WE4A-2

Superconducting Non-reciprocal Bandpass Filter Based on Spatio-Temporal Inductance Modulation

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Outline

- Introduction to Quantum Computing Systems
- Superconducting Non-Reciprocal Bandpass Filter Concept
- Simulation Results
- Measurement Setup and Results
- Conclusion

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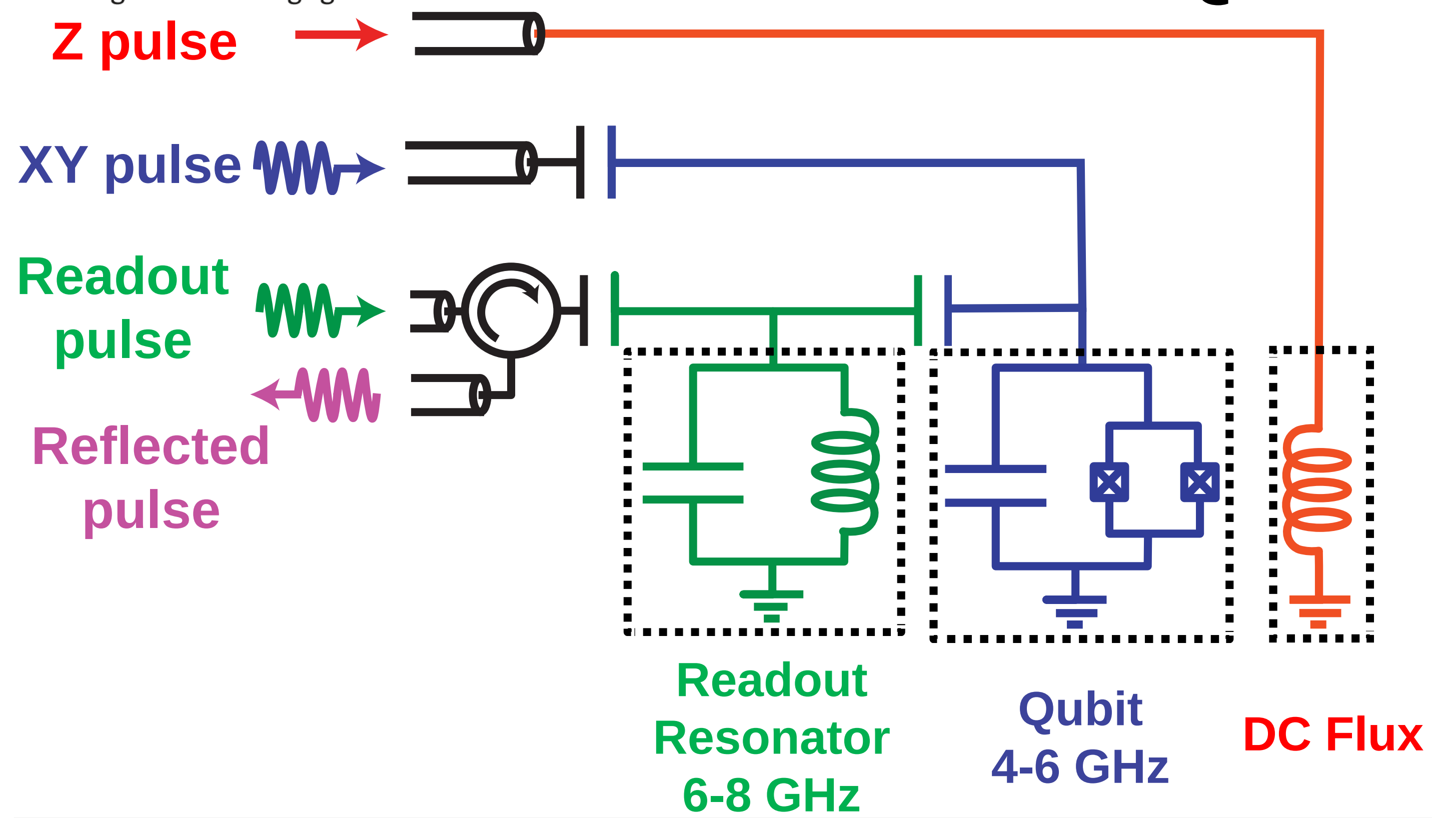
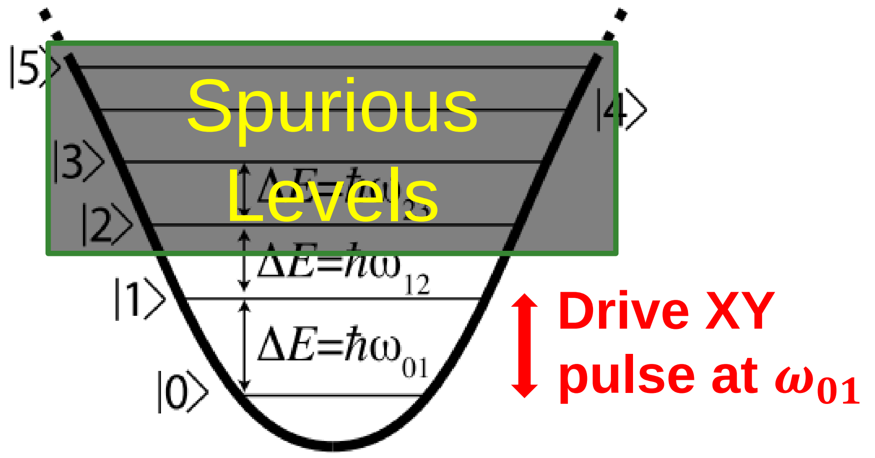
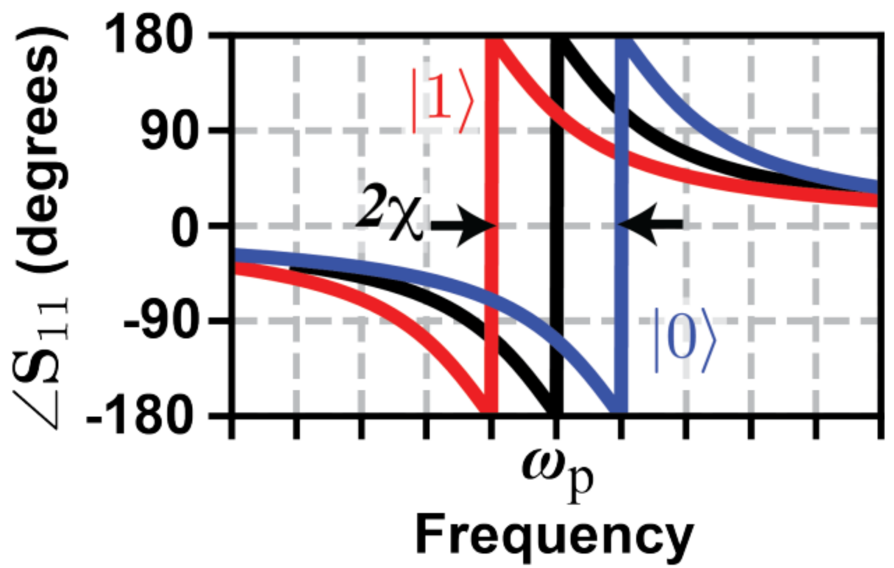
Transmon Qubits Operation





