The 13th School of Mesoscopic Physics:
Mesoscopic Quantum Devices

MAY 23 ~ 25, 2024 | POSCO International Center, POHANG, KOREA

What you should know about RF measurement

Jaseung Ku

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KRISS
한국표준과학연구원

2024.5.23 @ POSTECH

apctp
asia pacific center for theoretical physics

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OVERVIEW

The "School of Mesoscopic Physics" is a meeting to teach graduate students the basic knowledge of mesoscopic physics and promote information exchange, scientific discussions, and collaborations among scientists. This year, the school aims to cover the topic of "Mesoscopic quantum devices," which has recently attracted attention.

TOPICS

1. Mesoscopic theory
2. Quantum technologies
3. Topological materials

INVITED SPEAKERS

Seigo Tarucha (RIKEN)
Christian Schönenberger (Univ. of Basel)
Jaseung Ku (KRISS)
Myunglae Jo (Kyungpook Nat'l Univ.)
Eunjong Kim (Seoul Nat'l Univ.)
Sang-Jun Choi (Kongju Nat'l Univ.)
Moon Jip Park (Hanyang Univ.)

ORGANIZERS

Hyungkook Choi (Jeonbuk Nat'l Univ.)
Yong-Joo Doh (GIST)
Minkyung Jung (DGIST)
Seok-Kyun Son (Kyung Hee Univ.)
Nojoon Myoung (Chosun Univ.)
Hee Chul Park (Pukyong Nat'l Univ.)

PROGRAM

23 MAY (KST)

12:00 Registration
13:30 Opening Remark
13:40 **What you should know about RF Measurement** (Jaseung Ku, KRISS, Korea)
16:00 **Fabrication Techniques for Quantum Devices** (Myunglae Jo, Kyungpook Nat'l Univ., Korea)
18:30 Banquet
21:00 Free Discussion

24 MAY (KST)

09:30 **Introduction to Superconducting Quantum Devices** (Eunjong Kim, Seoul Nat'l Univ., Korea)
11:30 Group Photo
11:40 Lunch
13:00 **1. Fundamentals for quantum computer 2. Advances in spin quantum computer** (Seigo Tarucha, RIKEN, Japan)
15:10 **1. Search for the Fractional Josephson Effect 2. Qubits in nanowires** (Christian Schönenberger, Univ. of Basel, Switzerland)
17:20 **A crash course in Quantum Transport Theory: Coherent & Metallic Conduction** (Sang-Jun Choi, Kongju Nat'l Univ., Korea)
19:30 Dinner

25 MAY (KST)

09:30 **Introduction to Topological Materials: Topological Insulator and Superconductor** (Moon Jip Park, Hanyang Univ., Korea)
11:30 Closing Remark

REGISTRATION & CONTACT

https://www.apctp.org/theme/d/html/activities/activities01_read.php?id=2065
Registration Fee: free | Period for Registration: 2024. 04. 19 ~ 05. 19
Contact: **sori.kim@apctp.org** 054-279-8679 (Academic Support Team of APCTP)

Organized by The Mesoscopic Physics Society of Korea and Quantum and Nano Devices Research Society in Korea

apctp asia pacific center for theoretical physics | POSTECH | Ministry of Science and ICT International Research Network for Hybrid Quantum Systems and Interfaces | GIST Quantum Devices Laboratory

The APCTP is supported by the Korean Government through the Science and Technology Promotion Fund and Lottery Fund and strives to maximize public value through its various activities.

Outline

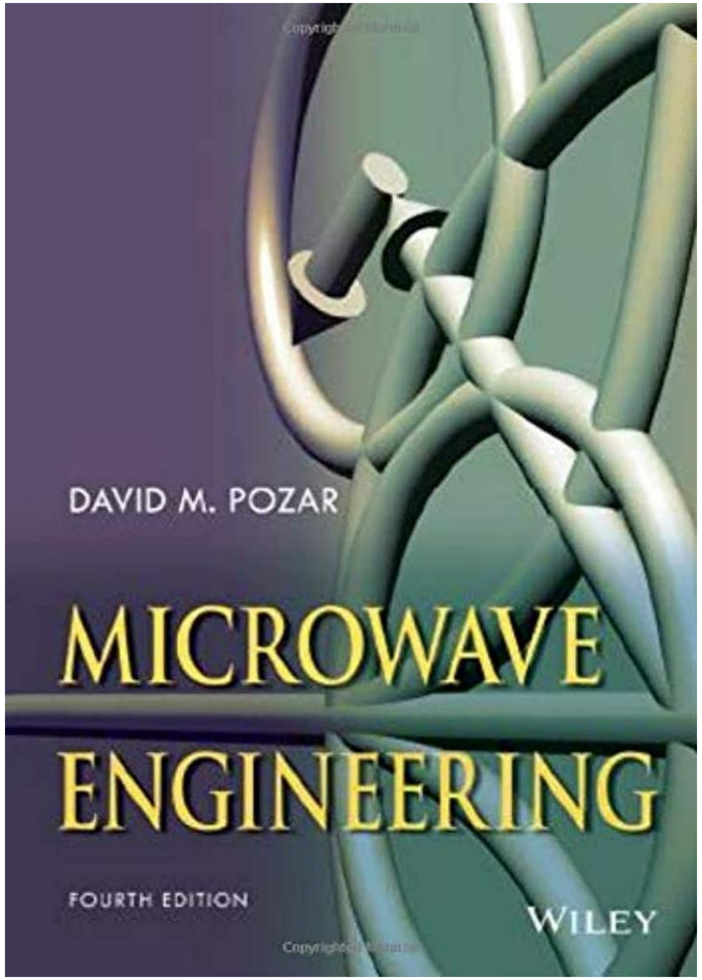
Part I: RF/MW concepts and hardware

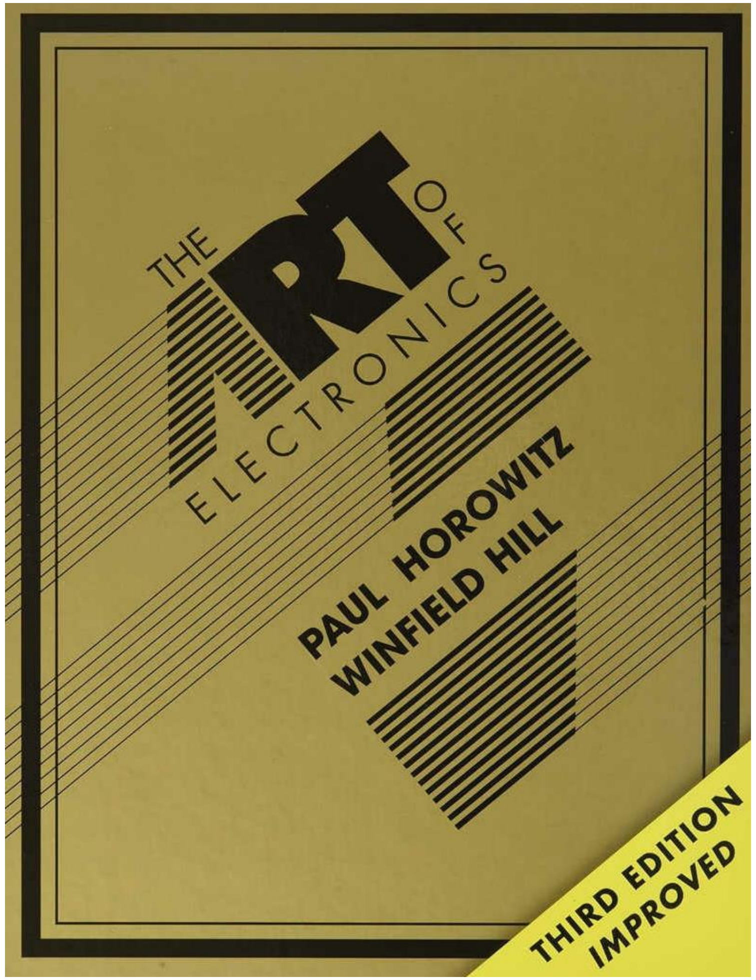
- What and why RF measurement?
- RF essential concepts
- RF Hardware
  - ✓ Components
  - ✓ Electronics

Part II: RF measurement applications in real experiments

- RF measurement technique
  - ✓ “Measure” RF/MW
  - ✓ Time-domain (pulsed) measurements
    - Creating RF pulse (Modulation, upconvert)
    - Measuring RF pulse (Demodulation, downconvert)
- Examples of RF/MW measurement in real experiments

Reference books

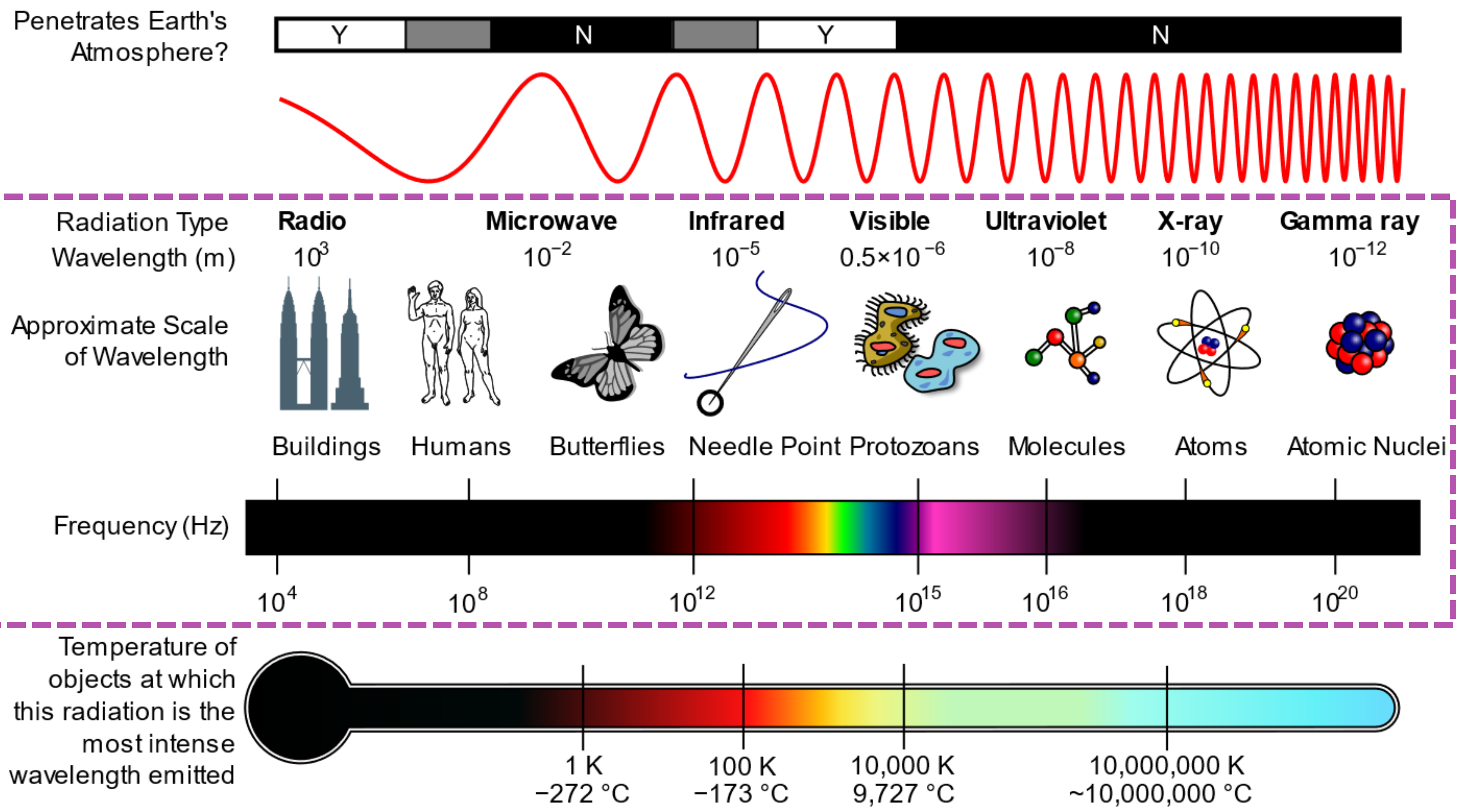




- Introductory reference book for microwave engineering

- *E*lectronics reference book
- Cover both analog and digital

What is RF (Radio Frequency) & Microwave?



$$f = \frac{c}{\lambda}$$

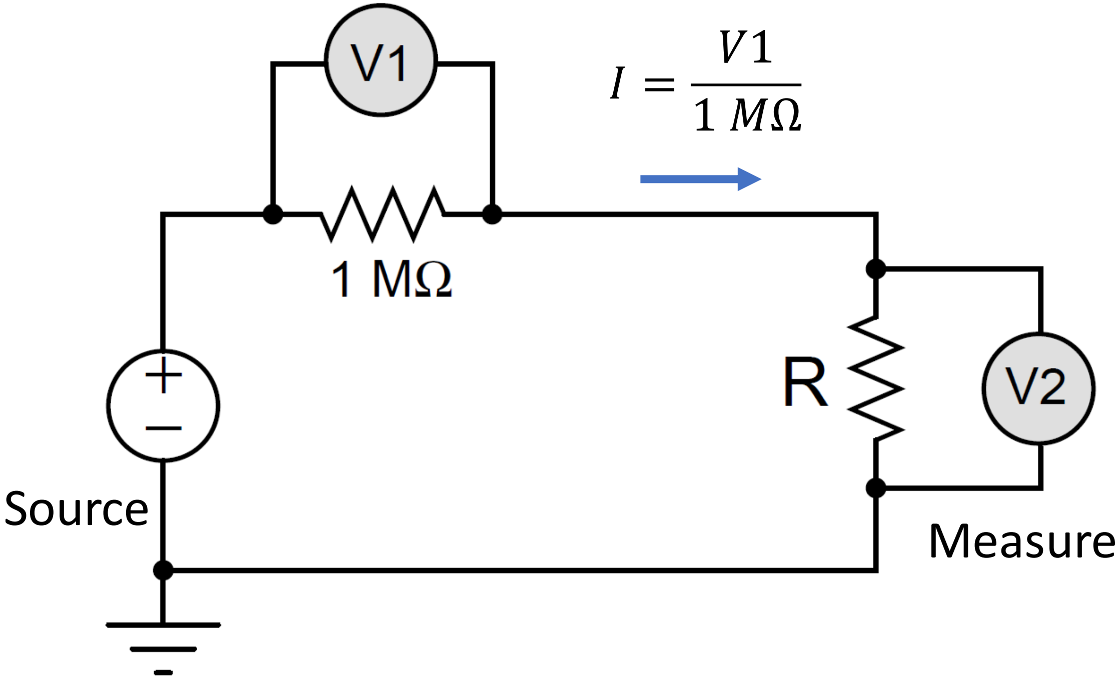
RF
30 kHz – 300 MHz
10 km – 1 m

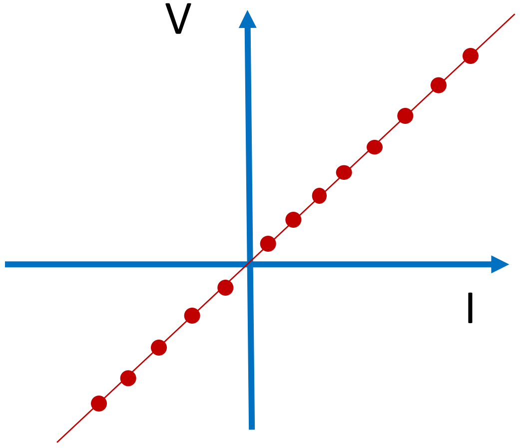
Microwave
300 MHz – 300 GHz
1 m – 1 mm

[Ref: Wikipedia]

DC measurement?

