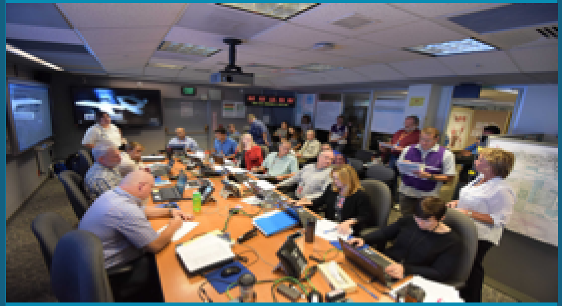
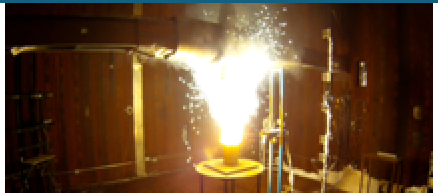
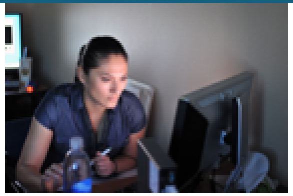
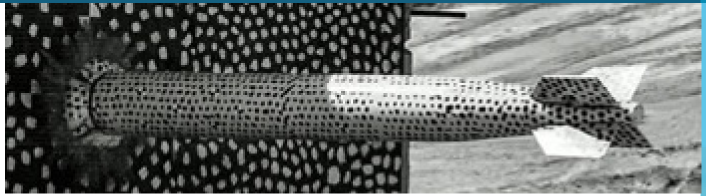
SAND2021-12773C

Tunable Filters and Parametric Amplifiers from NbTiN Transmission Line Resonators









PRESENTED BY

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in collaboration with Will Kindel, Tzu-Ming Lu, Lisa Tracy, and Dwight Luhman

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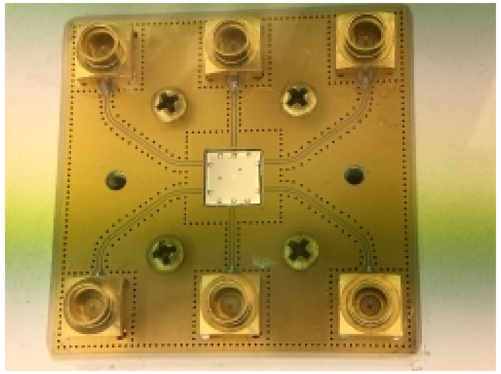
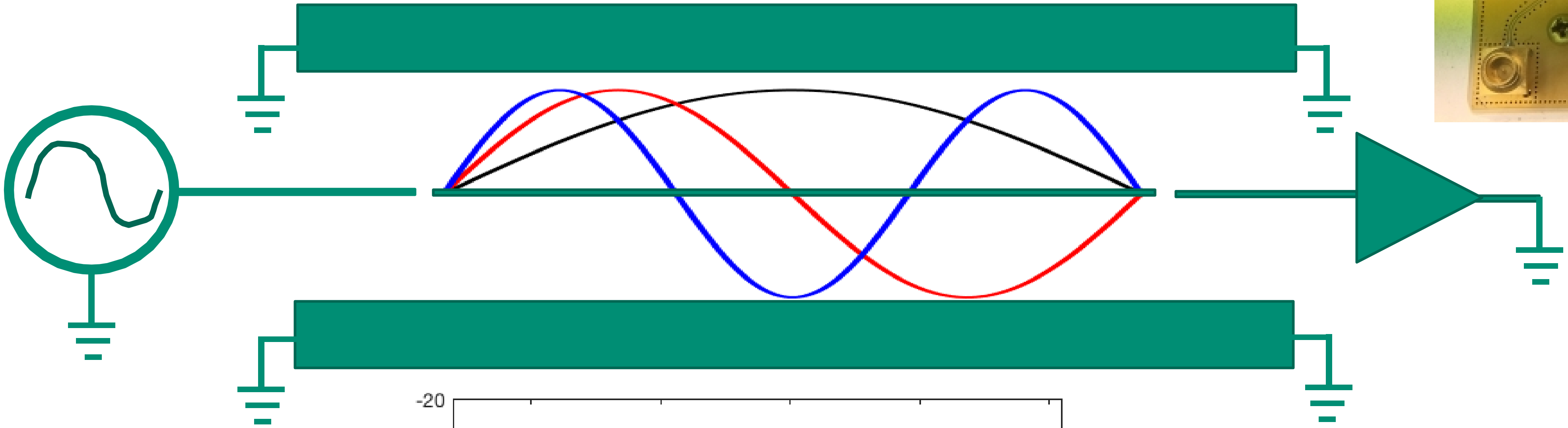
Agenda

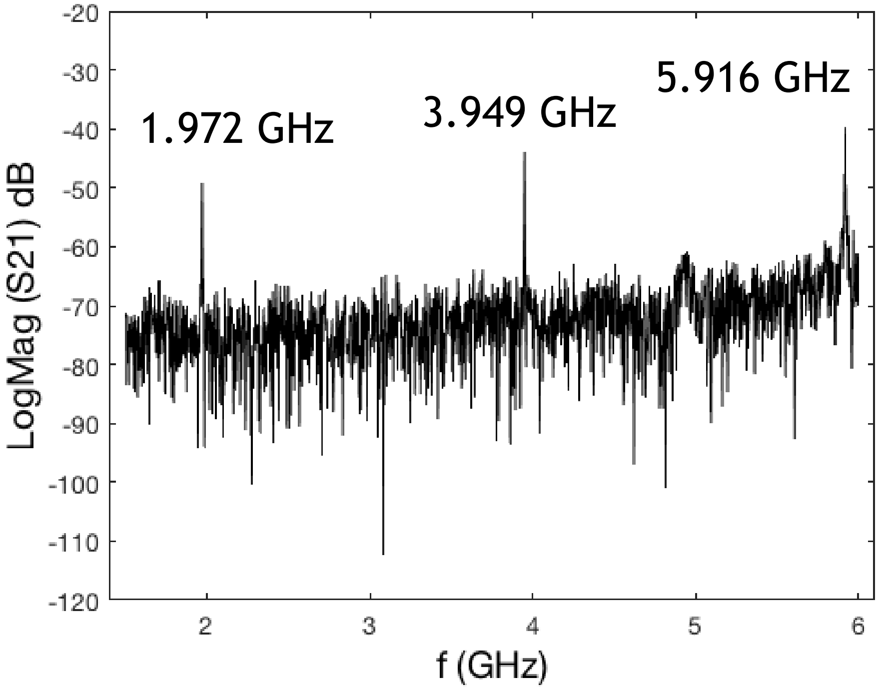
- Mode structure can be used to influence circuit behavior
- Simple non-linear system
- Data
- Conclusions

