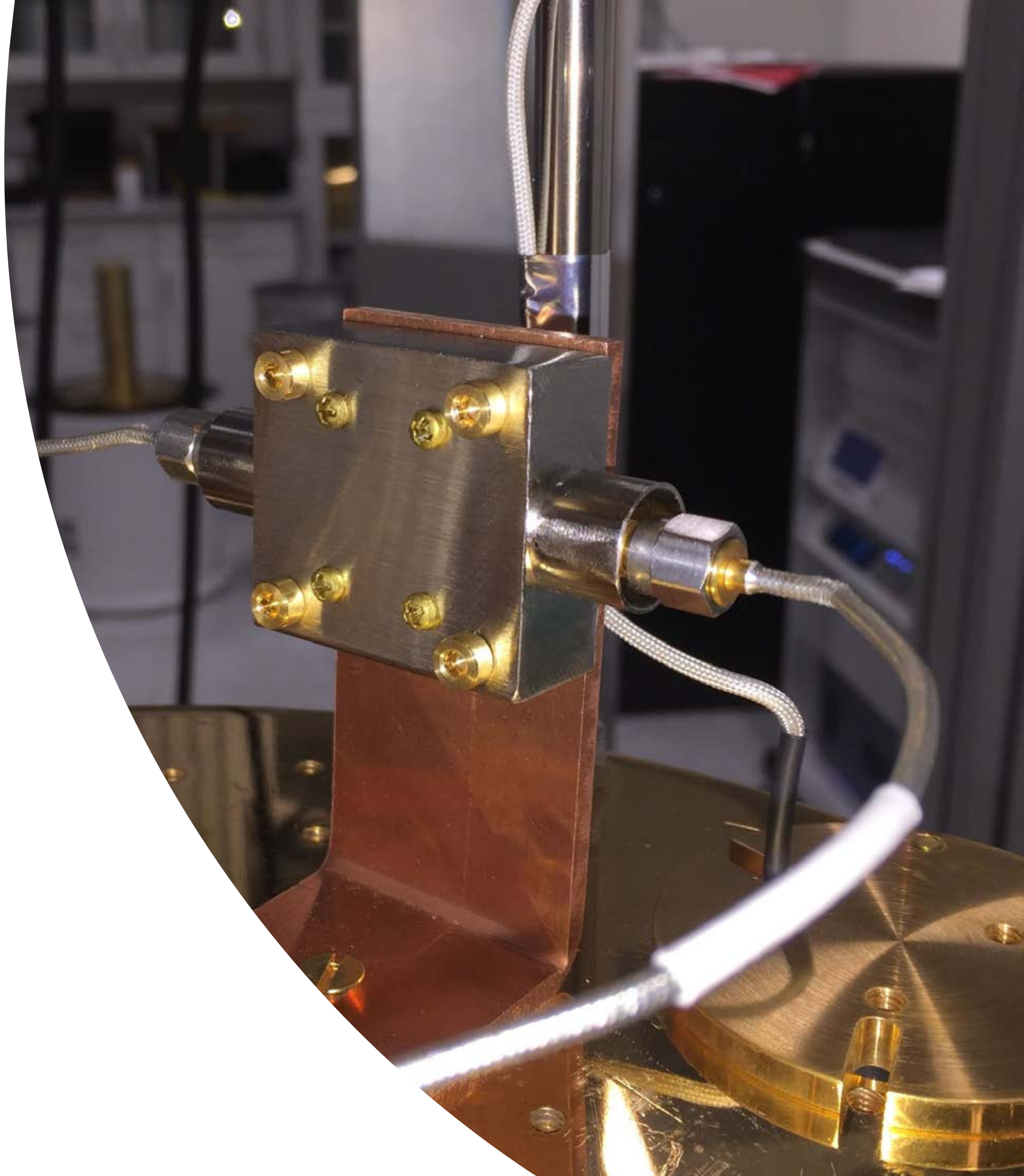
Summer Research Summary

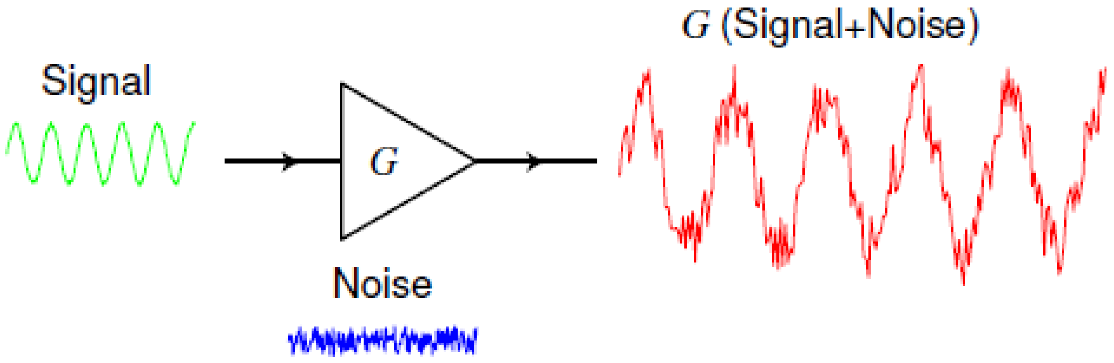
10/17/2019

Yuxiang Pei

- Characterization of TWPA
- Enhancing sensitivity of EPR
- Setting up of HEMT



Motivation



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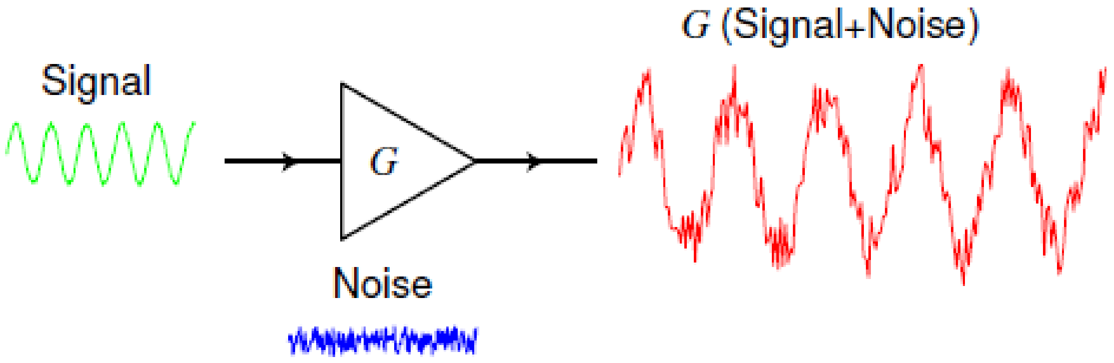
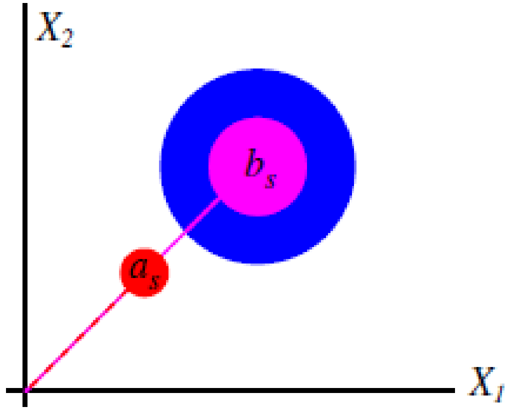
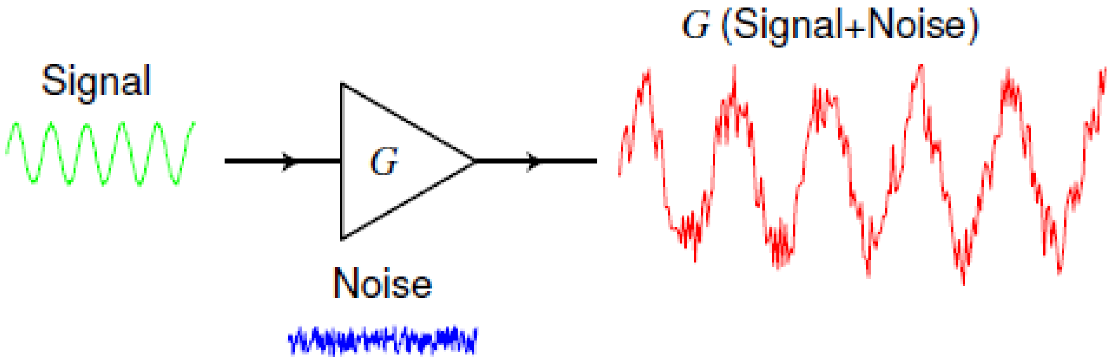


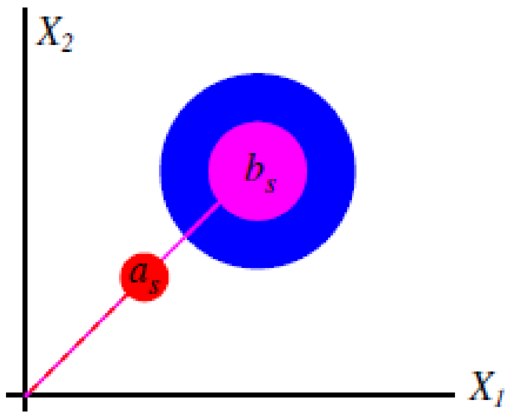


Quantum limit of amplification:

minimum amount of added noise to quadratures

Motivation





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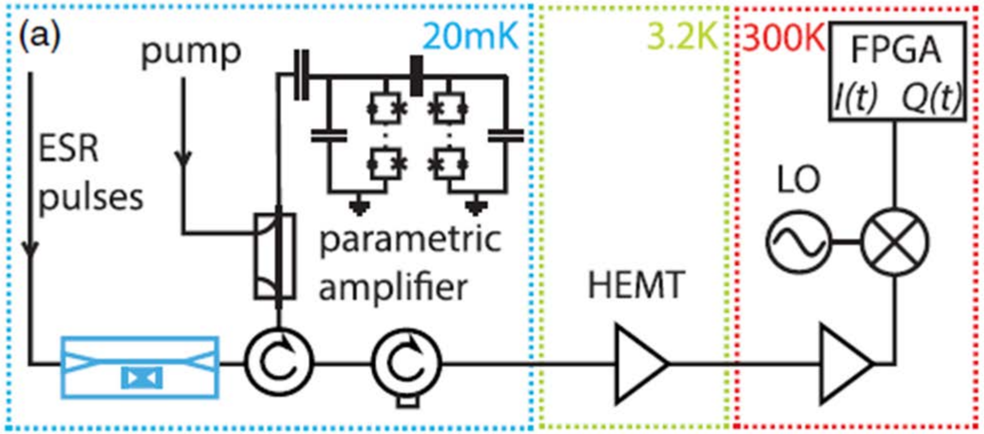
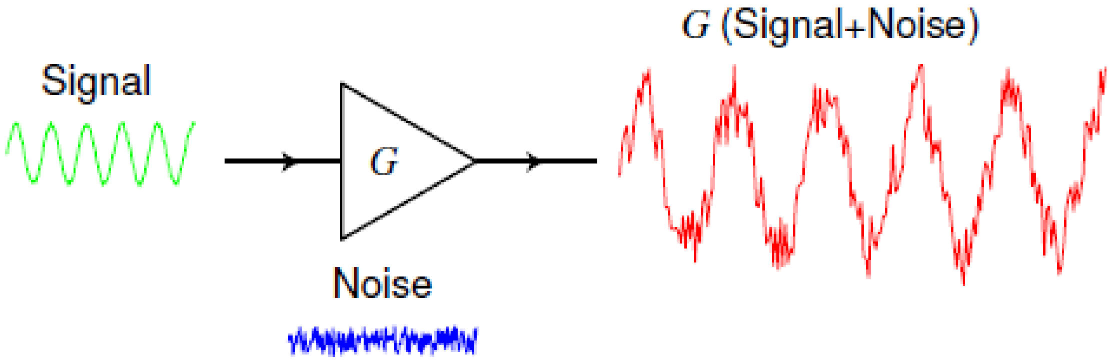
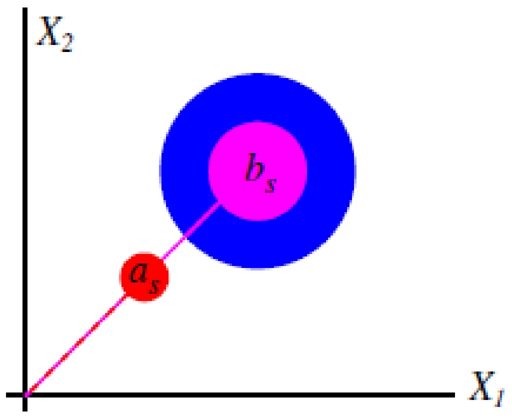


Sensitive measurements

Motivation





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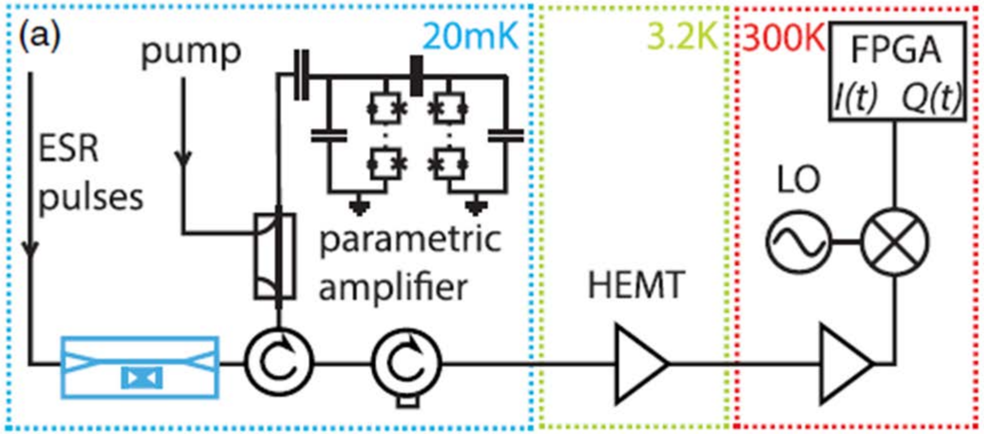
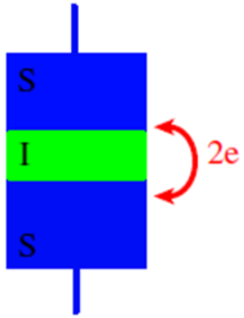
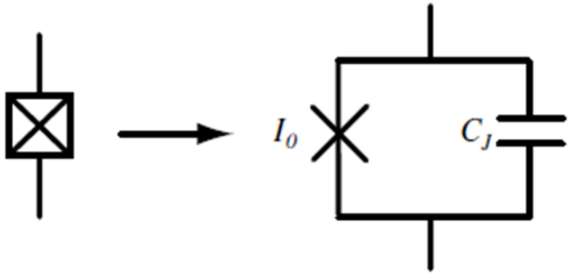


Sensitive measurements

Traditional JPA:
single frequency measurements
low bandwidth and saturation power

Non-linear nature of Josephson junctions





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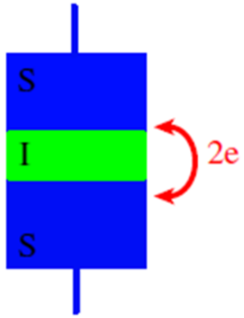
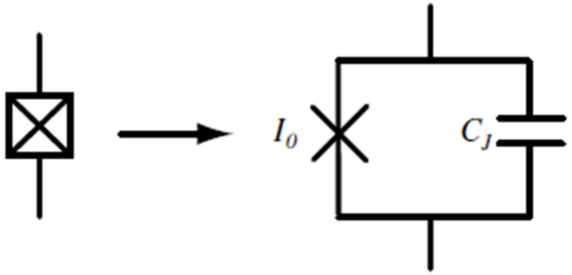
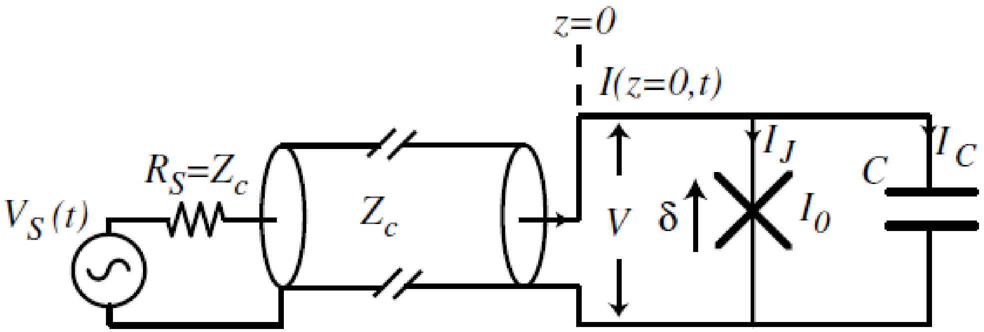
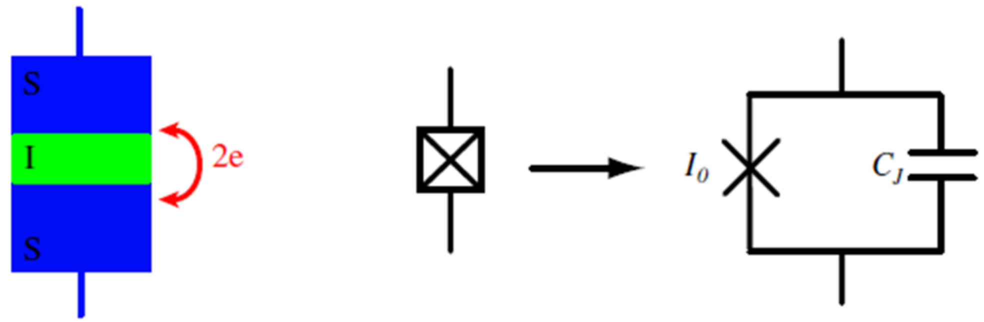


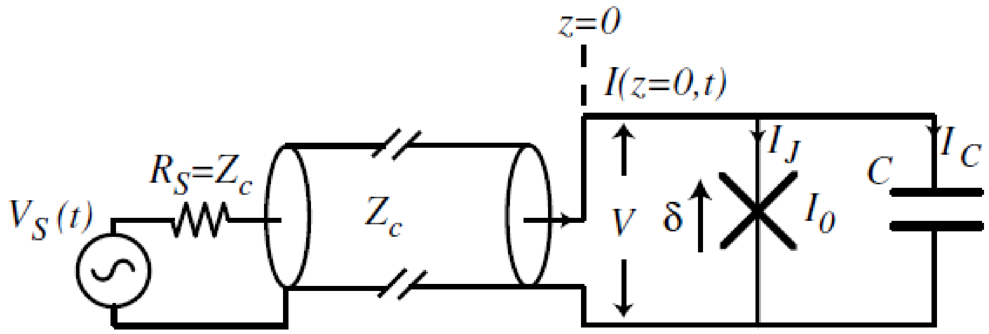




$$C\varphi_0\frac{d^2\delta(t)}{dt^2}+\frac{\varphi_0}{Z_c}\frac{d\delta(t)}{dt}+I_0\sin(\delta(t))=I_S(t)$$

Non-linear nature of Josephson junctions





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$$\frac{d^2\delta(t)}{dt^2} + 2\gamma \frac{d\delta(t)}{dt} + \omega_0^2 \left(\delta(t) - \frac{\delta^3(t)}{6}\right) - \omega_0^2 \frac{I_p}{I_0}\cos(\omega_p t) = \frac{2}{C\varphi_0 Z_c} v_s^{in}(t)$$

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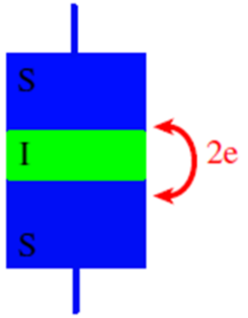

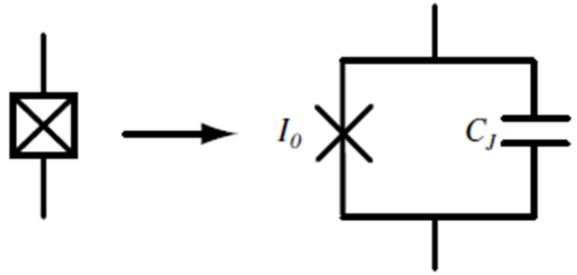

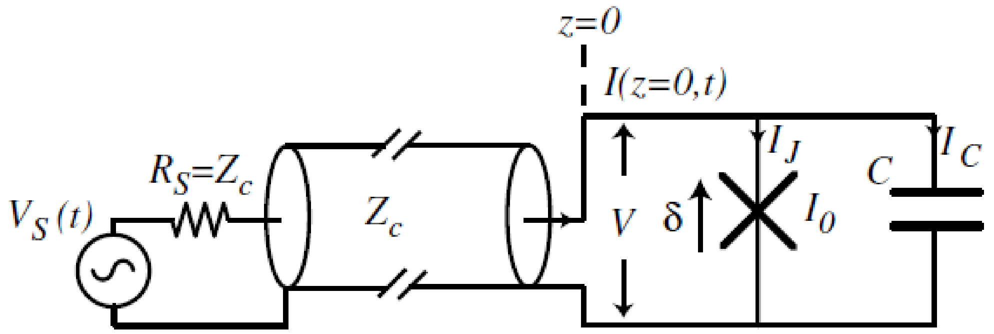

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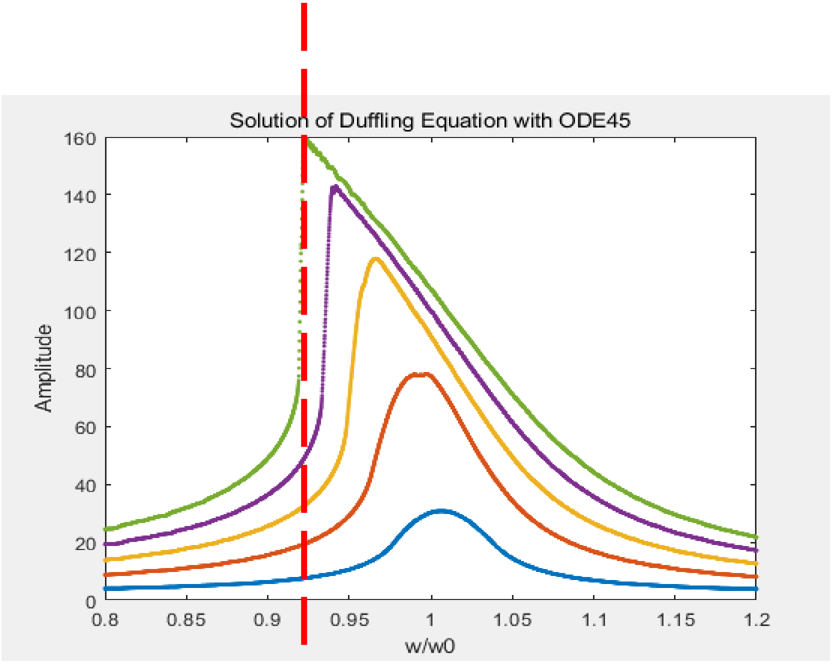
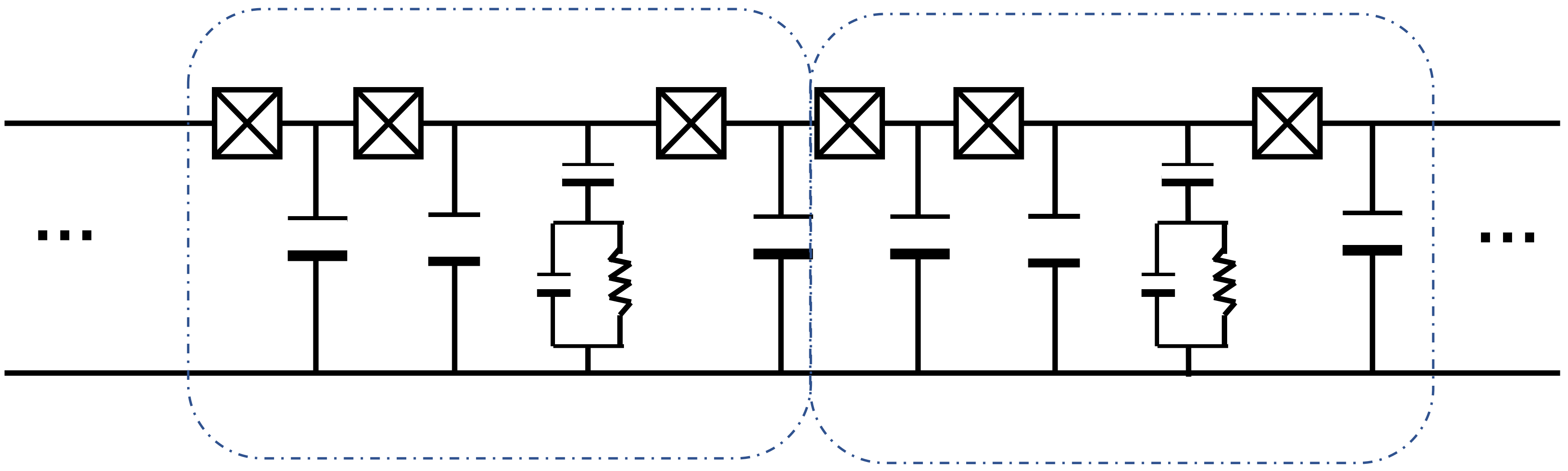


Resonant phase matching



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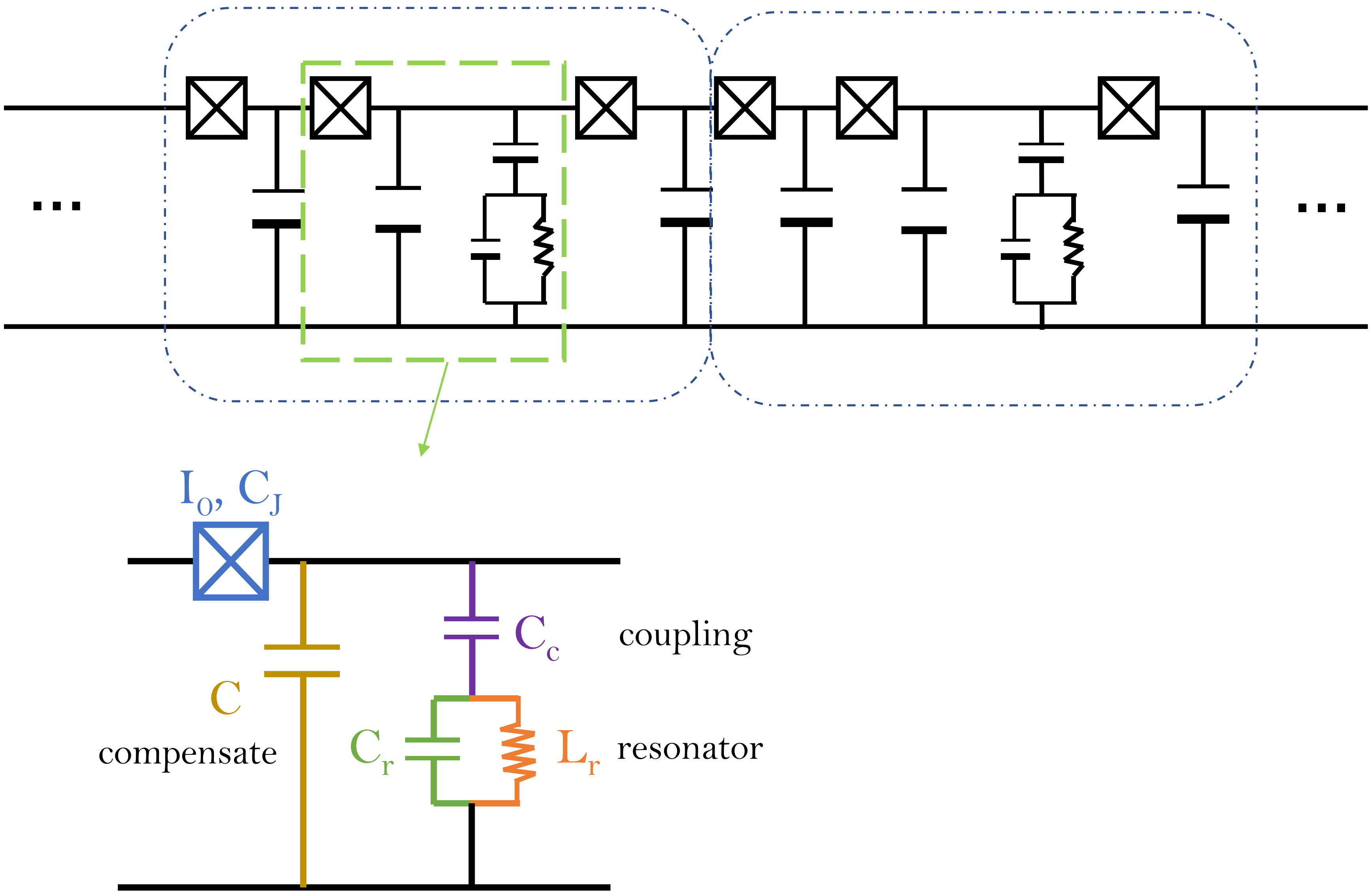

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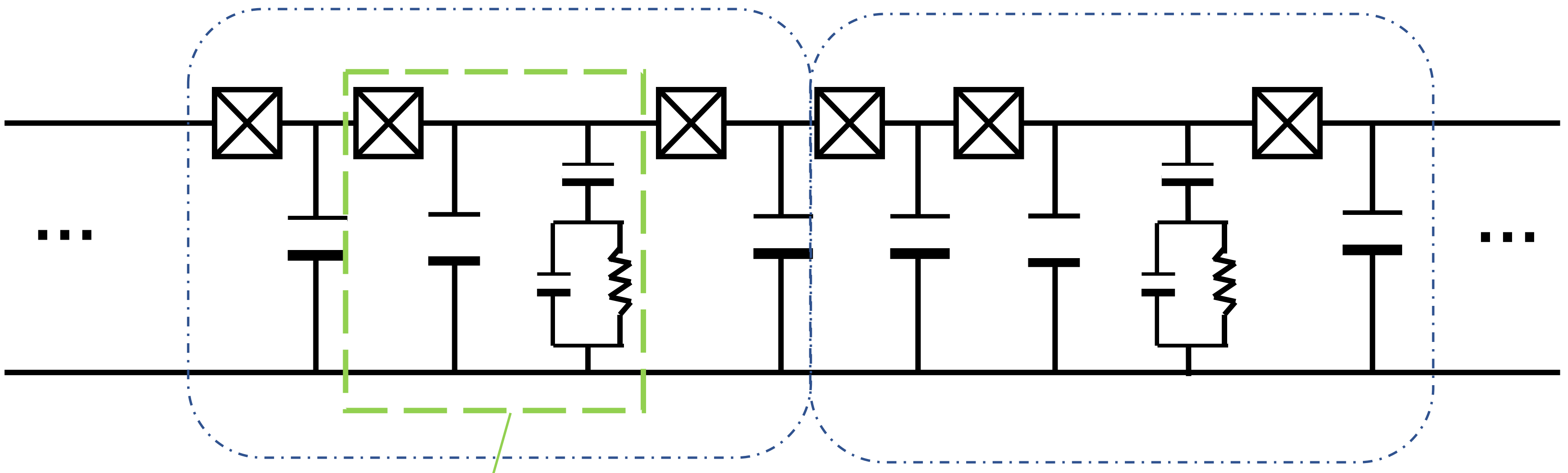
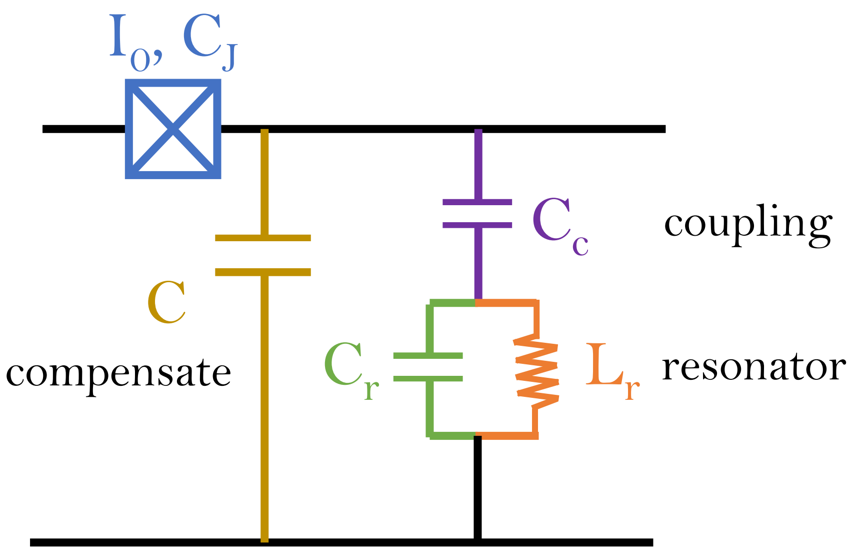
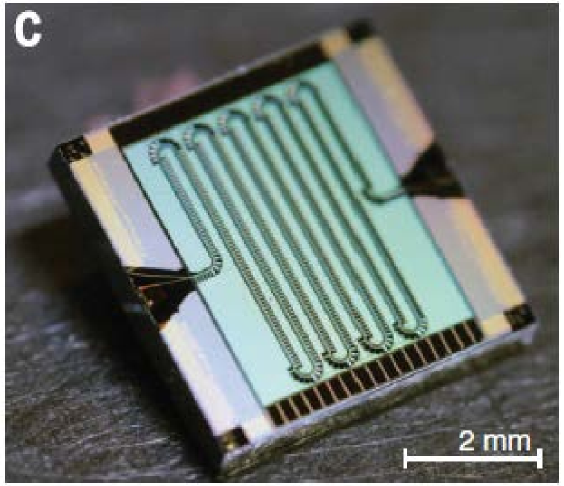




a 2037 junction JTWPA



A near–quantum-limited Josephson traveling-wave parametric amplifier C. Macklin et al.