Transport measurement





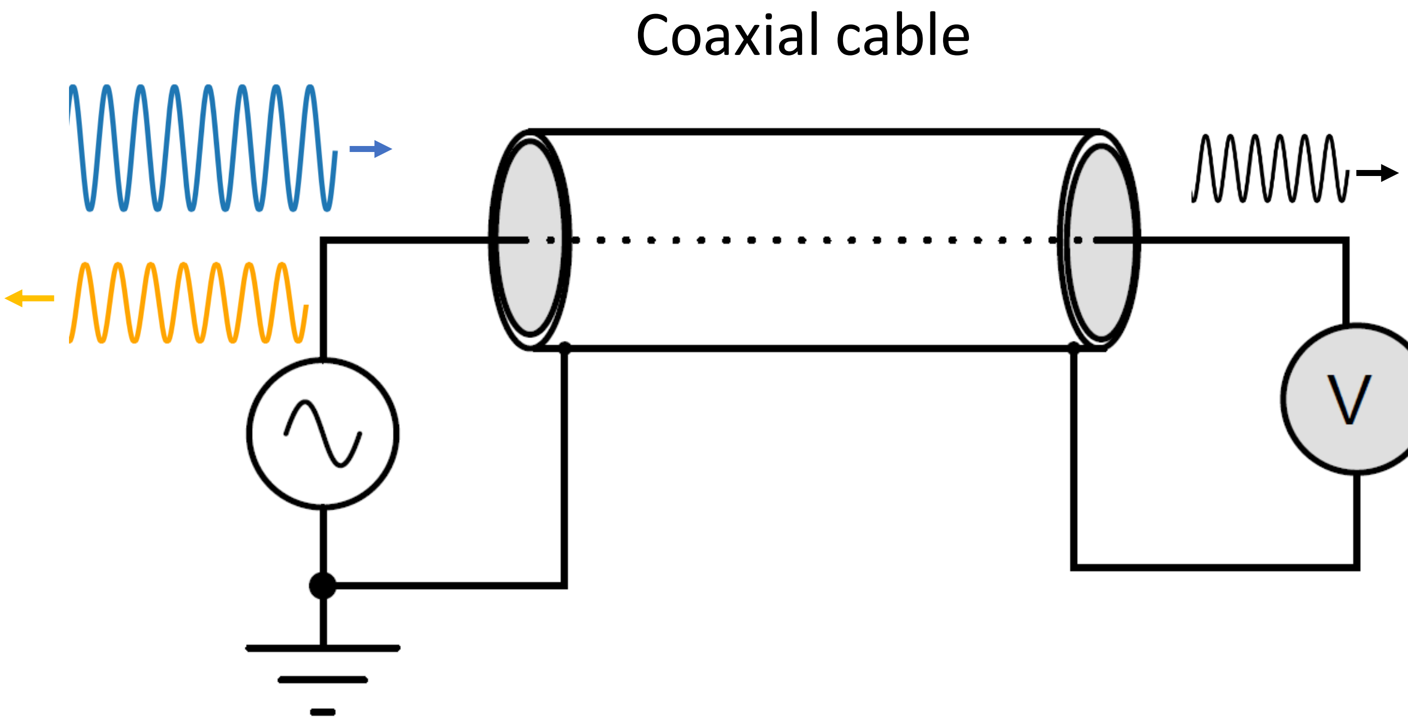
- Low frequency measurement
- Source frequency < 1 kHz
- Wavelength >> physical dimension

- Measured quantity:
  - ✓ V, I, R, dV/dI, …

- Commonly used instrument
  - ✓ Function generator (i.e., AC voltage source)
  - ✓ DC voltmeter
  - ✓ Low-frequency DAQ(Data Acquisition Board)
  - ✓ Low-frequency lock-in

Q: What happens if the frequency of voltage source increases?

RF measurement?

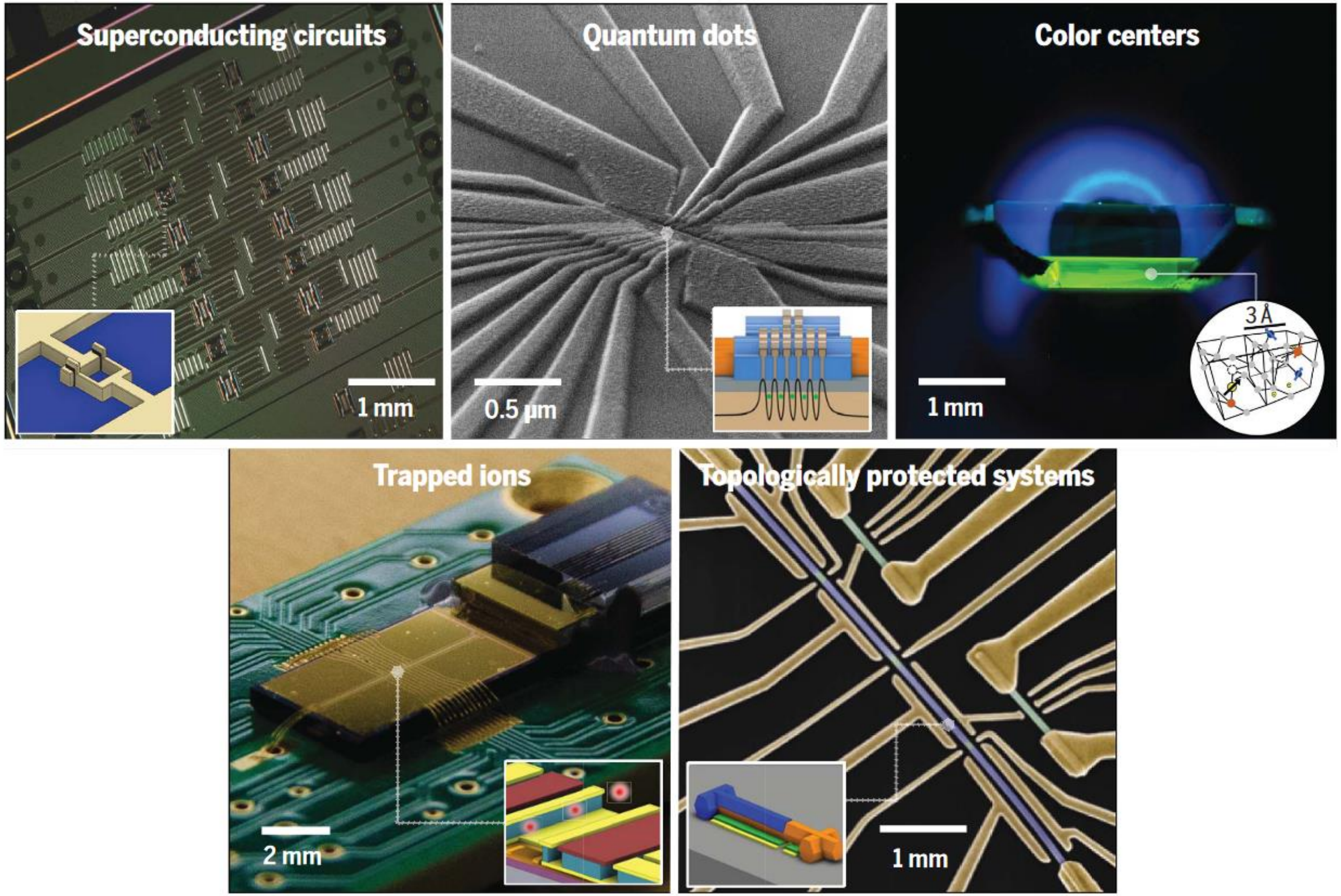


- High frequency measurement
- Sensitive measurement
- Wavelength < physical dimension

- Measured physical quantity:
  - ✓ Frequency, impedance, phase, amplitude, …

- Commonly used instrument:
  - Signal generator, AWG
  - Oscilloscope, spectrum analyzer
  - Network analyzer (S-parameter)

RF measurements in quantum devices?



[de Leon et al., Science 372, 253 (2021)]

❖ Quantum Computing & Quantum Sensing

- Control of qubit state
- Measurement of qubit state

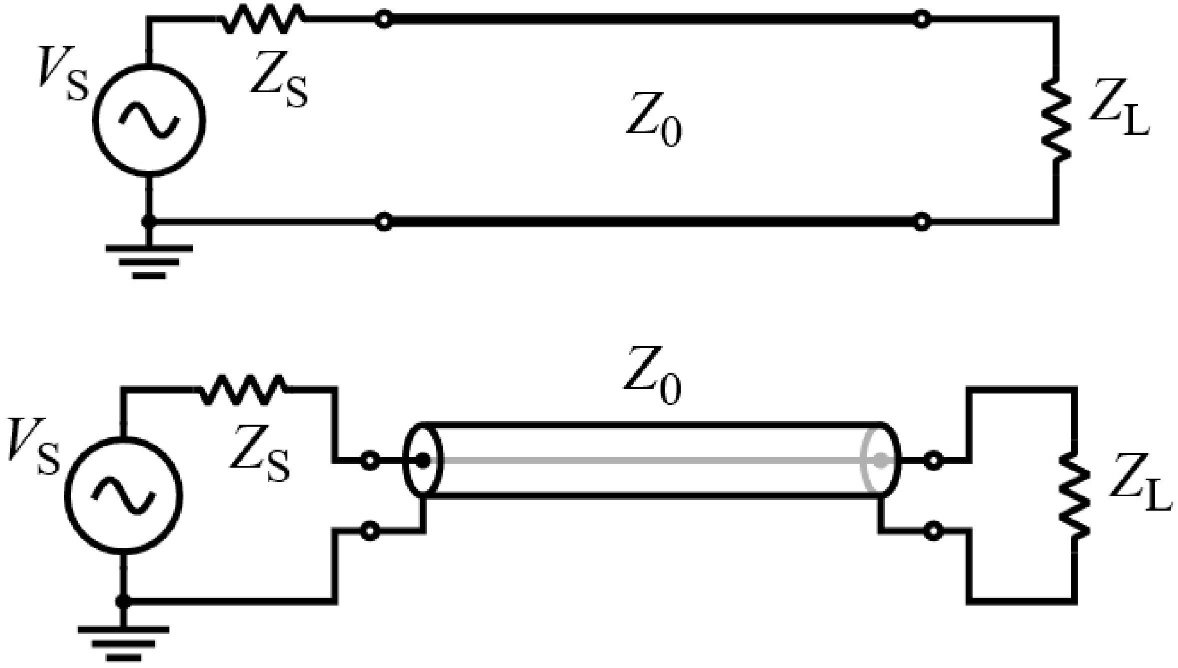
Energy scales suitable for microwave (~GHz)

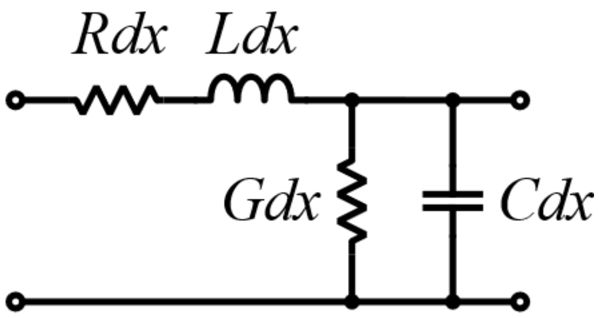
Essential RF/MW concepts

Transmission line

- Cable or structure that allows electromagnetic wave propagation

Schematic of transmission line





Transmission line theory

- Modelled by a infinite series of lumped-elements
- V(z, t), I(z, t) governed by two wave equations.

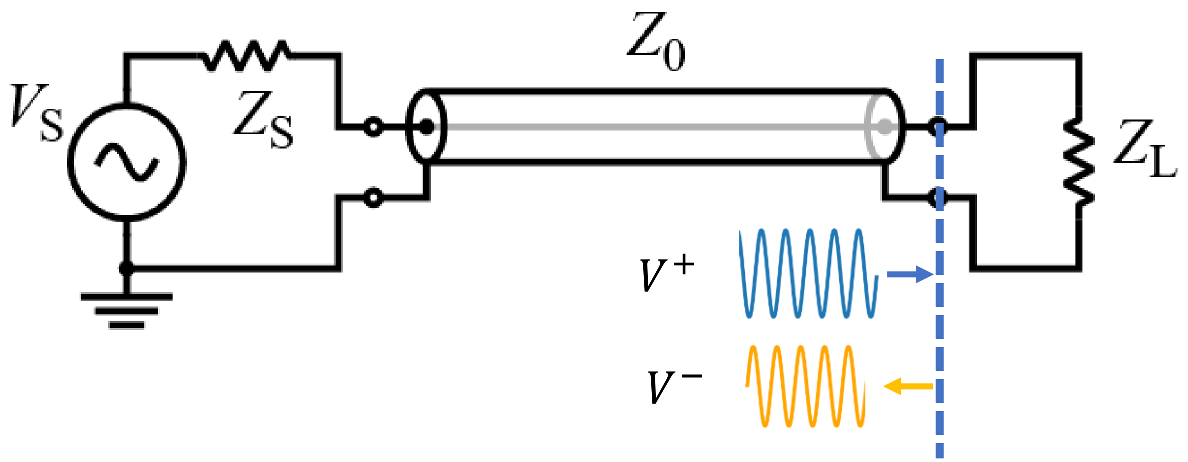
[Ref: Wikipedia]

Transmission line - continued

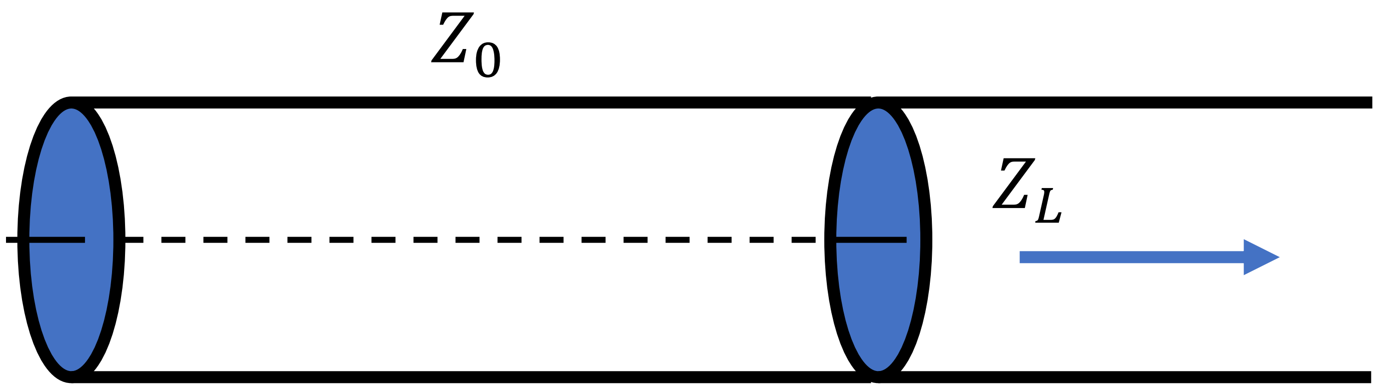
- Characteristic Impedance (Z_0) = $\frac{V^+}{I^+}$
  - ✓ Ratio of voltage to current for a single traveling wave on a transmission line
  - ✓ For a typical coaxial cable, $Z_0 = 50\ \Omega$

- Voltage Reflection Coefficient (Γ)

$$\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$



Reflection due to Impedance mismatch



$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

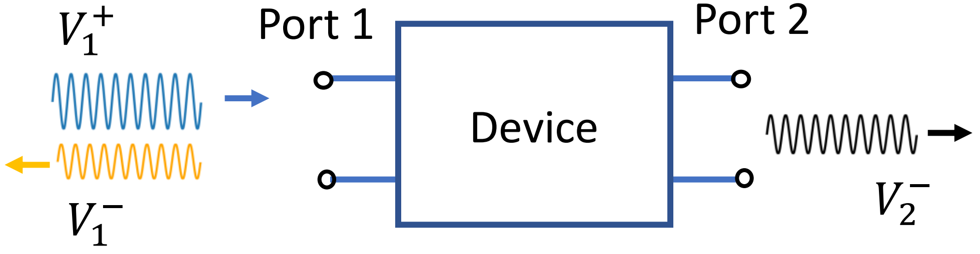
For Z_L = 70 Ω, Z_0= 50 Ω,

Γ = (70 – 50) / (70 + 50)
= 0.16 (-8.0 dB)

- Impedance matching is necessary to minimize reflection(Max. power transfer)
- 20 dB (Γ=0.01) is a good number, i.e., $Z_L = 51\ \Omega$

S-parameters

- In RF/MW measurement, consider 1) incident, 2) reflected and 3) transmitted waves.



- S-parameters define relation between them.

$$S_{ij} = \frac{V_i^-}{V_j^+} = |S_{ij}|e^{i\varphi}$$

- For 2-port network,

$$S_{21} = \frac{V_2^-}{V_1^+} \rightarrow \text{Transmission,}$$

$$S_{11} = \frac{V_1^-}{V_1^+} \rightarrow \text{Reflection}$$

- Network analyzer is used to measure S-parameters.

