Typical cryogenic setup for microwave experiments

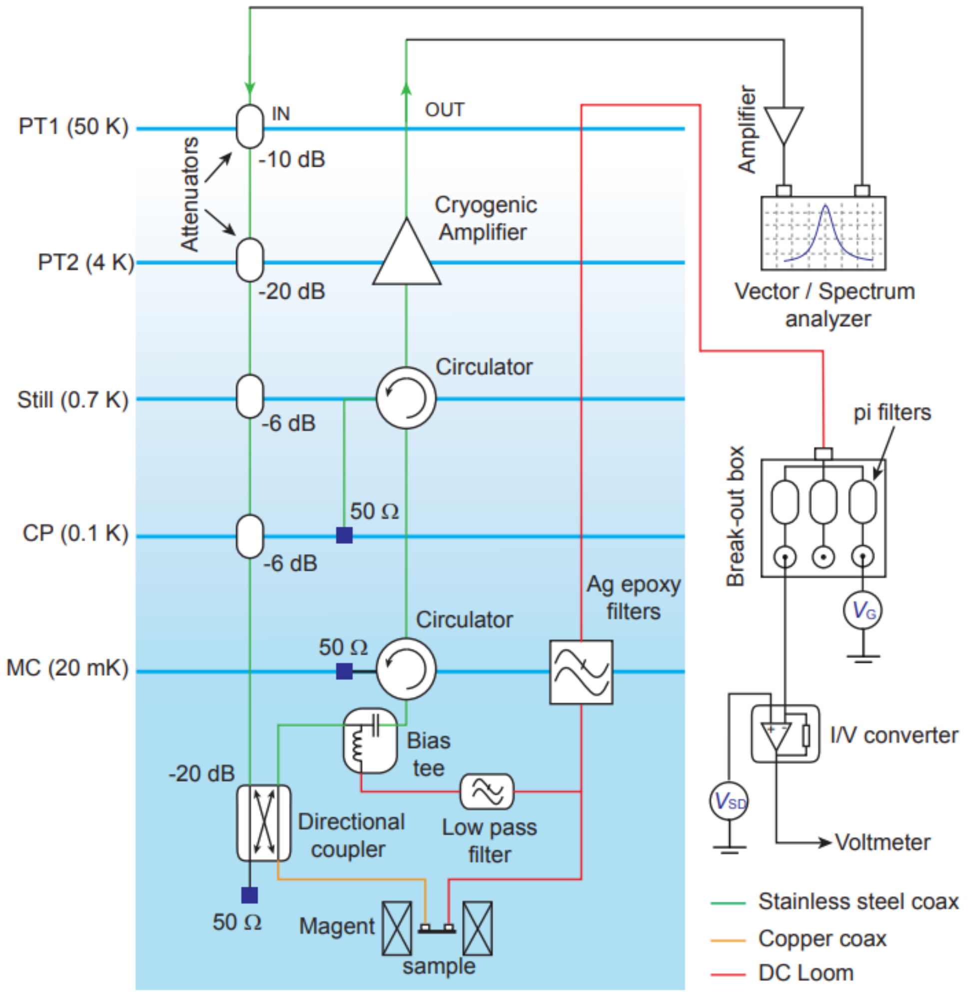
Gergő Fülöp
RF seminar
2019-02-21

Outline

- Coaxial cables
- Attenuators
- Directional coupler
- Bias tee
- Isolator/circulator
- Filters
- Amplifiers
- DC block

- Mixer
- (Power detector)
- Multiplexer
  - Diplexer

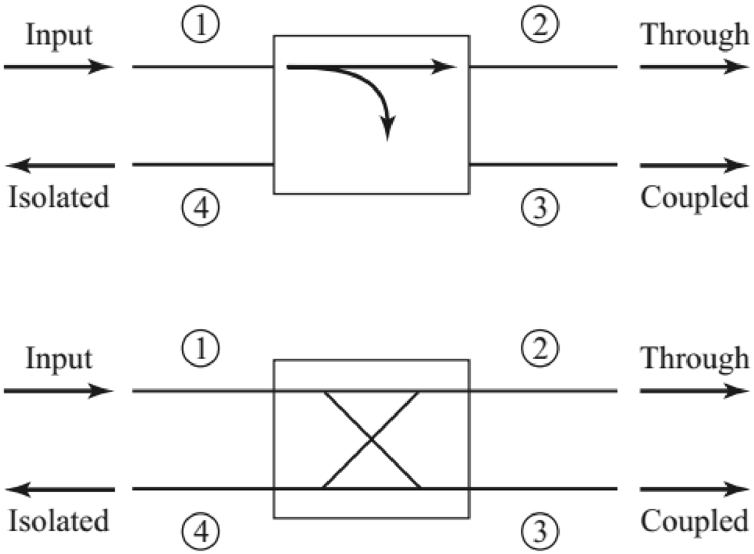
Oxford Triton dilfridge



V. Ranjan, PhD thesis

Directional couplers

- Passive, ideally lossless, has 3 or 4 ports



$$\text{Coupling} = C = 10 \log \frac{P_1}{P_3}$$

$$\text{Directivity} = D = 10 \log \frac{P_3}{P_4}$$

$$\text{Isolation} = I = 10 \log \frac{P_1}{P_4}$$

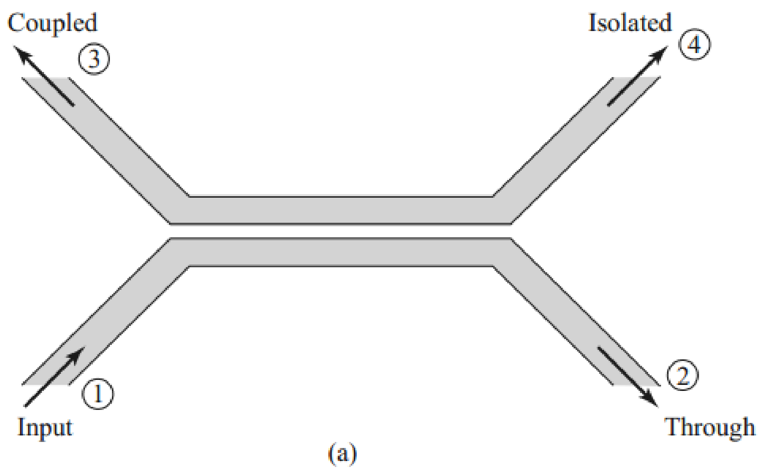
$$\text{Insertion loss} = L = 10 \log \frac{P_1}{P_2}$$

  - Hybrid coupler: special case of directional couplers, with 3 dB coupling
    - The *quadrature hybrid* has a 90◦ phase shift between ports 2 and 3
    - The *magic-T hybrid* and the *rat-race hybrid* have a 180◦ phase difference between ports 2 and 3 when fed at port 4
- Purpose in the reflectometry setup

D. Pozar

Directional couplers

- Passive, ideally lossless, has 3 or 4 ports
  - Single section



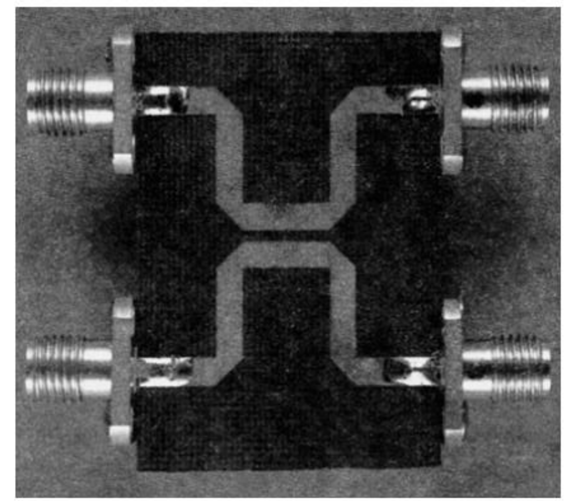
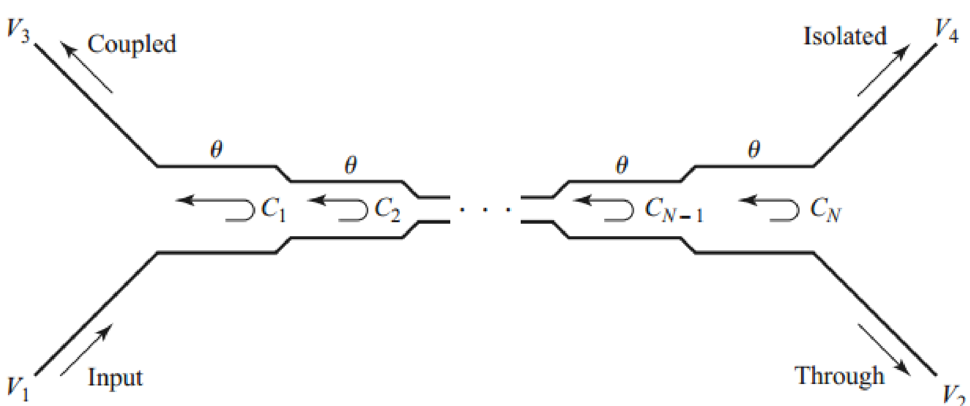


FIGURE 7.36 Photograph of a single-section microstrip coupled line coupler.

  - Multiple sections



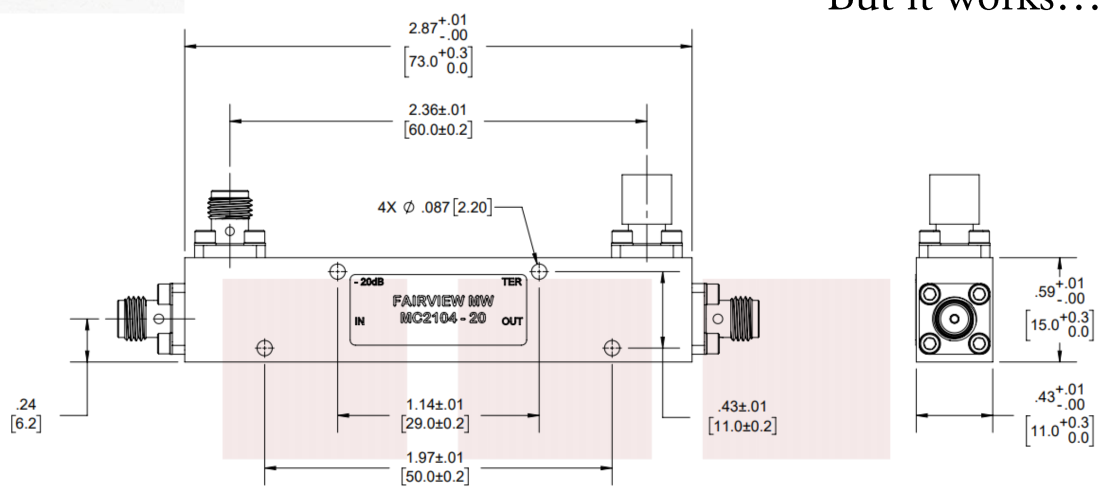
Directional couplers

- Fairview Microwave MC 2104-20

Approx. 200 USD
20 dB coupling
1-4 GHz

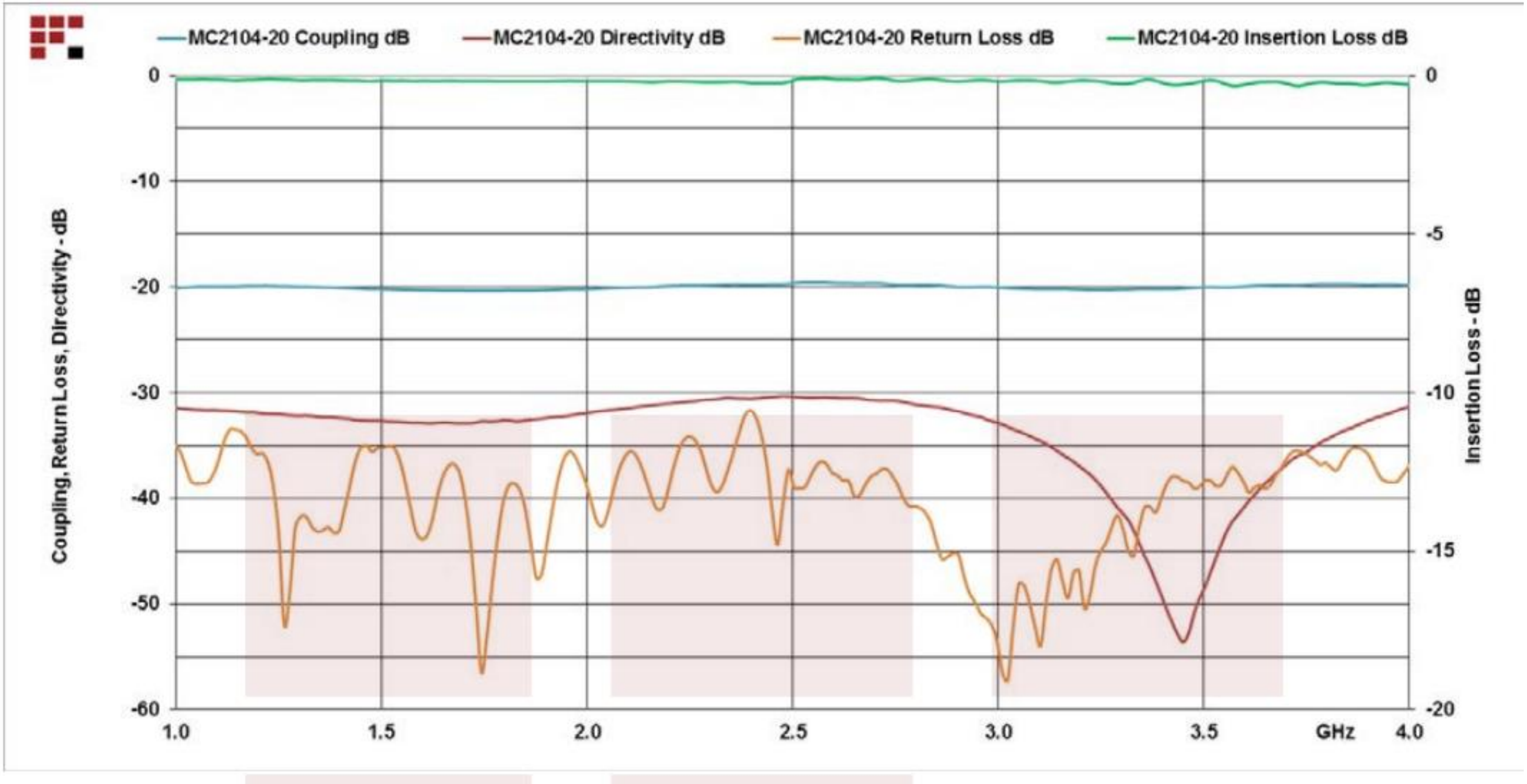
Environmental Specifications
Temperature
Operating Range -55 to +85 deg C

