The 2nd IBS-KIAS

Joint Workshop at High 1

Jan.7(Sun.) - Jan. 13(Sat.),2018

High 1 Resort

SQUID Amplifiers for Axion Search Experiments

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기초과학연구원

CAPP

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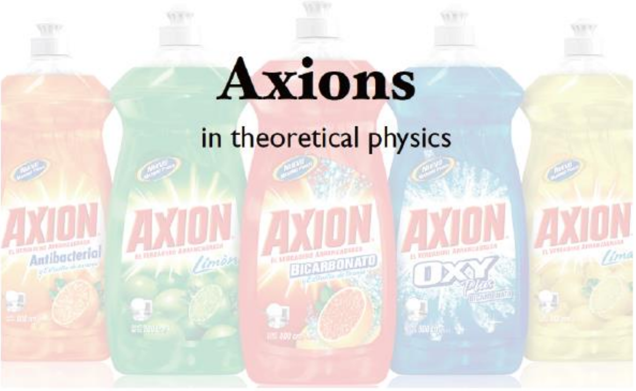
Outline

- ❑ **Axions**
- ❑ **Axions detection**
- ❑ **CULTASK overview**
- ❑ **Microstrip SQUID Amplifiers**
- ❑ **Resonant MSAs**
- ❑ **Wideband Microwave SQUID Amplifiers**

Axions



Named by Frank Wilczek after a detergent because they "cleaned-up" a messy problem in strong interactions (QCD), also known as the Strong CP-problem.

A theory parameter θ_{QCD} describing this effect is too close to zero…

Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), *a*(x)/*fa*.
It goes to zero naturally…

Wilczek and Weinberg: axion particle (1977)

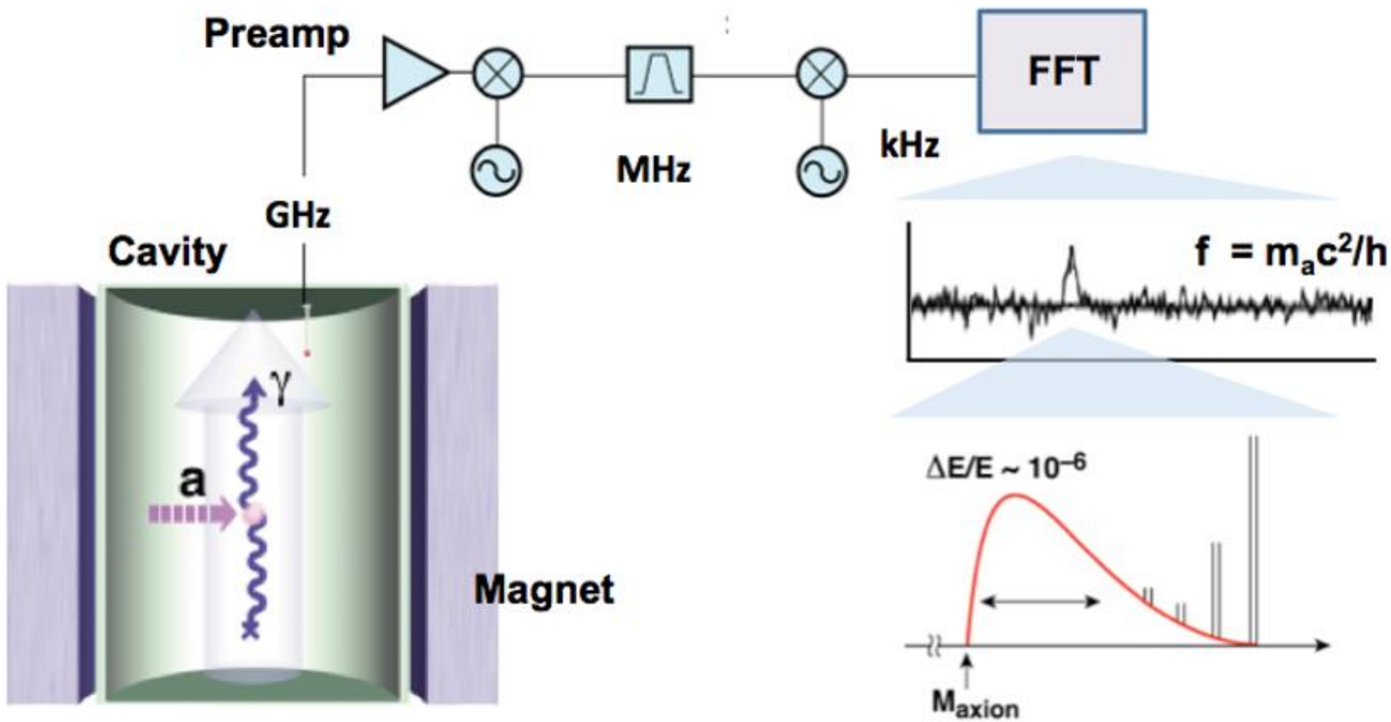
Jihn E. Kim: hadronic axion KSVZ (1979)

If the axion exists, it can be considered as a dark matter candidate

Axions Detection

The current favored technique for detecting dark-matter axions is to convert Milky Way halo axions into microwave photons.

P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983)



Axions resonantly convert to a quasi-monochromatic microwave signal in a high-Q cavity in a strong magnetic field; the signal is extracted from the cavity by an antenna, amplified, mixed down to the audio range, and the power spectrum calculated by a FFT.