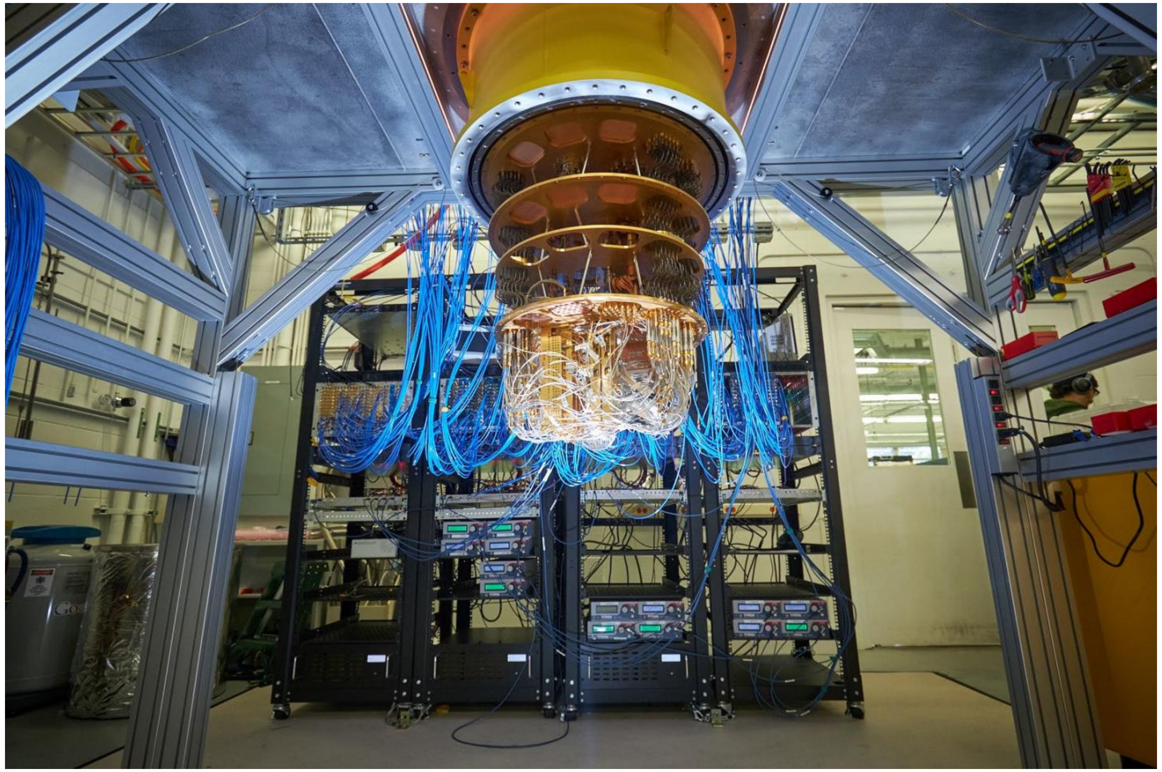
Dispersive Readout



- XY pulse realized qubit gates
- Z pulse change the phase of the state
- Reflectometry based readout measures shift in the readout resonator frequency

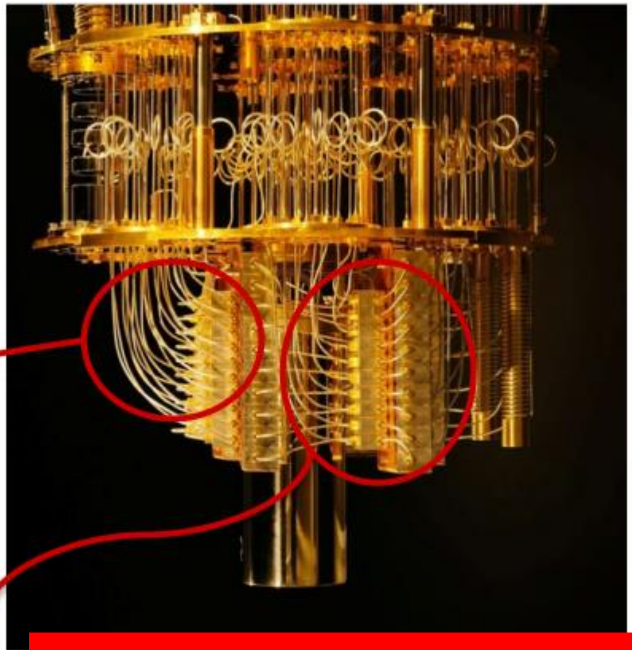
State of the Art Quantum Computer

Google's Sycamore Quantum Computer



[J. Bardin, ISSCC 2023]

Internals of IBM's Quantum Computer



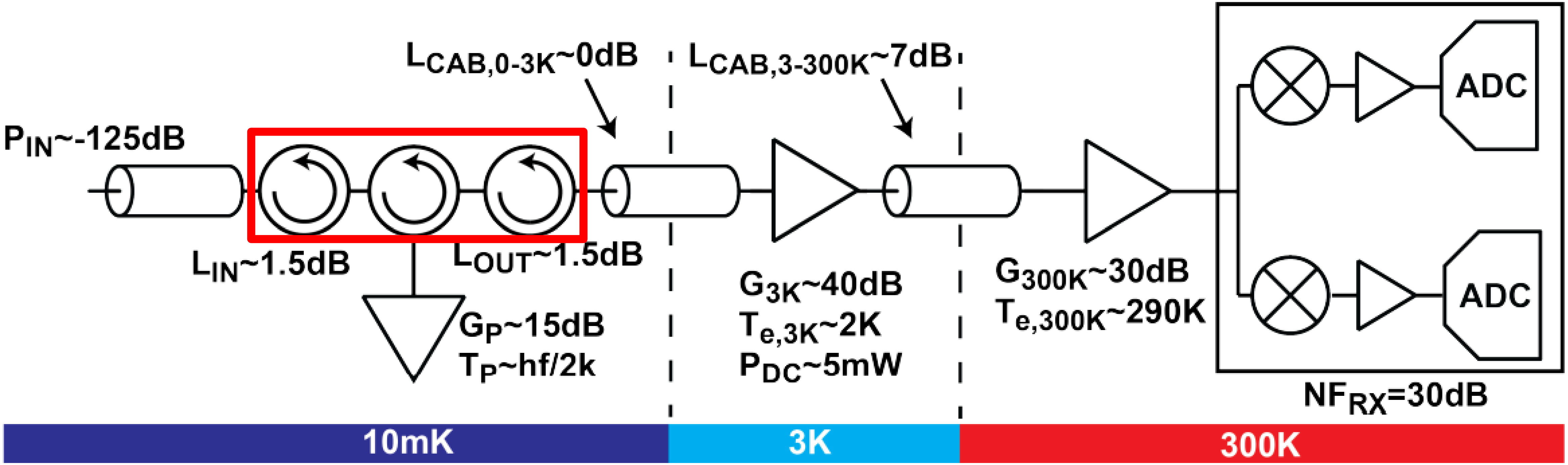
Cryo Flex Lines

Amplifiers, Attenuators and Isolators

[D. Frank, ISSCC 2023]

Currently room temperature equipment, off-the-shelf amplifiers, attenuators and non-reciprocal devices are used for qubit control and readout