But it works…



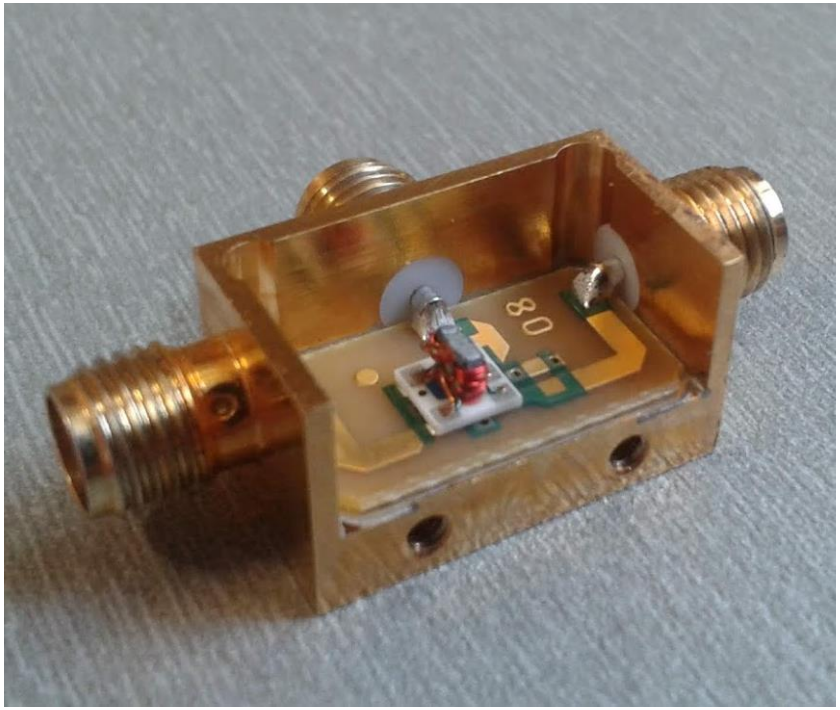
Directional couplers

- Fairview Microwave MC 2104-20



Directional couplers

- MiniCircuits
  - Transformer-based

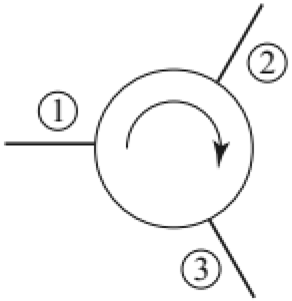


Circulator/isolator

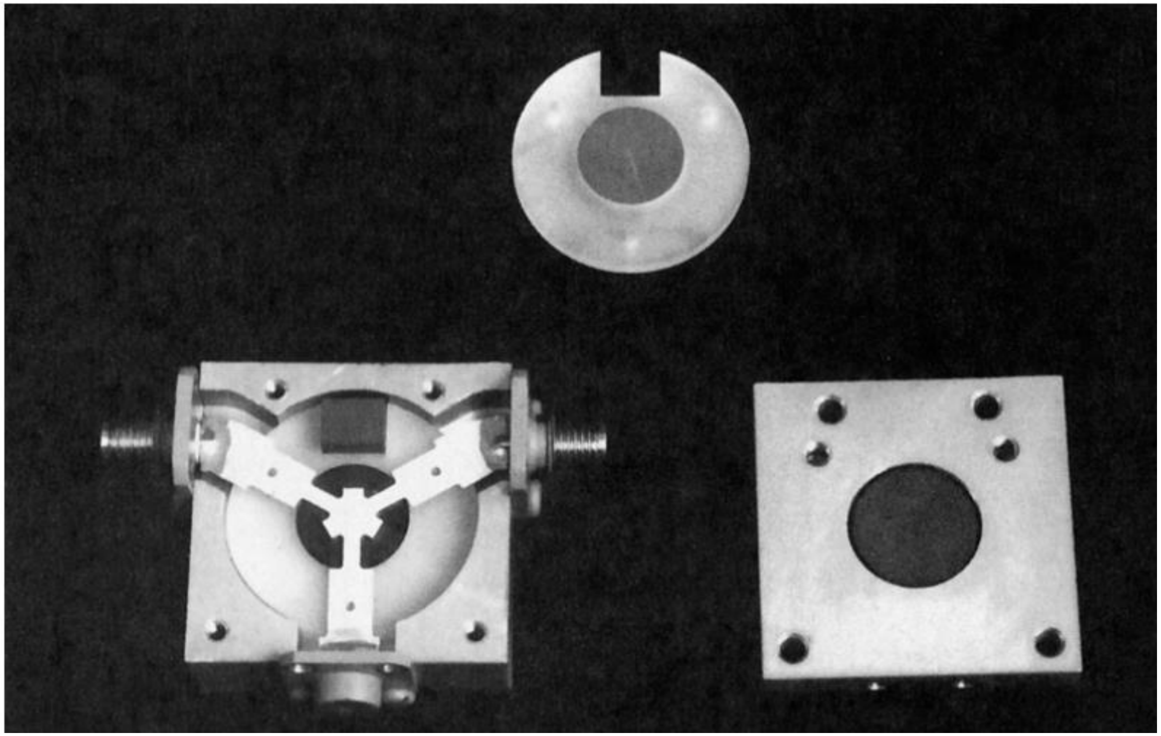
- Passive, ideally lossless
- Non-reciprocal!
- Permanent magnets inside (ferrite)
- Sensitive to external B field
- Circulator: 3 ports
- Isolator: 2 ports

- Circulator can be used alternatively to the dir. coupler in the setup

$$[S] = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

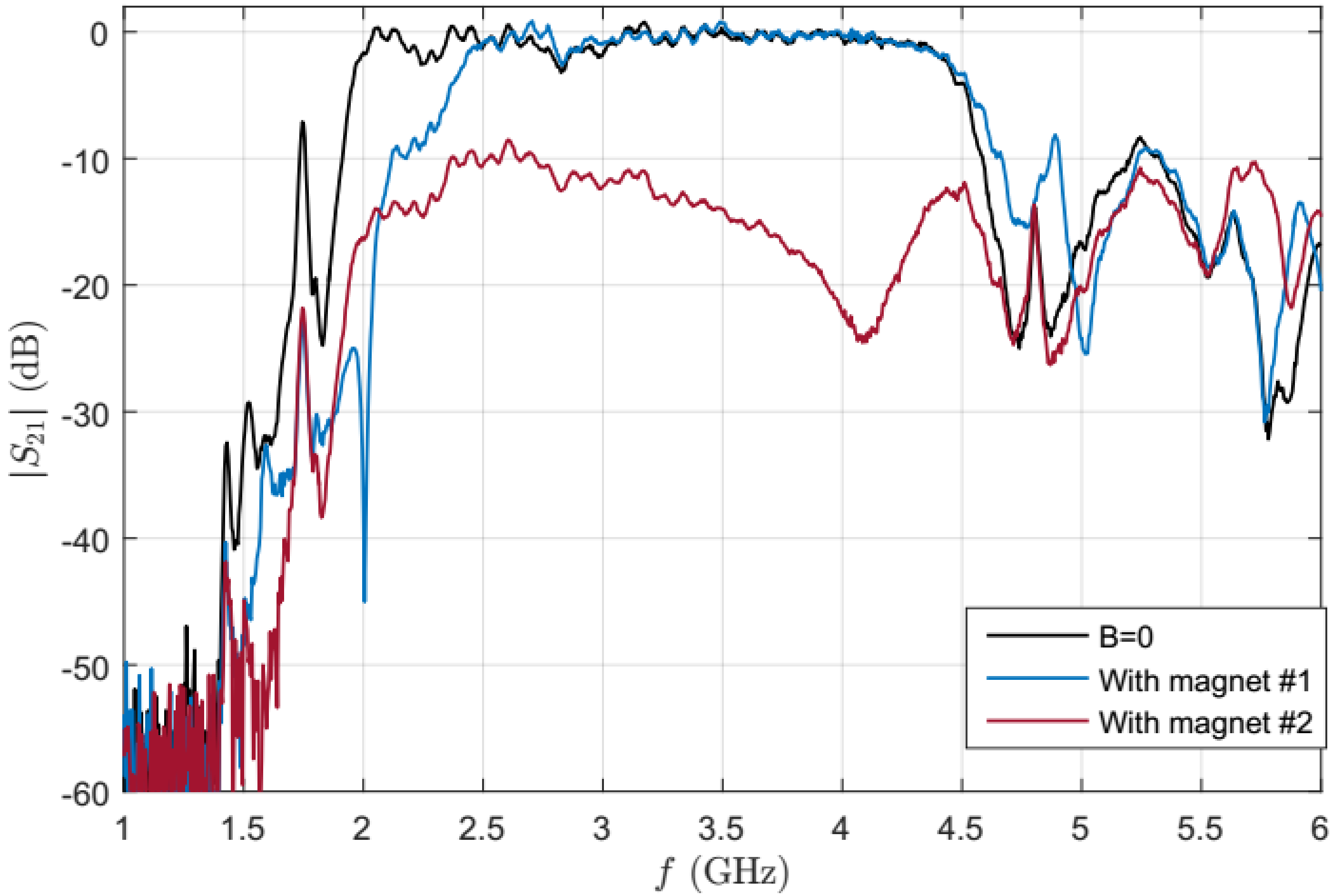


(a)



Circulator

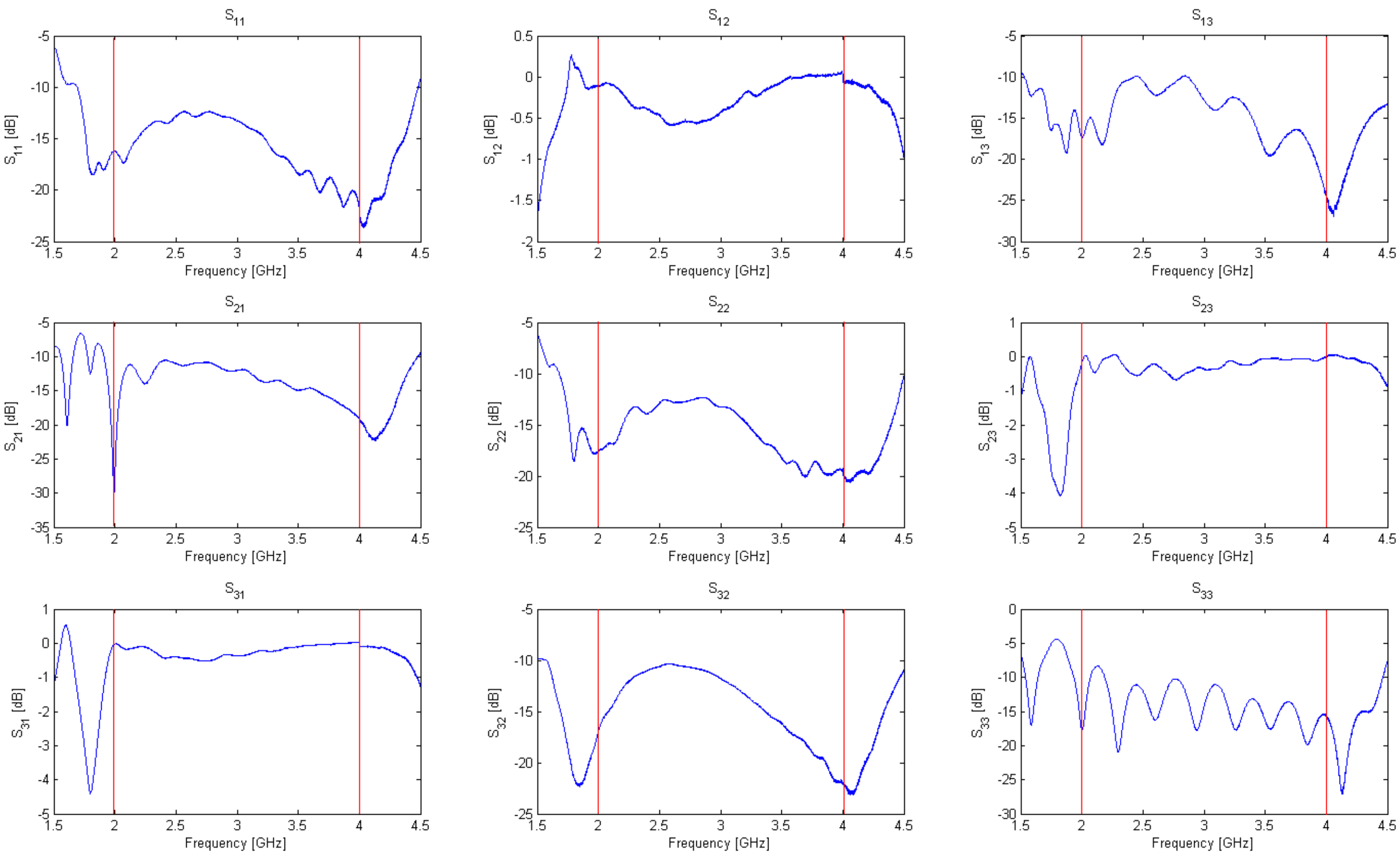
- Magnetic field sensitivity (“forward path”)



