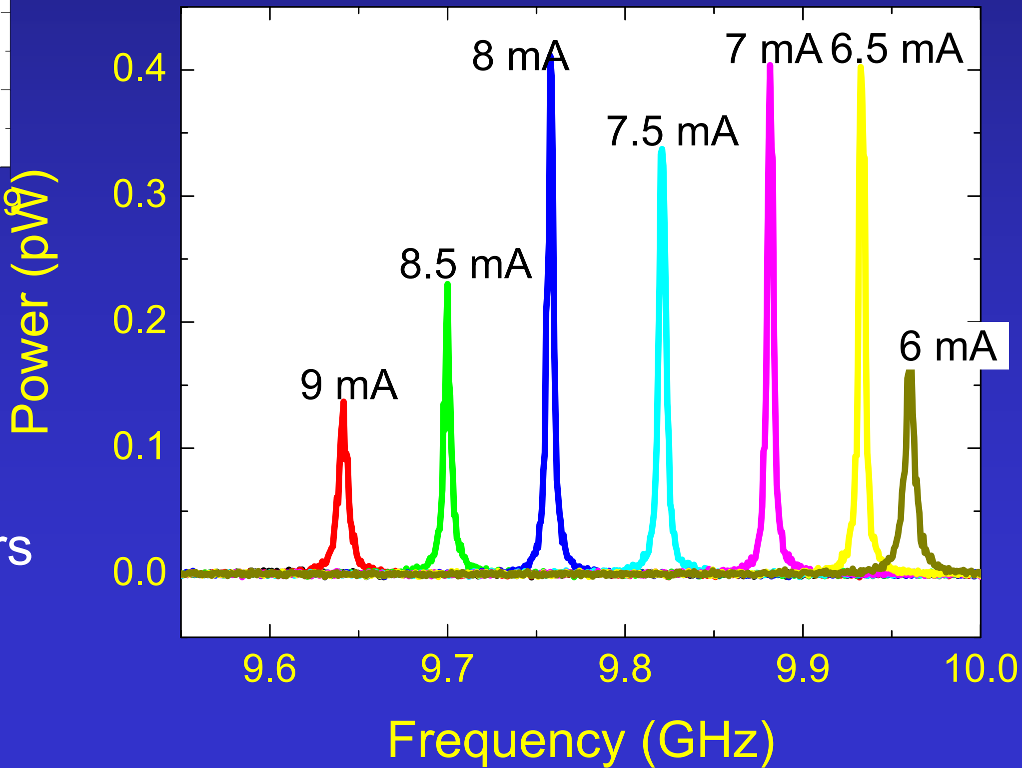
T = 300K

“Free” layer

“Fixed” layer



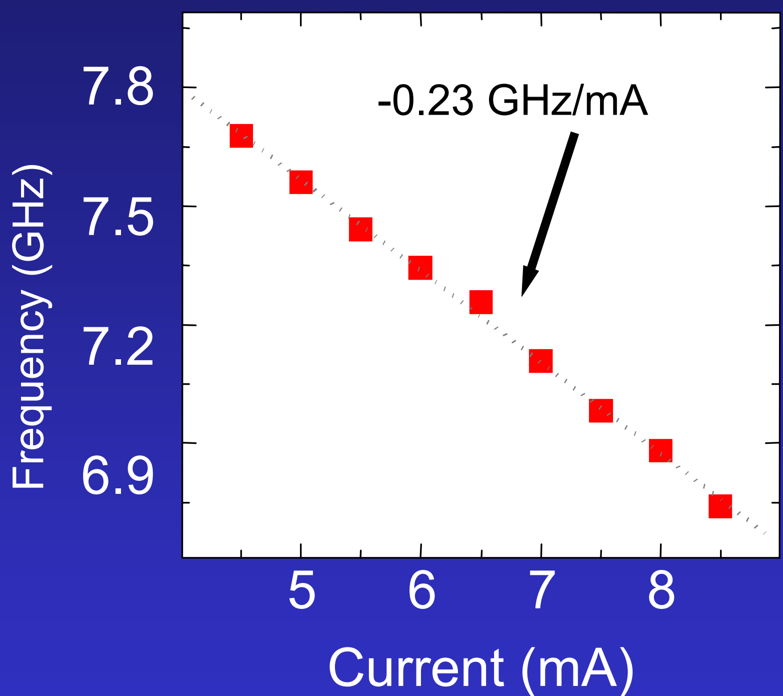




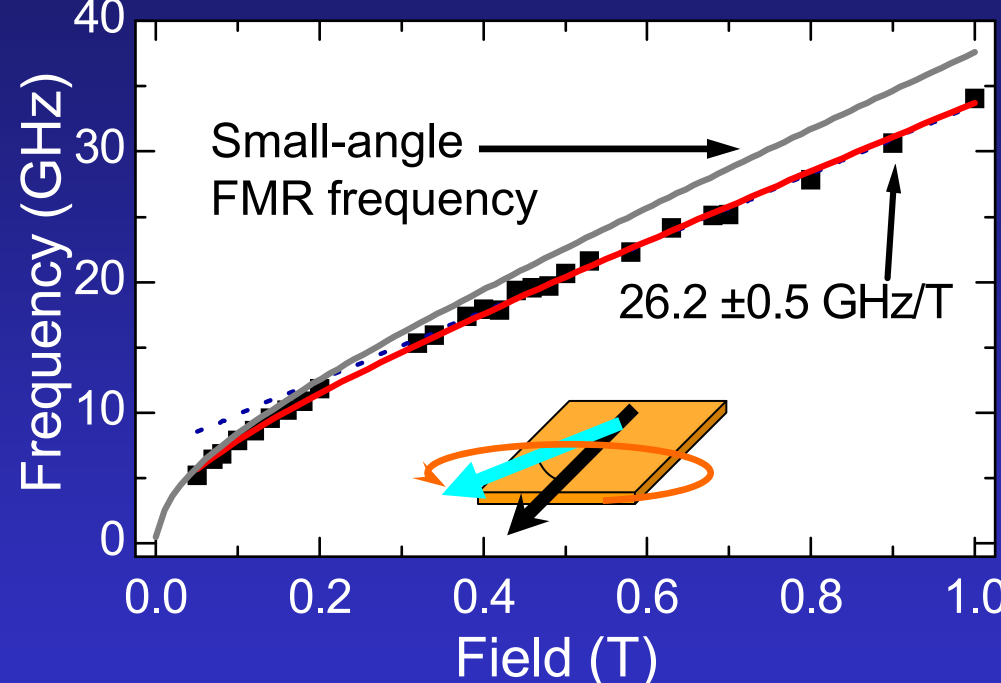
Devices are nanoscale current controlled microwave oscillators

In-Plane Applied Fields

Current Response



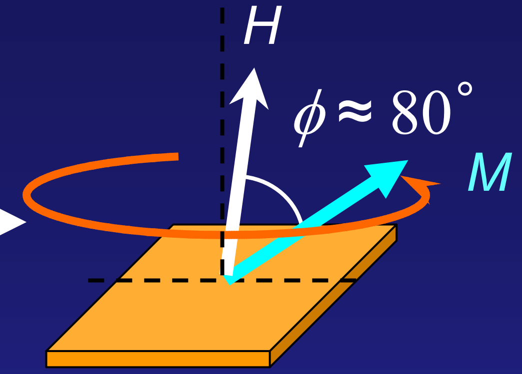
Field Response



Consistent with large angle version of FMR

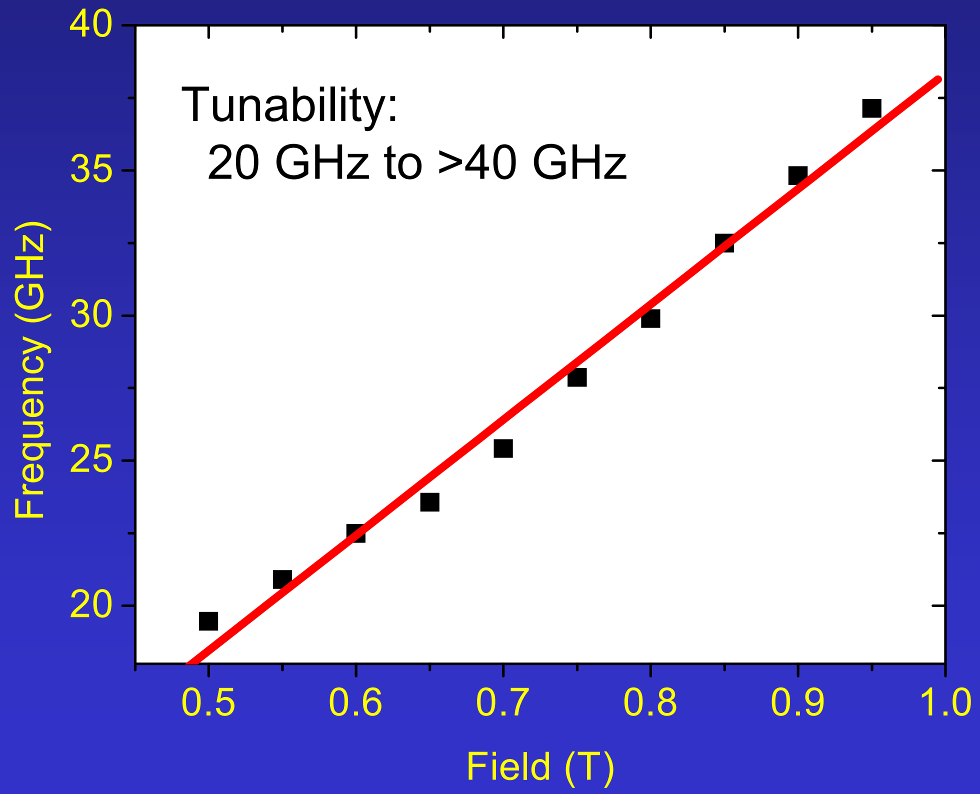
Qualitative behavior in accordance with
Slonczewski equation