Axions Detection

PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 40, NUMBER 10 — 15 NOVEMBER 1989

Results of a laboratory search for cosmic axions and other weakly coupled light particles

W. U. Wuensch,* S. De Panfilis-Wuensch,† Y. K. Semertzidis,
J. T. Rogers, and A. C. Melissinos
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

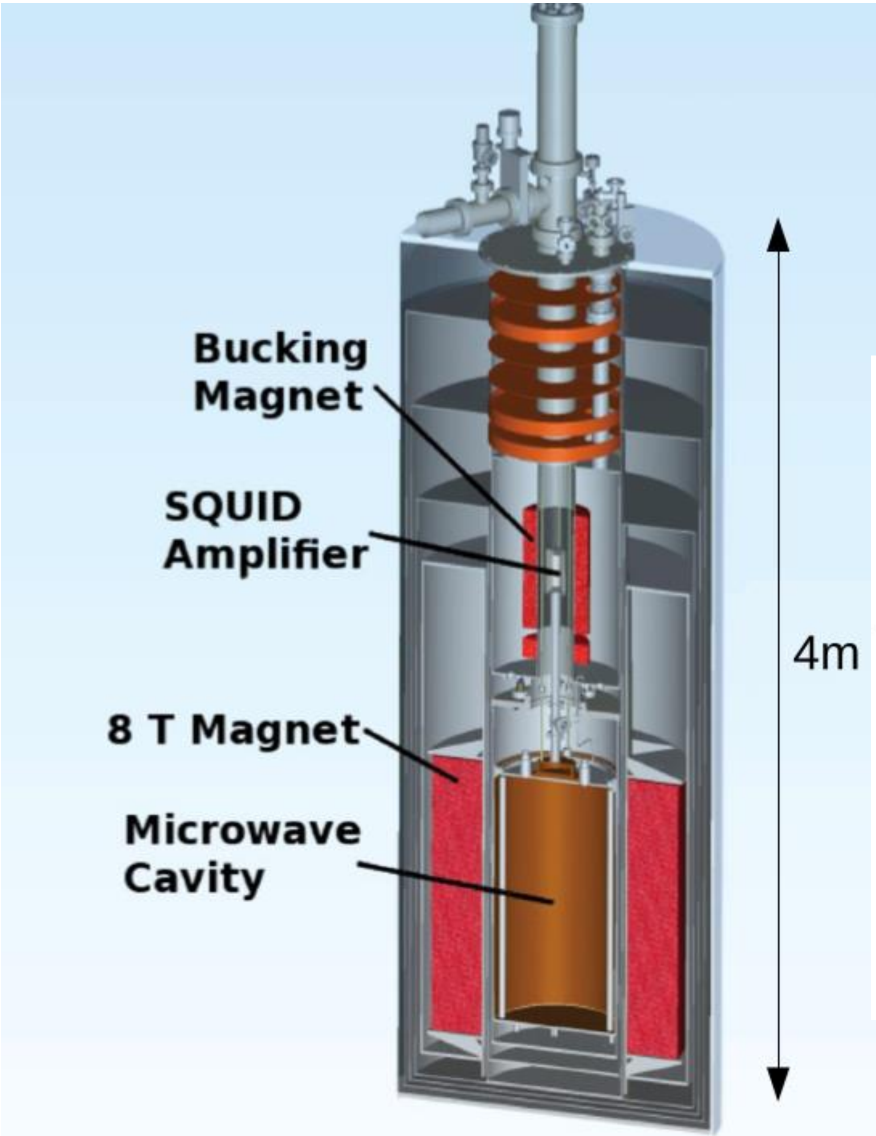
H. J. Halama, B. E. Moskowitz, and A. G. Prodell
Brookhaven National Laboratory, Upton, New York 11973

W. B. Fowler and F. A. Nezrick
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 8 June 1989)

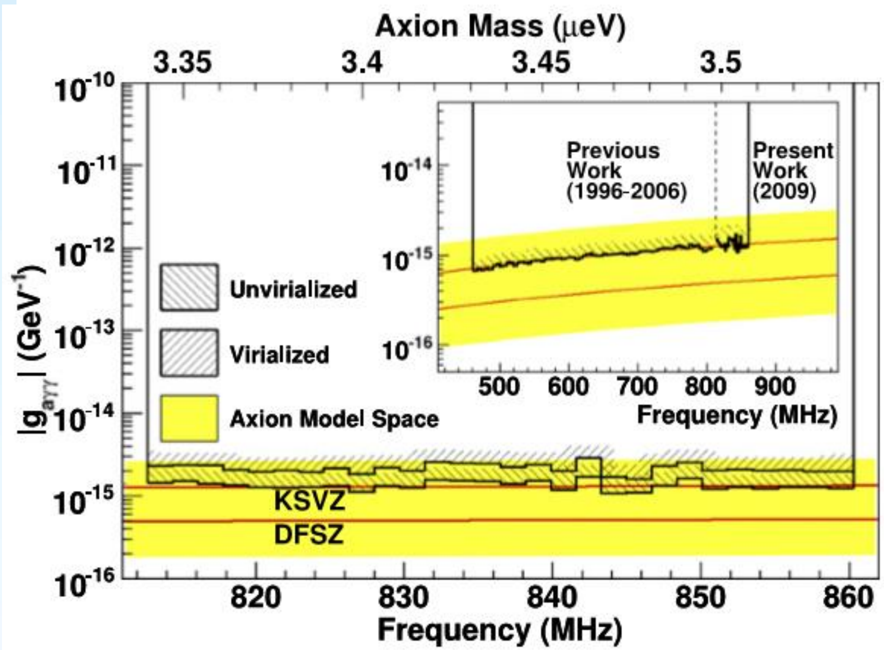
RBF: Rochester-Brookhaven-Fermi lab collaboration

S. DePanfilis et al., Phys. Rev. Lett. 59, 839 (1987);
W. Wuensch et al., Phys. Rev. D40, 3153 (1989);
C. Hagmann et al., Phys. Rev. D42, 1297 (1990).

