Methods for Extending the Scanning Frequency Range of Flux-Driven Josephson Parametric Amplifiers Designed for Axion search Experiments

Jinmyeong Kim[1,2], **Minsu Ko**[1,2], Sergey V. Uchaikin[1], Boris I. Ivanov[1], Arjan F. van Loo[3,4], Yasunobu Nakamura[3,4], Çağlar Kutlu[1,2], Seonjeong Oh[1], Violeta Gkika[1], Andreit Matlashov[1], Woohyun Chung[1], and Yannis K. Semertzidis[1,2]

[1] *Center for Axion and Precision Physics Research, IBS, Daejeon 34051, Republic of Korea*
[2] *Department of Physics, KAIST, Daejeon 34051, Republic of Korea*
[3] *RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351–0198, Japan*
[4] *Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*

CAPP Center for Axion and Precision Physics Research · KAIST · APPLIED PHYSICS THE UNIVERSITY OF TOKYO · RIKEN · RIKEN QUANTUM COMPUTING

Abstract

The axion, a hypothetical particle proposed to solve the strong CP problem, is a promising candidate for dark matter. To detect axion-induced photons via the inverse Primakoff effect, axion haloscope experiments require highly sensitive amplifiers at millikelvin temperature. Flux-Driven Josephson Parametric Amplifiers (FDJPAs) are a compelling option due to their noise levels, which approach the quantum noise limit. However, the tunable range of FDJPAs is limited, and increasing the scanning frequency range requires complex cryogenic assemblies with multiple single JPAs, as well as careful tuning of the RF circuit and DC flux bias. To address this challenge, we have developed several approaches to extend the tunable range of FDJPAs while maintaining low noise levels. Our measurements indicate that the total system noise with JPA as the first-stage amplifier is less than 200 mK in the frequency range from 1.19 GHz to 1.5 GHz.

Introduction

The axion, a theoretical particle proposed to resolve the strong CP problem within the Standard Model, is a potential dark matter candidate generated in the early universe. Axion haloscope experiments aim to directly identify axions in the dark matter halo of our galaxy by exploiting the fact that axions transform into photons when exposed to an external magnetic field. Since it is predicted that the conversion power of the axion is extremely low, approximately 10^{-22} W[1], haloscope is required to be very sensitive.

The scanning speed of haloscope experiments depends on the strength of external magnetic field and system noise temperature[2].

$$\frac{df}{dt} \sim \frac{B_0^4}{T_{sys}^2}$$

Therefore, operation of low-noise amplifiers under strong magnetic field is one of the crucial challenges in haloscope experiments. Here, Josephson parametric amplifier (JPA) is a compelling option due to its intrinsic noise approaching quantum noise limit. The working frequency range of JPAs around 1~2 GHz is limited (usually <60 MHz)[3]. Replacing the amplifier necessitates warming up the fridge, which is time-consuming and requires a significant amount of expensive liquid helium. To address this issue, we developed methods for extending the scanning frequency range of JPAs based on multiple connection of JPAs.

Flux-Driven Josephson Parametric Amplifier

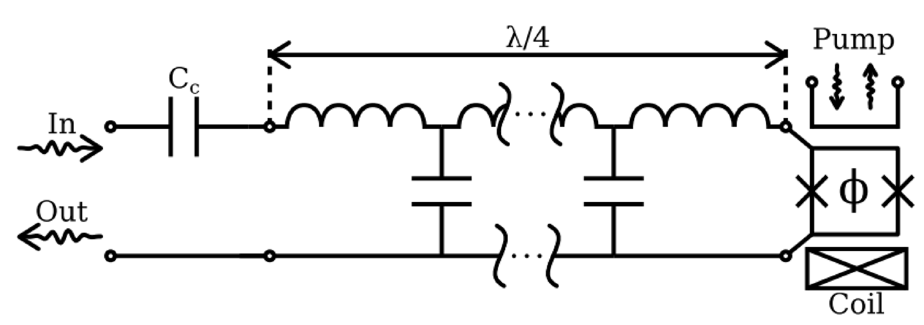

Fig. 1. Equivalent circuit diagram of a flux-driven JPA[4]

- Superconducting λ/4 resonator grounded via a DC-SQUID[5] .
- DC flux through a superconducting coil tunes the central frequency of the resonator.
- The pump line couples an AC flux to the loop. When the AC flux frequency is twice the resonance frequency, the JPA amplifies the signal (three wave mixing).