Circulator

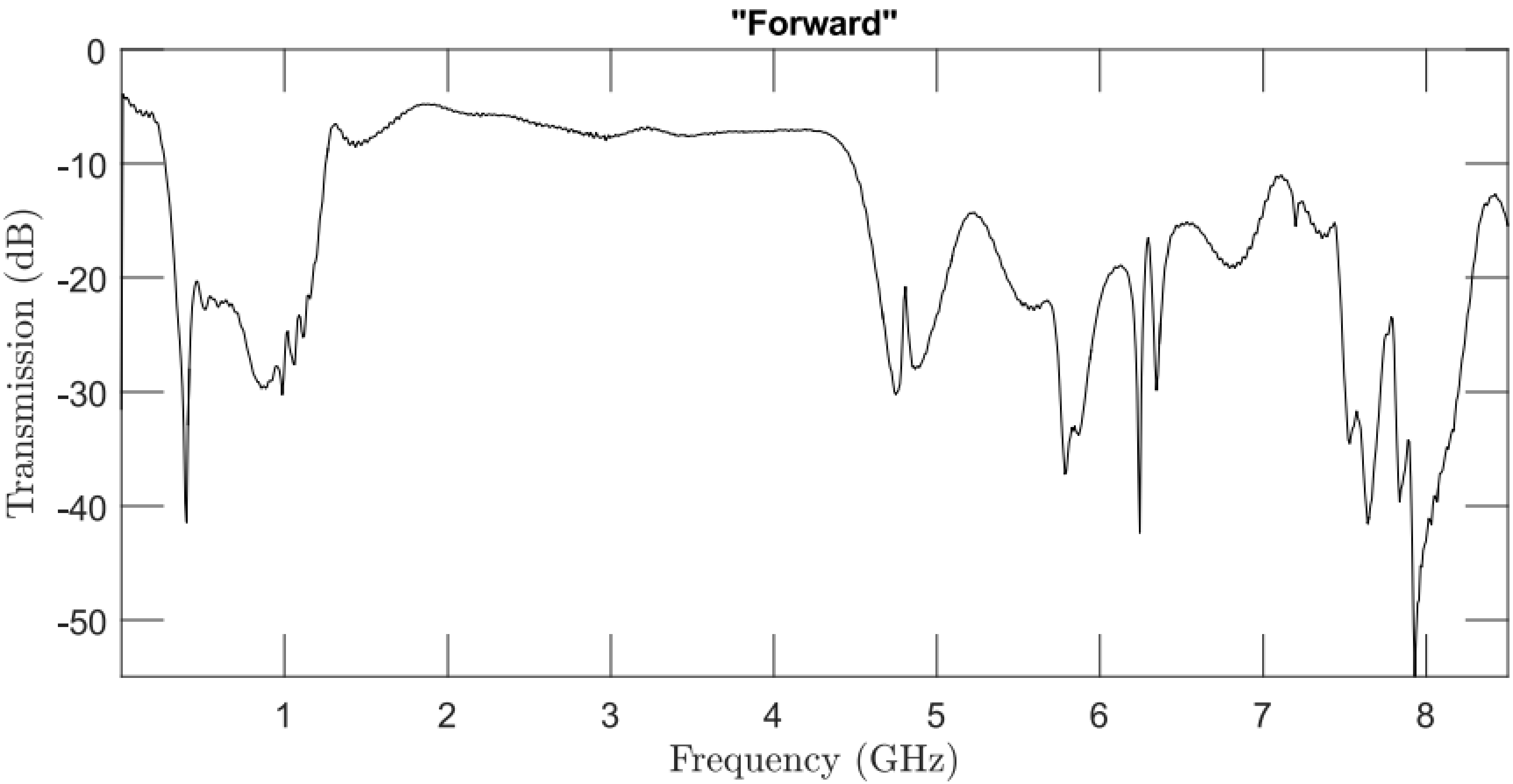
- CTD0304KC
  - Approx. 2k USD
  - 2-4 GHz
  - 18 dB isolation (typical)

Data from Basel:



Circulator, outside specs?

- Bluefors, 3 GHz line (2.5 - 4 GHz), transmission of circulator+isolator



Circulator, outside specs?

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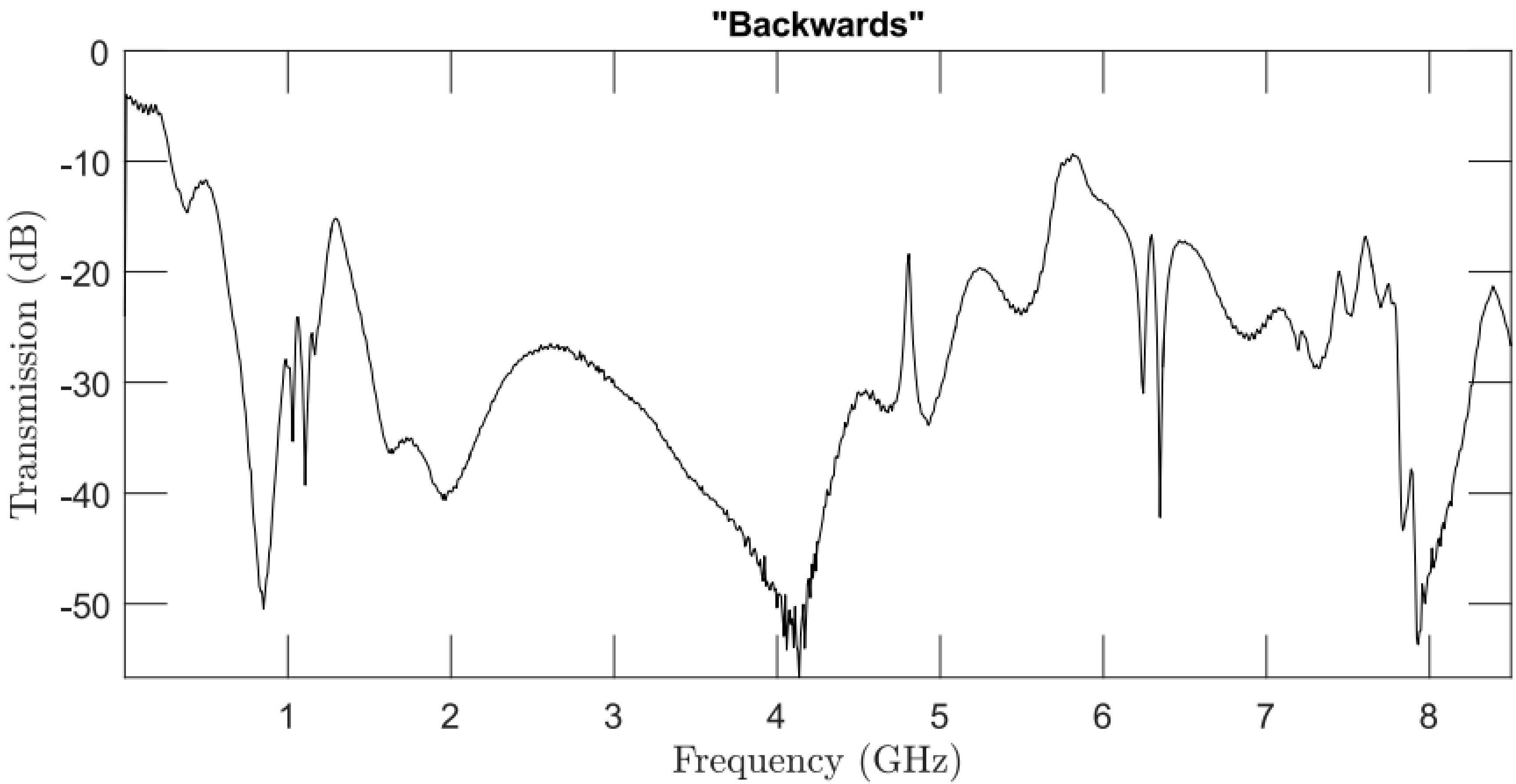


Isolator (dual)

- LNF-XXXXC4_12A
  - RF bandwidth: 4-12 GHz
  - Insertion loss: 0.4 dB typical
  - Isolation: 30 dB typical
  - Port match: 16 dB typical
  - RF-connectors: SMA
  - Cost: 10k USD (?)

Isolator (dual)

- LNF-XXXXC4_12A

Maximum external magnetic field imposed on the isolator

Parameter	Condition	Value	Unit
Maximum perpendicular external magnetic field	At chassis	650	Gauss
Maximum parallel external magnetic field	At chassis	1500	Gauss

- “Maximum field” means the field when the passband frequency edge has shifted 150 MHz, and insertion loss degradation becomes noticeable.
- The optional MuMetal shield improves the maximum external magnetic field very little. MuMetal alloys are good at shielding very low level “stray” magnetics fields, however the material saturates quickly and doesn’t shield well against high field external sources

Supra qubits vs. spin qubits…

Coaxial cables

- Heat load
  - Especially for scalability
  - **Passive: through cables**
  - Active: dissipative elements (amplifier, attenuator)
  - Radiative
  - Attenuation: ∼60 dB (needed for thermalization)

Engineering cryogenic setups for 100-qubit scale superconducting circuit systems
S. Krinner, S. Storz, P. Kurpiers, P. Magnard, J. Heinsoo, R. Keller, J. L¨utolf, C. Eichler, A. Wallraff

- Material
  - SS
  - CuNi
  - Supra
    - Japanese company

arXiv:1806.07862v1 [quant-ph]

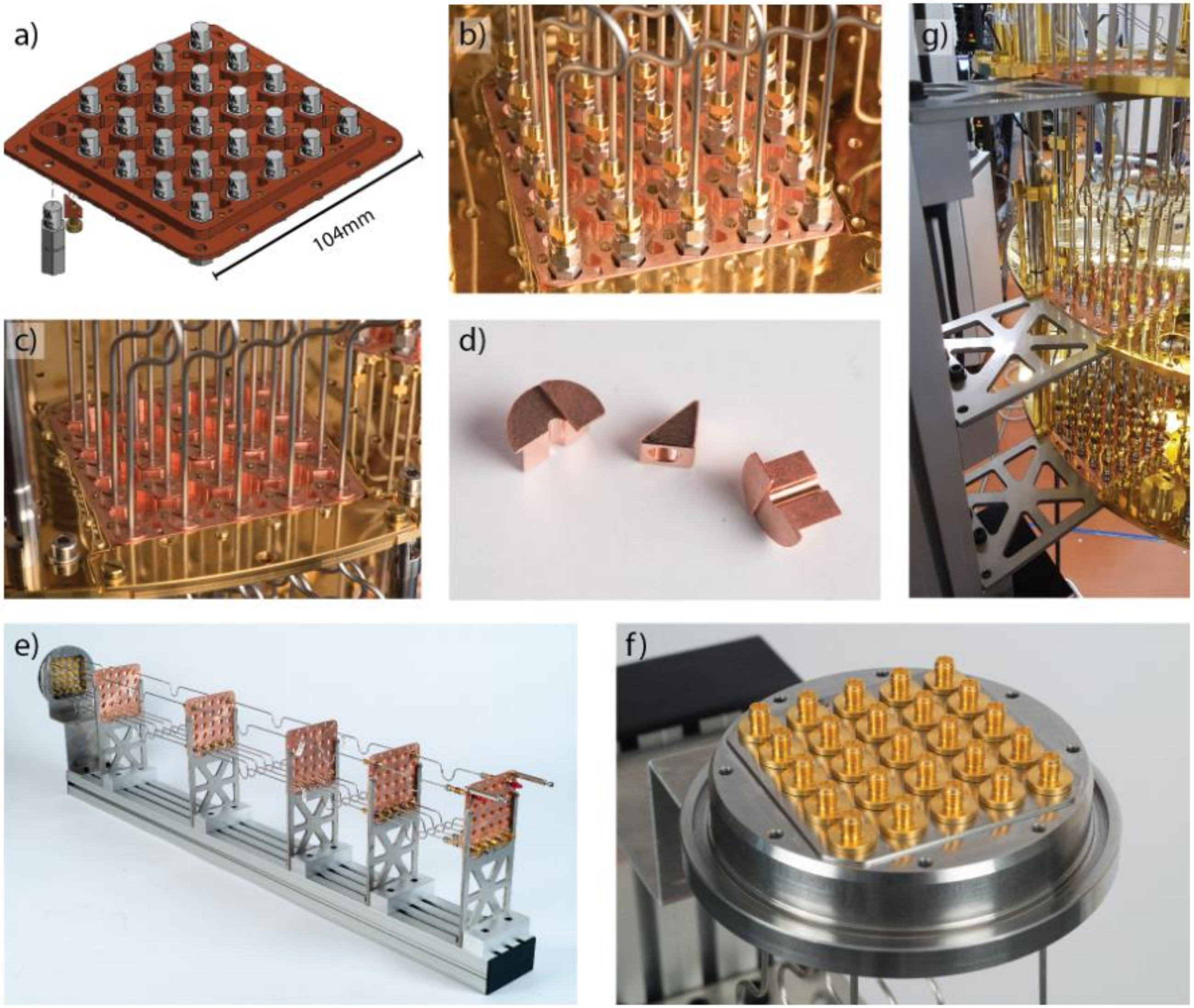
Coaxial cables

- Heat load
  - Passive: through cables
- Attenuation: ~60 dB (needed for thermalization)
- “**Stainless steel** cables (UT85-SS-SS) and **NbTi** cables (UT85-NbTi) have the lowest passive load. The flows of these two cable types are dominated by their outer conductor, which has a cross-sectional area that is by a factor 10 larger than the center conductor. The contribution of the Teflon dielectric is of the same order of magnitude as the one of the inner conductor.”