The “complicated” mode structure of a λ/2 resonator





First 3 modes

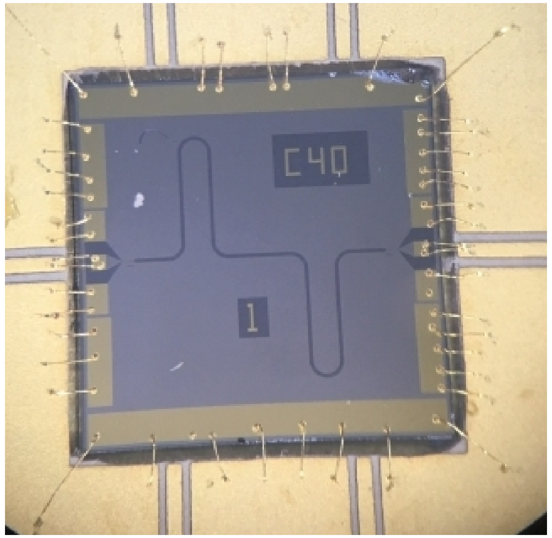


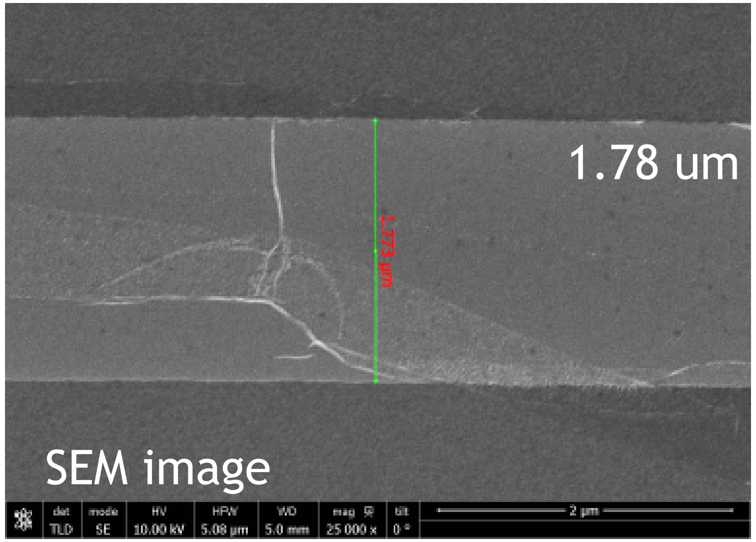
add nonlinearity for interesting physics!

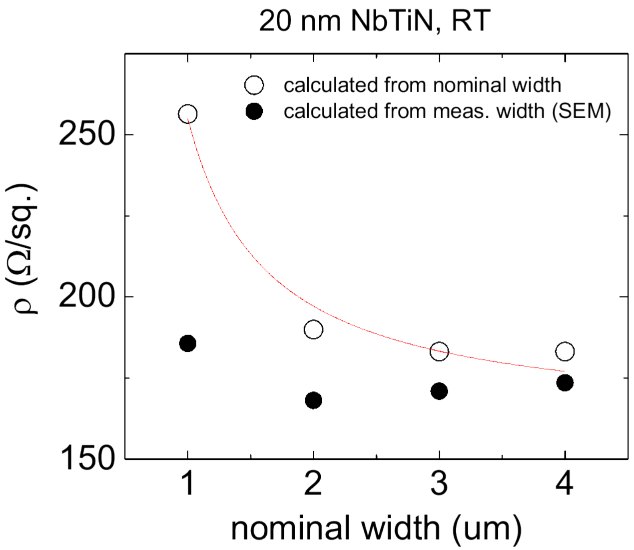
More modes: 7.89 GHz, 9.86, 11.83, …

NbTiN films provide nonlinearity to the resonator

- $\lambda/2$ resonator
- 4 fF input/output caps
- 11.4 mm length
- 2 um line/30 um gaps
- Z = ~330 Ω
- Sputtered NbTiN
- T_c ~ 13 K
- 20 nm thick
- high resistivity ~160 Ω/sq
- high kinetic inductance (α = 0.86)