JPA Measurement Chain

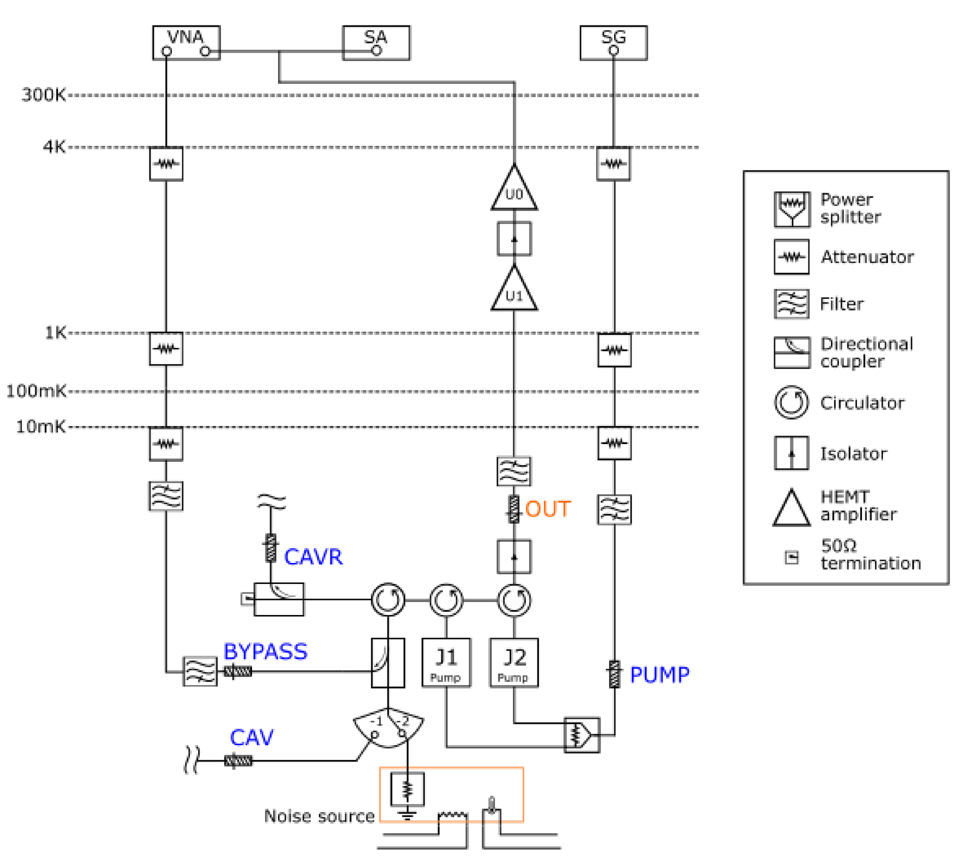

Fig. 2. RF schematics of JPA measurement chain

- Setup for measuring tuning frequency, gain, and noise.
- J1, J2 blocks include 3 JPAs respectively as shown in Fig. 3.