Axions Dark-Matter eXperiment (ADMX)



University of Washington, Seattle, WA, USA
2010 – Present

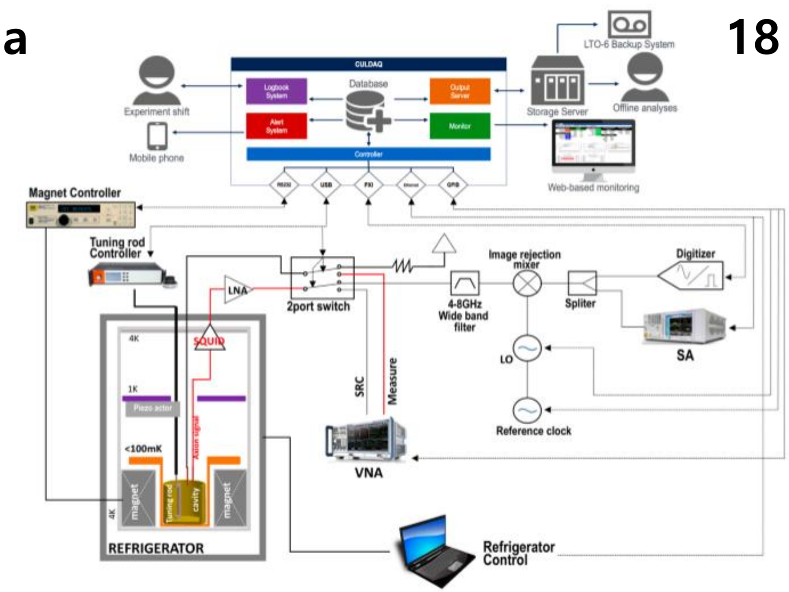


1995 – 2004 HEMT
2007 – 2009 SQUID

CULTASK since January 2017:
CAPP Ultra-Low Temperature Axion Search in Korea

8 Tesla

18 Tesla



CULTASK

Axion detection scheme

Axion Conversion Power (~10^{-24}W): $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

Signal to Noise Ratio: $SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$

Scan rate: $\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$

Cryogenics

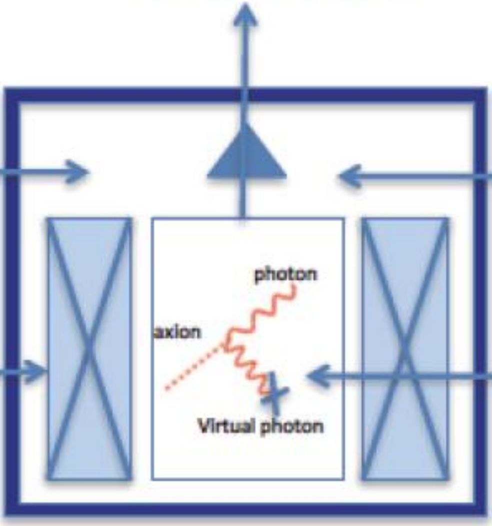
<50mK, Collaboration with KAIST

High Field SC Magnet

12T, 18T, 25T and then 35T

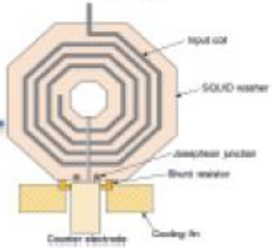
LTS & HTS Technology

To RF Receiver



Quantum-noise Limited Amplifier

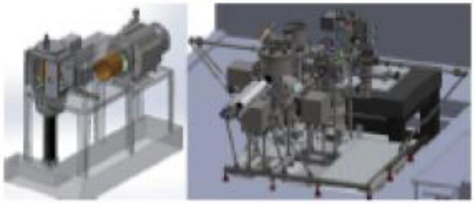
SQUID, JPA or Single photon detectors



High Q Tunable Cavity

Superconducting Coating

Collaboration with KAIST



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Refrigerators and SC magnets

Refrigerators					Magnets			
Manufacturer	Model	Installa-tion	Usage	Location	Strength & Bore size	Material	Manufacturer	Delivery
BlueFors (BF3)	LD400	2016	RF and Cavity test	RF room				
BlueFors (BF4)	LD400	2016	JPA & RF chain test	RF room				
Janis	^{3}He	2017	Magnet test		9T 12 cm	NbTi	Cryo-Magnetics	2017
BlueFors (BF5)	LD400	2017	Axion Exp DAQ & RF	LVP 6	8T 12 cm	NbTi	AMI	2016
BlueFors (BF6)	LD400	2017	Axion Exp Large bore	LVP 7	8T 16.5 cm	NbTi	AMI	2017
Oxford	Kelvinox	2017	Axion Exp.	LVP 4	18T 7.5 cm	HTS	SuNAM	2017
Leiden	DRS1000	2018	Axion Exp	LVP 3	12T 32 cm	Nb_3Sn	Oxford	2019
			Axion Exp	LVP5	25T 10 cm	HTS	BNL	2019