Resonant phase matching

$$\frac{\partial a_s}{\partial x} - i\kappa_s a_i^* e^{i(\Delta k_L + 2\alpha_p - \alpha_s - \alpha_i)x} = 0$$

$$\frac{\partial a_i}{\partial x} - i\kappa_i a_s^* e^{i(\Delta k_L + 2\alpha_p - \alpha_s - \alpha_i)x} = 0,$$

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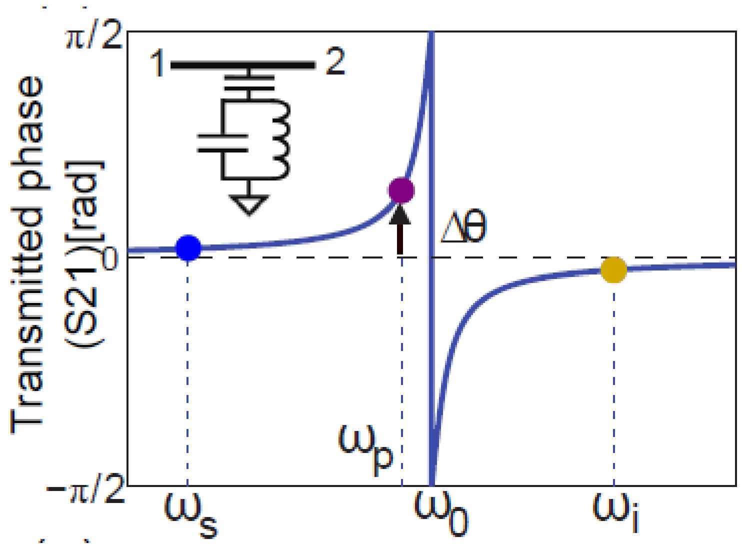

Phase shift due to a shunt resonator to ground

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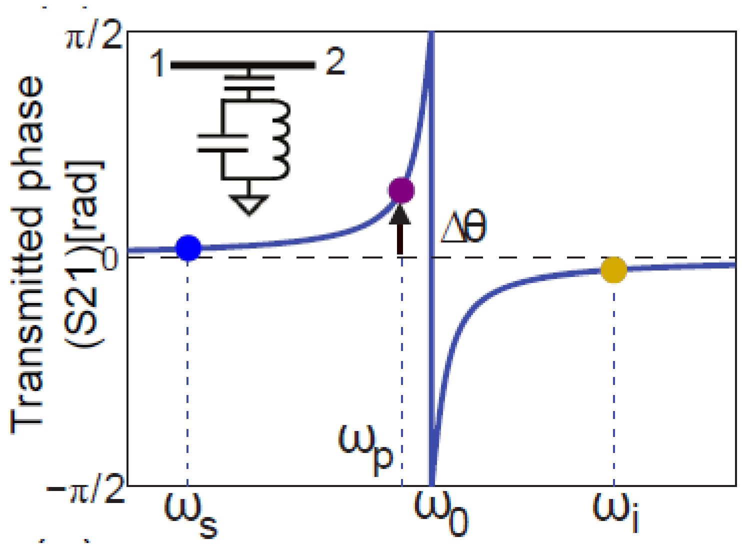

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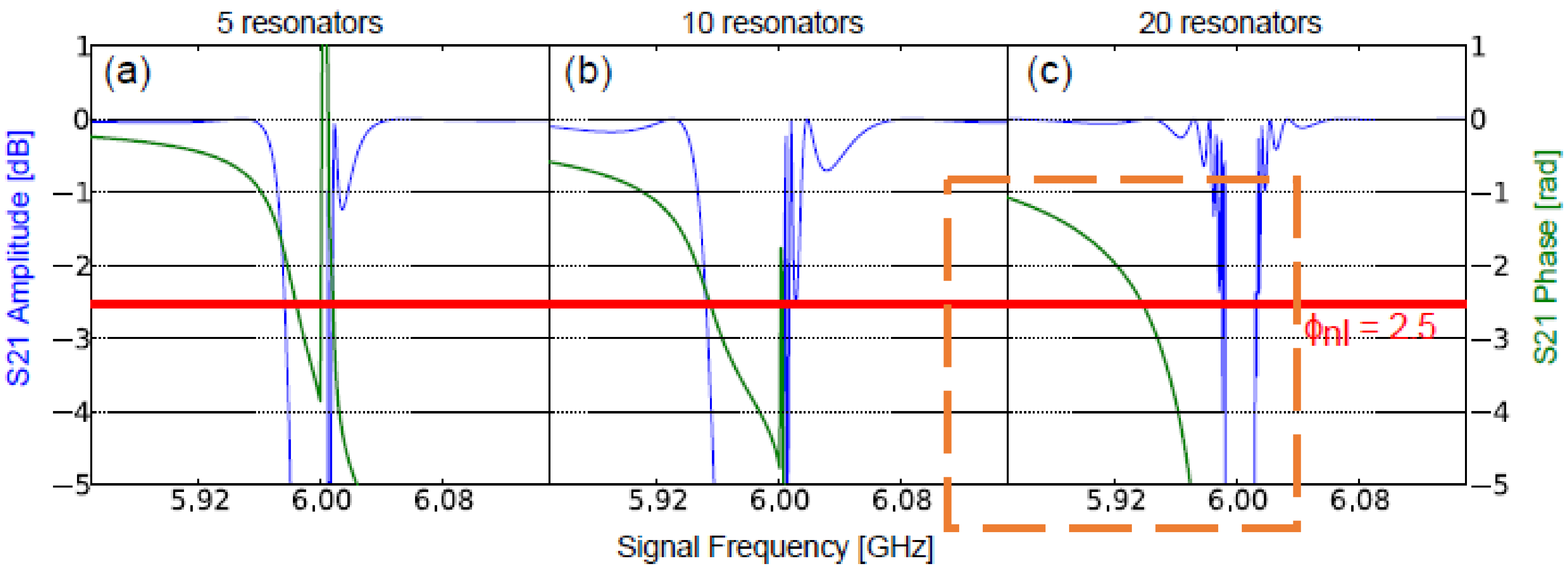

simulated signal phase and A vs f for different numbers of resonators

Traveling wave parametric amplifier with Josephson junctions using minimal resonator phase matching T.C. White et al.

TWPA gain

TWPA gain

$$G_s = \cosh^2(gz) + \left(\frac{\kappa}{2g}\right)^2 \sinh^2(gz)$$

$$g = \sqrt{\frac{k_s k_i}{k_p^2}(\gamma k_p)^2 - (\kappa/2)^2}$$

$$\kappa = 2\gamma k_p + k_s + k_i - 2k_p$$

z: the length along the transmission line
γ: nonlinearity, the ratio of drive current to junction critical current
κ: effective dispersion
Δk: difference in wave vectors, phase mismatch

TWPA gain

- linear superconducting transmission line

$$G_s = 1 + (\gamma k_p z)^2 = 1 + \phi_{nl}^2$$

nonlinear phase shift of the pump

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TWPA gain

- linear superconducting transmission line

$$G_s = 1 + (\gamma k_p z)^2 = 1 + \phi_{nl}^2$$

nonlinear phase shift of the pump

- Proper phase matching (κ=0)

$$G_s = \cosh^2(\gamma k_p z) \approx \frac{\exp(2\phi_{nl})}{4}$$

$$G_s = \cosh^2(gz) + \left(\frac{\kappa}{2g}\right)^2 \sinh^2(gz)$$

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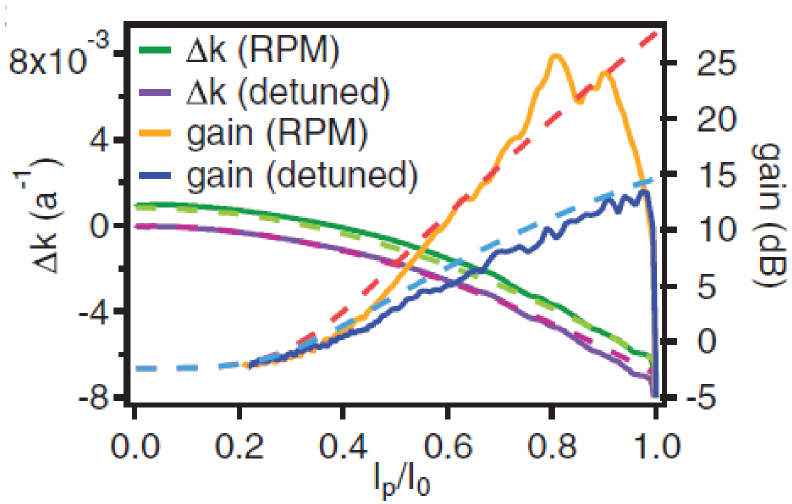
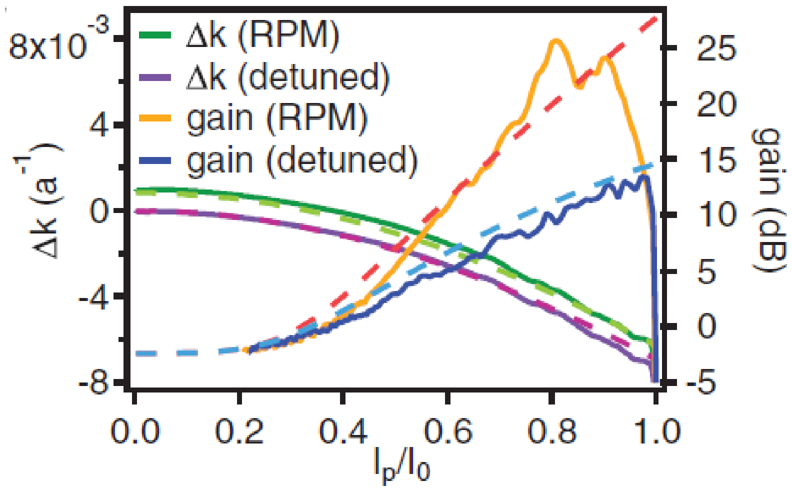


Phase mismatch and gain.
7.157 GHz and 6.5 GHz versus pump power, with a signal at 6.584 GHz.

A near–quantum-limited Josephson traveling-wave parametric amplifier C. Macklin et al.



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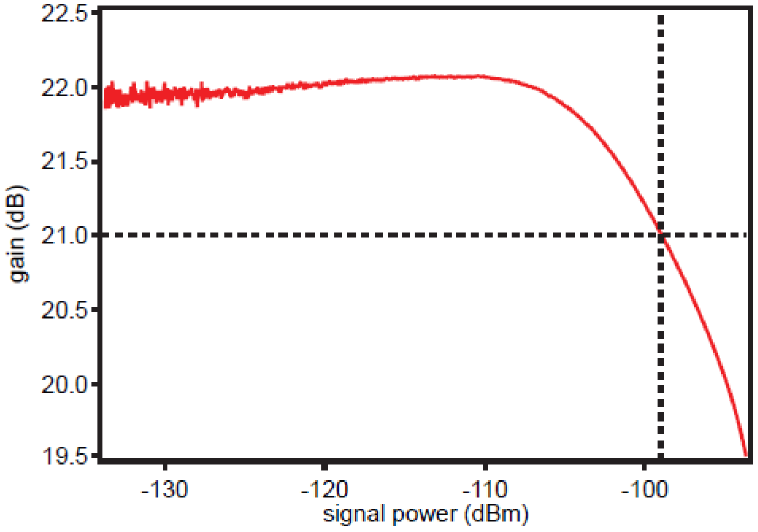
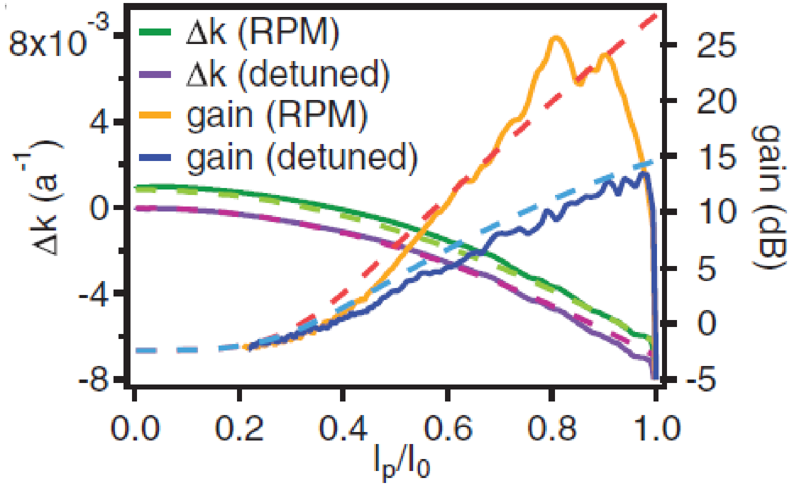


1-dB Compression point



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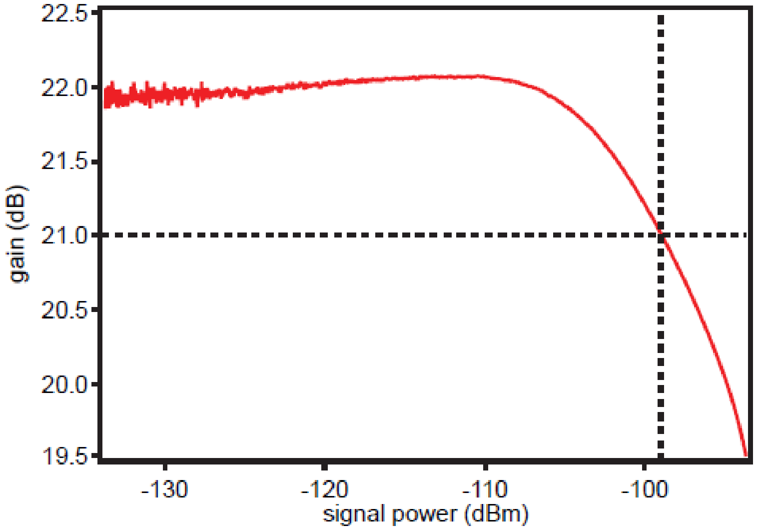

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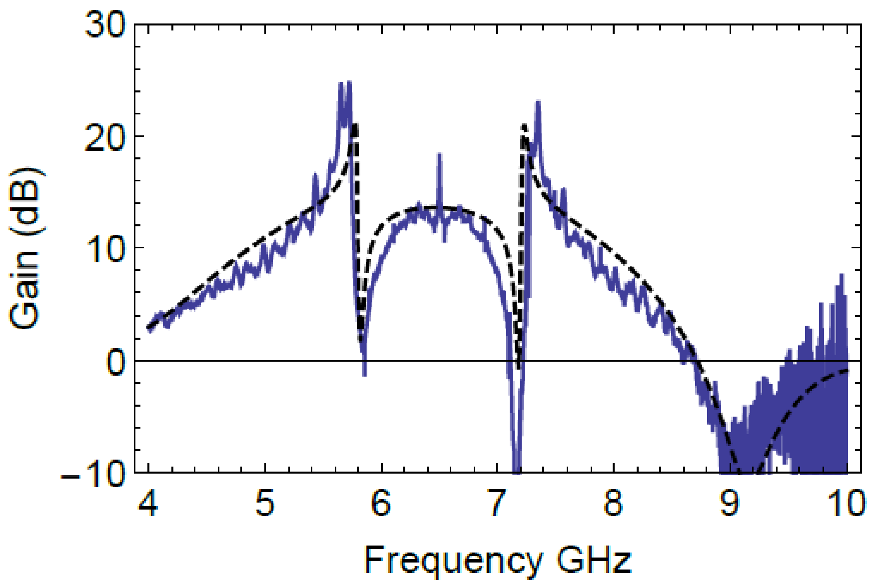
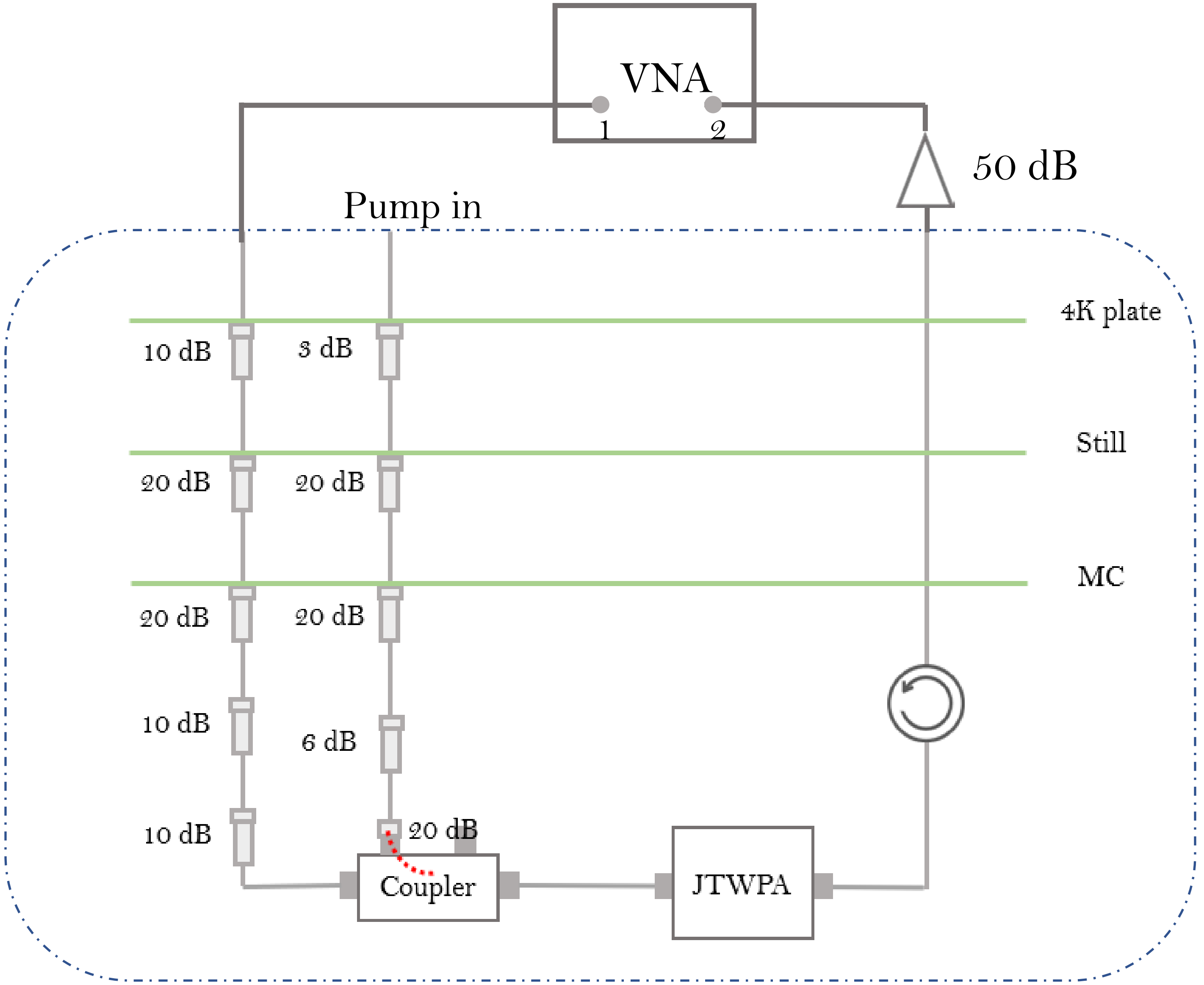


Measured gain spectrum when the pump is detuned

Current Setup



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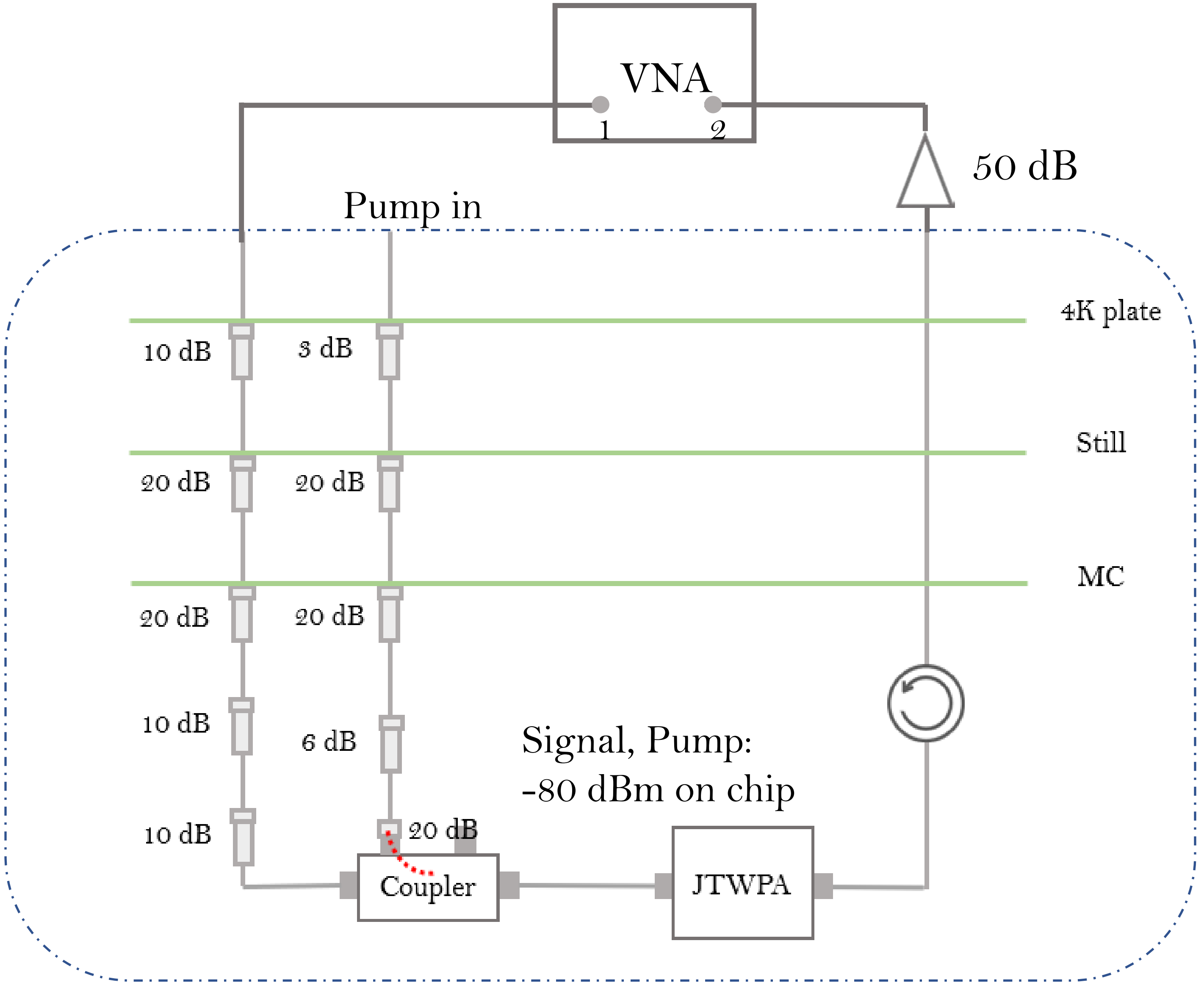

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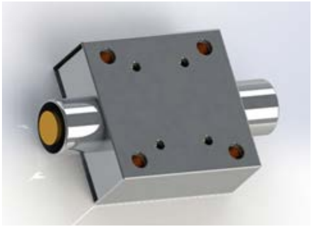
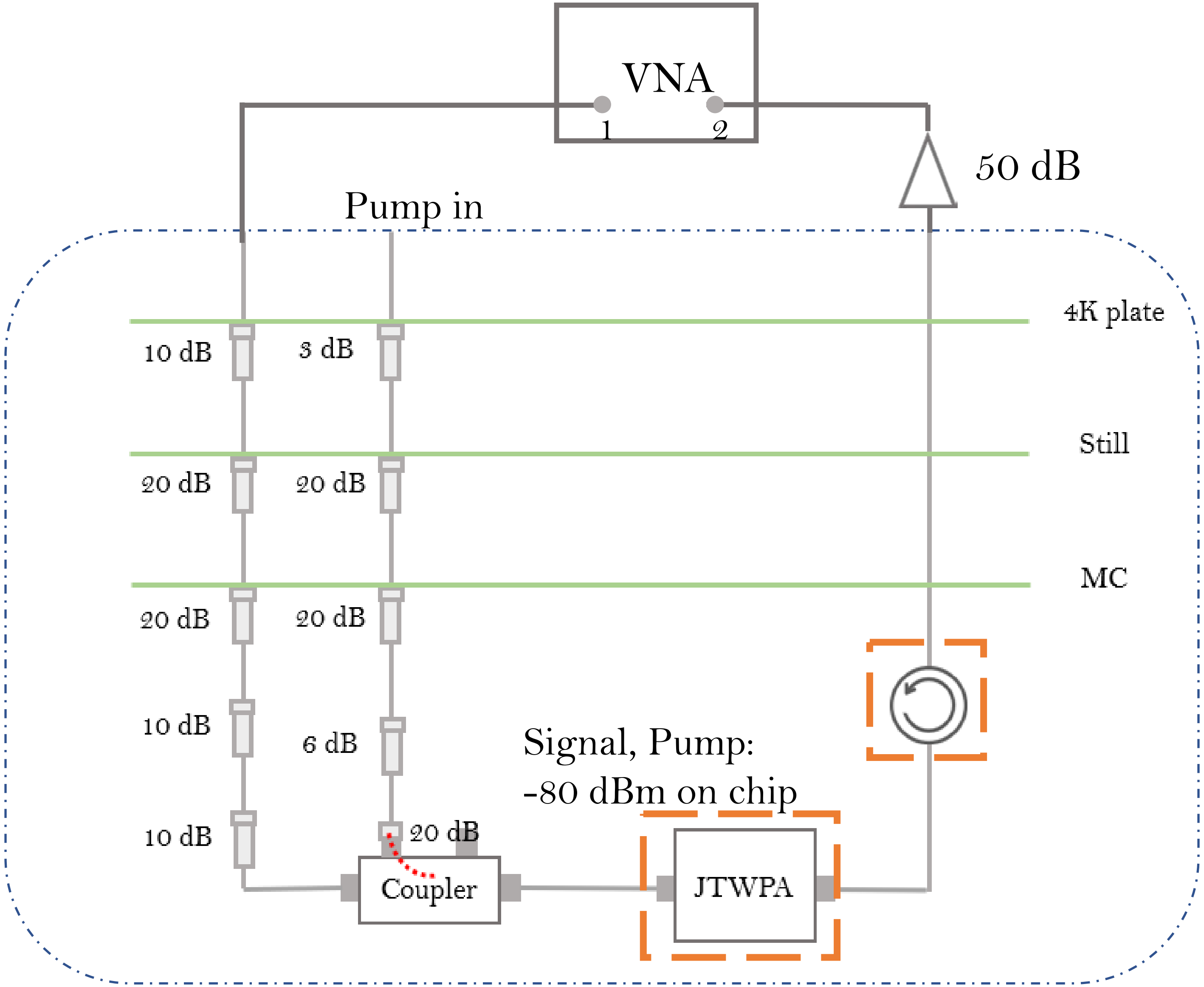
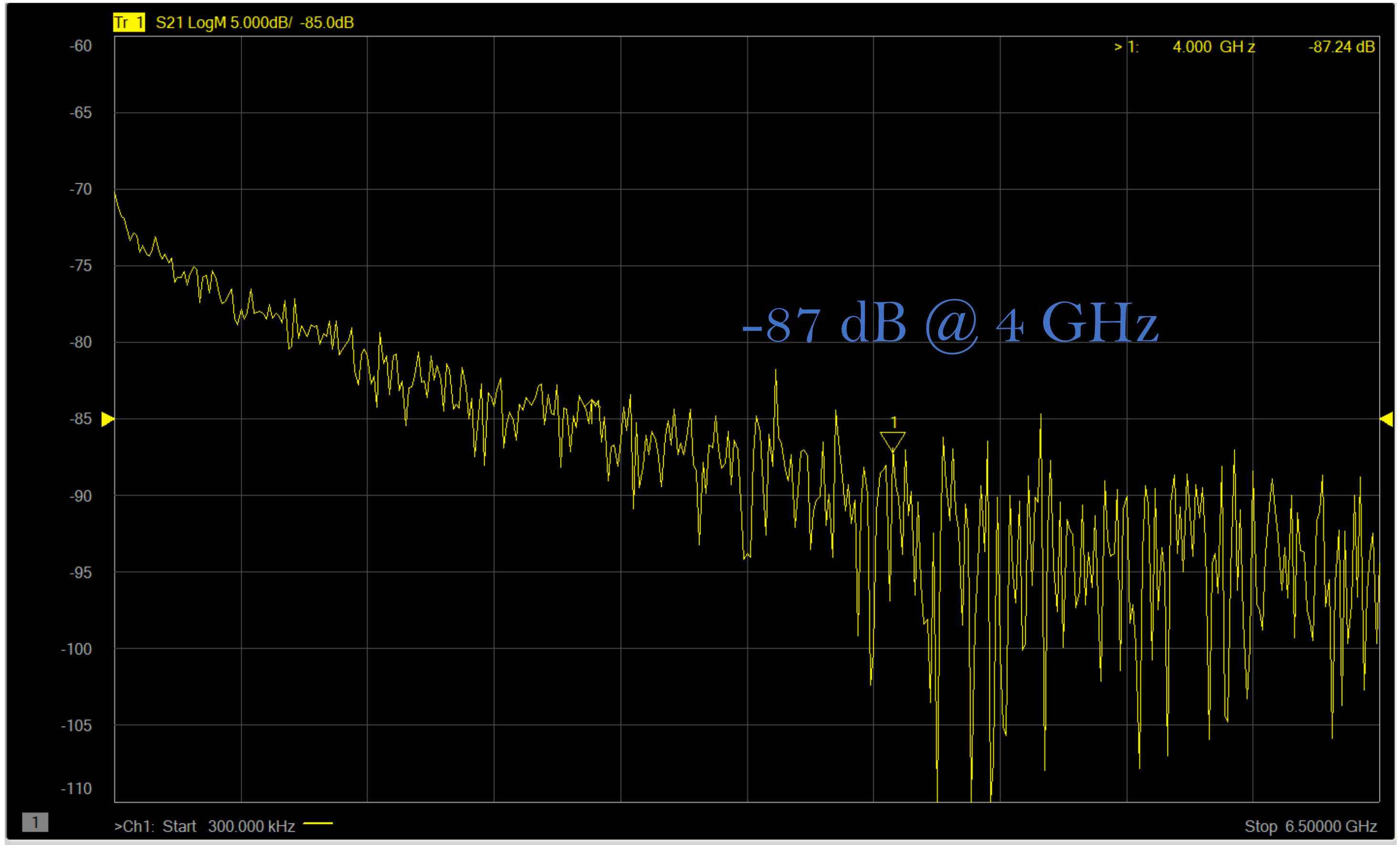




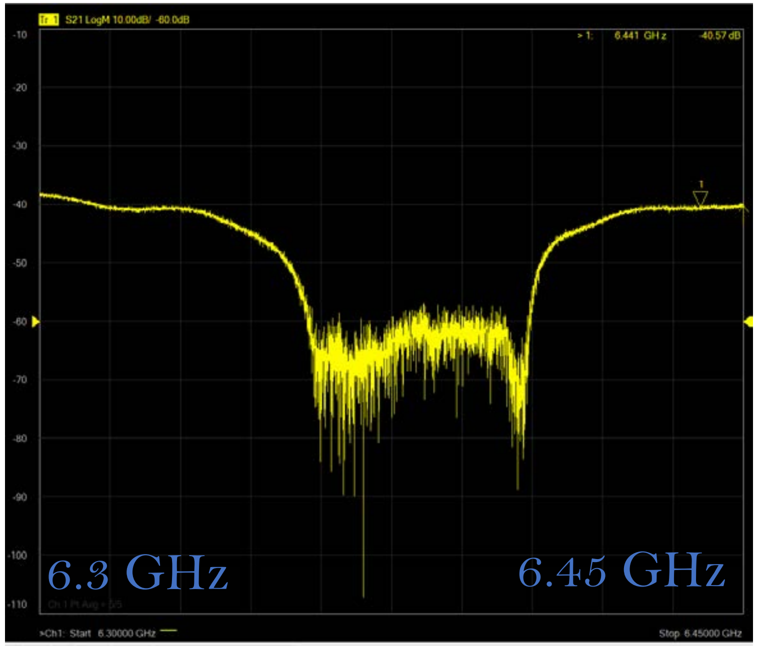
Room temperature calibration

apply cryogenic switches in the future for better comparision



Characterization of TWPA

Without shield



Dispersive feature

Characterization of TWPA

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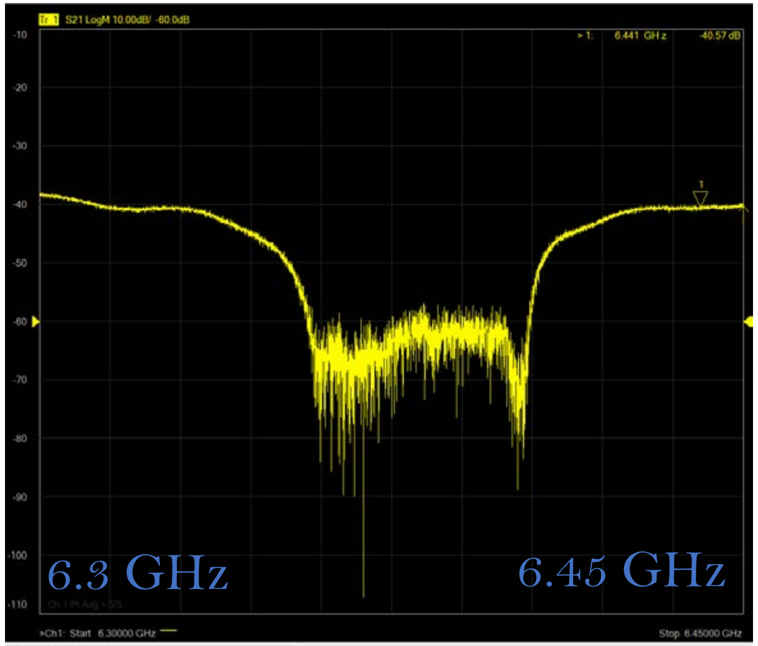