Parallel – Series Connection of 6 JPAs

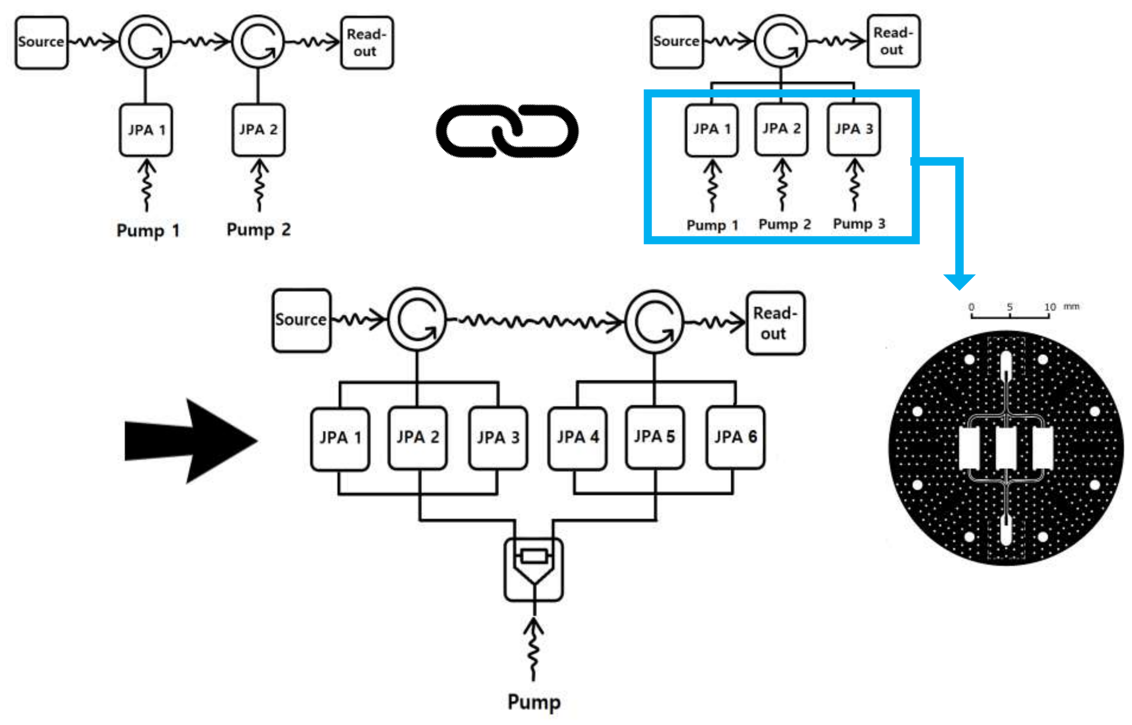

Fig. 3. Schematics of Parallel – Series connection of JPAs

- Two 3-JPA assemblies are connected in series.
- 3 JPAs are attached on a PCB sharing input and pump line.
- A superconducting-wire coil is wound around the holder to provide a DC magnetic flux.
- The PCB and coil are placed inside to a magnetic shield to reduce the effect of external magnetic fields.

Overlapping Problem

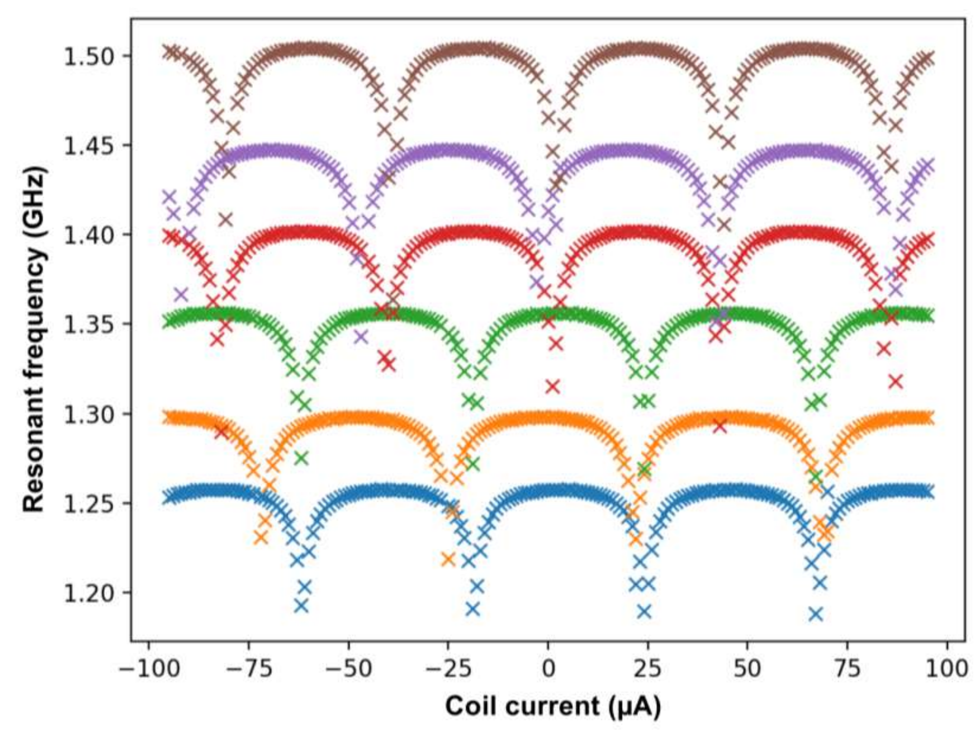

Fig. 4. Resonant frequency of 6 JPAs

- Working frequency ranges of JPAs overlap each others.
- It causes the interference between JPAs which yields additional noise.