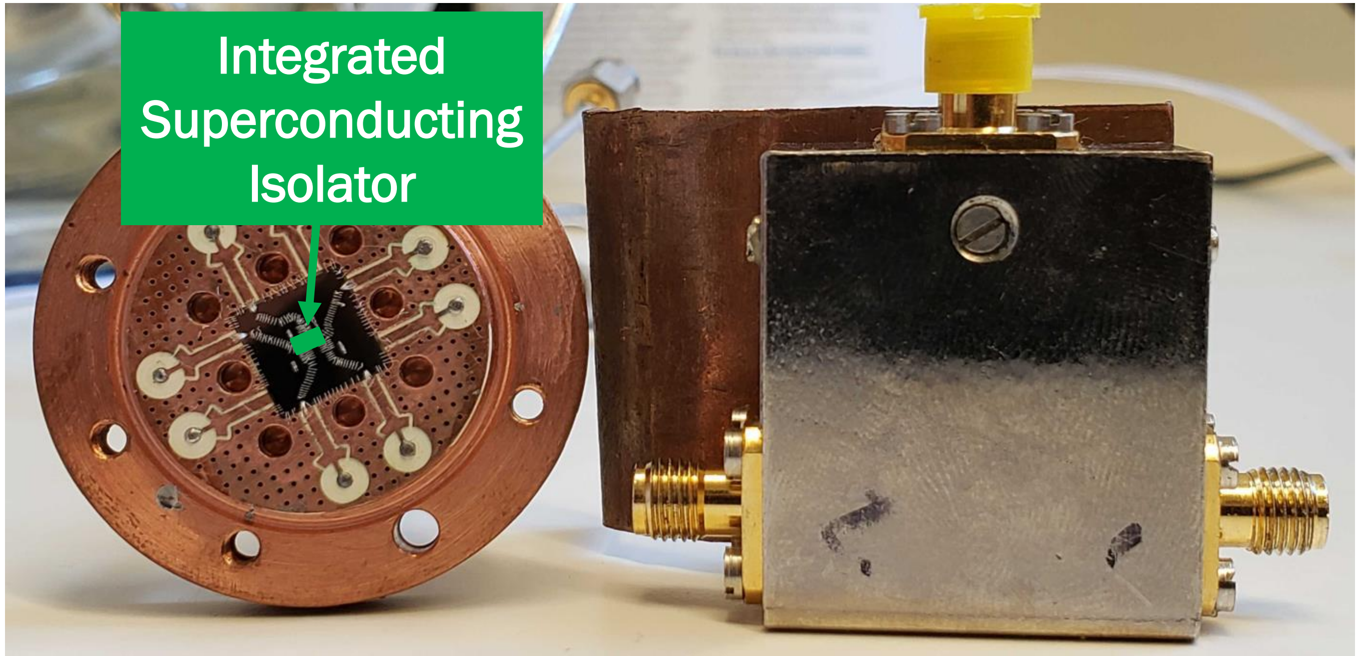
Qubit Control & Readout



[J. Bardin, ISSCC 2023]

- Fully-Integrated CMOS and superconducting control and readout is scalable, reliable and cost effective
- Isolation is required to protect the qubit from the back reflections

Comparison With Ferrite Isolator



1st Gen. WashU's Isolator
1 × 2 × 0. 3 mm
(1 day of a first year Ph.D. student)/ piece

Ferrite Isolator
22.3 × 24.6 × 10.2 mm
(3K$ – 5K$)/piece
Source: LNF

- Commercial ferrite circulators/isolators can create undesirable interference due to their strong magnetic bias
- Parametrically modulated isolators does not require strong magnetic bias, 100-1000x compact, and can be fabricated in academic labs at a fraction of cost

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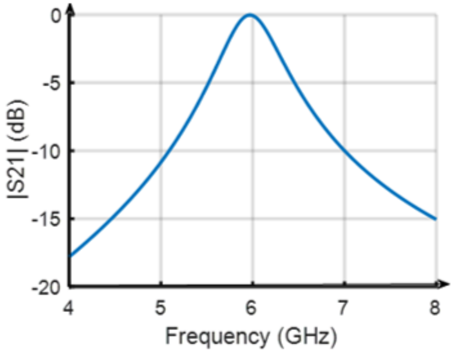
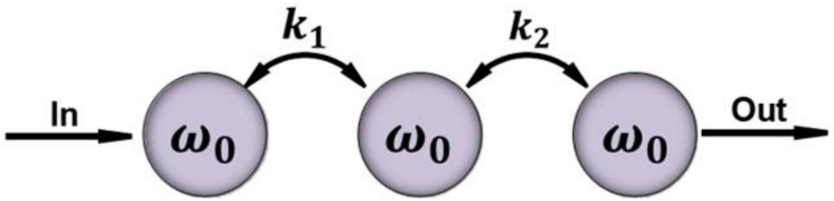
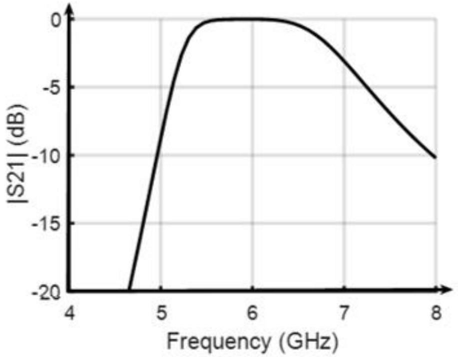
Non-Reciprocal Bandpass Filters

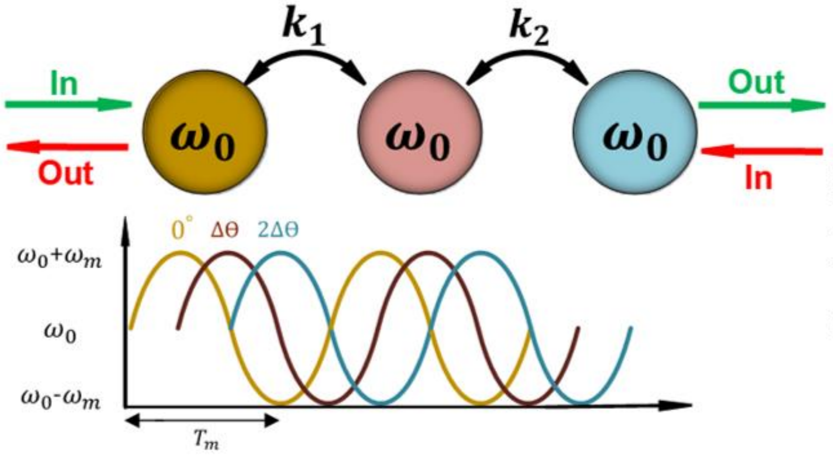


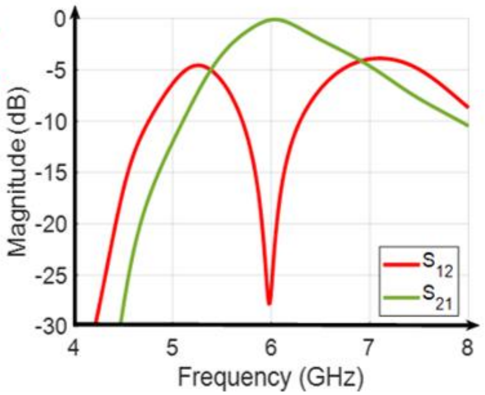
First order Bandpass filter





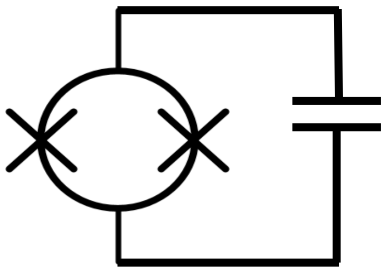
Third order Bandpass filter without modulation



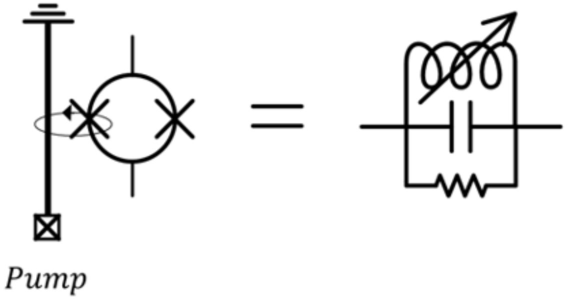


Third order Bandpass filter with modulation

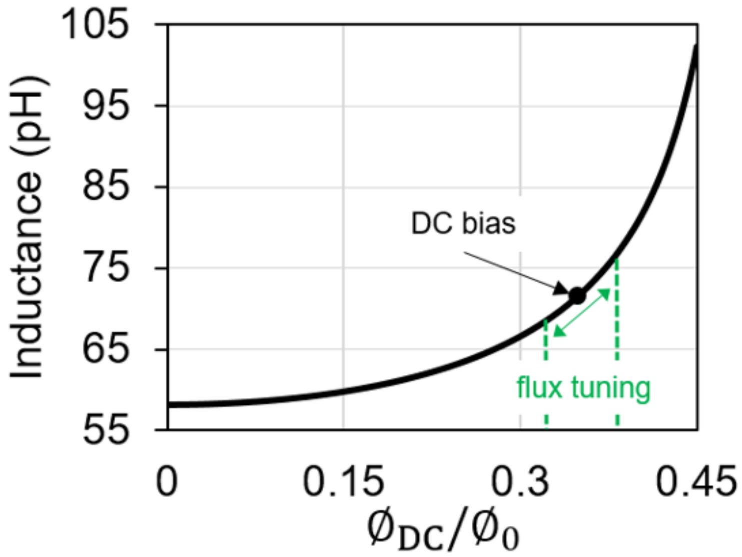
Non-Reciprocal Bandpass Filters



- $I_{sig} << I_c$
- Increasing Ic require larger capacitor
- Narrow band performance