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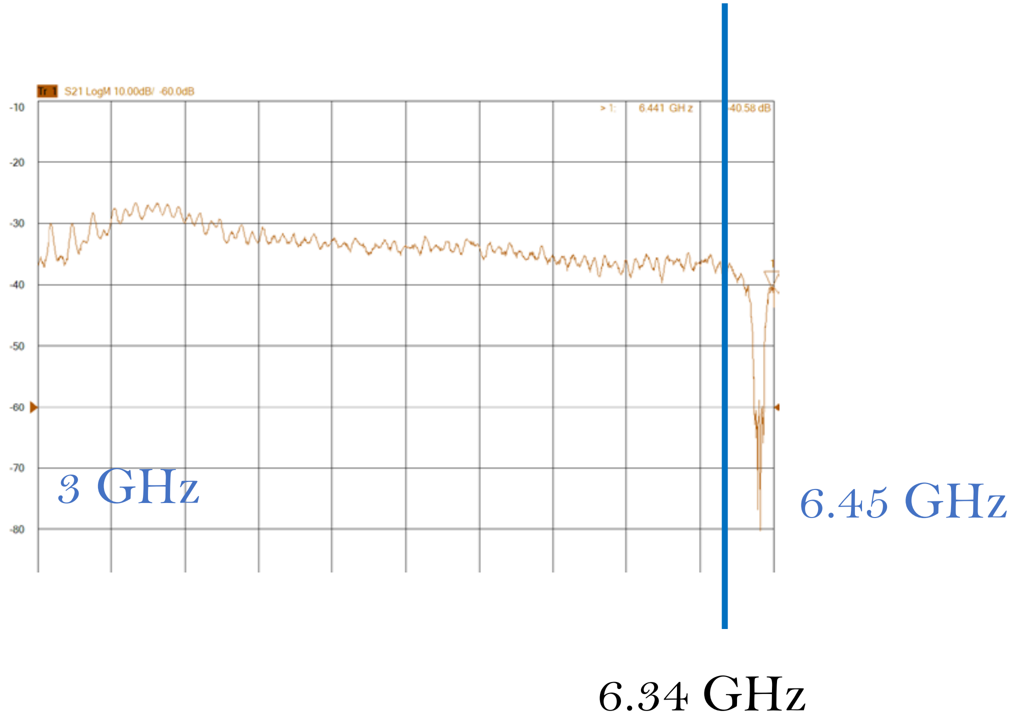

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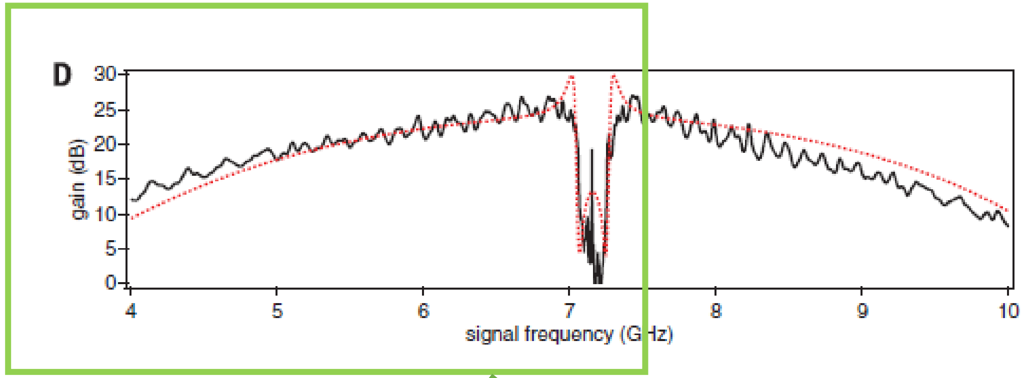

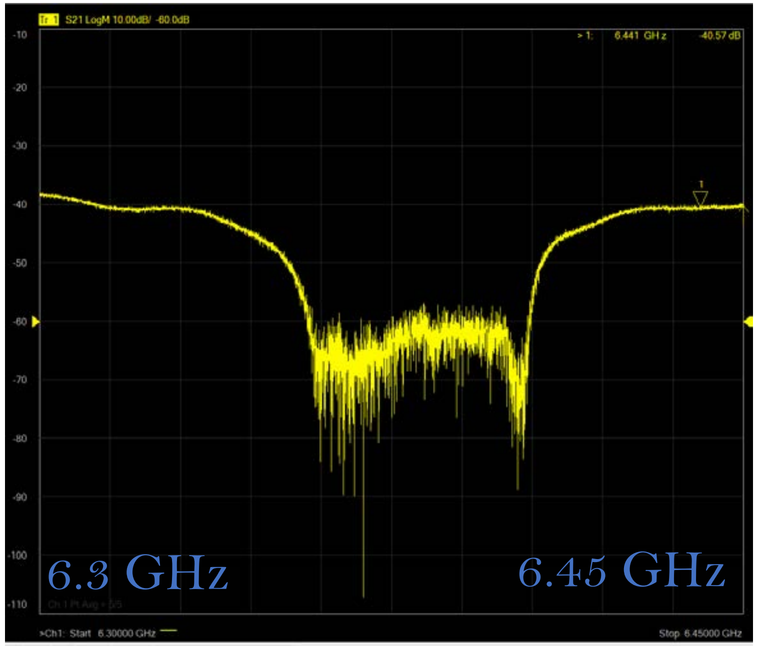

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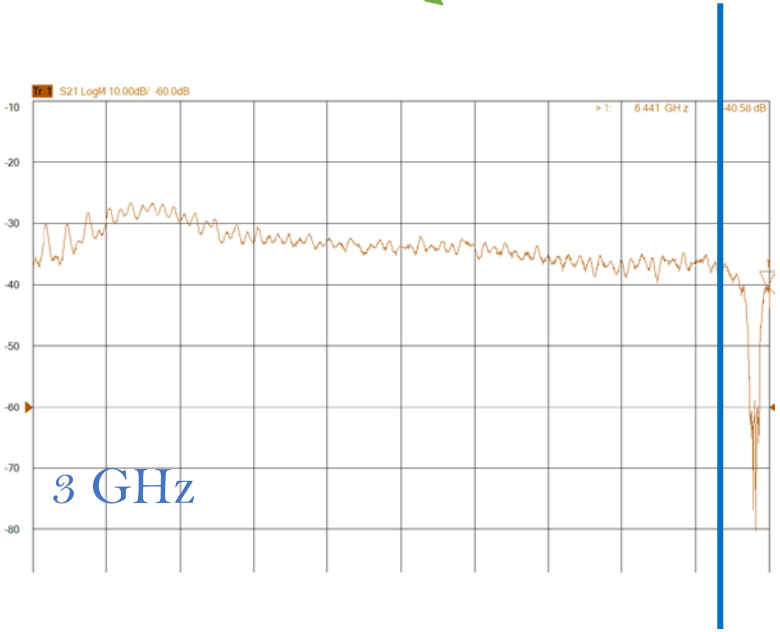


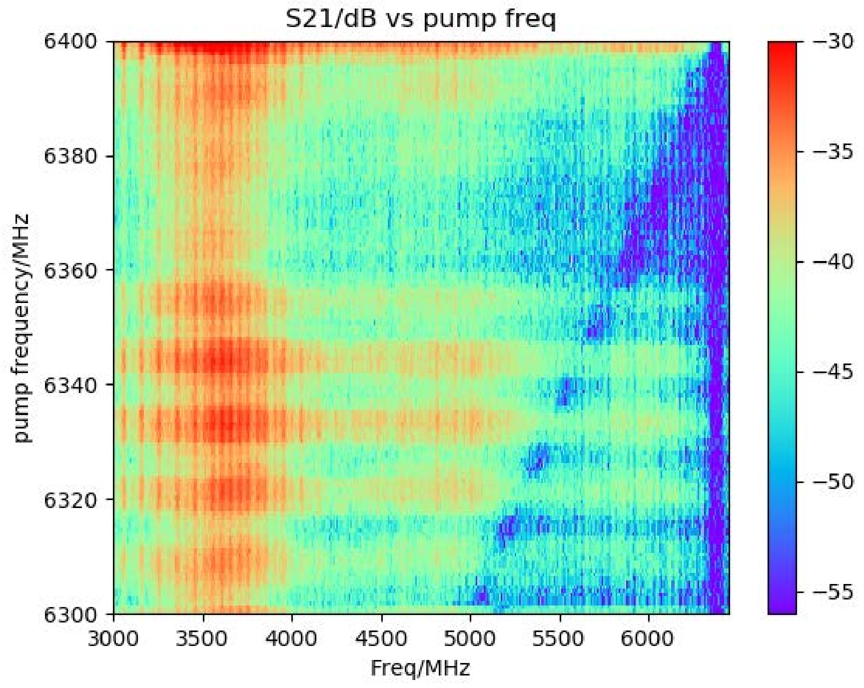
6.45 GHz

6.34 GHz

Pump frequency/power search

Pump frequency/power search

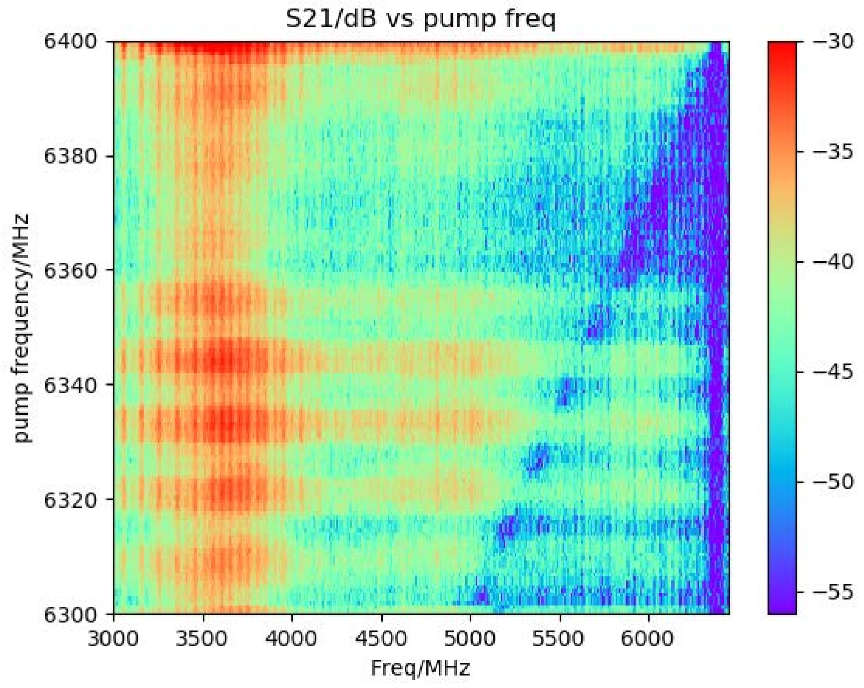
Sweep pump frequency from 5 GHz to 6.4 GHz in 10 MHz step, pump power -14 dBm

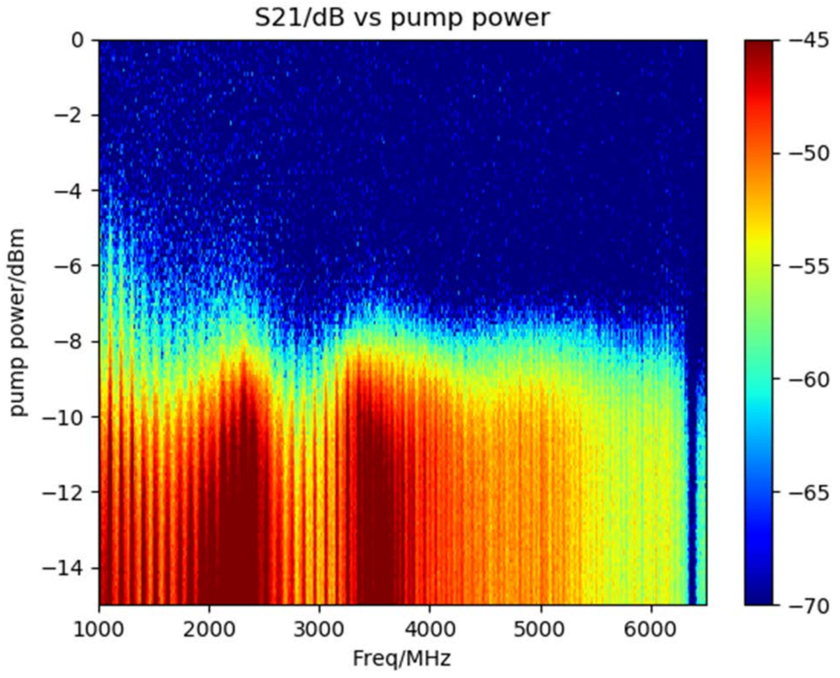


Pump frequency/power search

Sweep pump frequency from 5 GHz to 6.4 GHz in 10 MHz step, pump power -14 dBm

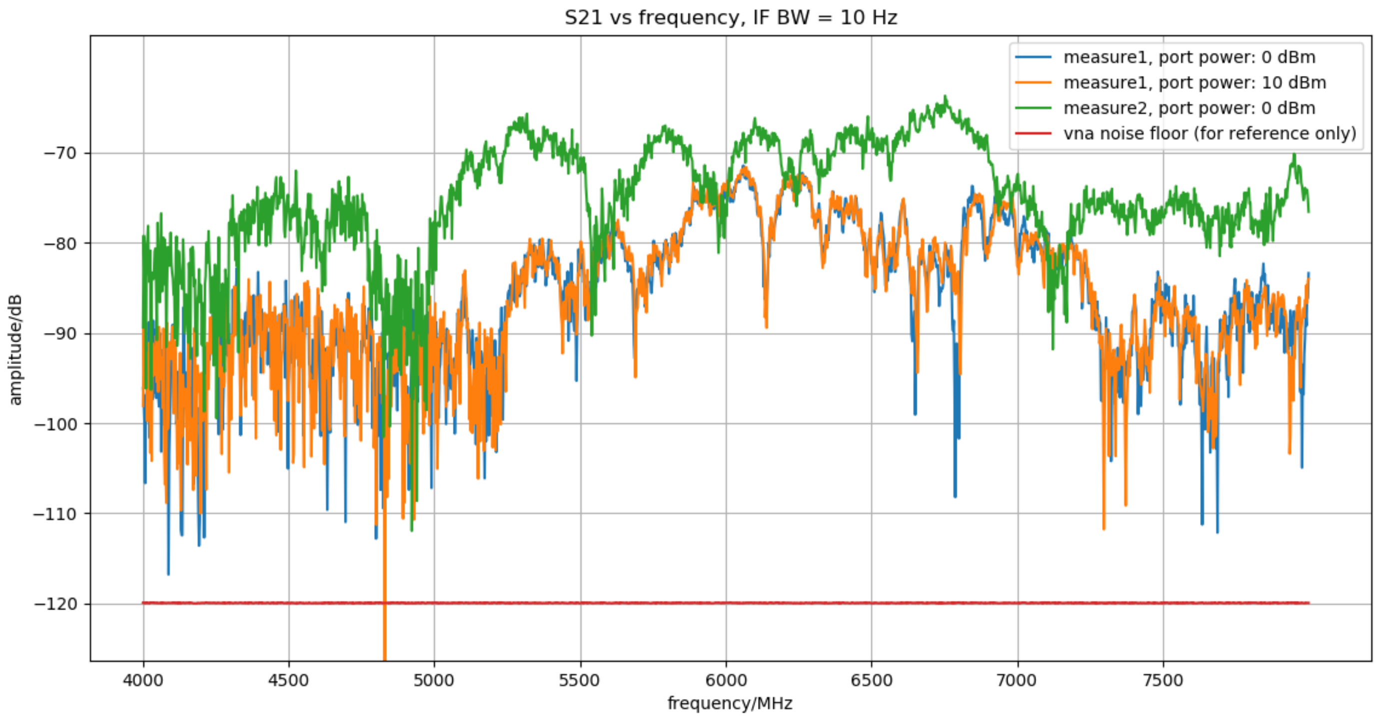
Sweep pump power from -15 dBm to 0 dBm in 0.1 dB step





Weird behavior without shield

Without shield, with circulator



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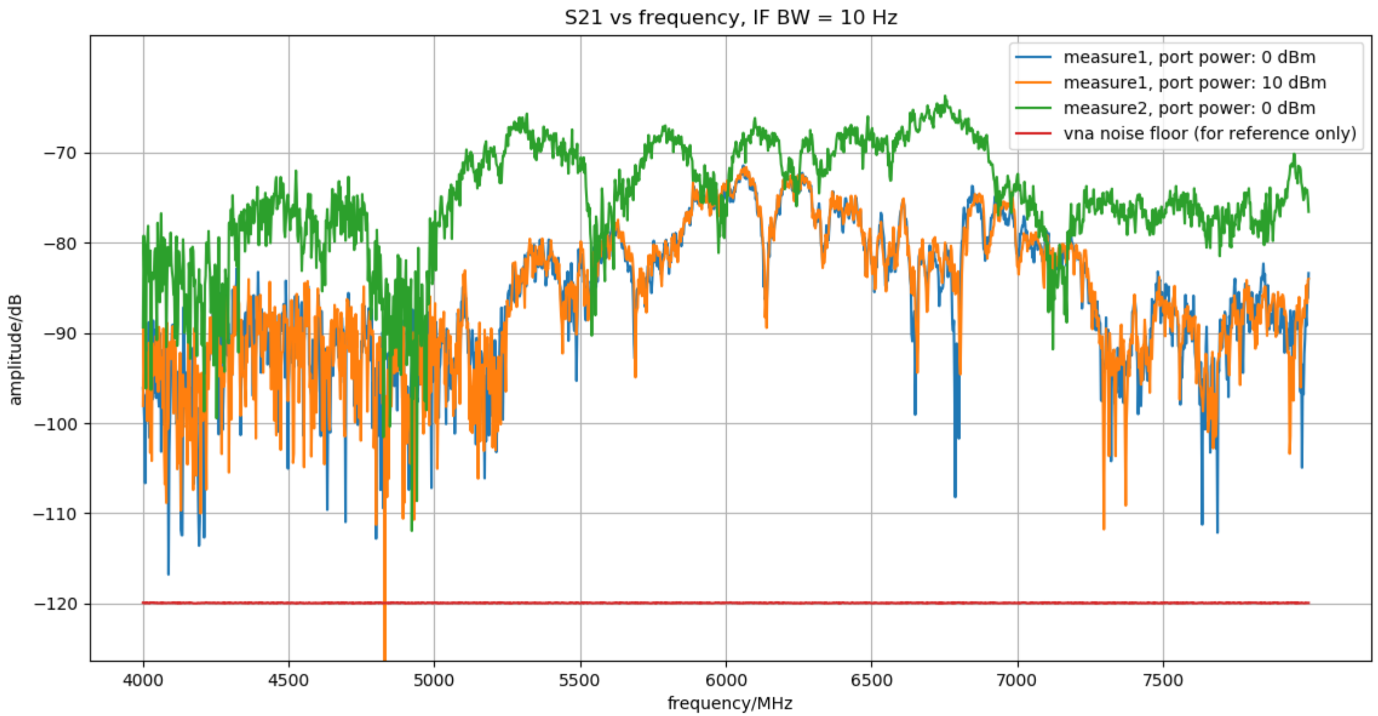

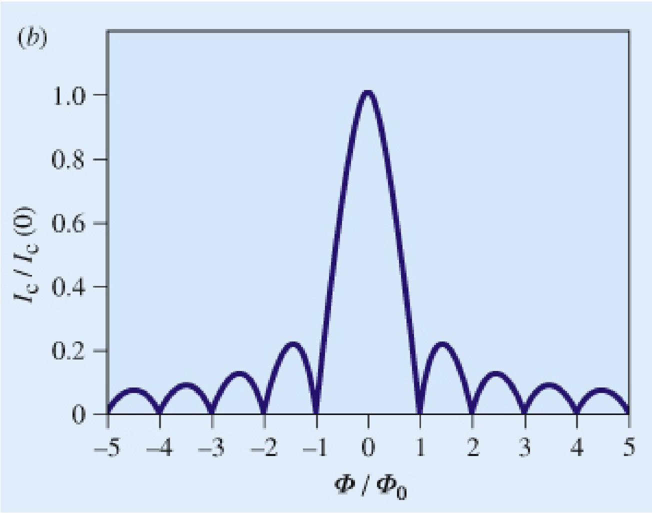

Critical current vs magnetic flux

The Josephson effect: 50 years of science and technology. Paul A Warburton

Characterization of TWPA

With magnetic shield, without circulator

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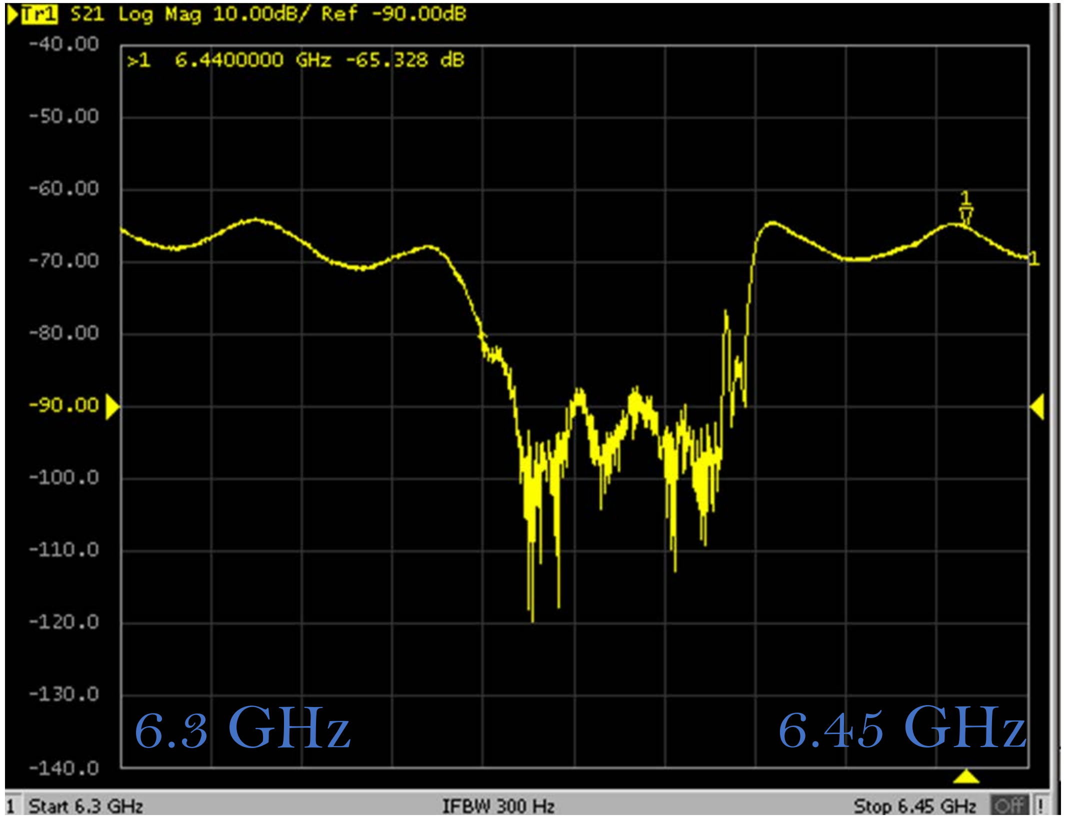
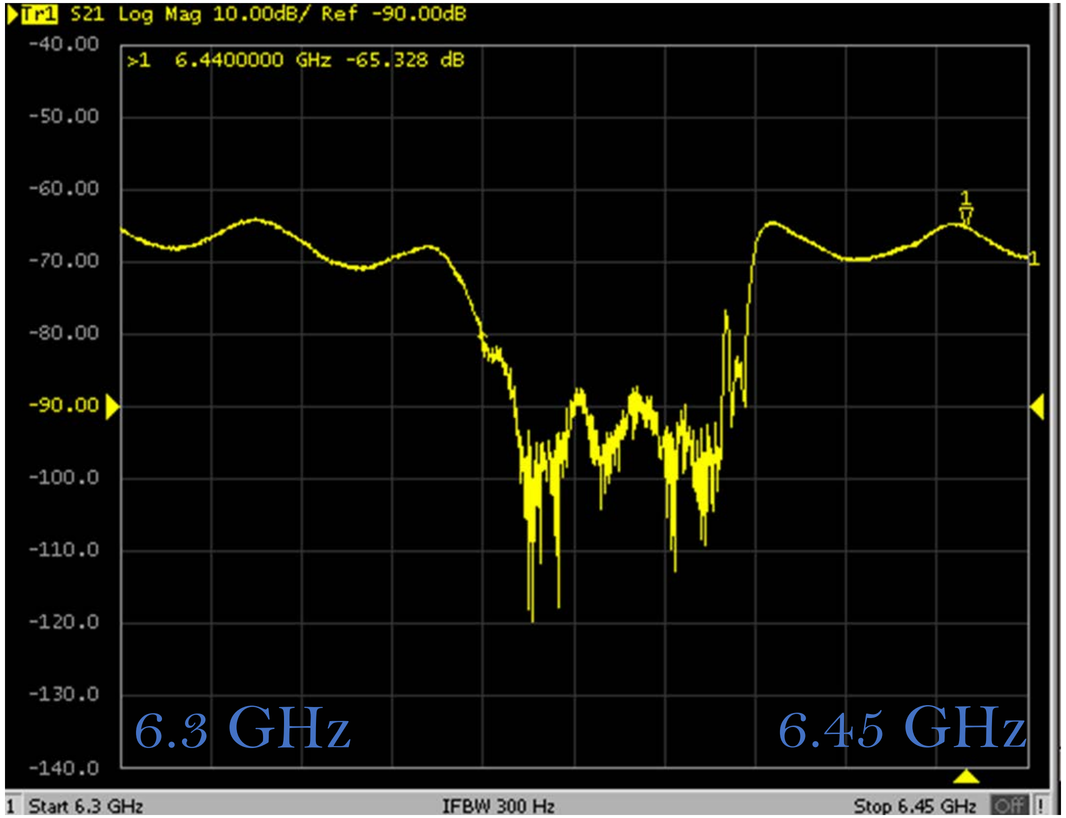


Dispersive feature

Characterization of TWPA

With magnetic shield, without circulator



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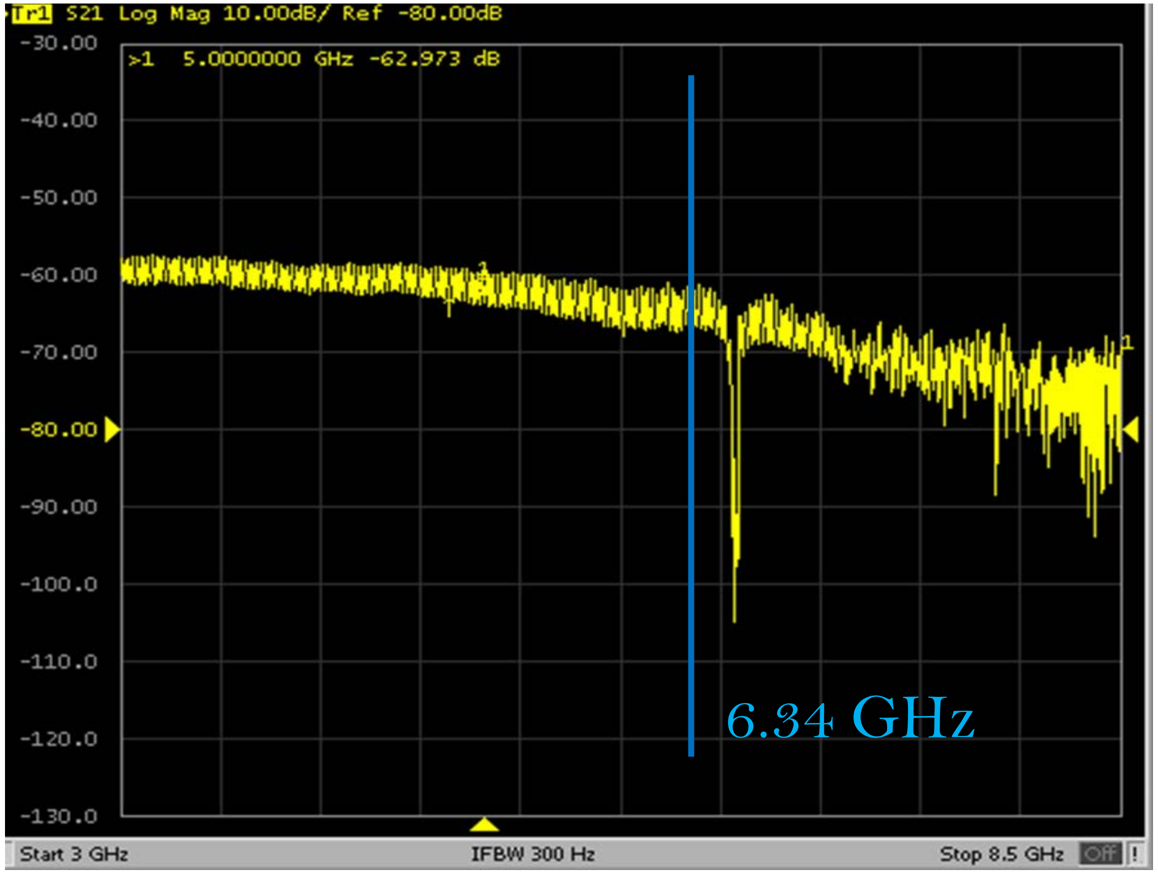

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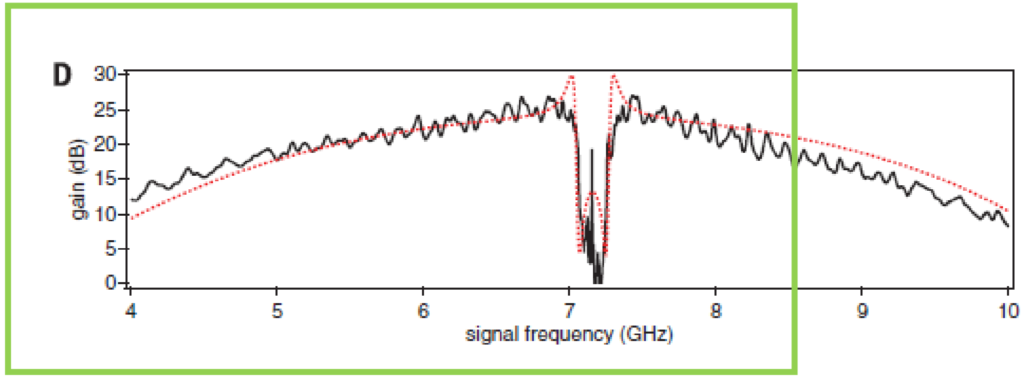