- “An alternative to stainless steel cable is **Cupronickel (CuNi)** cable. It is expected to have a 20-30% higher passive load than SS-SS cable. Another commonly used cable type is UT85-SS cable (stainless steel CC, SPCW center conductor). Due to its comparably low attenuation, see Appendix A, it is suited for the sections in the output lines, for which NbTi is not superconducting, i.e. from the vacuum flange of the dilution refrigerator to the 4K stage”

arXiv:1806.07862v1 [quant-ph] 20 Jun 2018

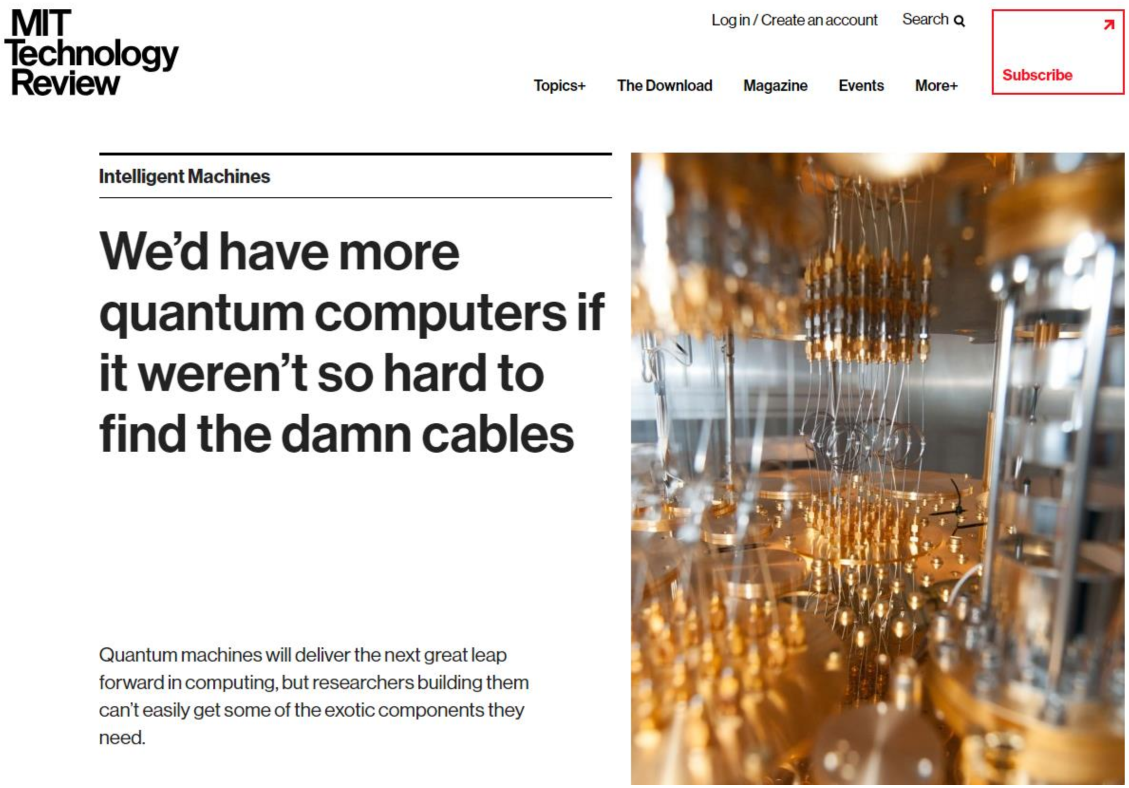
Coaxial cables



arXiv:1806.07862v1 [quant-ph] 20 Jun 2018

Coaxial cables

- Supra:
  - Japanese company Coax Co.



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Intelligent Machines

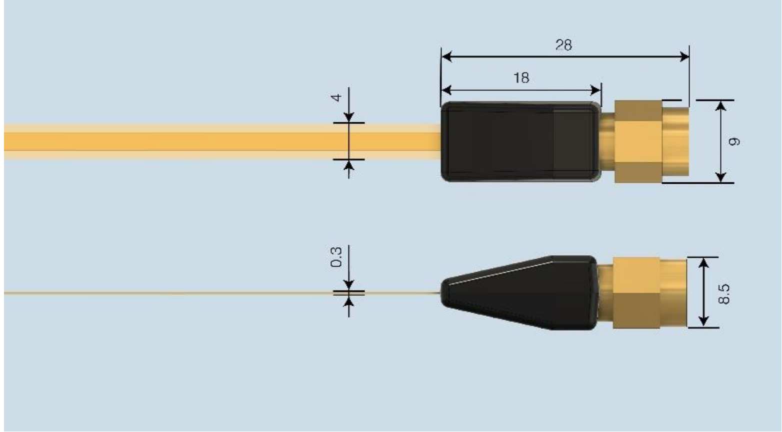
We'd have more quantum computers if it weren't so hard to find the damn cables

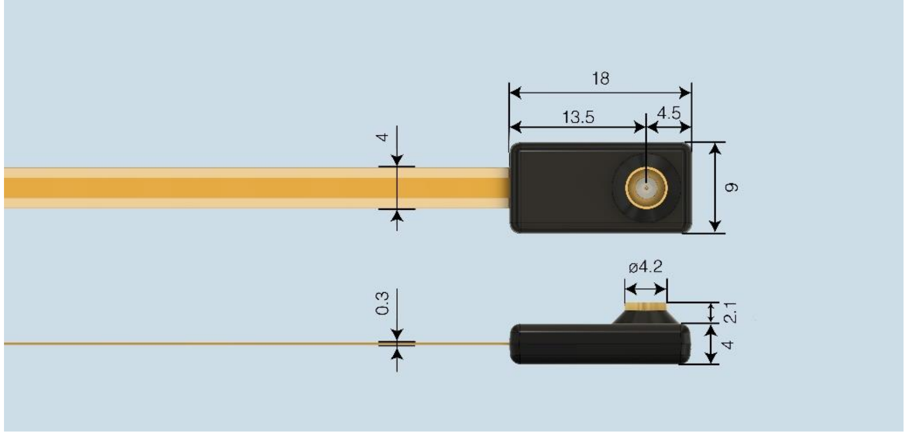
Quantum machines will deliver the next great leap forward in computing, but researchers building them can't easily get some of the exotic components they need.

https://www.technologyreview.com/s/612760/quantum-computers-component-shortage/

Coaxial cables

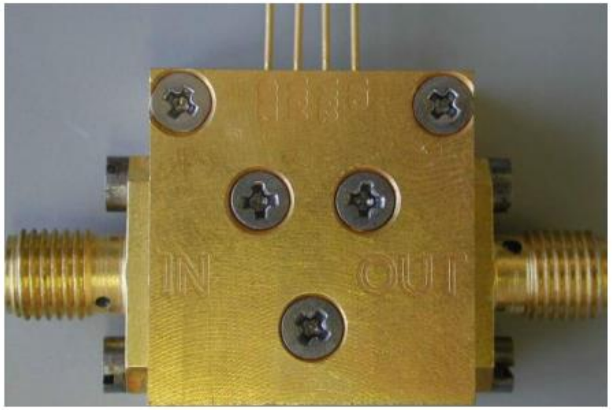
- http://www.delft-circuits.com/
  - “Cri/oFlex® CF2 series is specifically design for cryogenic environments where thermal load, microwave performance, small form factor and phase stability are critically important. Our standardized CF2 series is ideally suited to solve space constraints in crowded setups, such as table-top cryo systems or densely populated mixing chambers of dilution refrigerators. ”





Amplifier

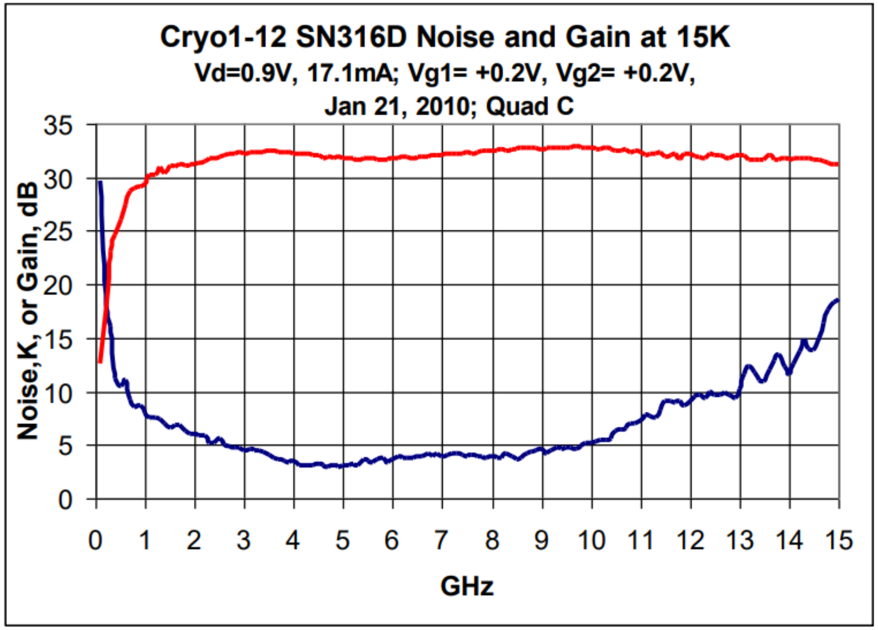
- HEMT
  - Active element
  - Supply brick + biasing box
  - Power supply: possible ground loop
- E.g. Caltech CITCRYO1-12D
  - 1-12 GHz
  - Gain: 32 dB
    - In an experiment: to be calibrated
  - DC power @ 20 K: 1.2V, 23mA, 28 mW
  - Mounted on the 4K plate
  - Cost: 6k USD (?)
- Quantum-limited amplifiers? TWPA, JPA