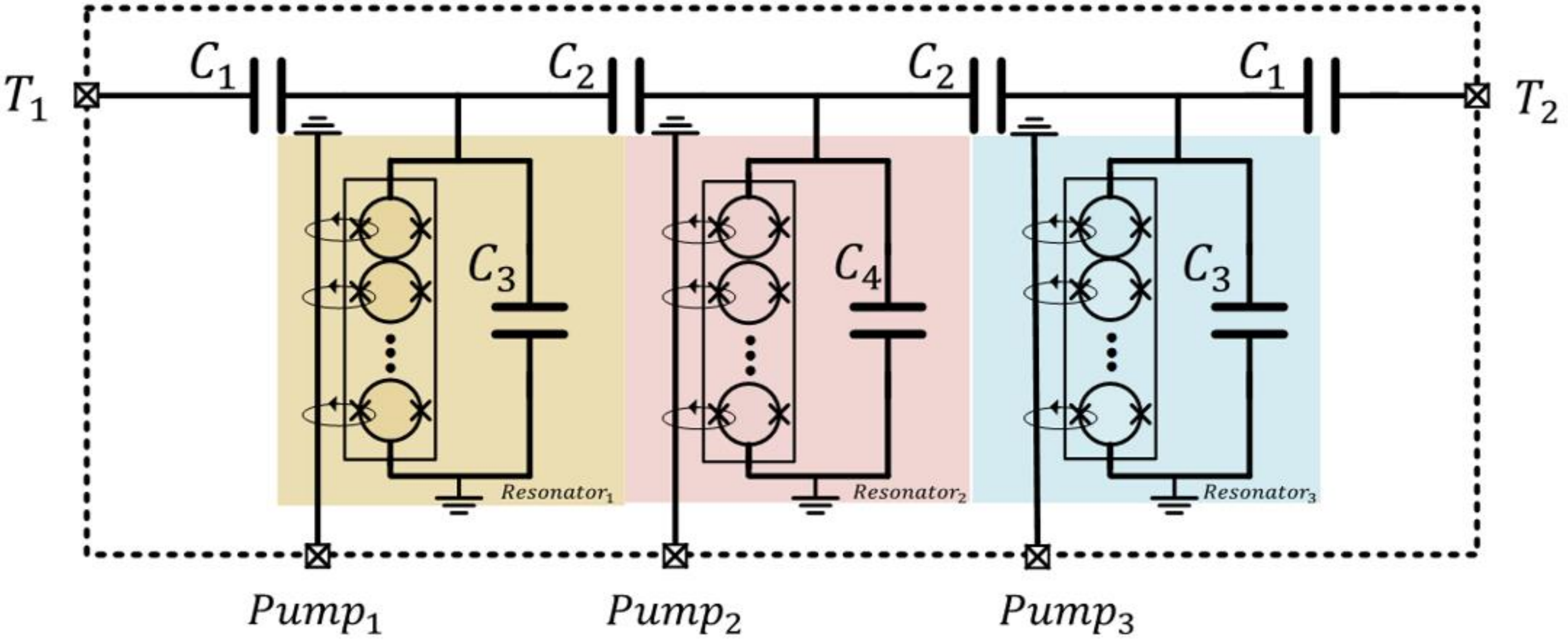


$$L_{SQUID} = \frac{\emptyset_0}{4\pi I_c \cos(\frac{\pi\emptyset}{\emptyset_0})}$$



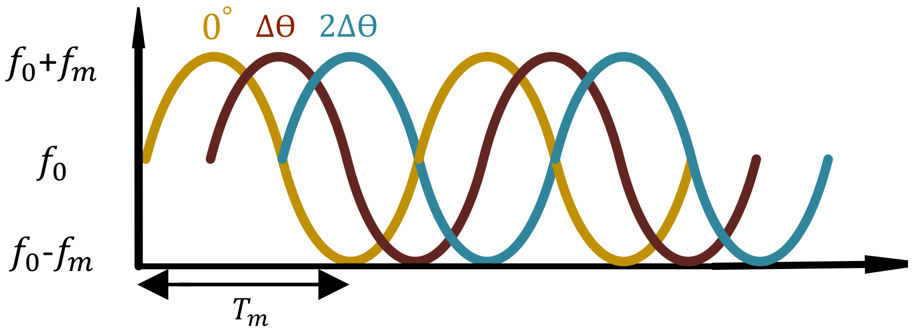
- SQUID is biased around 0.35 flux quanta

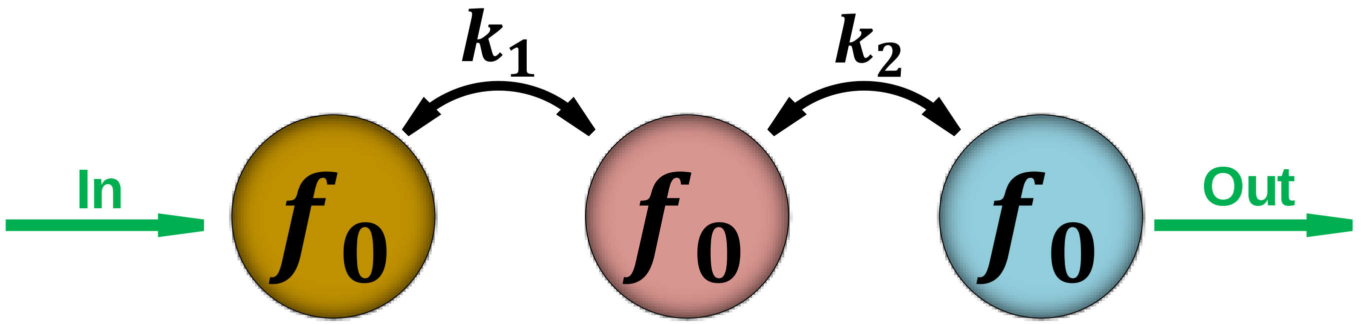
Non-Reciprocal Bandpass Filters

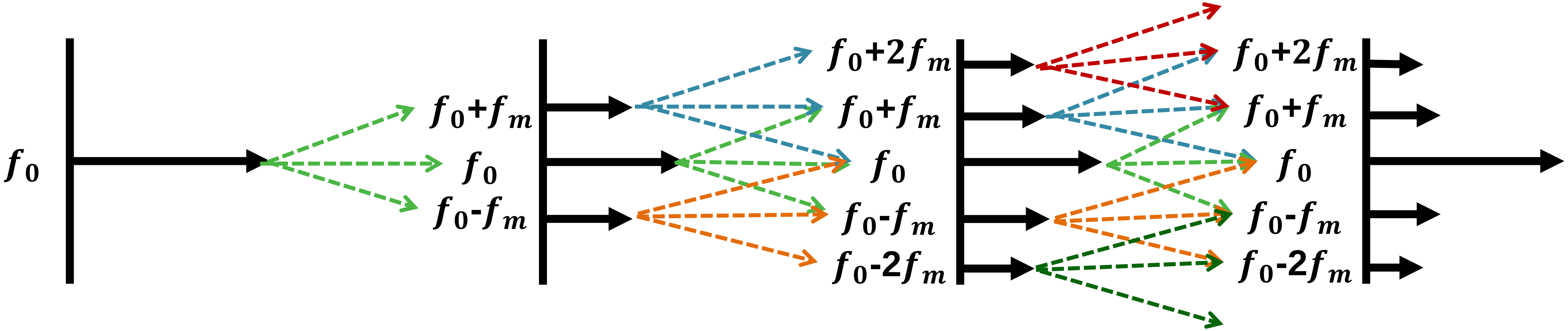


- Stacked SQUID structure increases inductance
- Improves power handling
- Support wideband transmission

