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# Superconductor modulation circuits for Qubit control at microwave frequencies

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## Introduction

The main challenge in scaling quantum computers to address real-world problems and making it viable is the scale-up to many thousand qubits. The usual method for readout and control of qubits consists of many subsystems spreading over a high temperature gradient from room to ~mK temperatures, implying significant wiring lengths between them. This brings a lot of unwanted noise to the system, is bulky and expensive, and significantly limits the number of qubits. An alternate solution consists of using integrated circuits at cryogenic temperatures. Field Programmable Gate Arrays (FPGAs) have recently shown improvements in terms of integration and lowering cost, but the noise issue remains. Application Specific ICs (ASICs) can also lower the noise and perform well at cryogenic temperatures.

However, the best solution is to integrate, close from the quantum system, energy-efficient superconductor circuits to perform preprocessing tasks with orders of magnitude lower power consumption, hence correspondingly lower noise, to reach ultimate performance at cryogenic temperatures. In this context single flux quantum (SFQ) and adiabatic quantum flux parametron (AQFP) circuits are natural energy-efficient candidates to design cryogenic qubits readout and control systems.

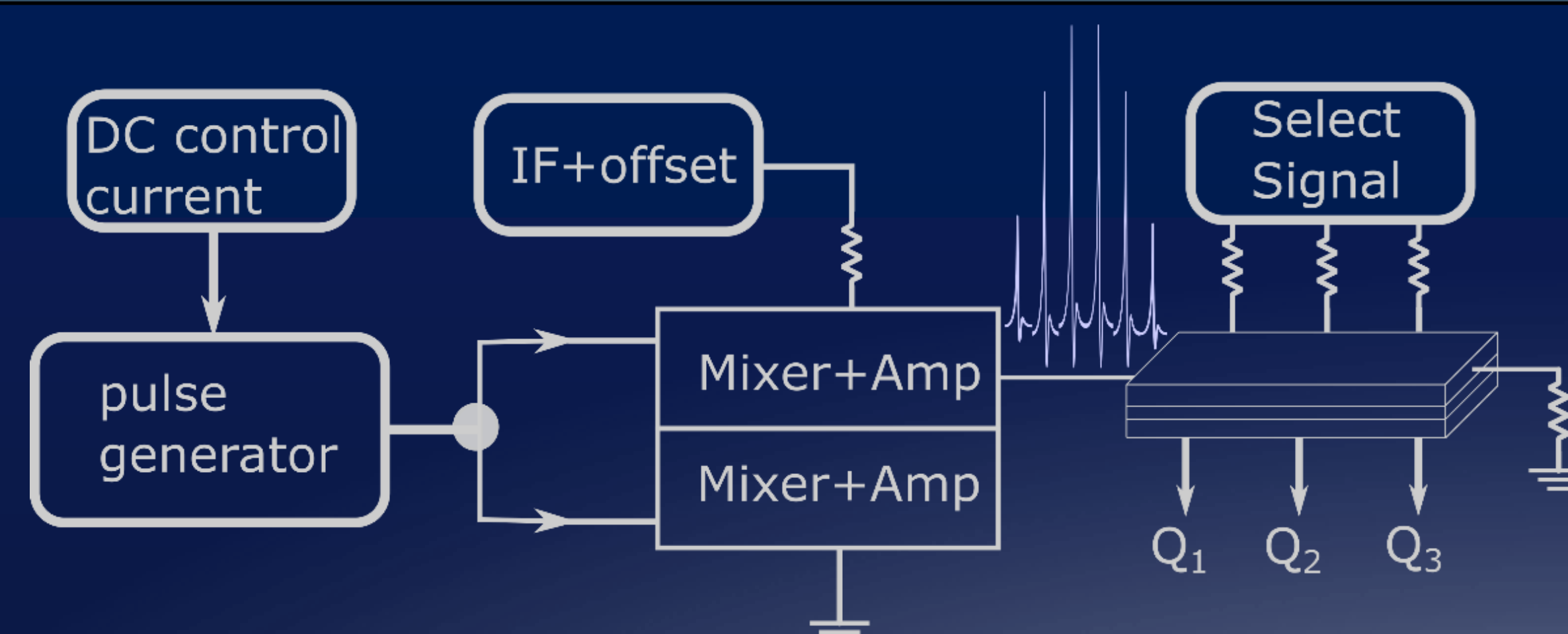
## Methodology

The proposed method uses Josephson oscillations as the source for high frequency oscillations.