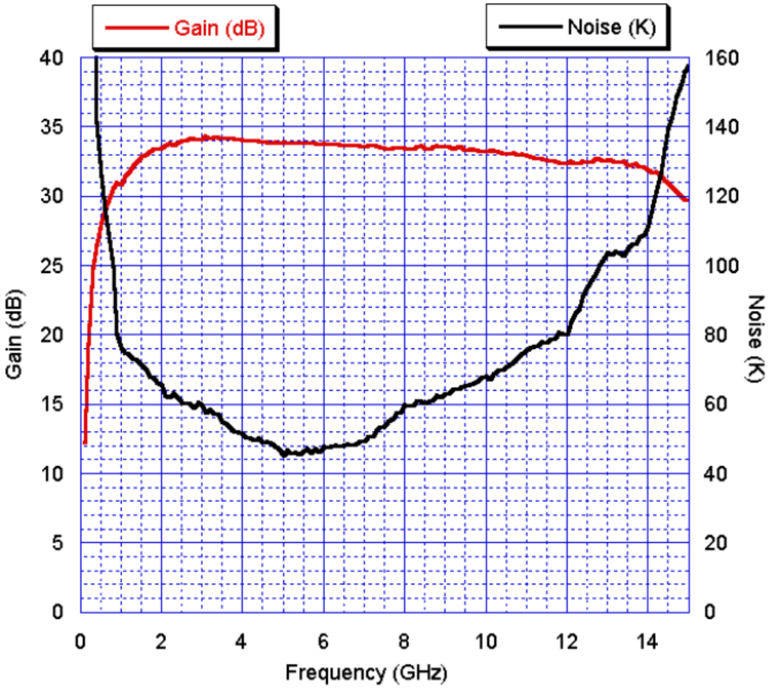
Amplifier

- Caltech CITCRYO1-12D

Typical Gain and Noise at 21K



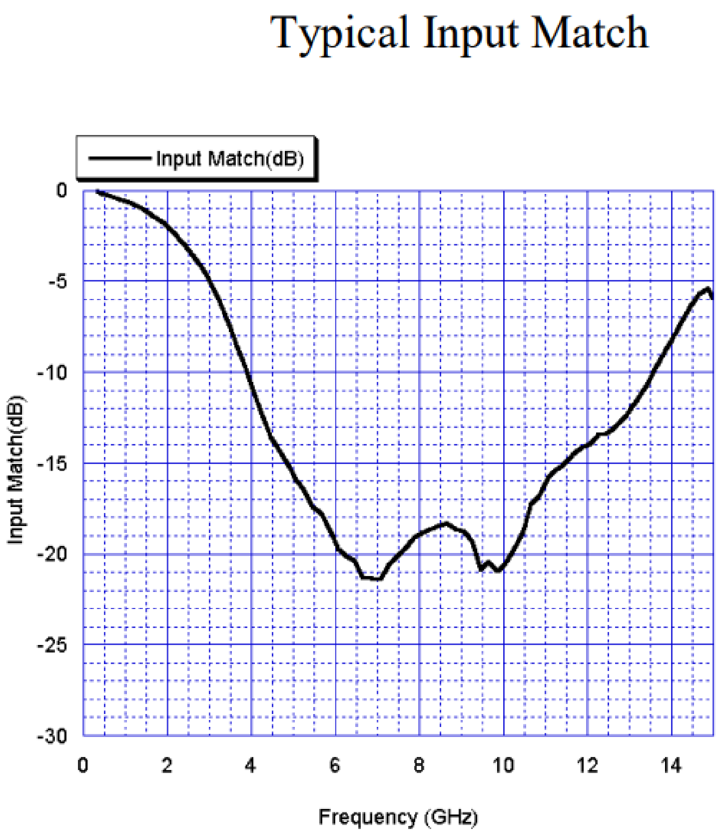
Typical Gain and Noise at 295K

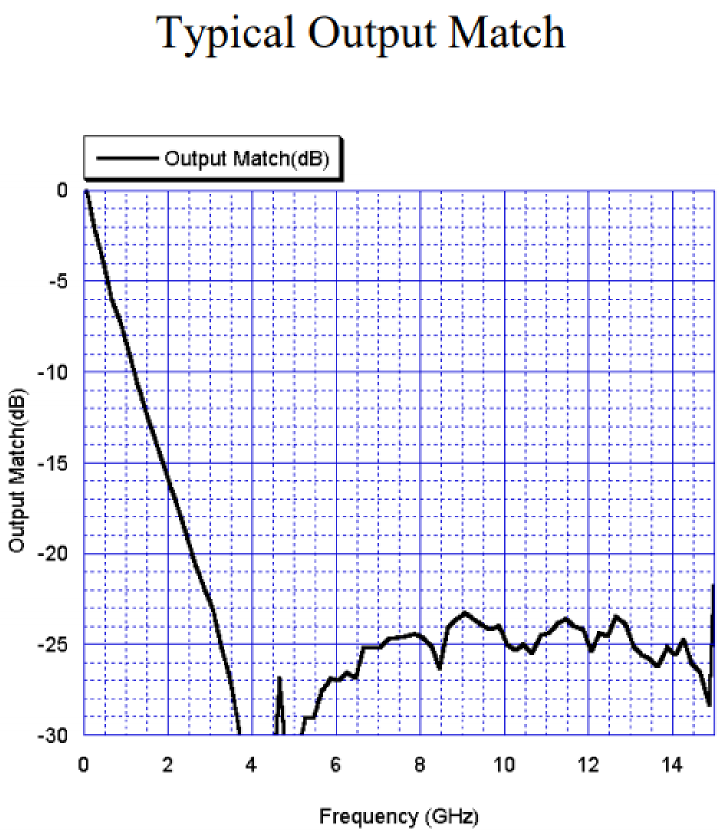


https://docs.wixstatic.com/ugd/b329ad_3f335f80dedb40b8bb775d9014f383d2.pdf

Amplifier

- Caltech CITCRYO1-12D

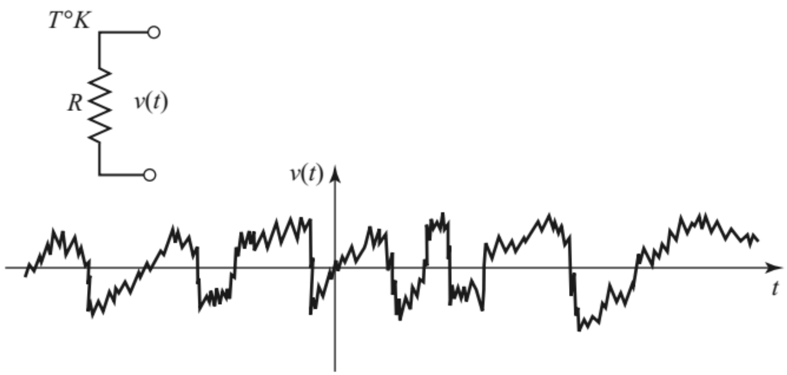




https://docs.wixstatic.com/ugd/b329ad_3f335f80dedb40b8bb775d9014f383d2.pdf

Amplifier noise

- Thermal noise

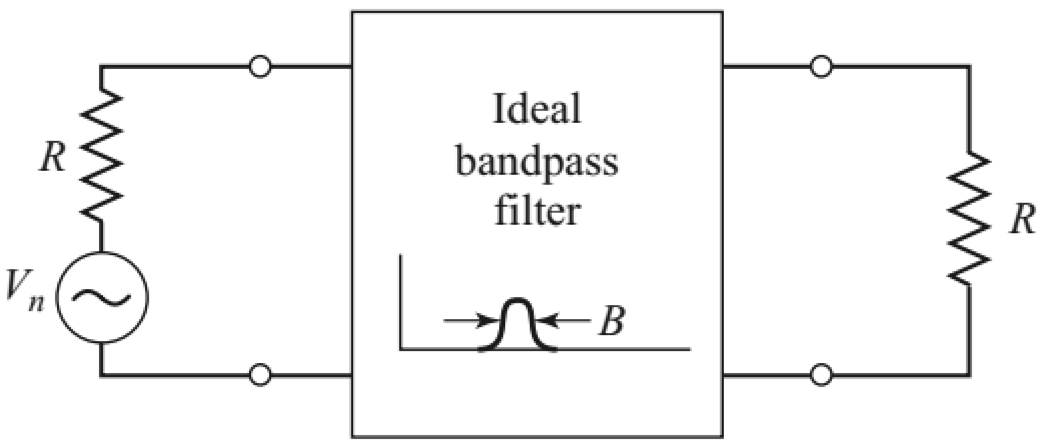


$$V_n = \sqrt{\frac{4hf\,BR}{e^{hf/kT} - 1}}$$

$$V_n = \sqrt{4kTBR}$$

Rayleigh–Jeans approximation

- Noise power

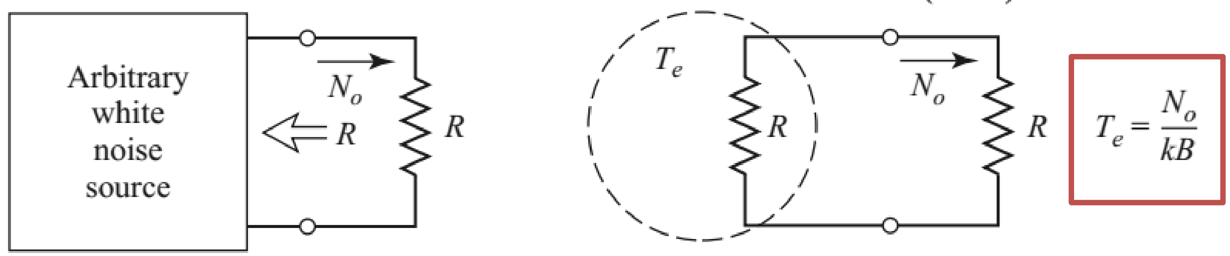


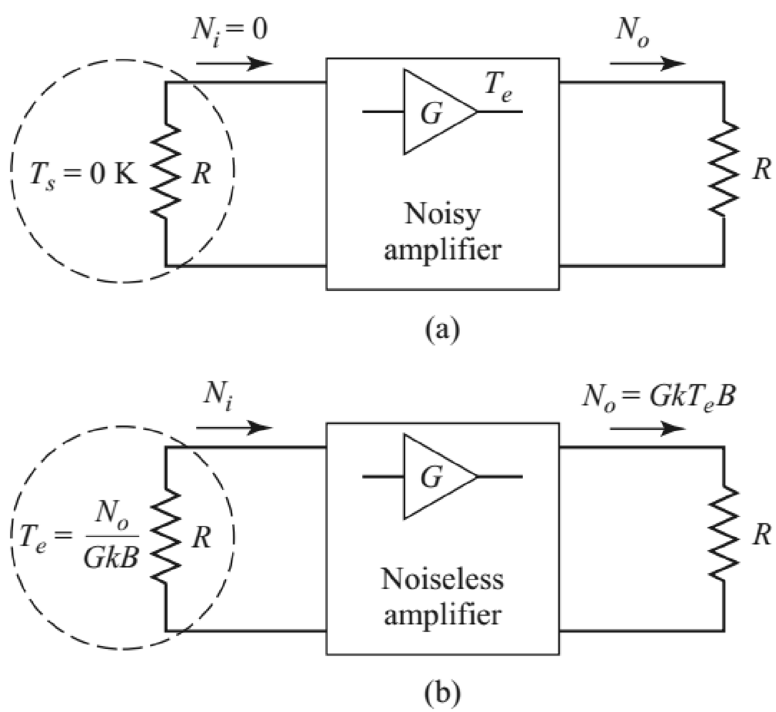
$$P_n = \left(\frac{V_n}{2R}\right)^2 R = \frac{V_n^2}{4R} = kTB$$

Amplifier noise

- Equivalent noise temperature

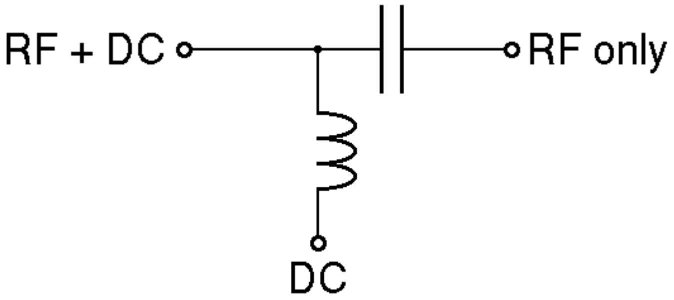
$$P_n = \left(\frac{V_n}{2R}\right)^2 R = \frac{V_n^2}{4R} = kTB$$





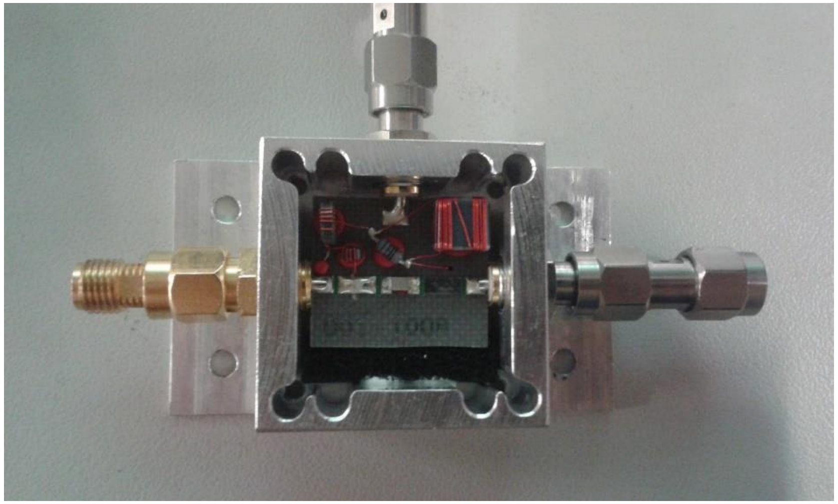
Bias tee

- Simplest
  - Self-made (on PCB)
  - + resistor
  - (On-chip RF shunt)
- Commercial, wide-band



$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} \ll Z_0,$$

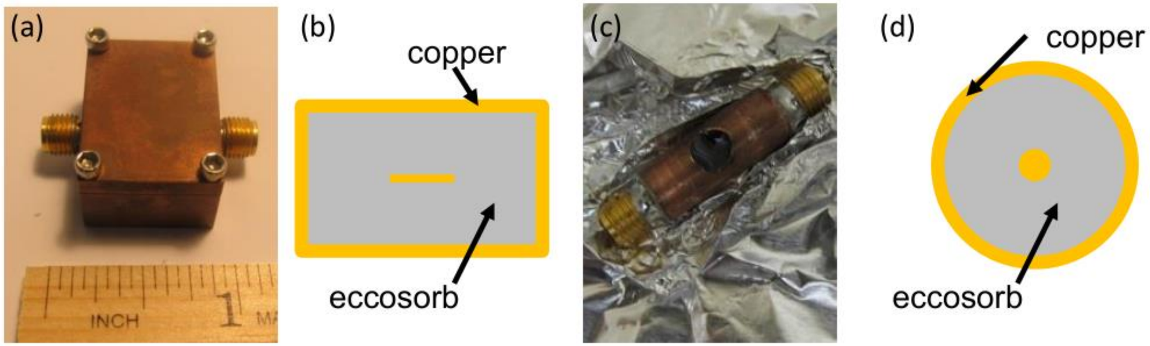
$$X_L = \omega L = 2\pi f L \gg Z_0,$$



Filtering

- Commercial
  - K&L low-pass filter
  - Cost: 500 EUR

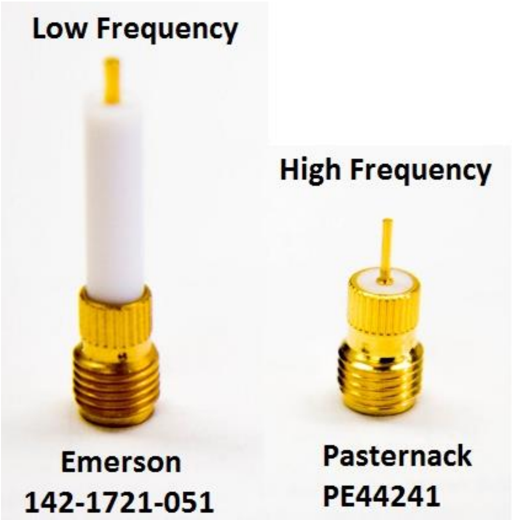
- Homemade
  - Cu powder
  - Eccosorb

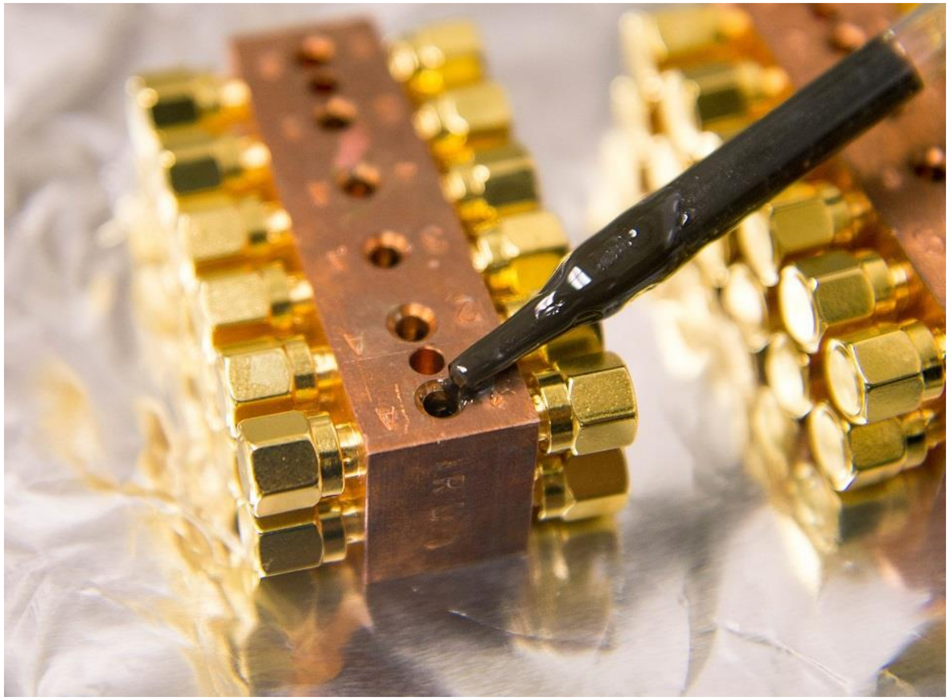


Kurtis Lee Geerlings, PhD Thesis 2013 (M, Devoret group)
http://qulab.eng.yale.edu/documents/theses/Kurtis_ImprovingCoherenceSuperconductingQubits.pdf