Spectral Diagram in Forward Direction

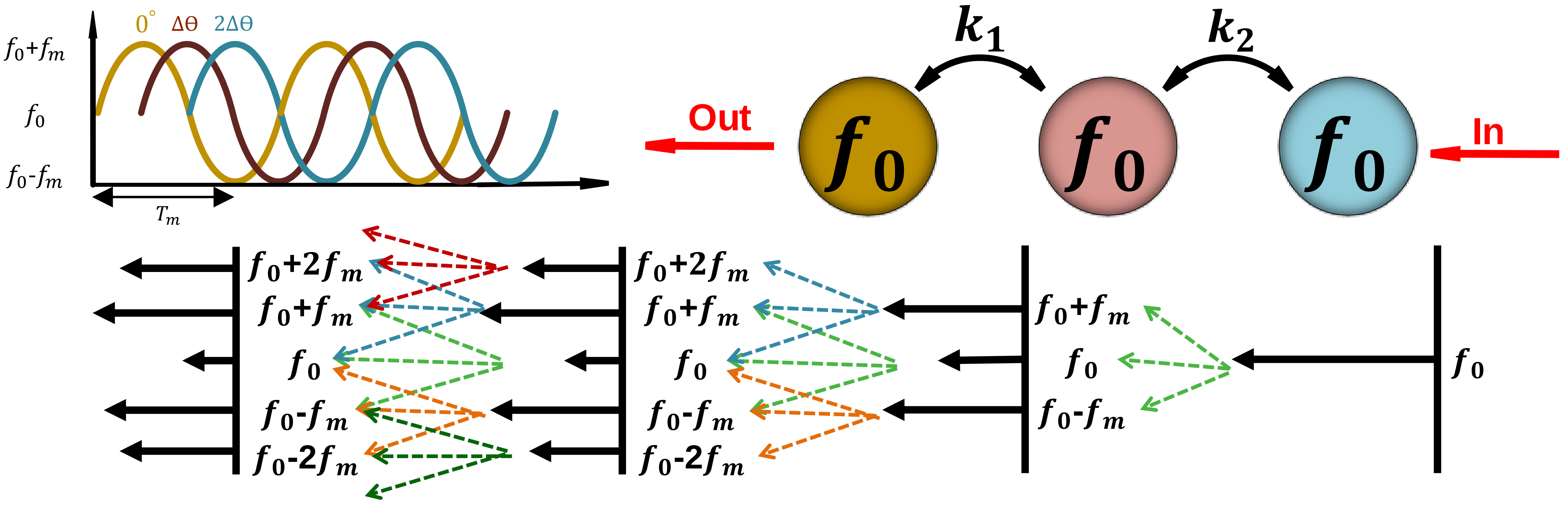






- By choosing proper ΔΘ, IM frequency signal converted back to signal frequency and add up constructively.

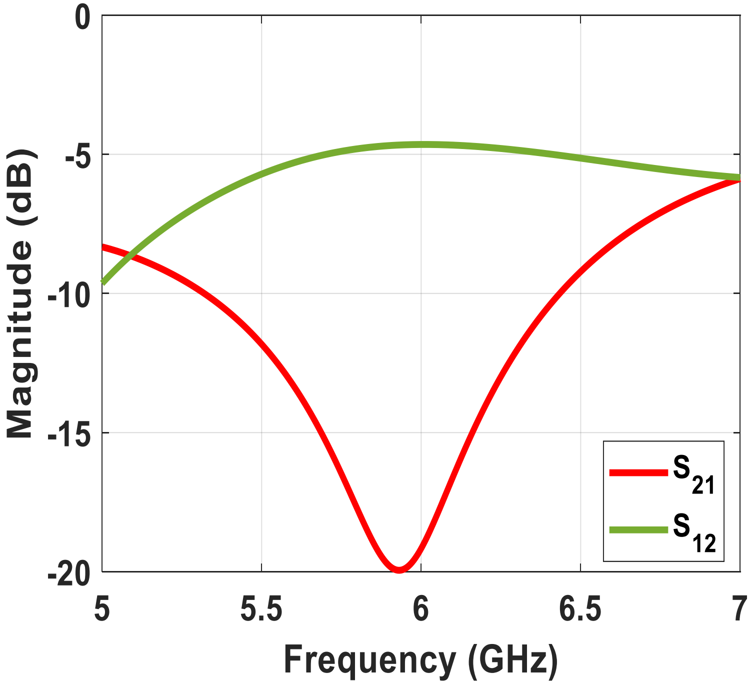
Spectral Diagram in Reverse Direction



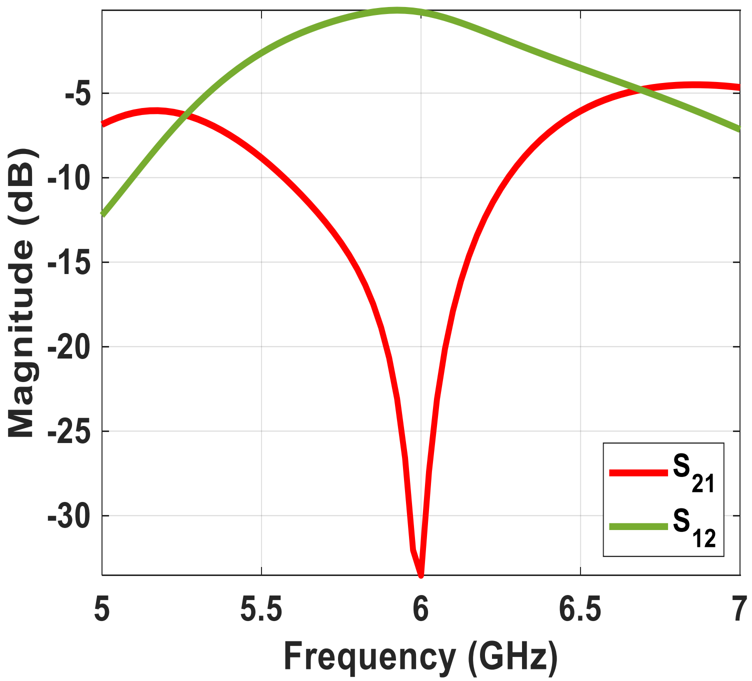
- By choosing proper ΔΘ, IM frequency signal converted back to signal frequency and add up destructively.

Comparison

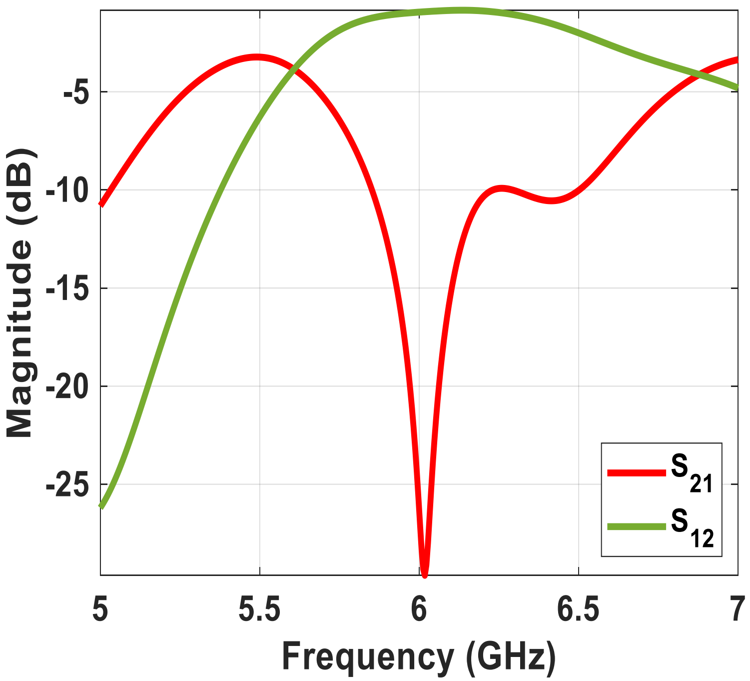
2nd order



3rd order



4th order



- 2nd order results in high isolation but with high insertion loss
- 3rd order results in high isolation with near-zero insertion loss
- 4th order also has good performance but require larger area