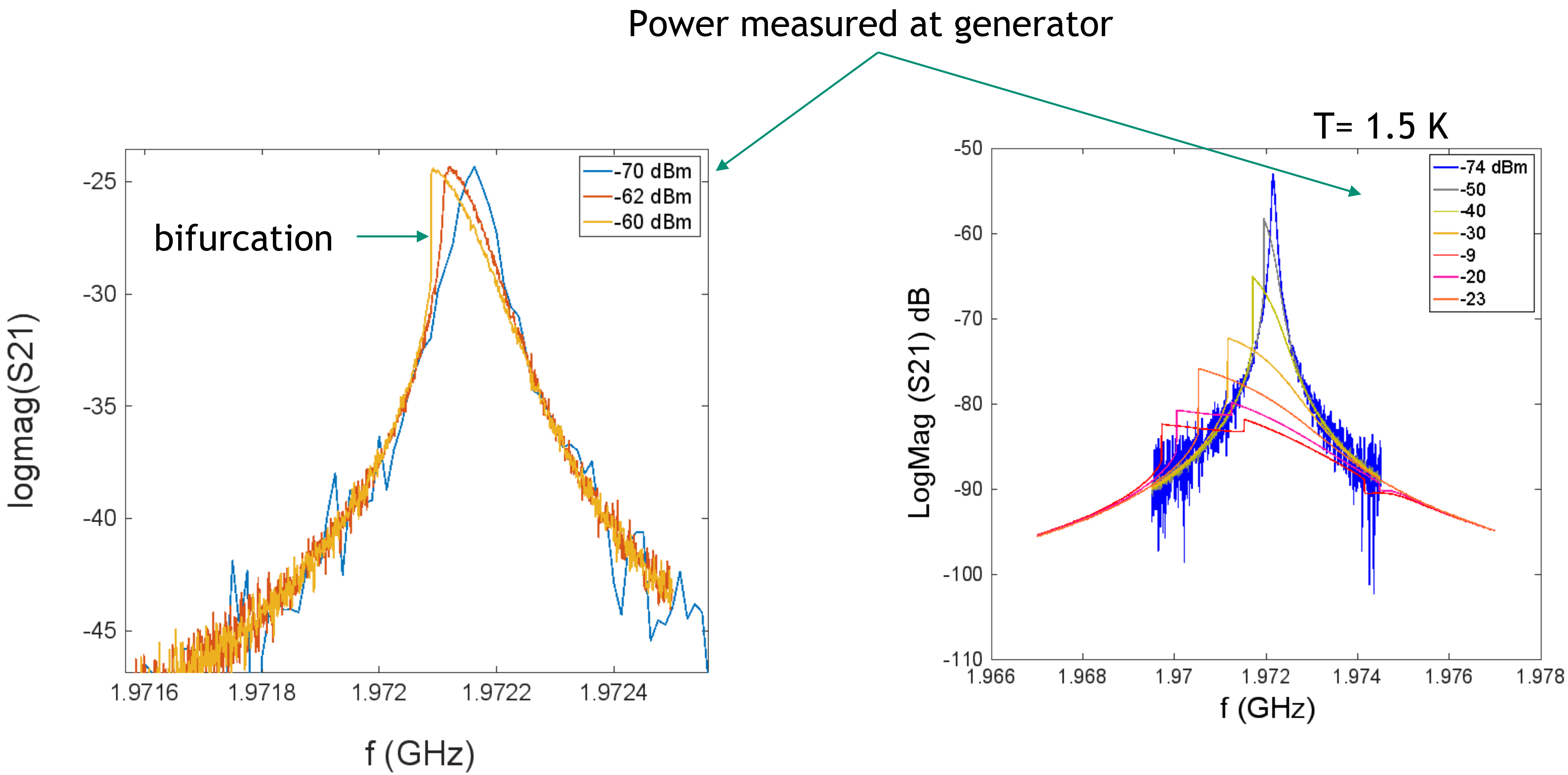




I_c ~1-2 mA @ 4K

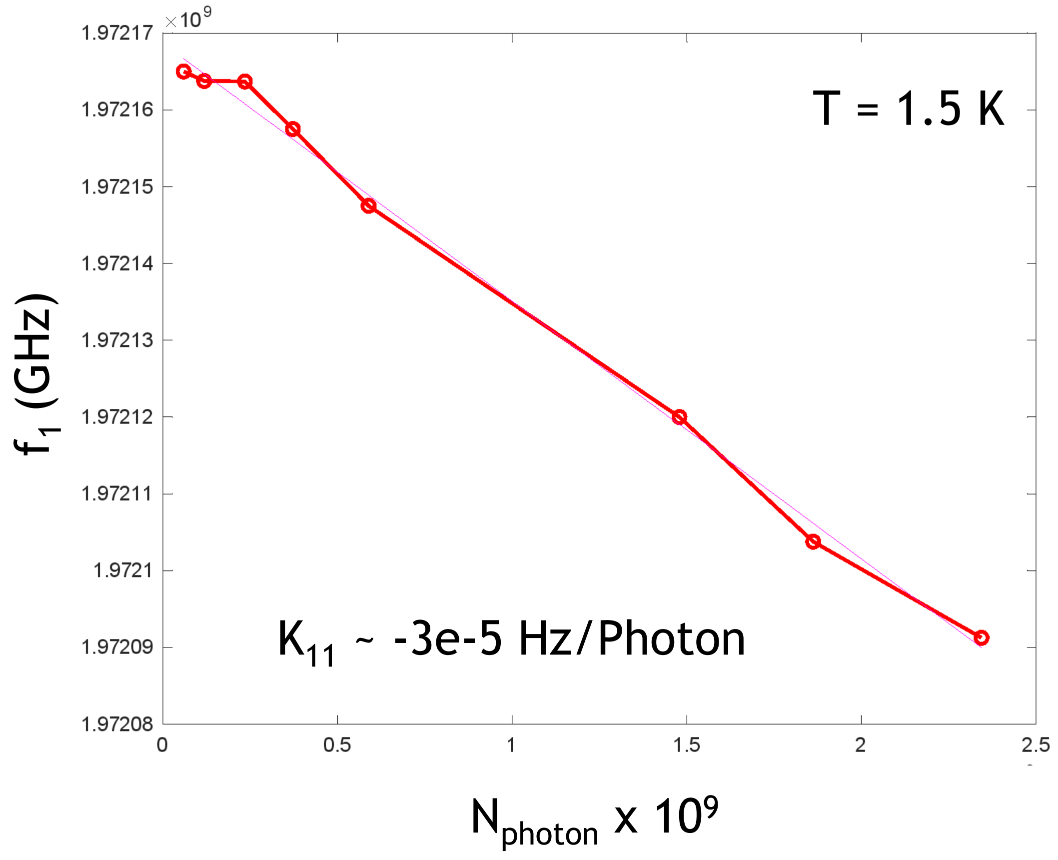
System has distributed nonlinearity

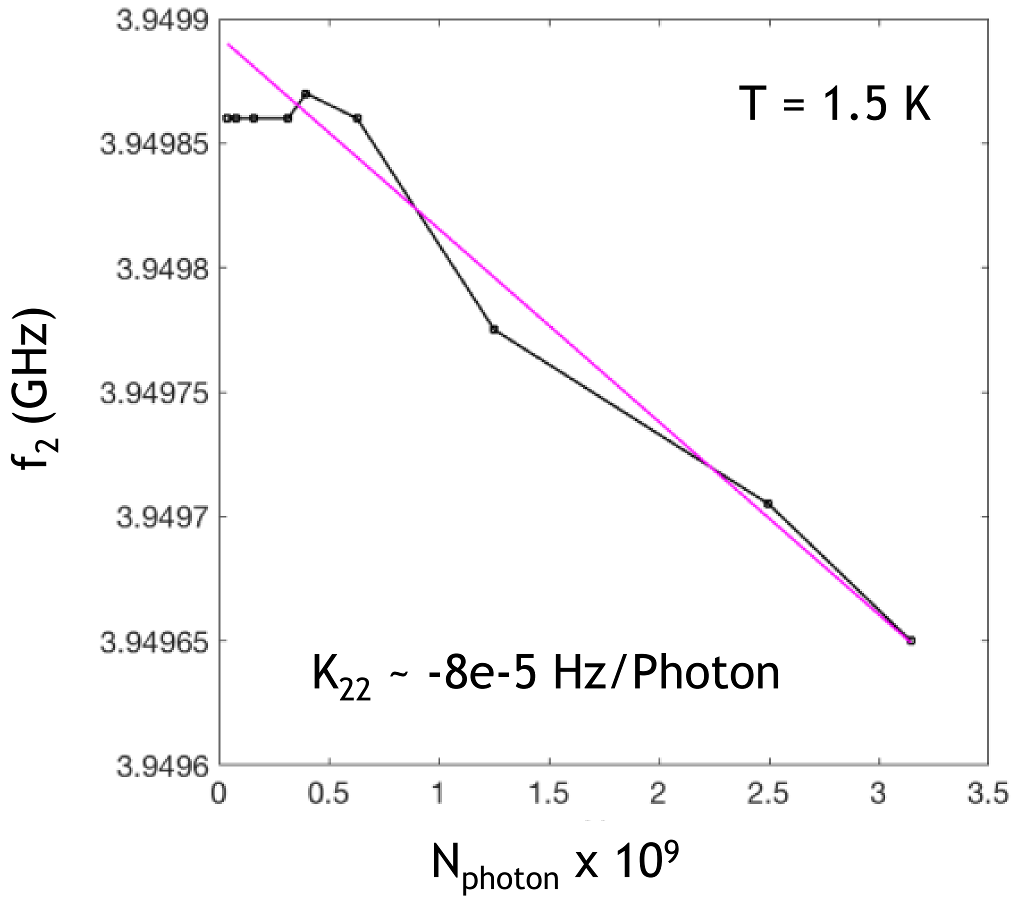
Nonlinearity is evident as measurement power increases



Peaks translate to lower frequency due to increased kinetic inductance (L_k) as power increases