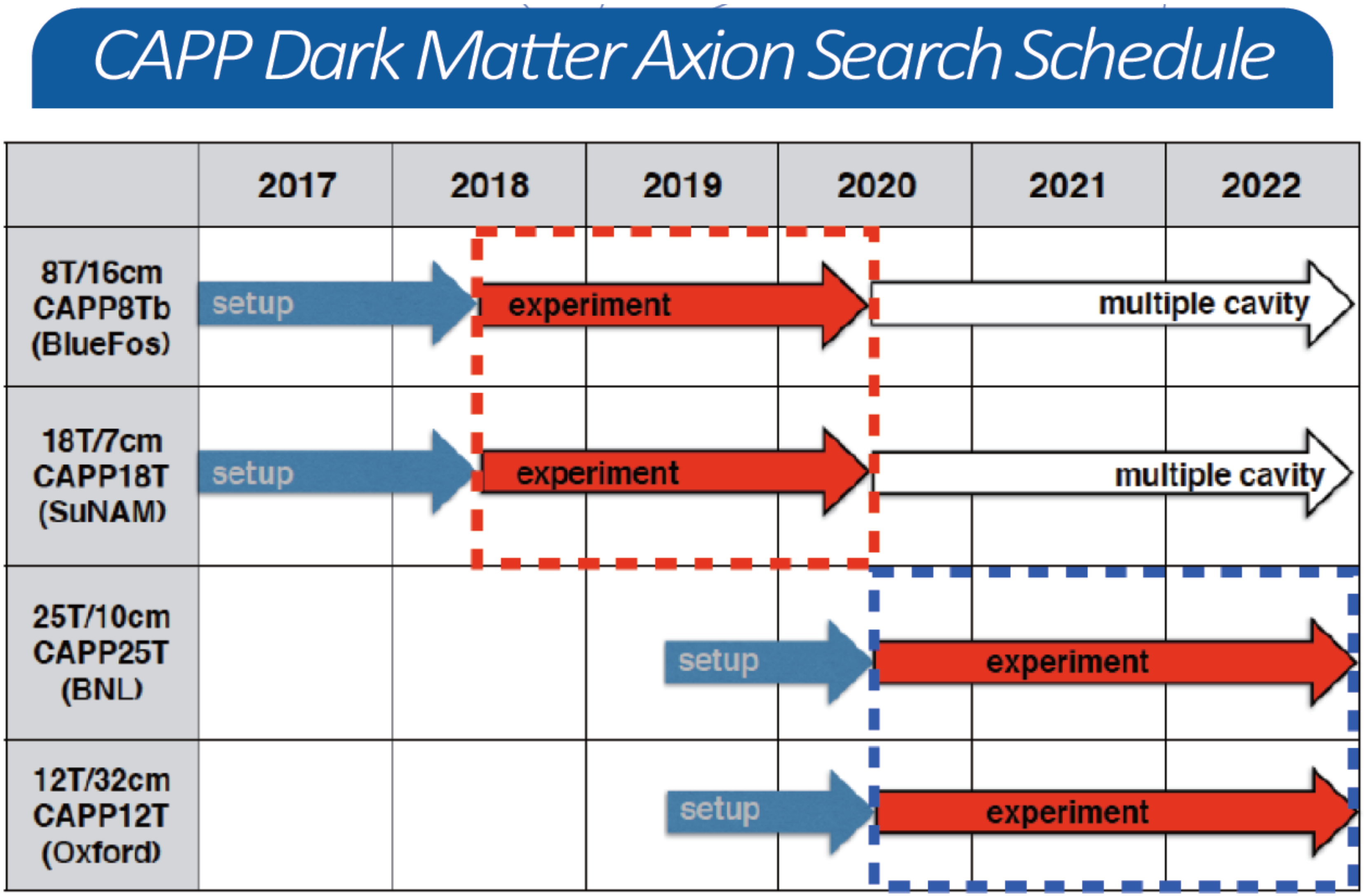
MinAxion 2-2.5 GHz

CAPP8TB 1.5-2 GHz

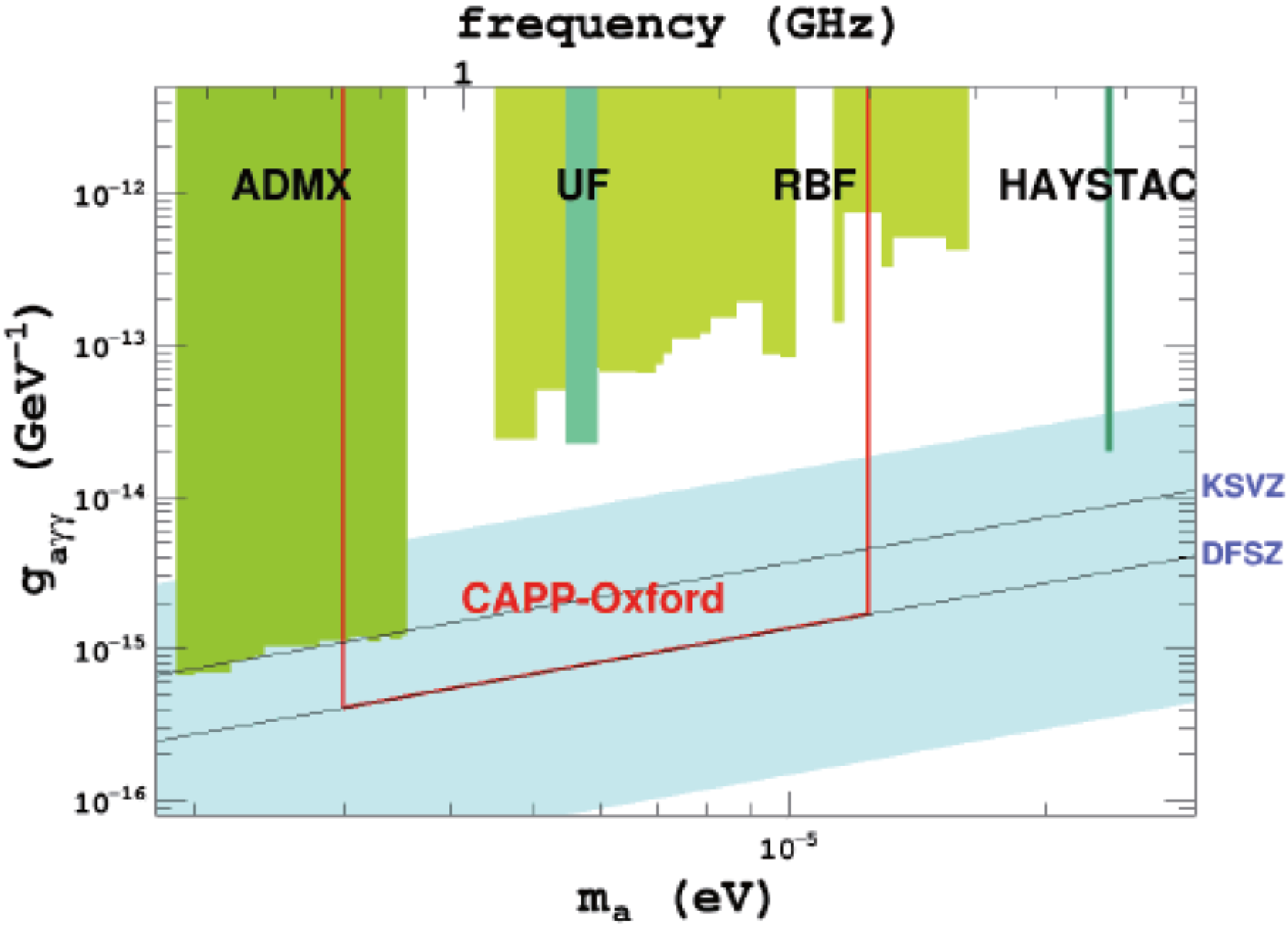
CAPP18T 3-6 GHz

Oxford 0.8-3 GHz

CULTASK


CAPP Dark Matter Axion Search Schedule
2017
2018
2019
2020
2021
2022
8T/16cm
CAPP8Tb
(BlueFos)
setup
experiment
multiple cavity
18T/7cm
CAPP18T
(SuNAM)
setup
experiment
multiple cavity
25T/10cm
CAPP25T
(BNL)
setup
experiment
12T/32cm
CAPP12T
(Oxford)
setup
experiment

CULTASK

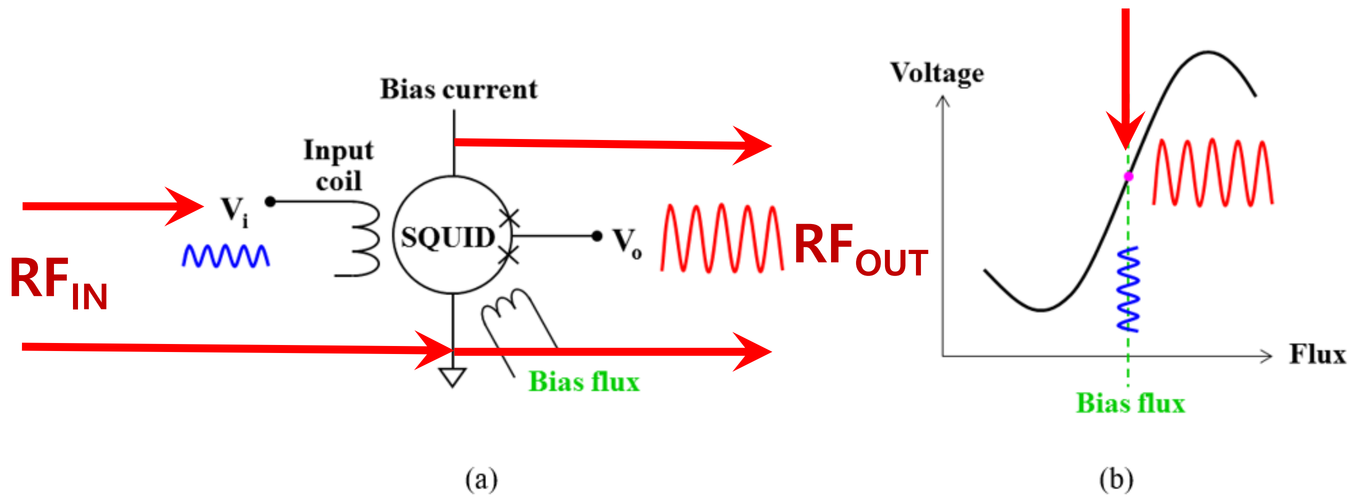


B ≈12 T, T_P<0.1 K, Ø320 mm, SQUID amplifiers

Microstrip SQUID Amplifier (MSA)

Superconducting Quantum Interference Device (SQUID)
Input RF modulates input flux in SQUID loop
It produces RF Voltage on SQUID leads

Working Point: I_W and Φ_{DC}



Michael Mück, Marc-Oliver Andre, John Clarke, *Applied Physics Letters*, 72, 22, p. 2885 (1998)

MSA – the near-quantum-limited Amplifier

IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. 23 (2010) 093001 (11pp) doi:10.1088/0953-2048/23/9/093001