Filtering

- Homemade
  - ECCOSORB CR-110
  - ECCOSORB CR-124





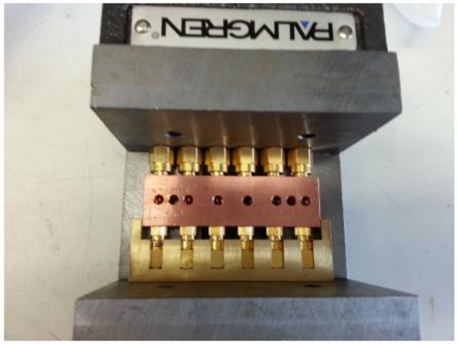
Press-fit + long pin = hard to get

Michael Fang, BSc Thesis (J. Martinis group)
https://web.physics.ucsb.edu/~martinisgroup/theses/Fang2015.pdf

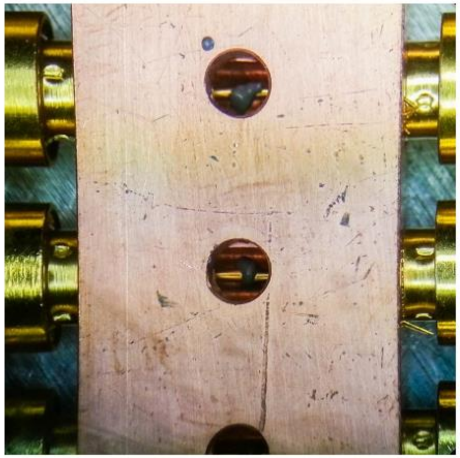
Filtering

- Homemade

(A) Press fitting first side



(B) Press fitting second side



(C) Before soldering

(D) After soldering

Michael Fang, BSc Thesis (J. Martinis group)
https://web.physics.ucsb.edu/~martinisgroup/theses/Fang2015.pdf

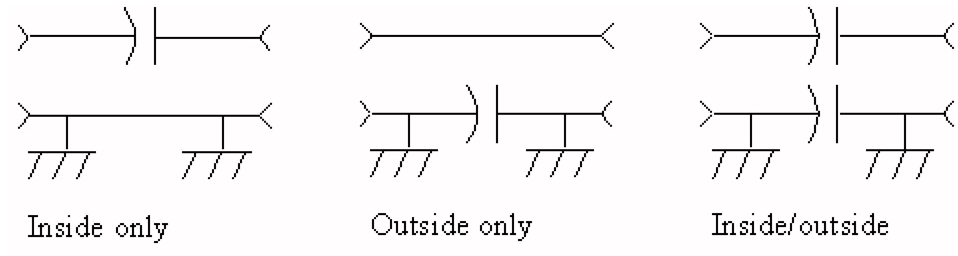
Shielding

- Homemade IR shielded can
  - Hermetic seal
  - Stycast 2850 and carbon powder, containing 7% carbon powder by weight

Kurtis Lee Geerlings, PhD Thesis 2013 (M, Devoret group)
http://qulab.eng.yale.edu/documents/theses/Kurtis_ImprovingCoherenceSuperconductingQubits.pdf

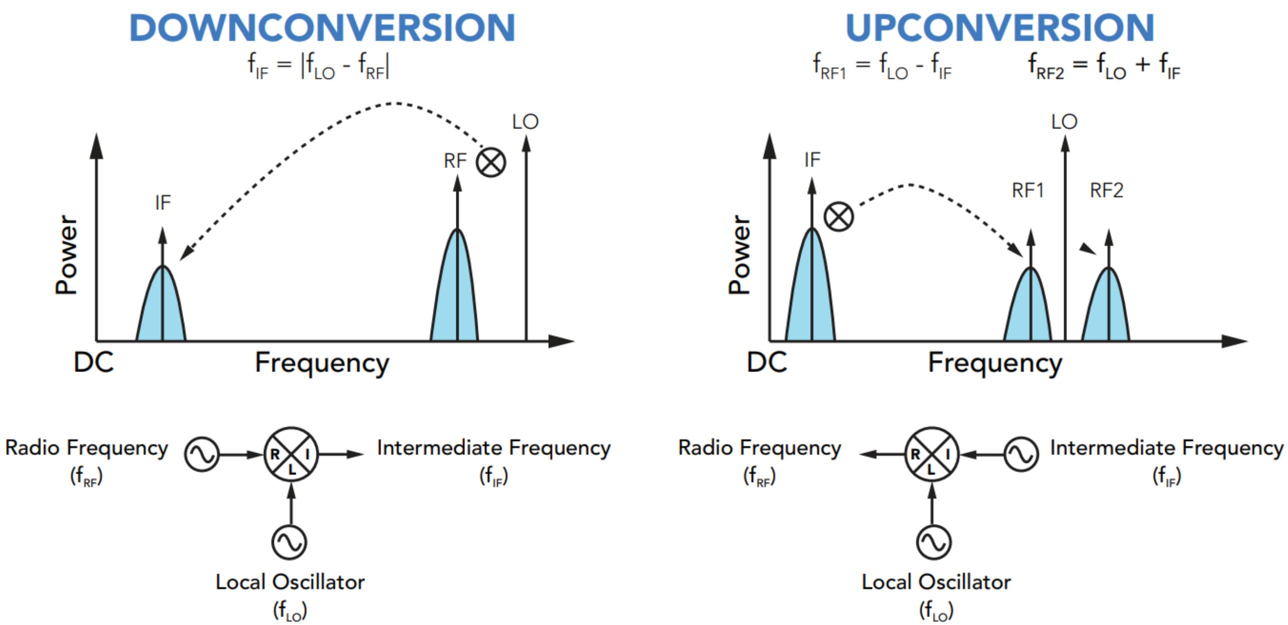
DC block

- Inner only
- Outer only
- Inner-outer
  - Cost: 200 USD



Mixer

- Basic operation



$$\cos f_{LO} \cos f_{RF} = \frac{1}{2}\left(\cos(f_{LO} + f_{RF}) + \cos(f_{LO} - f_{RF})\right)$$

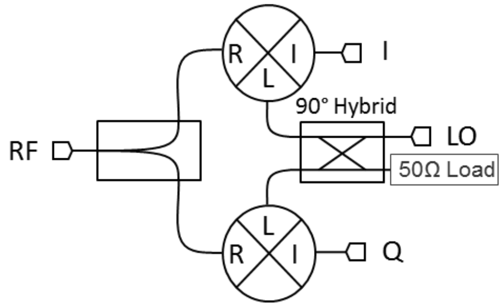
- Practice: LO and RF are close to each other
- Non-ideal properties: loss, leakage, higher harmonics

Marki Microwave Mixer primer
https://www.markimicrowave.com/assets/appnotes/mixer_basics_primer.PDF

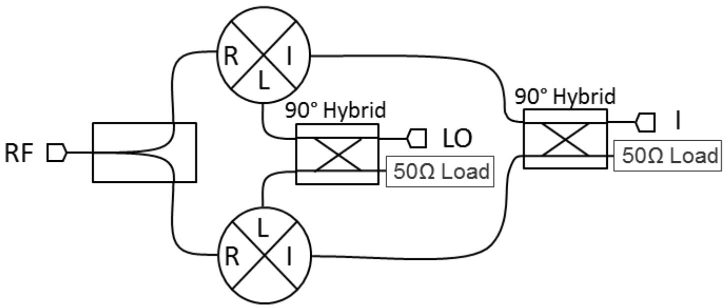
Mixer

- IQ mixer
  - Down-conversion: get both I and Q
  - Up-conversion: control the phase

$$A\sin(\omega t+\Phi) = \underbrace{[A\sin(\Phi)]}_{:=I}\sin(\omega t) + \underbrace{[A\cos(\Phi)]}_{:=Q}\sin(\omega t)$$



IQ Mixer



IR/SSB Mixer

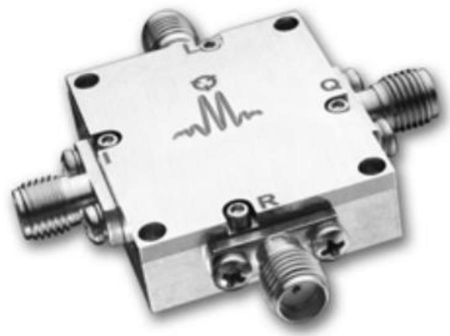
- IR/SSB mixer
  - Down-coversion: image reject
  - Up-conversion: single sideband

Mixer

- IR-1545
  - IMAGE REJECT DOUBLE-BALANCED MIXER

Features

- LO/RF 1.5 to 4.5 GHz
- IF 50 to 90 MHz
- 5.5 dB Typical Conversion Loss
- 43 dB Typical LO to RF Isolation
- 25 dB Typical Image Rejection
- Open Carrier or Connectorized



- IQ-1545LMP
  - Cost: 1.2k USD

Features

- LO/RF 1.5 to 4.5 GHz
- IF DC to 500 MHz
- 5.5 dB Typical Conversion Loss
- 43 dB Typical LO to RF Isolation
- 3 degree Typ Quadrature Phase Deviation
- .3 dB Typical Amplitude Deviation

Saclay setup

- Phase shifter, JPA, calibration with MW switches (?)

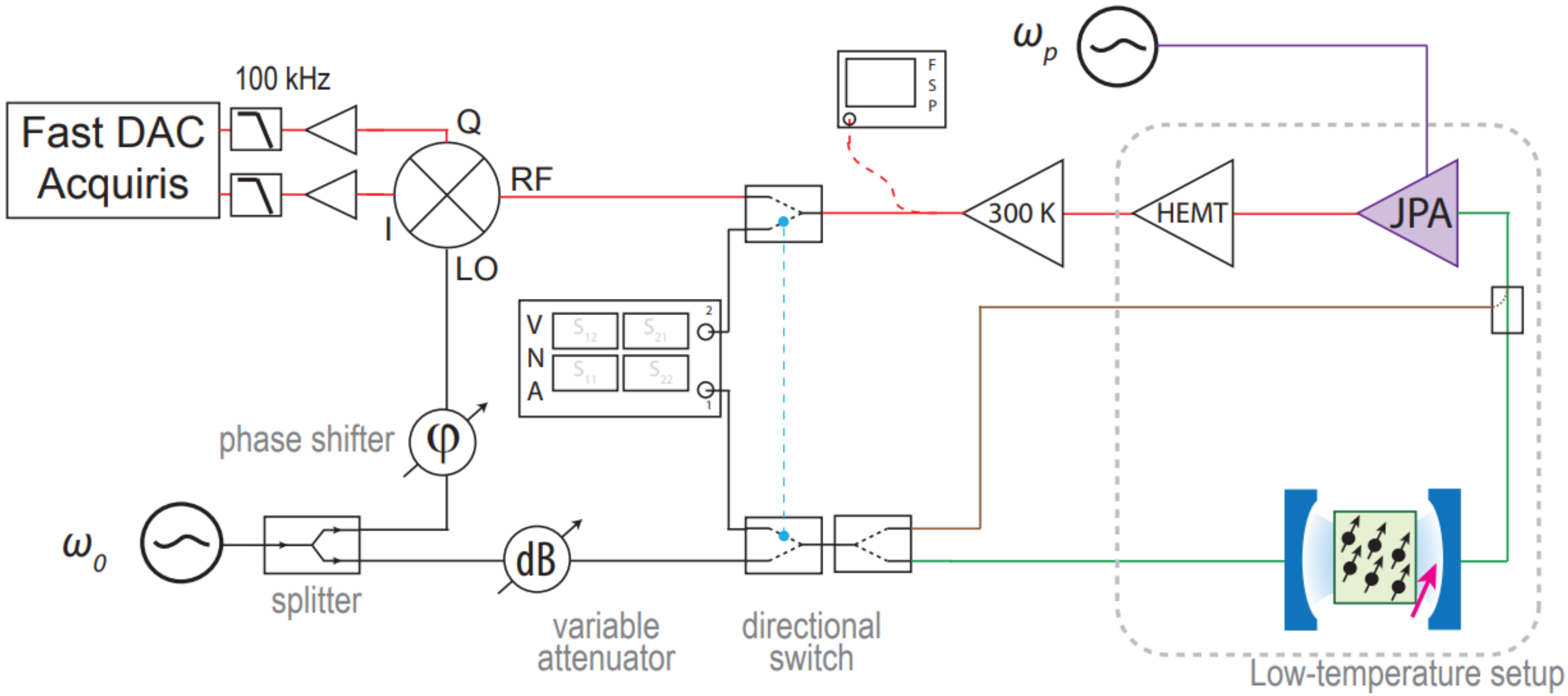


FIGURE 5.5: **Room-temperature setup.**

http://iramis.cea.fr/spec/Pres/Quantro/static/wp-content/uploads/2018/06/PhDAudreyBienfaitCorrJune2018.pdf

