Measurement setup for microwave characterization of superconducting quantum systems

Skoltech

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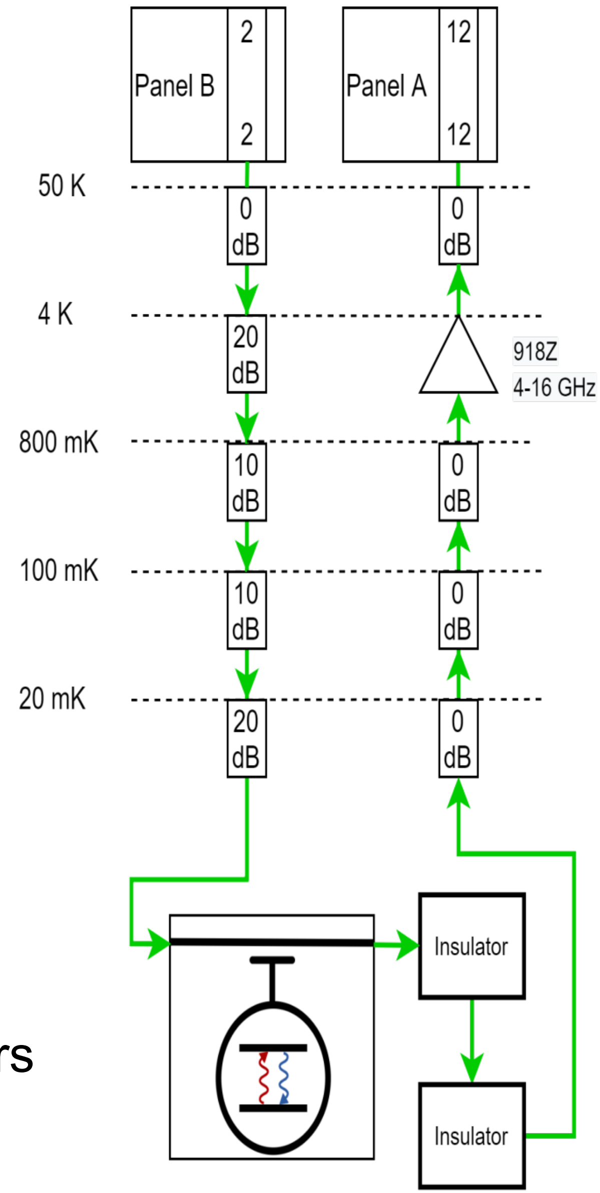
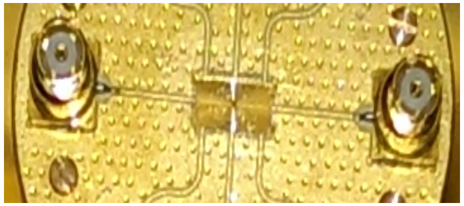
Equipment and usage schematics

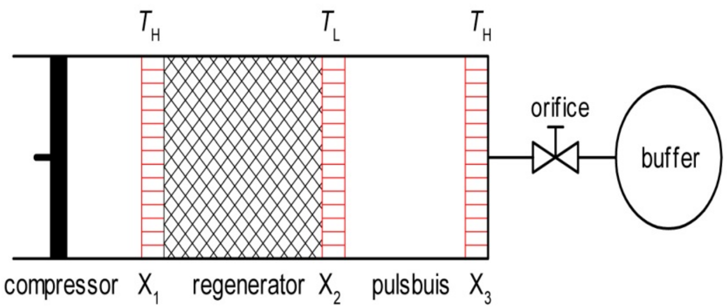
1. Cryogenic system:
   1.1 Dilution refrigerator
2. DC measurement equipment
   2.1 Current/voltage source
   2.2 Digitizers
3. Passive devices
   3.1 Attenuators
   3.2 Line couplers
   3.3 Filters
   3.4 Mixers
   3.5 Circulators
4. CW measurements
   4.1 MW amplifiers
   4.3 Microwave generators
   4.4 Vector Network Analyzers
   4.5 Spectrum Analyzers