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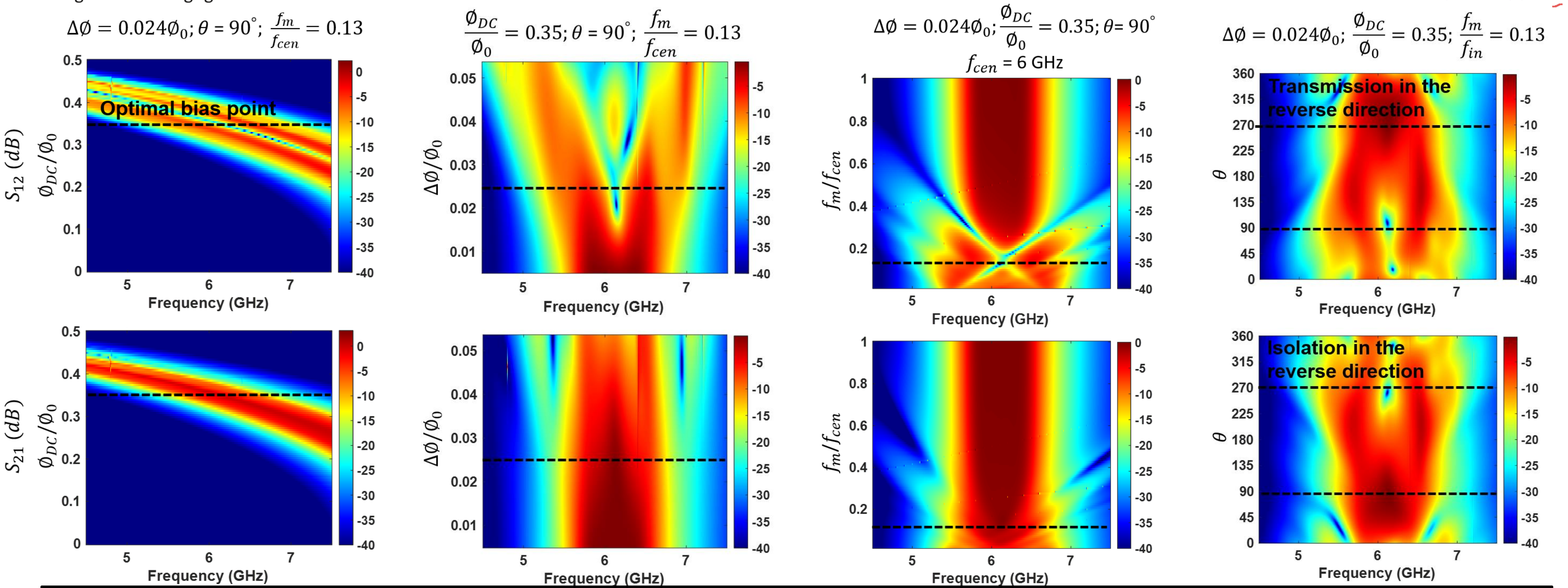
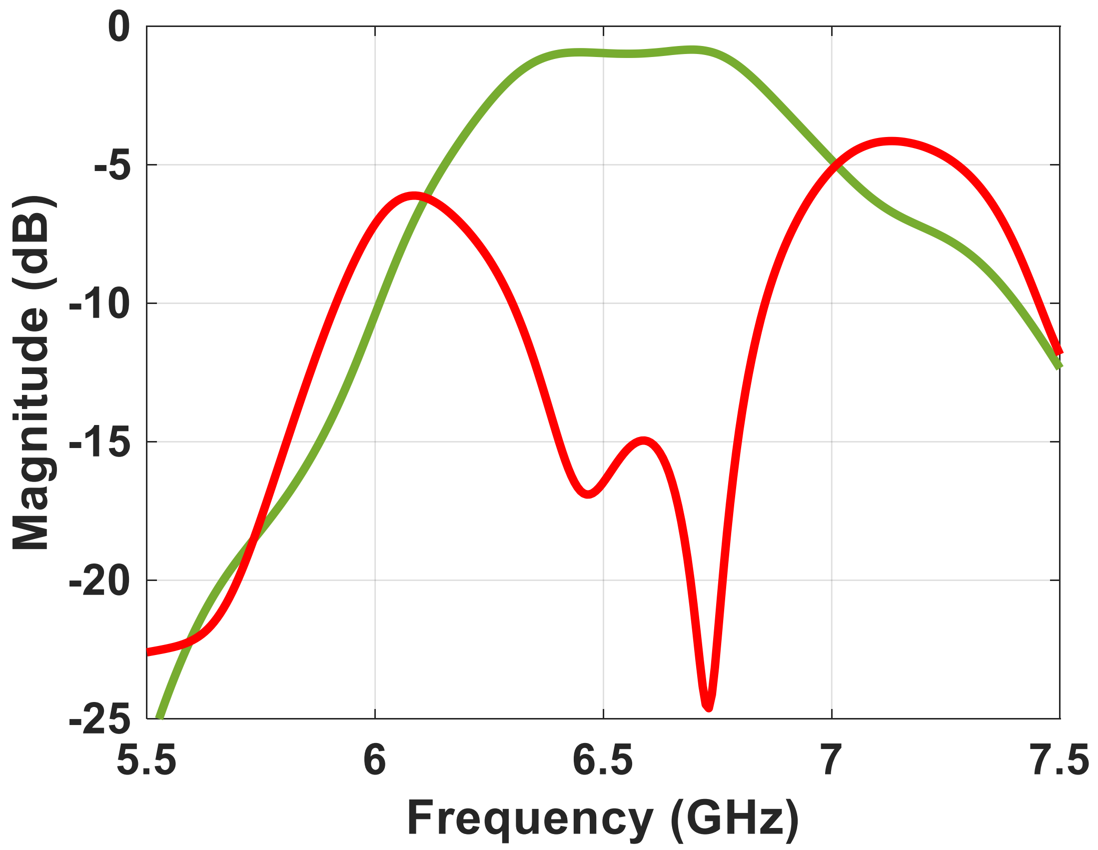
Parametric Study of the Modulation Parameters



- Modulation parameters: φ_{DC} (DC Flux), $\Delta\varphi$ (Mod. Amp.), fm (Mod. Freq.), and θ (phase staggering)
- Optimal modulation parameters are determined through extensive study