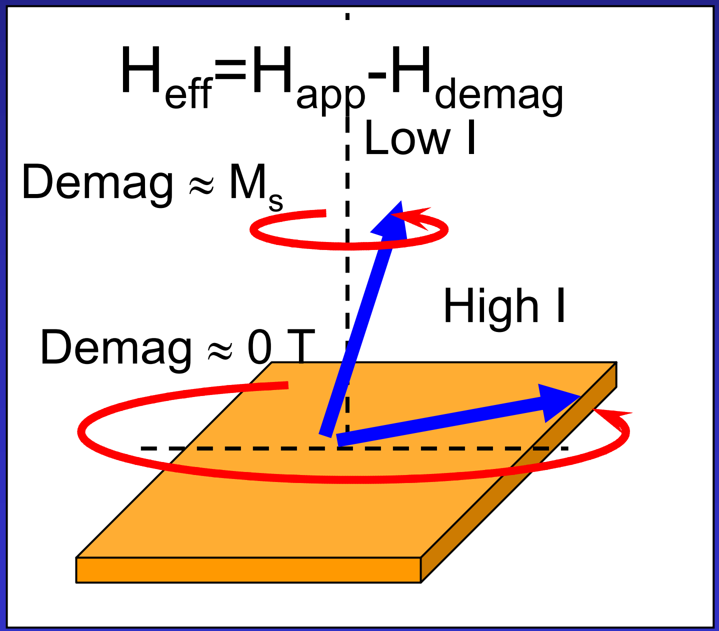
Out of Plane Fields



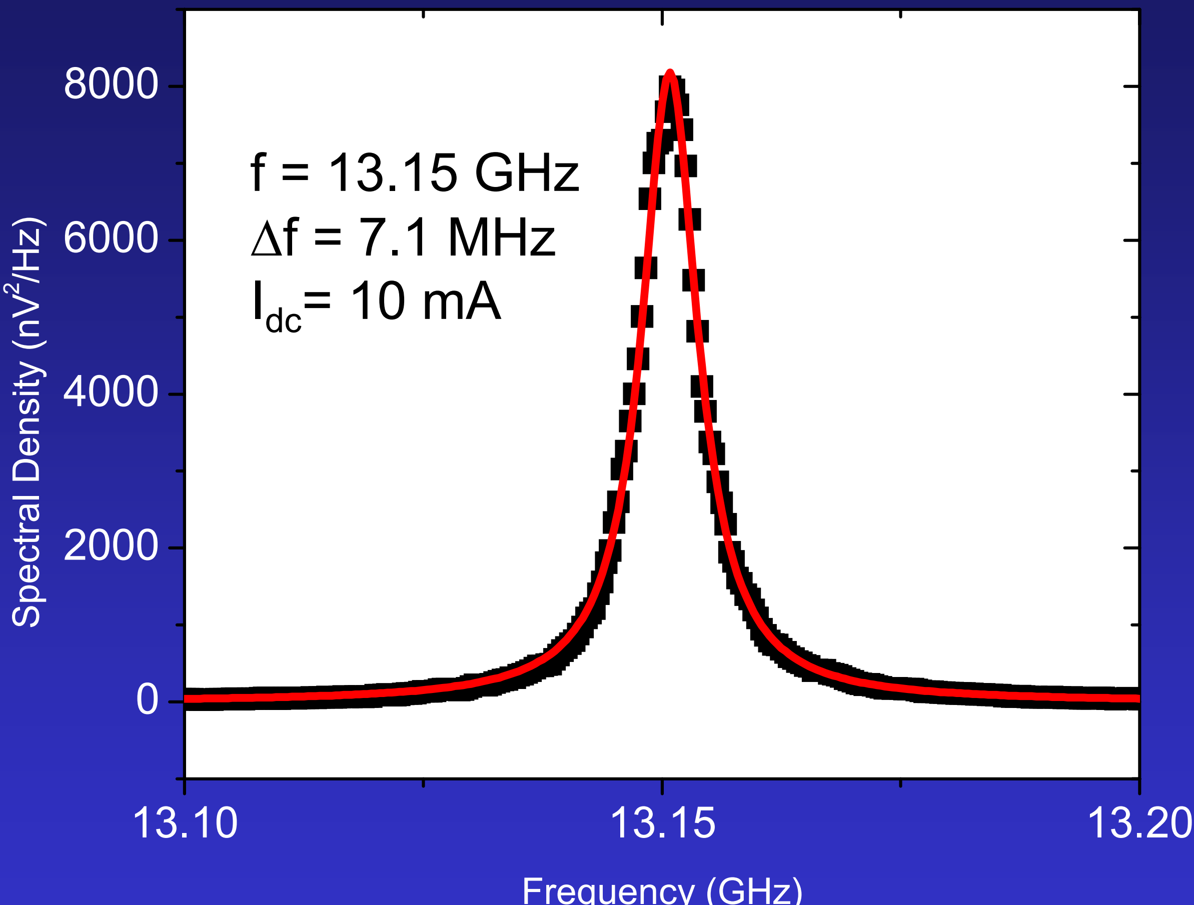
Precession occurs about the applied field direction
larger tunablity with current

Field Response





Device Output



Integrated voltage output:

V = 850 μV

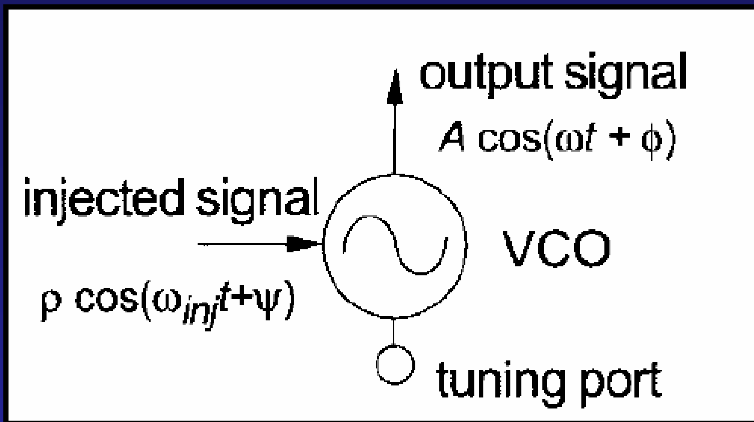
Maximum GMR response:

ΔR = 250 mΩ
I = 10 mA
ΔV = 2.5 mV

Lower bound: Impedance mismatch not accounted for

Both frequency and power indicate approaching ~80° precessional angles

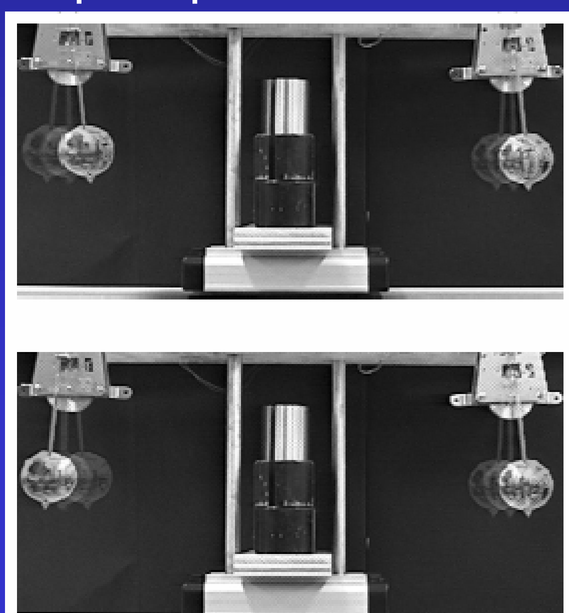
Injection Locking



Synchronized Fireflies

http://www.pojman.com/NLCD-movies/NLCD-movies.html

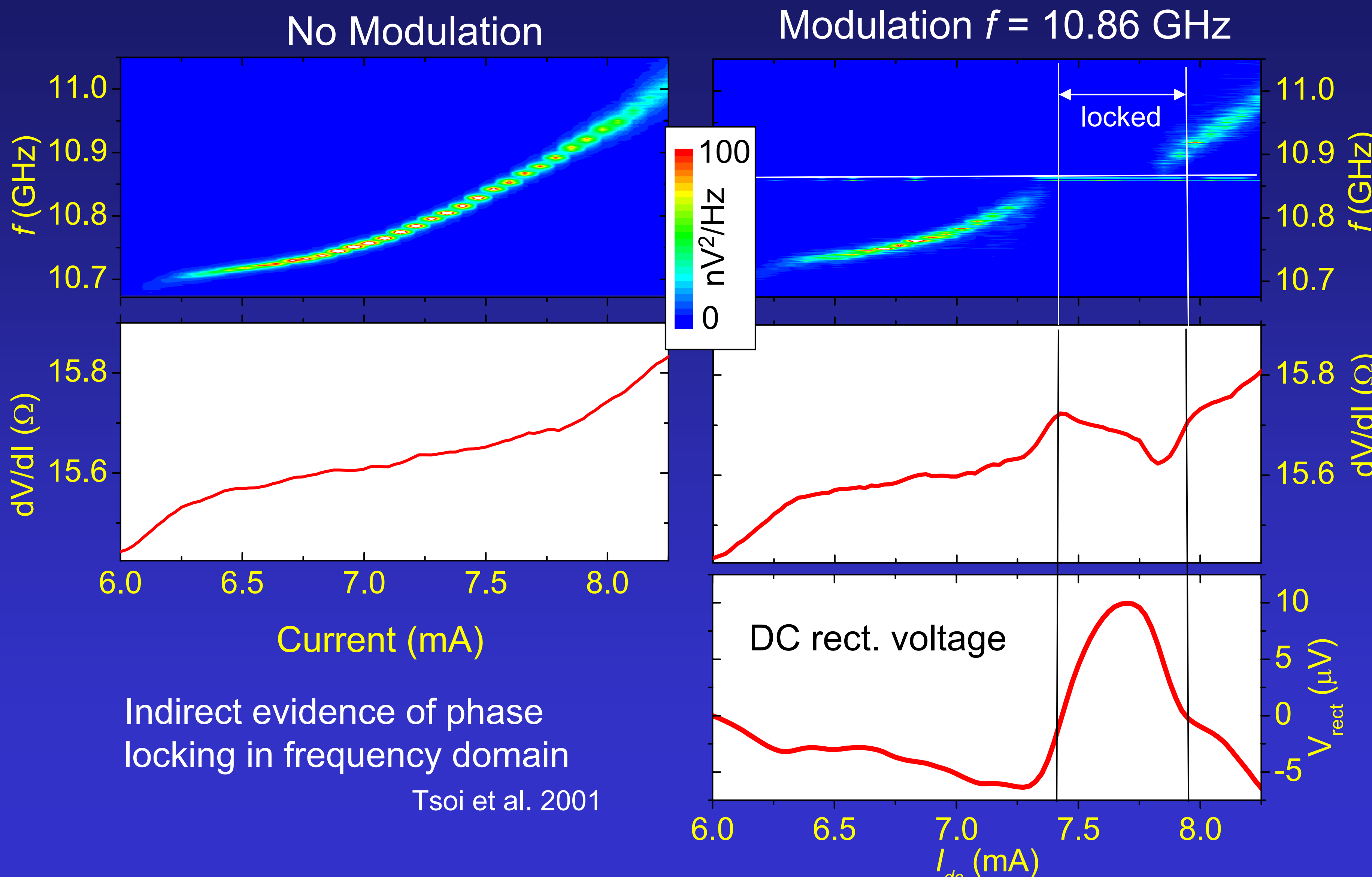
Huygens (1665)
Coupled pendulum clocks



General characteristic of all nonlinear oscillators:

Circadian rhythms, Huygens' clocks, power grid, Josephson junctions, fireflies…….