Even at the lowest powers, non-linearity is evident

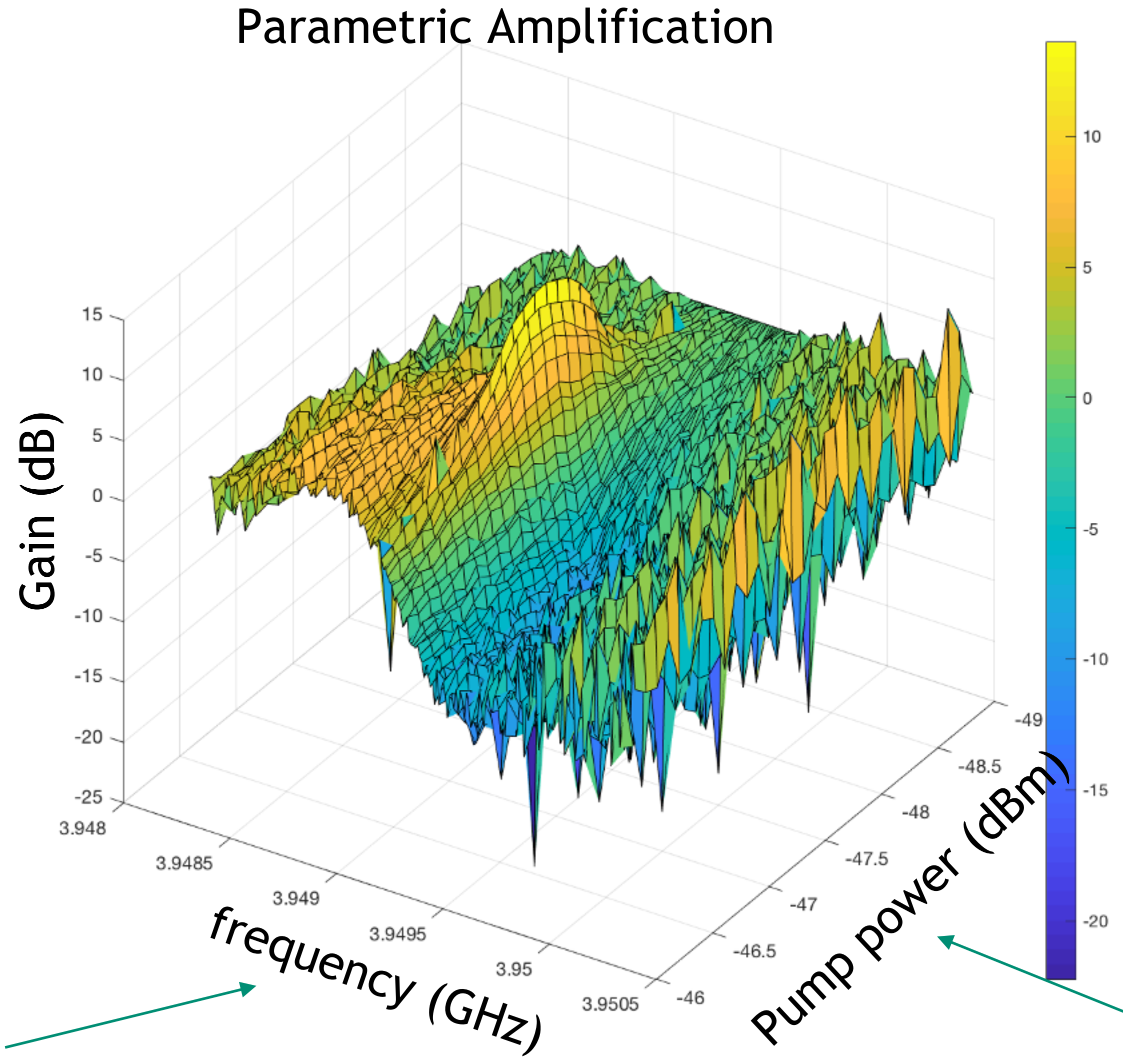




linear frequency shift with photon number—conventional Kerr term

Fun things you can do with non-linear resonators

Normalized by S21 at low power



2[nd] Harmonic

Power at generator

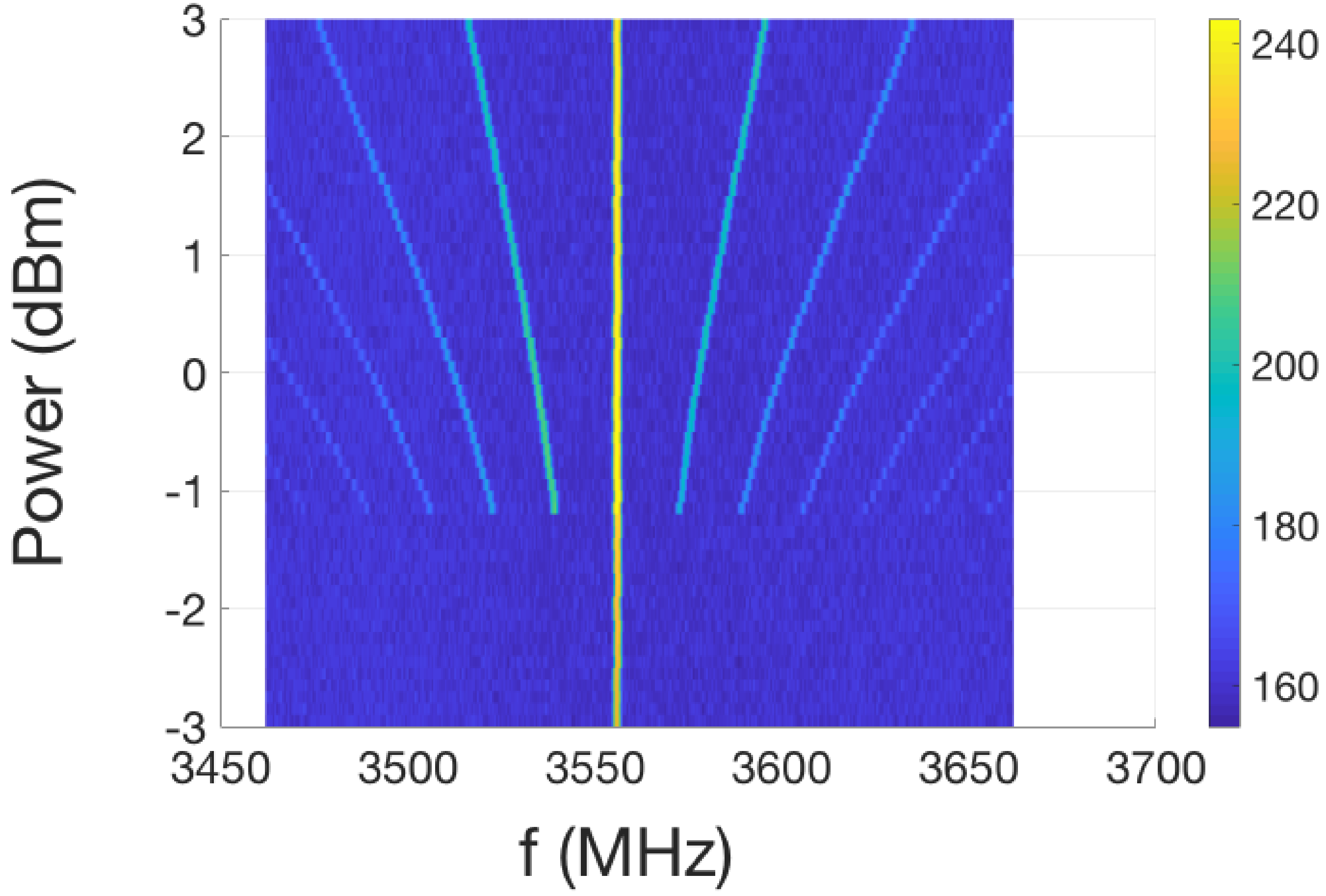
fixed @ $\omega_r - \delta$

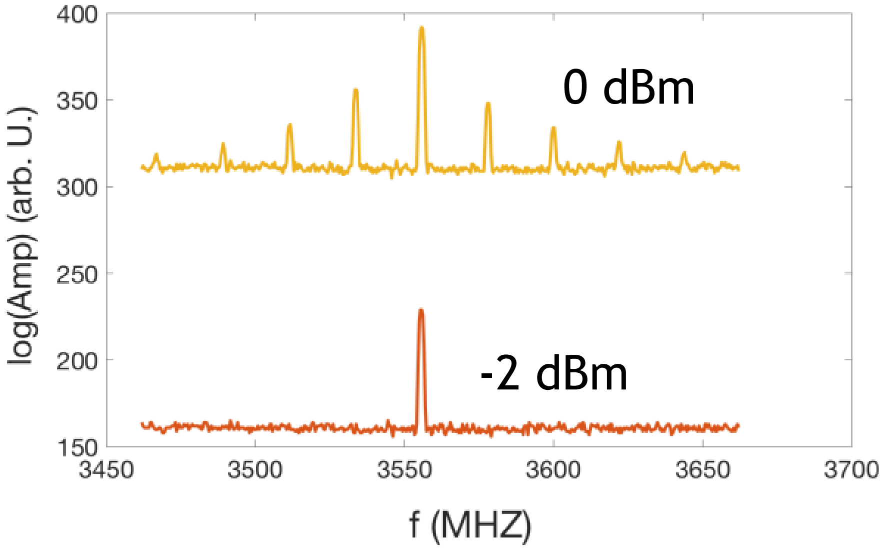
NWA scans ω_r

Frequency comb in driven SC oscillators

(similar to results by Erickson et al. PRL 113, 187002 (2014).