- The intermediate source (IF) comes from room and determines the envelope over the HF source.
- The signals are mixed, amplified and passed through a band-pass filter for desired value.

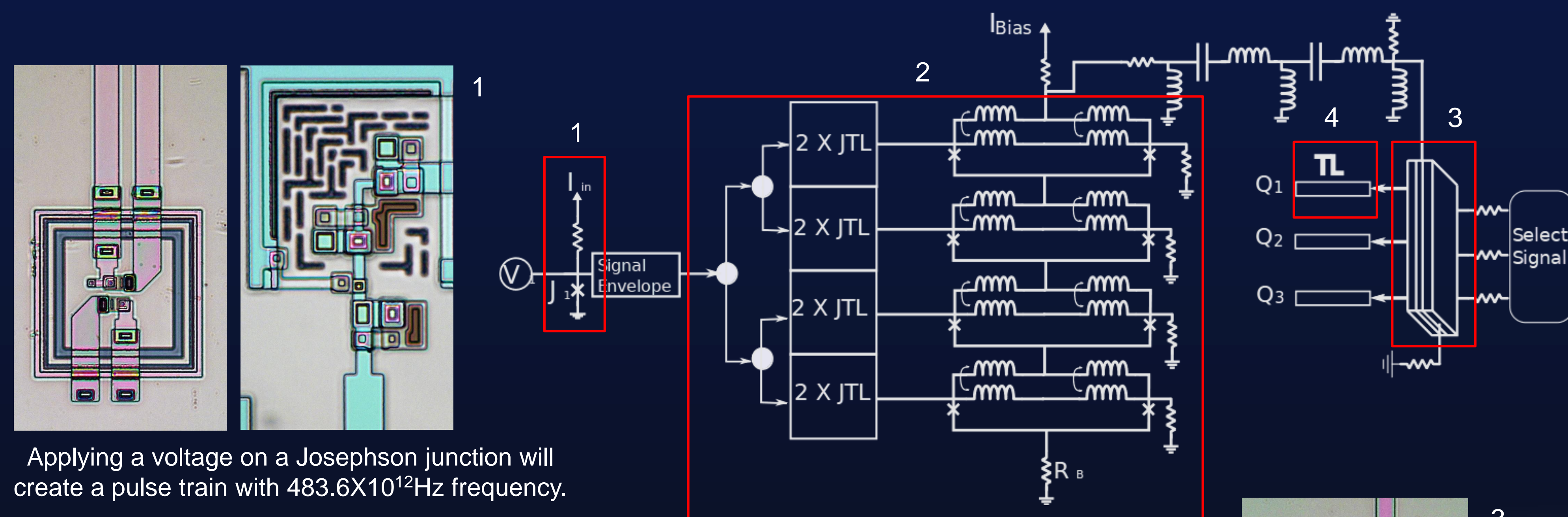
- The resulting output signal is distributed by a long Josephson junction (LJJ) that is controlled by external DC bias lines. The outputs are connected to the quantum chip via impedance-matched ports.

(For the purpose of simulation, LJJ is replaced with series junctions each with its own bias line in JTL-like structure.)