[Network analyzer]

dB (decibel)

- dB (decibel) is **ratio of power in logarithmic scale,** i.e., **unitless**

$$\left(\frac{P1}{P2}\right)(\text{dB}) \equiv 10\log_{10}\left(\frac{P_1}{P_2}\right)$$

- Useful to compare large orders of magnitude

- Example: 3 dB → P1/P2 = 2
  6 dB → P1/P2 = 4
  10 dB → P1/P2 = 10 (=10^1)
  20 dB → P1/P2 =100 (=10^2)

- Convert multiplication to addition,
  Ex) 10 * 100 → 10 (dB)+ 20 (dB) = 30 dB

“dBm” is not the same as “dB”

dBm is a **logarithmic power unit** referenced to 1mW.

$$P(\text{dBm}) \equiv 10 \log_{10}\left(\frac{P(W)}{1\ mW}\right)$$

Example:

0 dBm = 1 mW
-10 dBm = 0.1 mW
-20 dBm = 0.01 mW
10 dBm = 10 mW
20 dBm = 100 mW

dBm, W, Vrms, Vp, Vpp chart

[dBm]	[Watts]	[Volts]rms	[Volts]p	[Volts]pp
-10	0.100E-03	70.711 mV	99.985 mV	199.970 mV
-9	0.126E-03	79.339 mV	112.185 mV	224.370 mV
-8	0.158E-03	89.019 mV	125.874 mV	251.747 mV
-7	0.200E-03	99.881 mV	141.232 mV	282.465 mV
-6	0.251E-03	112.069 mV	158.465 mV	316.931 mV
-5	0.316E-03	125.743 mV	177.801 mV	355.602 mV
-4	0.398E-03	141.086 mV	199.496 mV	398.992 mV
-3	0.501E-03	158.301 mV	223.838 mV	447.677 mV
-2	0.631E-03	177.617 mV	251.151 mV	502.301 mV
-1	0.794E-03	199.290 mV	281.796 mV	563.591 mV

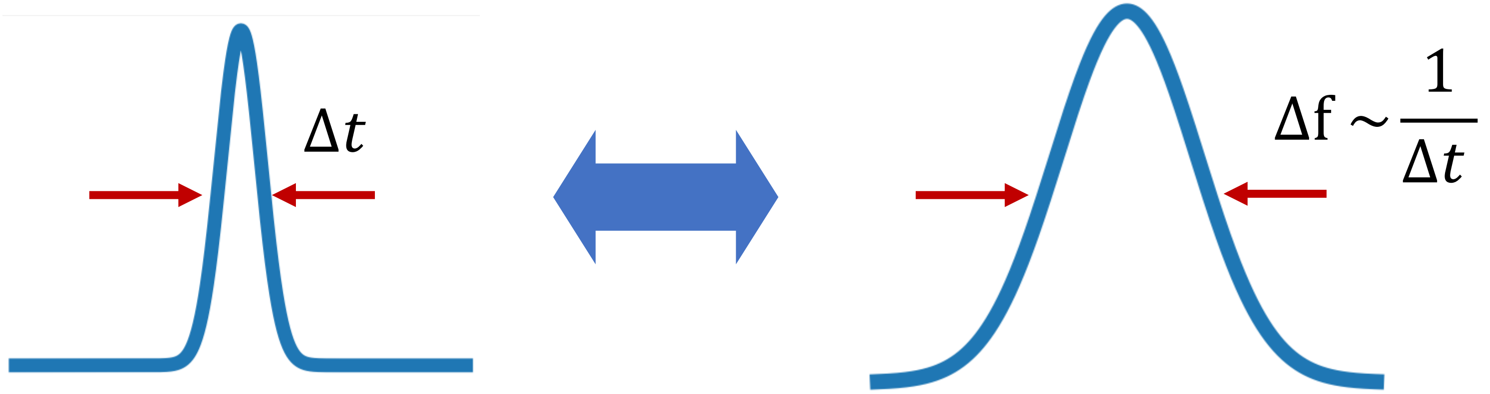
Time domain vs Frequency domain

In **time-domain**, we talk about:

- How signal varies in time
- Rise/fall time
- Overshoot, ringing, settling time
- Timing and sync.
- Trigger

In **frequency-domain**, we talk about:

- Frequency component
- Bandwidth
- Cutoff frequency

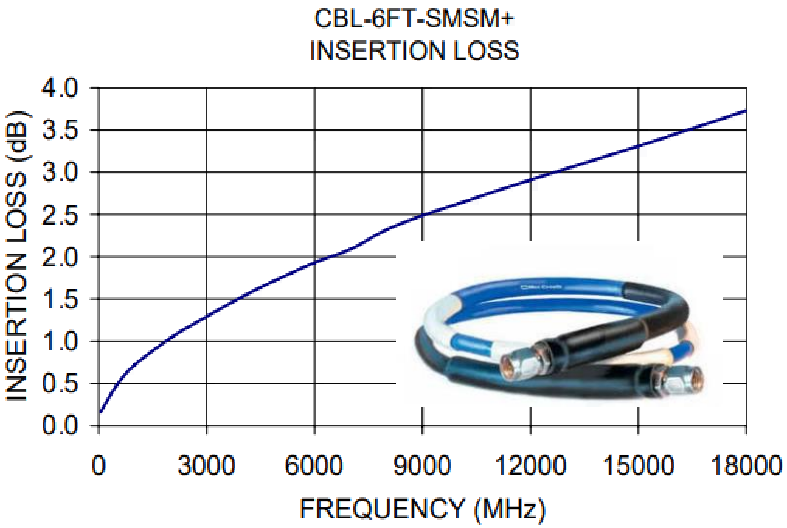


RF/MW Components & Electronics

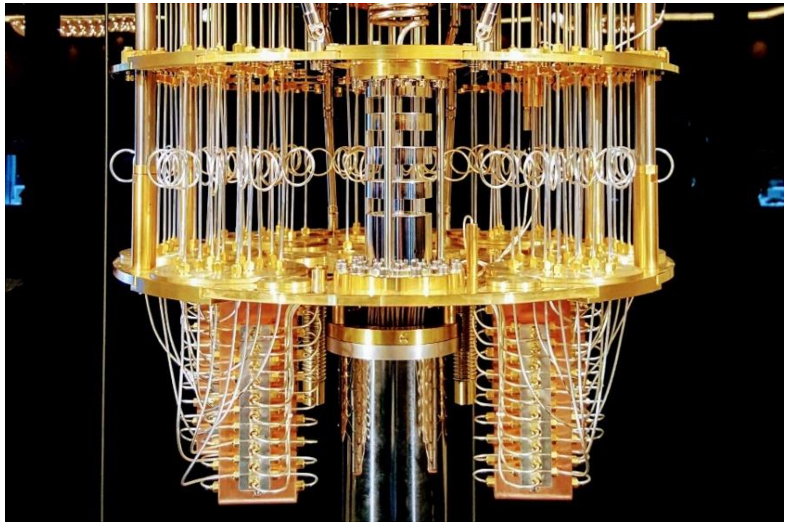
Coaxial cable & connector

@ Room temperature
- BNC cable (<1 GHz)
- SMA cable (DC – 18 GHz)
- Loss increases as frequency and length.

BNC   SMA

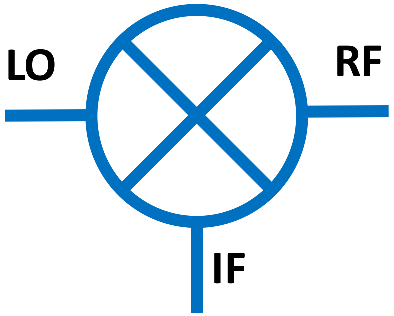


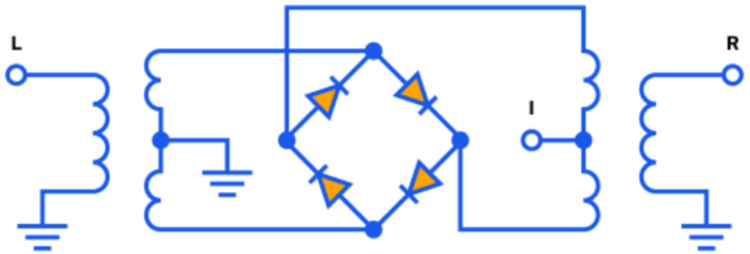
@Cryogenic temperature
- Semi-rigid or flexible coaxial cable (DC-18 GHz)
- CuNi/CuNi, NbTi/NbTi, Nb/Nb,SS/SS
  → low thermal conductivity



[Ref: IBM]

Mixer (3-port)

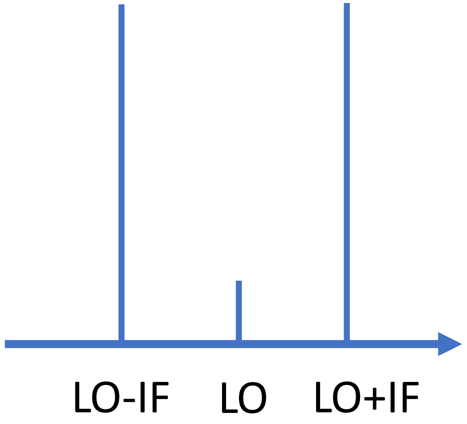




(Ref: Mini-circuit blog)

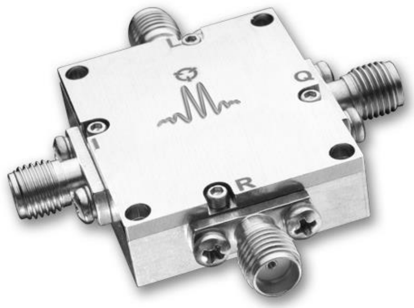
- LO = Local Oscillator
- IF = Intermediate Frequency
- RF = Radio Frequency

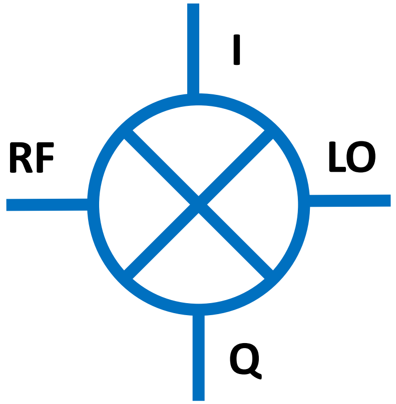
- Nonlinear RF component
- Multiply two signals (LO & IF)
- Generate LO+IF, LO-IF



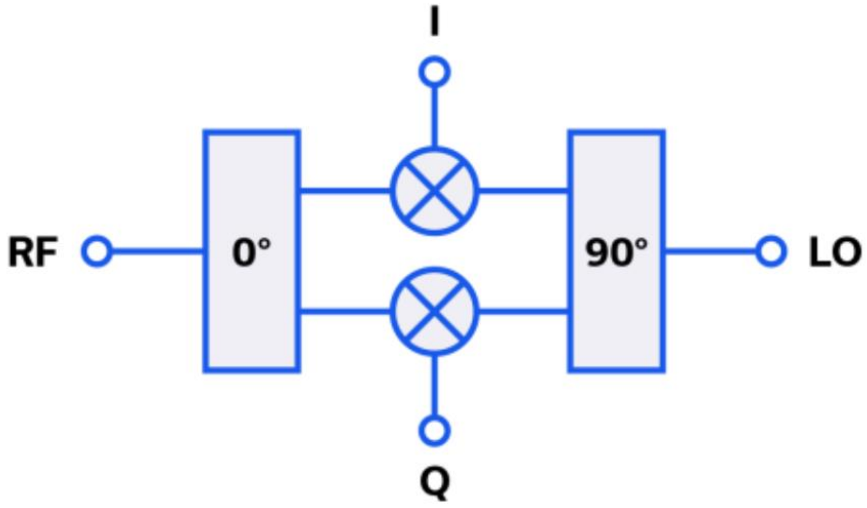
$$\begin{aligned} RF &= A\sin(\omega_{IF}t)\times\sin(\omega_{LO}t) \\ &= \frac{A}{2}\left[\cos\left((\omega_{LO}-\omega_{IF})t\right)+\cos\left((\omega_{LO}+\omega_{IF})t\right)\right. \end{aligned}$$

IQ Mixer (4-port)





- Can be used to create a MW pulse
- Single-side-band



I mixers / **Q mixer**

$$RF = \underbrace{\sin(\omega_{IF}t) \times \sin(\omega_{LO}t)}_{\text{I mixers}} + \underbrace{\cos(\omega_{IF}t) \times \cos(\omega_{LO}t)}_{\text{Q mixer}}$$

$$= \cos\big((\omega_{LO} + \omega_{IF})t\big)$$

single frequency!

Mixer Key Specs

- Frequency range
- Conversion loss
- Isolation
- Drive power level

Coaxial, Wideband

Frequency Mixer

ZMDB-24H-K+

Level 15 (LO Power +15 dBm) 5000 to 21000 MHz

Generic photo used for illustration purposes only

CASE STYLE: UK2938

Connectors	Model
2.92mm-Female	ZMDB-24H-K+

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
RF Power	125mW

Permanent damage may occur if any of these limits are exceeded.

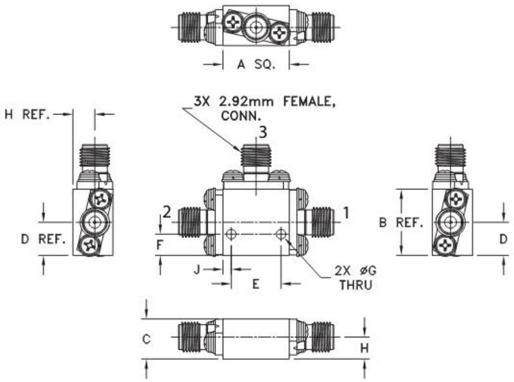
Coaxial Connections

LO	2
RF	1
IF	3

Features
- wide bandwidth, 5000 to 21000 MHz
- low conversion loss, 8.5 dB typ.
- high L-R isolation, 30 dB typ.
- excellent IF BW, DC to 5000 MHz
- rugged construction
- small size
- useable as up and down converter

Applications
- defense radar and communications
- VSAT
- ISM
- line of sight links
- WiFi
- satellite up and down connectors

Outline Drawing



Outline Dimensions (inch/mm)

A	B	C	D	E

Electrical Specifications at 25°C

Parameter	Min.	Typ.	Max.	Unit
Frequency Range, RF	5000	—	21000	MHz
Frequency Range, LO	5000	—	21000	MHz
Frequency Range, IF	DC	—	5000	MHz
Conversion Loss*	—	8.5	10.8	dB
LO to RF Isolation	15	30	—	dB
LO to IF Isolation	20	40	—	dB
IP3	—	22	—	dBm
RF Input at 1 dB Compression	—	+10	—	dBm

* Conversion loss at 30 MHz IF. Increases with IF frequency.

Typical Performance Data

Frequency (MHz)		Conversion Loss (dB)	Isolation L-R (dB)	Isolation L-I (dB)	VSWR RF Port (:1)	VSWR LO Port (:1)
RF	LO	LO +15dBm	LO +15dBm	LO +15dBm	LO +15dBm	LO +15dBm
5000.10	5030.10	7.09	29.14	29.50	1.44	3.25
5500.10	5530.10	6.66	34.55	31.42	1.20	2.67

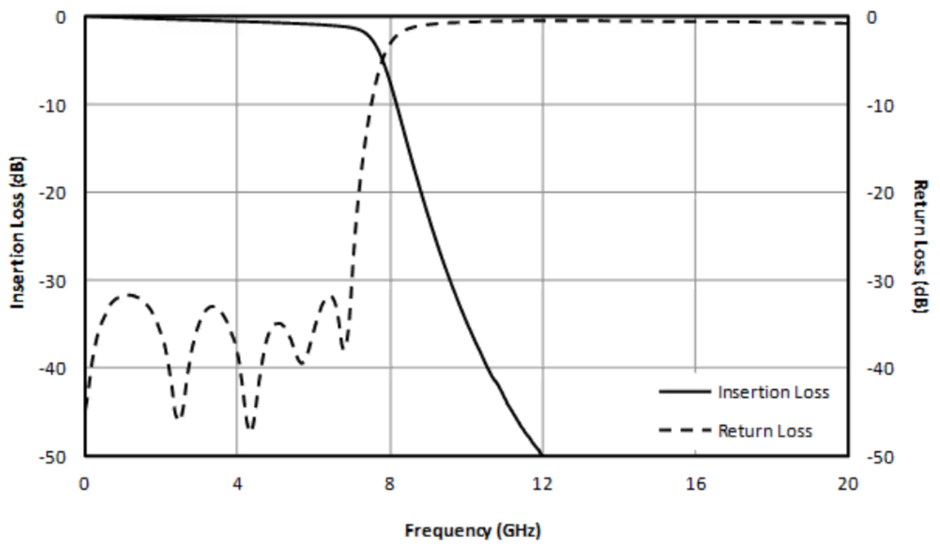
Low Pass Filter / High pass filter

- LPF filter out high frequencies
- HPF filter out low frequencies

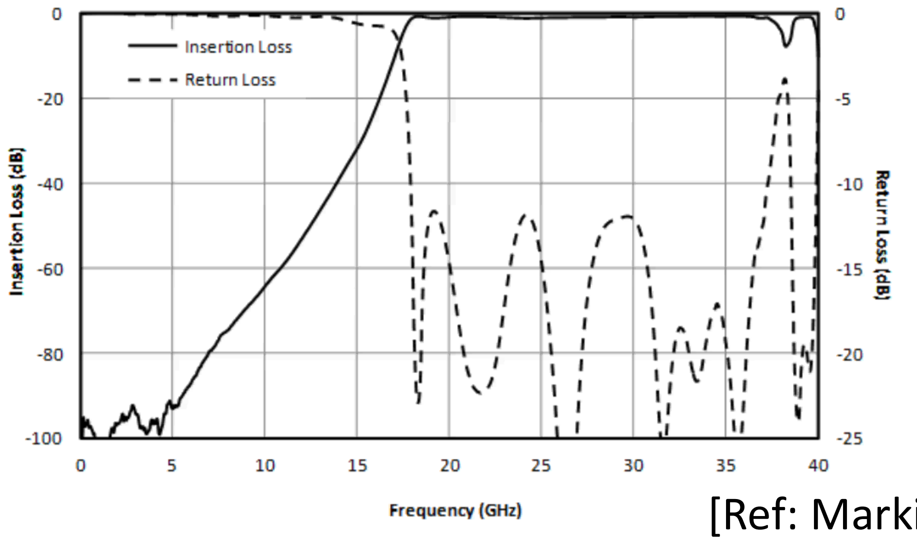
- Key specs:
  - ✓ Cutoff frequency (3dB point)
  - ✓ Slope (order of filter)
  - ✓ Insertion loss@ passband