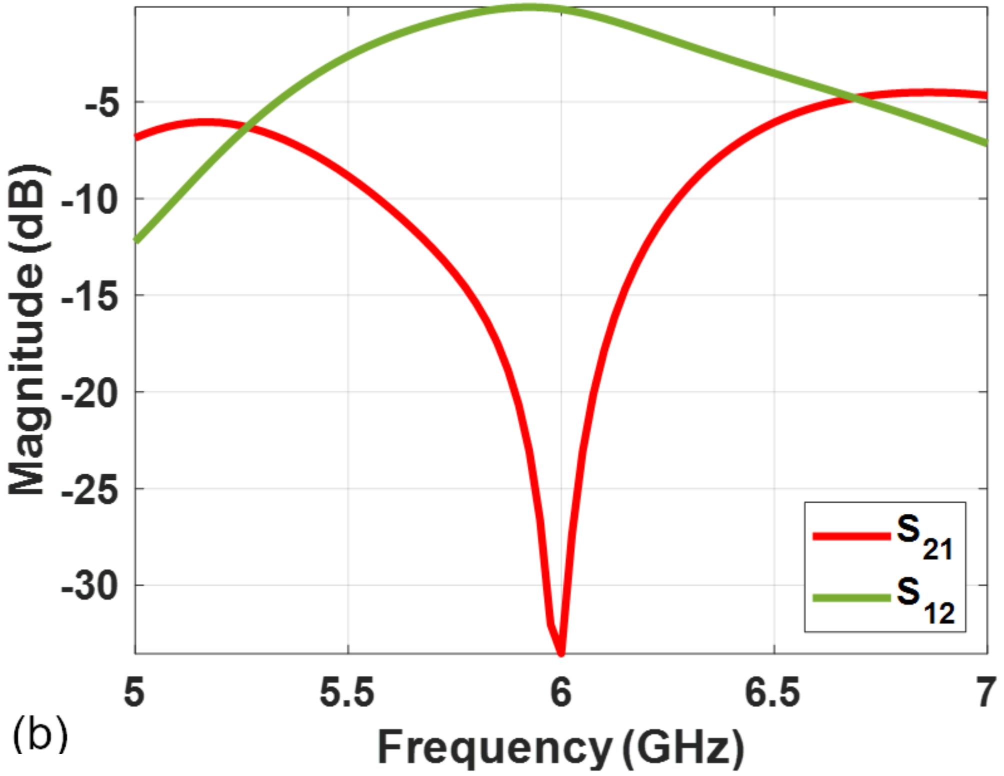
S Parameter



- φ_{DC} = 0.4 Flux Quanta
- $\Delta\varphi$ = 0.025
- f_m = 770 MHz
- $\Delta\theta$ = 124 degree

- Center frequency at 5.6 GHz
- Insertion loss =1dB
- Isolation >20dB across 350 MHz

S Parameter



(b)

- φ_{DC} = 0.35 Flux Quanta
- $\Delta\varphi$ = 0.025
- f_m = 700 MHz
- $\Delta\theta$ = 90 degree

- Center frequency at 5.8 GHz
- Insertion loss <0.5dB
- Isolation >15dB across 200 MHz

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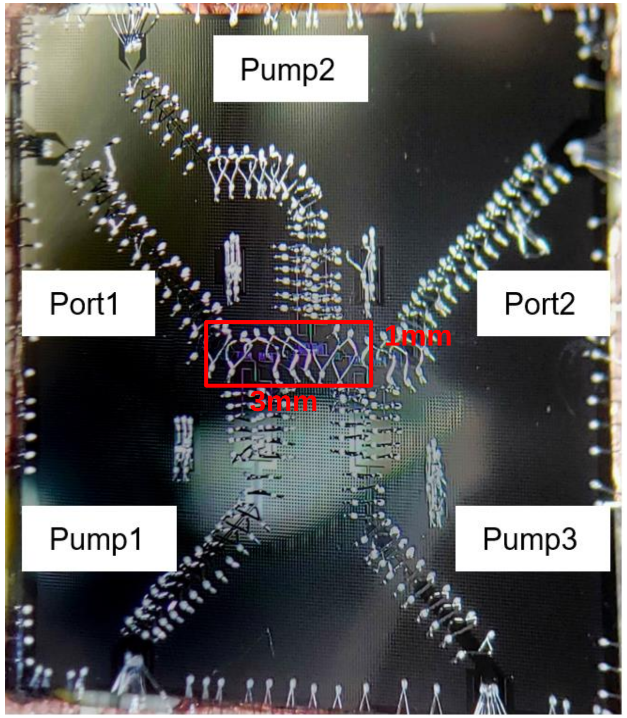
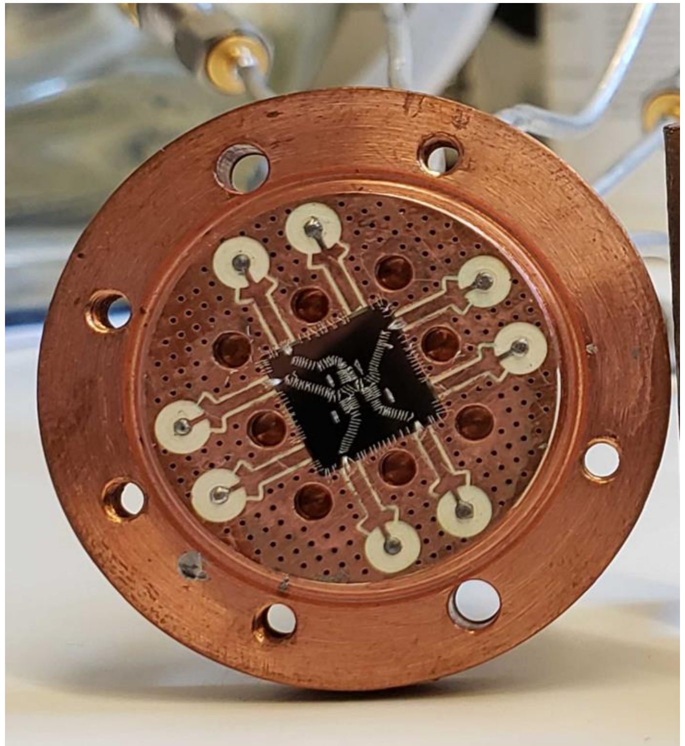
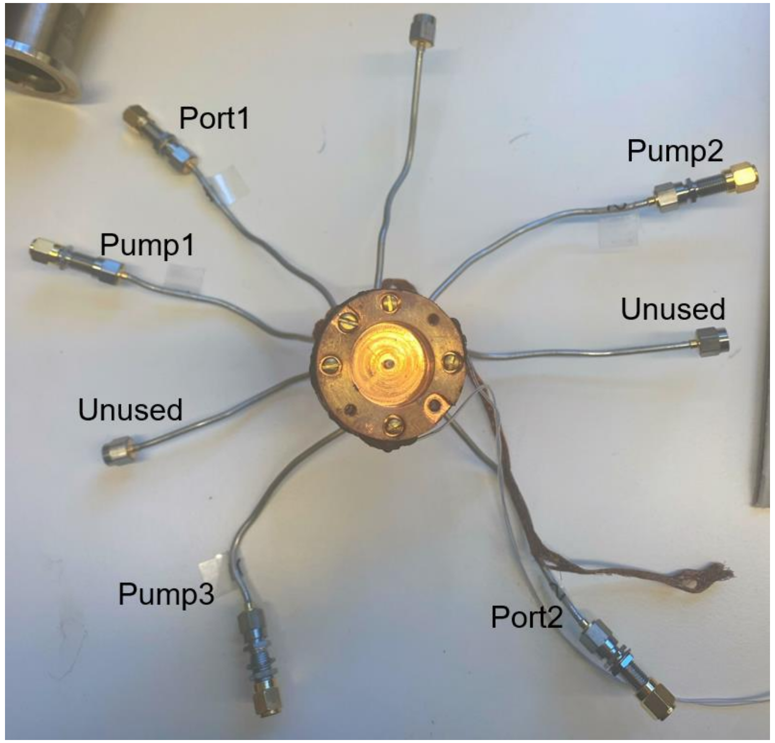
Superconducting Chip & Packaging