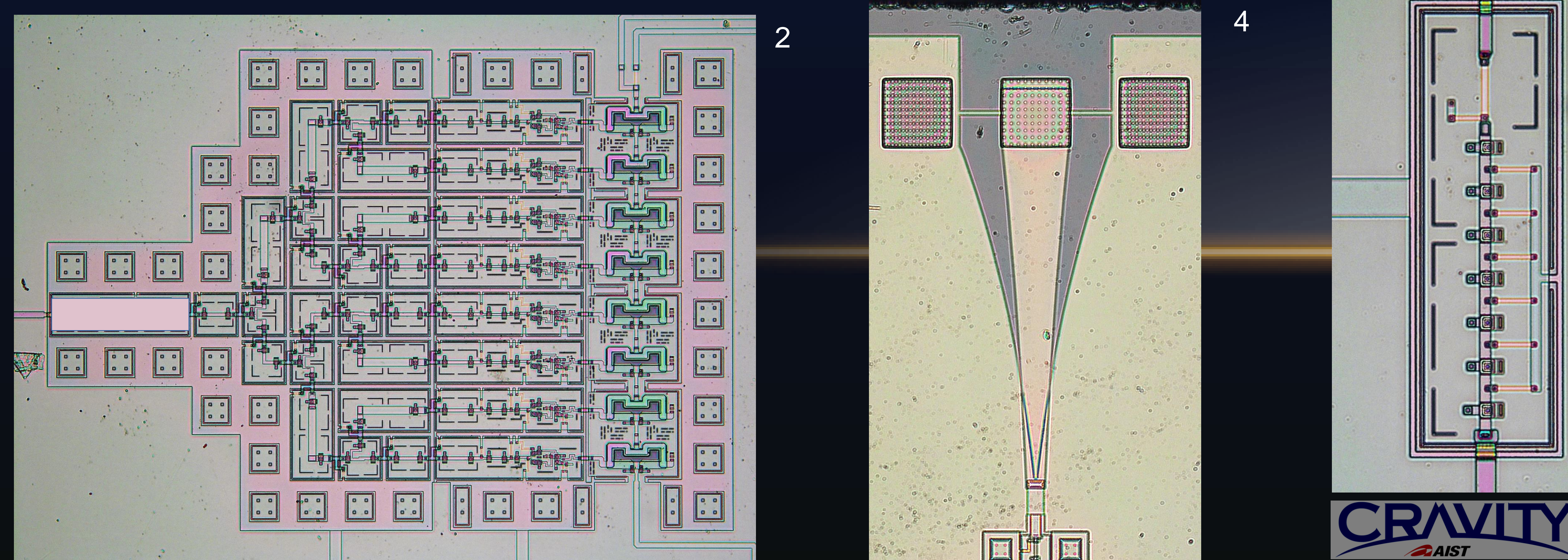


Schematic of the integrated superconductor control circuit.