data taken using a 3 um signal line



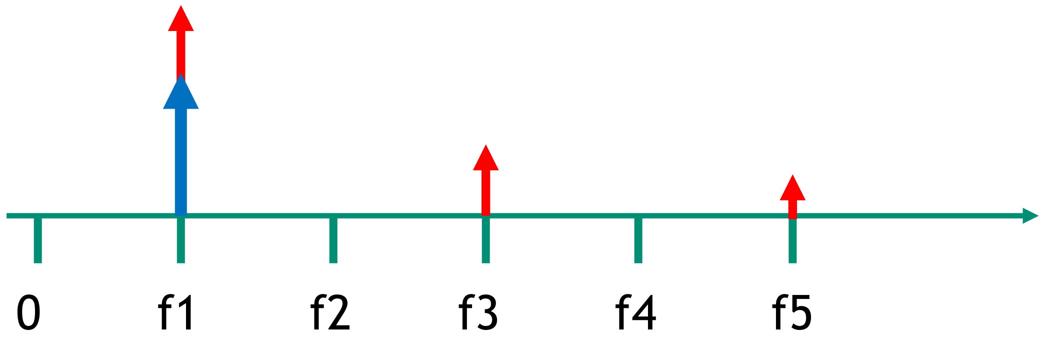


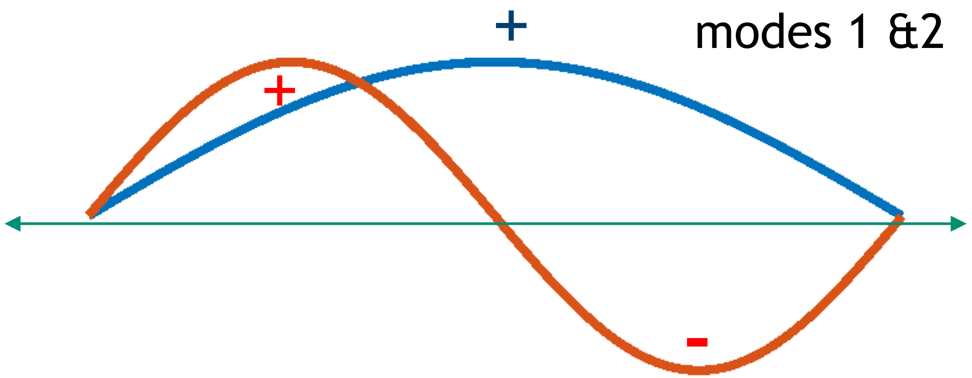
seen in multiple samples

Above a critical driving power, a single input tone produces a frequency comb—tunable with frequency and power!

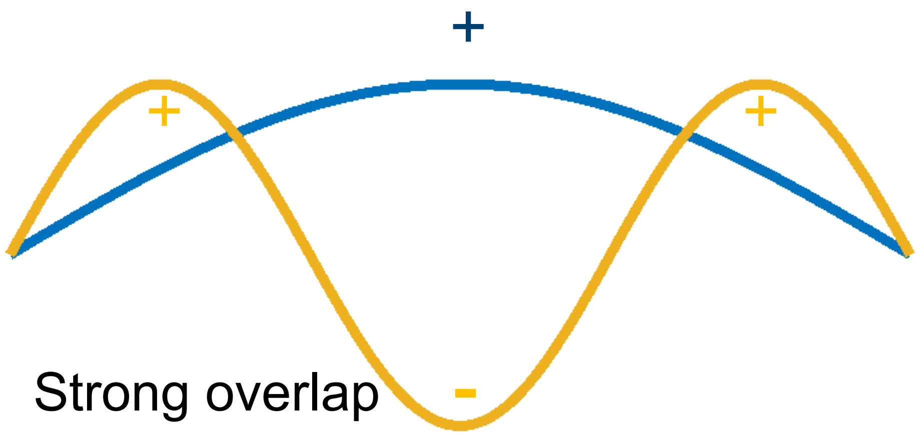
Details on frequency mixing

below P_c: Only f1
above P_c : f1, f3, & f5





Weak overlap, contributions cancel.
→Coupling suppressed by symmetry!



Strong overlap
→Coupling enhanced by symmetry!