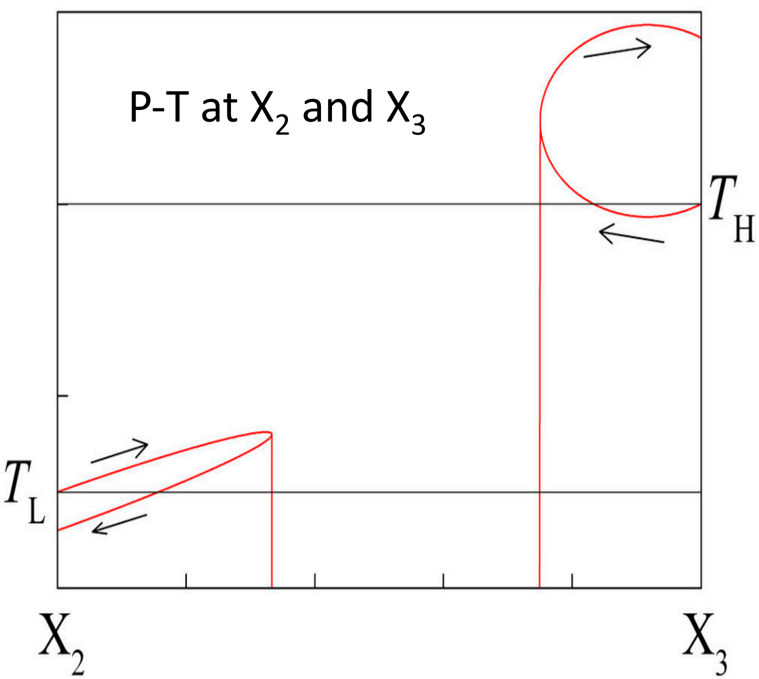


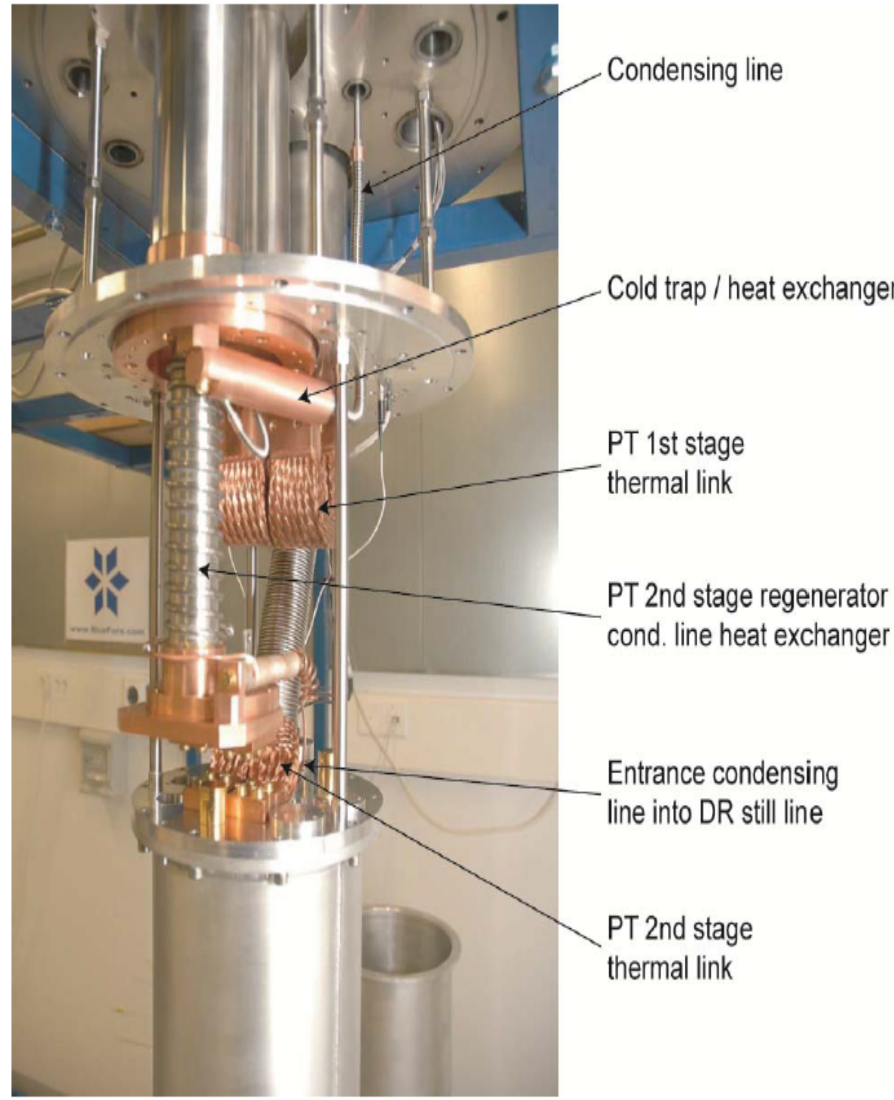


Dilution refrigerator

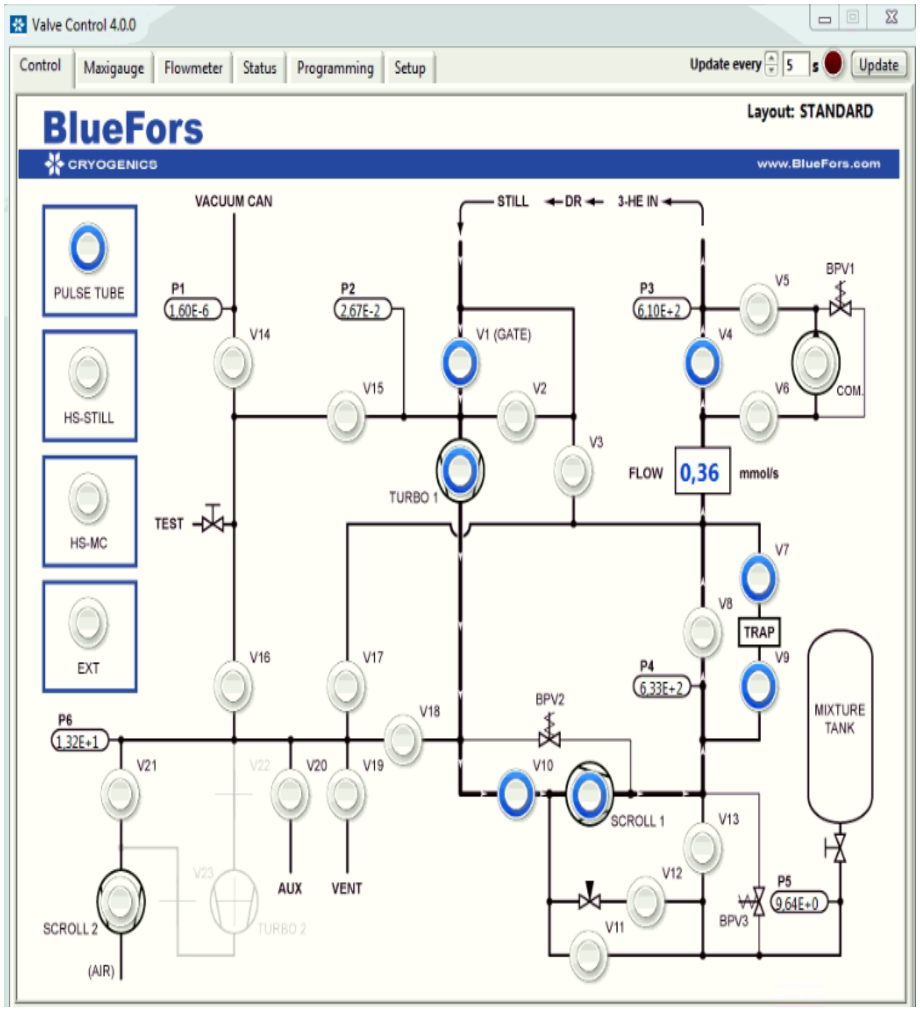
Stirling type pulse tube cooling

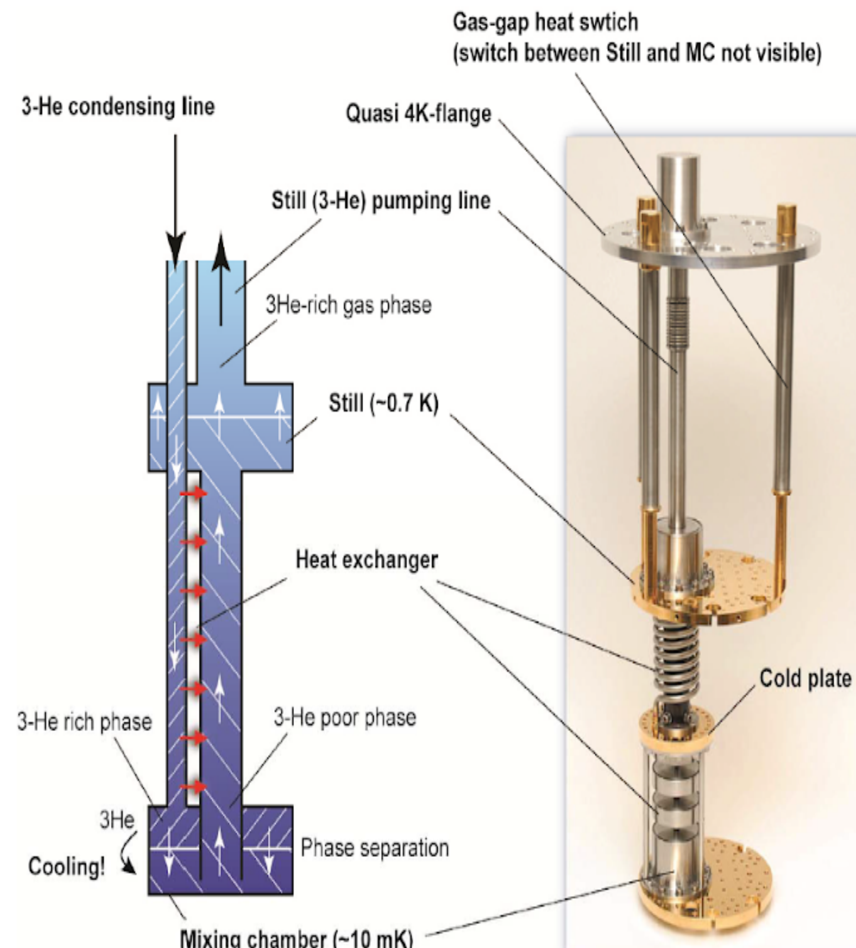




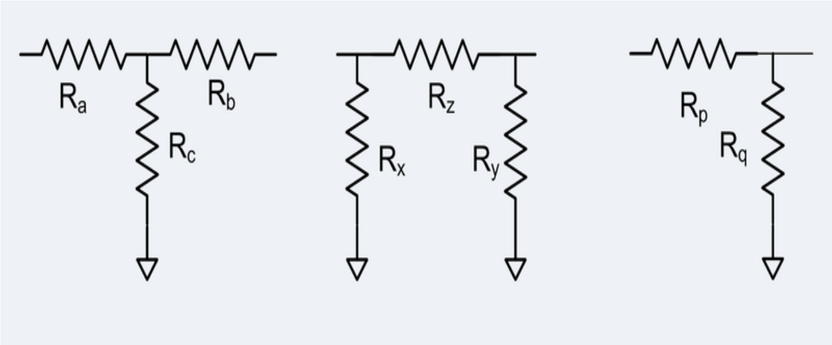