## Circuit Design and Layout

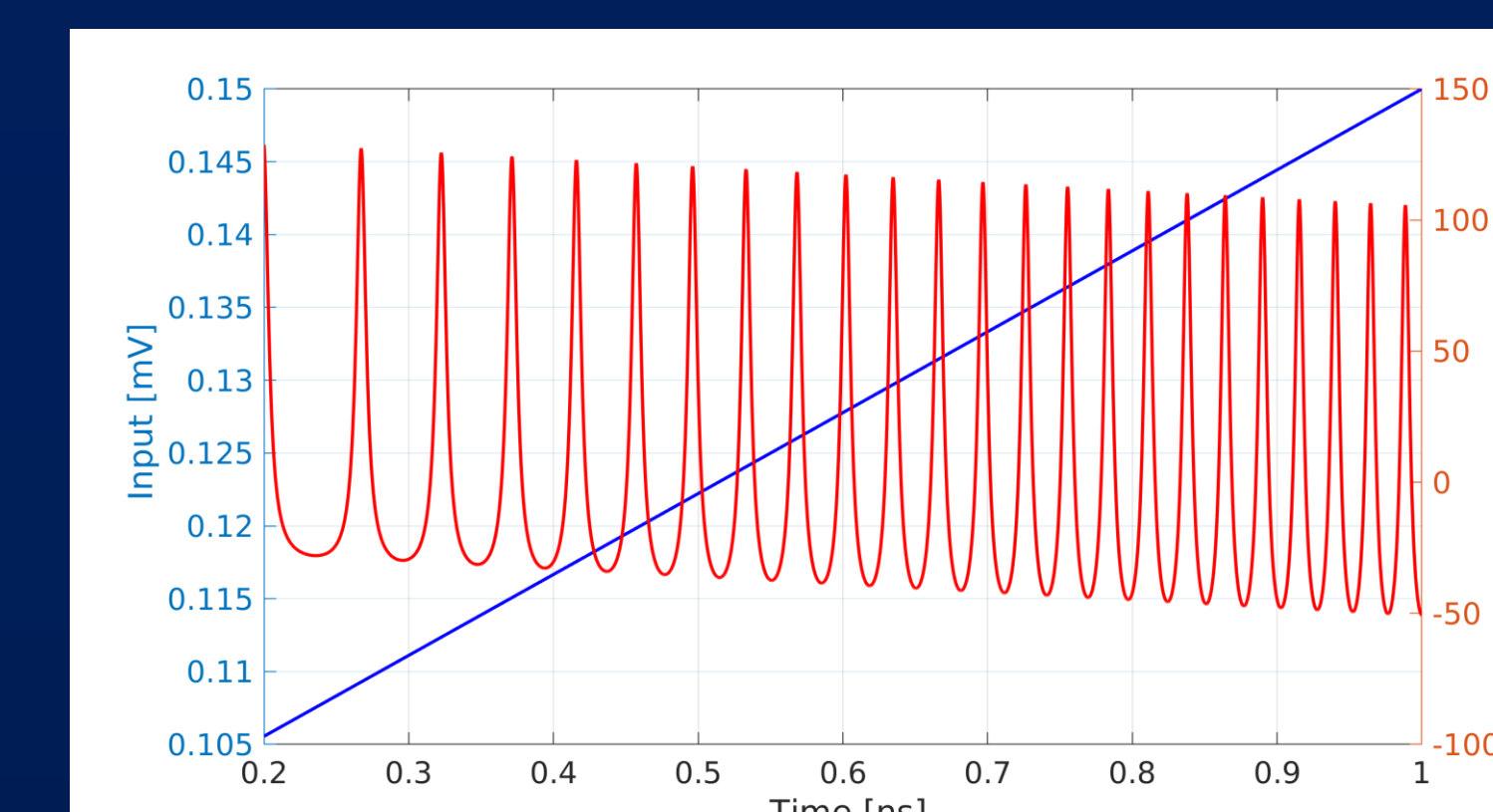


Applying a voltage on a Josephson junction will create a pulse train with  $483.6 \times 10^{12}$  Hz frequency.