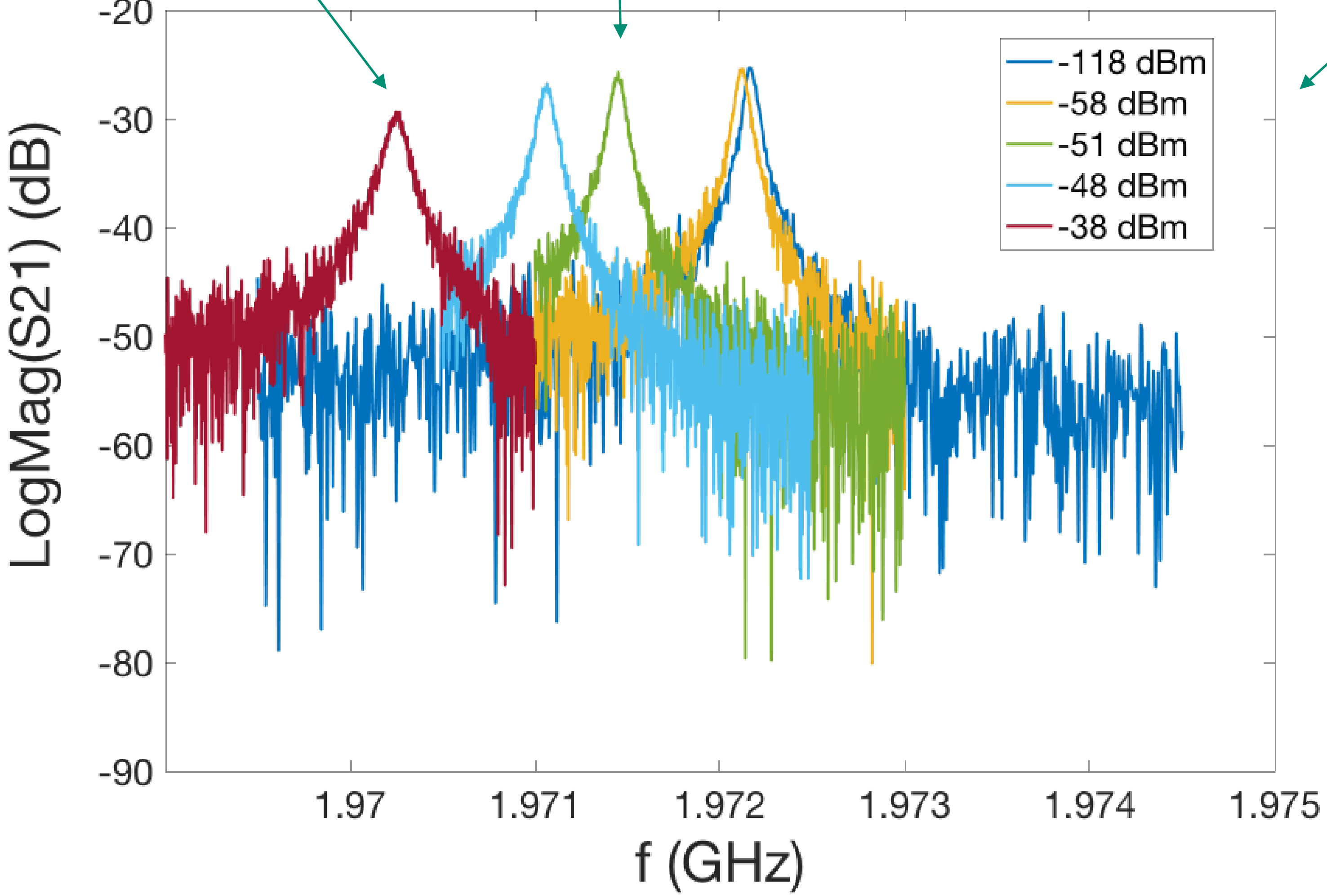
P_c = bifurcation power

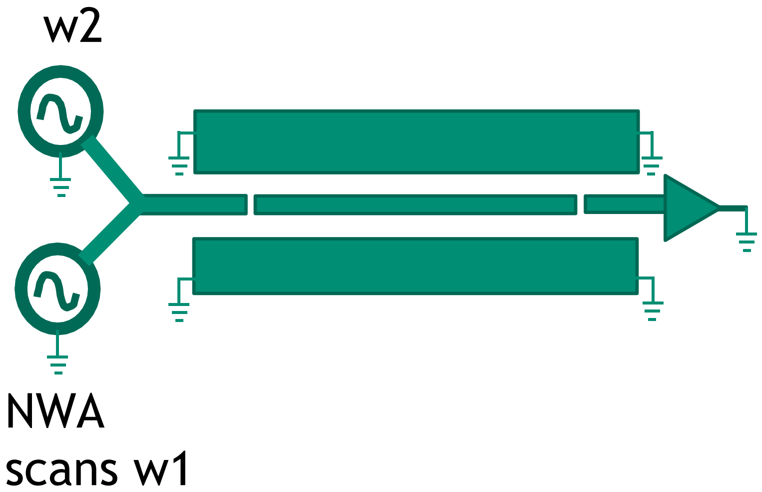
Shifting f_1 by applying power to f_2

Lineshape remains Lorentzian!