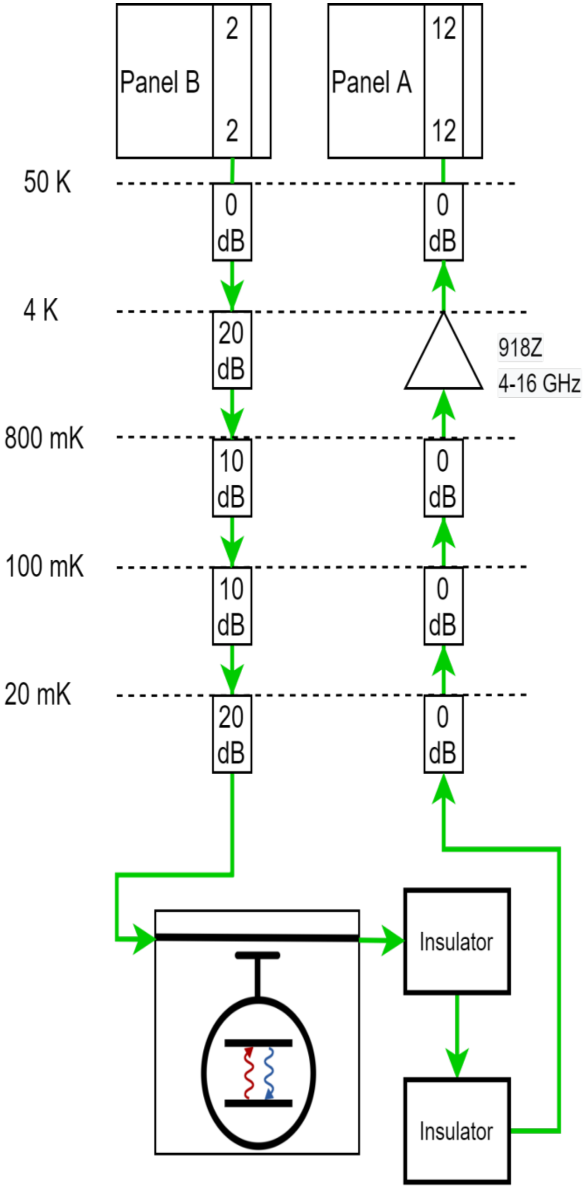
Dilution principle



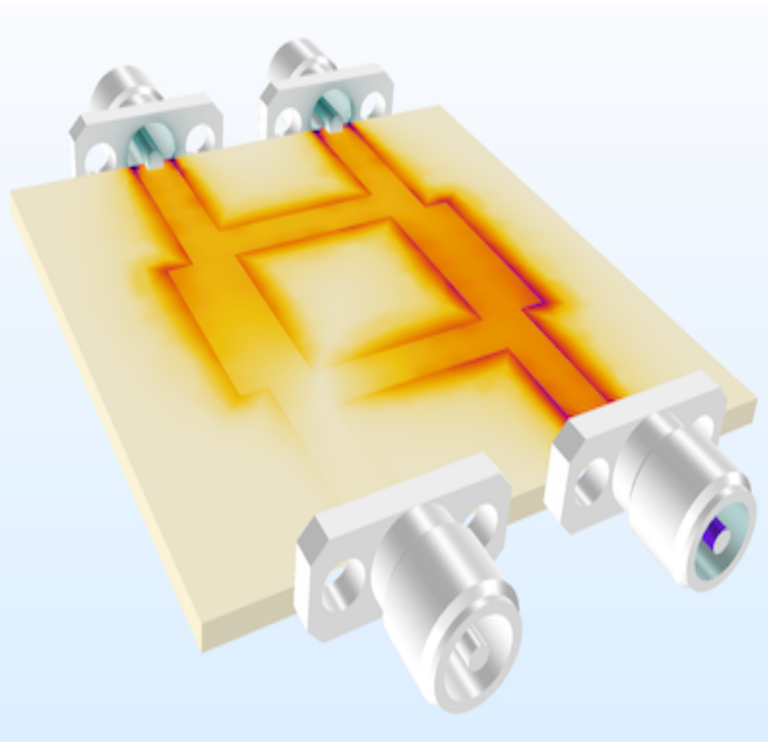


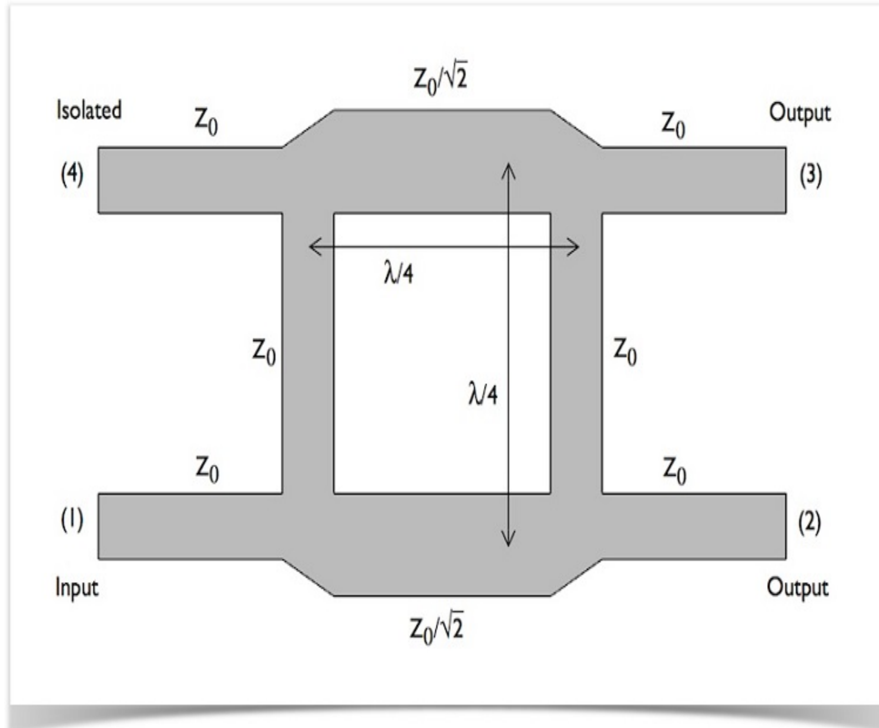
Passive devices. Attenuators



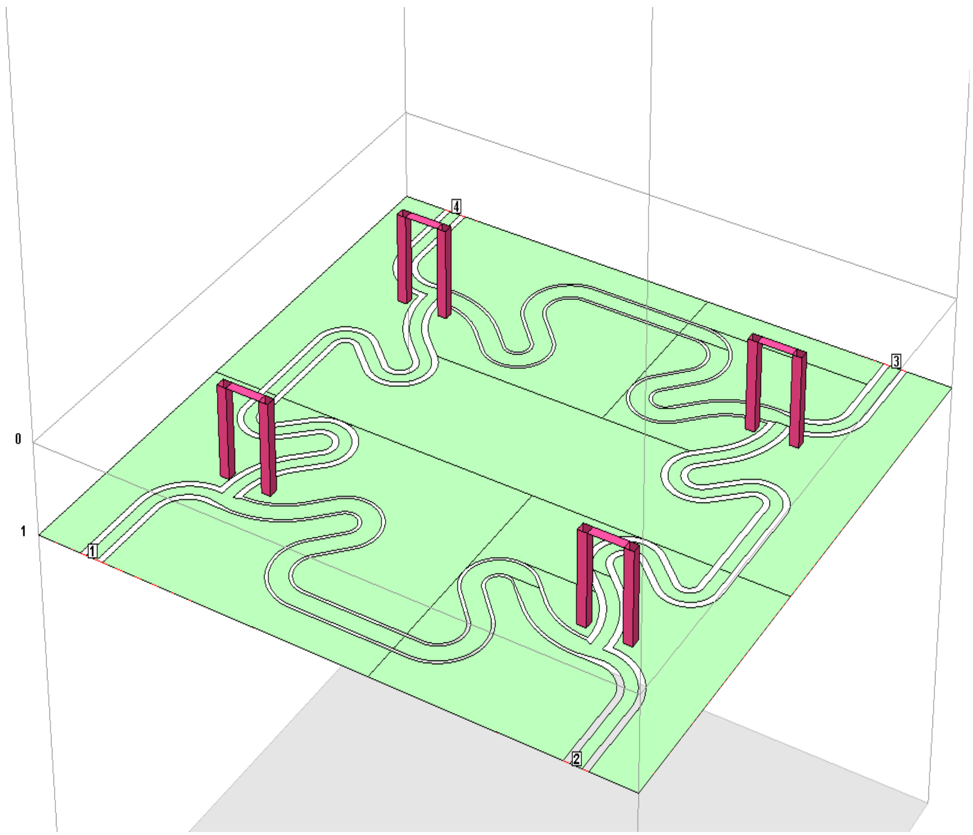


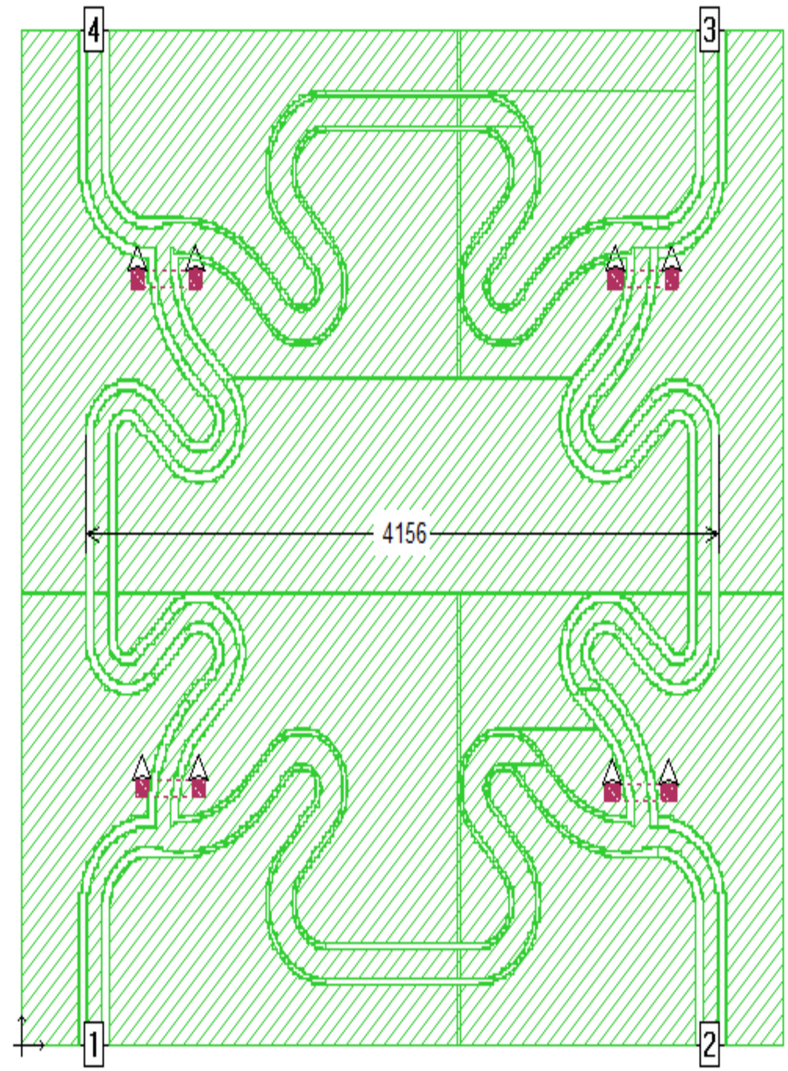