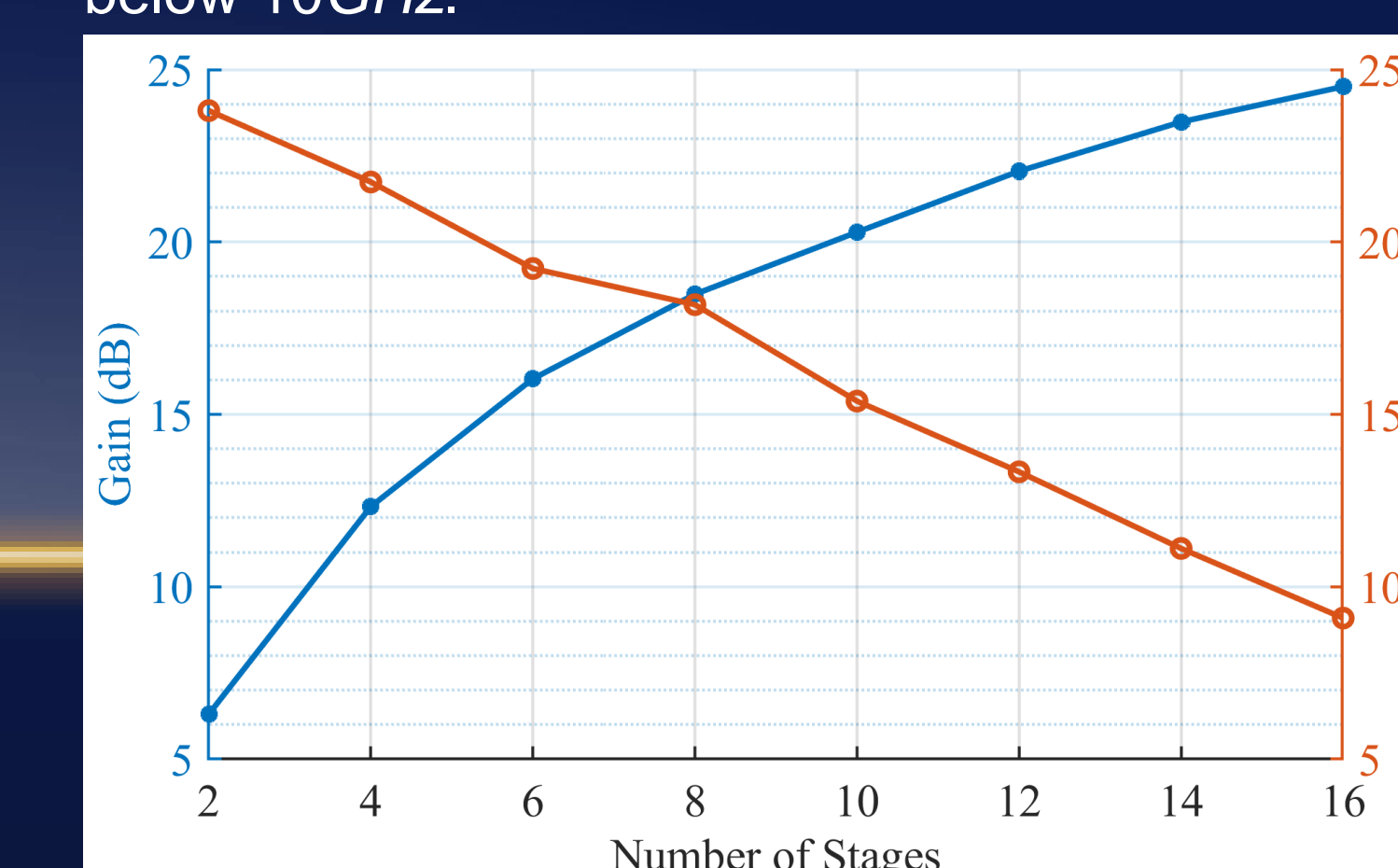


## Simulation Results

The Josephson junction starts oscillating when a voltage is applied to it, the oscillation frequency is directly linked to the value of the voltage by the factor of  $483.6 \text{ GHz/mV}$ .