TOPICAL REVIEW **2010**

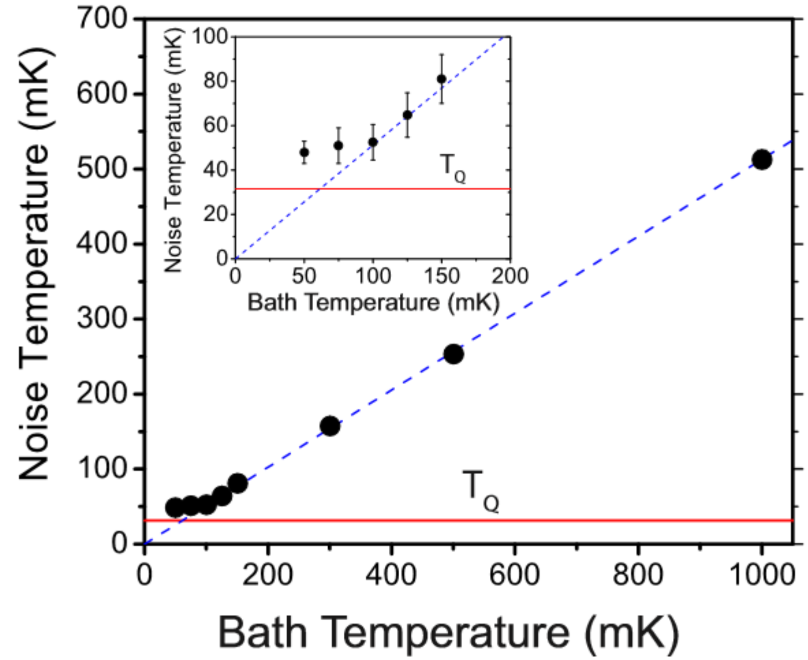
Radio-frequency amplifiers based on dc SQUIDs

Michael Mück[1] and Robert McDermott[2]

[1] Institut für Angewandte Physik, Justus-Liebig-Universität Gießen, D-35392 Gießen, Germany
[2] Department of Physics, University of Wisconsin, Madison, WI 53706, USA

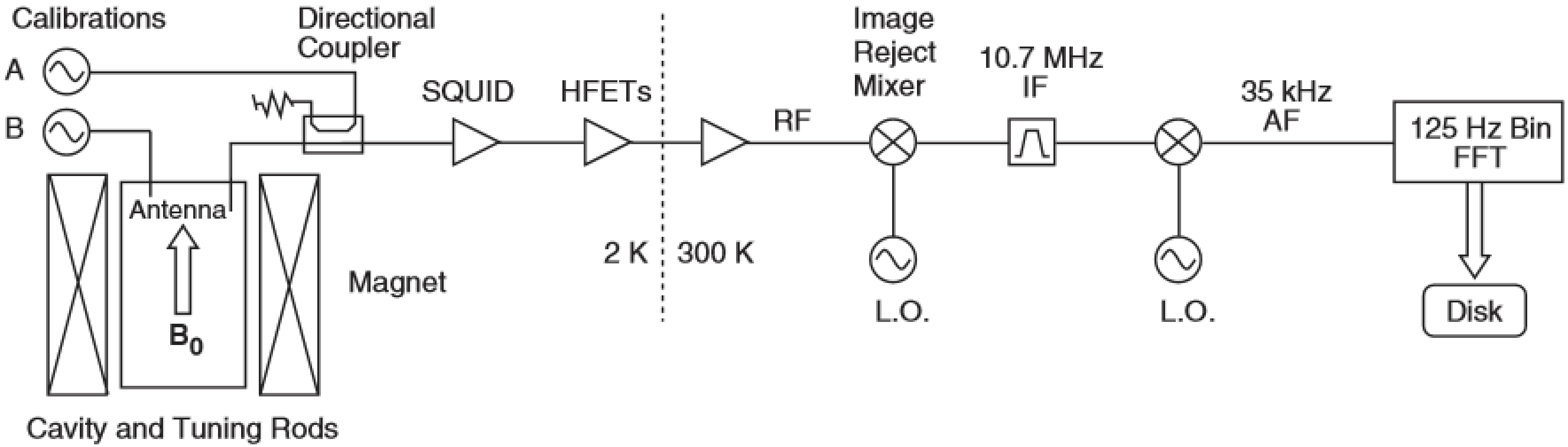
$$T_Q = hf/k_B$$

≈ 50 mK at 1 GHz



Noise temperature of a SQUID amplifier as a function of bath temperature T.
Red line indicates T_Q, the quantum noise temperature at 700 MHz.
Dotted line has a unity slope, indicating that T_A~T in the classical regime.

MSA in Axion Search Experiments



MSA: T ≈ 30 mK, T_N ≈ 50 mK, Gain ≈ 20 dB

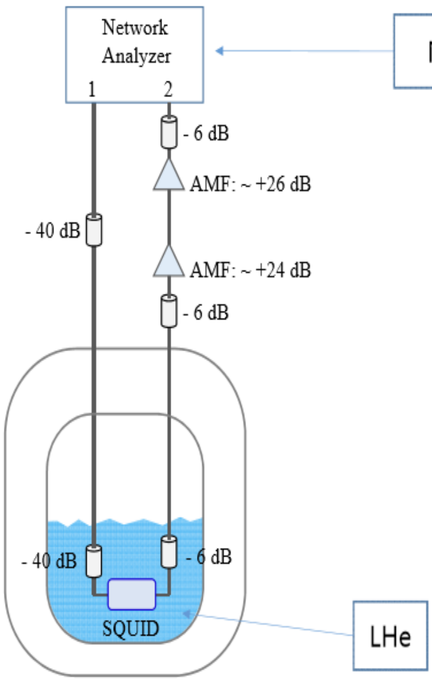
HFET: T ≈ 2 K, T_N ≈ 1.0 K, Gain ≈ 40 dB