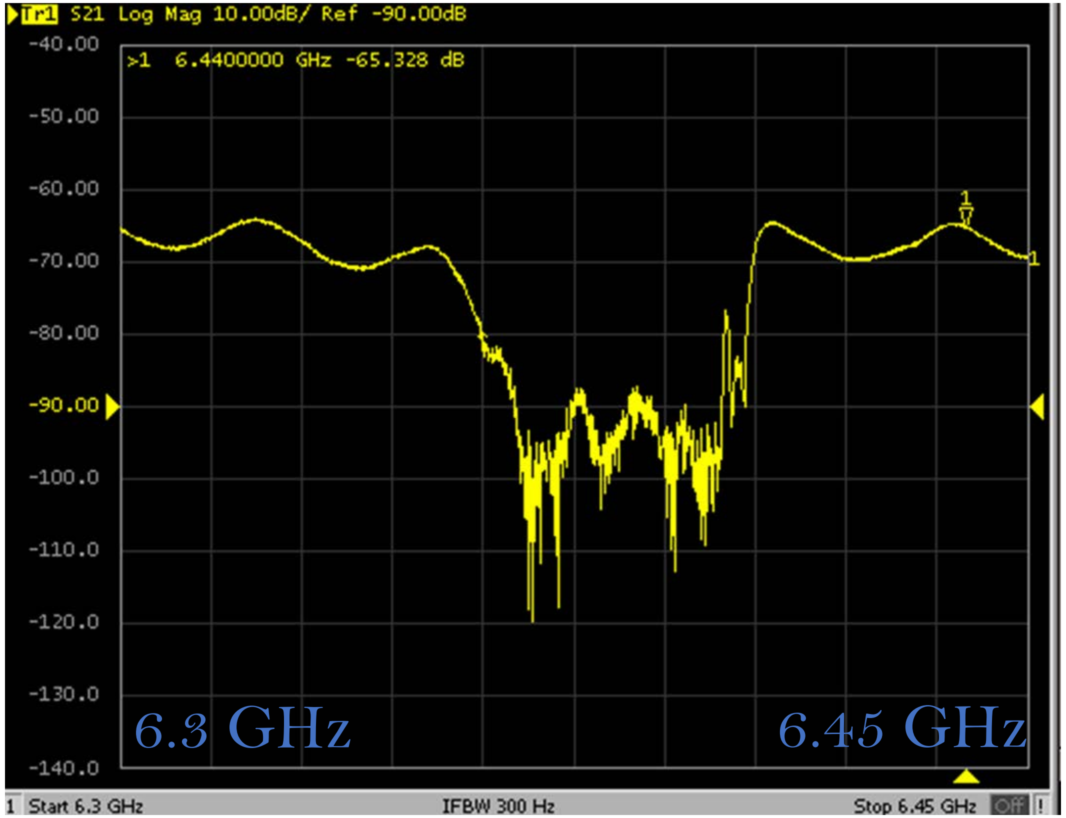

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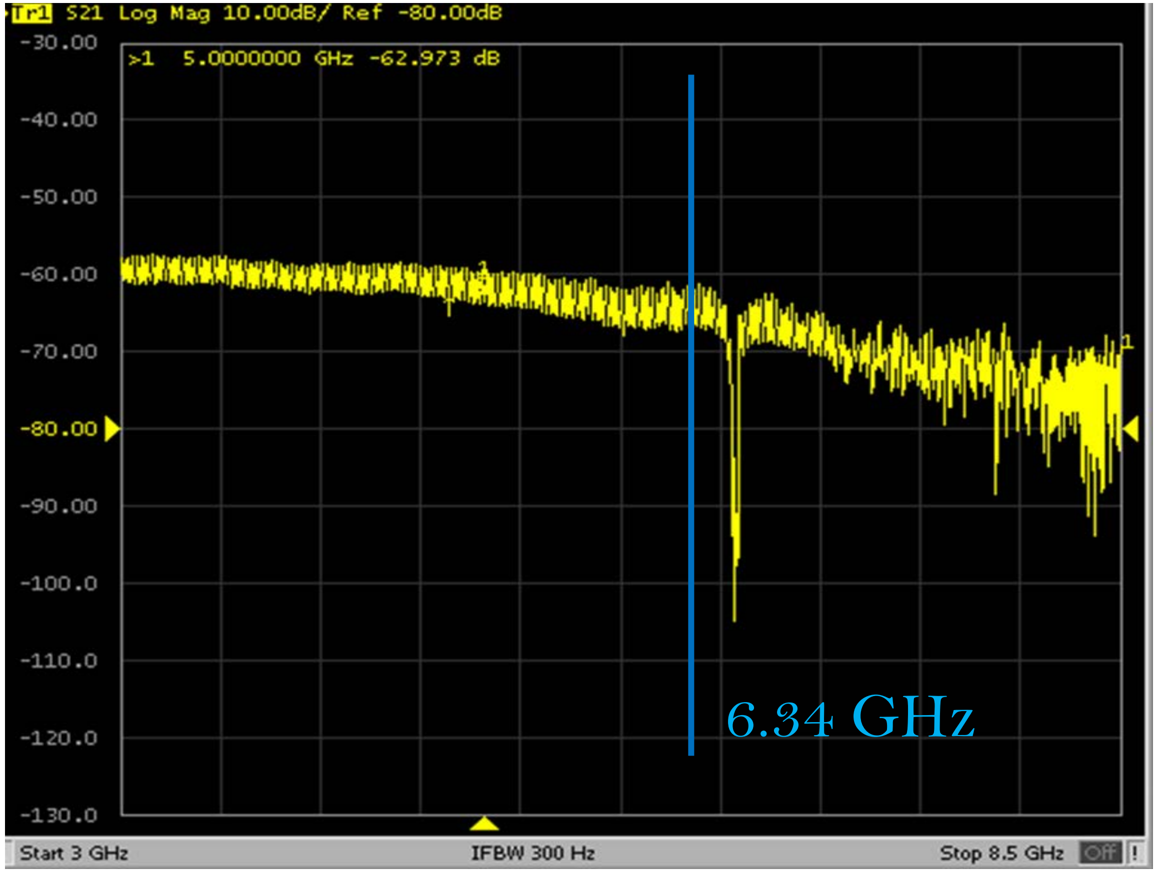
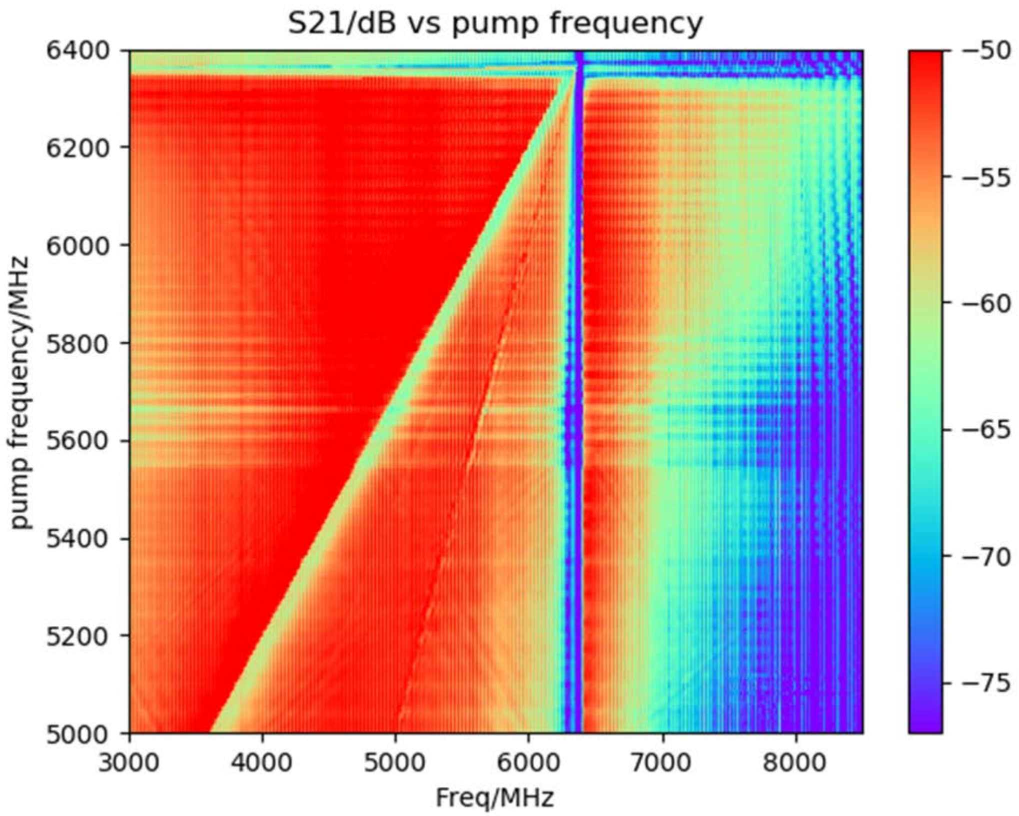
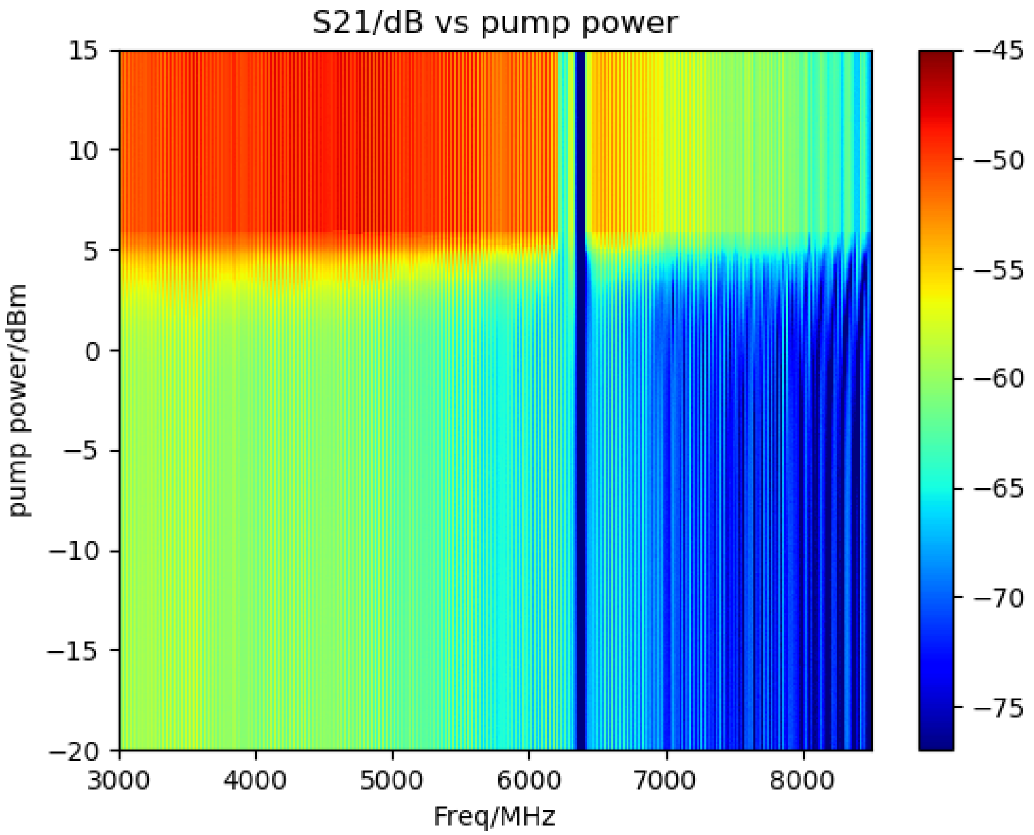


Pump frequency/power search (port power: 0 dBm)

Sweep pump frequency from 5 GHz to 6.4 GHz in 1 MHz step, pump power 7.5 dBm

Sweep pump power from -20 dBm to 15 dBm in 0.1 dB step @6.31 GHz

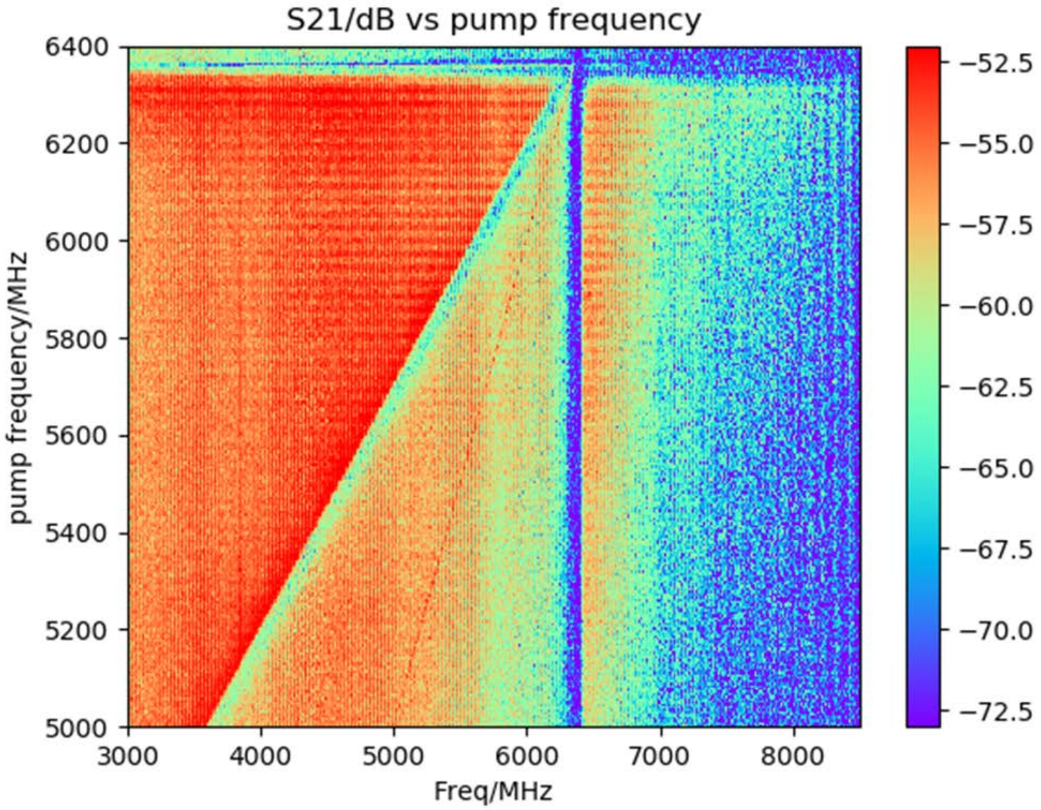


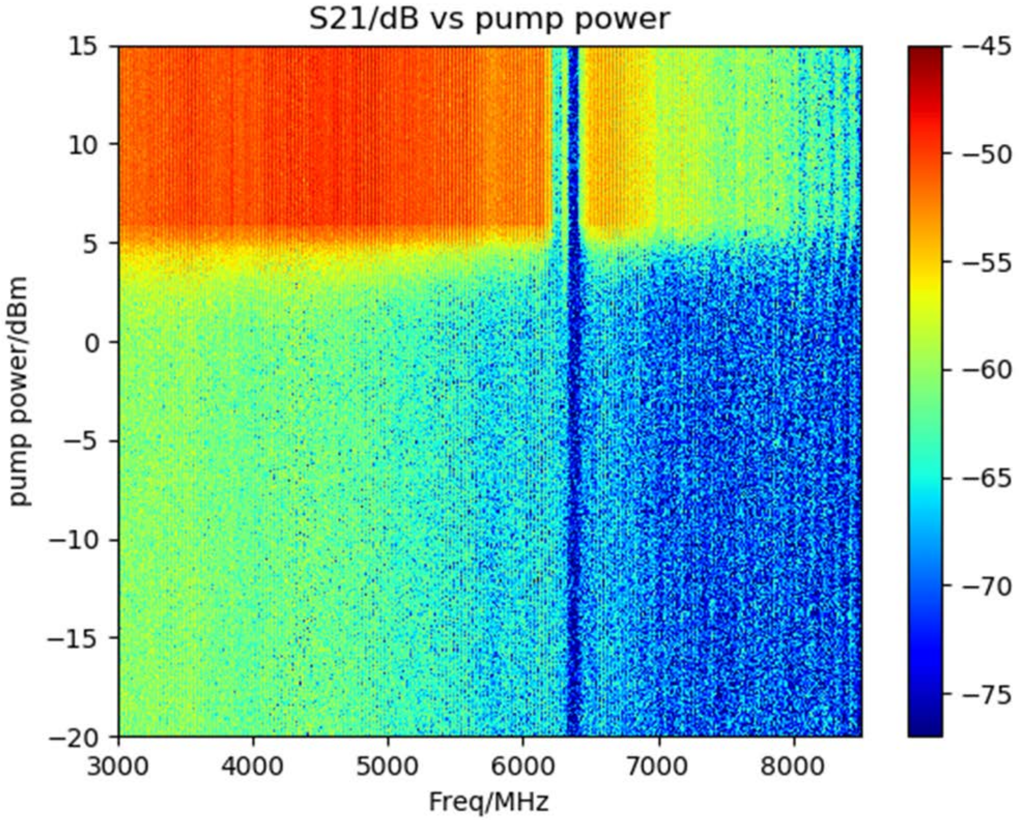


Pump frequency/power search (port power: -30 dBm)

Sweep pump frequency from 5 GHz to 6.4 GHz in 1 MHz step, pump power 5 dBm

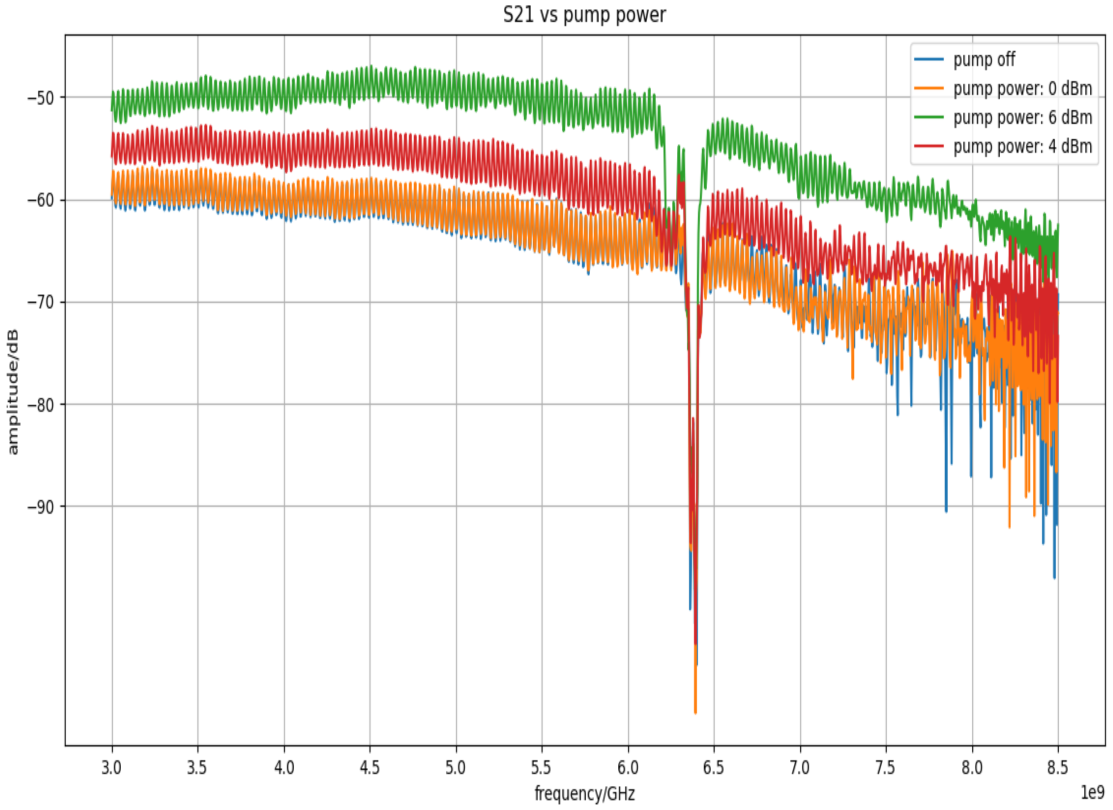
Sweep pump power from -20 dBm to 15 dBm in 0.1 dB step @6.31 GHz





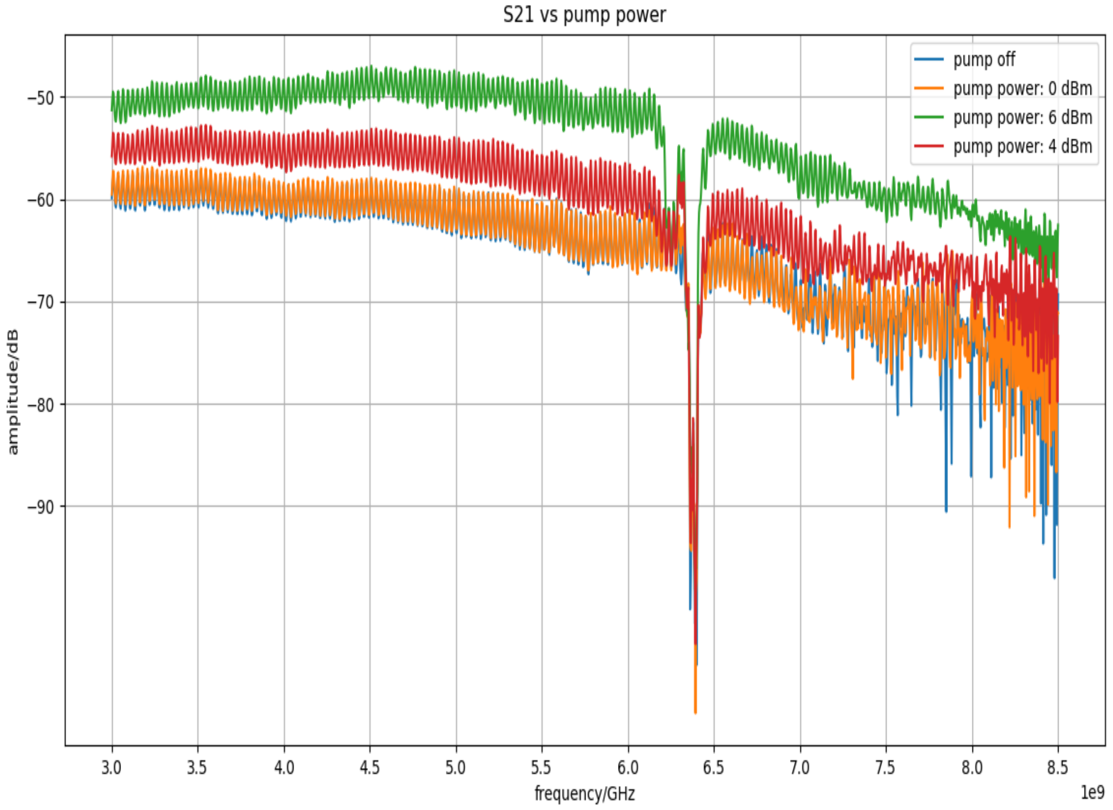
Pump power linecut

Port power: 0 dBm

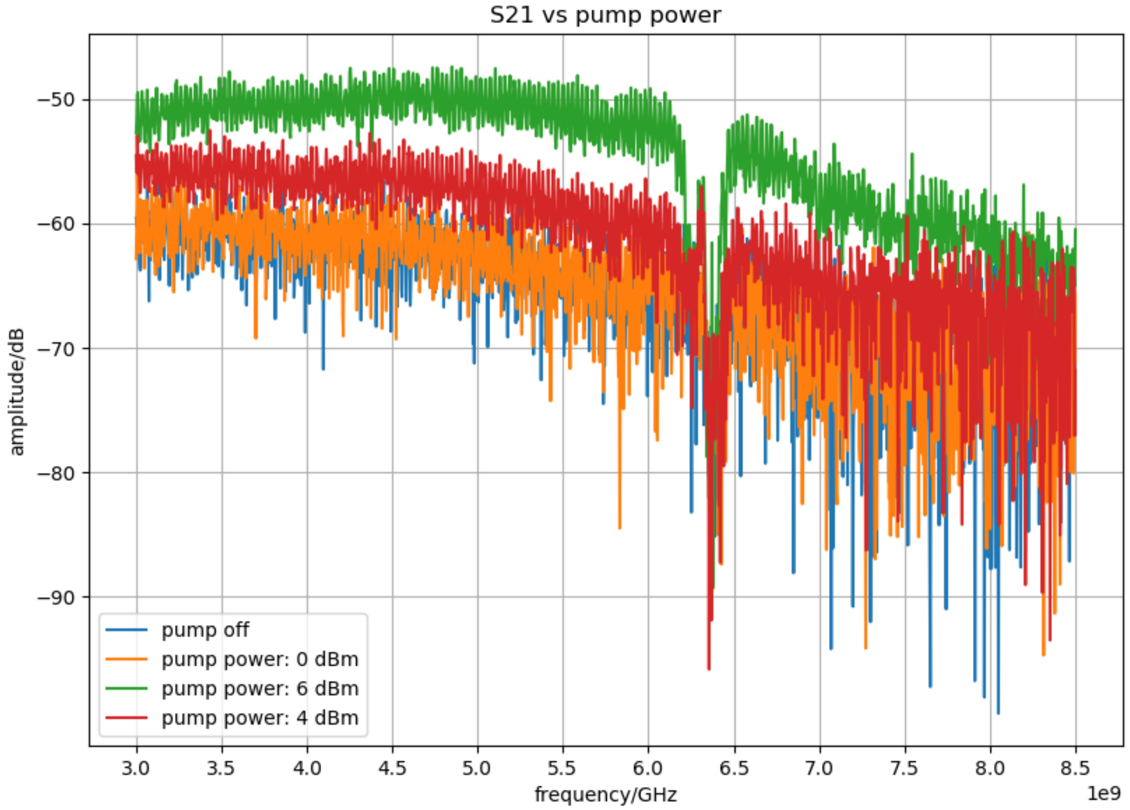


Pump power linecut

Port power: 0 dBm



Port power: -30 dBm

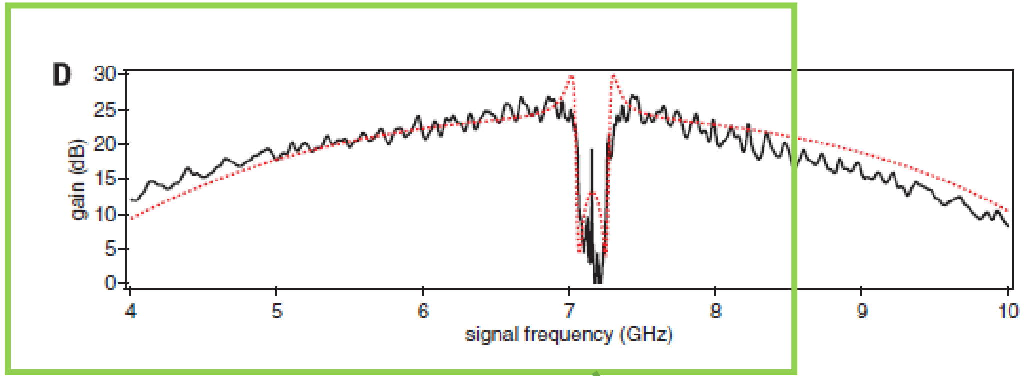


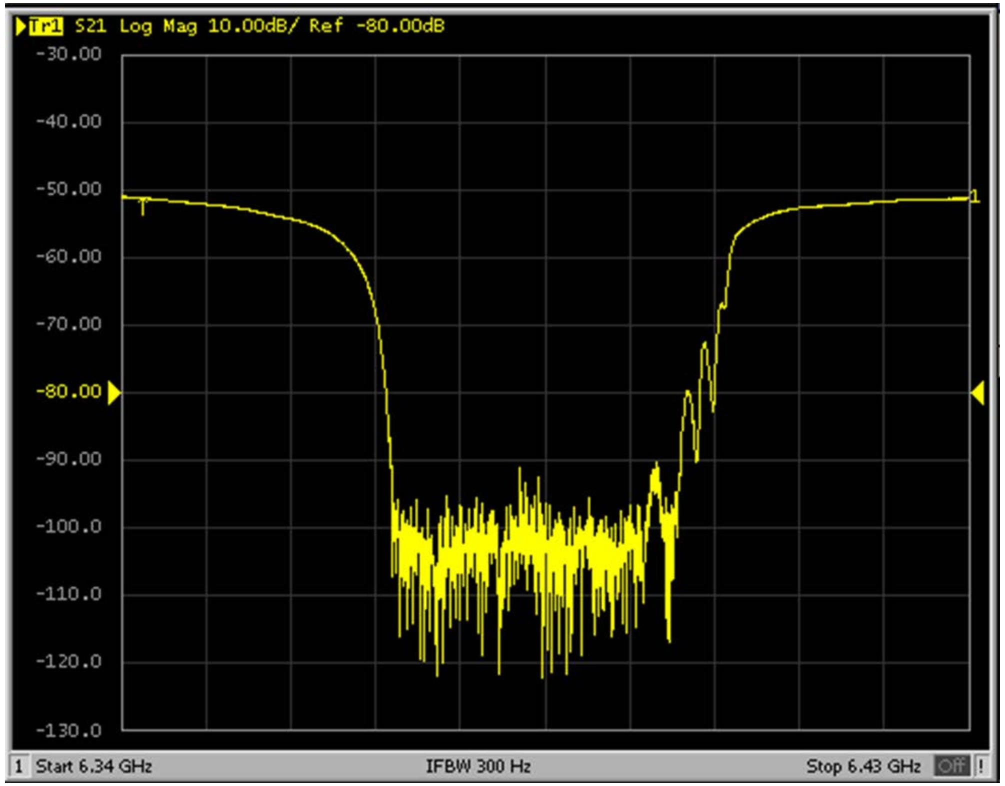
Characterization of TWPA

With magnetic shield, with circulator

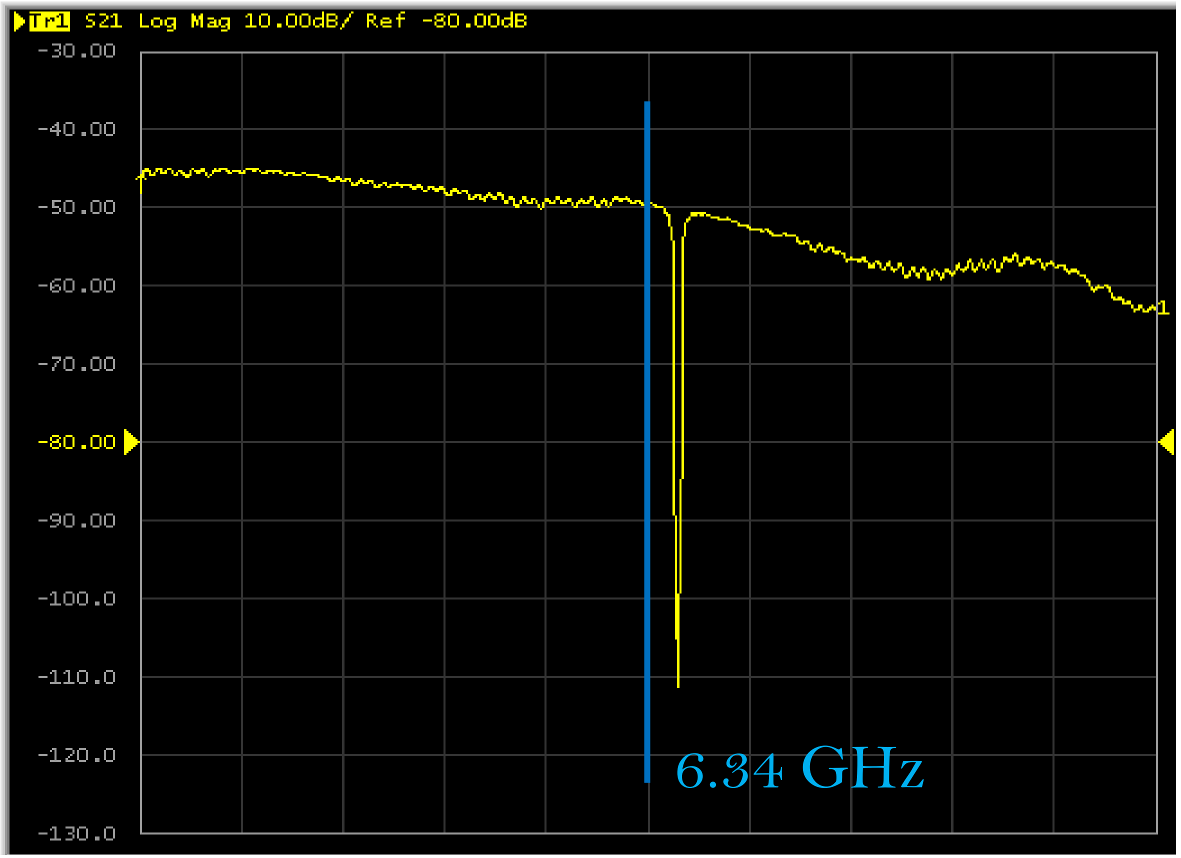
Characterization of TWPA

With magnetic shield, with circulator





Dispersive feature



signal and idler

Four wave mixing: $\omega_i = 2\omega_p - \omega_s$

signal and idler

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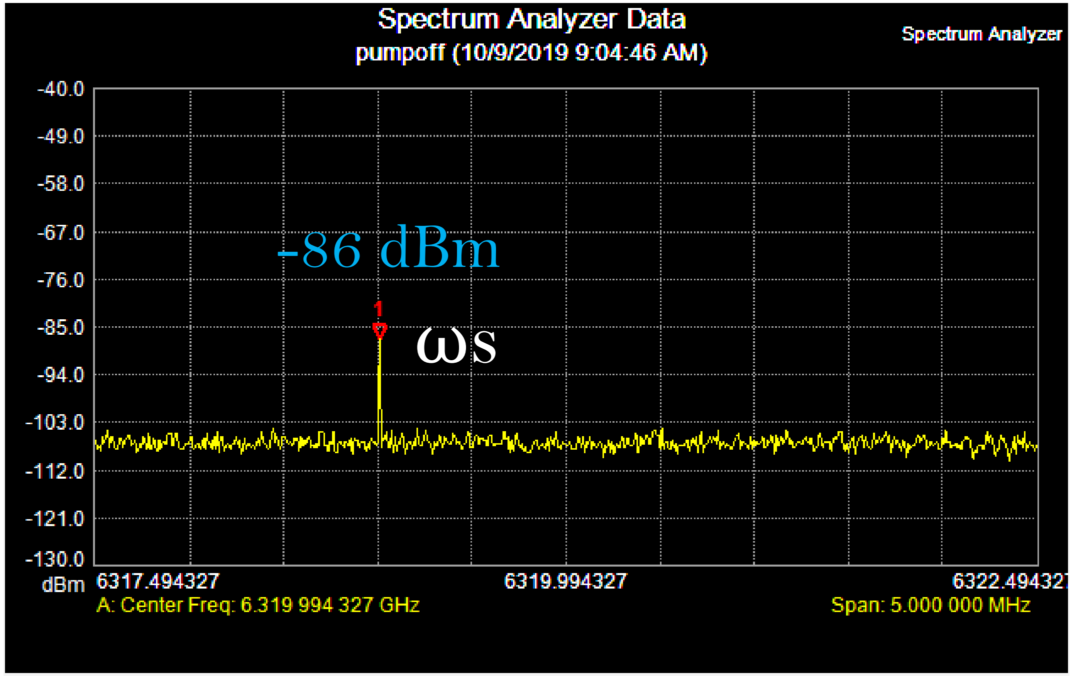
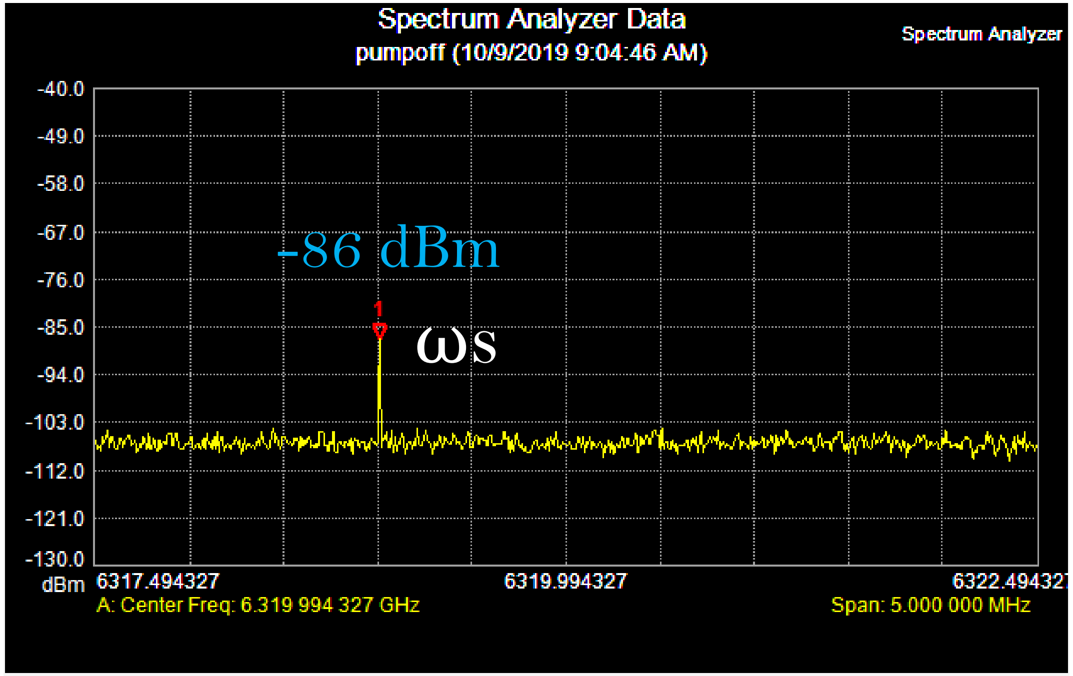