- Filter type
  - ✓ Butterworth (flat passband)
  - ✓ Chebyshev (steepest)
  - ✓ Bessel (flat time delay)

❖Typical LPF frequency response (cutoff~7.5 GHz)



Typical HPF response (cutoff~12.5 GHz)



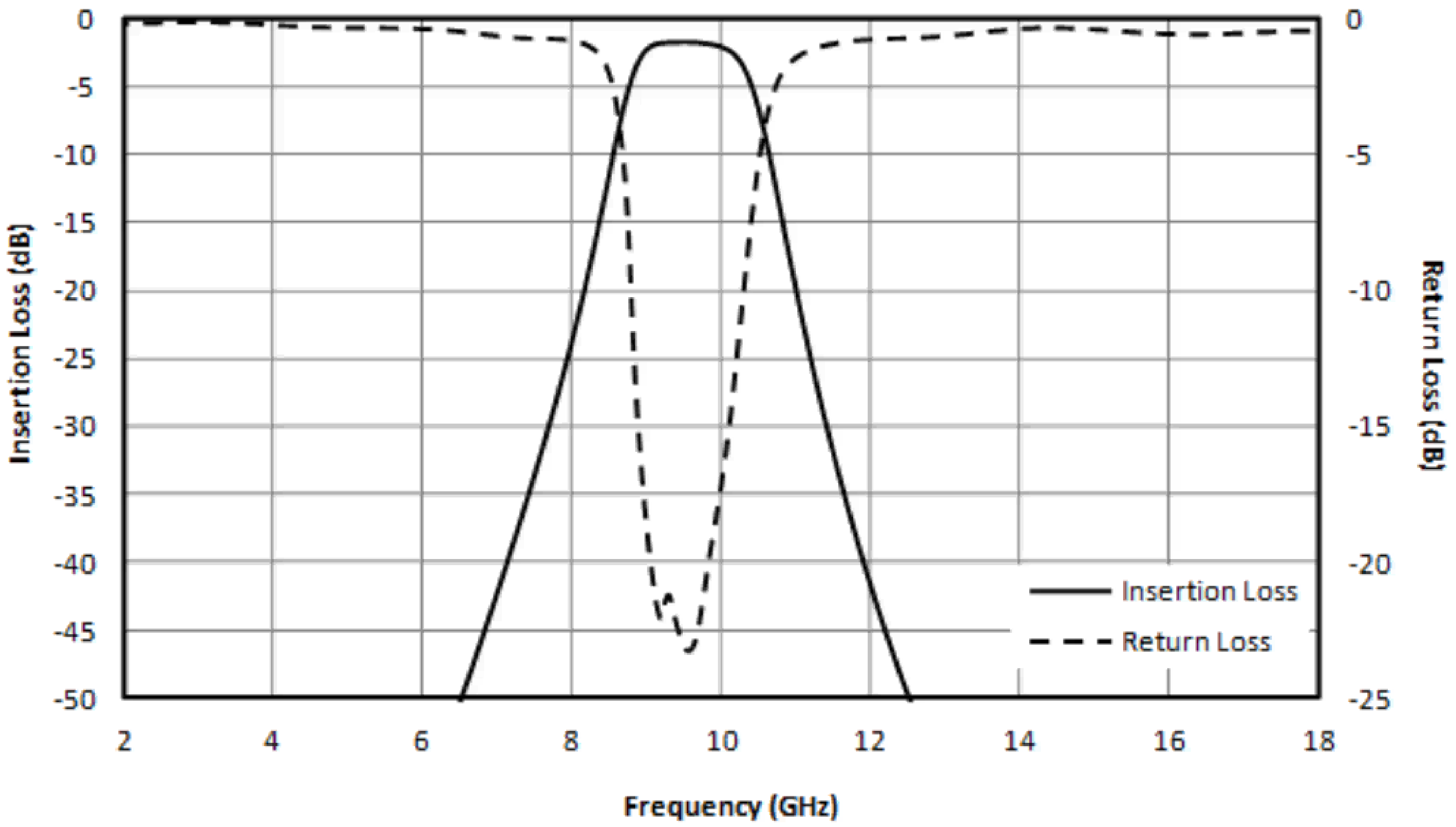
[Ref: Marki Microwave]

Band pass filter

❖Typical BPF response (center freq.~9.55 GHz)

- BPF has passband.

- Key specs:
  - ✓ Center frequency
  - ✓ Bandwidth (3dB point)
  - ✓ Slope (order of filter)
  - ✓ Insertion loss@ passband

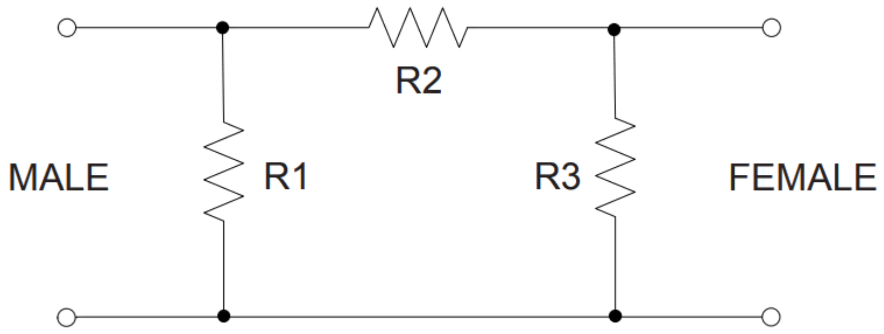


[Ref: Marki Microwave]

Attenuator & Terminator

- Attenuates RF power
- Pi- or T- network inside
- $Z_0 = 50\ \Omega$
- Ex) 20 dB attenuator
  → power reduced by 100

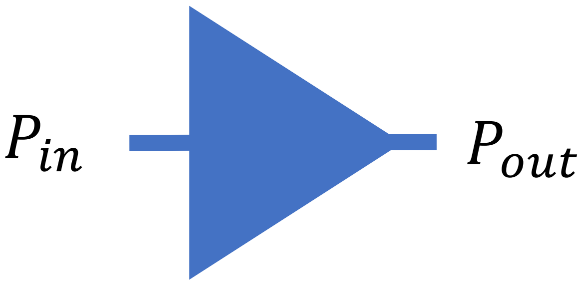
- Key specs
  ✓ bandwidth
  ✓ attenuation
  ✓ material

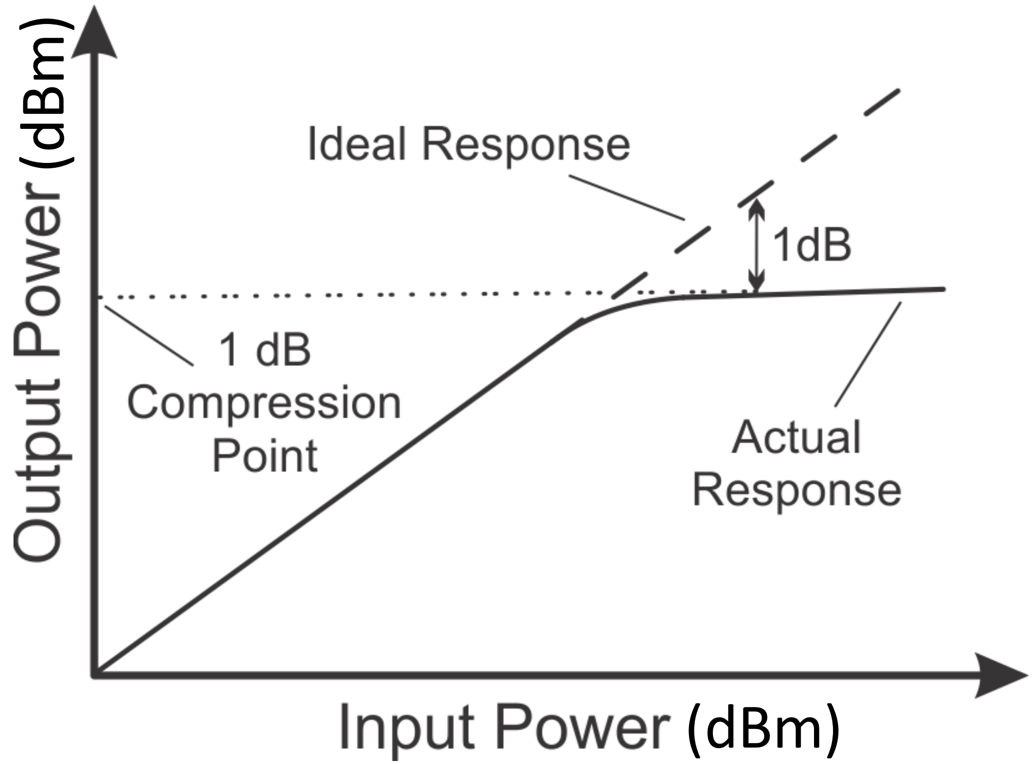


Pi-type attenuator

RF/MW Amplifier

- Amplify signals
- Key specs:
  - ✓ Frequency range
  - ✓ Gain (dB) = $P_{out}(dBm) - P_{in}(dBm)$
  - ✓ Noise temperature, $P_{noise} = kBT_N$
  - ✓ 1 dB compression point
  - ✓ Maximum output power





[Ref: Texax Instruments]

Isolator/circulator

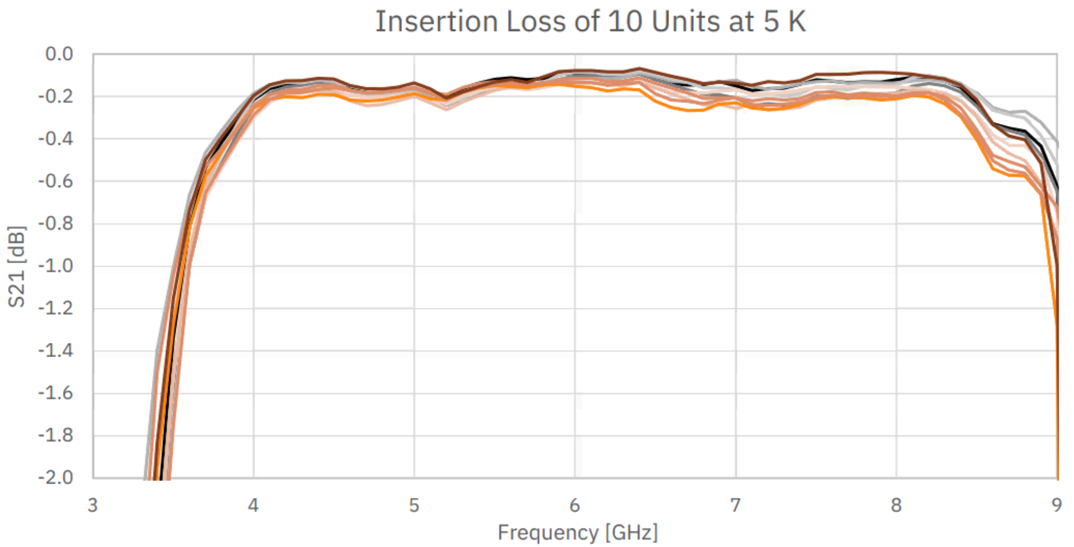
- Allows signal transmission in only one directior
- 2 or 3-port device
- Protect sample from unwanted signal

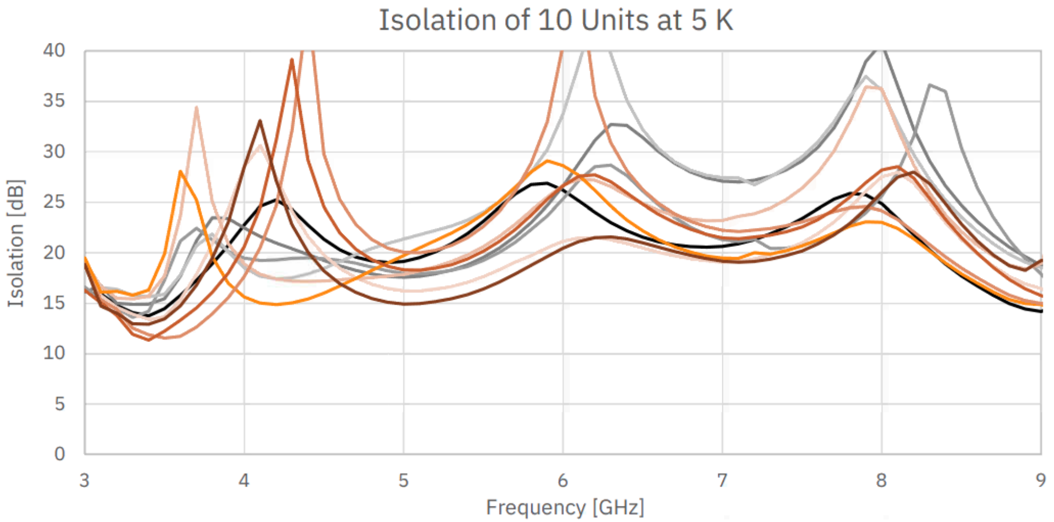
- Key specs:
  - ✓ Frequency range
  - ✓ Insertion loss
  - ✓ Isolation

Circulator

Isolator

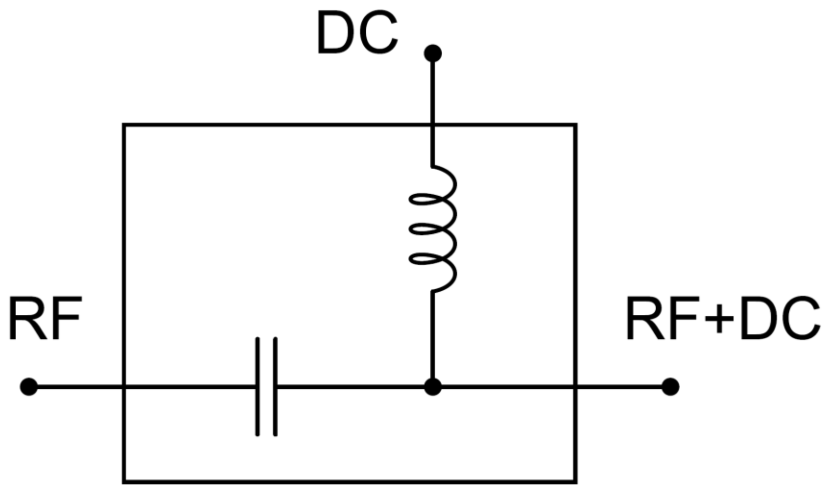
❖ Typical 4-8 GHz isolator response





[Ref: Low noise Factory]

Bias-T



- Combine DC and RF
- Used when it's necessary to apply both DC & RF

- Key specs:
  - ✓ Frequency range
  - ✓ Insertion loss
  - ✓ Isolation

RF/MW Electronics

ADC & DAC

ADC (Analog-to-Digital Converter)

- Convert analog signal to digital signal
- Number of bits → Resolution

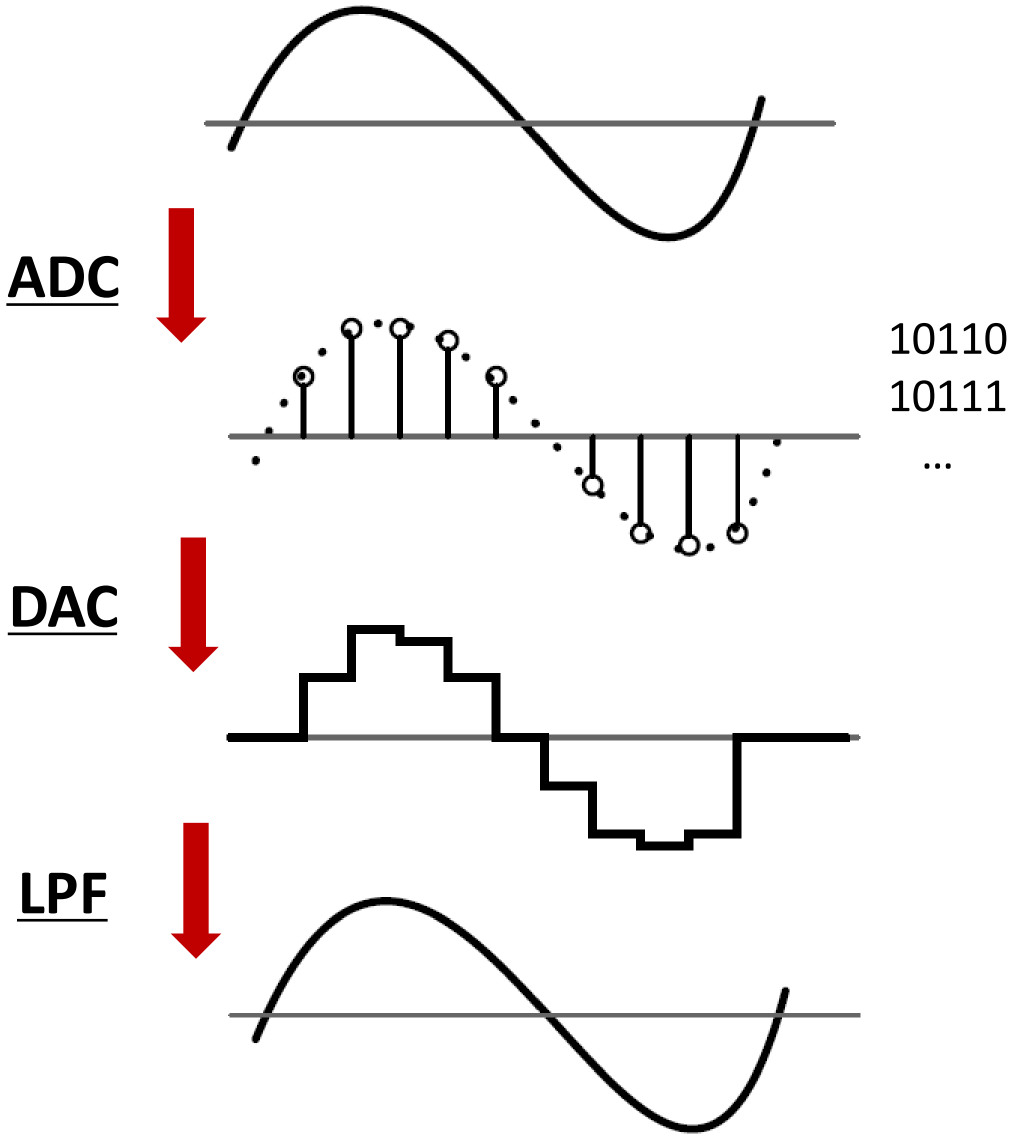
$$\text{resolution} = \frac{\text{Voltage range}}{2^N - 1}$$