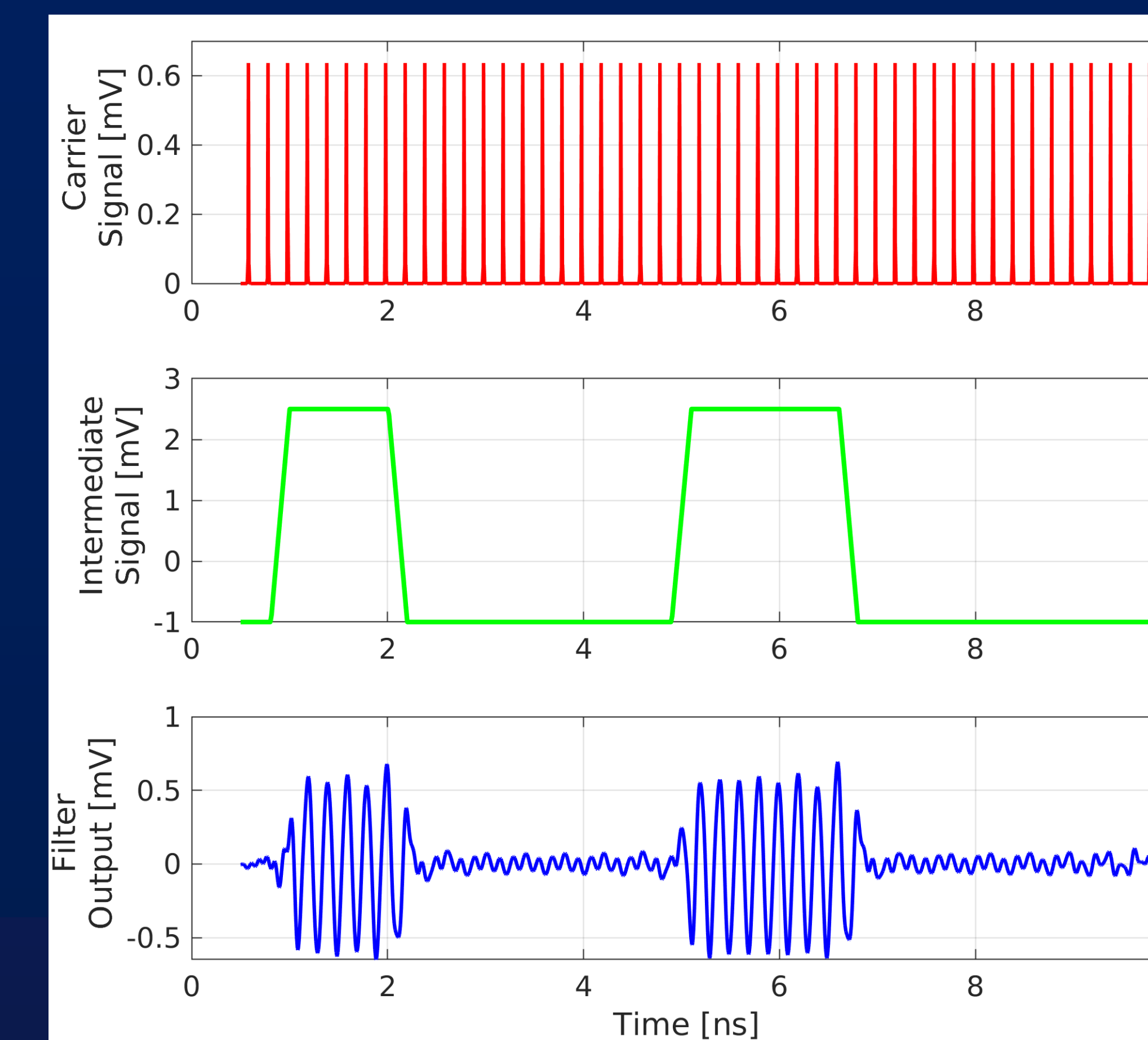


We cannot directly connect the circuit output to qubits since the signal needs to be attenuated to avoid carrying thermal noise between stages. Therefore, the signal is amplified with a compact on-chip superconductor amplifier stage\* before attenuating it. Gain is over 20dB for frequencies below 10GHz.