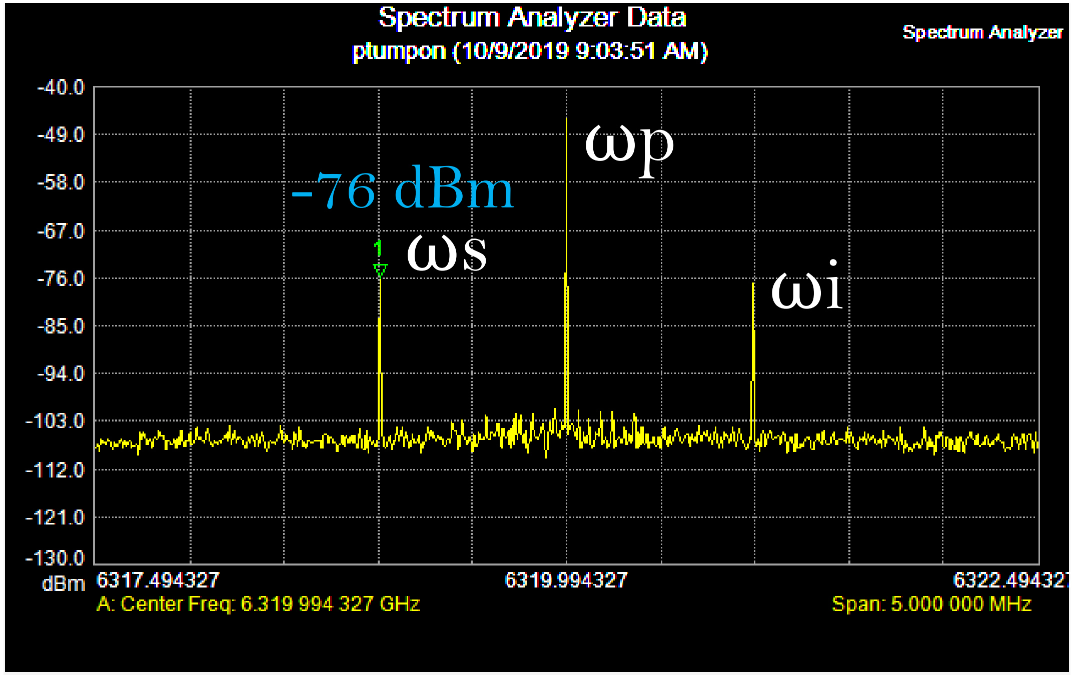
Pump off

signal and idler

Four wave mixing: $\omega i = 2\omega p - \omega s$



Pump off

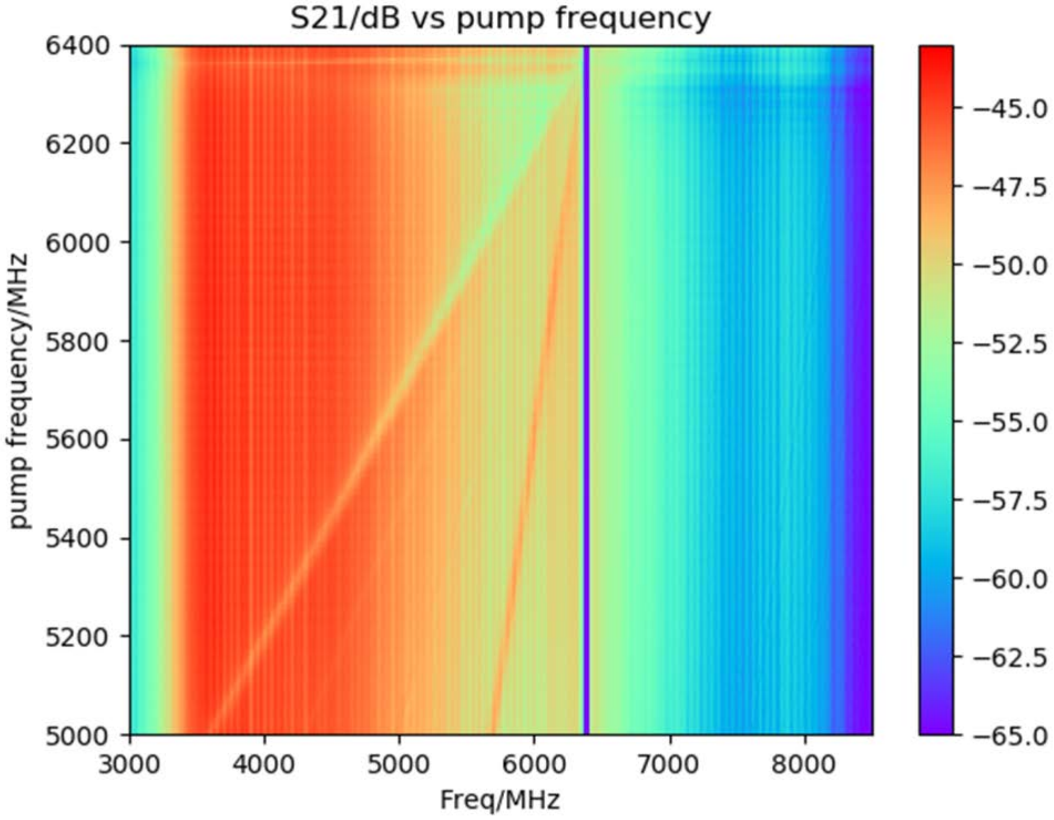


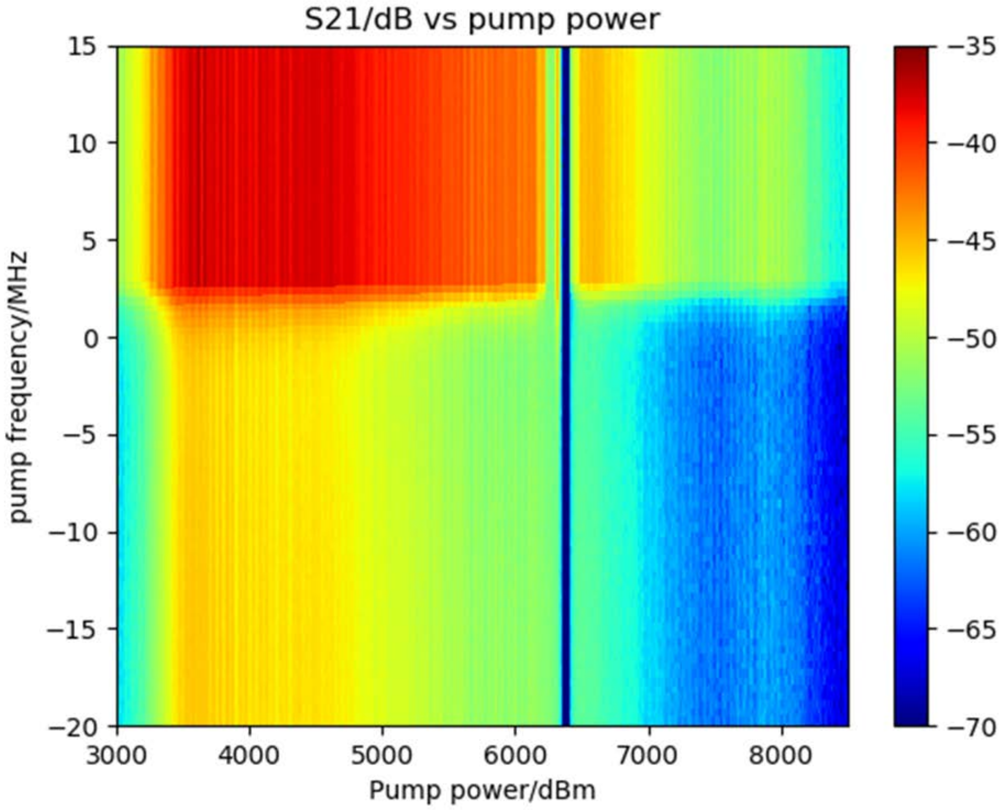
Pump on

Pump frequency/power search (port power: 0 dBm)

Sweep pump frequency from 5 GHz to 6.4 GHz in 1 MHz step, pump power 0 dBm

Sweep pump power from -20 dBm to 15 dBm in 0.1 dB step @6.31 GHz

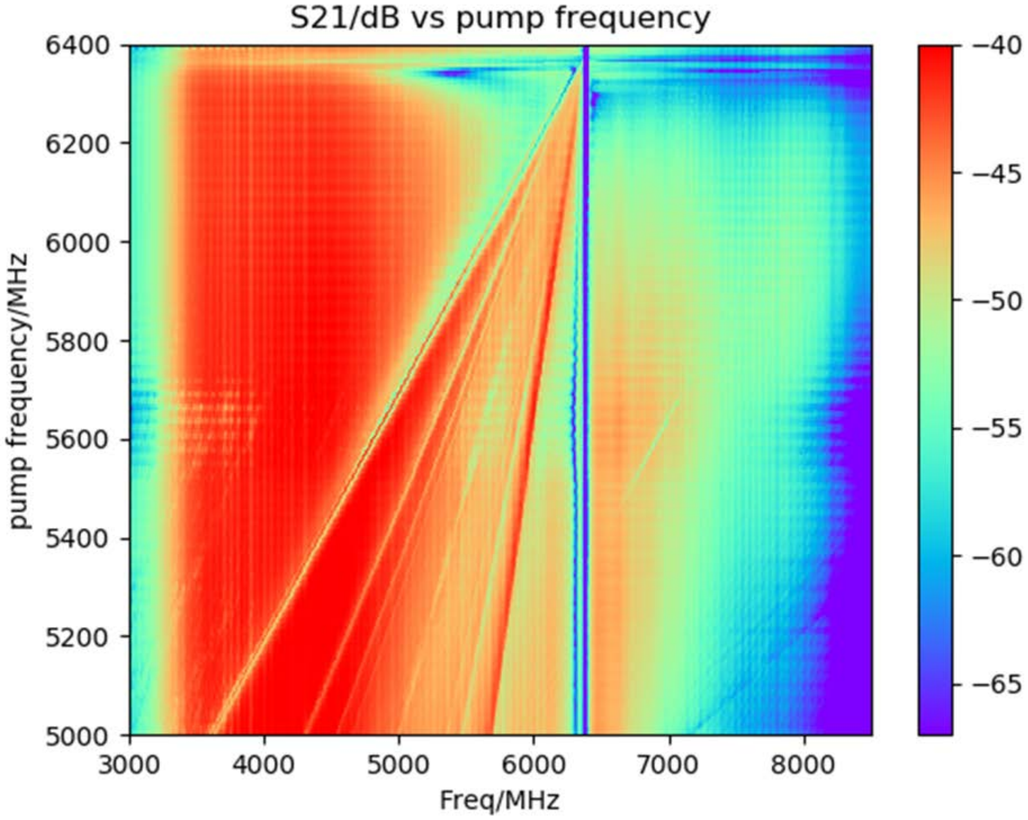


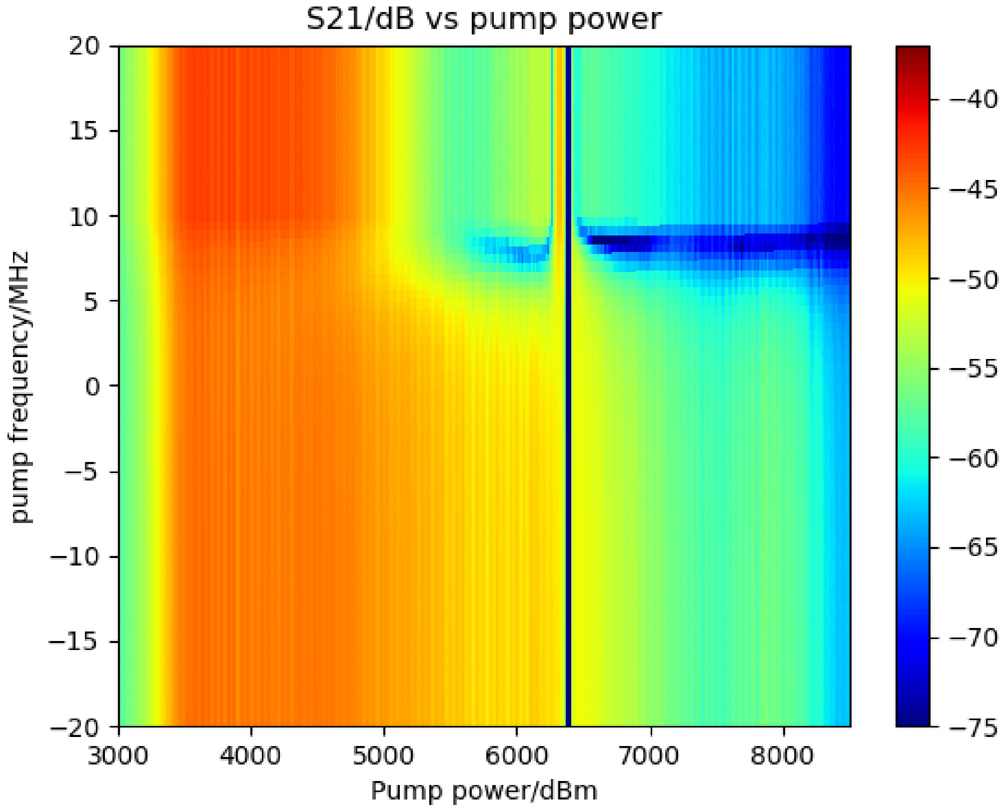


Pump frequency/power search (port power: 0 dBm)

Sweep pump frequency from 5 GHz to 6.4 GHz in 1 MHz step, pump power 7.5 dBm

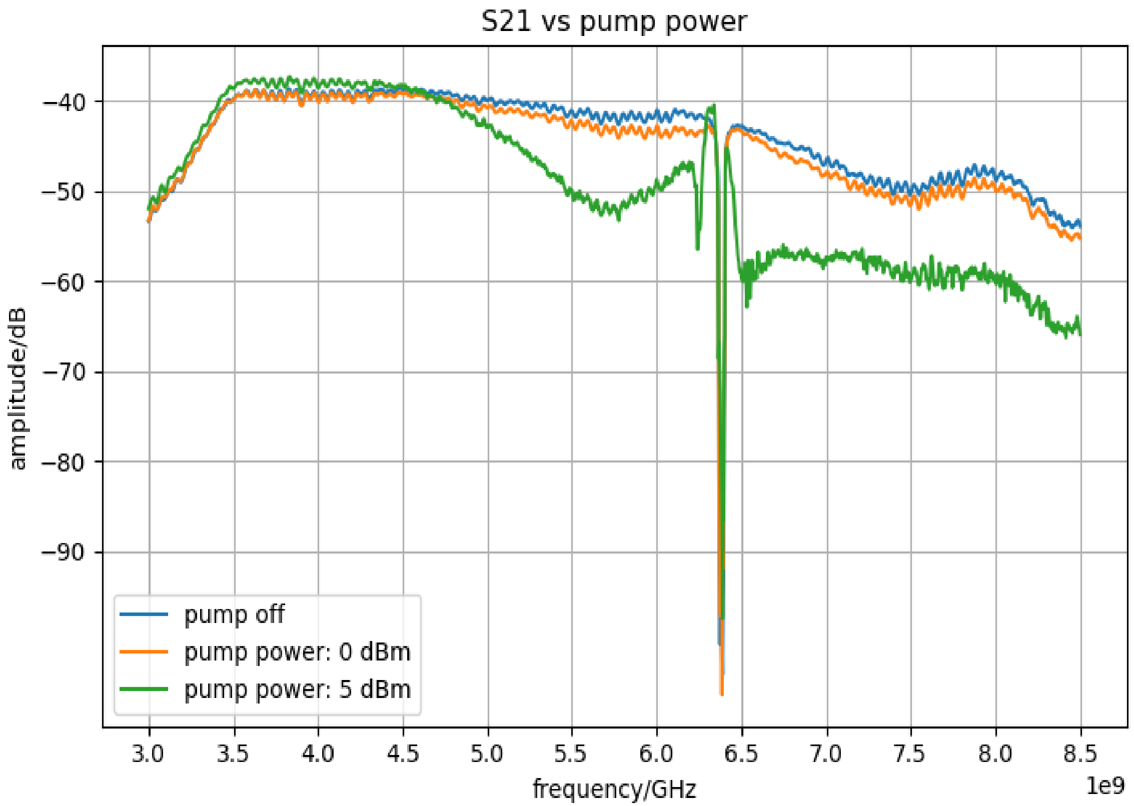
Sweep pump power from -20 dBm to 15 dBm in 0.1 dB step @6.31 GHz



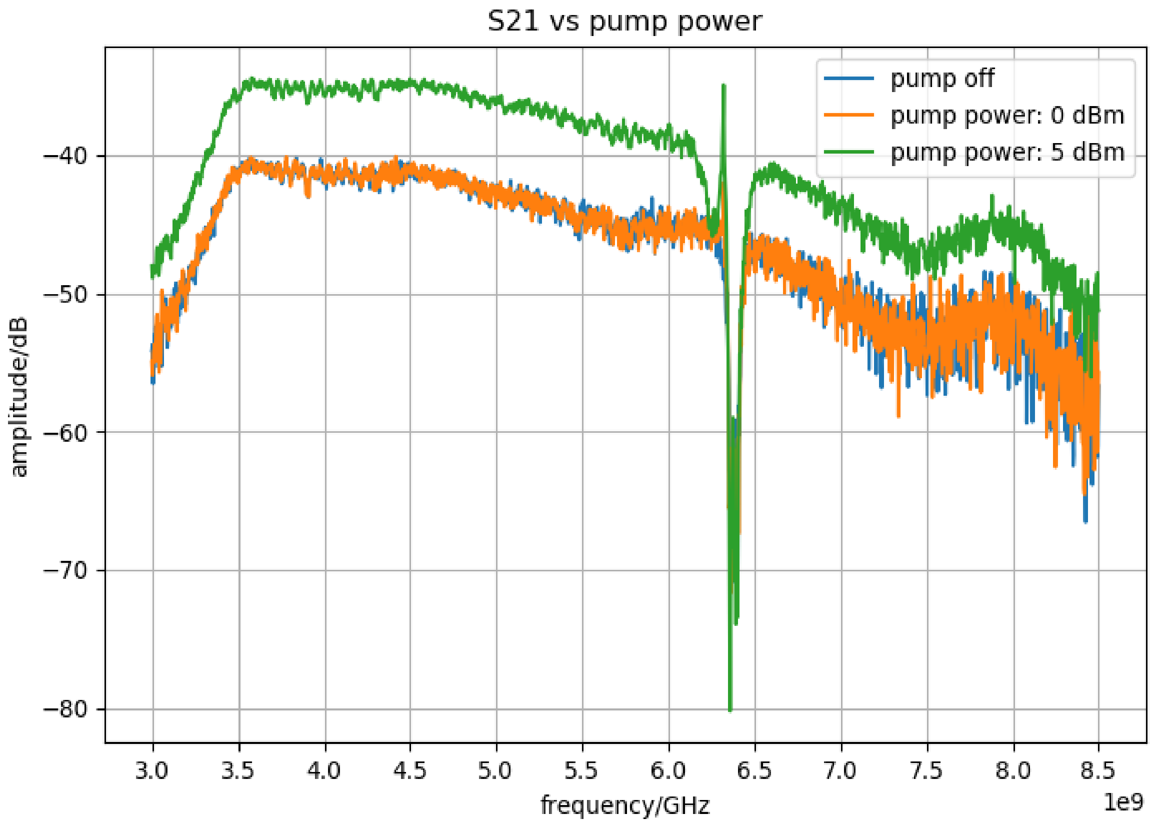


Pump power linecut

Port power: 0 dBm

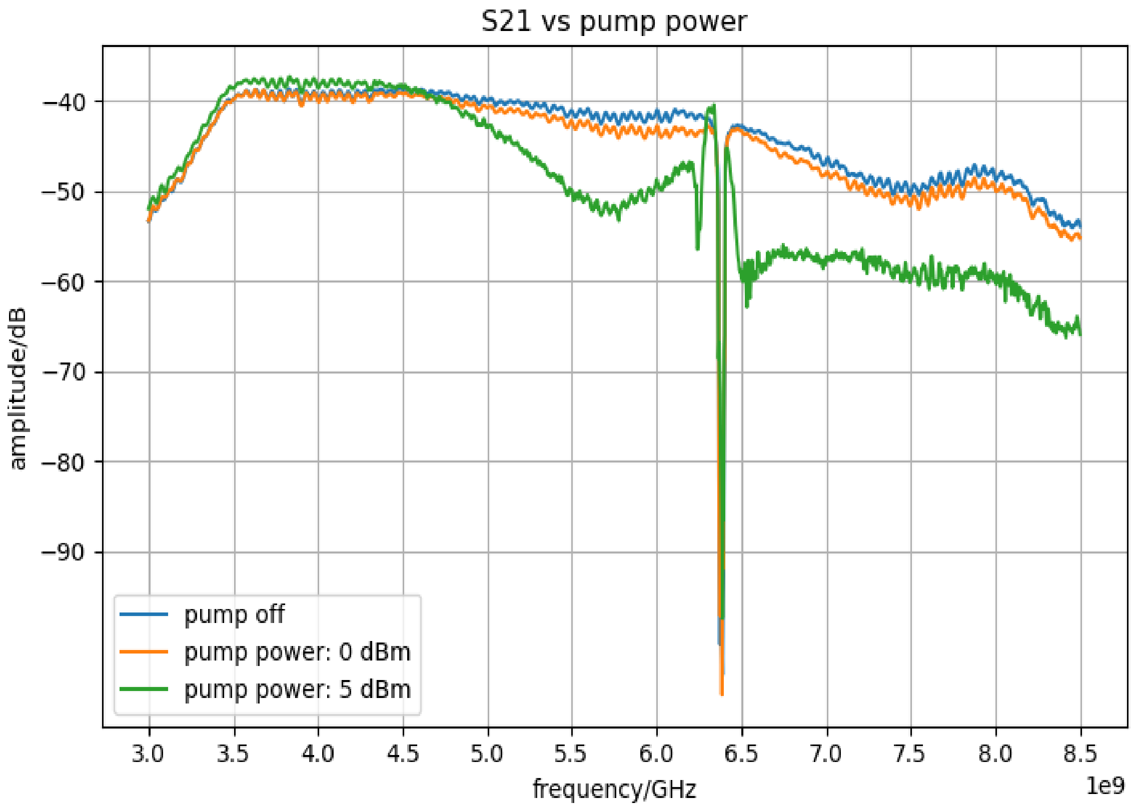


Port power: -30 dBm

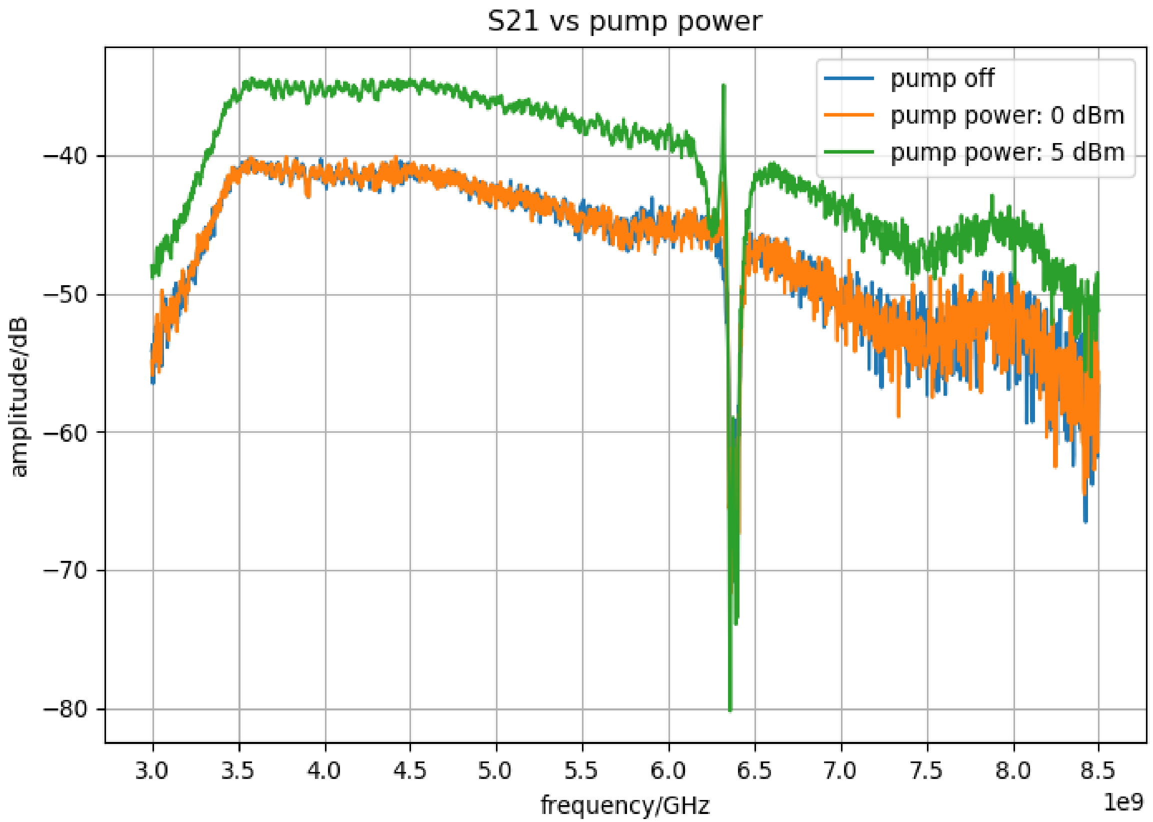


Pump power linecut

Port power: 0 dBm



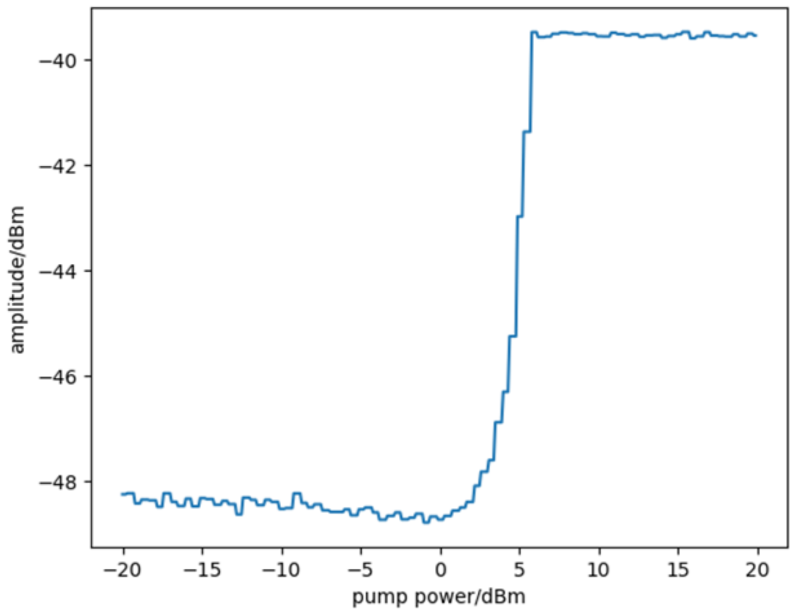
Port power: -30 dBm

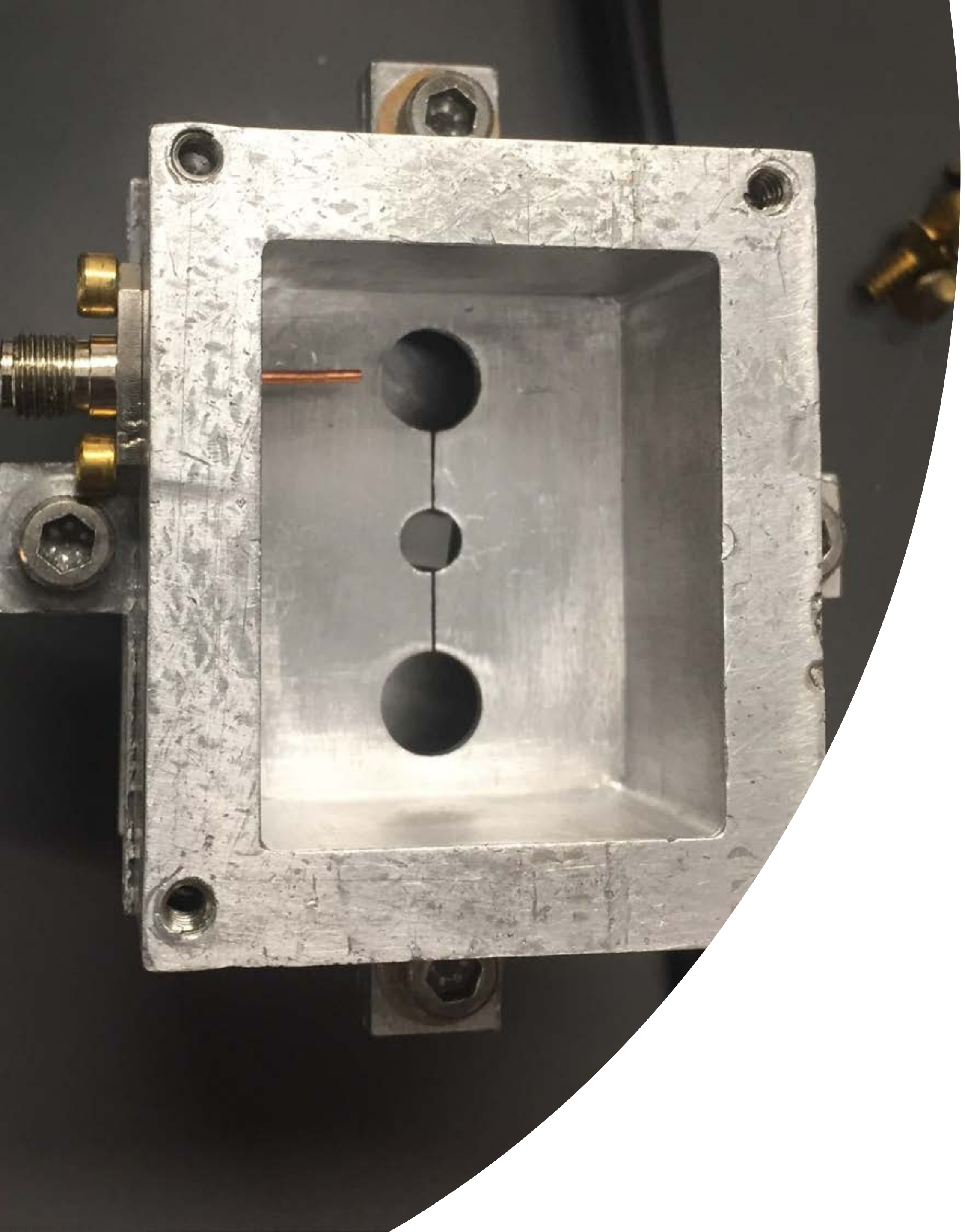


Leakage of pump power into higher harmonics, which may reduce gain
the onset of a shock wave