1V , 12-bit →
res = 0.00024 V

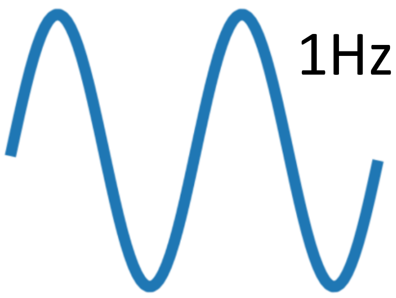
- Bandwidth set by sampling rate
- Usage: microphone, digital camera, oscilloscope, digitizer,…

DAC (Digital-to-Analog Converter)

- Convert digital to analog signal
- Resolution, bandwidth, …
- Usage: speaker, function generator, AWG, …



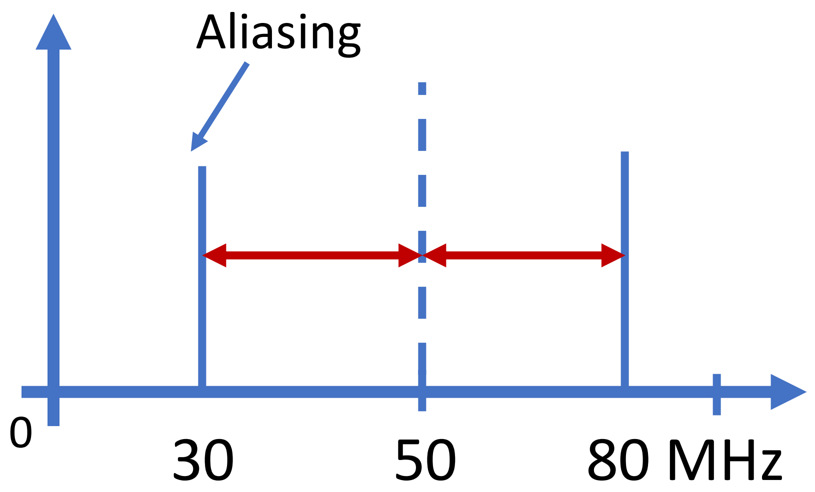
Sampling theory: Nyquist Frequency

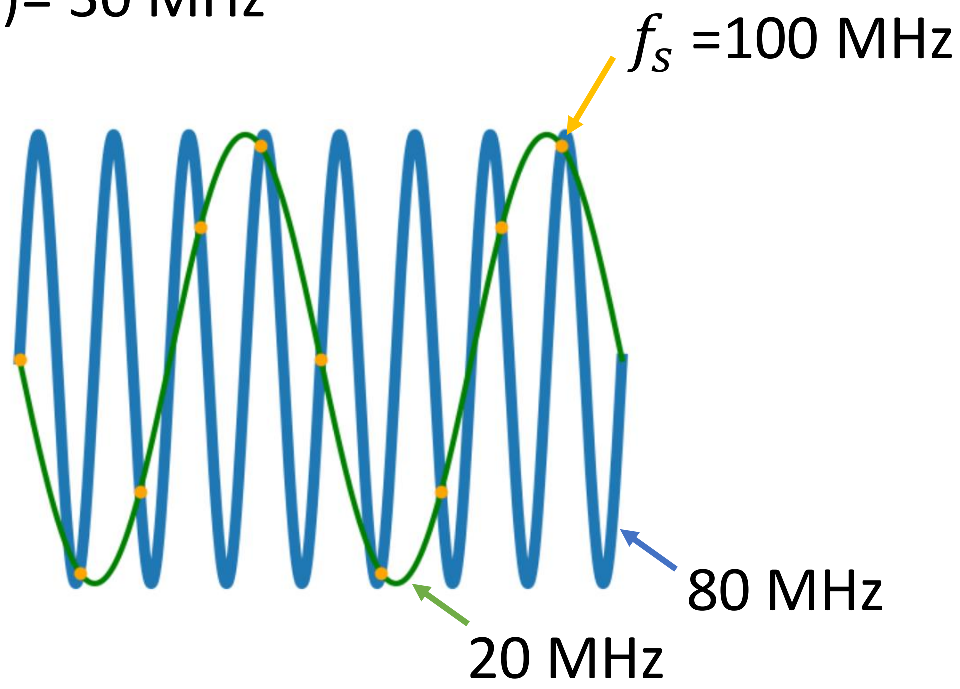


Q: In digital process, given the sampling rate f_s, what is the maximum frequency measurable?

A : $\frac{f_s}{2}$, which is called **Nyquist frequency** f_N

Q: What happens if you measure 80 MHz signal with 100 MHz sampling rate?
A: You will see the aliased signal at frequency of (80 – 50)= 30 MHz





Network Analyzer, Spectrum analyzer

[Keysight]

- Measure S-parameters
- Very versatile and useful, but expensive!
- Various form factors available

[Keysight]

- Measure RF/MW signal in frequency domain
- Measure frequency component of periodic signal

Source: Signal Generator & Arbitrary Waveform Generator

[Keysight]

- Generate MW signal in wide bandwidth
- Key specs:
  - ✓ Frequency range & resolution
  - ✓ Power range & resolution
  - ✓ Phase noise

[Zurich Instruments]

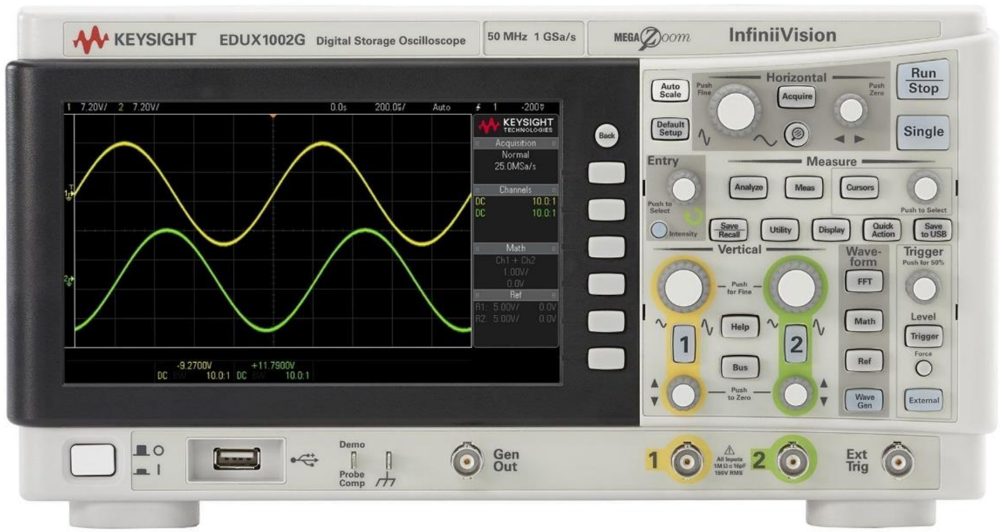
- This can generate arbitrary waveforms.
- The waveform is defined by user.
- Key specs:
  - ✓ Sampling rate
  - ✓ Bandwidth
  - ✓ Number of bits

Digitizer/Oscilloscope

- Measure voltage in real-time and/or display voltage signal vs time.

- Key specs:
  - ✓ Sampling rate
  - ✓ Bandwidth
  - ✓ Number of bits

[Keysight Digitizer]



[Keysight Oscilloscope]

RF/MW Measurement

“Measure” RF/MW?

- Power meter
  - ✓ Measure RF power in dBm
- Oscilloscope
  - ✓ Time-domain measurement
- Spectrum analyzer
  - ✓ Frequency-domain measurement
- Network analyzer
  - ✓ S-parameter measurement

How to make RF pulse

1. Turn on and off output of signal generator.

2. Use built-in gating function in the instrument

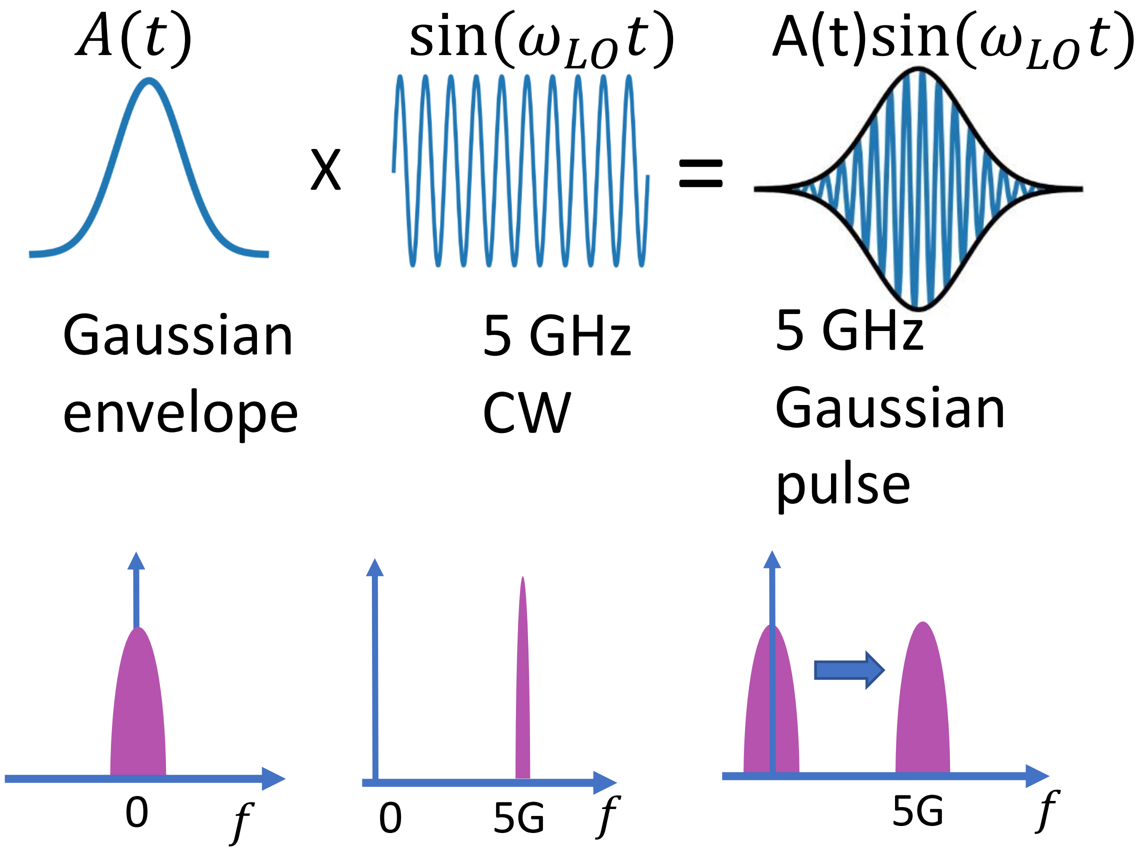
3. Use MW switch (for fast switching)

4. Use RF mixer.

5. Direct RF synthesis

How to make RF pulse: using 3-port mixer

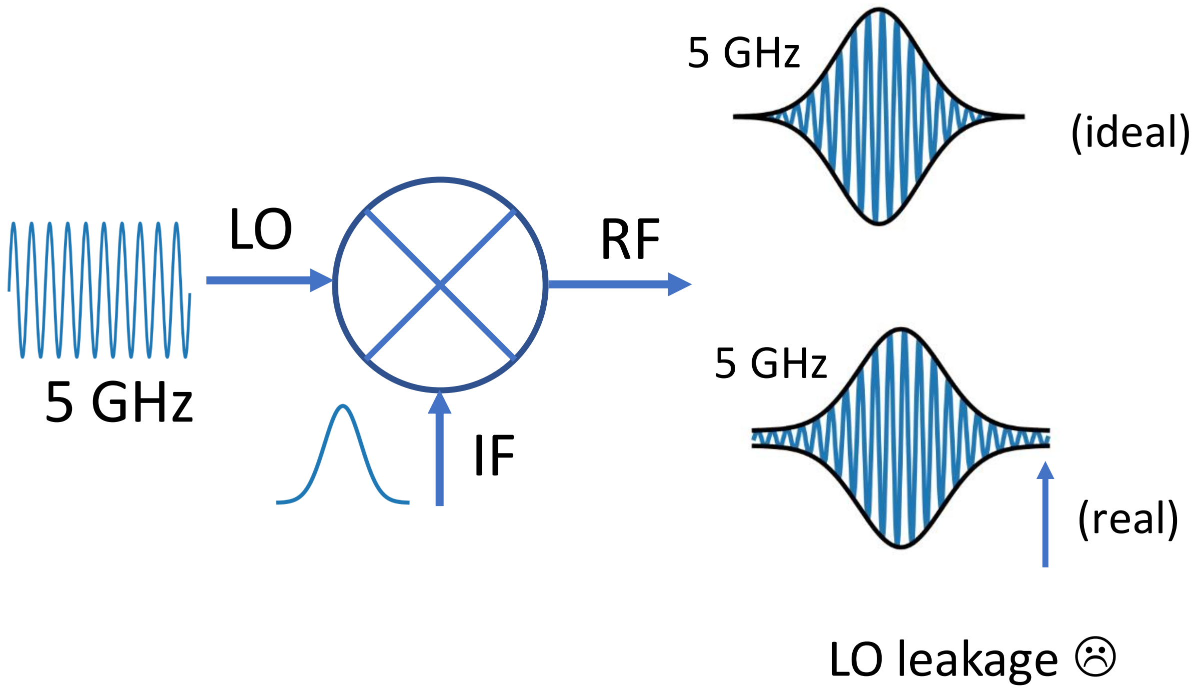
How to make a gaussian pulse?



"Upconversion"

Conventional way:

Mixer + AWG (IF) + signal generator(LO)



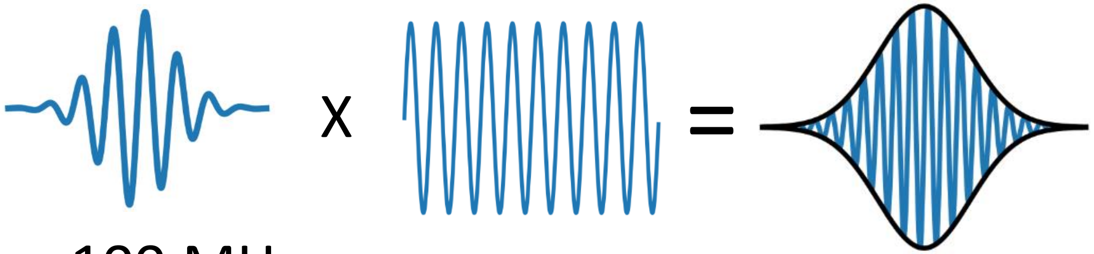
Problem:

- LO leakage
- No phase control

How to make RF pulse: sideband

How to make a gaussian pulse?