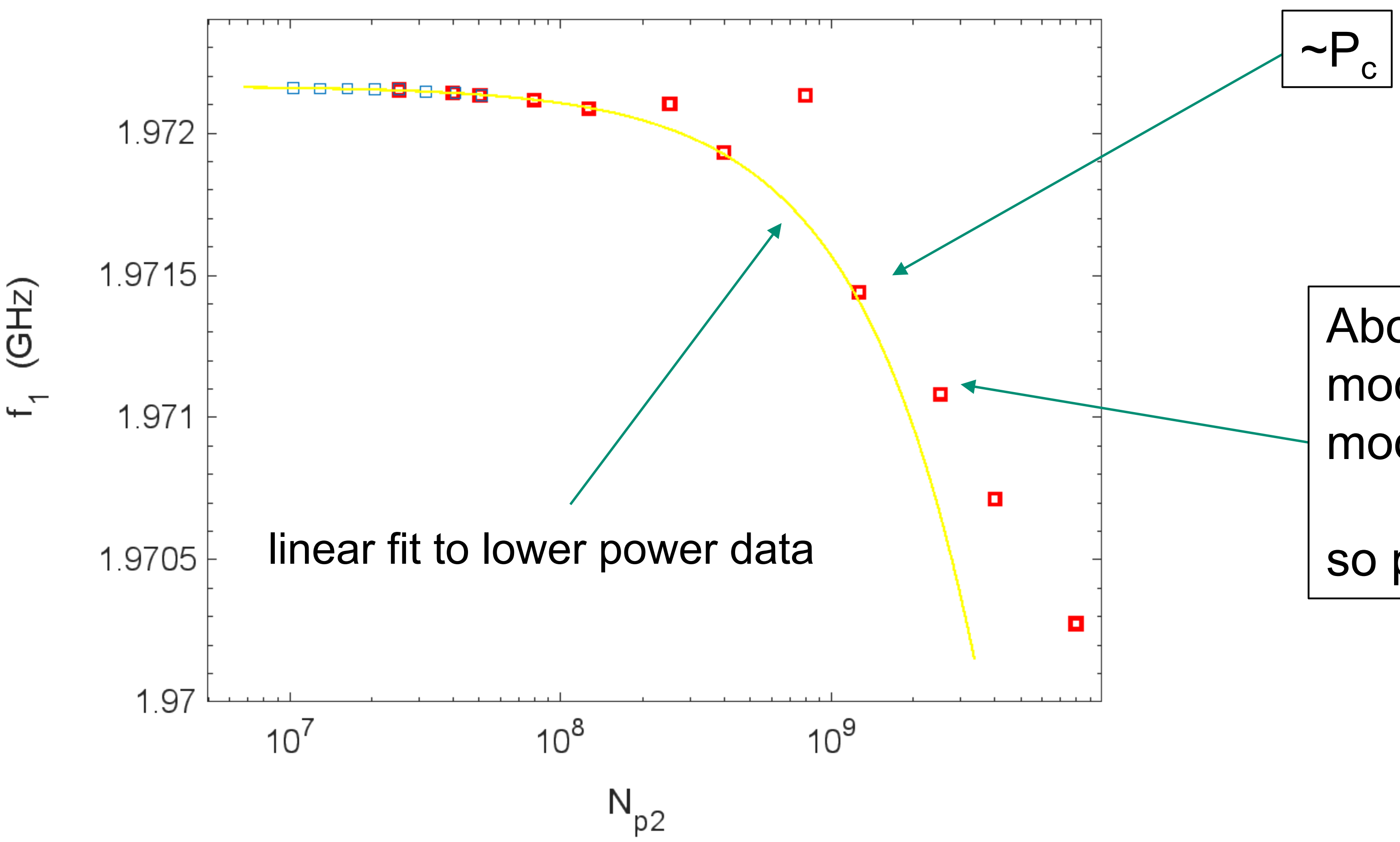
P_c for f_2

Power applied on resonance to f_2





“Cross” Kerr effect



Above P_c photons from mode 2 leak to higher modes (6, 10, …)

so points leave the line

Power in mode 2 is influencing the frequency of mode 1

Theoretical understanding…

starting with the resonant condition:
Ignore caps

$$\pi = \int_0^l k\, dx = \int_0^l dx\, 2\pi f / v_p$$

$$v_p = \frac{1}{\sqrt{L_0 C_0}}$$

$L_0 = L_g + L_k\{1+(I/I^*)^2\}$

$$\pi \approx 2\pi f \int_0^l dx \sqrt{C_0 \left(L_g + L_{k0}\right)} \left\{1 + \frac{L_k}{2\left(L_g + L_k\right)} \left(\frac{I}{I*}\right)^2\right\}$$

$$f = \frac{v_{p0}}{2l} \frac{1}{\left[1 + \alpha\left({}^{I}/_{I_*}\right)^2\right]}$$

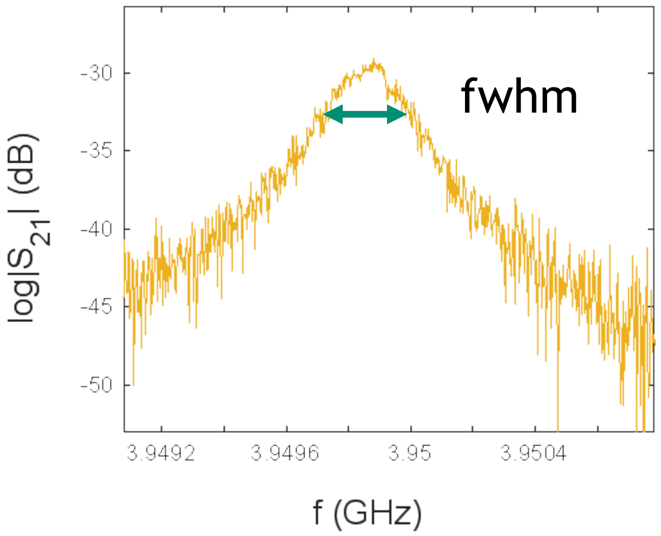
or

$$\delta f \approx -f_{np}\alpha \frac{\widehat{n_2}}{\hat{n}_{2*}}$$

If I_* ~ 1 mA

Gives correct order of magnitude

Fast turn on/off



δf_2 = 187 kHz

- Resonant response ~ 1/δf (fwhm)
- δf gets larger at higher modes
- 2nd mode δf = 56 kHz The 8th mode δf ~ 10 MHz. So switch on/off in ~100 ns.

Can use higher even mode to switch on/off fast at the cost of higher power

Take Aways

- Multi-mode systems + nonlinearity = interesting physics
- Engineering mode structure enables useful function
- Some modes couple. Some just influence each other
- Tunable filter is a simple example

the end.