Conclusion

- We could have a signal gain of 10 dB with -75 dBm, 6.31 GHz pump on chip
- Might exist saturation of room temperature amplifiers
- Even with field off, put on magnetic shield to ensure normal operation





- Characterization of TWPA
- Enhancing sensitivity of EPR
- Setting up of HEMT

Motivation

Er^{+3}: Y_2O_3 has long spin coherence time and large, anisotropic g-factor

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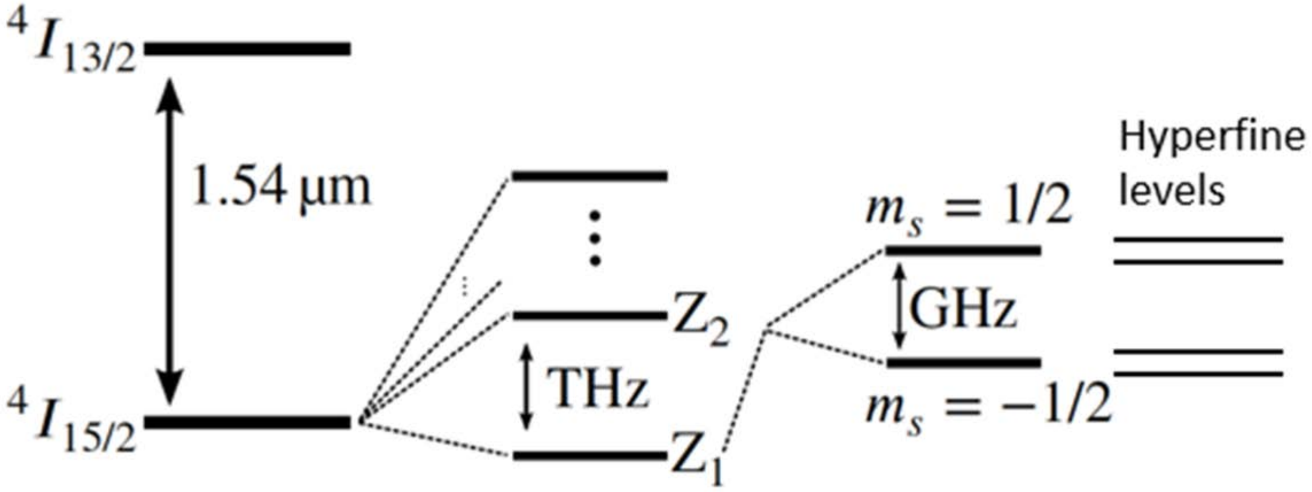
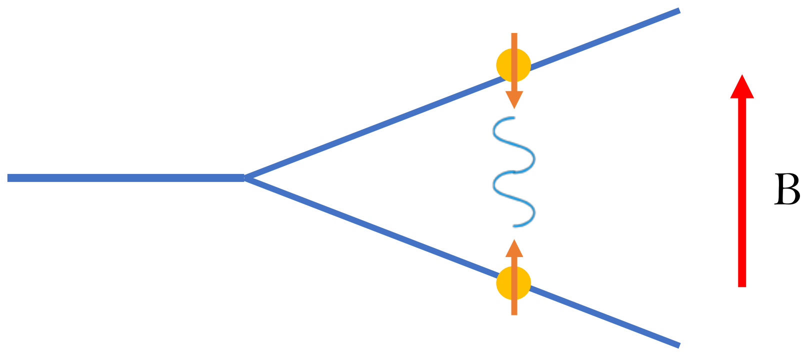
Er^{+3}: Y_2O_3 has long spin coherence time and large, anisotropic g-factor

$$\mathcal{H} = \mu_B(B.g_e.S) + S.A.I + I.Q.I - \mu_N(B.g_n.I)$$



EPR working principle

Absorption of photon increases the cavity loss rate



$h\upsilon = E = g\mu_B B$

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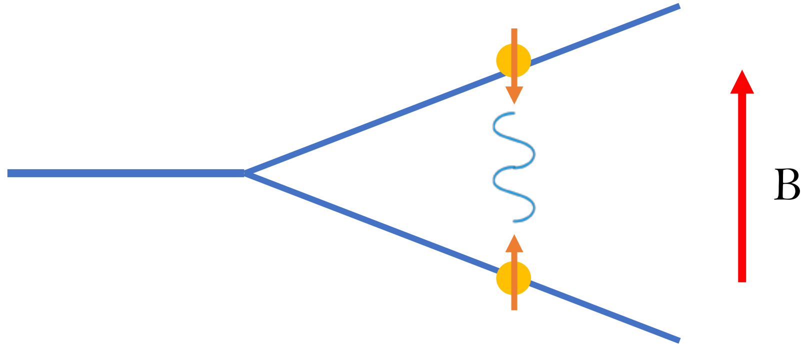

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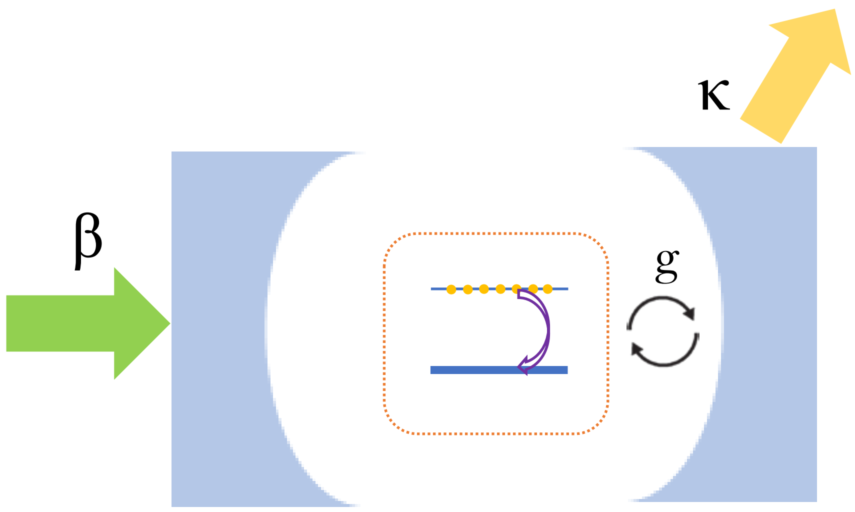

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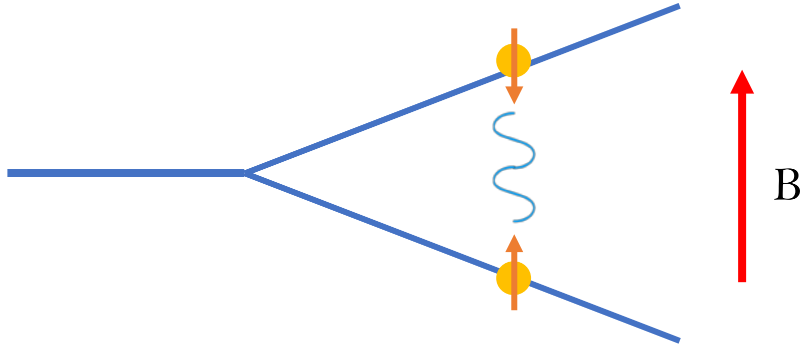

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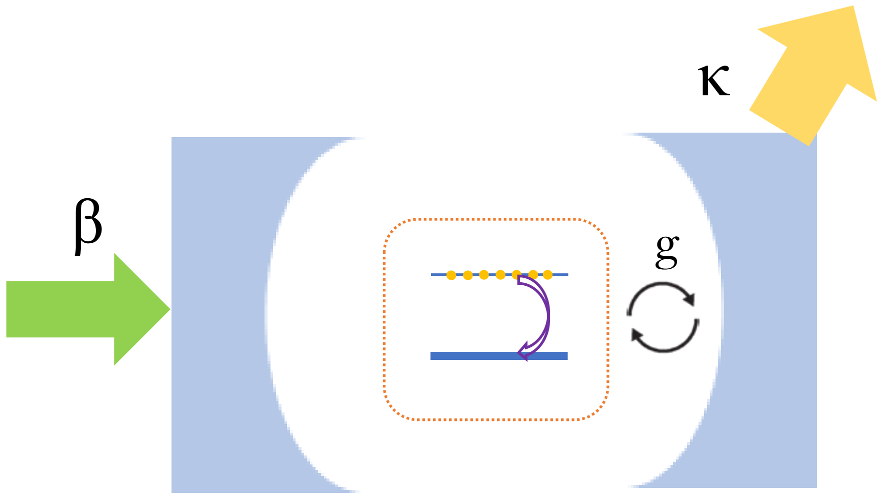
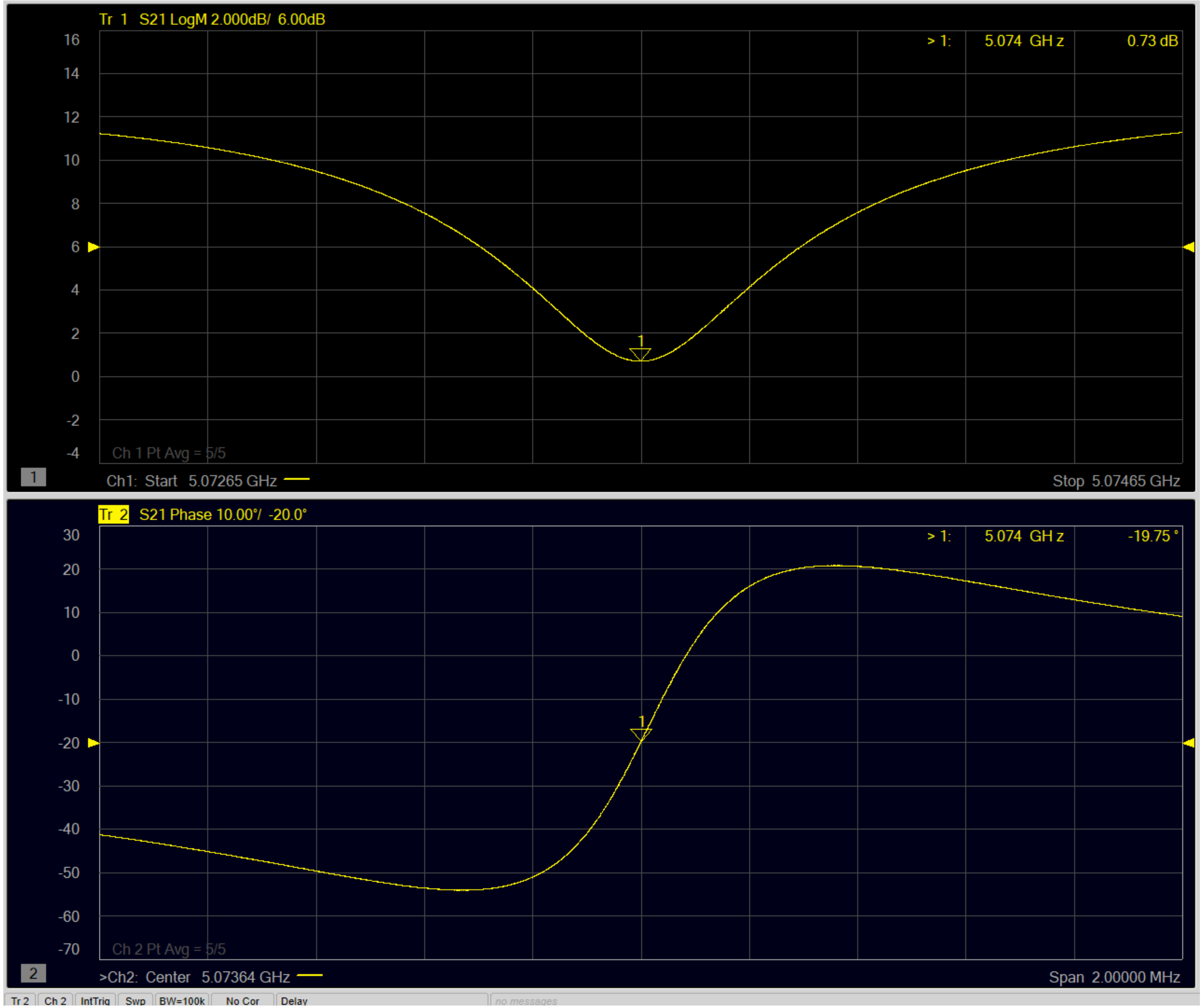
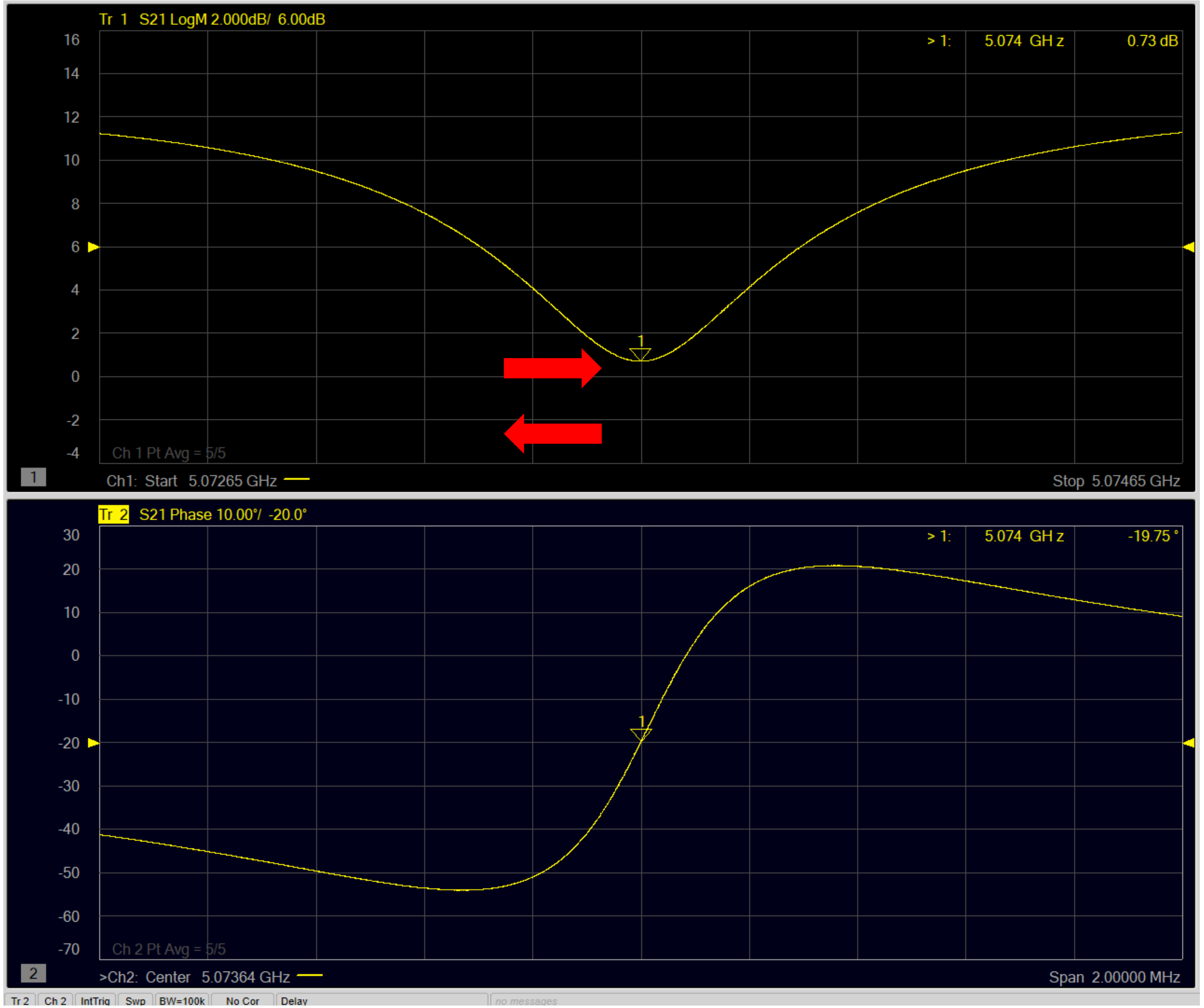




Tr 1 S21 LogM 2.000dB/ 6.00dB
> 1: 5.074 GHz 0.73 dB
Ch 1 Pt Avg = 5/5
Ch1: Start 5.07265 GHz
Stop 5.07465 GHz
Tr 2 S21 Phase 10.00°/ -20.0°
> 1: 5.074 GHz -19.75 °
Ch 2 Pt Avg = 5/5
>Ch2: Center 5.07364 GHz
Span 2.00000 MHz
Tr 2
Ch 2
IntTrig
Swp
BW=100k
No Cor
Delay



Tr 1 S21 LogM 2.000dB/ 6.00dB
> 1: 5.074 GHz 0.73 dB
16
14
12
10
8
6
4
2
0
-2
-4
Ch 1 Pt Avg = 5/5
1
Ch1: Start 5.07265 GHz
Stop 5.07465 GHz
Tr 2 S21 Phase 10.00°/ -20.0°
> 1: 5.074 GHz -19.75 °
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Ch 2 Pt Avg = 5/5
2
>Ch2: Center 5.07364 GHz
Span 2.00000 MHz
Tr 2
Ch 2
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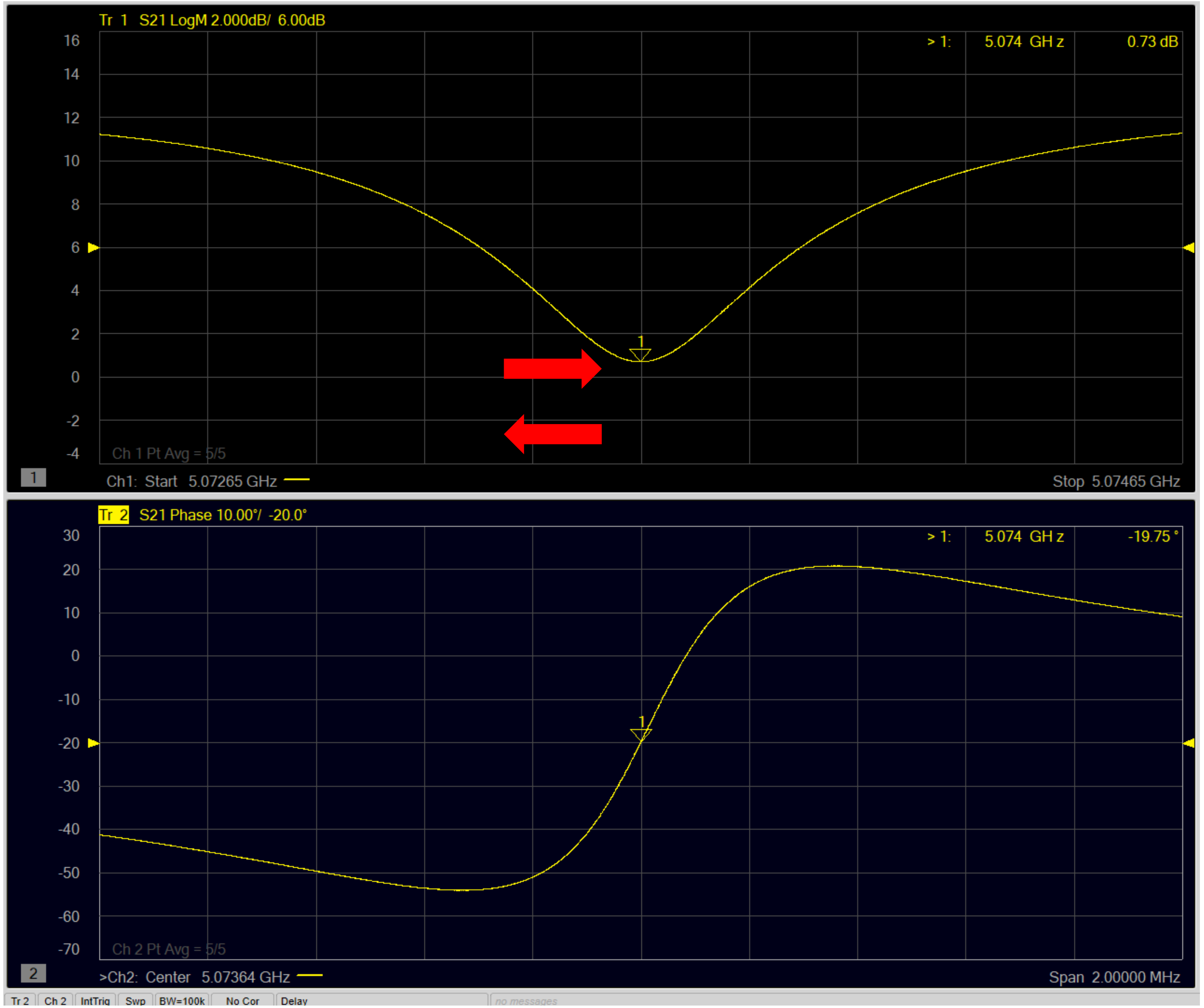
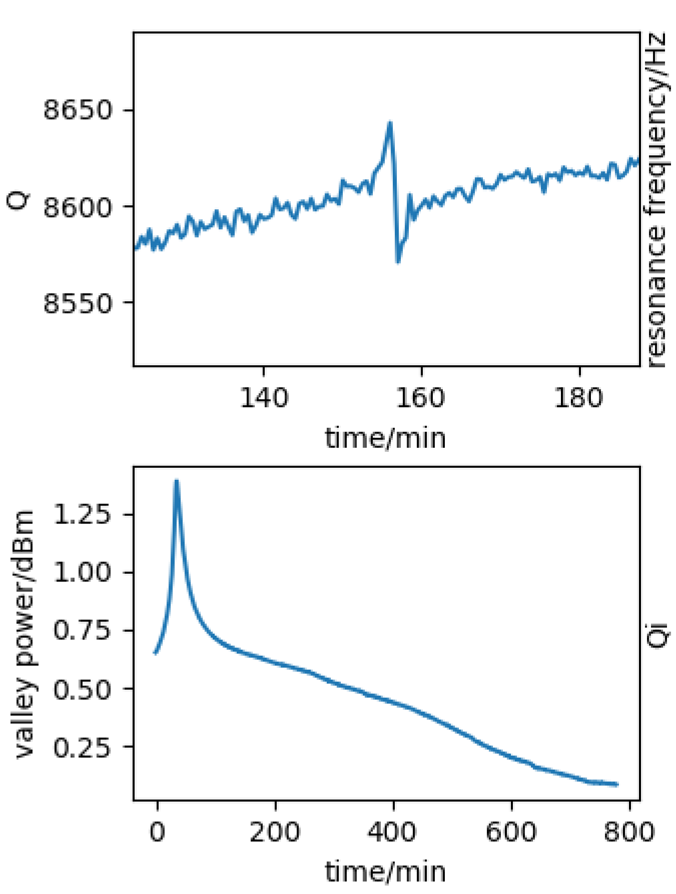


2 MHz span
1601 points
->up to 1.25 kHz sensitivity

slow and noisy
uncertainty of the size of frequency steps
contain much unnecessary data

VNA monitoring result of Nd:YSO

Ramp up from 75 - 375 mT, 0.2 mT step size, D2 direction



VNA monitoring result of Nd:YSO

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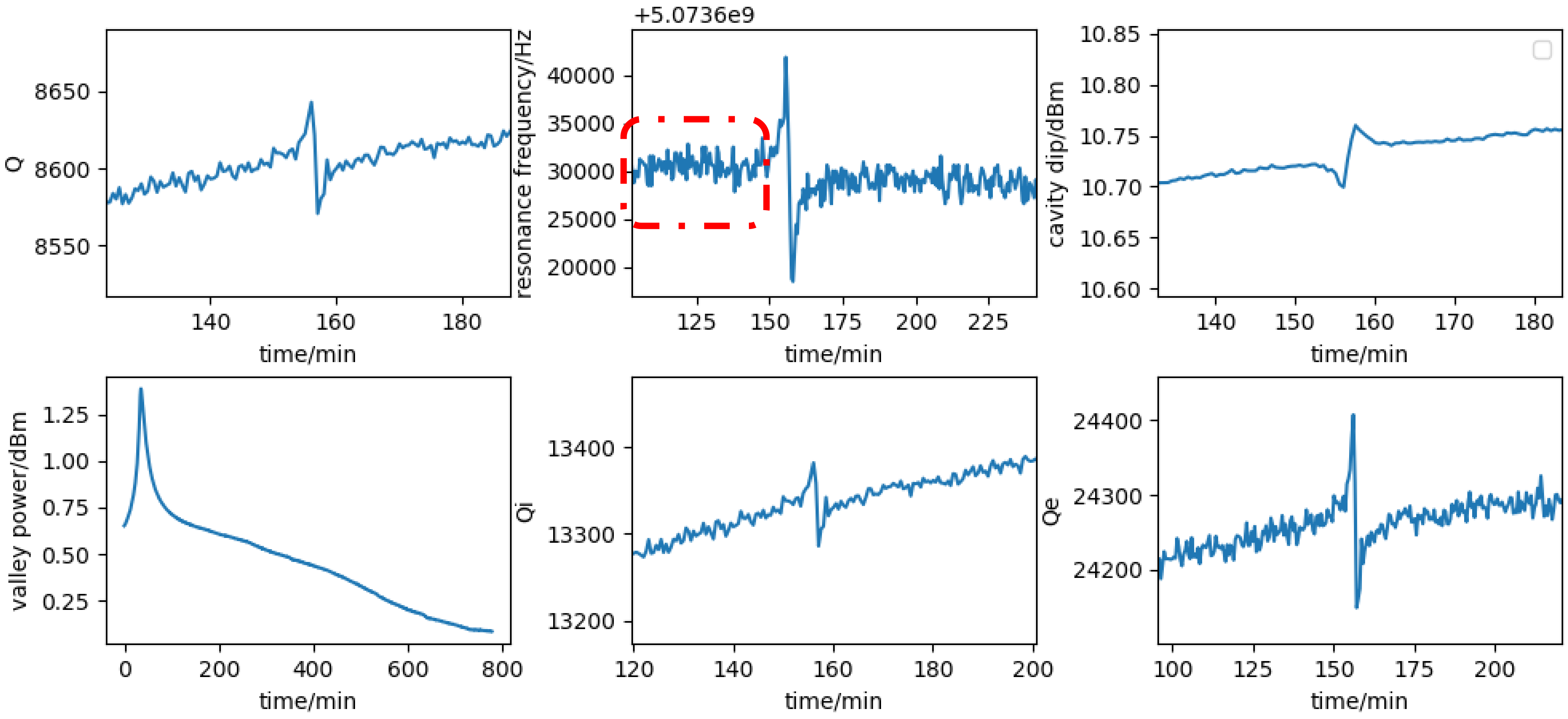
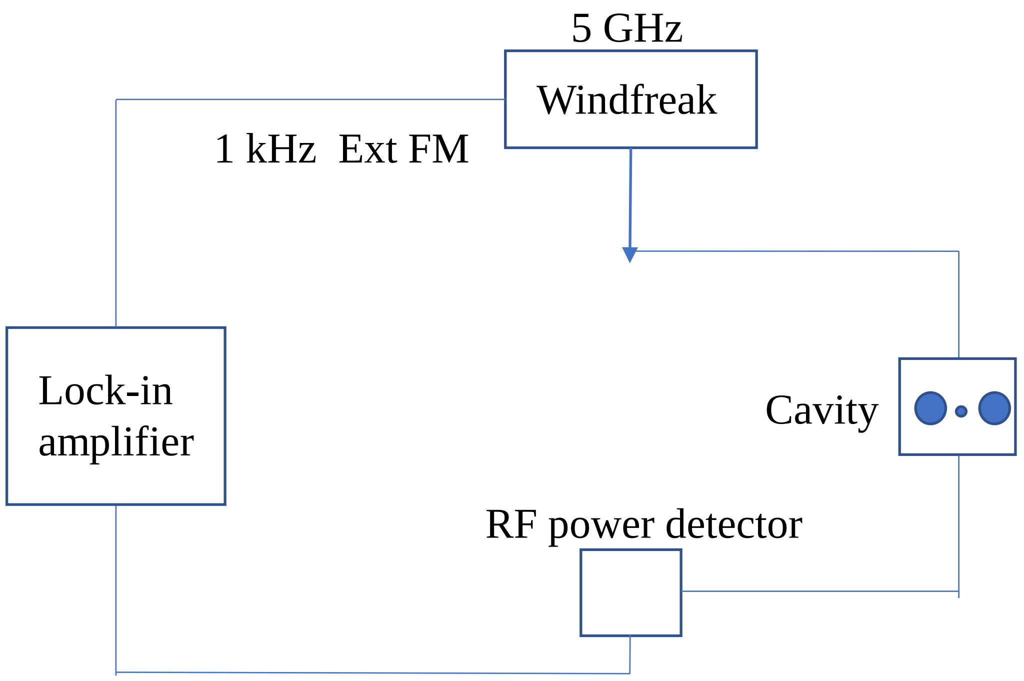
~ 4000 Hz resolution



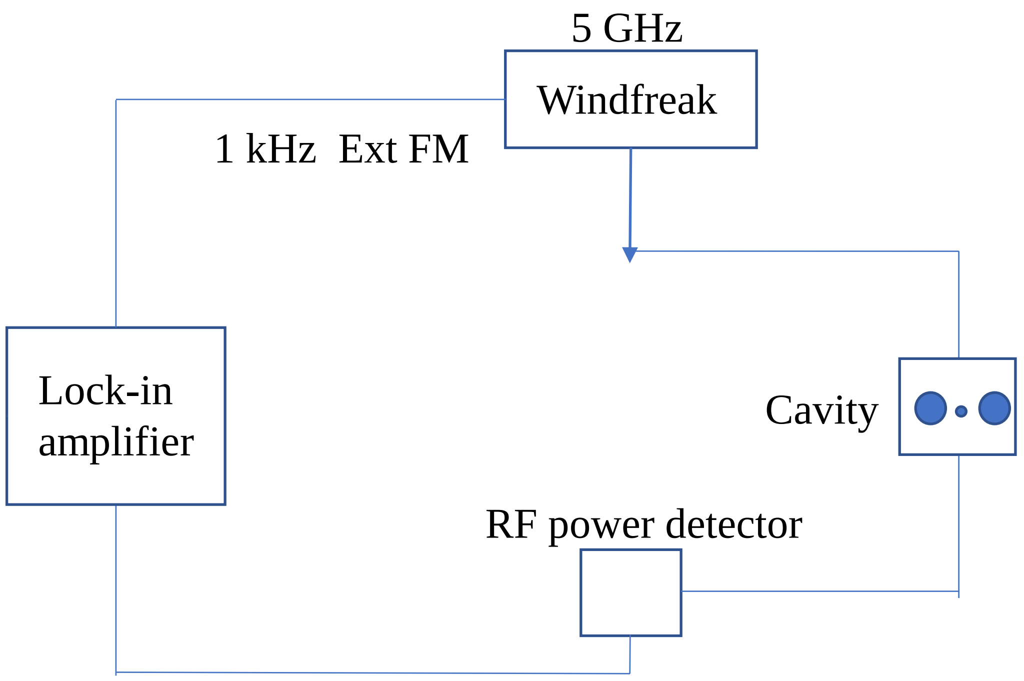
Lock-in setup



Lock-in setup

Cavity output: $a_1(t) = V_1 T(w(t)) * cos[(w_c + \Delta * cos(w_d t))t]$

Quasi-sinusoid error signal, demodulated by lock-in amp



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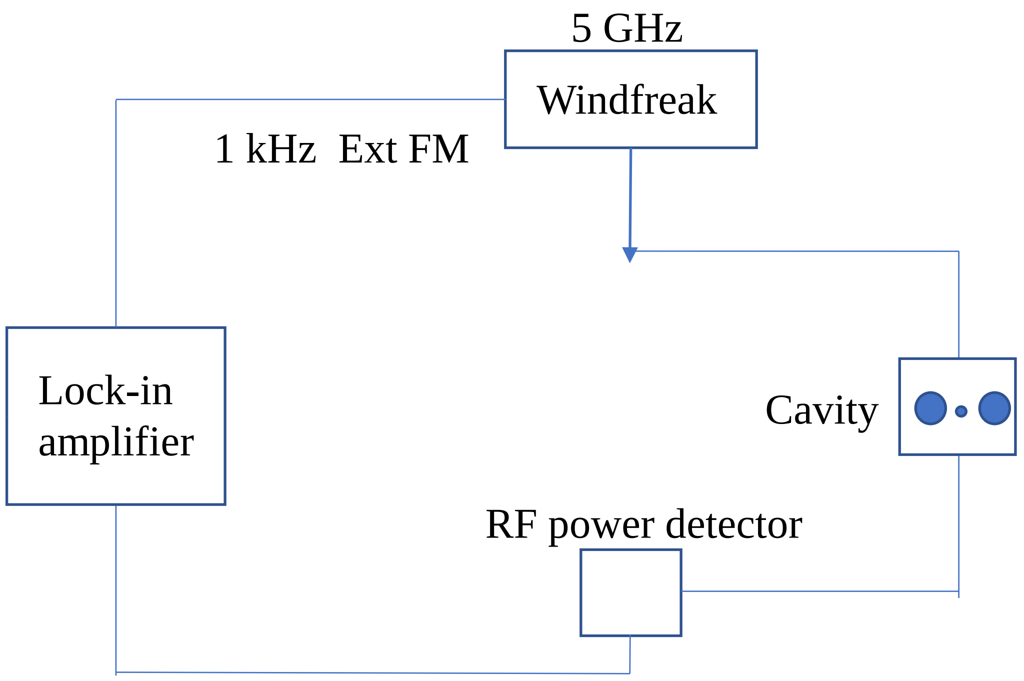
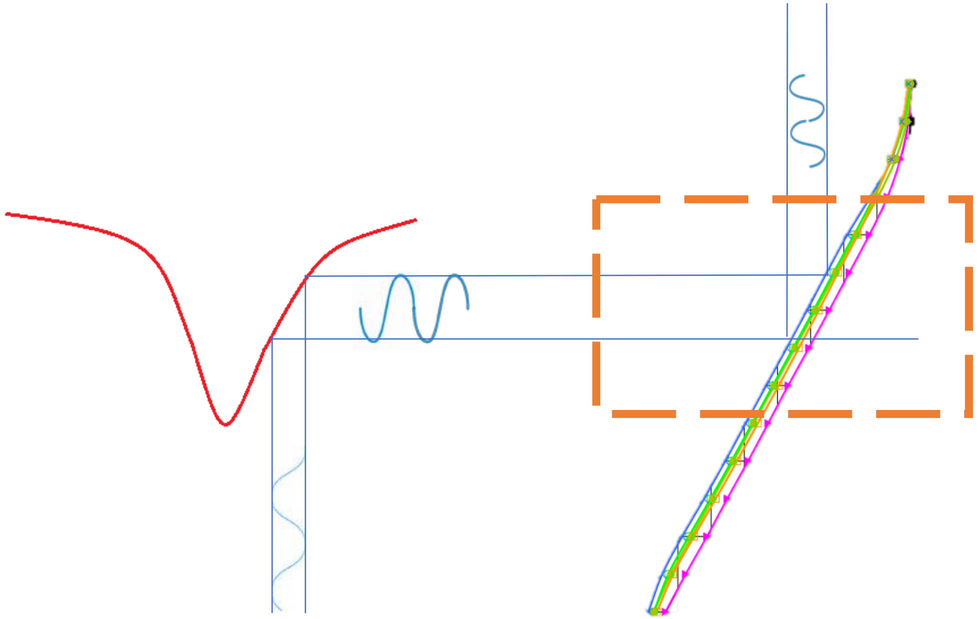
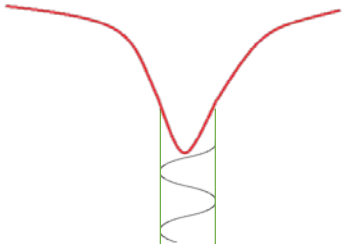