Injection Locking Measurements

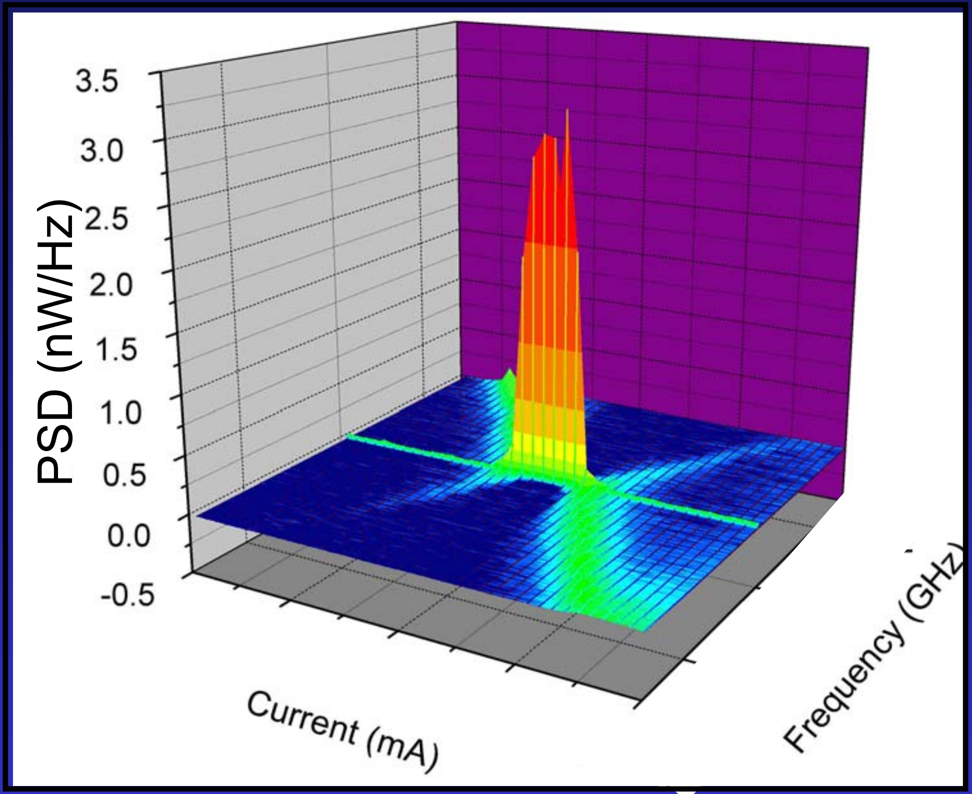


Indirect evidence of phase locking in frequency domain

Tsoi et al. 2001

Spectral Measurement of Locking

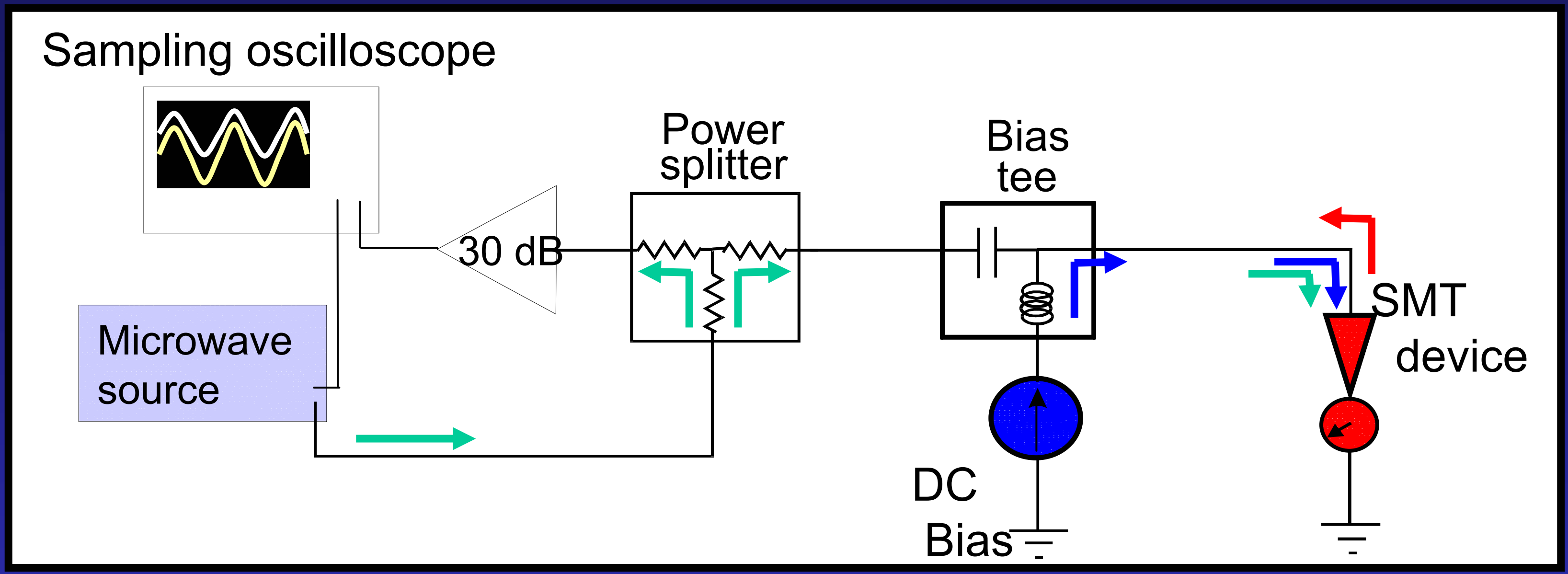
Spectral measurement of locking



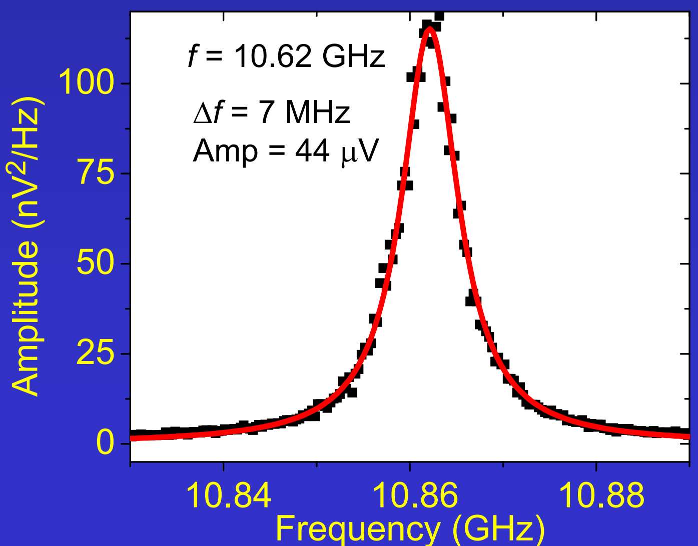
During locking the device takes on the noise characteristics of the input signal