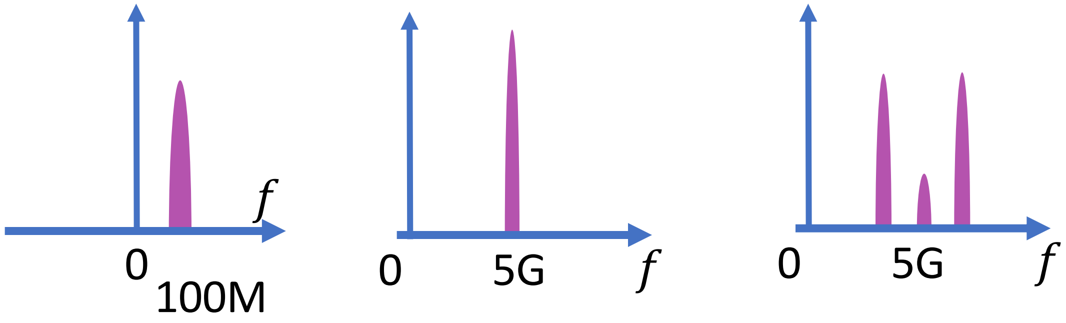
$A(t)\sin\omega_{IF}t$ $\sin(\omega_{LO}t)$ $\mathrm{A(t)}\sin(\omega_{IF}t)\sin(\omega_{LO}t)$



100 MHz Gaussian envelope

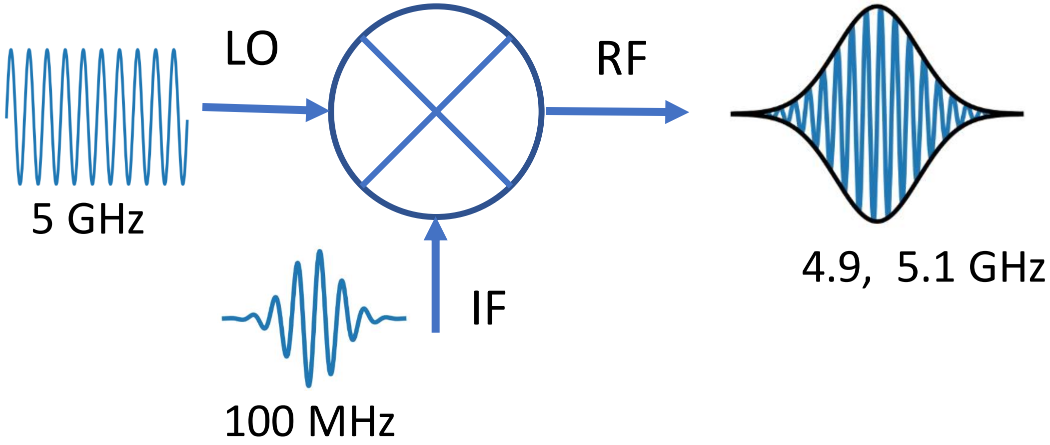
5 GHz CW

5 $\pm$0.1 GHz Gaussian pulse



Conventional way:

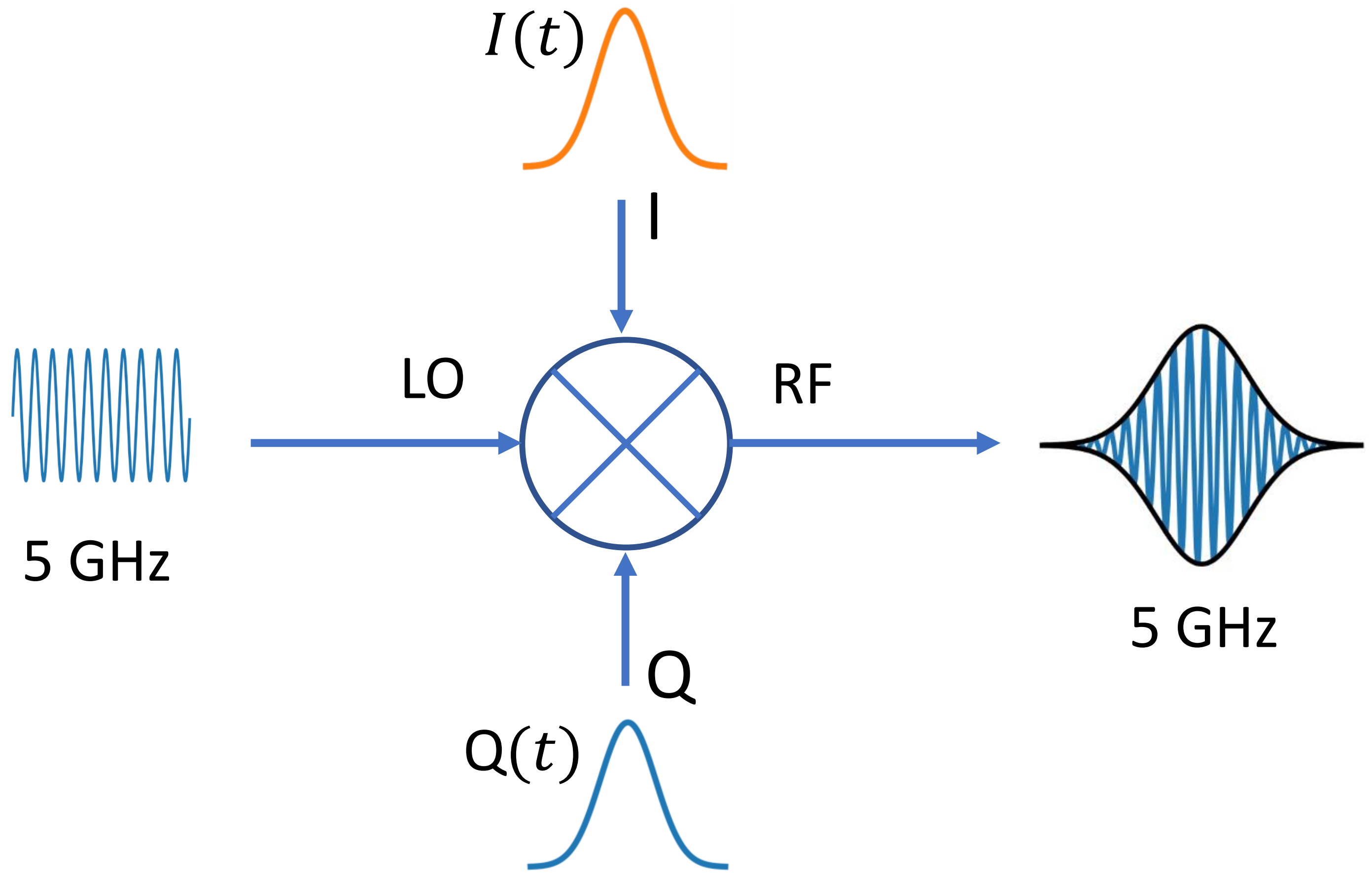
Mixer + AWG (IF)+ signal generator(LO)

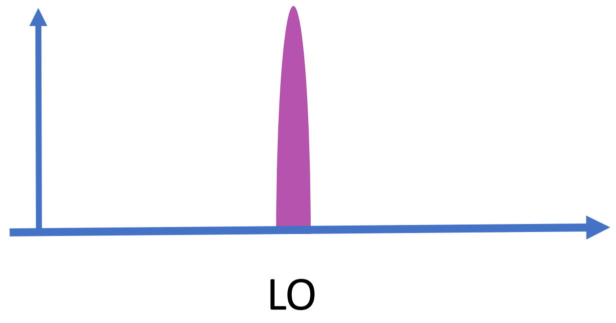


Problem: Unwanted sideband

(hard to remove if IF is small)

Modulation with IQ-mixer

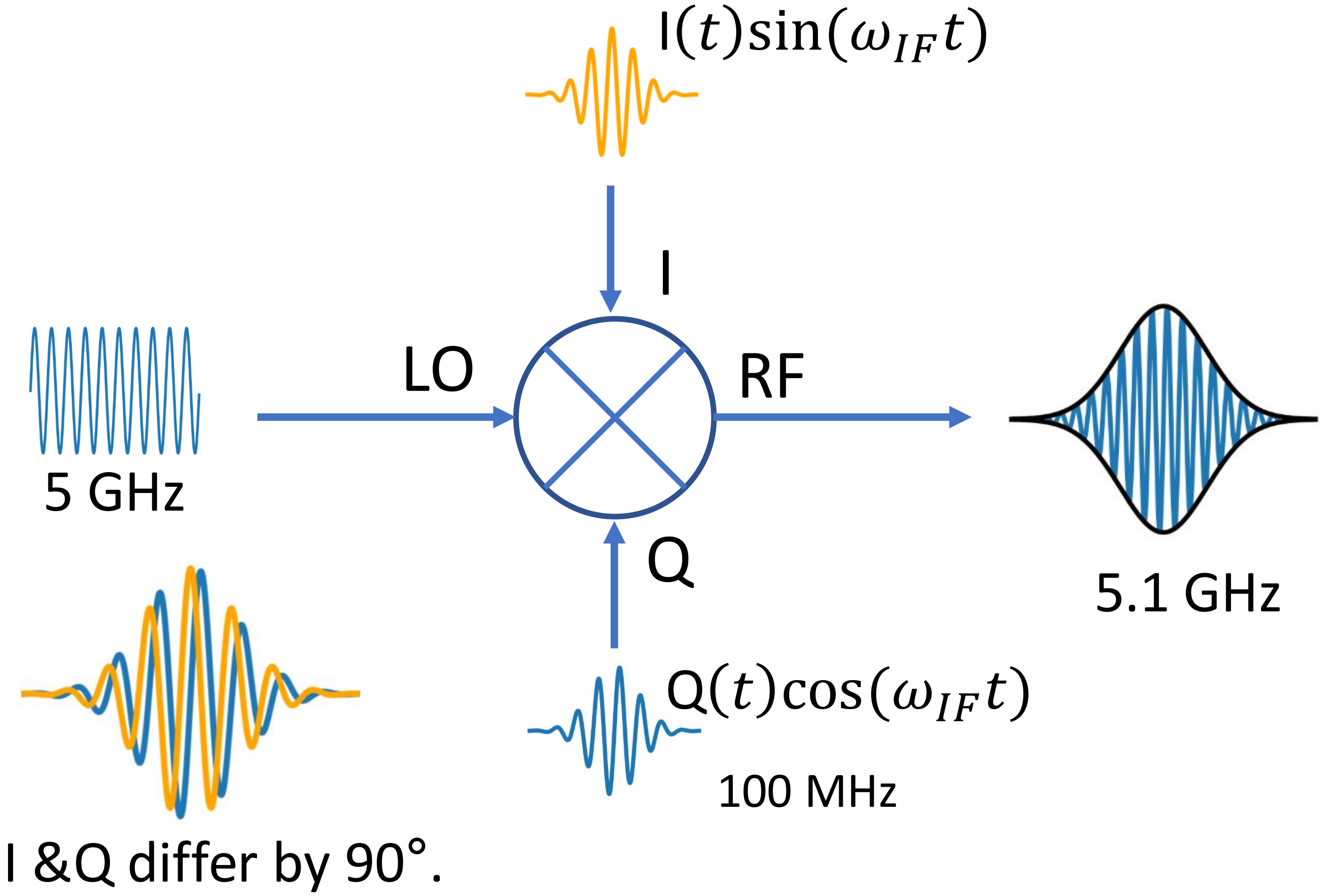


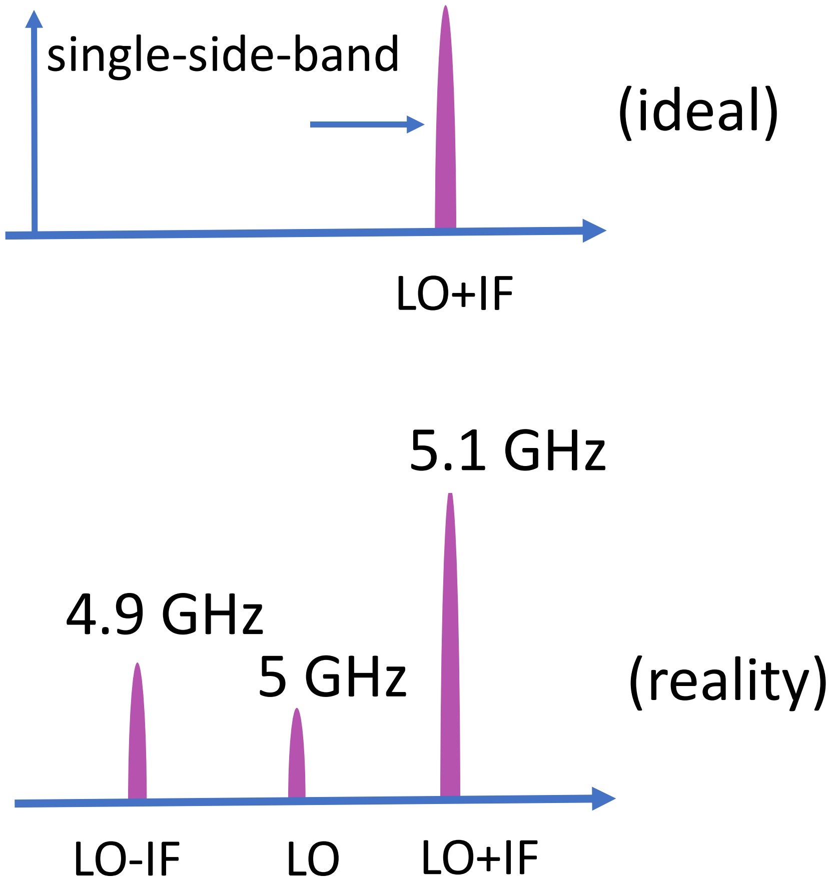


Problem: LO leakage

$$V(t) = \left[A(t)e^{i\varphi}\right]e^{i(\omega_{LO}t)}, \mathrm{A}(t) = \sqrt{(I(t)^2+,Q(t)^2}\,, \varphi = \tan^{-1}(\frac{Q}{I})$$

Single-side-band Modulation with IQ-mixer





$$\widetilde{V(t)} = \left[A(t)e^{i\varphi}e^{i\omega_{IF}t}\right]e^{i(\omega_{LO}t+\phi)}$$

Mixer calibration can remove:
1) LO leakage and 2) unwanted sideband

Pulse control: amplitude and phase

Baseband (IF)

Upconversion

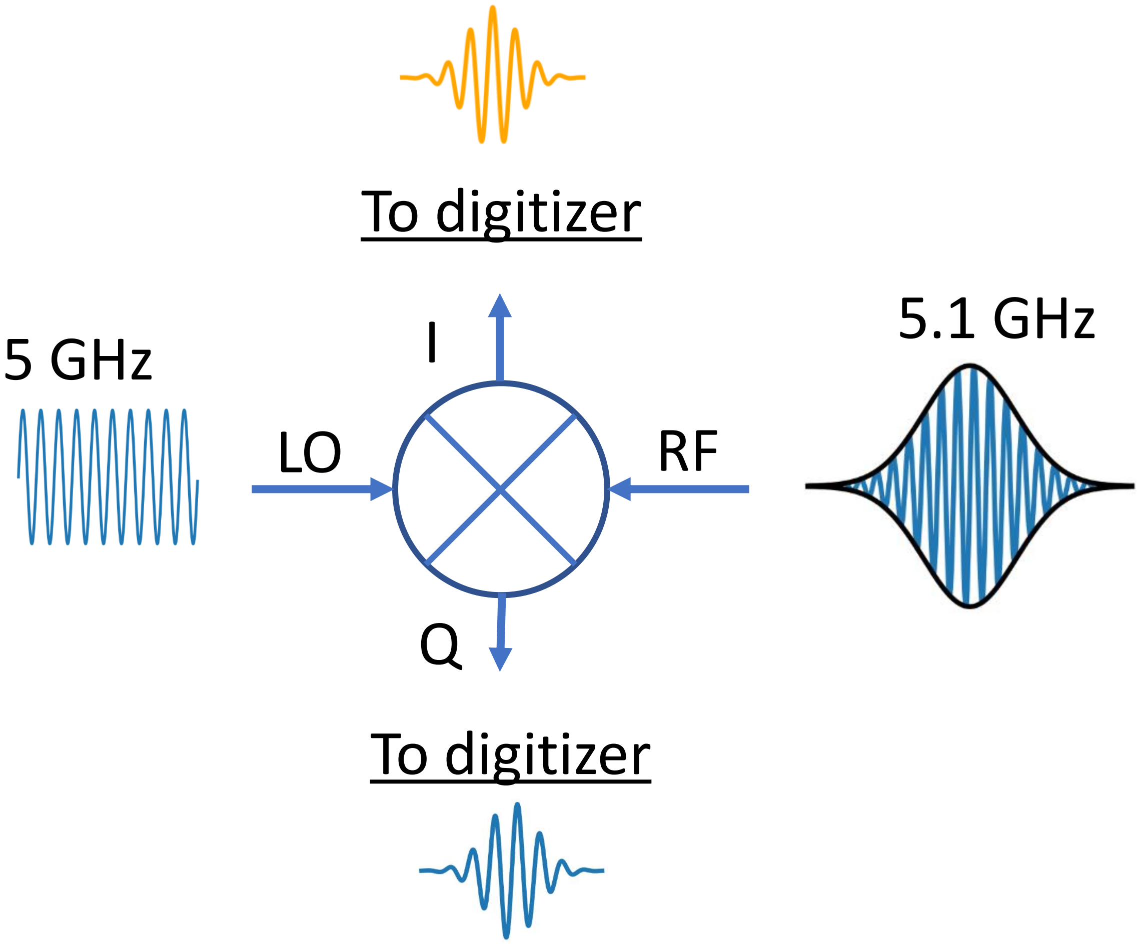
$$V(t) = \left[A(t)e^{i\varphi}e^{i\omega_{IF}t}\right]e^{i(\omega_{LO}t+\phi)}$$

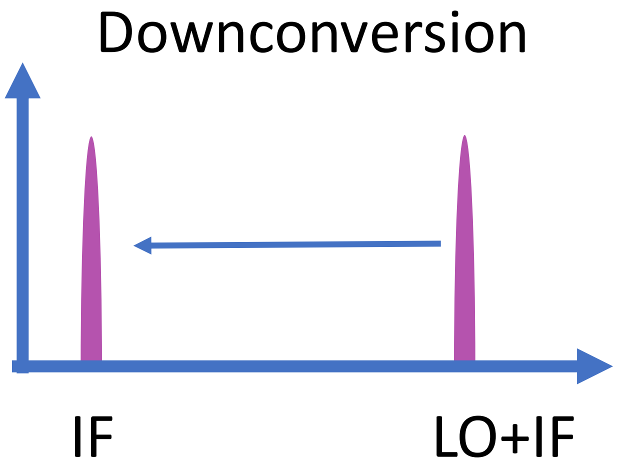
Amplitude

Phase

How to measure RF pulse: Demodulation

How to get $A(t)$, φ ?