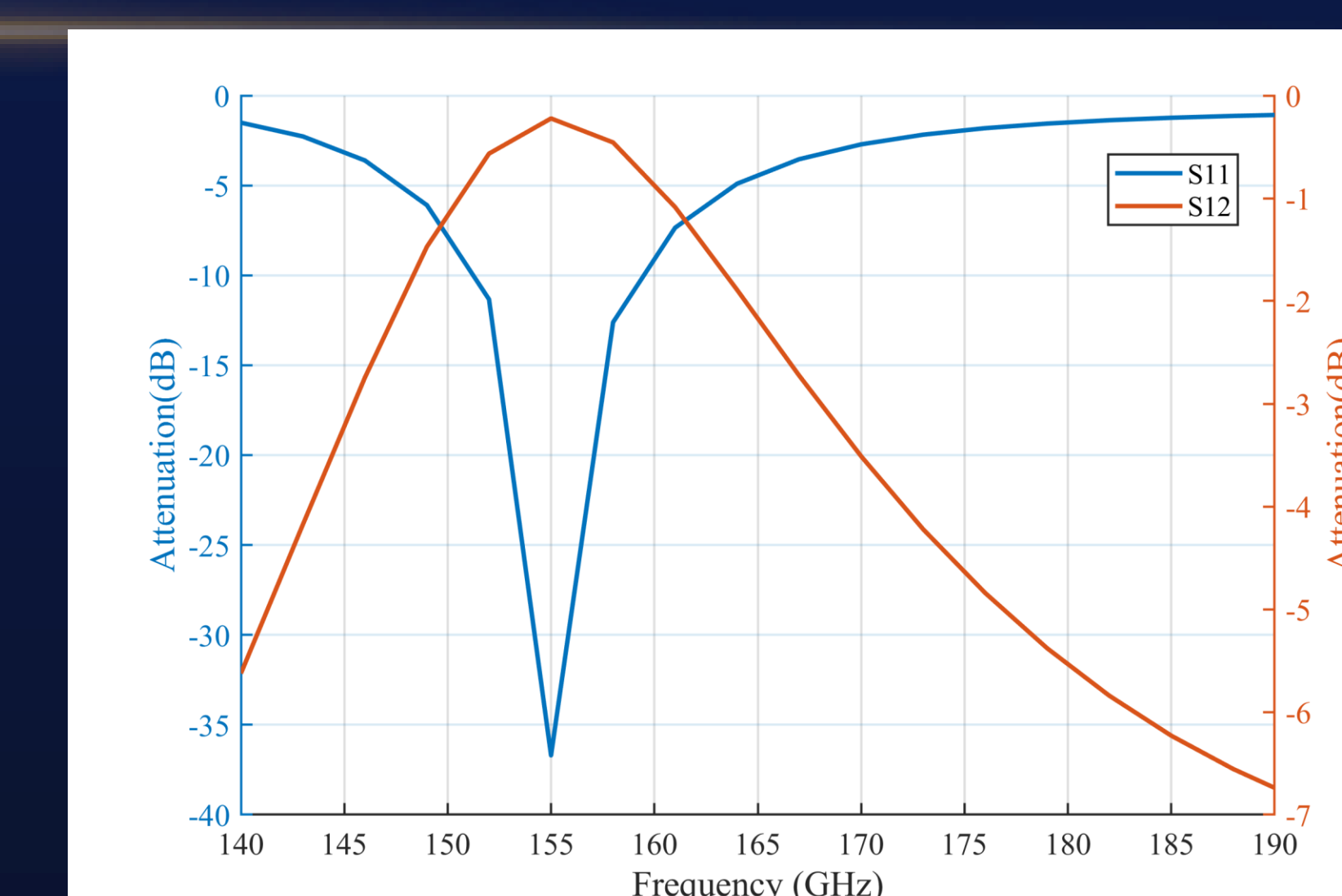


The transition lines between the chips can be designed to carry any specific frequency or pulse between stages. Here the stage is designed for 155GHz frequency, for SFQ pulse propagation, but it can be modified for other desired frequency from 1GHz up to 300GHz.

\*Razmkhah et al 2021 Supercond. Sci. Technol. 34 045013



The carrier signal is generated from junction oscillations. The IF signal comes from a room-temperature instrument. The driver combines the two frequencies and amplifies the resulting signal. After amplification, the signal is filtered for desired band and attenuated to match the noise level of the qubit, before it is transmitted to the ~mK stage via a transmission line that also acts as an impedance match.



## Result and Conclusion

In this work, we have designed and simulated a cryogenic driver stage for generating in-situ signals needed to drive superconductor quantum bits. The carrier frequency is produced by applying a DC current to the circuit which is mixed with the intermediate signal. The output is amplified by about 20dB via quantum accurate amplifiers, filtered with a band-pass filter and attenuated to match the ~mK stage noise level.

All parts for the circuit have been simulated and fabricated separately to be tested in the near future. The whole structure will be fabricated and tested inside a dilution fridge.

## Acknowledgments

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- The circuits are fabricated in the clean room for analog-digital superconductivity (CRAVITY) of National Institute of Advanced Industrial Science and Technology (AIST).