-oscillator linewidth approaches Hz

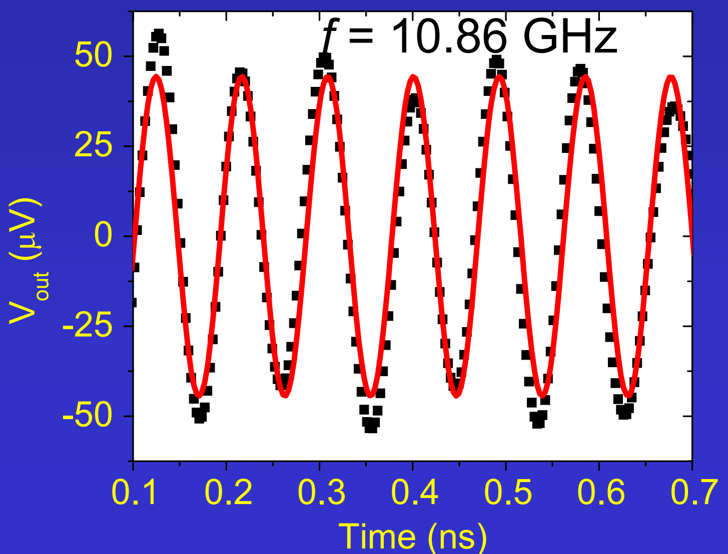
Time Domain Measurements



Spectral Measurement

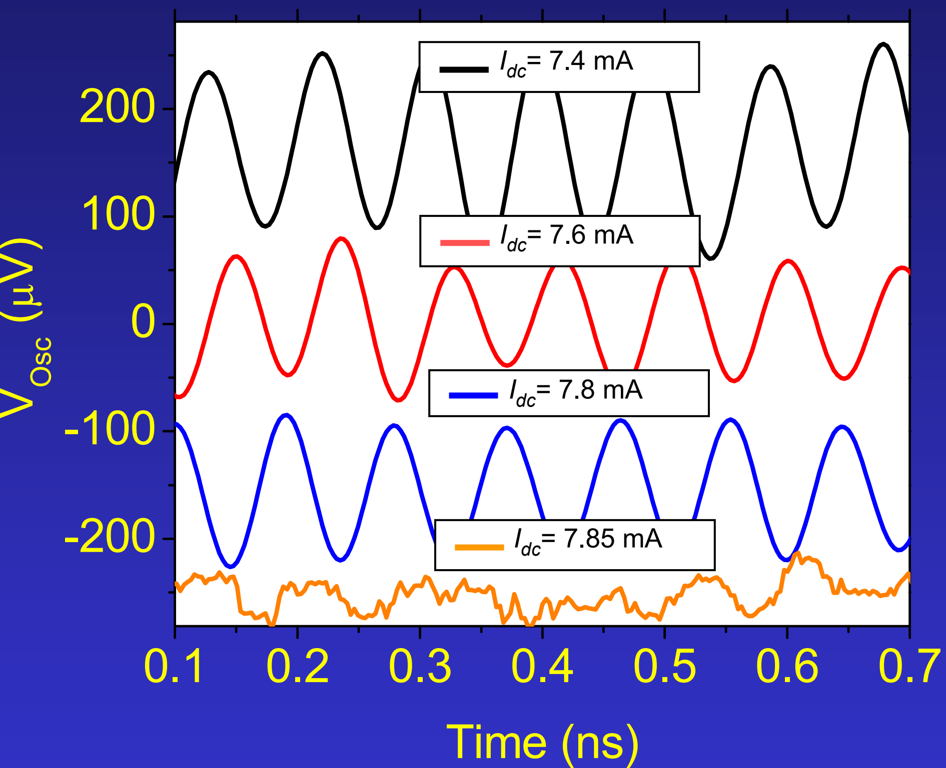


Time-domain Measurement

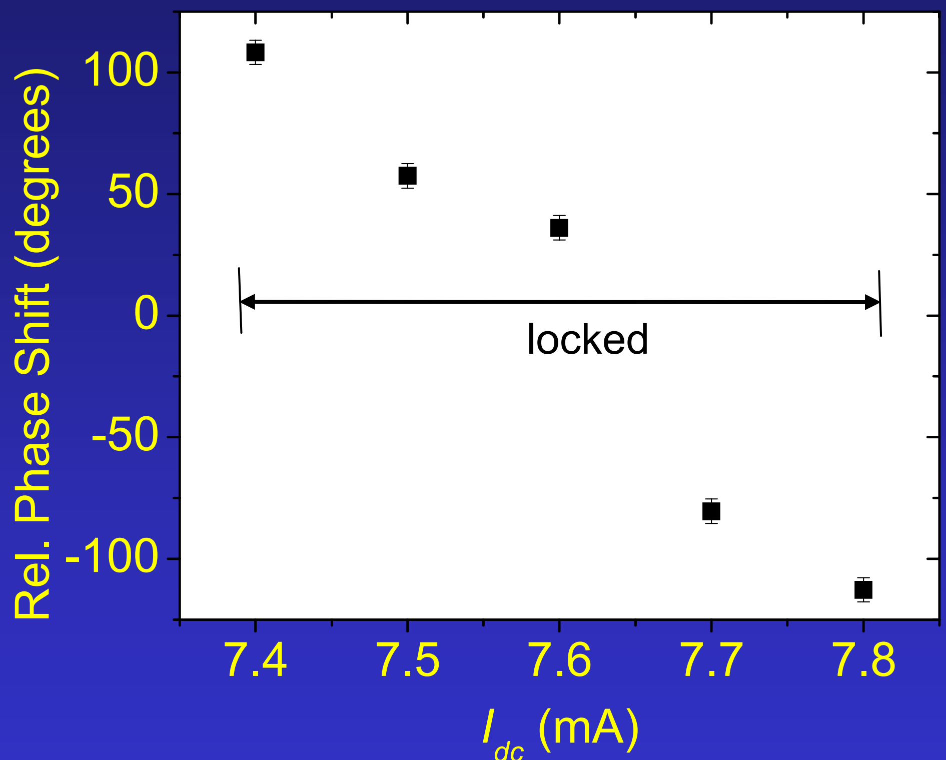


Electronic Phase Control of Oscillations

Time-domain Measurements



Relative Phase Change

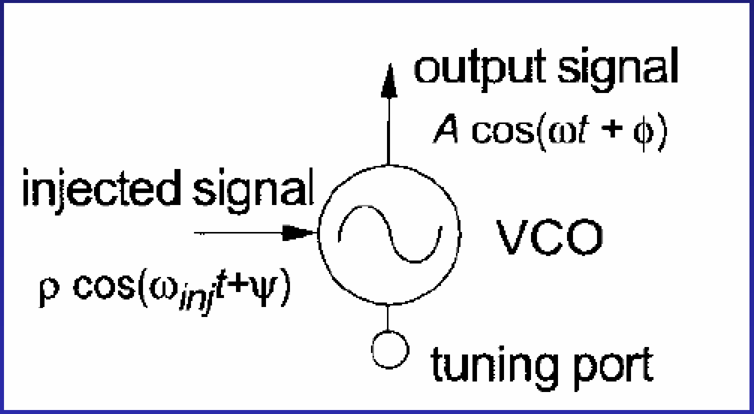


Relative phase change over locking region is approximately 180 degrees

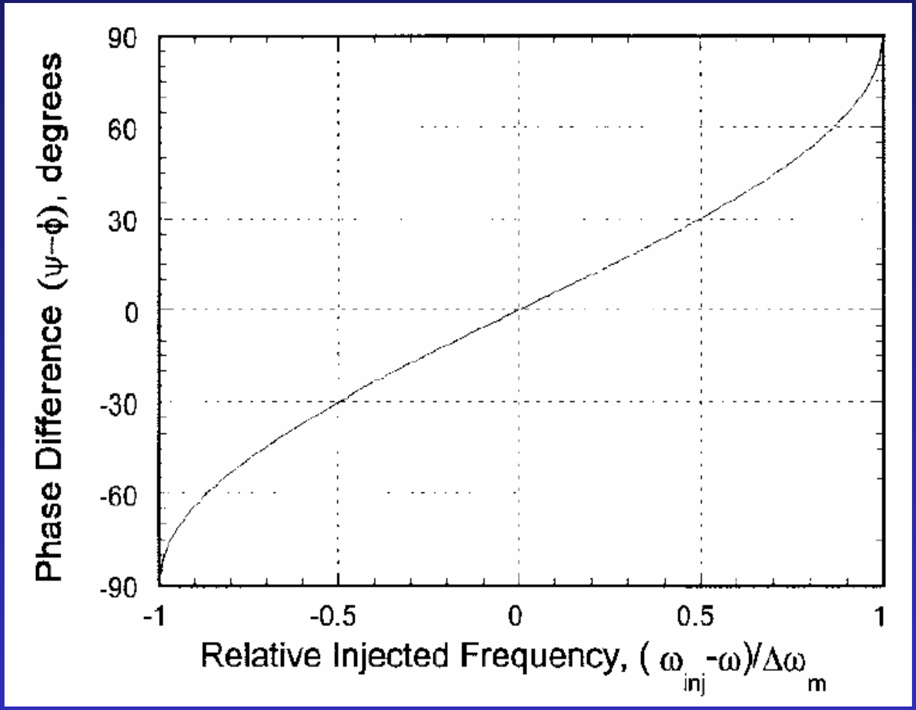
Demonstrates electronic phase control of oscillators

Injection Locking of Devices

General theory (Adler, 1973):



Phase relationship



The Adler Equation

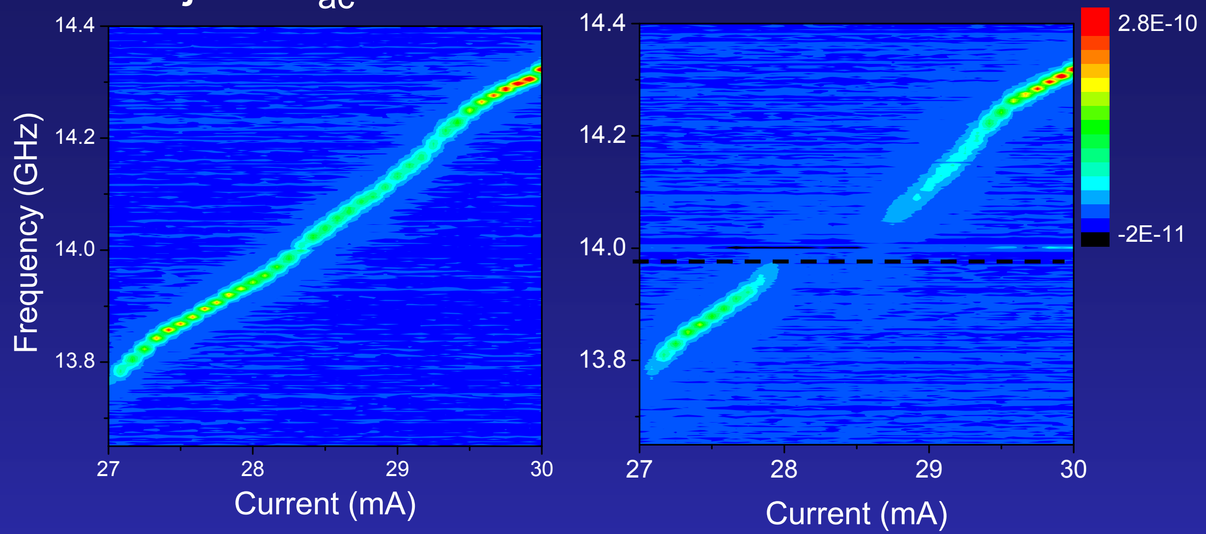
$$\Delta f_{\text{lock}} = \Delta f_{\text{linewidth}} \frac{V_{\text{inj}}}{V_{\text{osc}}}$$

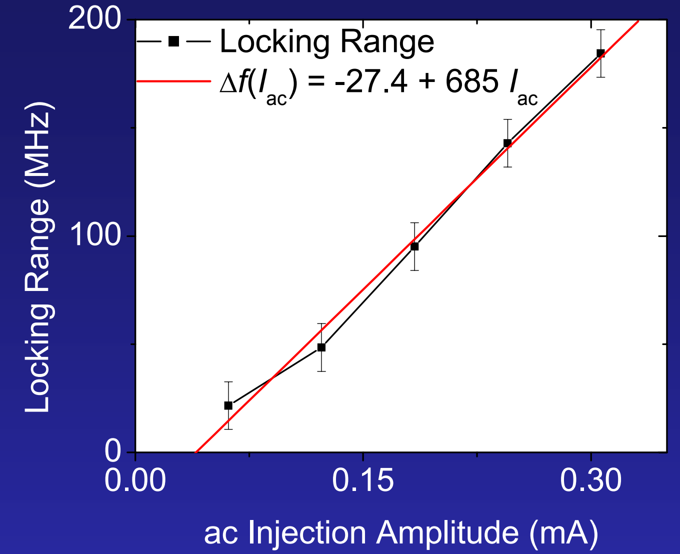
Generally expect linear relationship between locking range and oscillator