GaAs Schottky Diode Bias Circuit

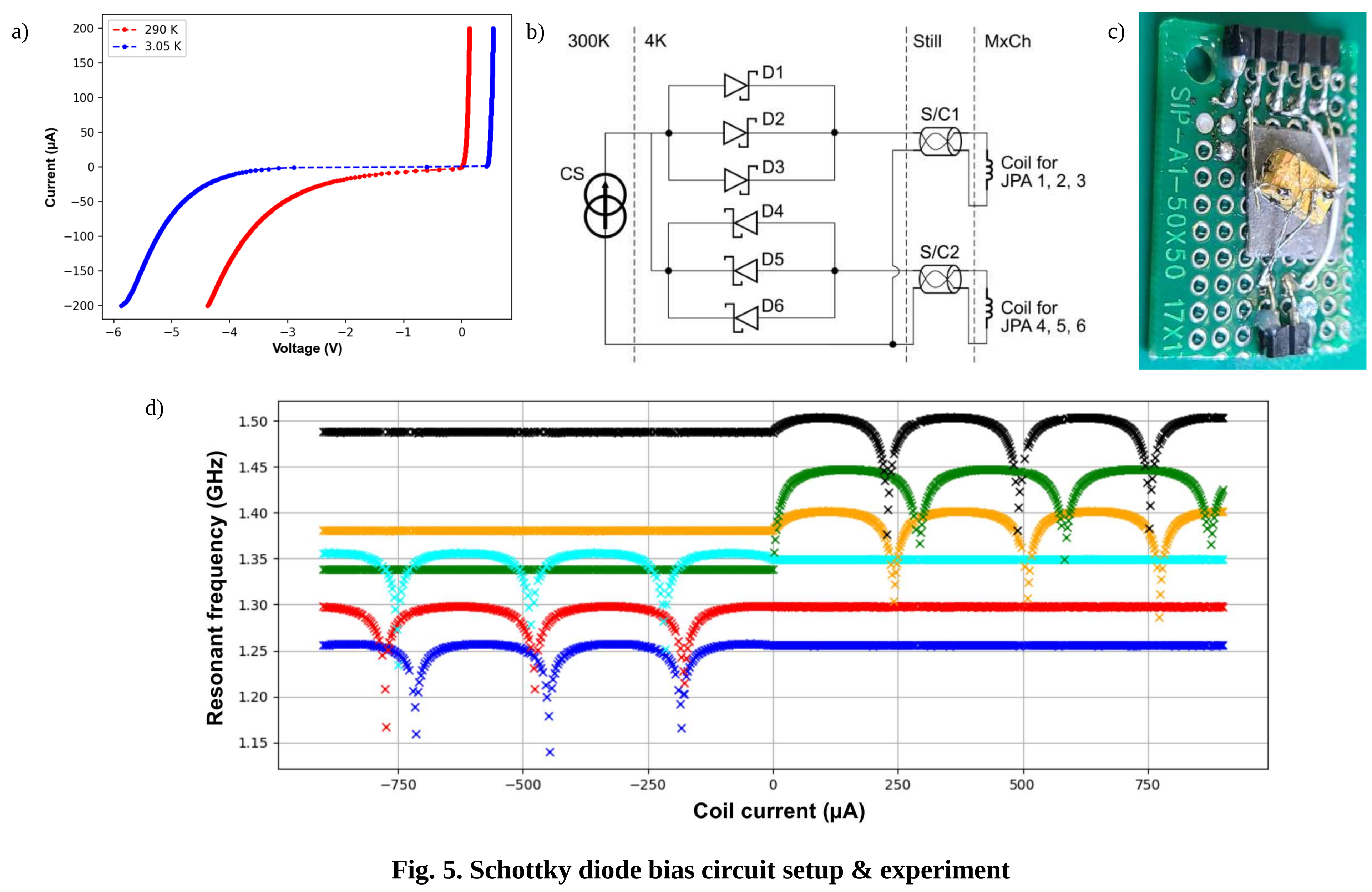

Fig. 5. Schottky diode bias circuit setup & experiment

- a) I – V curve of a GaAs Schottky diode (SMS7630-040LF) at 290 K and 3.05 K.
- b) DC schematics of Schottky diode bias circuit for flux bias for the 6 JPAs.
- c) A picture of 6 Schottky diodes soldered on a PCB.
- d) Flux sweep results of the 6 JPAs with the Schottky diode bias circuit.