Line couplers #1



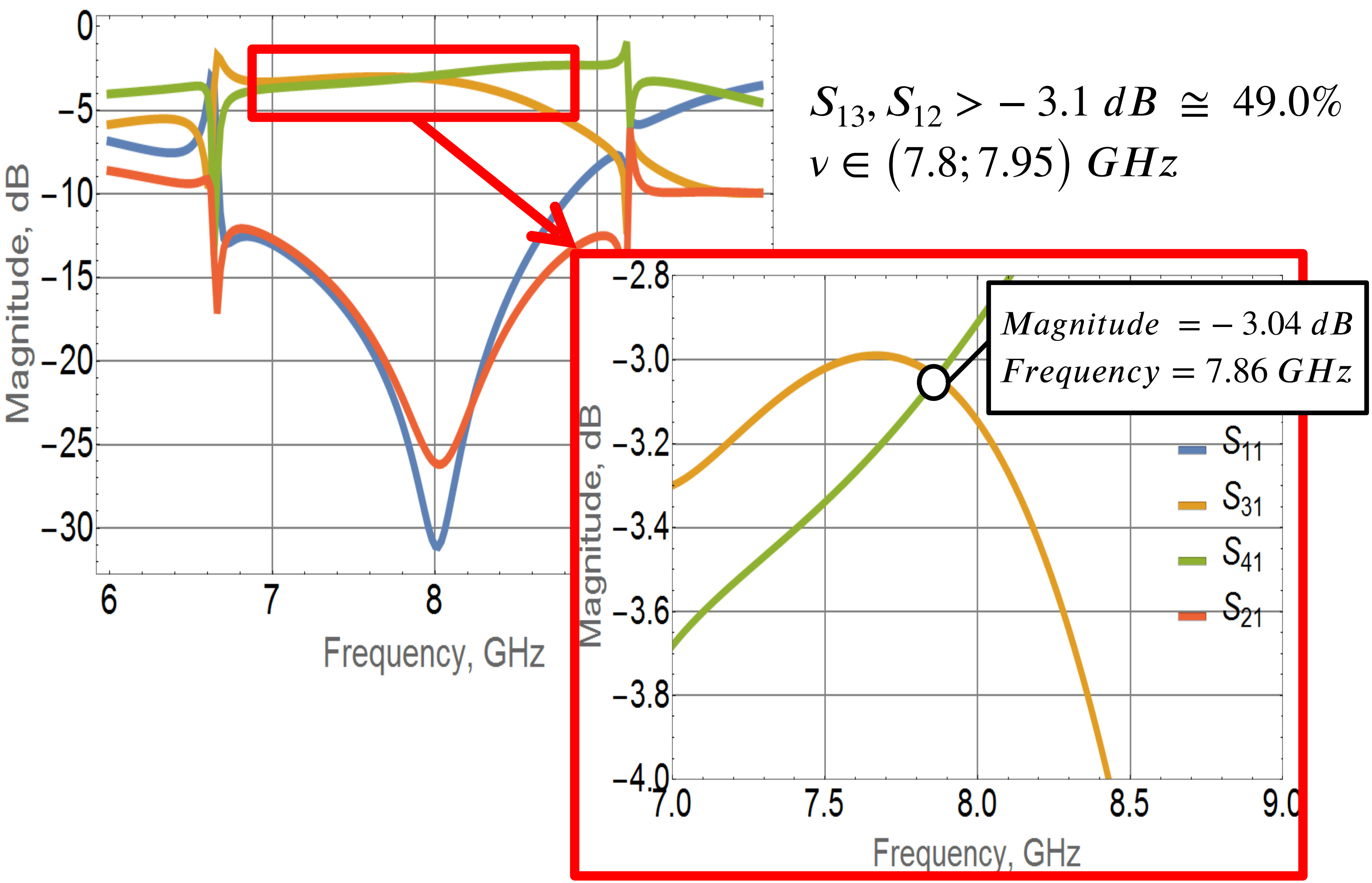


Line couplers #2



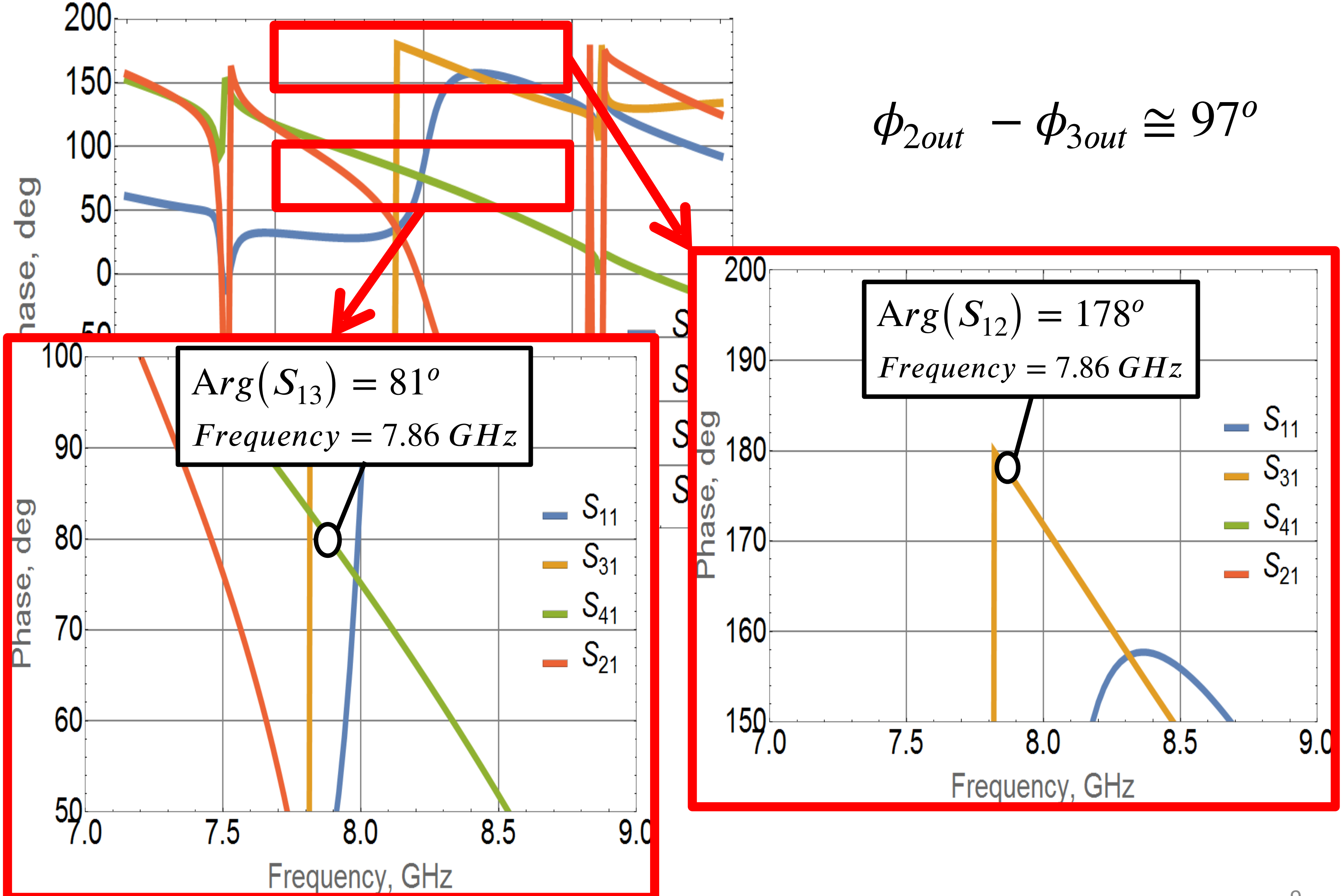


Microwave properties simulations #1



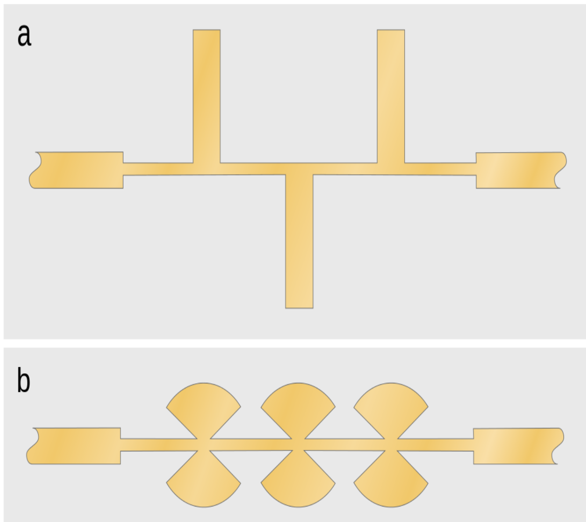
$$S_{13}, S_{12} > -3.1\ dB \cong 49.0\%$$
$$\nu \in (7.8; 7.95)\ GHz$$