Zürich setup

- Wallraff
  - Extra BPF
  - Eccosorb
  - TWPA
  - Flux line: less atten.

arXiv:1806.07862v1

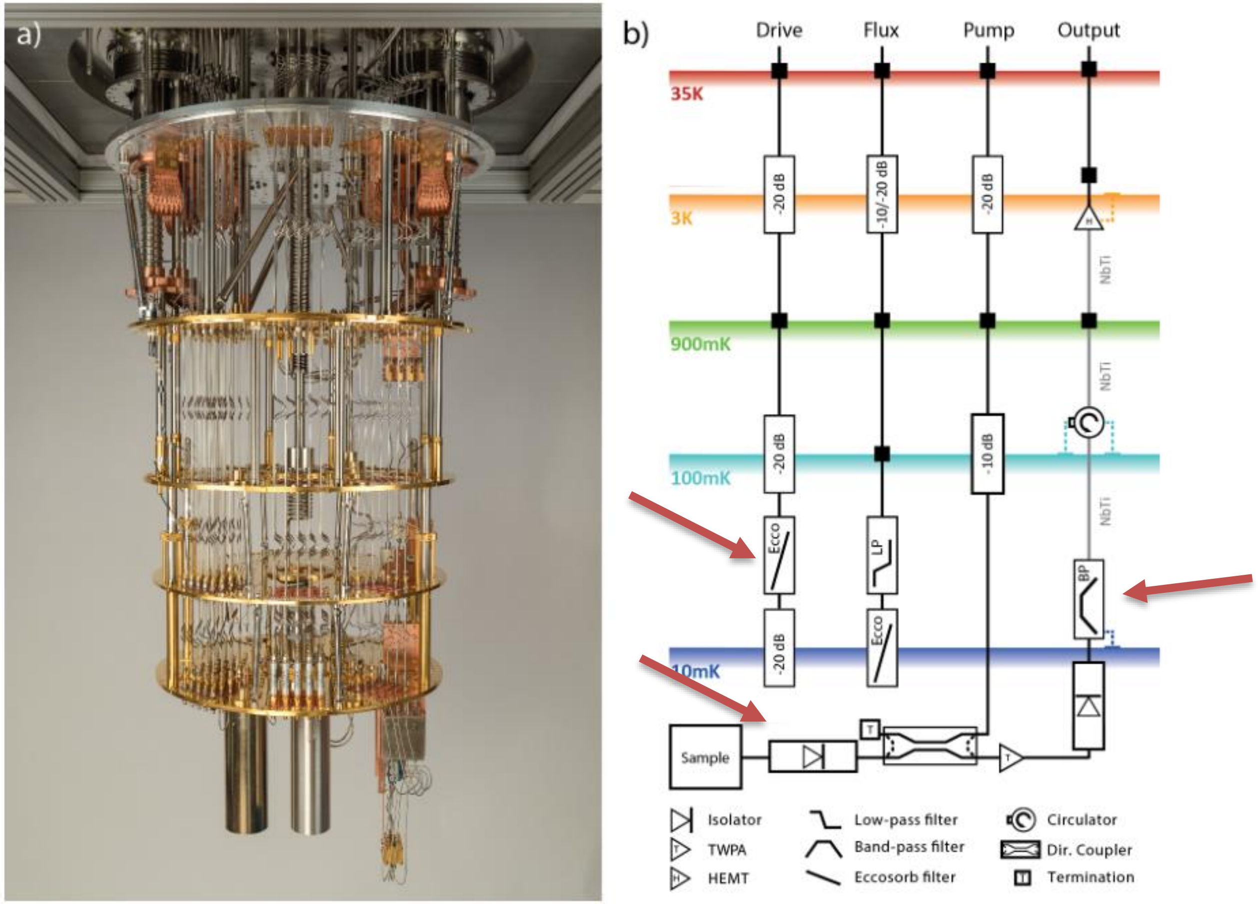
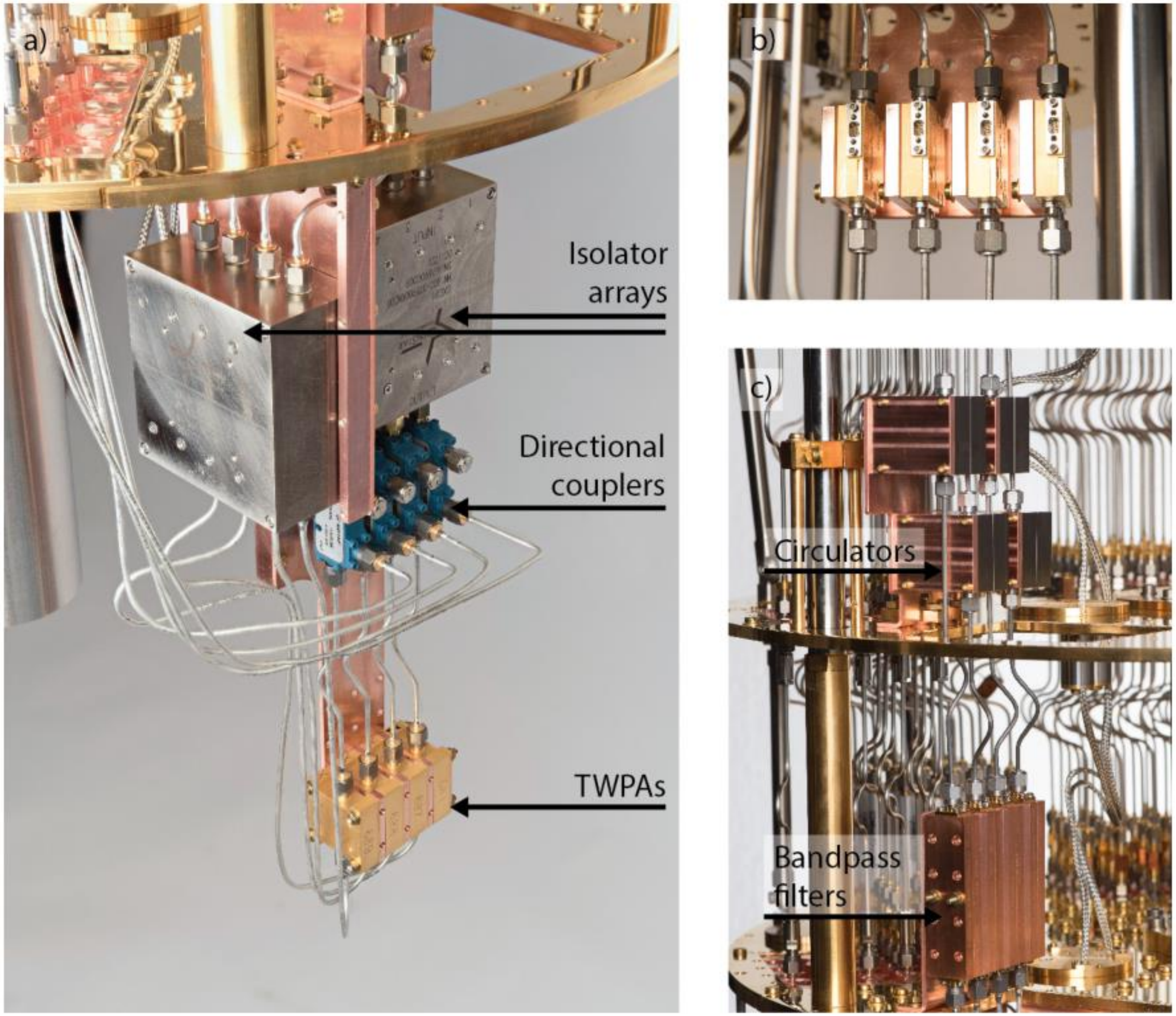


Fig. 3 Cabled dilution refrigerator (DR). a) Bluefors XLD DR with 25 drive lines, 25 flux lines, 4 read-out, 6 read-in, and 5 pump lines installed (see end of Section 3.1 for details). b) Schematic of the cabling configuration inside the DR.

Zürich setup

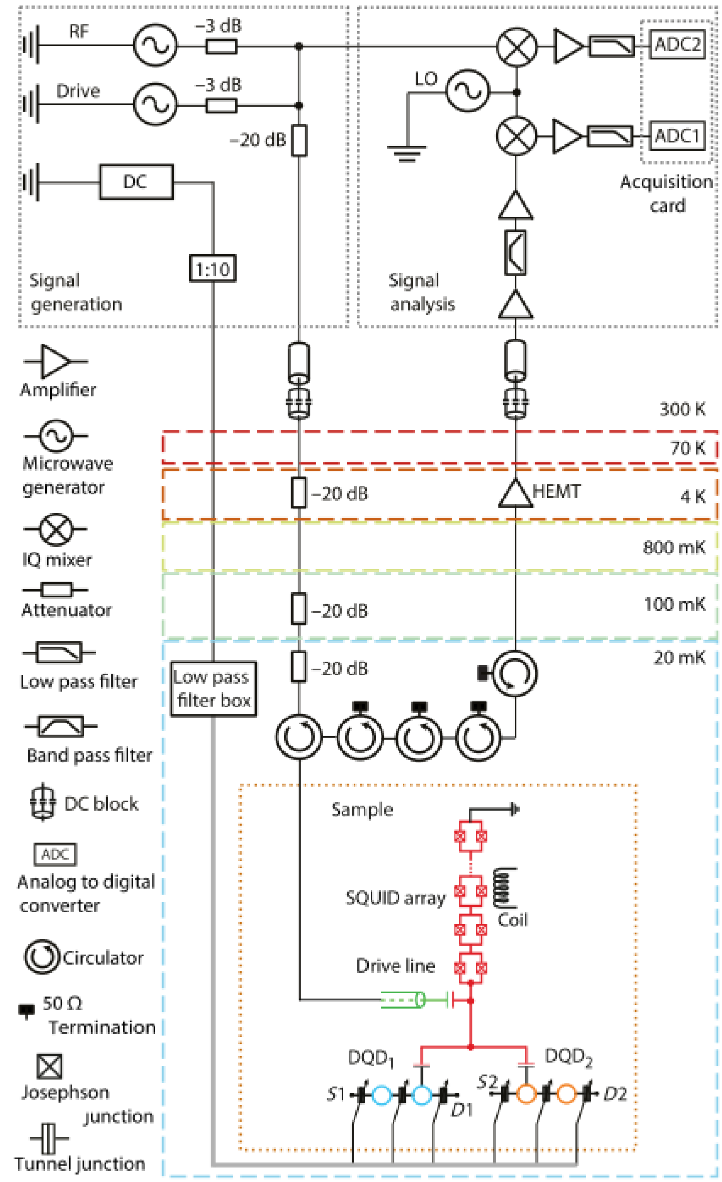
- Wallraff
  - Extra BPF
  - Eccosorb
  - TWPA
  - Flux line: less atten.

arXiv:1806.07862v1



Zürich setup no. 2

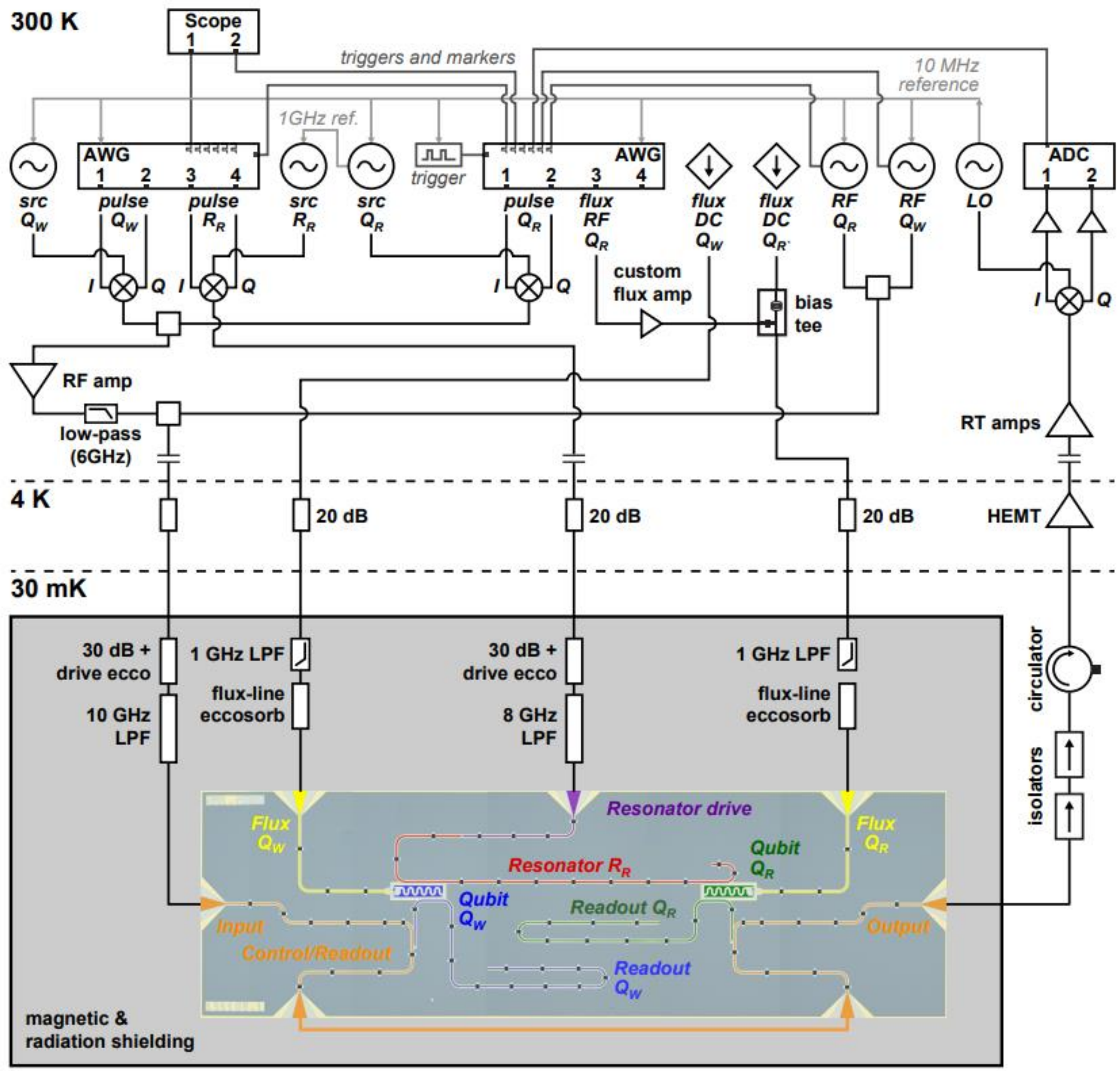
- Wallraff
  - 5 circulators!