- -linewidth
- -injected signal

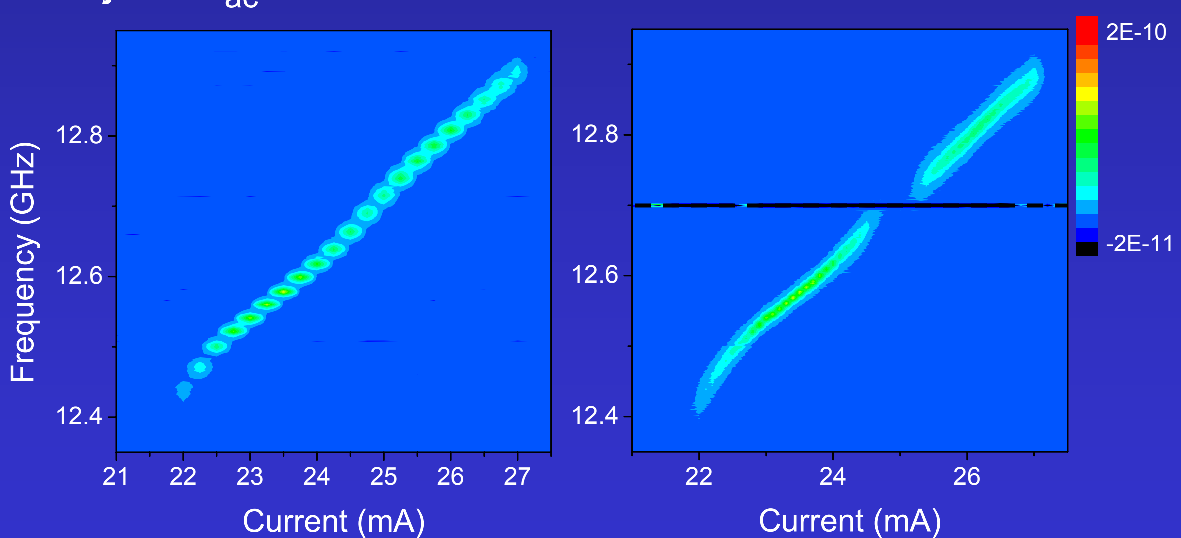
Injection Locking Results

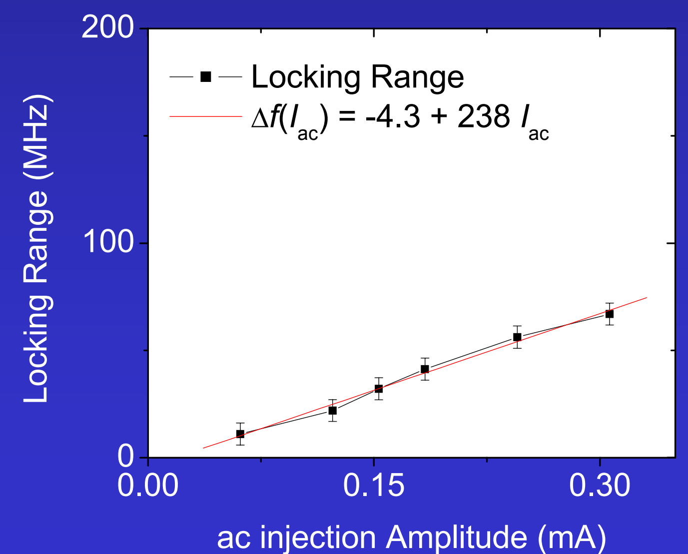
Inject V_{ac} at 14 GHz





Inject V_{ac} at 12.7 GHz

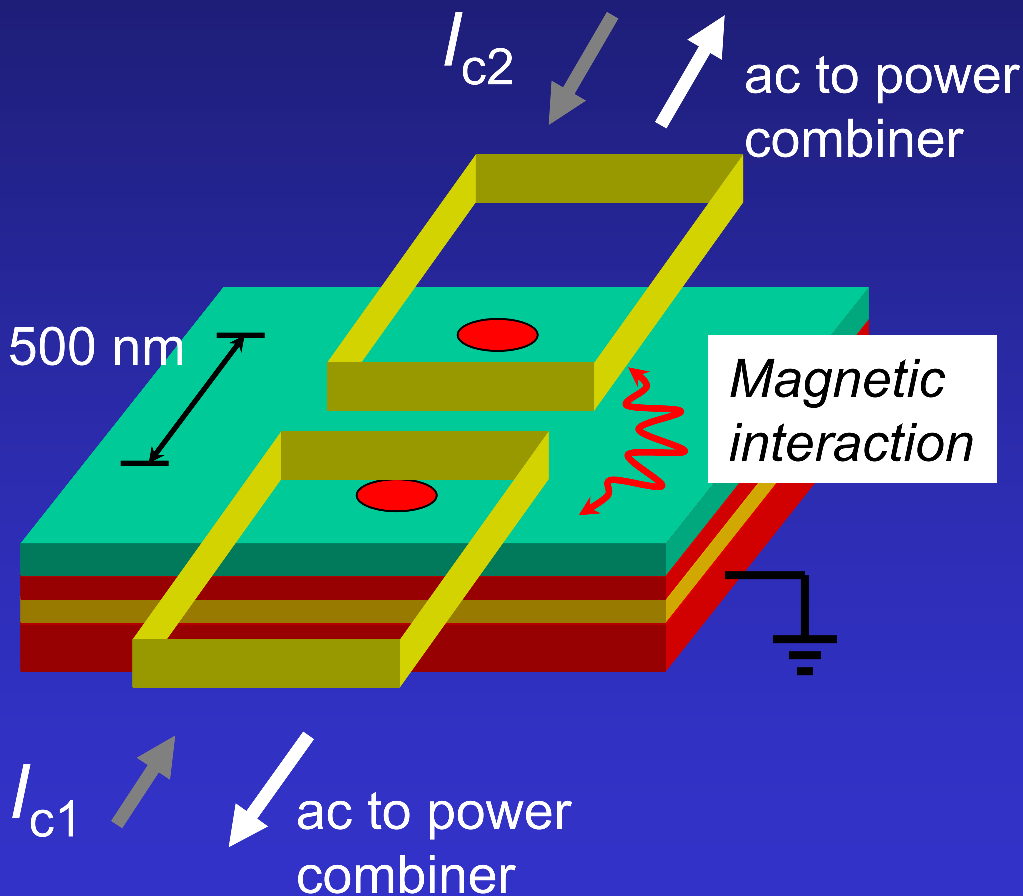




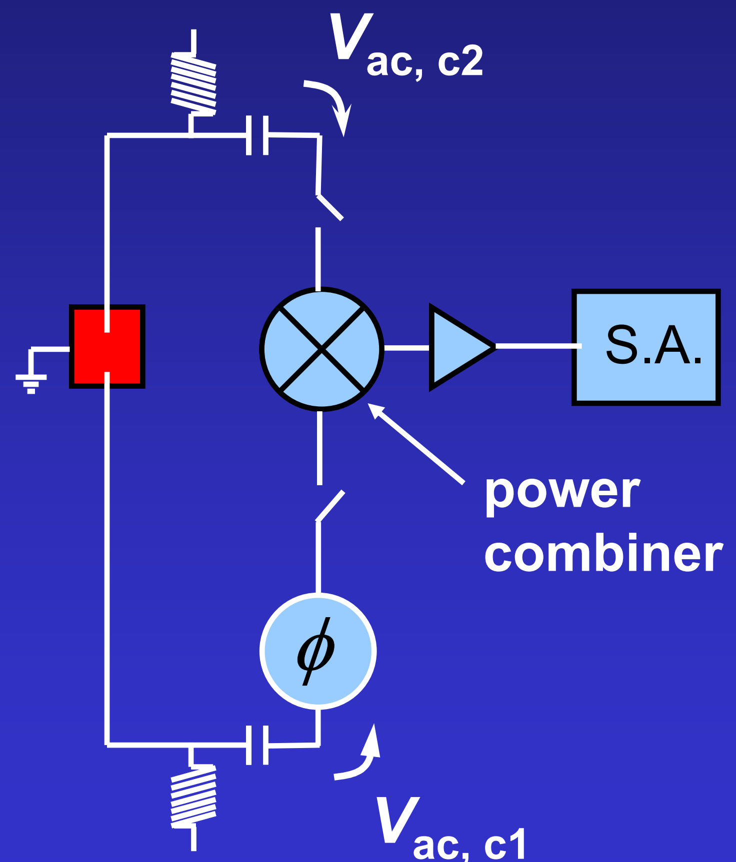
Lack quantitative understanding of locking range

Mutual Phase Locking

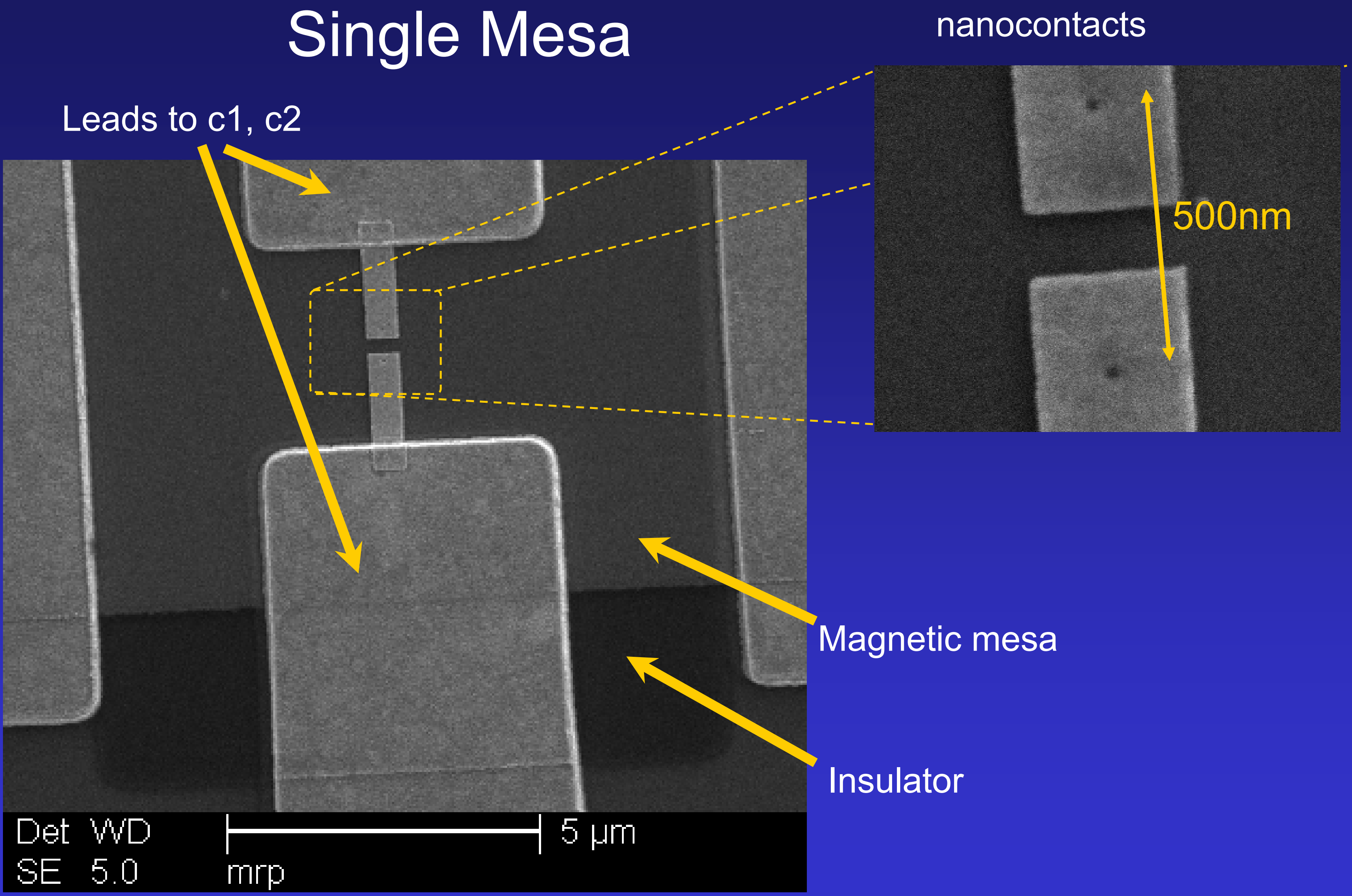
Device schematic:



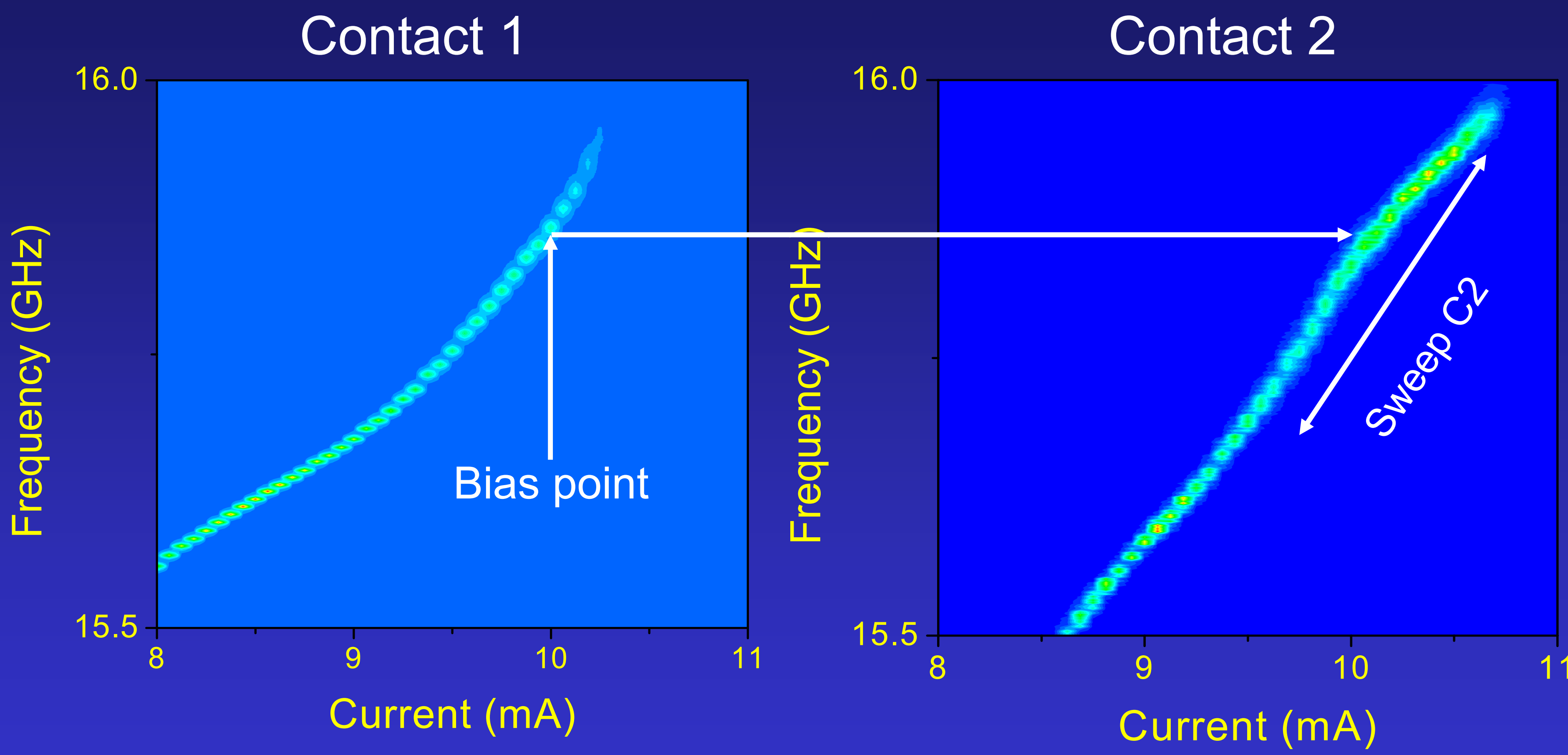
Measurement circuit:



Dual Contacts On Single Mesa

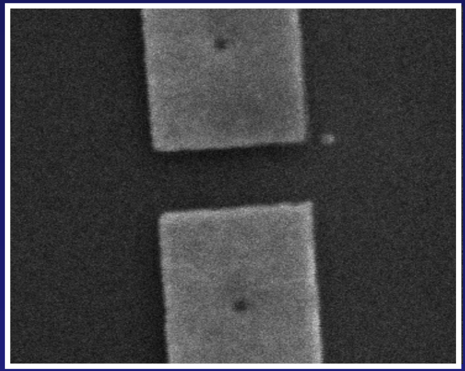


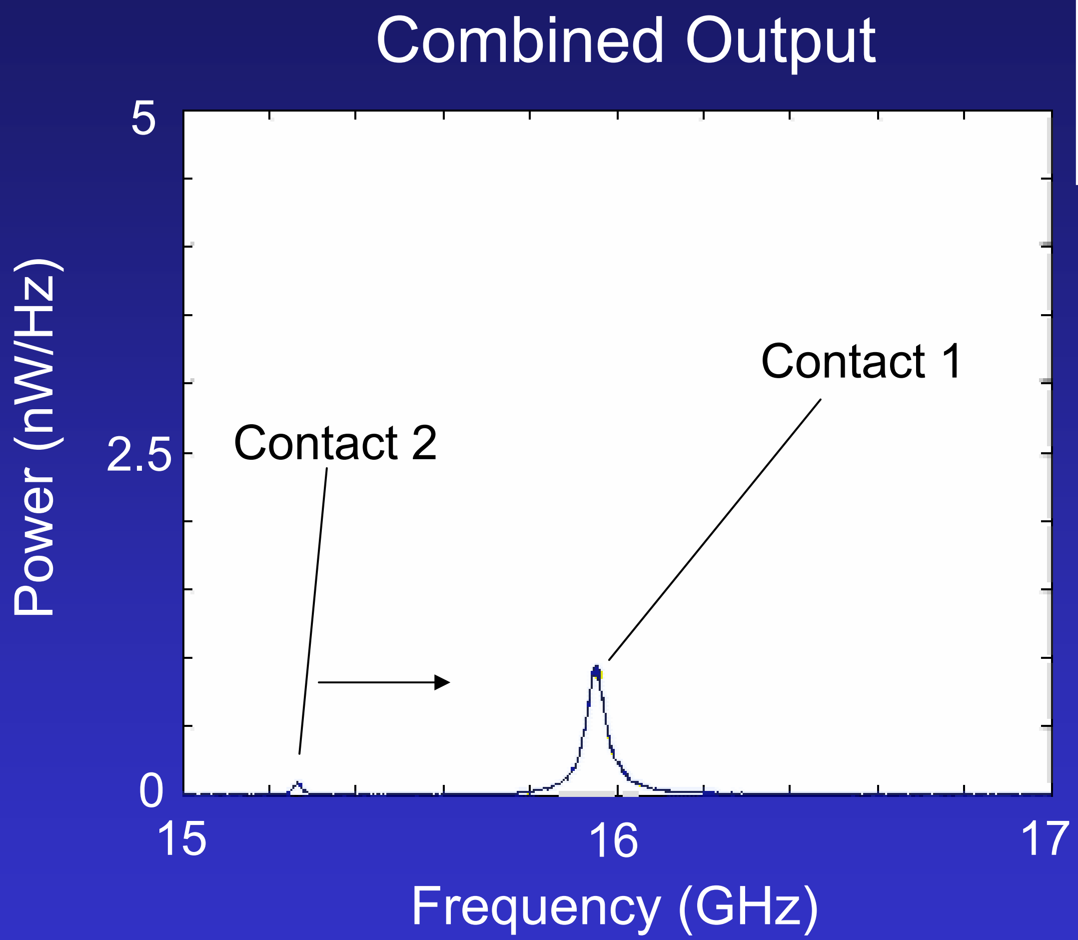
Individual Device Outputs



Bias contact 1 and sweep current through contact 2

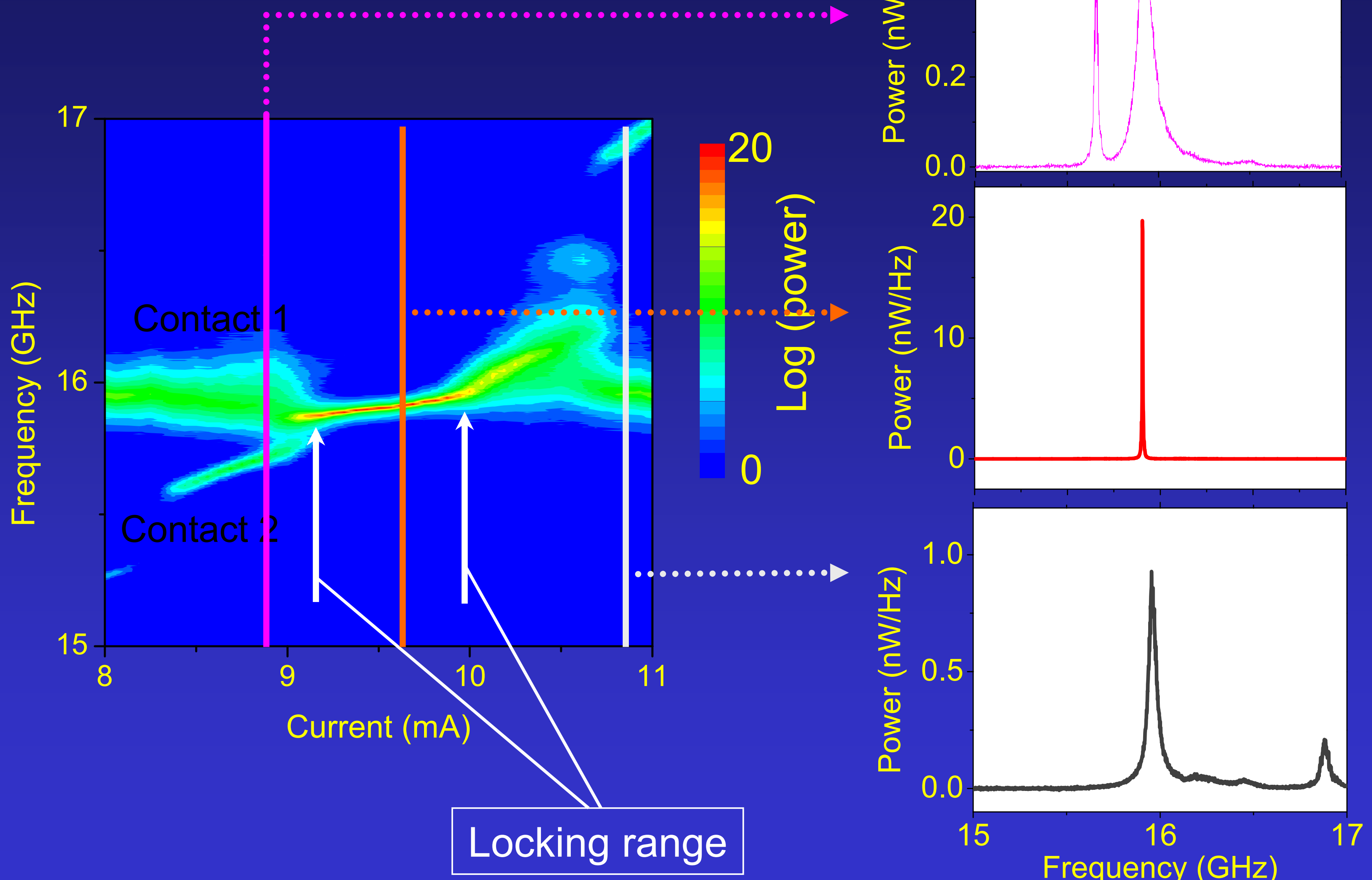
Output from Both Devices



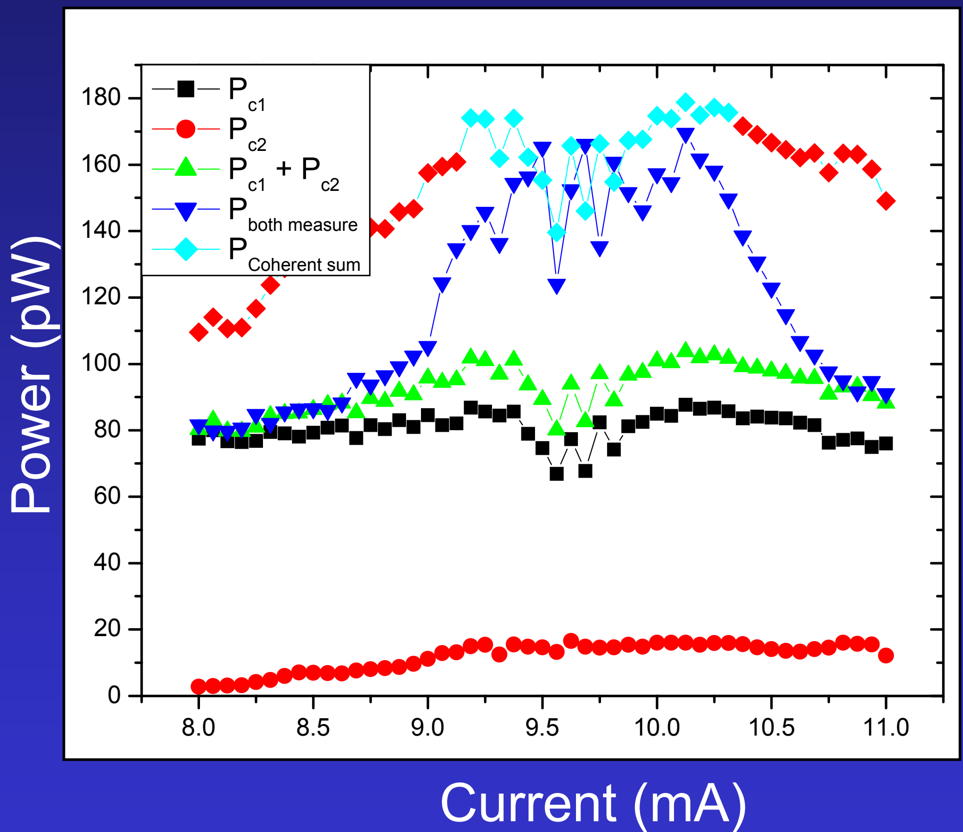


Contact 1 = Constant bias
Contact 2 = Swept bias

Mutual Phase Locking



Mutual Phase Locking: Power & Phase



Incoherent sum:

$$P_{out} = P_{c1} + P_{c2}$$

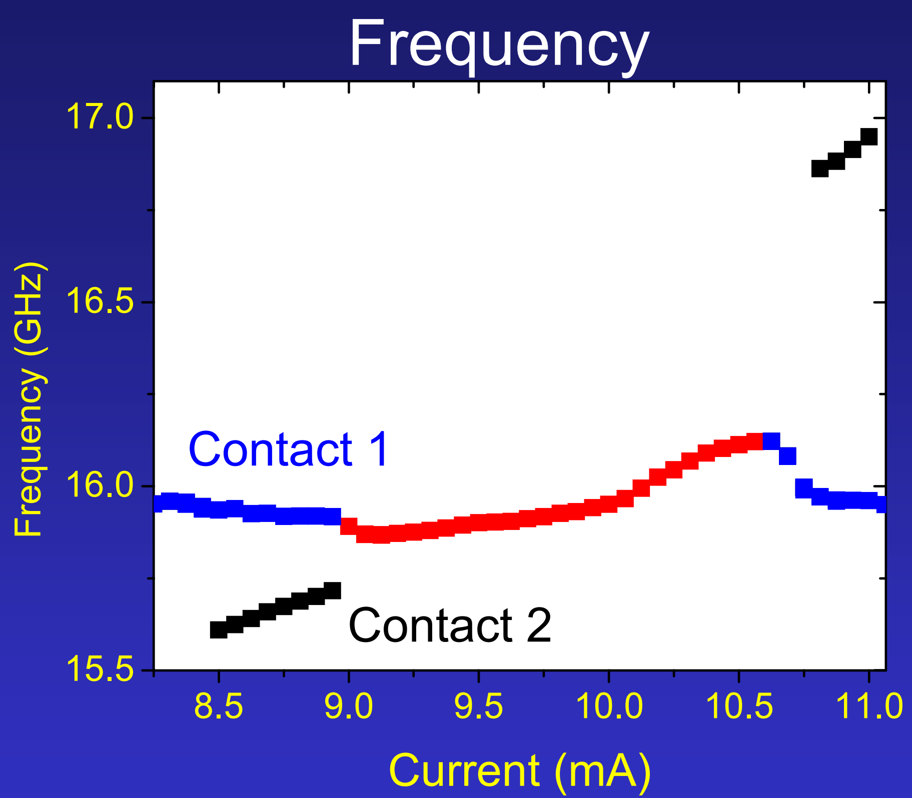
Coherent sum:

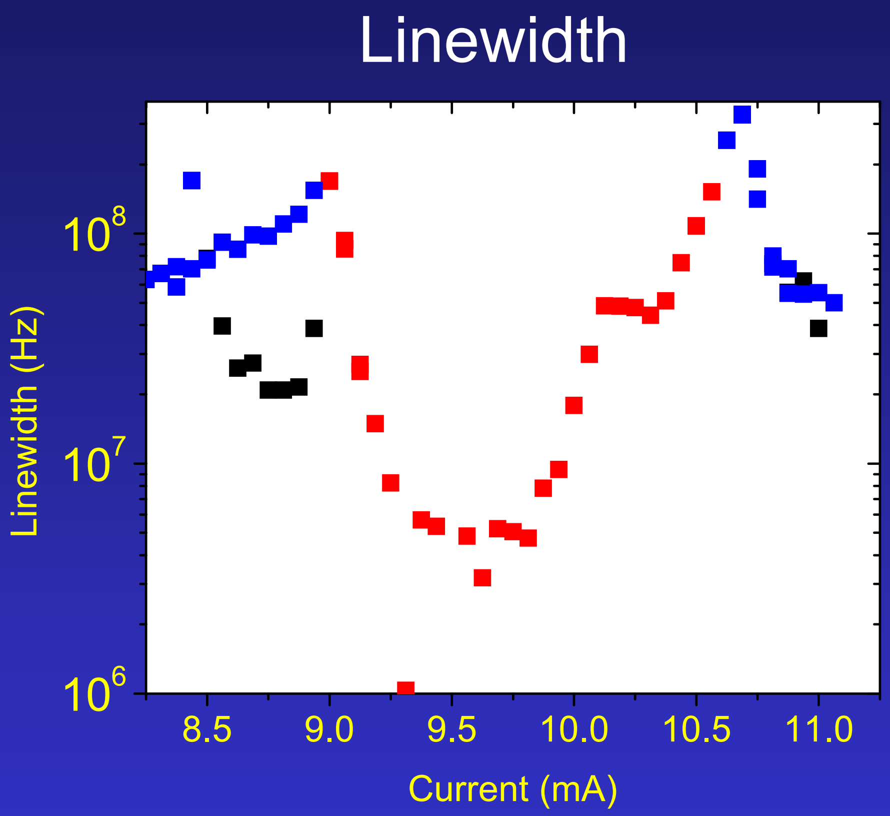
$$P_{out} = P_{c1} + P_{c2} + 2\sqrt{P_{c1}P_{c2}}\cos(\phi)$$

Rel. Phase ϕ during lock ≈ 0°

…Phase locking a route to higher powers (n^2), phased arrays

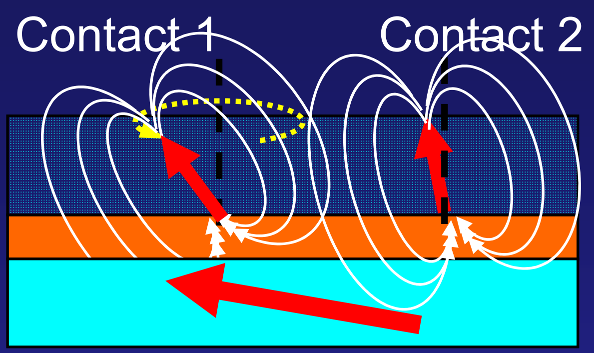
Mutual Phase Locking





Linewidth decreases below individual oscillators when locked
No clear master/slave relationship between devices
-stabilization against thermal effects?

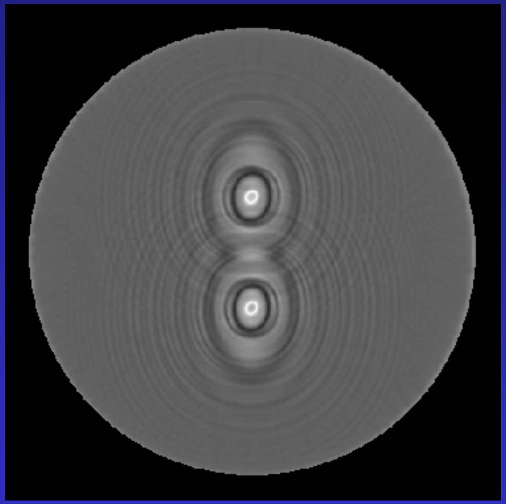
Possible Locking Mechanisms



- AC Dipole fields

  Estimate coupling field on the order of several Oe

  Possible mechanism



- Spin wave radiation between contacts

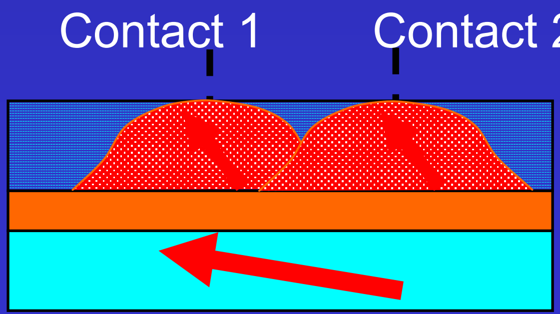
  Simulations support spinwave coupling between devices

  Possbile mechanism

- Mode Overlap

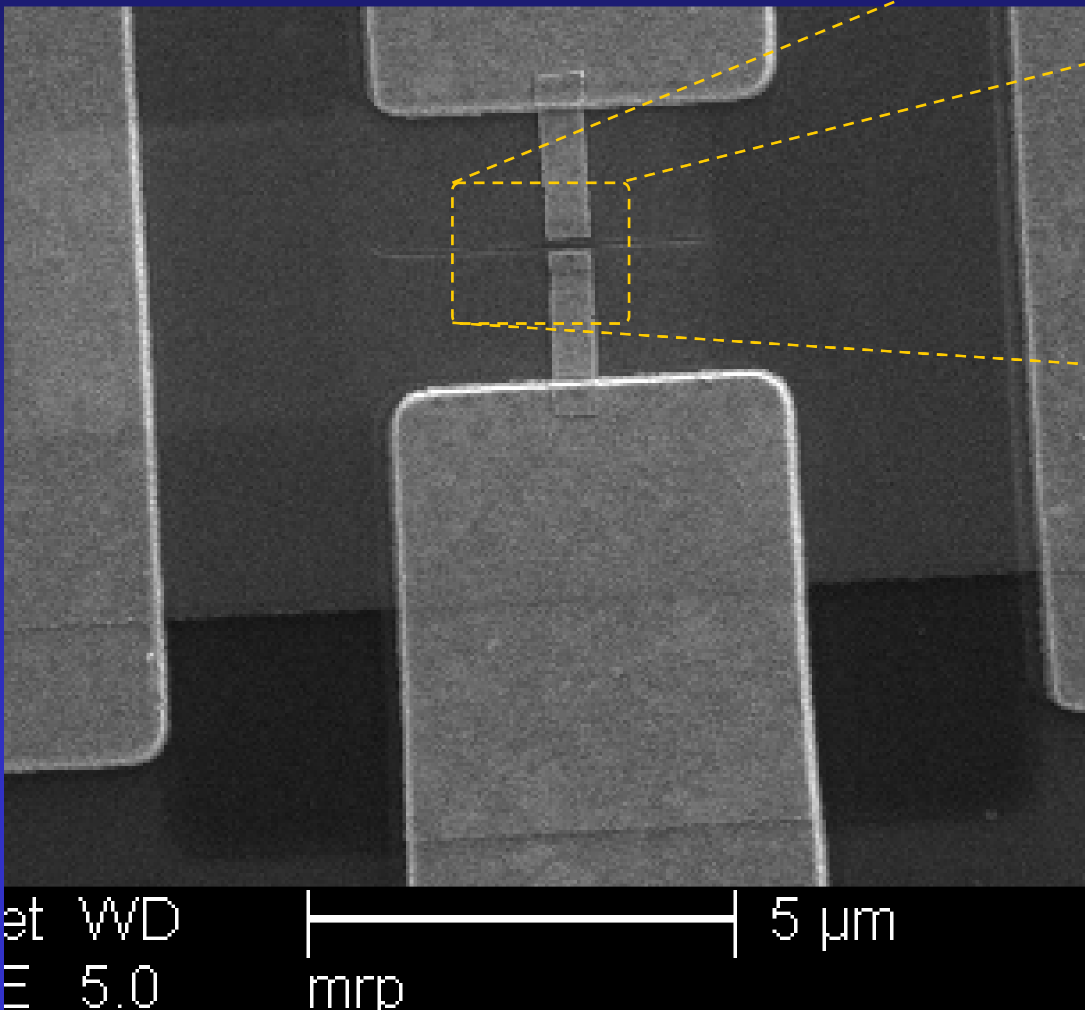
  Simulations do not support such large area of precession