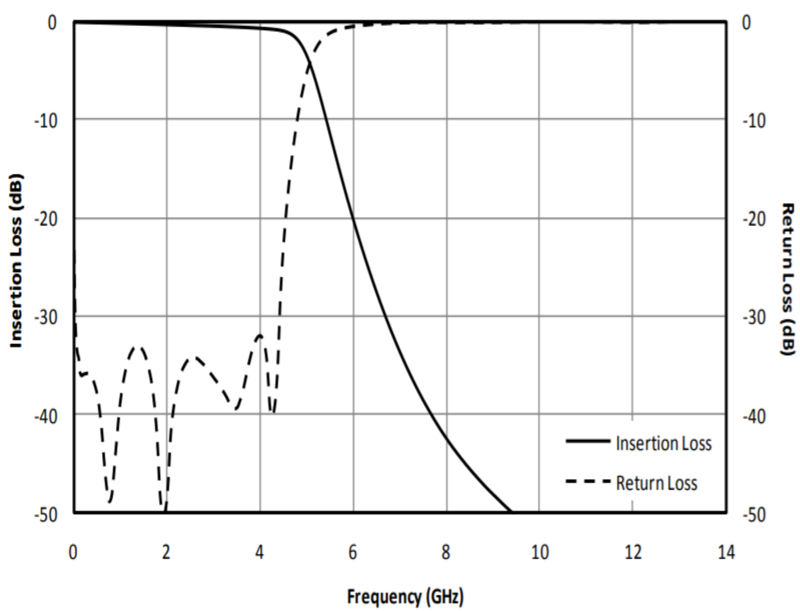
Microwave properties simulations #2

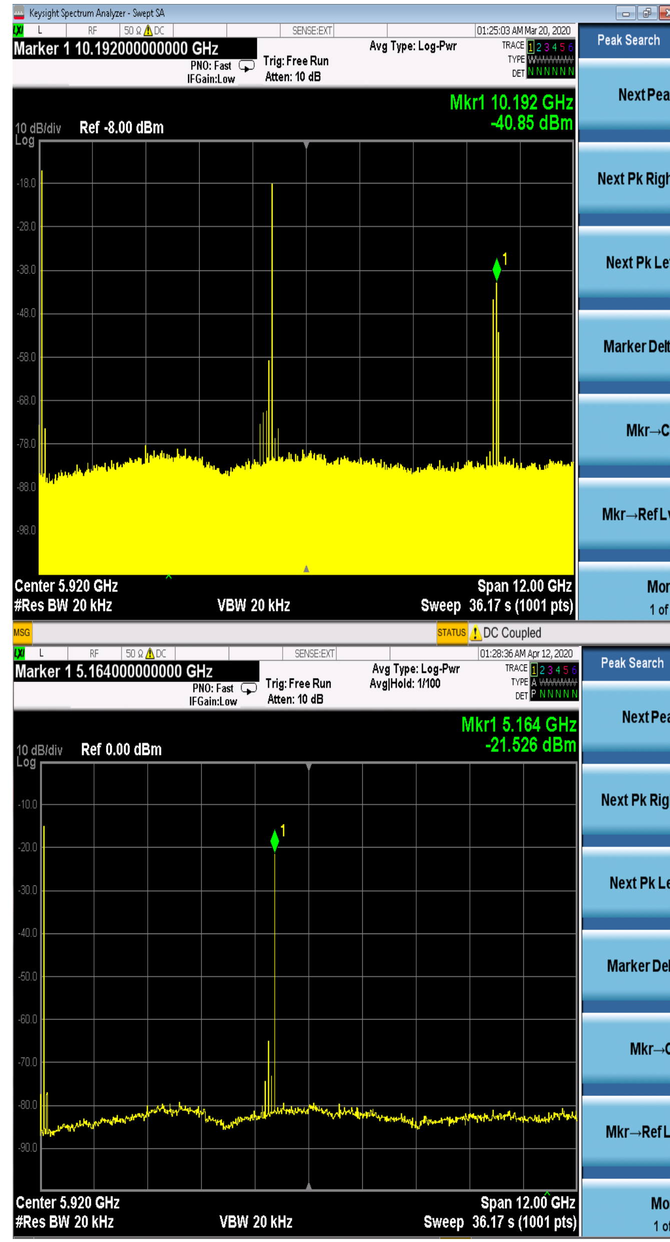


$$\phi_{2out} - \phi_{3out} \cong 97^{o}$$

Passive devices. Filters





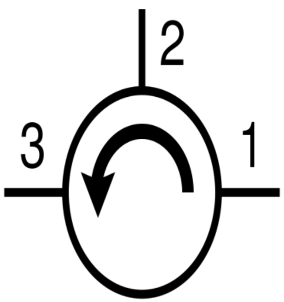


Passive devices. Circulators

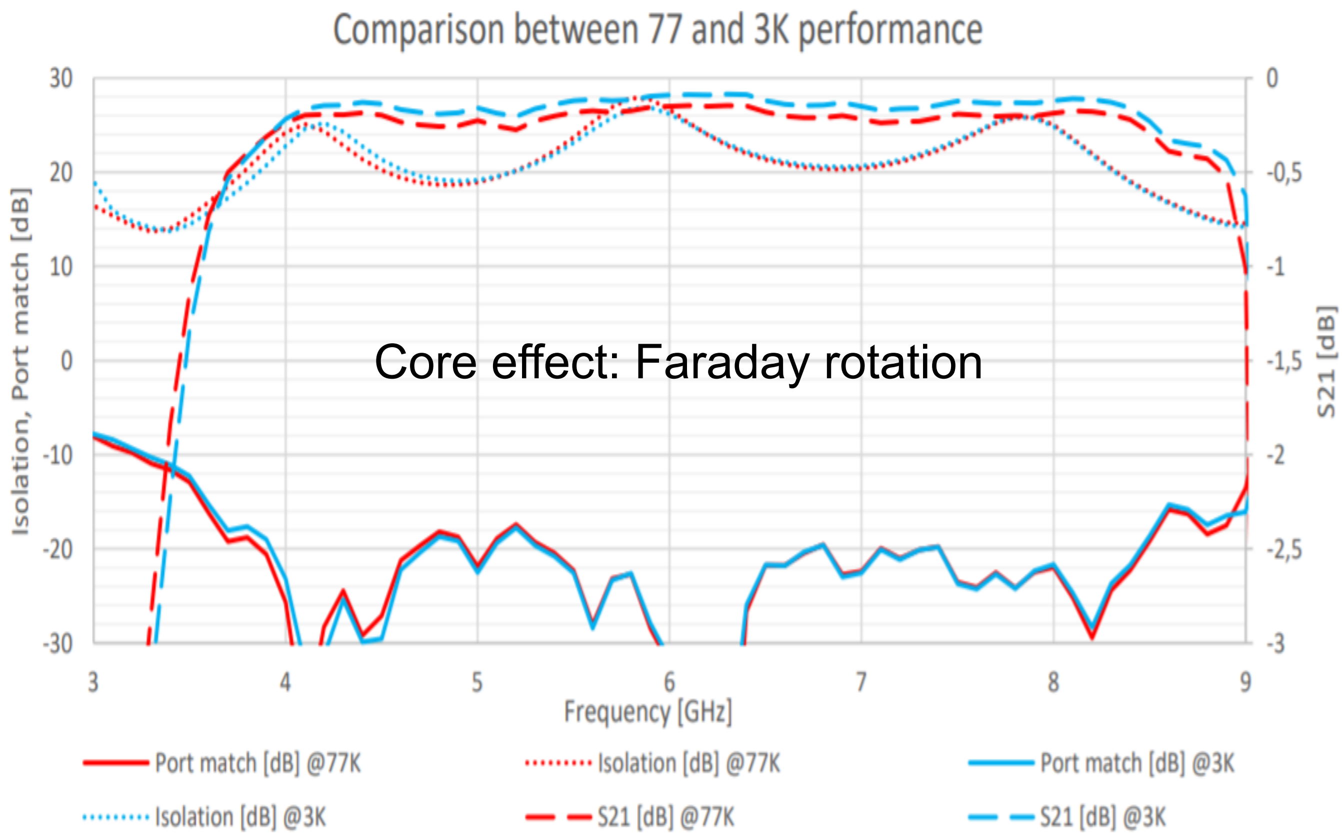
LNF-ISC4_8A

$$Isolation,\ dB = 10log_{10}\frac{P_2^{in}}{P_1^{out}}|_{Z_3=Z_0} = 20log_{10}S_{12}^{-1}$$

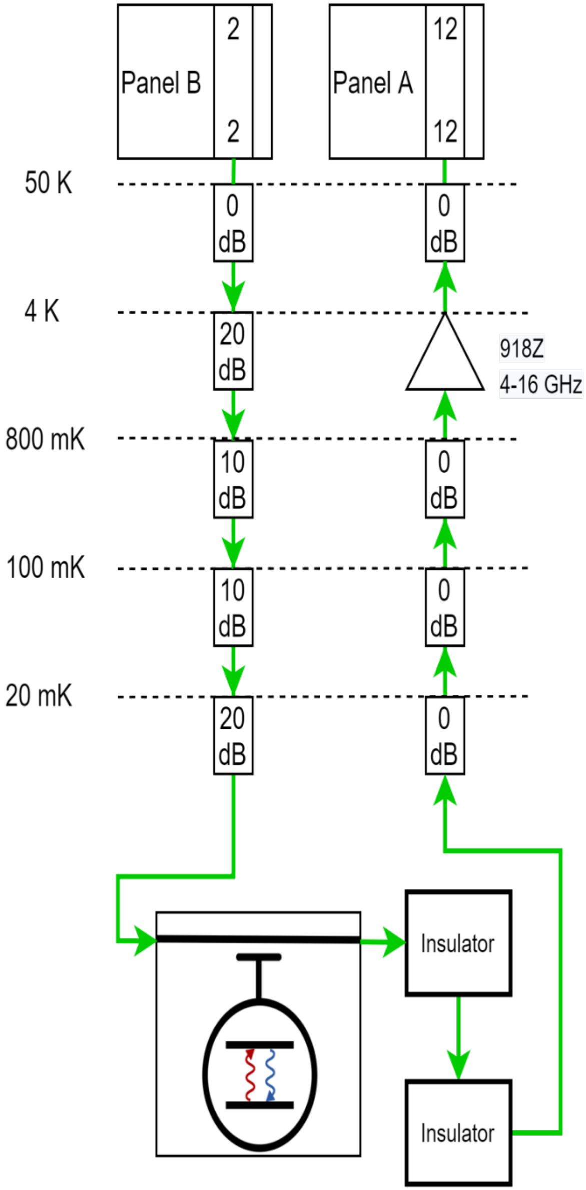
$$Port\ match,\ dB = 10log_{10}\frac{P_1^{out}}{P_1^{in}}|_{Z_3=Z_2=Z_0} = 20log_{10}S_{11}$$



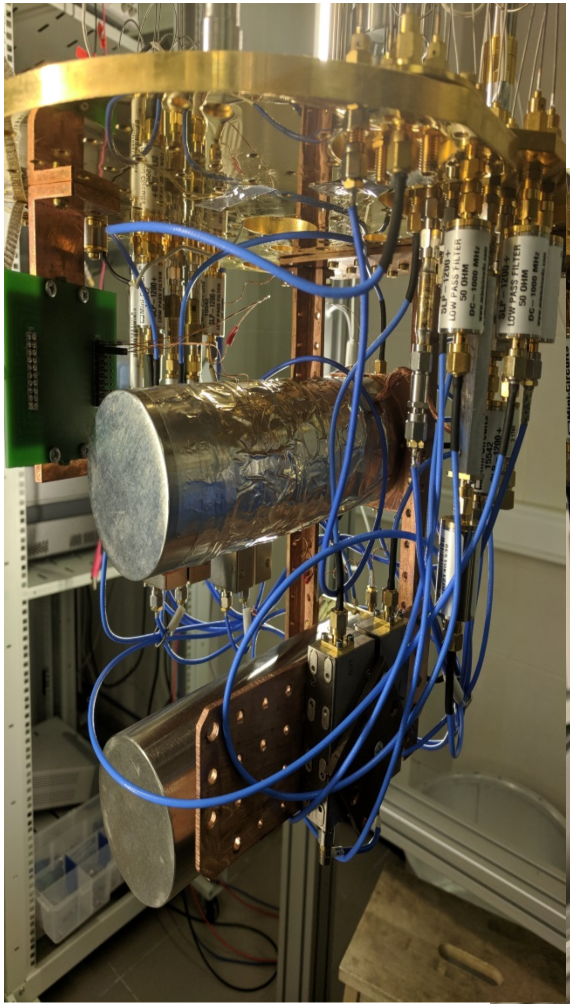
$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