Chip photo

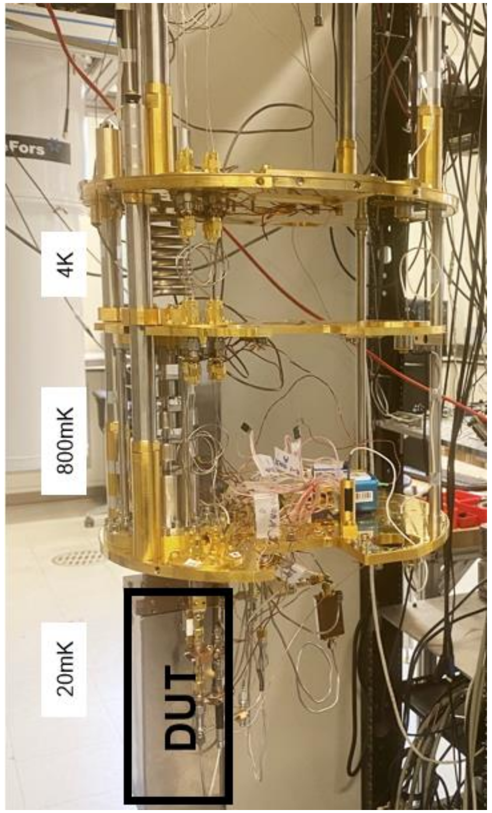


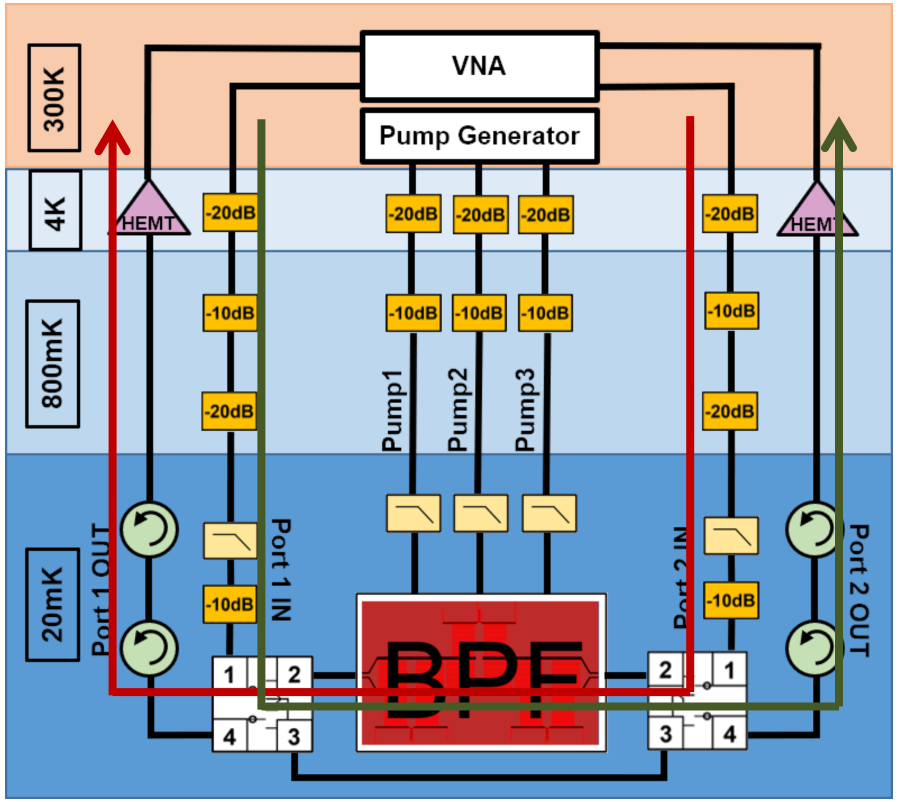


Copper package

- Chip occupy an area of 3mm x 1mm
- Chip is placed in a copper package with eight ports

Cryogenic Measurement Setup



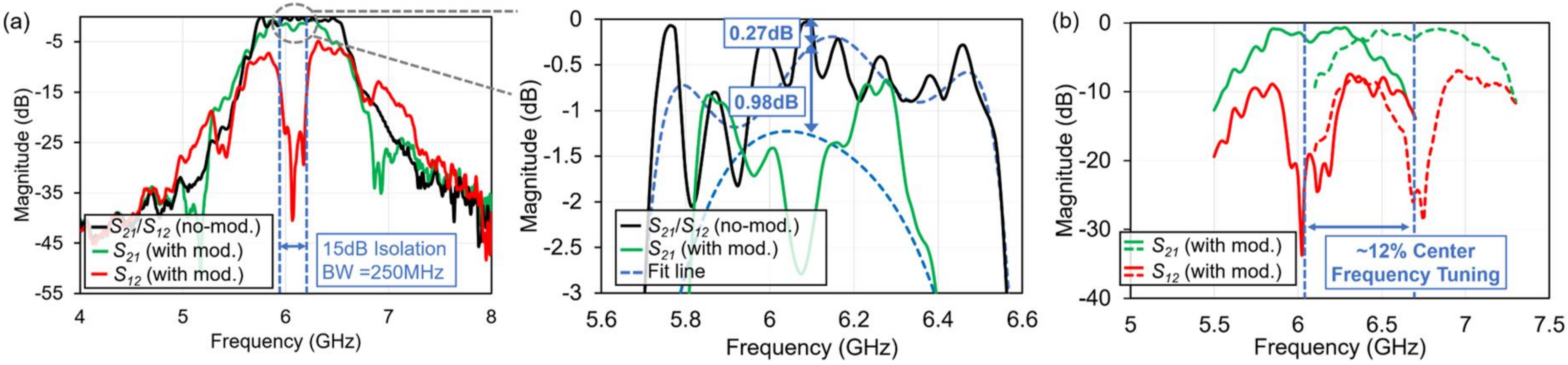


Forward Transmission

Reverse Transmission

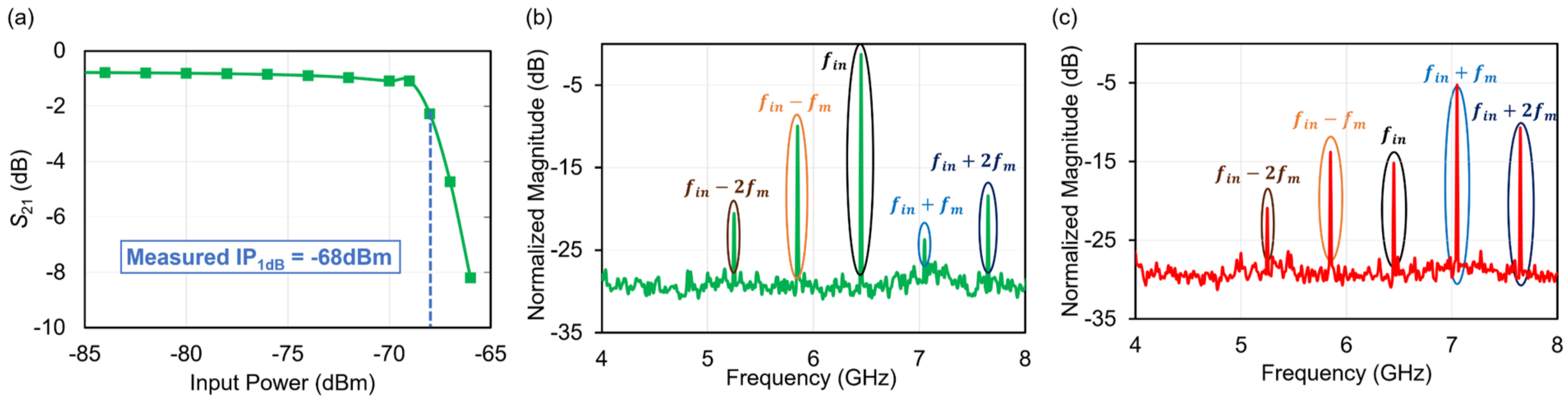
- NR-BPF is interfaced with room temperature VNA through cryogenic drive and readout path
- Muxing switches are used to measure the forward and reverse transmissions
- A through line is used to gain-calibrate the drive and readout paths

Cryogenic Measurement



- Transmission loss of the filter with no-modulation is 0.27 dB;
- An additional insertion loss of 0.98 dB in the forward direction, isolation is +25 dB at the center frequency and is >15 dB across 250 MHz bandwidth in the reverse direction with modulation.
- Tuning across 6 GHz to 6.75 GHz.

Cryogenic Measurement



- -1 dB compression point is -68dBm.
- In forward direction, input power concentrated at the input frequency.
- In reverse direction, input power translated to IM frequencies.

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Conclusion

- Presented a superconducting non-reciprocal BPF that combined BPF and isolator
- Integrated isolators can be 100-1,000× smaller and cheaper compared to ferrite based isolator
- Measured BPF
  - ✓ Insertion loss <1.5dB
  - ✓ Isolation >15dB across 200 MHz
  - ✓ GHz tuning range from 6 GHz to 6.75 GHz