  Improbable mechanism

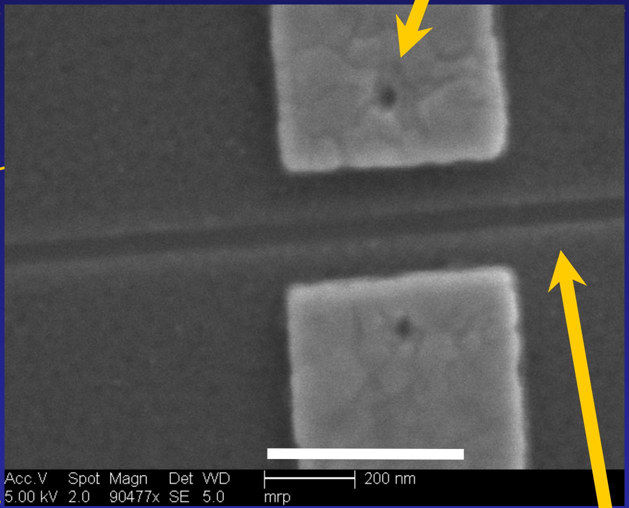


FIB cutting of magnetic mesa:

Cut Mesa



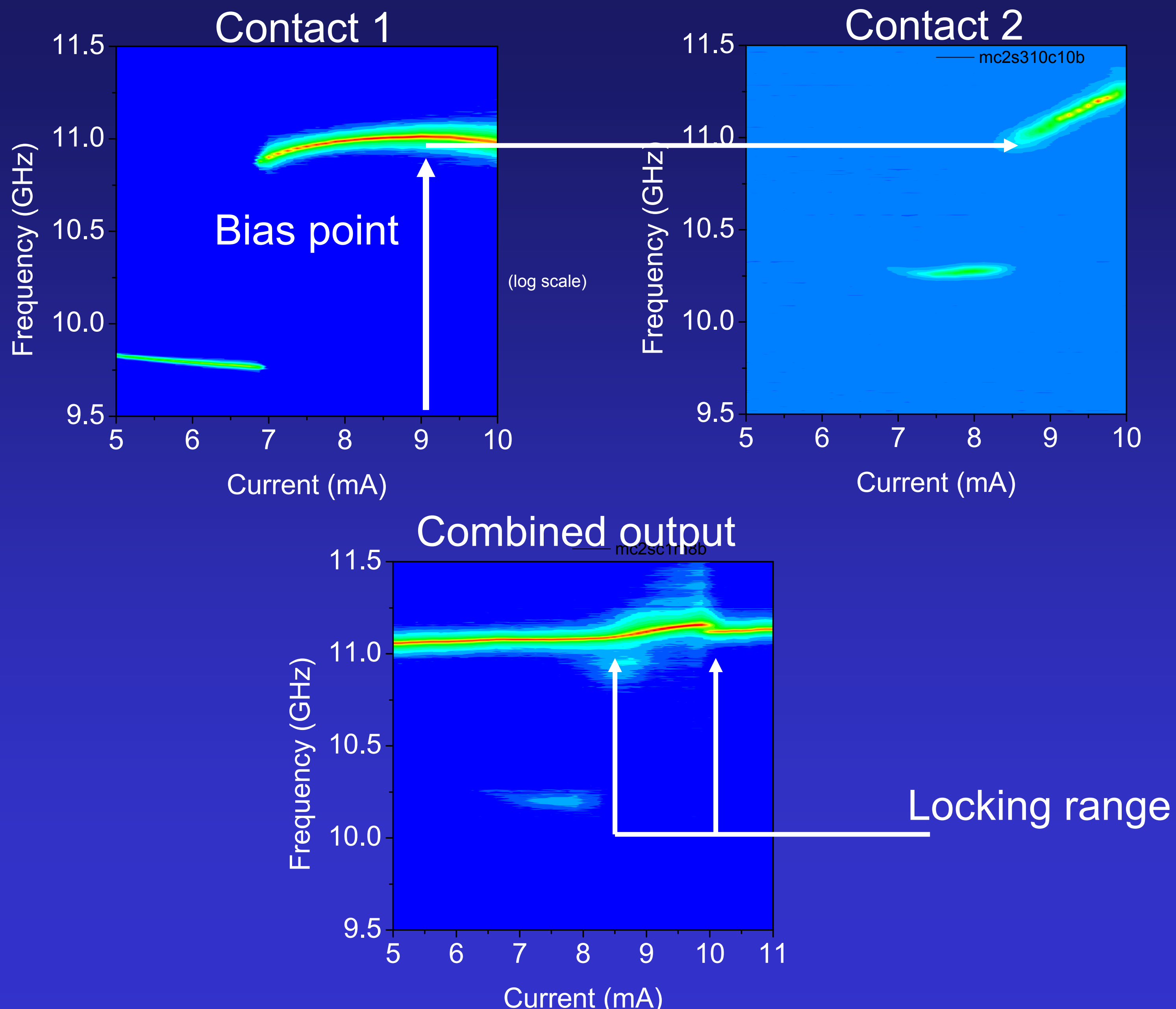
nanocontact



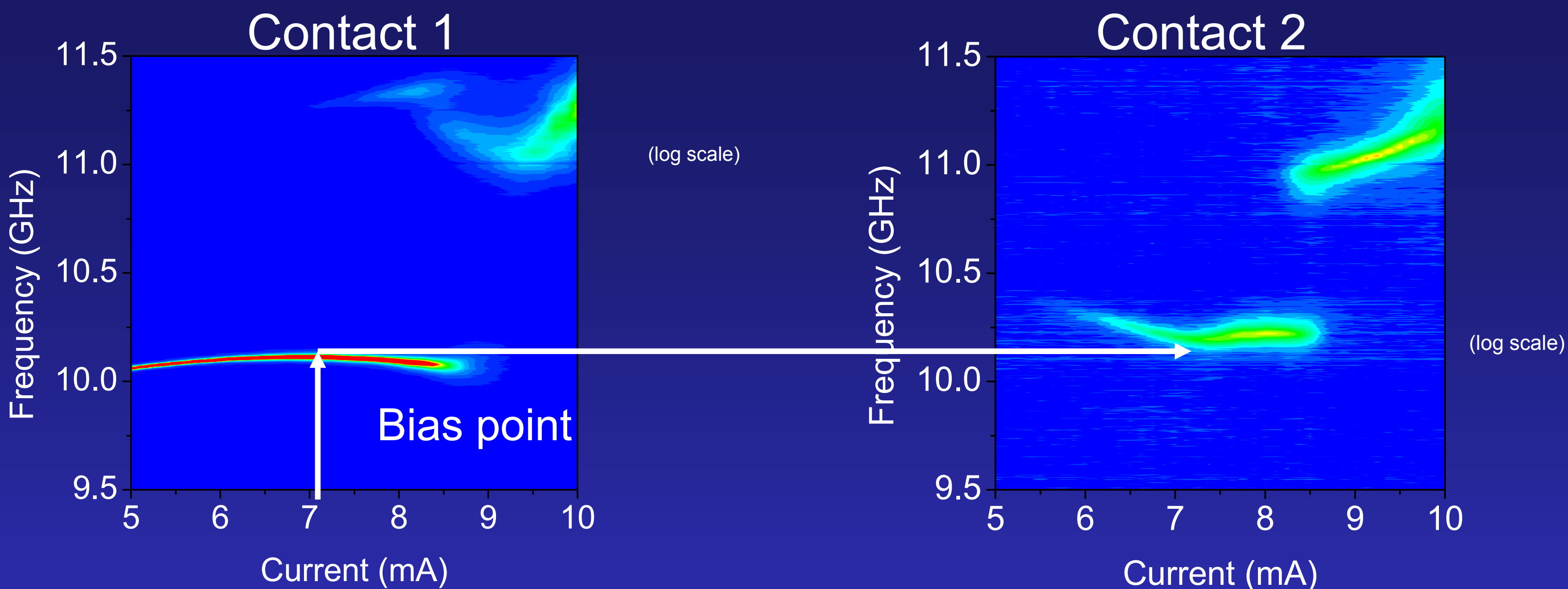
FIB cut

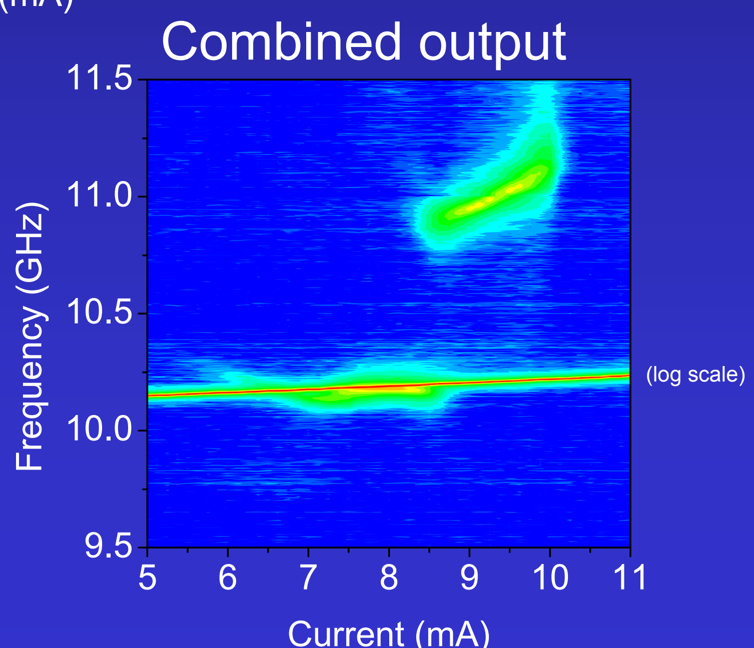
Cut between two contacts:
Look for change in interaction

Phase locking Pre-FIB



Post FIB Loss of Phase Locking





No phase locking

Indicates spinwave radiation responsible for synchronization at large distances

Summary

Observe coherent microwave dynamics resulting from spin
torque effect

Qualitative behavior consistent with Slonczewski equation

Oscillators can be injection locked to:
- Injected AC current
- Applied AC fields
- Proximate devices through spinwave interactions
  - (possibly through dipole fields at very close spacings)

Qualitative behavior consistent with non-linear oscillator analysis

Remaining questions:

What determines locking range:
- How do we *quantify* the strength of the spinwave interaction.

What determines linewidth and phase relation of synchronized devices:
- No clear master/slave relationship.

Quantitative agreement with current/field dependence:
- Not given by Slonczewski equation.

Likely all point to understanding of the mode structure