Noise Temperature Measurement

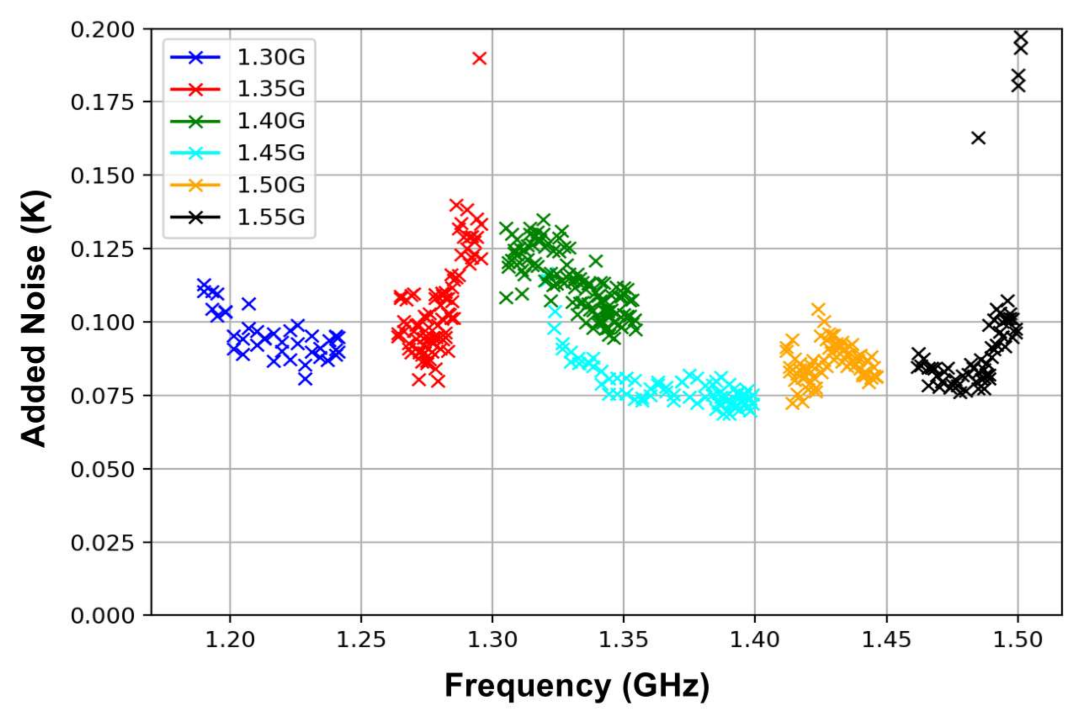

Fig. 6. Added noise of amplifiers as function of frequency

- Added noise is below 200 mK between 1.19 GHz and 1.5 GHz.

Conclusion

- An RF chain with parallel – series connection of 6 JPAs as the first amplifier has been experimentally studied with the GaAs Schottky diode bias circuit.
- The resonant frequency of JPAs are well separated avoiding the overlapping problem.
- We have characterized the measurement chain with JPA added noise temperature between 60 mK and 200 mK at frequencies between 1.18 GHz and 1.5 GHz.

Acknowledgements

This work is supported in part by the Institute for Basic Science (IBS-R017-D1), JST ERATO (Grant No. JPMJER1601) and JSPS KAKENHI (Grant No. 22H04937). Arjan F. van Loo was supported by a JSPS postdoctoral fellowship.

References
[1] C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, et al., *Physical Review Letters* **1998**, *80*, 2043.
[2] D. Kim, J. Jeong, S. Youn, Y. Kim, Y. K. Semertzidis, *Journal of Cosmology and Astroparticle Physics* **2020**, *2020*, 066.
[3] J. Kim, O. Kwon, Ç. Kutlu, et al., Phys. Rev. Lett. 130, 091602 (2023).
[4] Ç. Kutlu, A. F. van Loo, S. V. Uchaikin, *et al.*, Supercond. Sci. Technol. **34**, 085013 (2021).
[5] T. Yamamoto, K. Inomata, M. Watanabe, *et al.*, Appl. Phys. **93**, 042510 (2008)