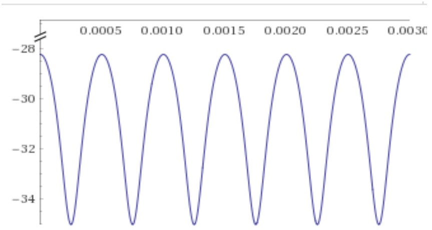


$$T(w) = \frac{k_i - k_e + 2i(w - w_0)}{k_i + k_e + 2i(w + w_0)}$$

Output of power detector V(w)

①





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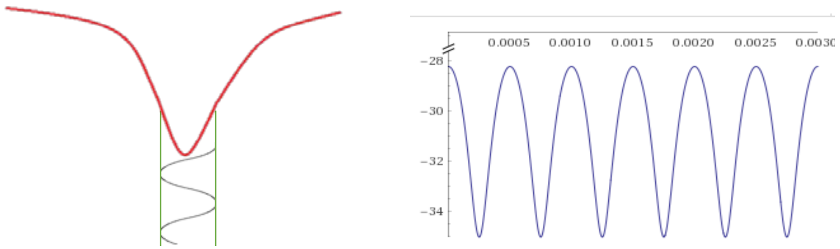
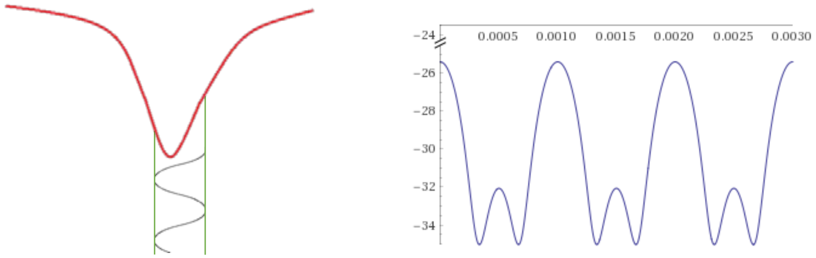


②



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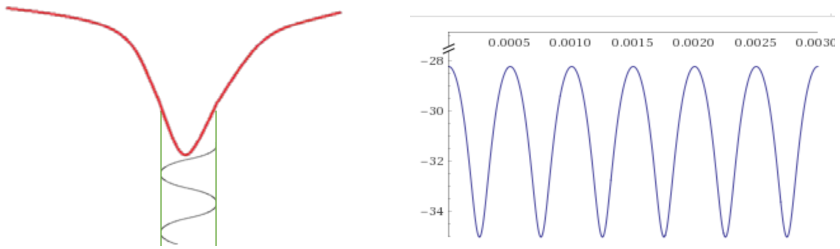

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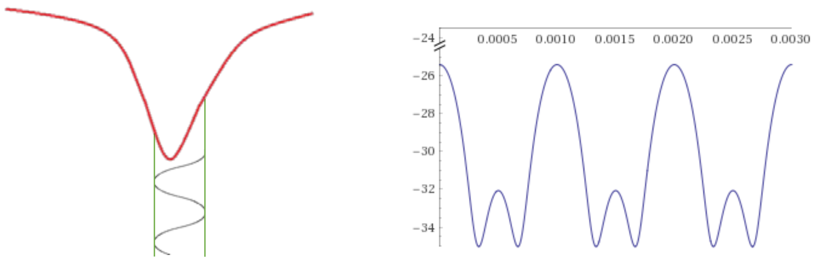

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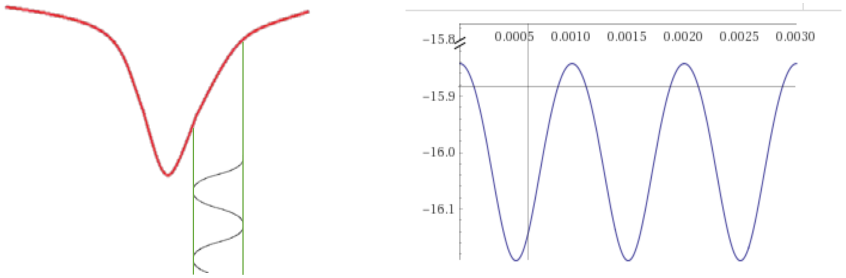

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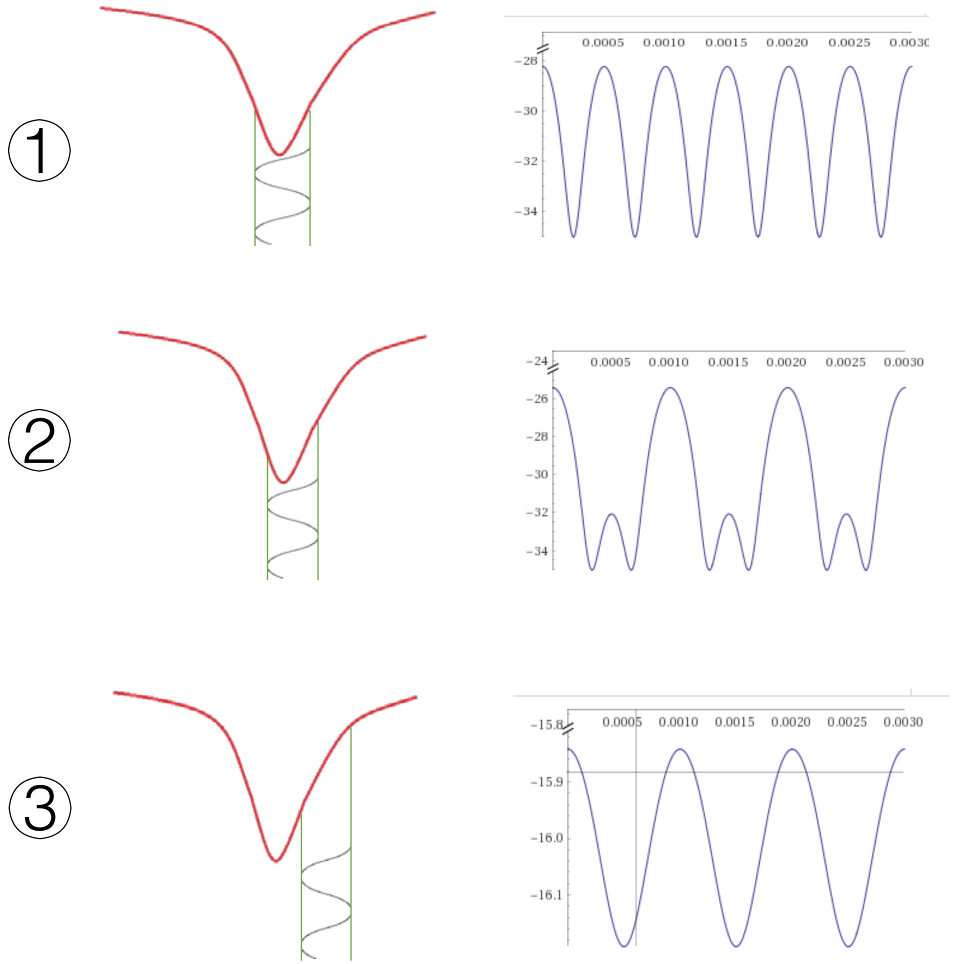
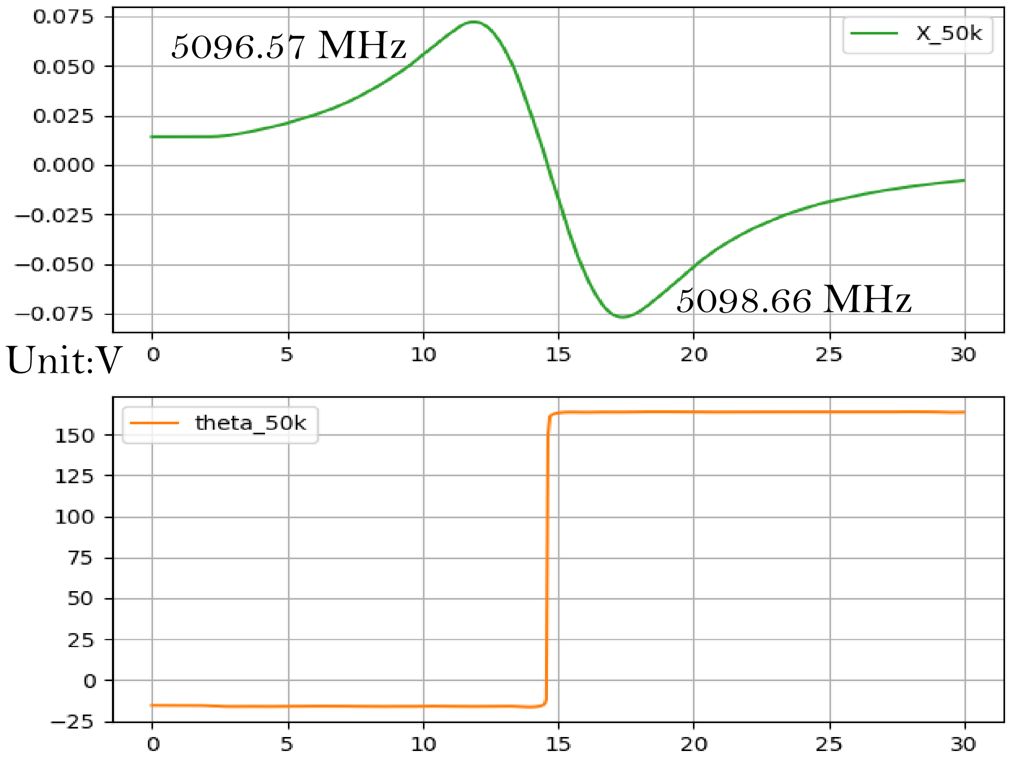
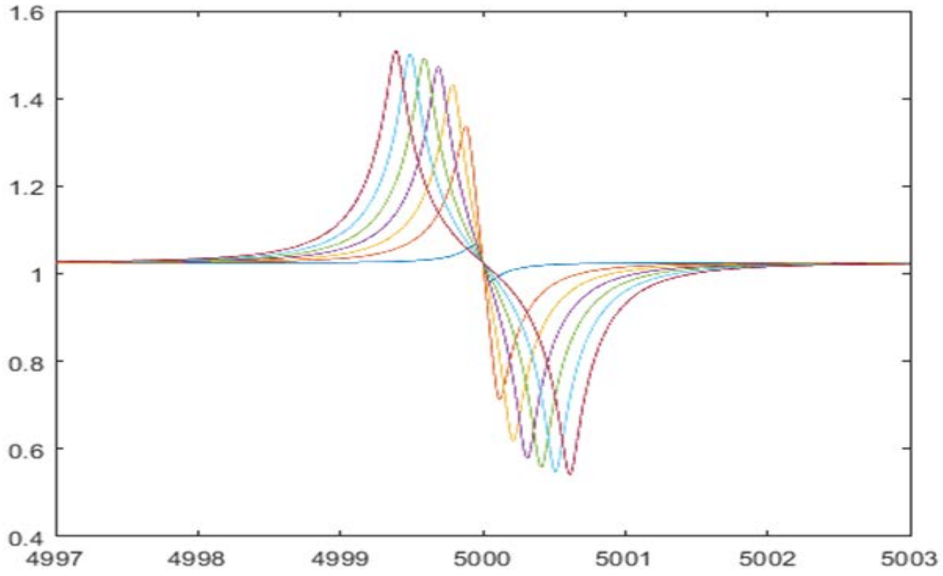


Lock-in display

$$a_1 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(w_d t)$$



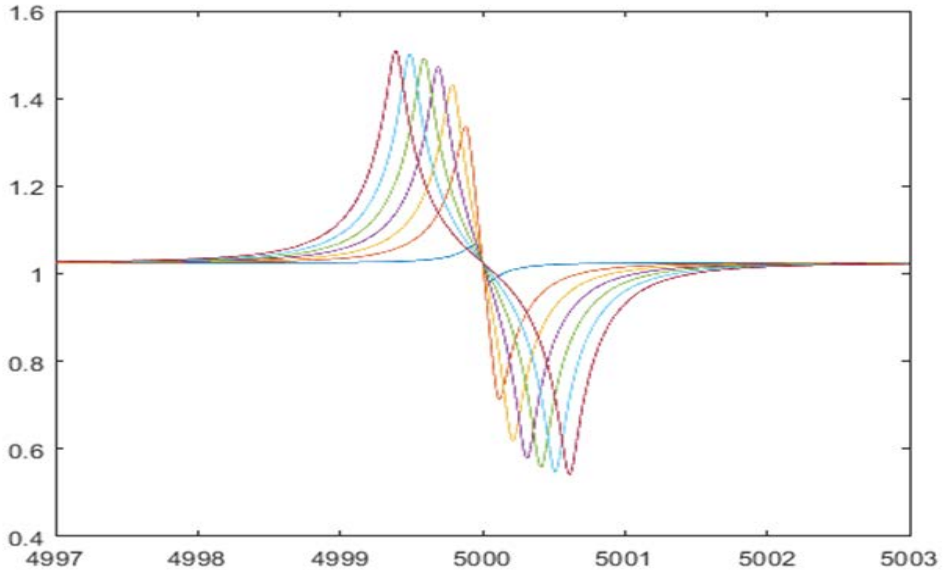
System optimization



Feature distorted at large deviation

Slope goes down

System optimization



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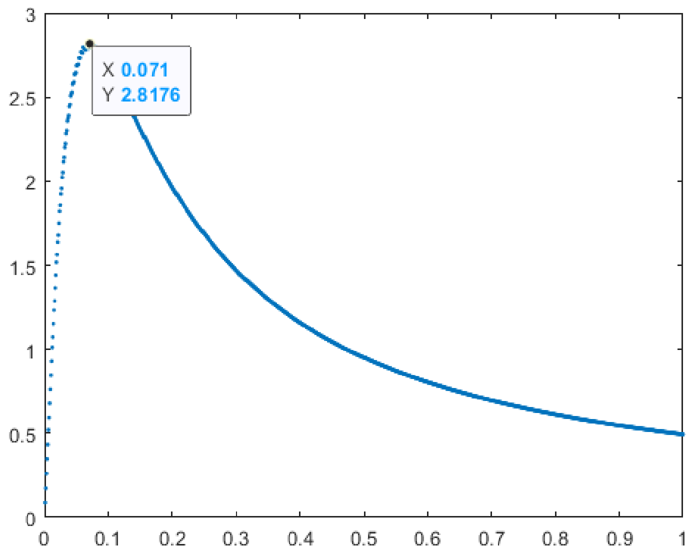
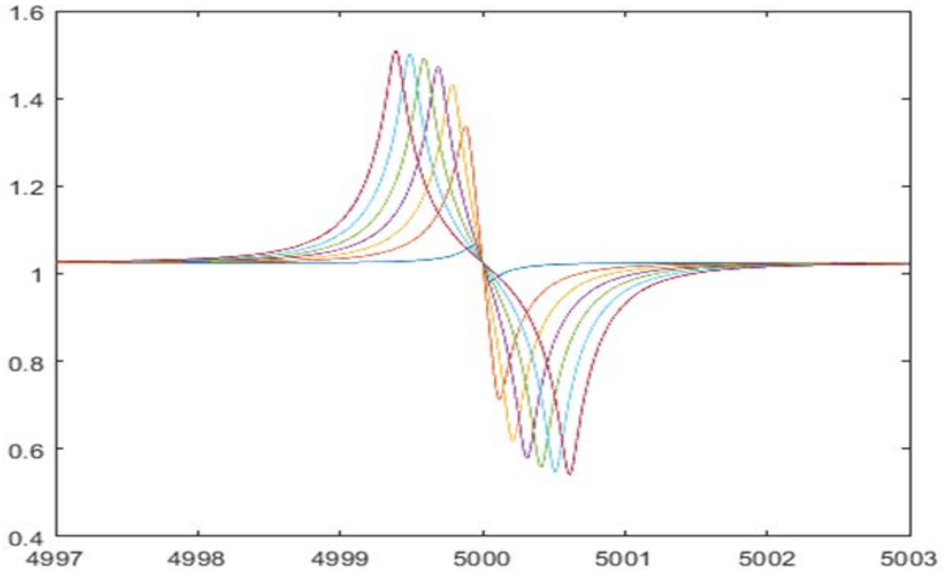


Cavity slope vs deviation frequency

System optimization



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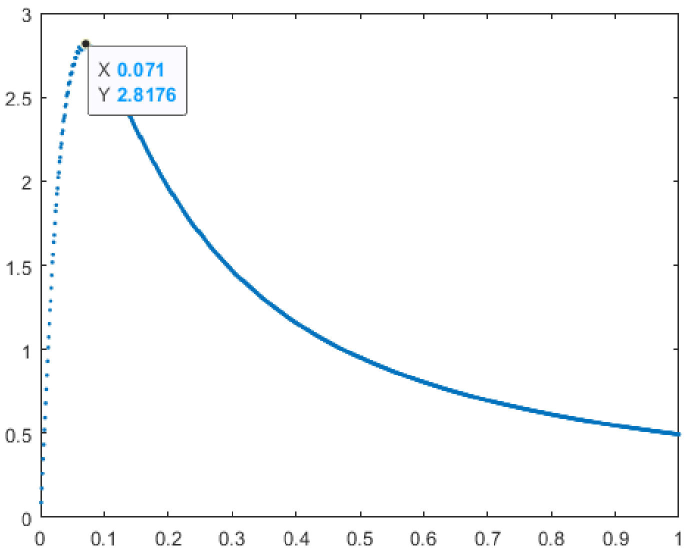
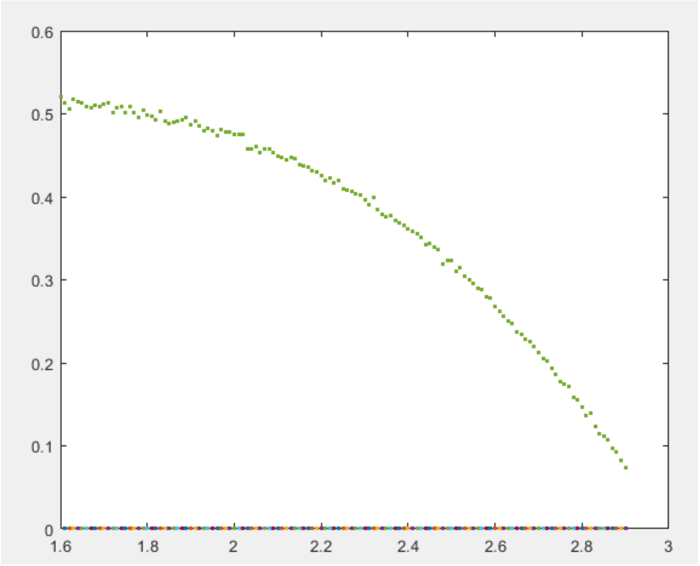


Cavity slope vs deviation frequency

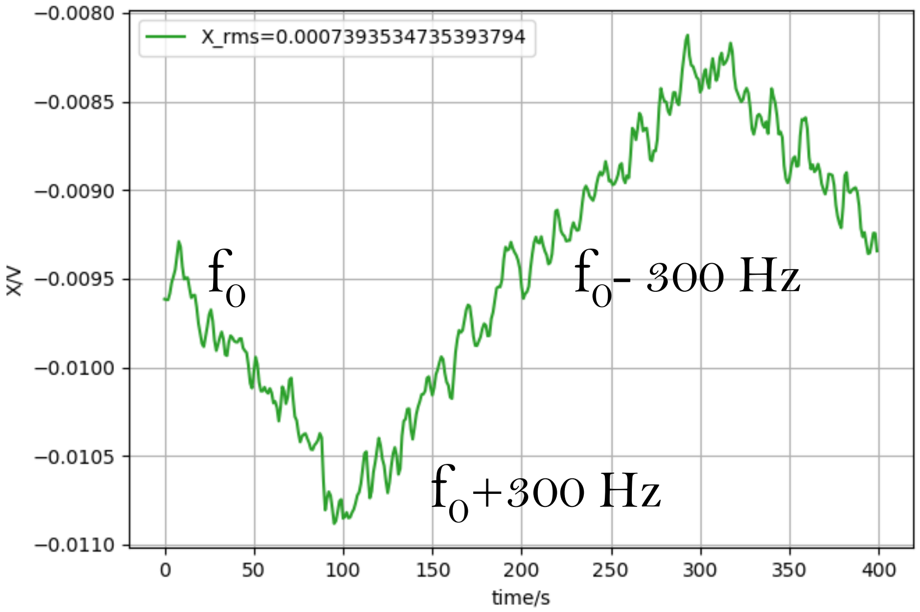


Best deviation vs κi+κe

Experimental result

Simulated frequency shift

10 times enhancement of sensitivity



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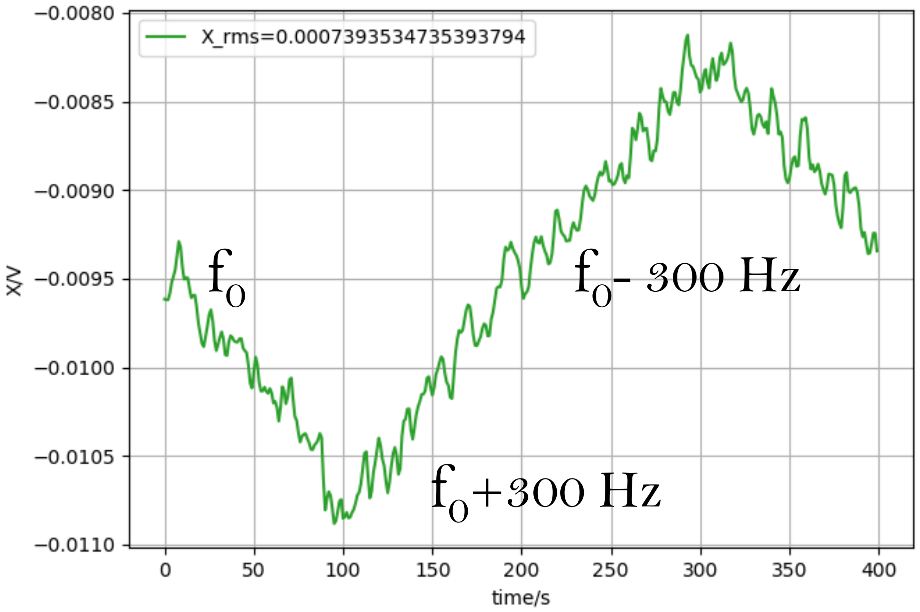
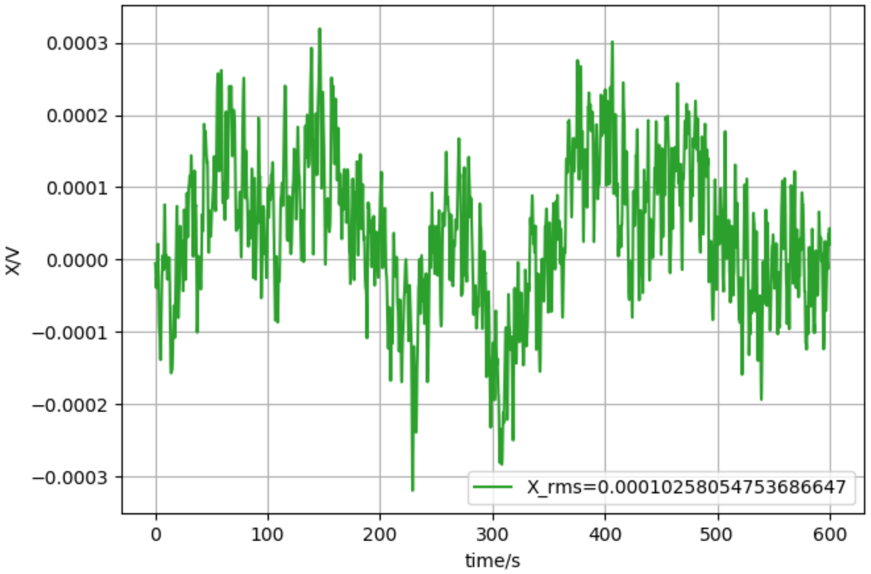


To further enhance sensitivity

① a feedback loop to stabilize the RF source frequency

② a better power detector

③ source with better FM control



0.1 V rms noise

Complex frequency shift

$$\frac{\Delta \tilde{f}}{f} = \frac{\Delta f}{f} + i\Delta \frac{1}{2Q}$$

Cavity perturbation by superconducting films in microwave magnetic and electric fields. D.-N. Peligrad et al.

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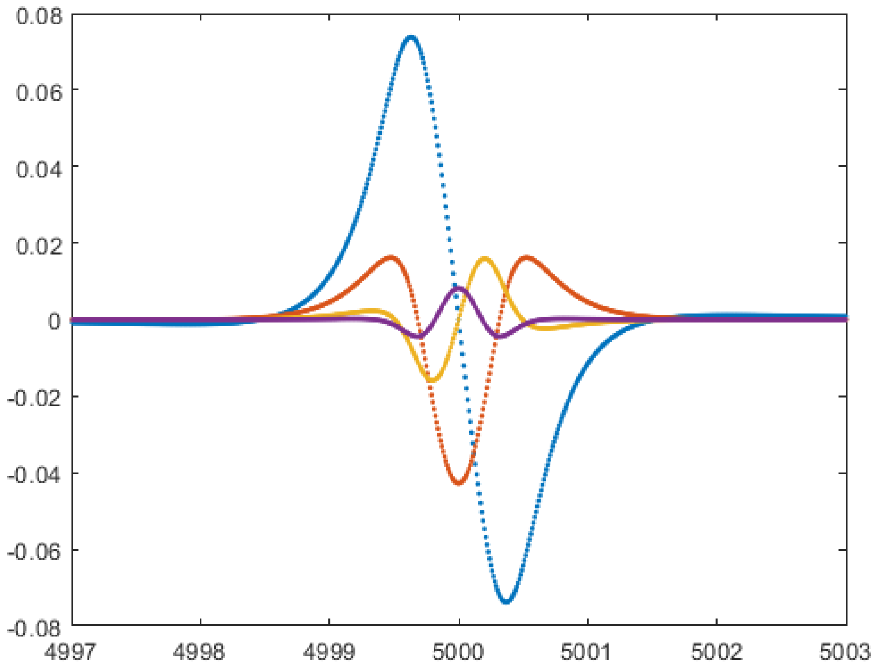

$$a_1 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(w_d t)$$

$$a_2 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(2w_d t)$$

$$a_3 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(3w_d t)$$

$$a_4 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(4w_d t)$$

Complex frequency shift

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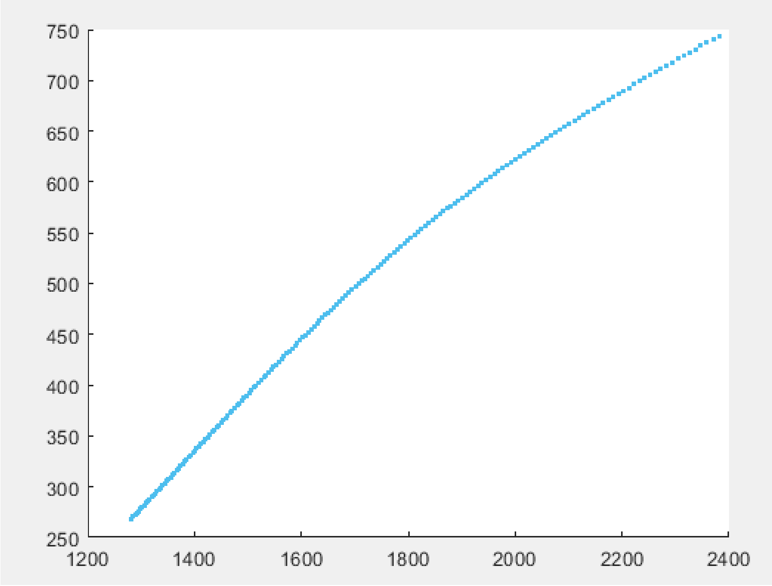
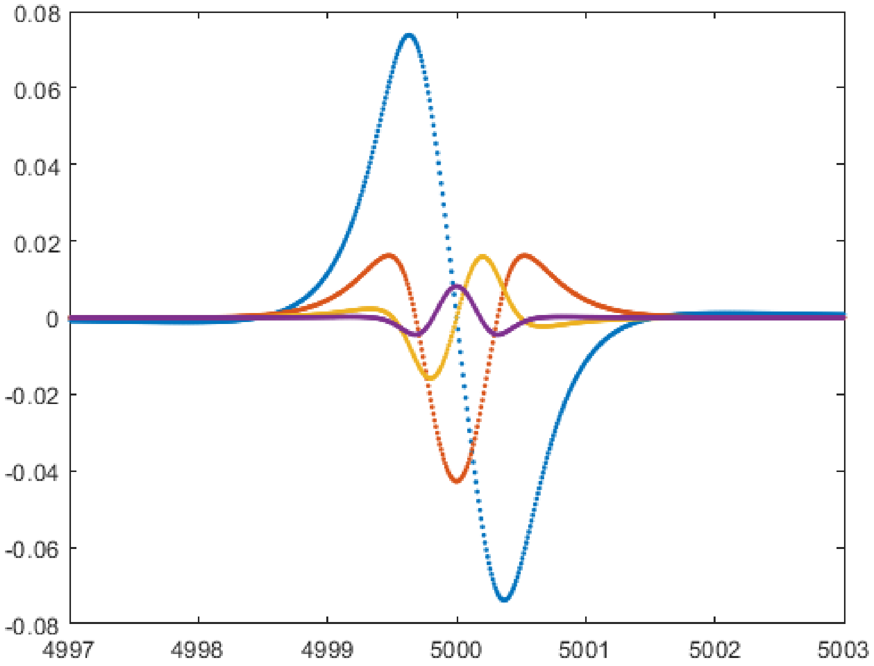


a_4/a_2 vs Q



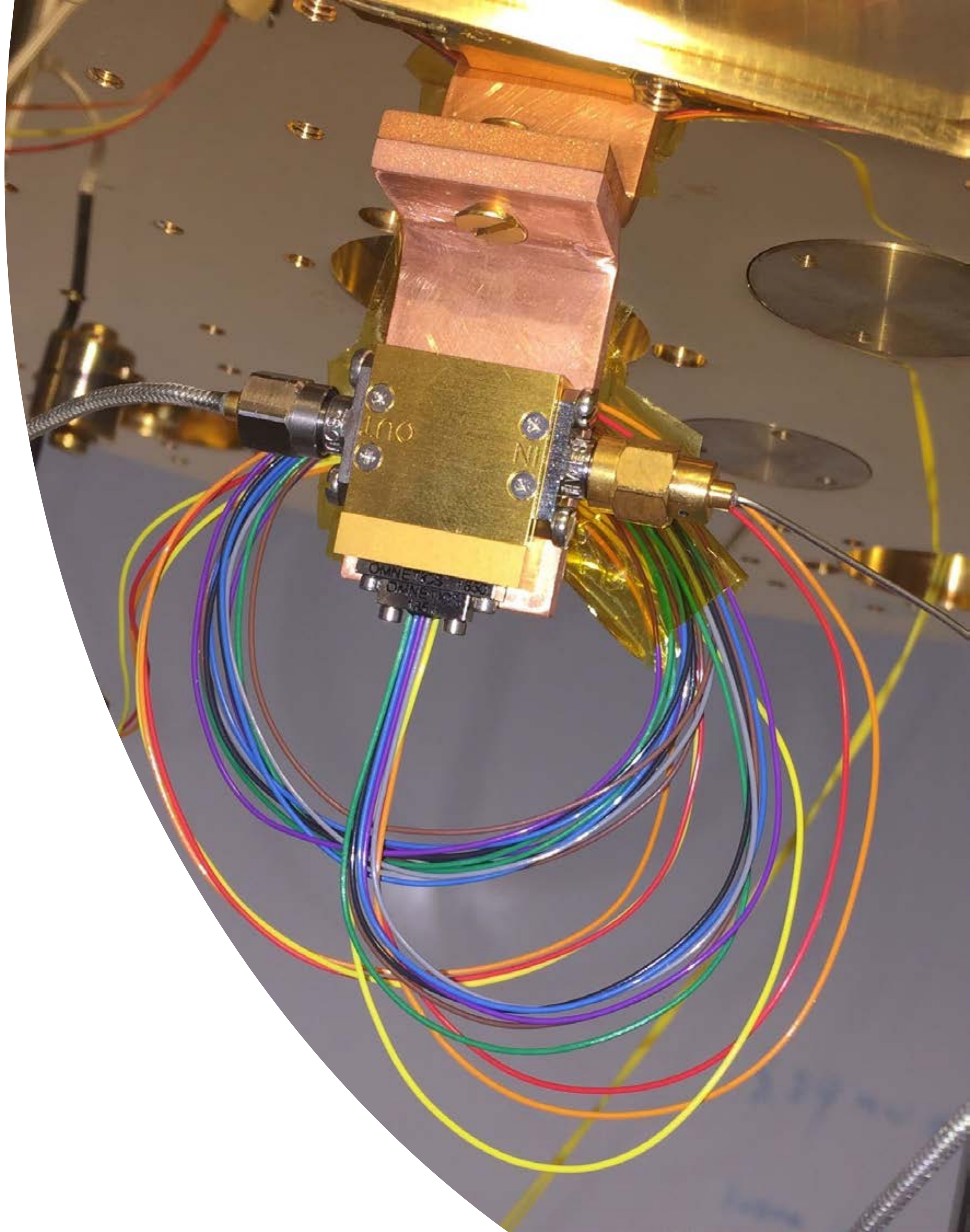
$$a_1 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(w_d t)$$

$$a_2 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(2w_d t)$$

$$a_3 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(3w_d t)$$

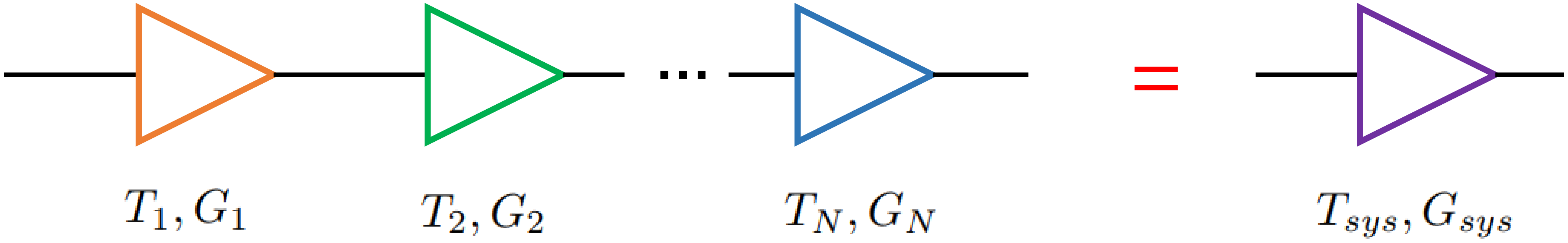
$$a_4 = \frac{w_d}{\pi} \int_0^{\frac{w_d}{2\pi}} V(w) * cos(4w_d t)$$