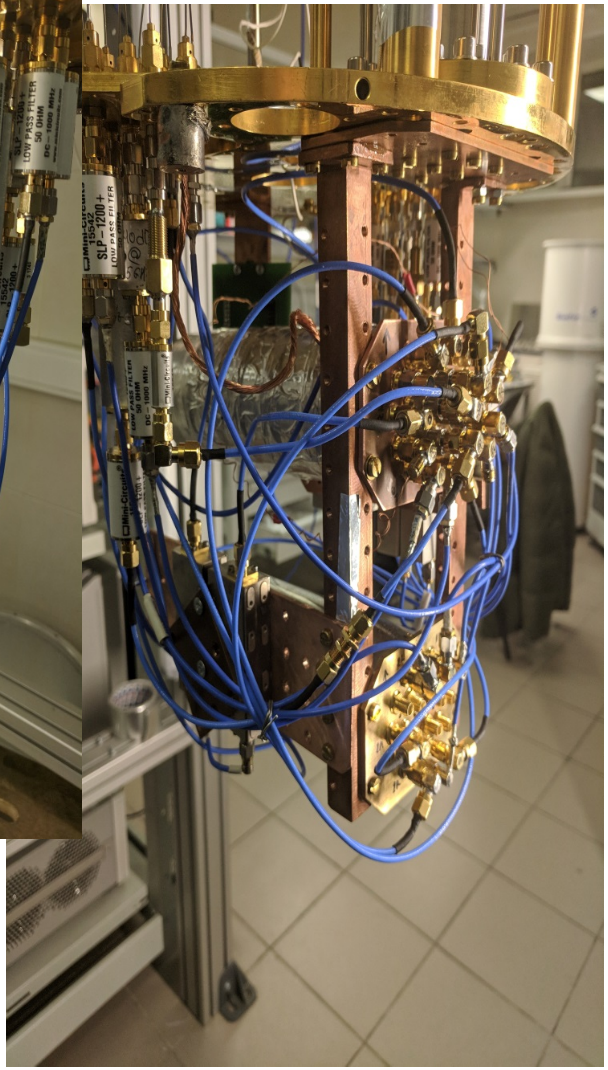


Core effect: Faraday rotation

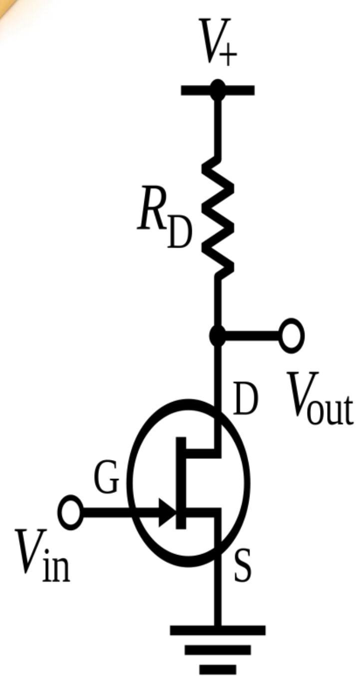


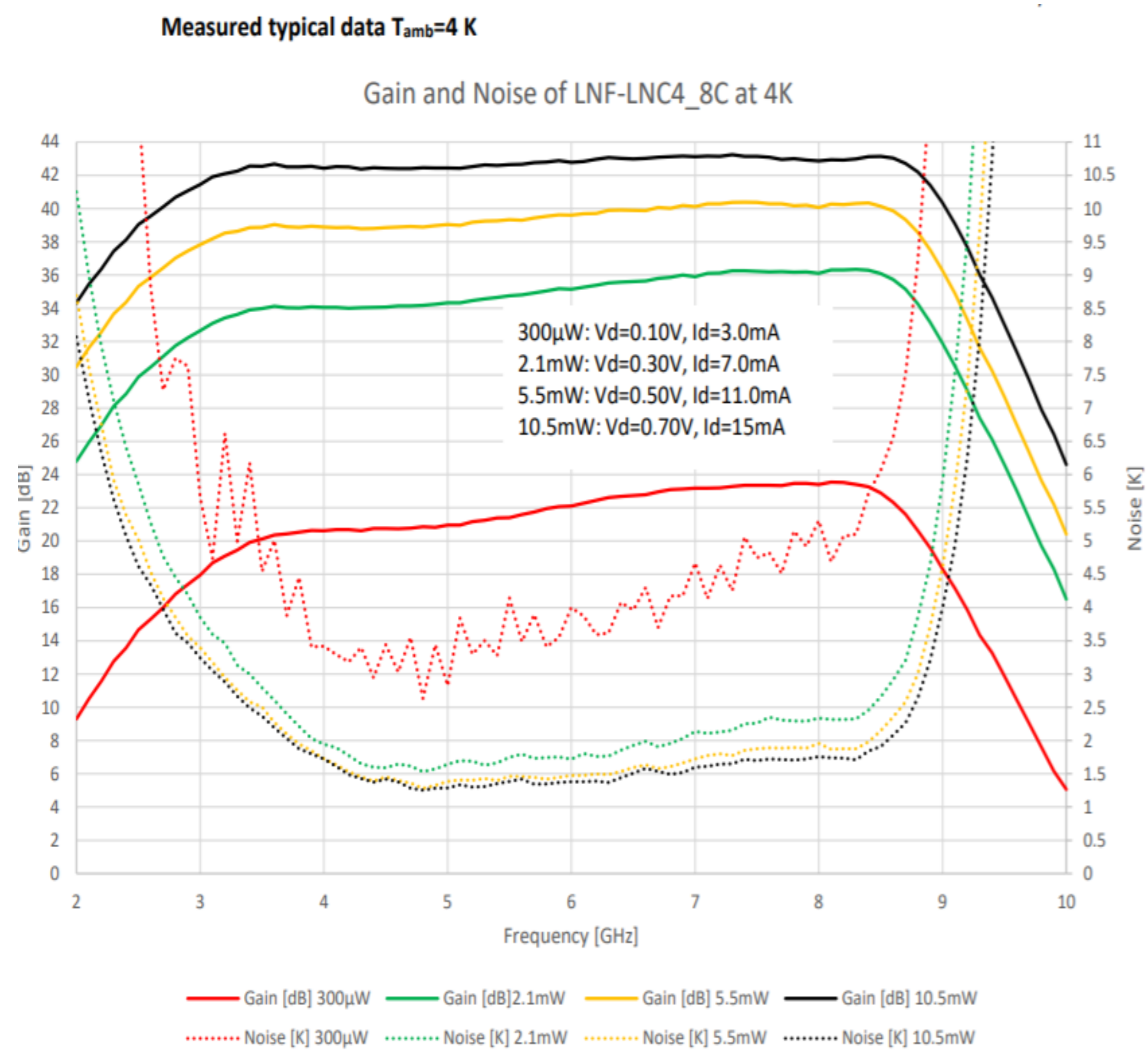
Panel B
2
2
Panel A
12
12
50 K
4 K
800 mK
100 mK
20 mK
0 dB
20 dB
10 dB
10 dB
20 dB
0 dB
918Z
4-16 GHz
0 dB
0 dB
0 dB
Insulator
Insulator