Experiments using RF/MW

Shapiro steps in Josephson junction

- IV of Josephson junction + RF irradiation

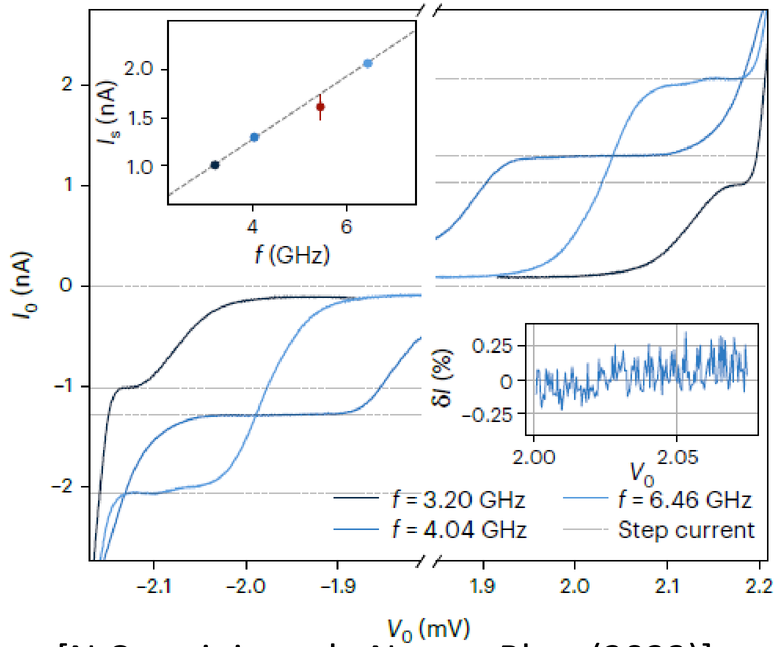
→ Shapiro steps: $V_n = \left(\frac{hf}{2e}\right) n$

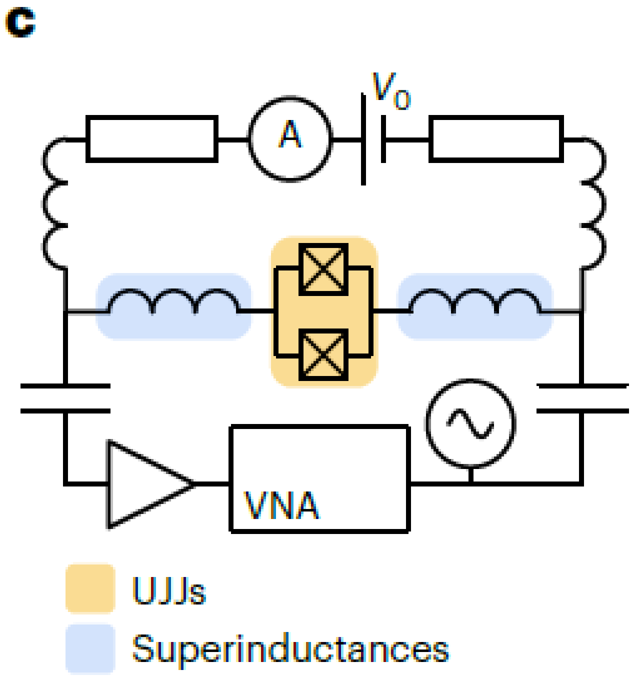
Article https://doi.org/10.1038/s41567-023-01961-4

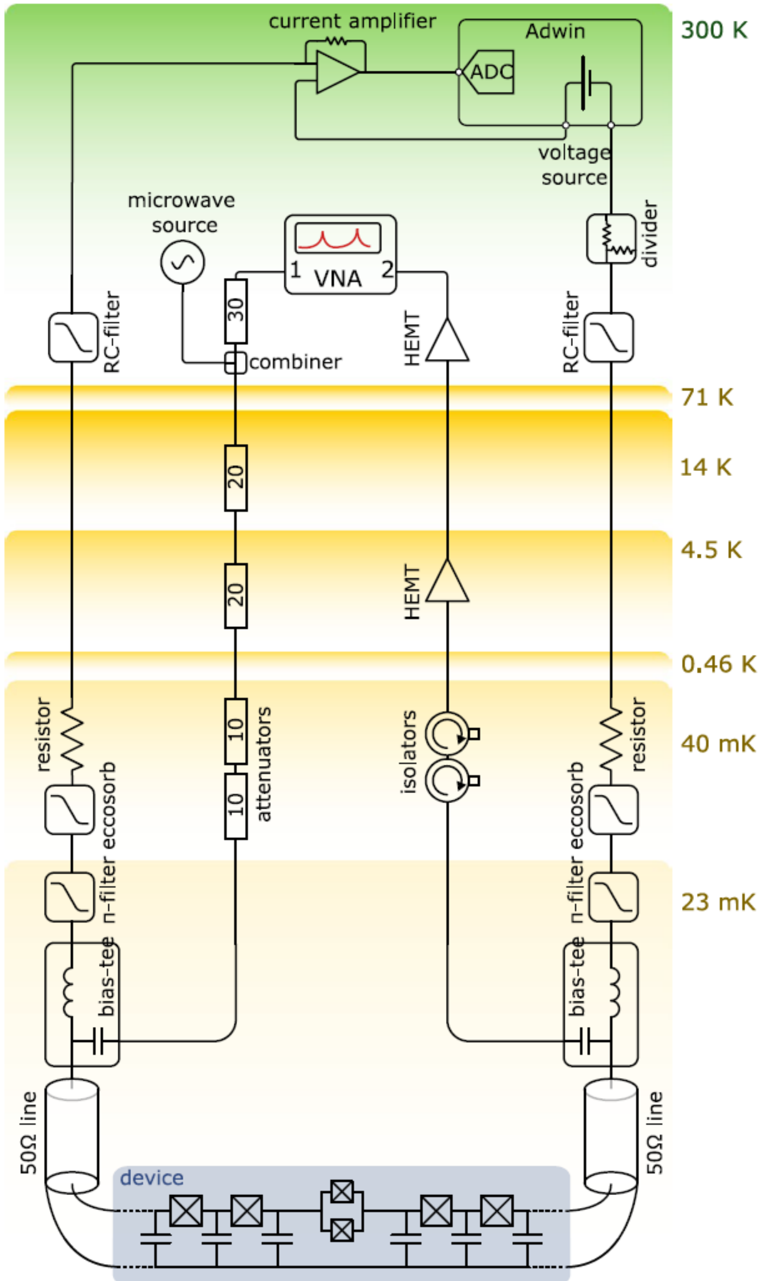
Evidence of dual Shapiro steps in a Josephson junction array

Received: 18 July 2022

Nicolò Crescini[1,3], Samuel Cailleaux[1,3], Wiebke Guichard[1], Cécile Naud[1], Olivier Buisson[1], Kater W. Murch[2] & Nicolas Roch



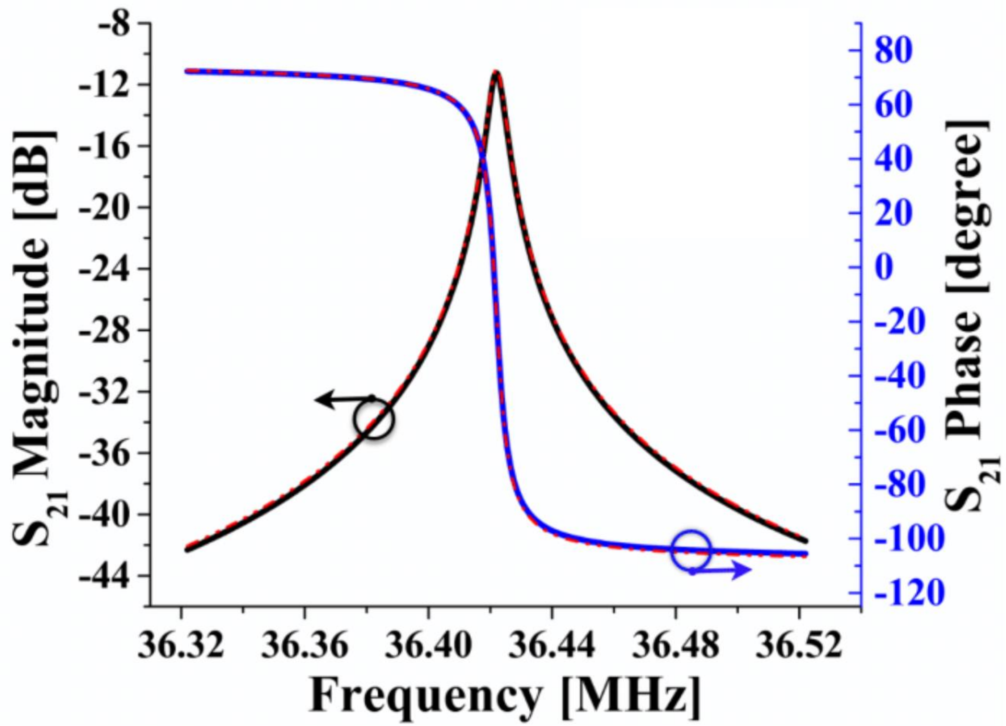


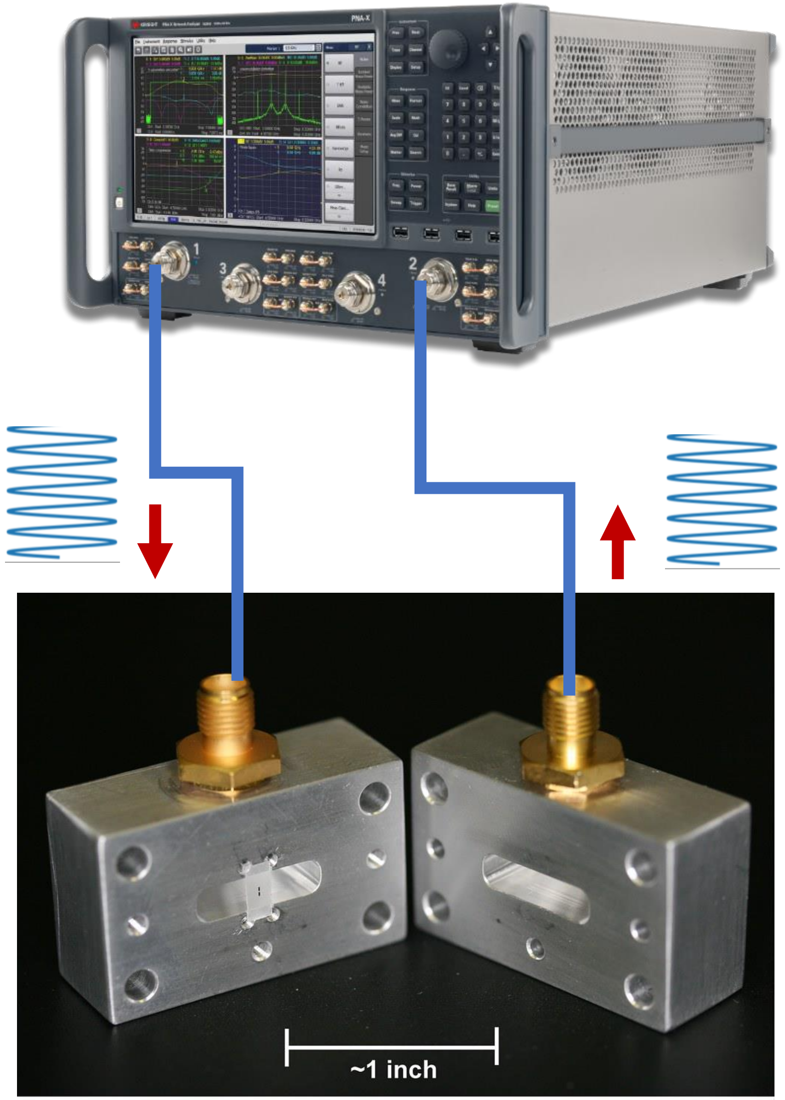


[N.Crescini, et.al., Nature Phys.(2023)]

Resonator measurement

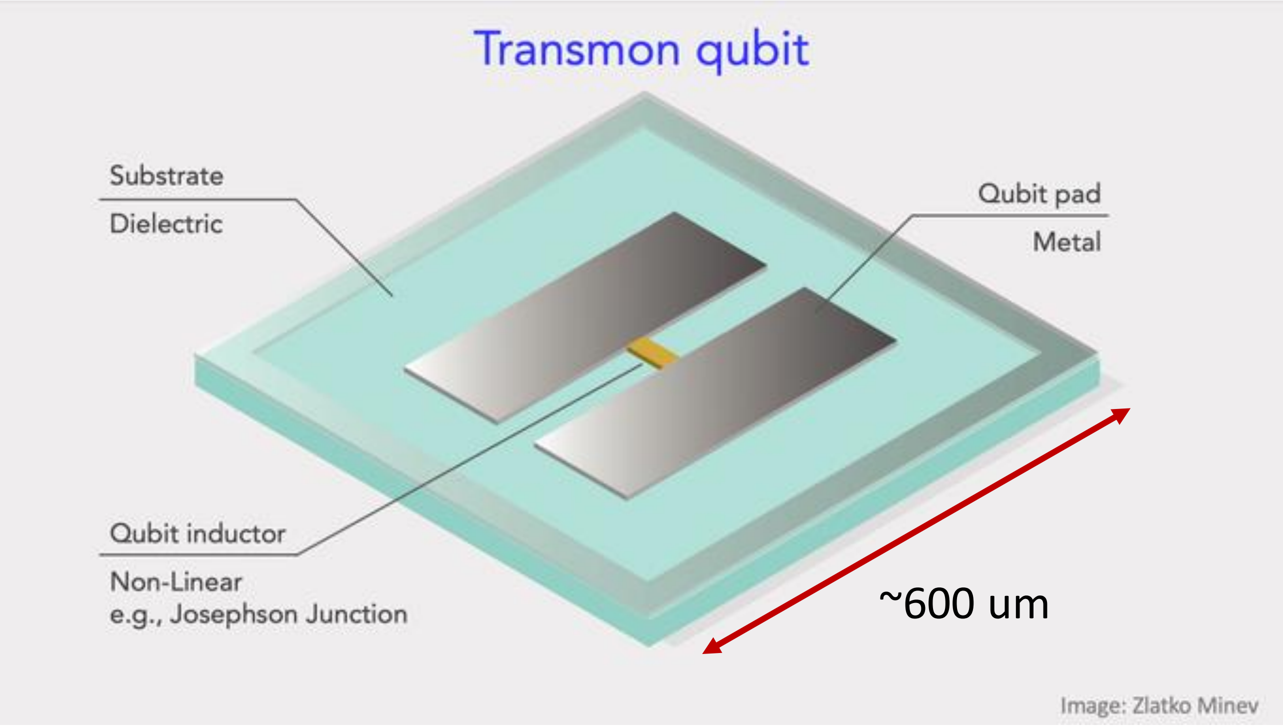
- Measure transmission (S_{21}) or Reflection (S_{11})
- Key parameters:
  - Quality factor
  - Resonator frequency