10.1103/PhysRevX.8.041018

Delft setup

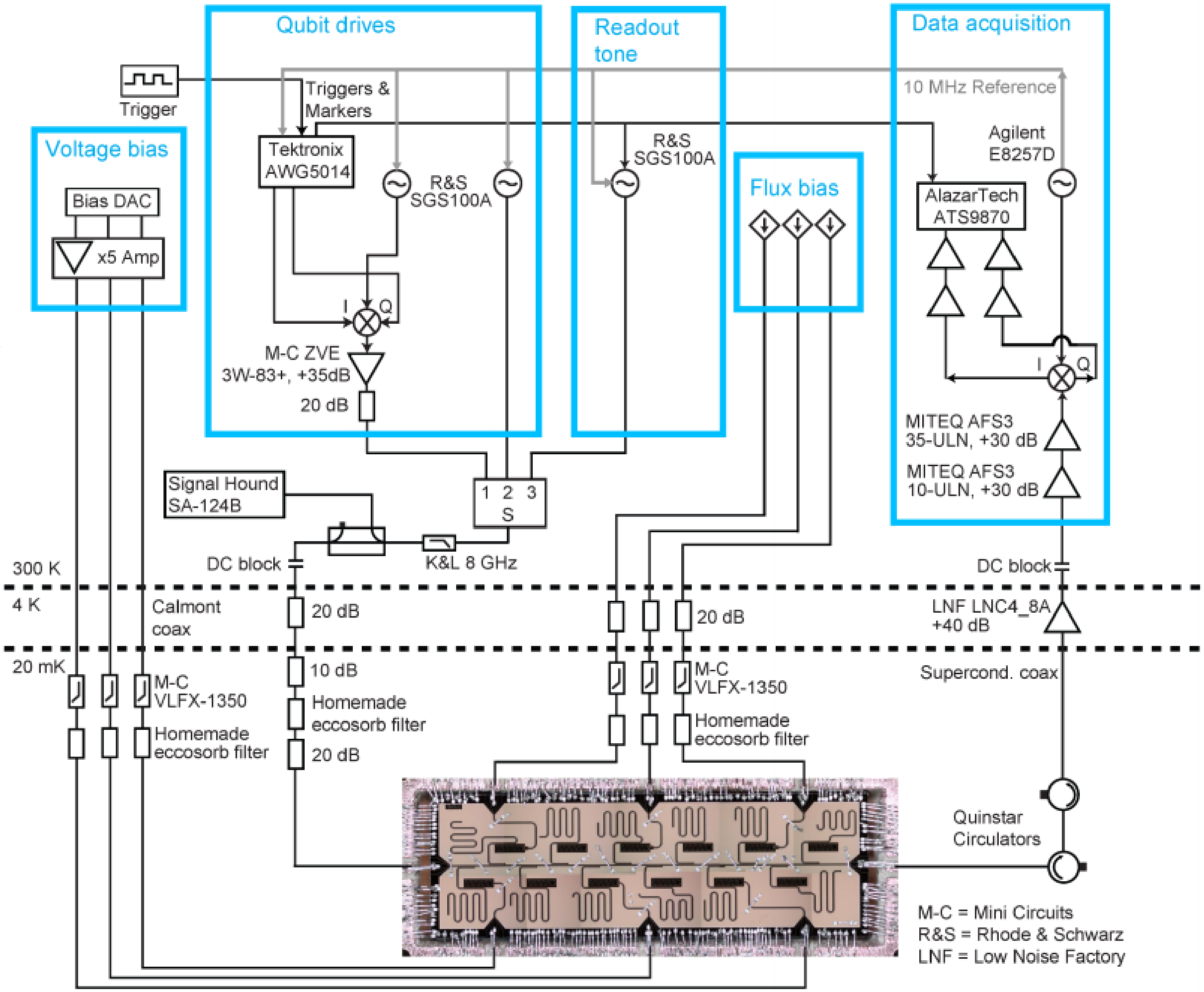
- DiCarlo lab
  - Eccosorb
  - K&L filter



https://arxiv.org/pdf/1610.10065.pdf

Delft setup

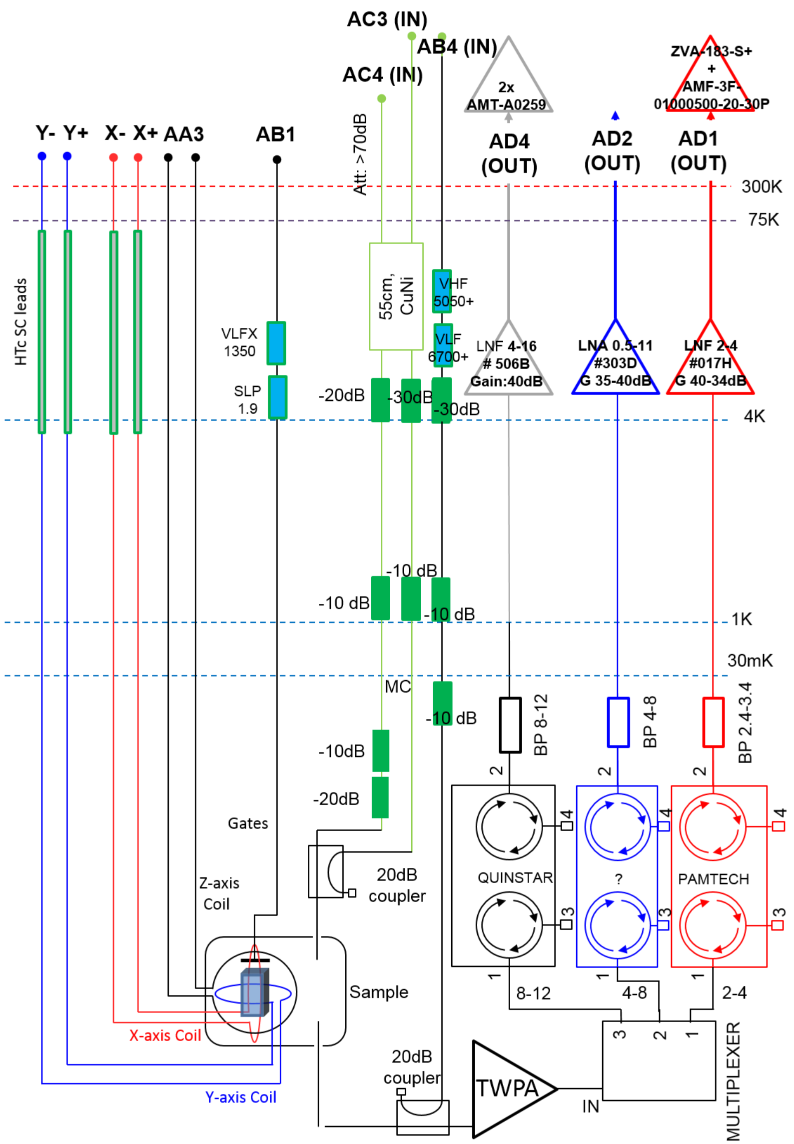
- DiCarlo lab
  - Eccosorb
  - MiniCircuits
  - Supra coax



https://arxiv.org/pdf/1711.07961.pdf

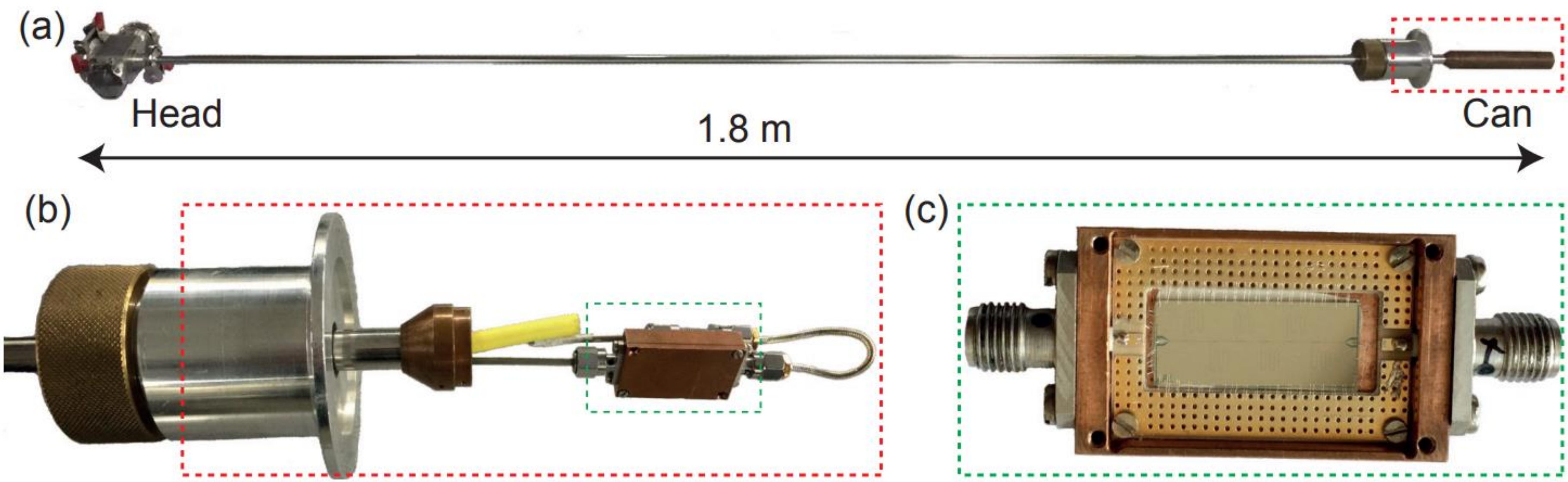
CEA Saclay setup

- Saclay
  - TWPA
  - Multiplexer



Simple RF dipstick

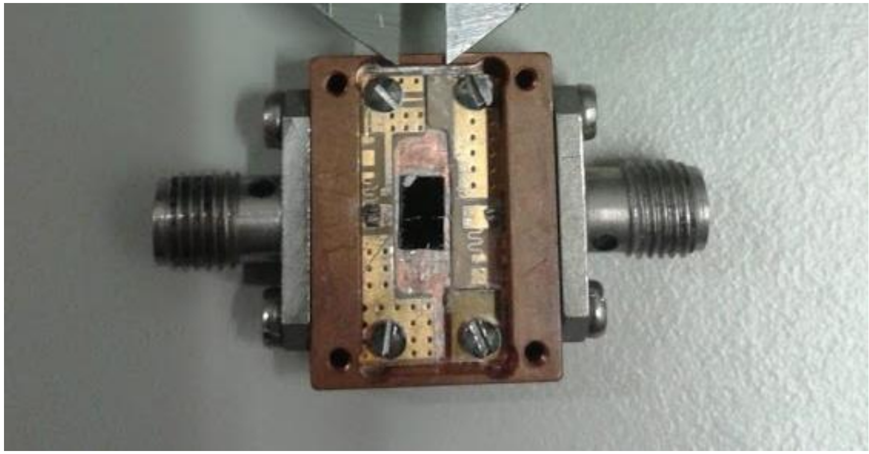
- Characterization of supra resonators at 4 K
- Reflection/transmission
- UT85-SS-SS coax, panel-mount SMA sockets
- Basic PCB

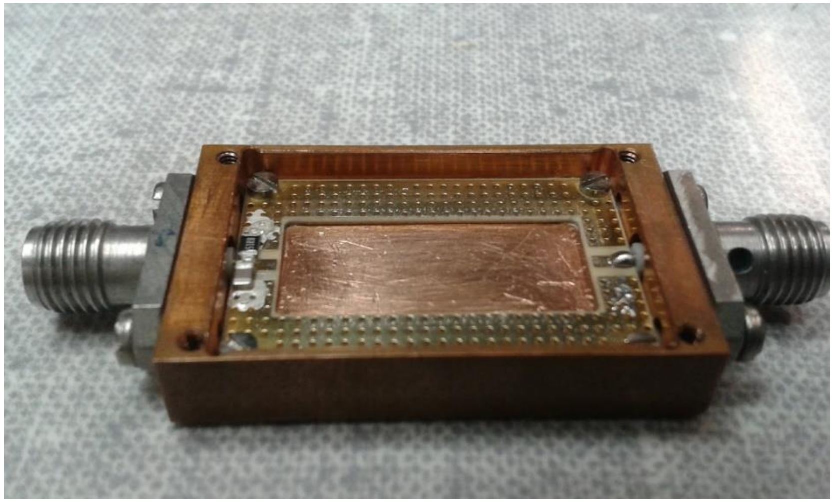


V. Ranjan, PhD Thesis

Simple RF dipstick

- Characterization of supra resonators
- 4 K
- Reflection/transmission
- Panel-mount SMA sockets
- Basic PCB
- Bonding?





Bonding?