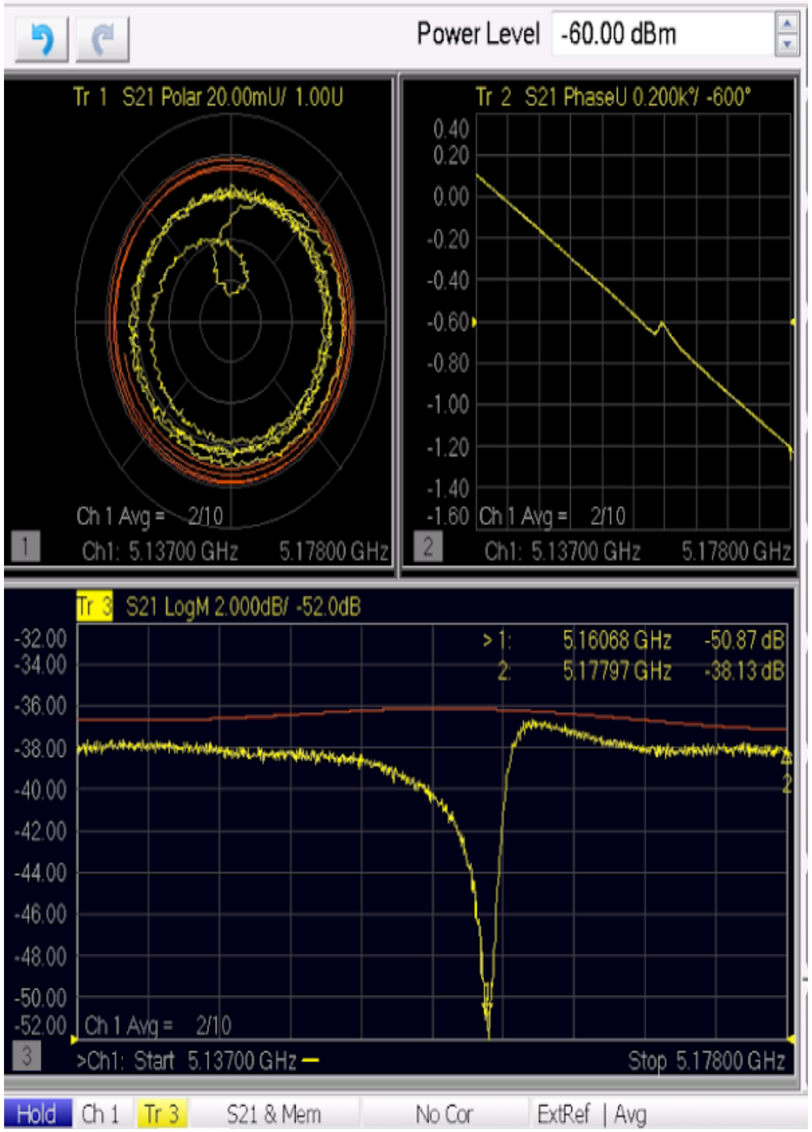
CW measurements. Amplifiers

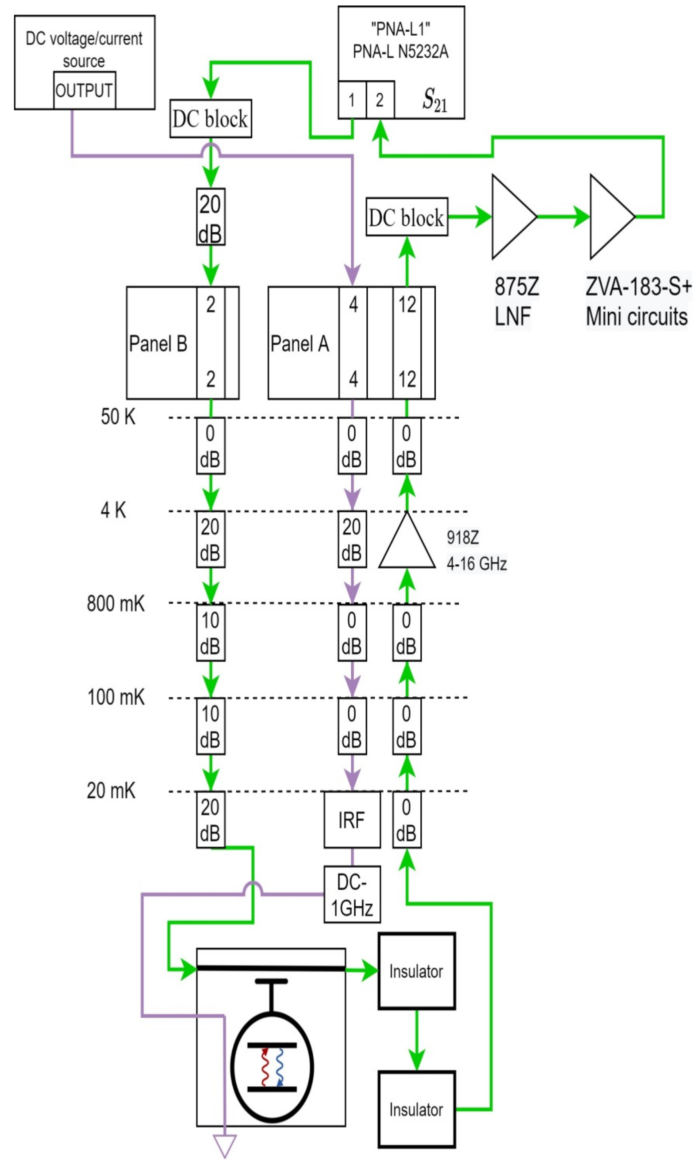




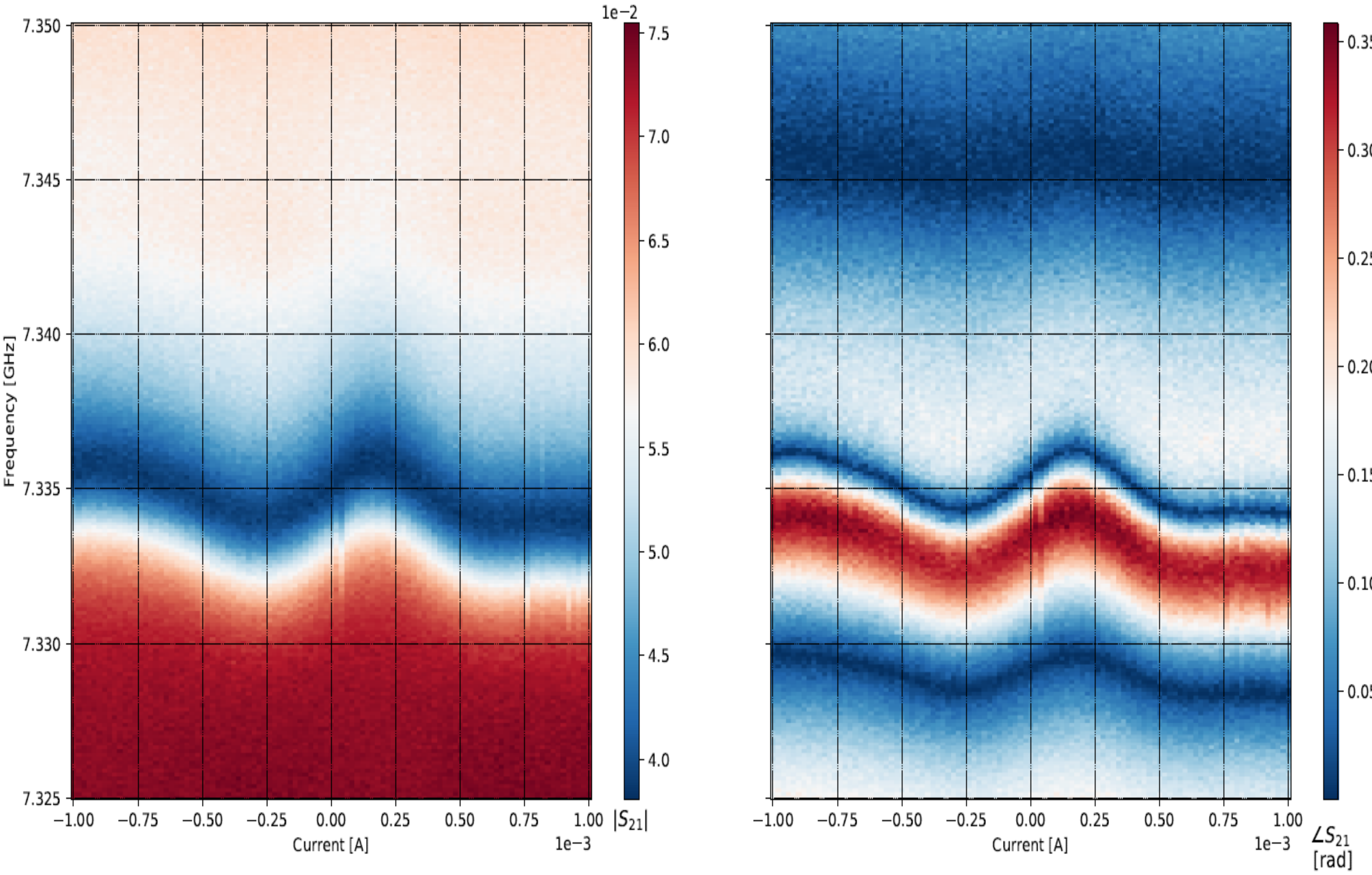
HEMT – High-electron-mobility transistor

CW measurements. VNA





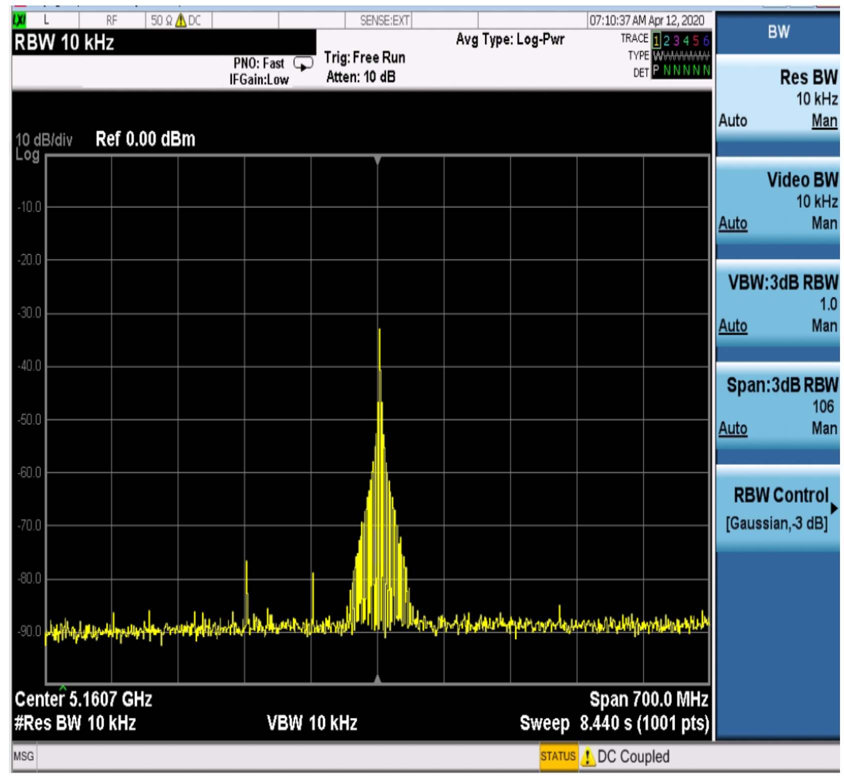
CW measurements. Single tone spectroscopy

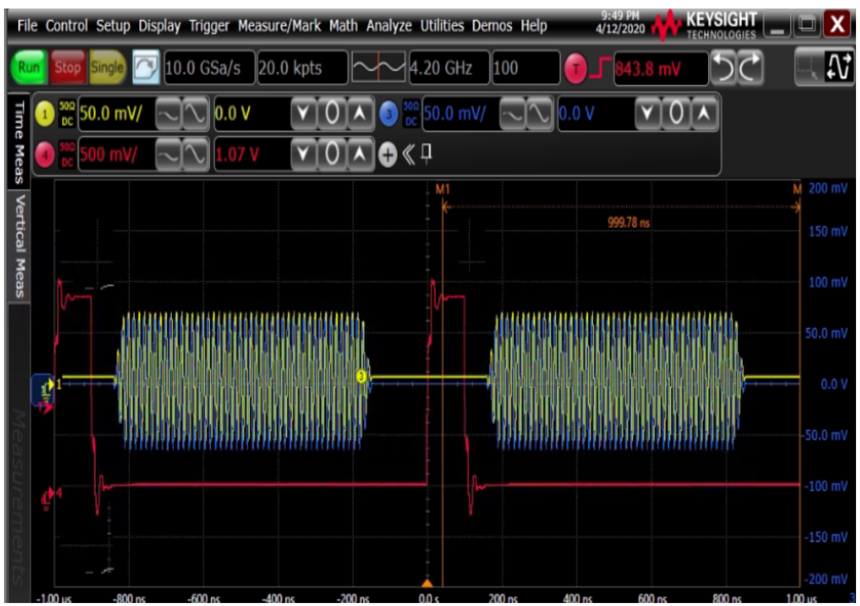


CW measurements. Microwave generators and spectral analyzers

$$Resolution \simeq 10^{-3}\ \mathrm{Hz}$$

$$P_{IO} \leq 10\ \mathrm{dBm}$$





CW measurements. Two tone spectroscopy #1

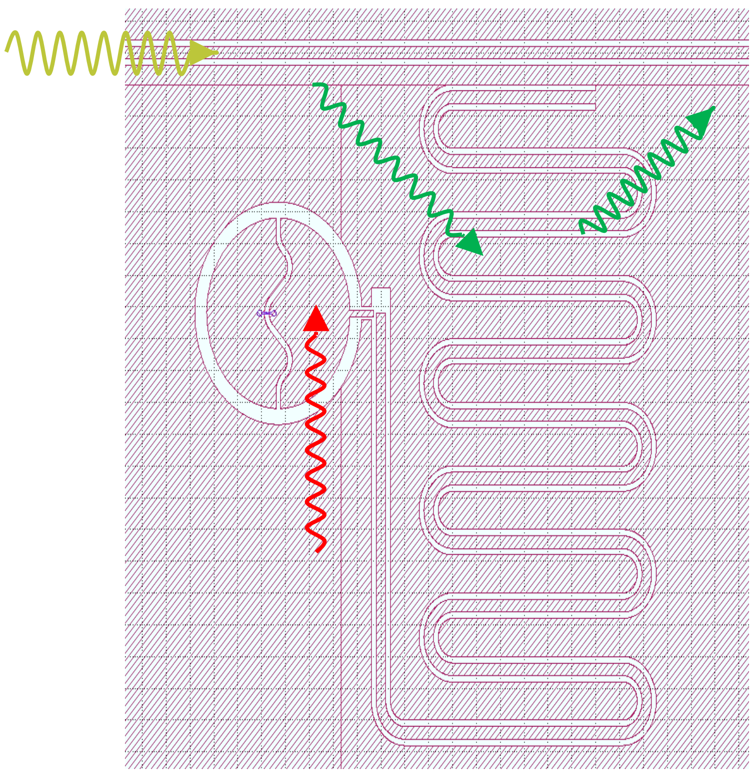
$$\hat{H}_{\mathrm{JC}} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\left(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-\right)$$

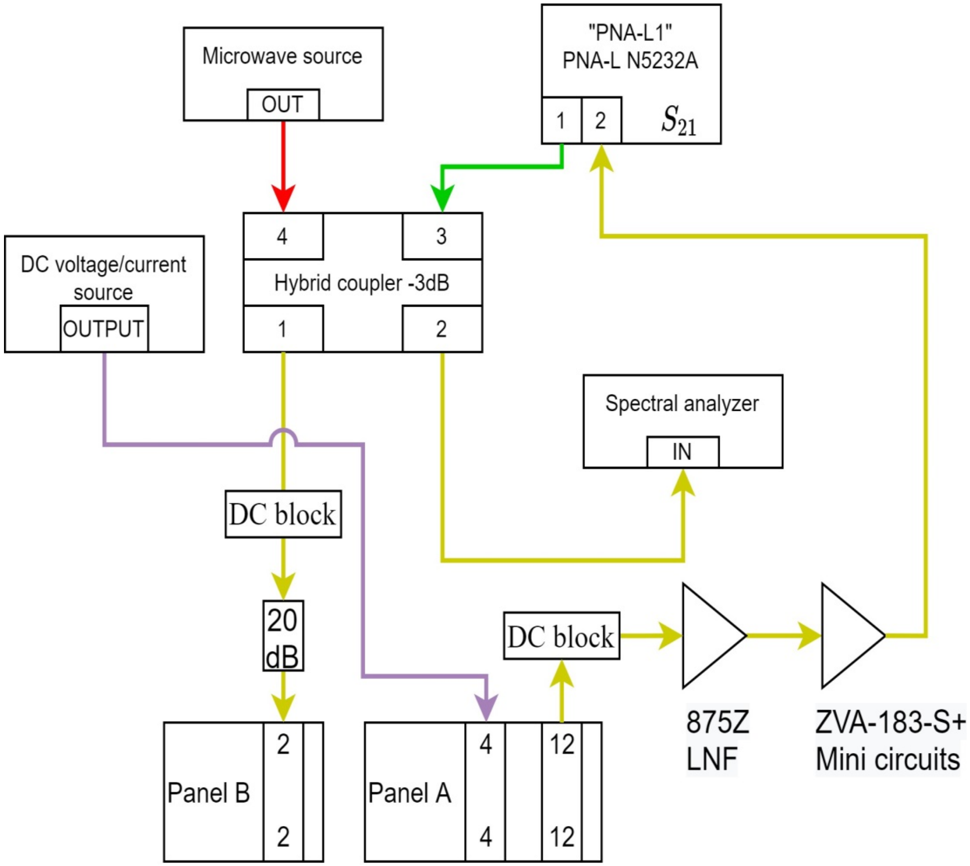
approximate diagonalization: $|\Delta| = |\omega_a - \omega_r| \gg g$:

$$H \approx \hbar\left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{\hbar}{2}\left(\omega_a + \frac{g^2}{\Delta}\right)\sigma_z$$