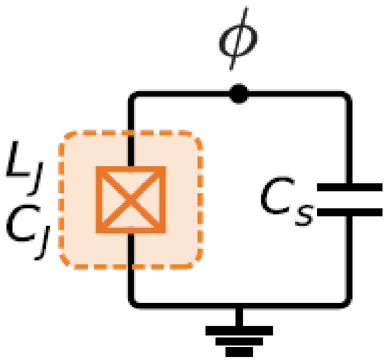


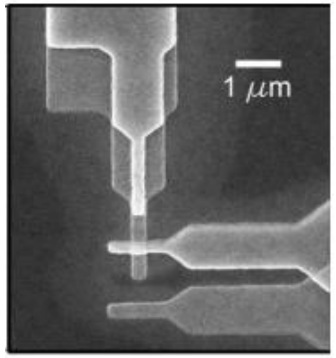


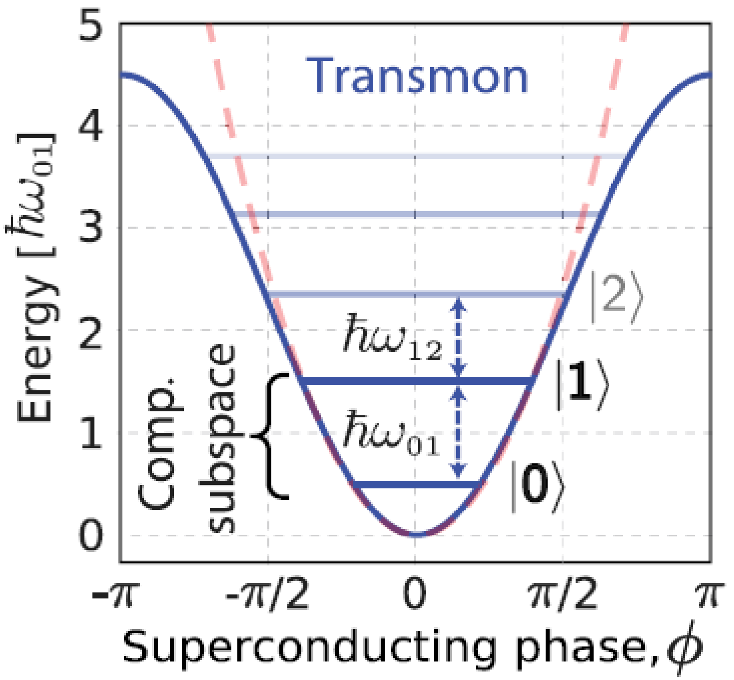
3D Cavity

Superconducting qubit : Transmon





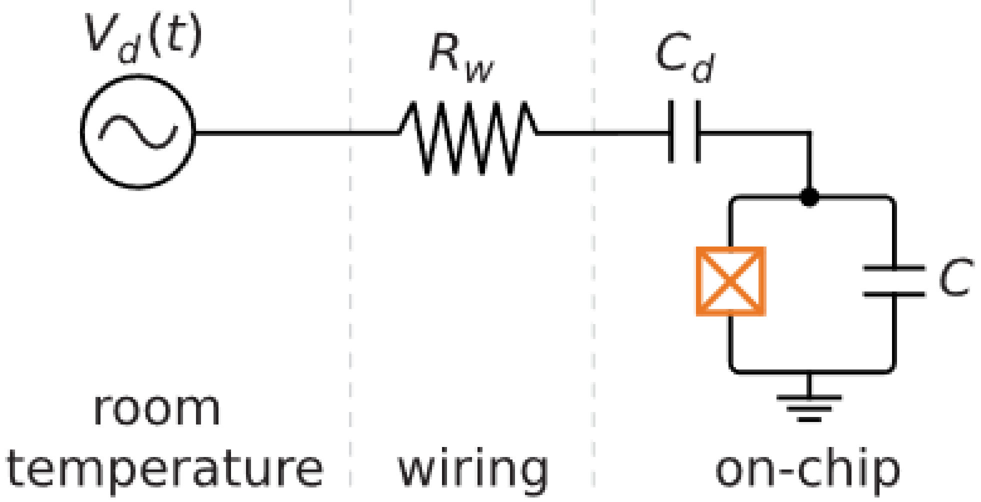




- Qubit Inductor + Large capacitor
- Weakly anharmonic
- Long coherence time
- $f_{01} \sim 5$ GHz

[P. Krantz et al., Appl.Phys.Rev. 6, 021318 (2019)]

Control superconducting qubit state

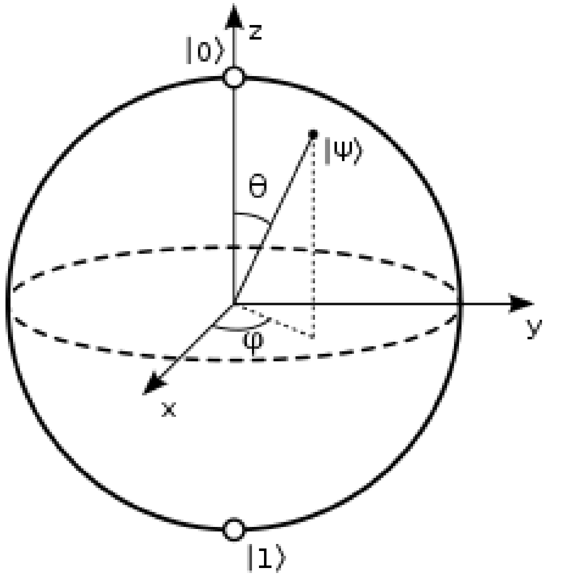


- In rotating frame, the driving Hamiltonian(Hd) is:

$$\mathrm{H_d} \propto \mathrm{V(t)(I}\,\sigma_\mathrm{x} + \mathrm{Q}\,\sigma_\mathrm{y})$$

[P. Krantz et al., Appl.Phys.Rev. 6, 021318 (2019)]

Bloch sphere: visualize qubit state



(Wikipedia)

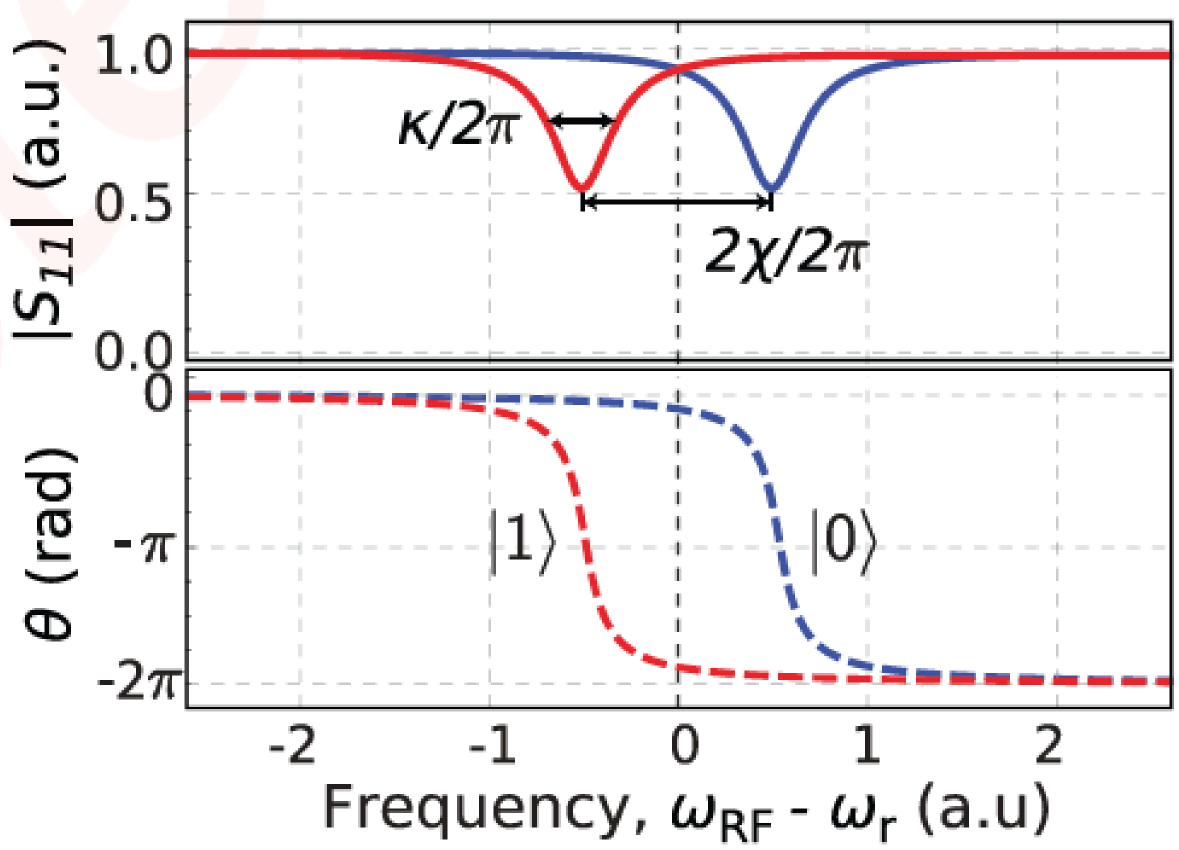
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

- Qubit state is controlled by microwave pulses (normally called **XY-control**)

- Microwave pulse rotates the state vector around a rotation axis on XY-plane.

Measure qubit state – Dispersive readout in circuit-QED

- Qubit coupled to superconducting resonator
- Qubit state-dependent resonant frequency shift

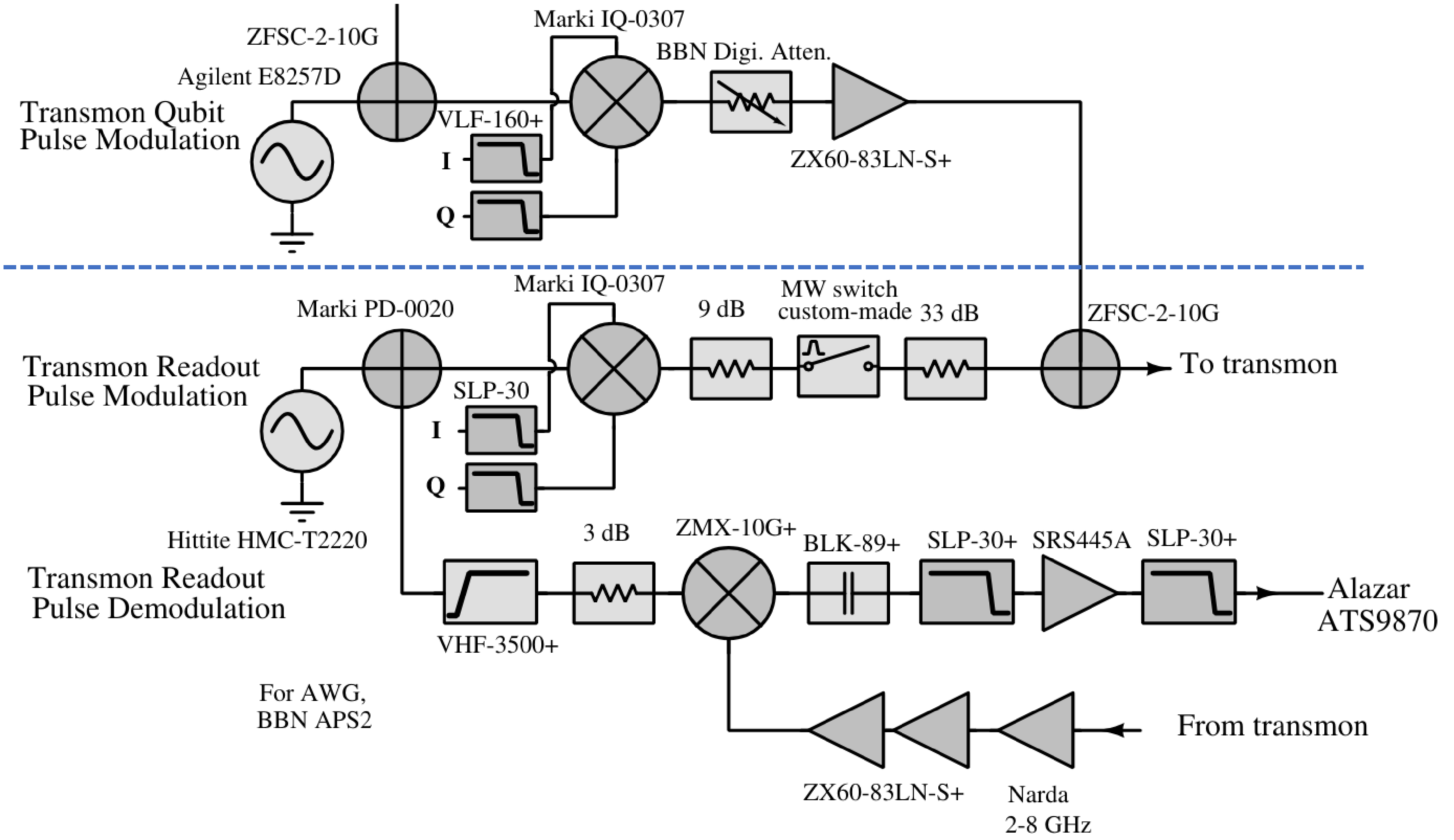


[P. Krantz et al., Appl.Phys.Rev. 6, 021318 (2019)]

Example of RF/MW setup for qubit measurement

Qubit Pulse

Readout Pulse

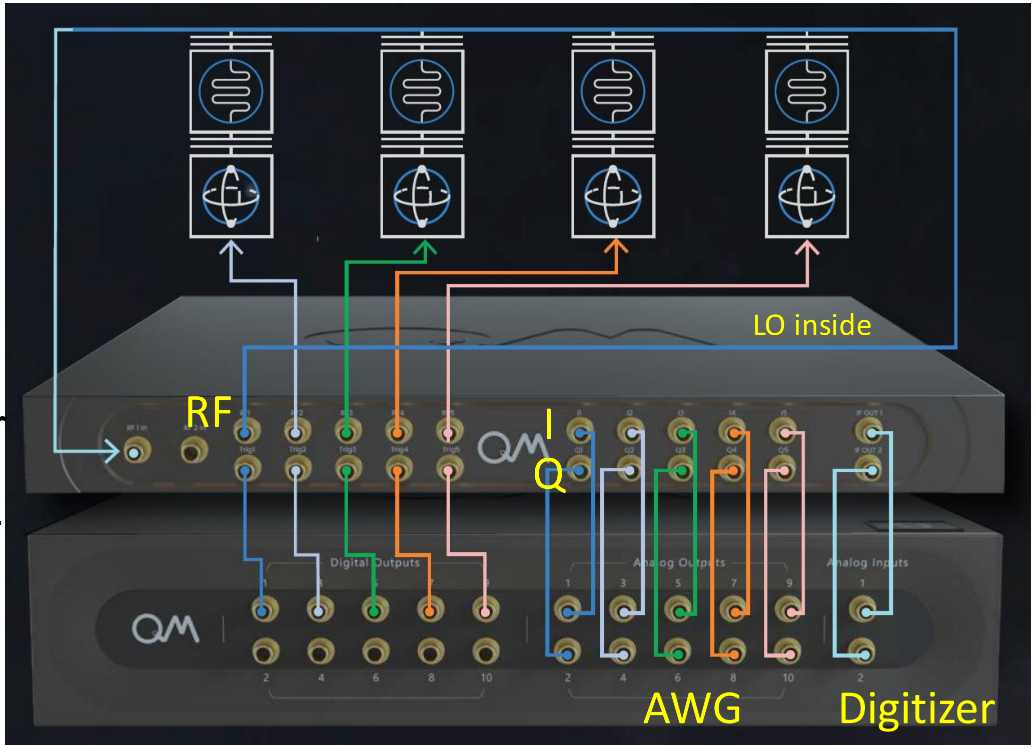


Modern RF Electronics for qubit experiment

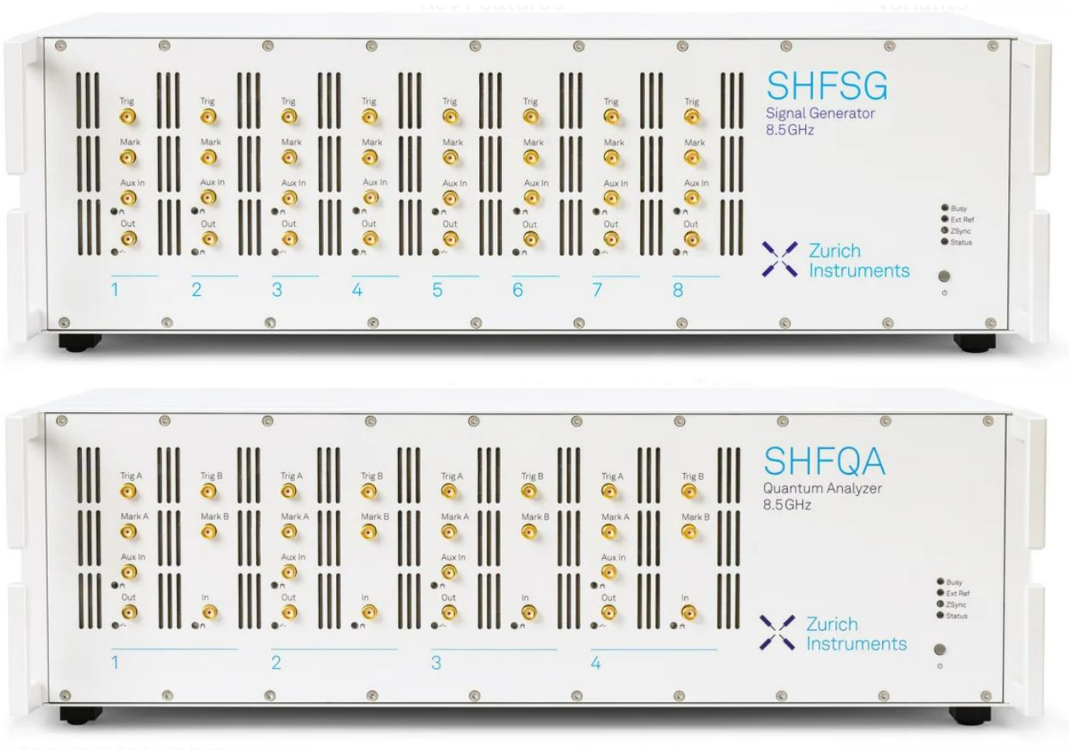
Quantum Machines

- IQ mixer
- LO

- AWG
- Digitizer



Zurich Instruments



Summary

- Covered RF concepts
- Covered RF/MW components and electronics
- Covered RF/MW measurement techniques

Let's try applying RF measurement techniques to your experiments

Thank you!