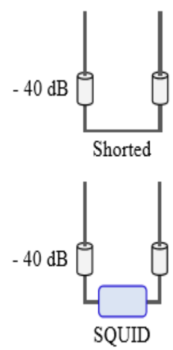
S.J. Asztalos et al. "SQUID-Based Microwave Cavity Search for Dark-Matter Axions." Phys. Rev. Lett., 104, 041301 (2010)

MSAs gain and noise measurements at CAPP

Measurement configuration

Network Analyzer Power : -30 dBm



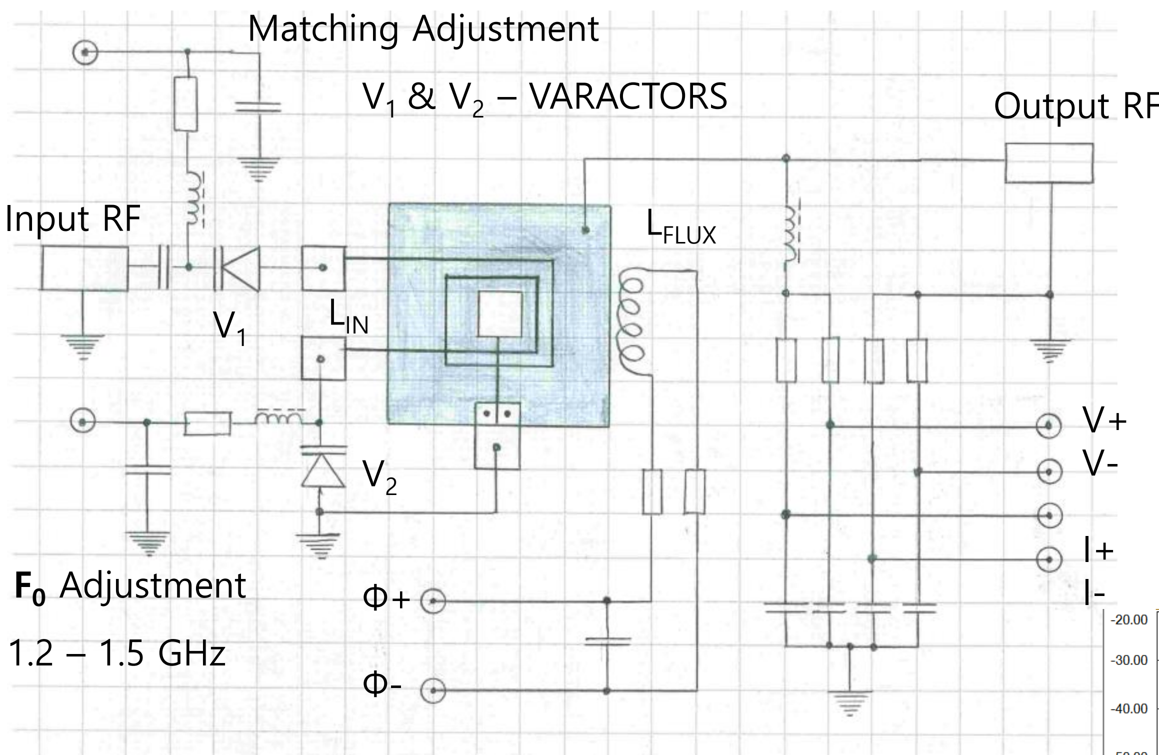


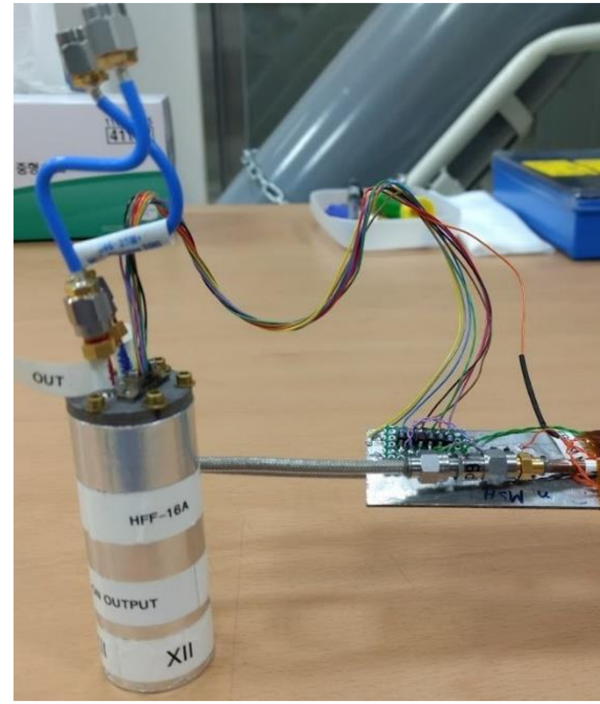
Gain = S_{21}(SQUID)-S_{21}(shorted)

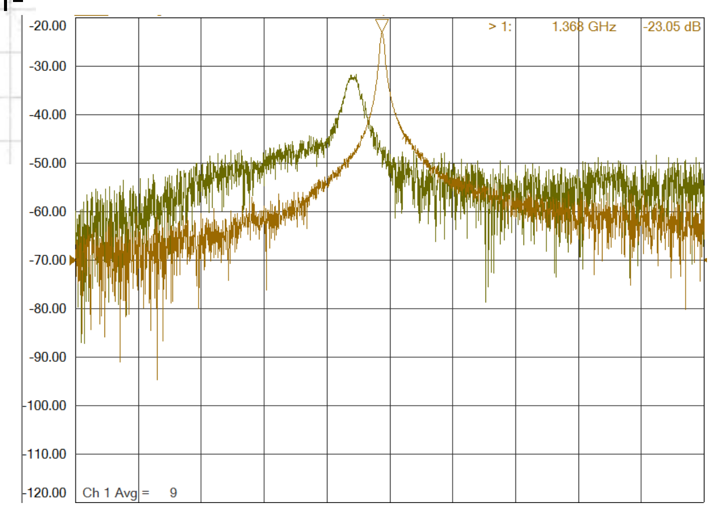
Short(CT) = Cryo Temp S_{21}(shorted)
Short(RT) = Room Temp S_{21}(shorted)