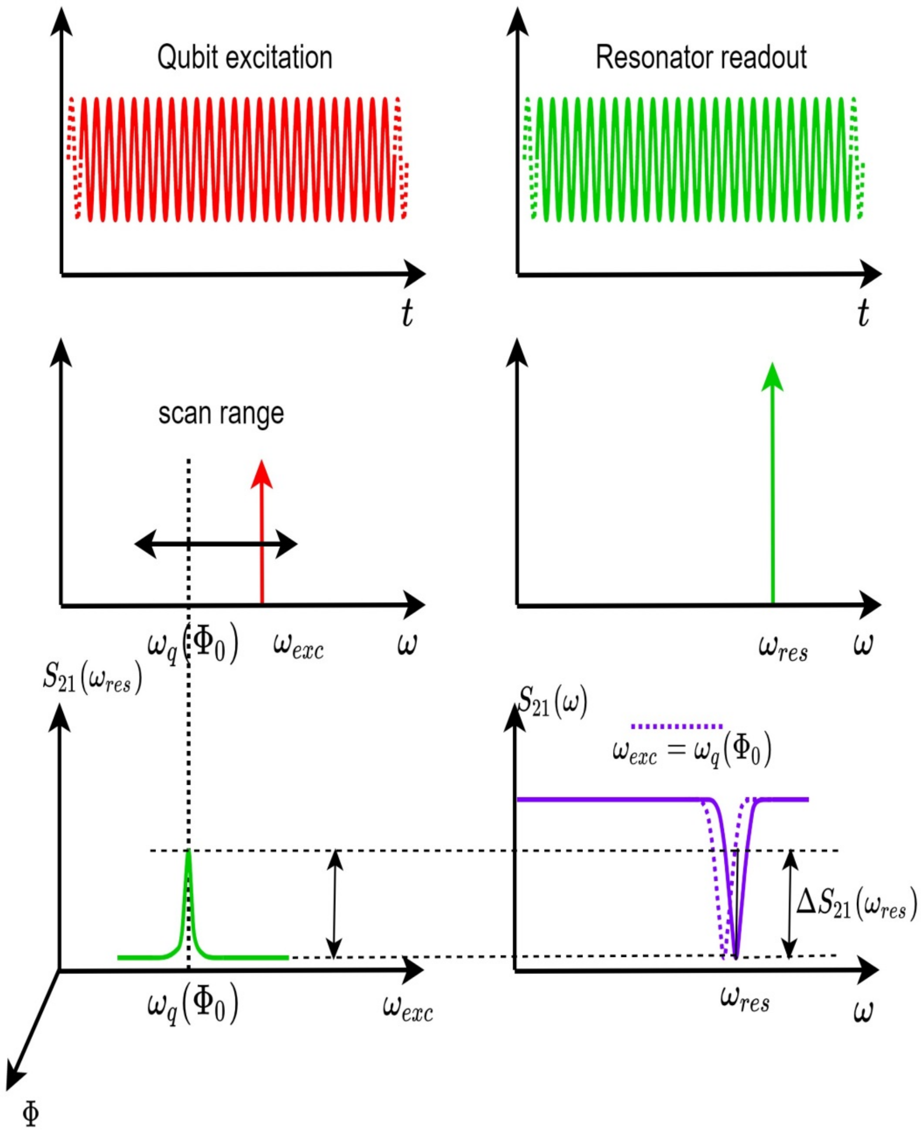
//
cavity frequency shift
and qubit ac-Stark shift

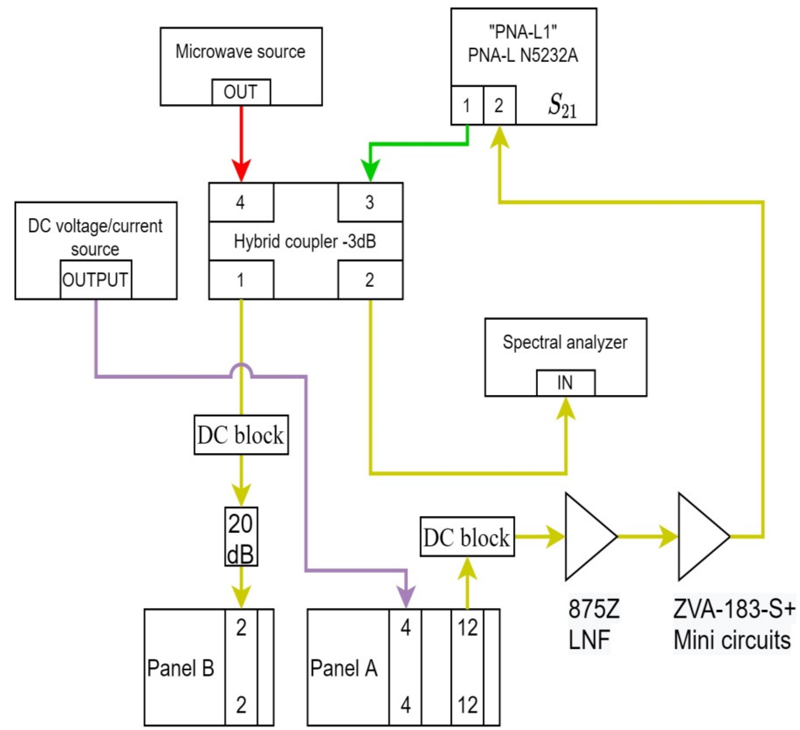
//
Lamb Shift

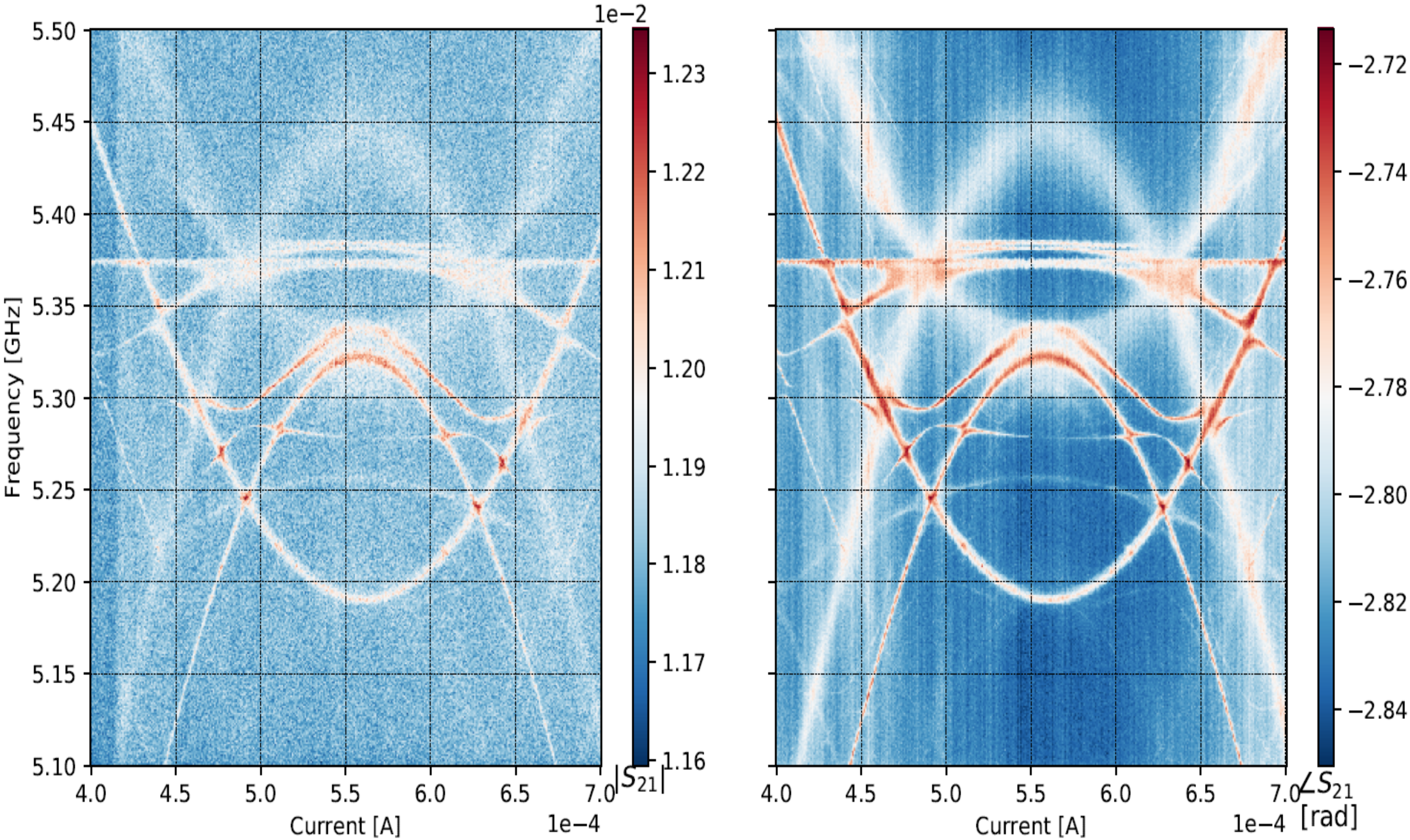




CW measurements. Two tone spectroscopy #2







1e−2
5.50
5.45
5.40
5.35
5.30
5.25
5.20
5.15
5.10
Frequency [GHz]
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Current [A]
1e−4
1.23
1.22
1.21
1.20
1.19
1.18
1.17
1.16
|S21|
−2.72
−2.74
−2.76
−2.78
−2.80
−2.82
−2.84
∠S21
[rad]

Part II starts here (spoilers alert)

1. Passive devices
    1.1 Flashback on previous lab
    1.2 Mixers
2. Time domain measurements
    2.1 Arbitrary waveform generators
    2.2 Digitizers
    2.3 Rabi oscillations
    2.4 Ramsey oscillations