- Characterization of TWPA
- Enhancing sensitivity of EPR
- Setting up of HEMT



Necessity of HEMT

- The noise figure of an amplification chain largely depends on the first amplifier

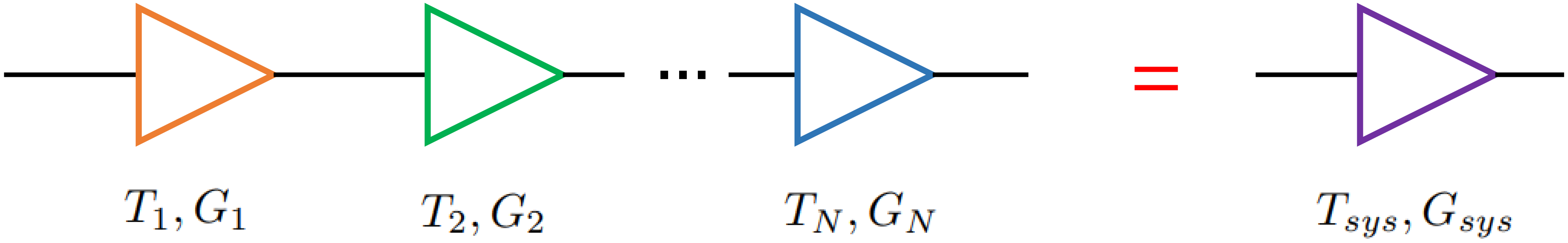


Necessity of HEMT

- The noise figure of an amplification chain largely depends on the first amplifier

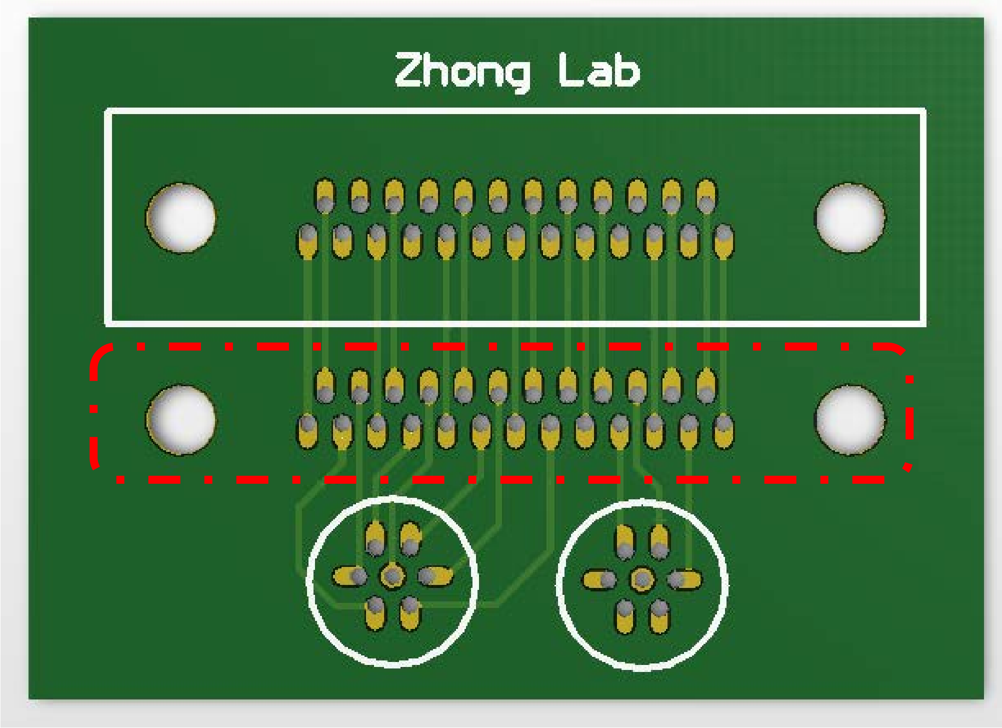
Friis formula:

$$T_{sys} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots + \frac{T_N}{G_1 G_2 \ldots G_{N-1}}$$



DC connection

- Split the 25 pins into three parts



DC connection

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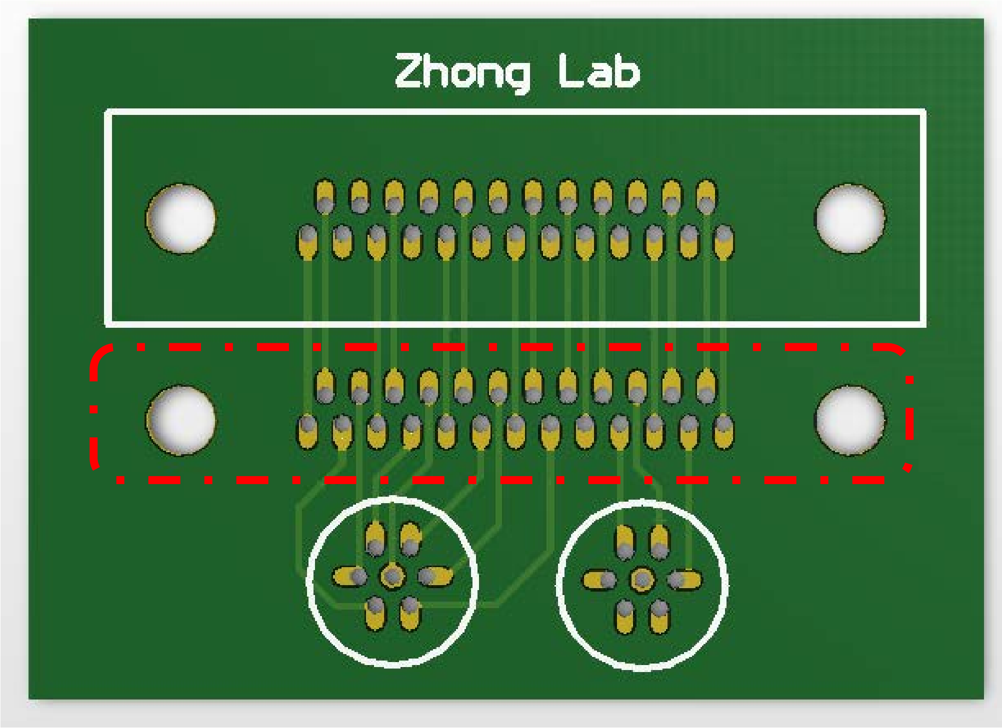
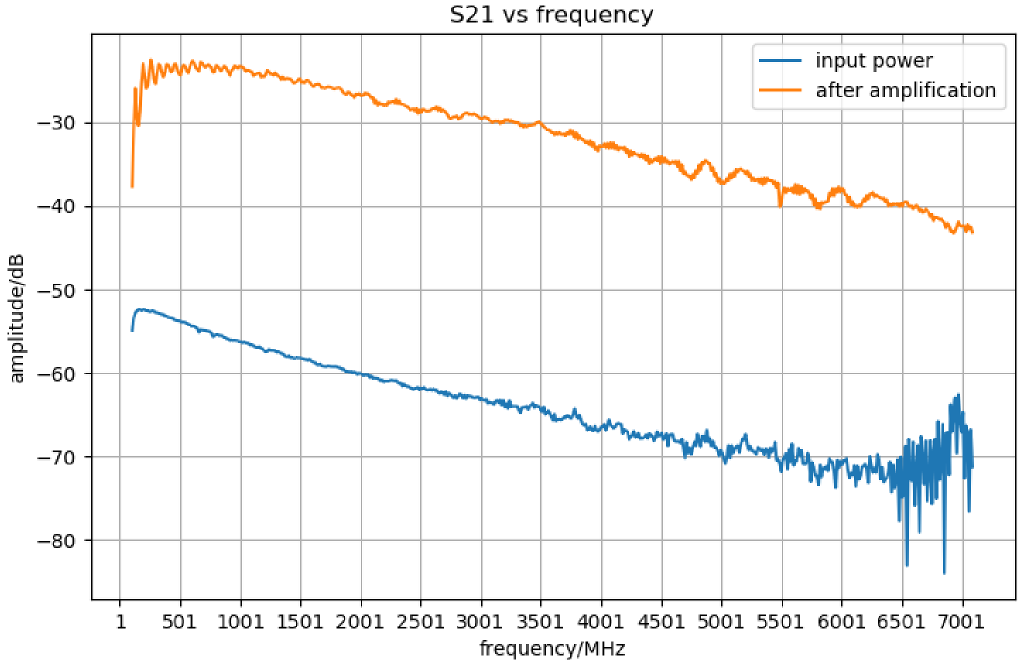
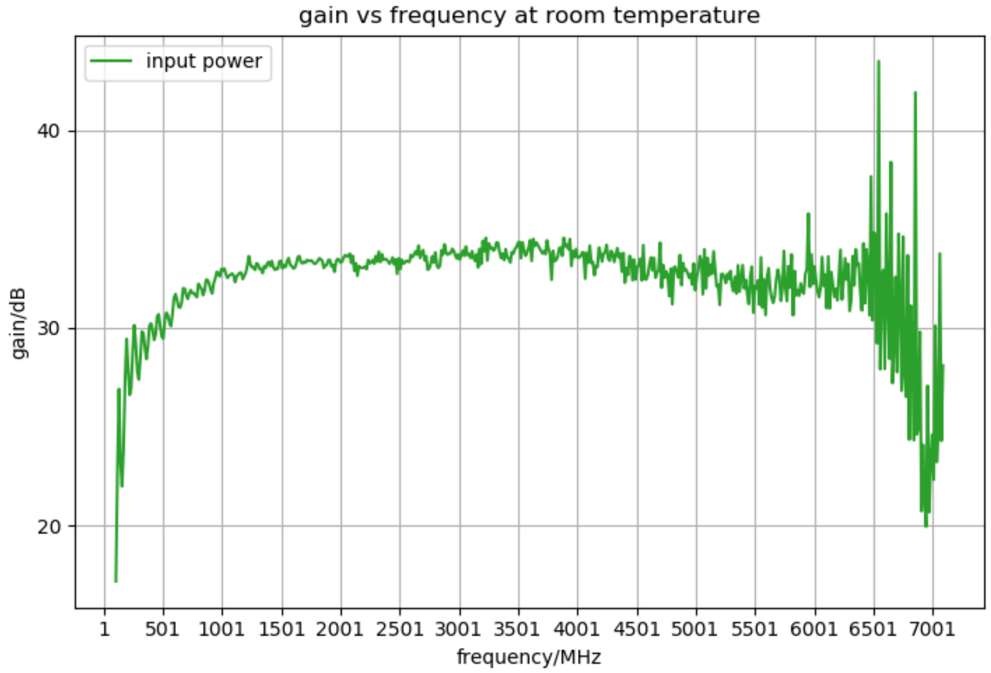


Room temperature amplification

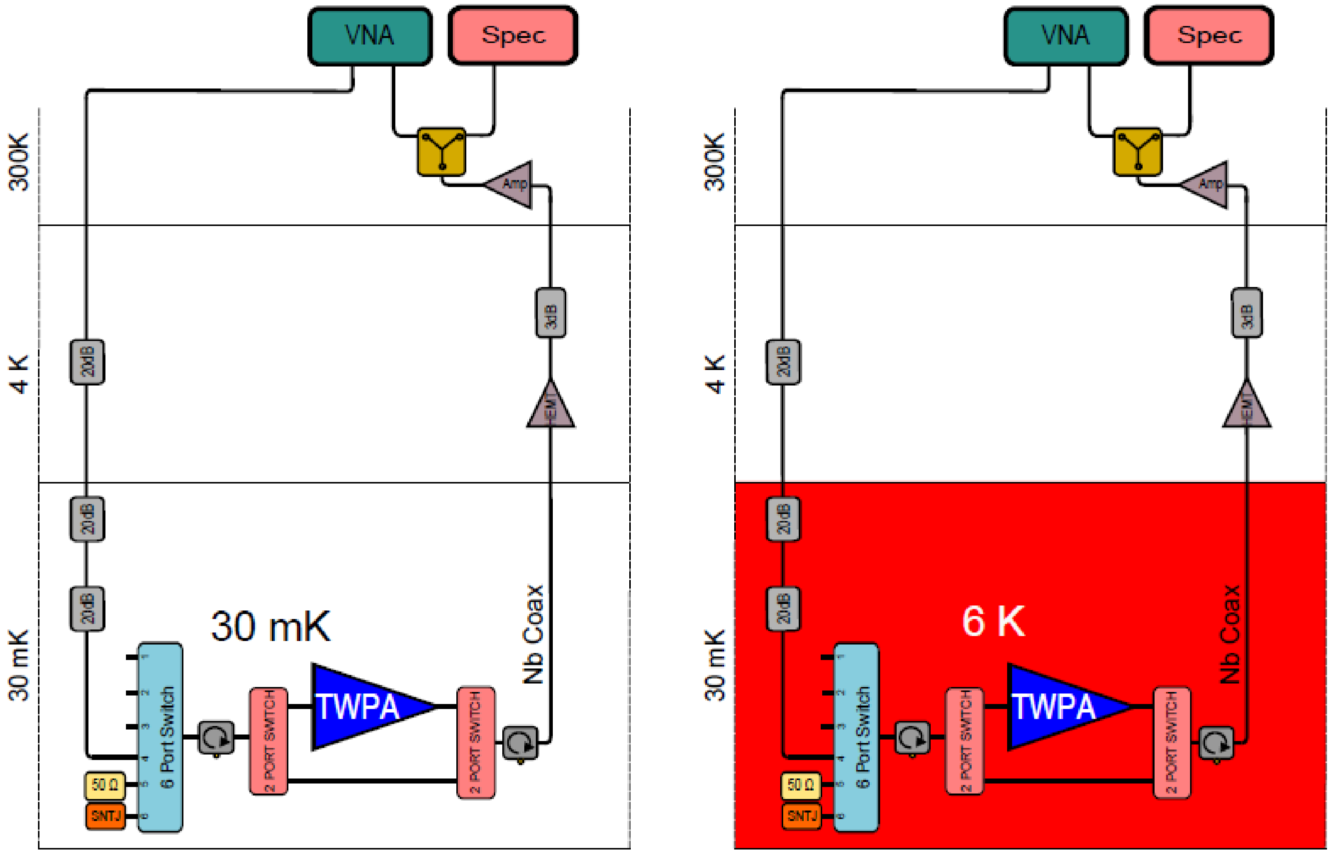
- To get better curve, use VNA with calibration





Noise figure measurement

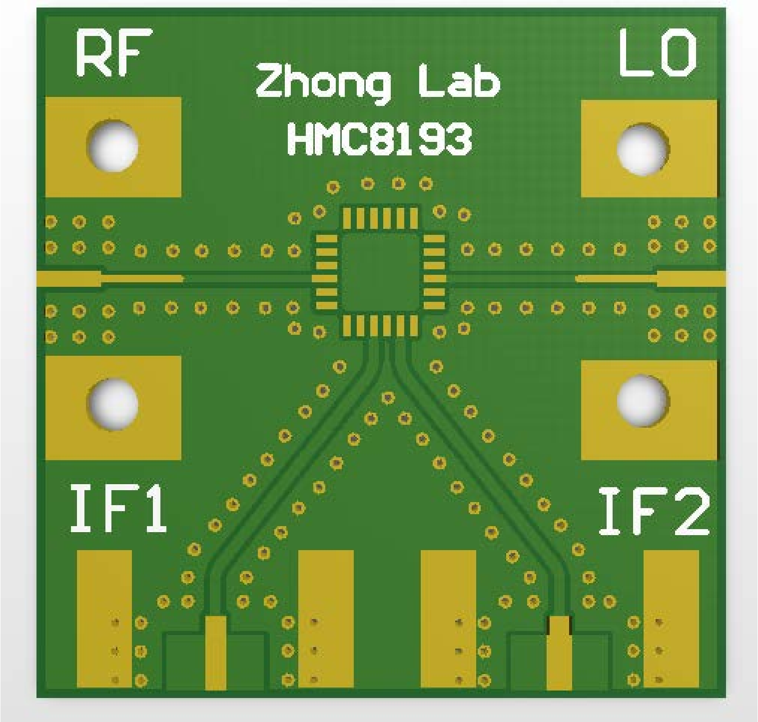
Y factor method



Traveling wave parametric amplifier with Josephson junctions using minimal resonator phase matching. Supplemental information. T.C. White et al.

Test board & IQ demodulator

- 10 mil width, 7.5 mil gap, 7.1 mil thickness



Test board & IQ demodulator

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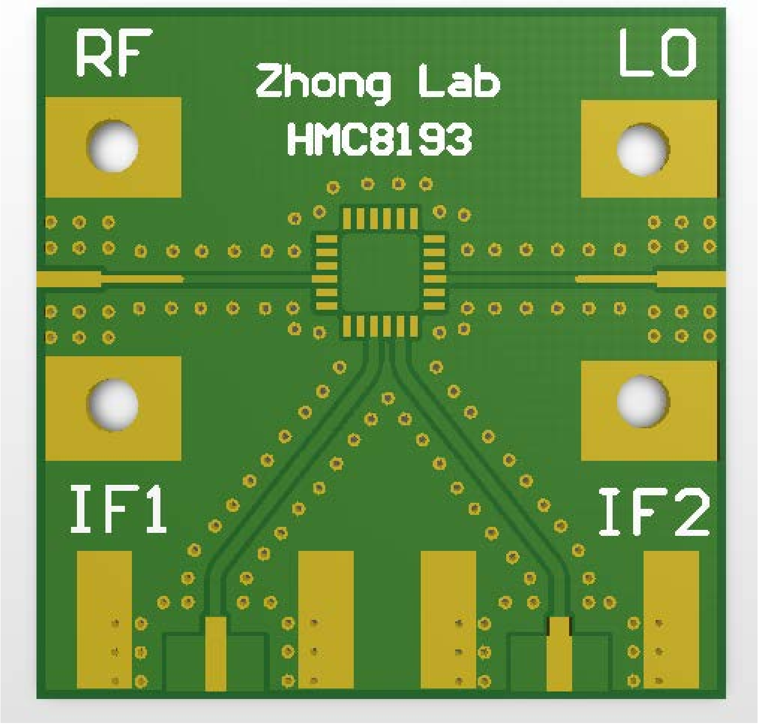

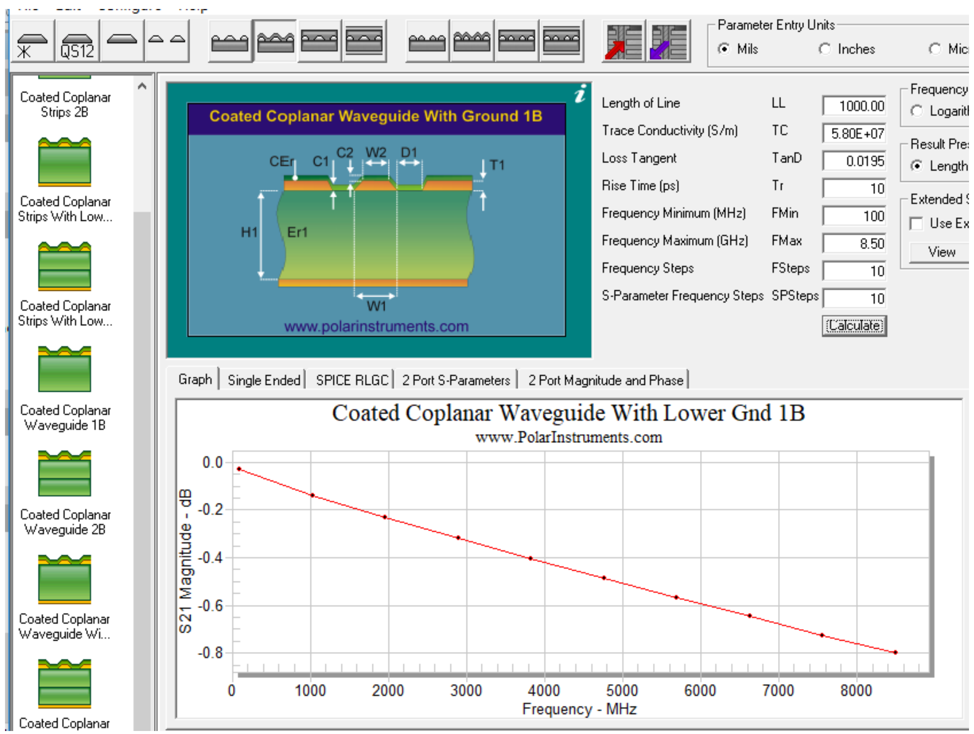

Test board & IQ demodulator

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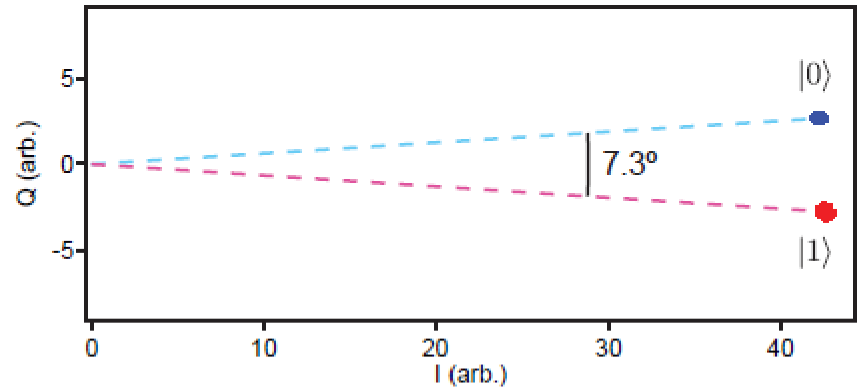

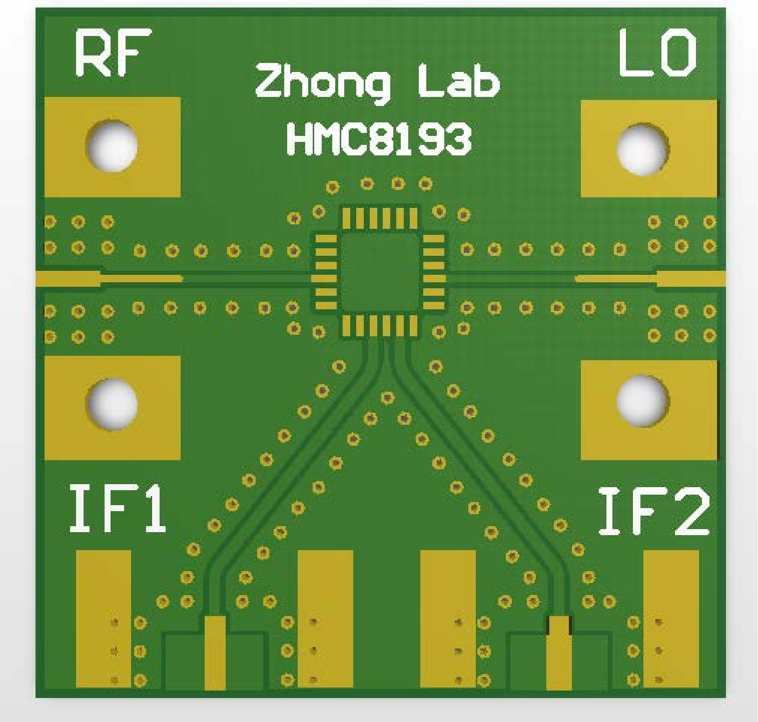

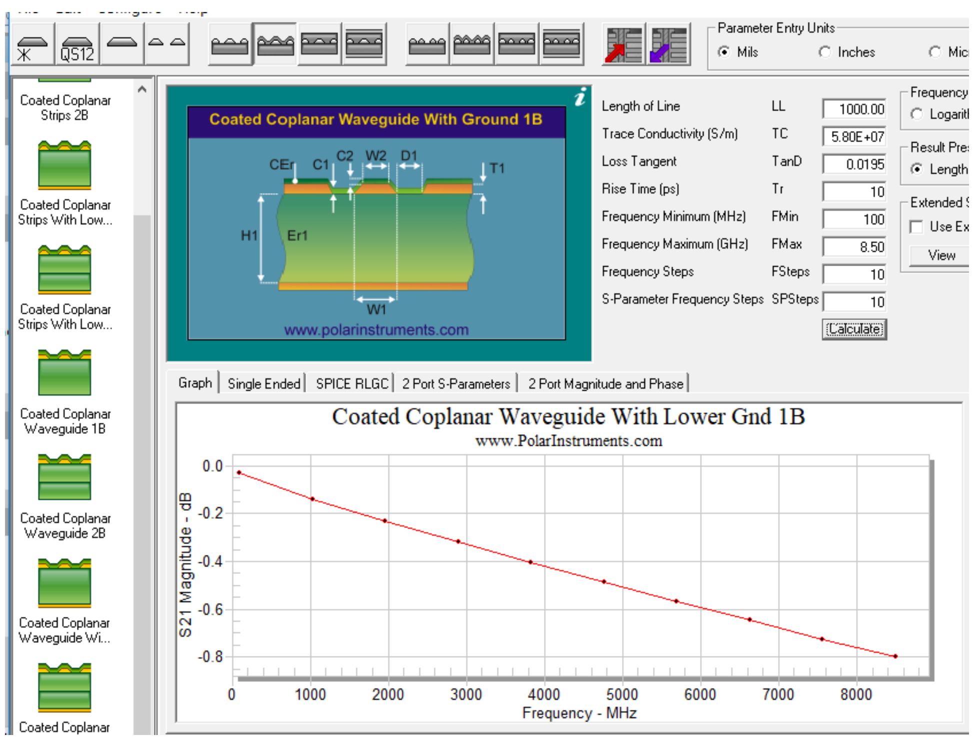

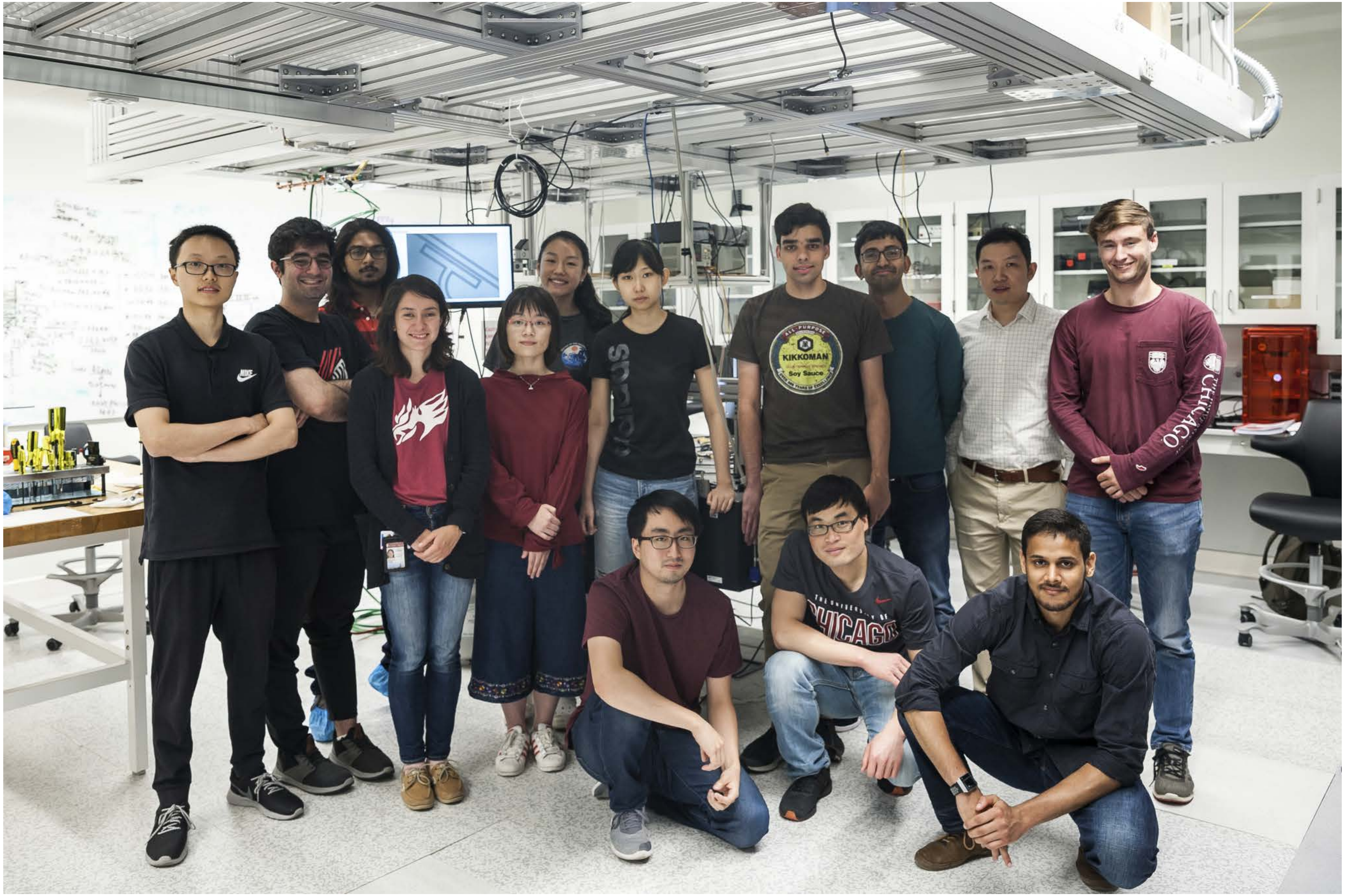
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