MSA gain measurement in BlueFors™ dilution refrigerators down to 10 mK

MSA from UC Berkeley, USA







5.43 V, F_0=1368 MHz

F_0 adjustable in the range 1.2–1.5 GHz, ΔF = 2.5–5.8 MHz, Gain = 24 dB

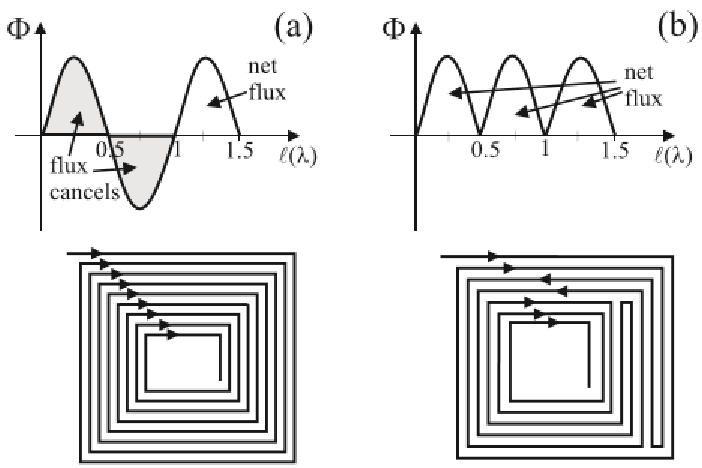
MSA from ezSQUID, Germany

APPLIED PHYSICS LETTERS 111, 042604 (2017)

Microstrip superconducting quantum interference device amplifier: Operation in higher-order modes

Michael Mück,[1] Bernd Schmidt,[2] and John Clarke[3]
[1]*ez SQUID Mess- und Analysegeräte, 35764 Sinn, Germany*
[2]*Institut für Angewandte Physik der Justus-Liebig-Universität Giessen, 35392 Giessen, Germany*
[3]*Department of Physics, University of California, Berkeley California 94720-7300, USA*

(Received 30 May 2017; accepted 30 June 2017; published online 26 July 2017)



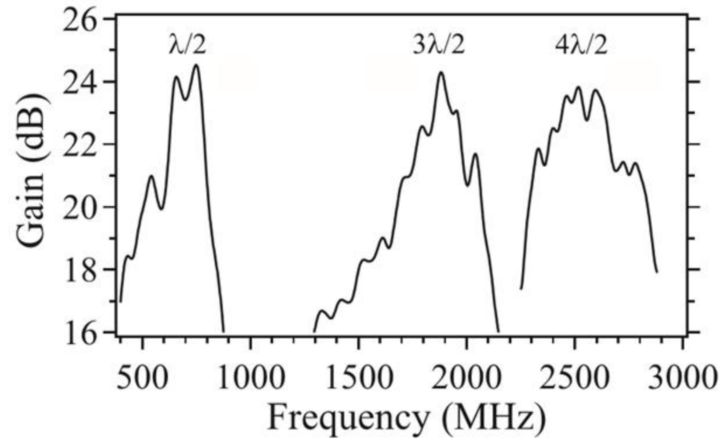
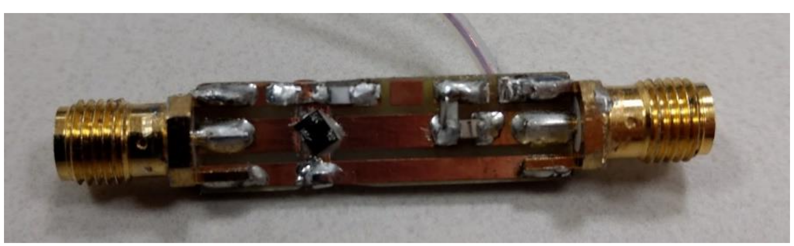
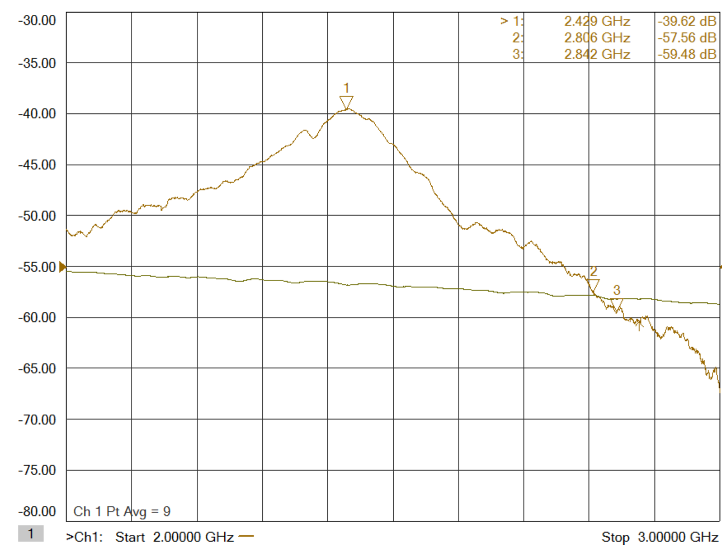


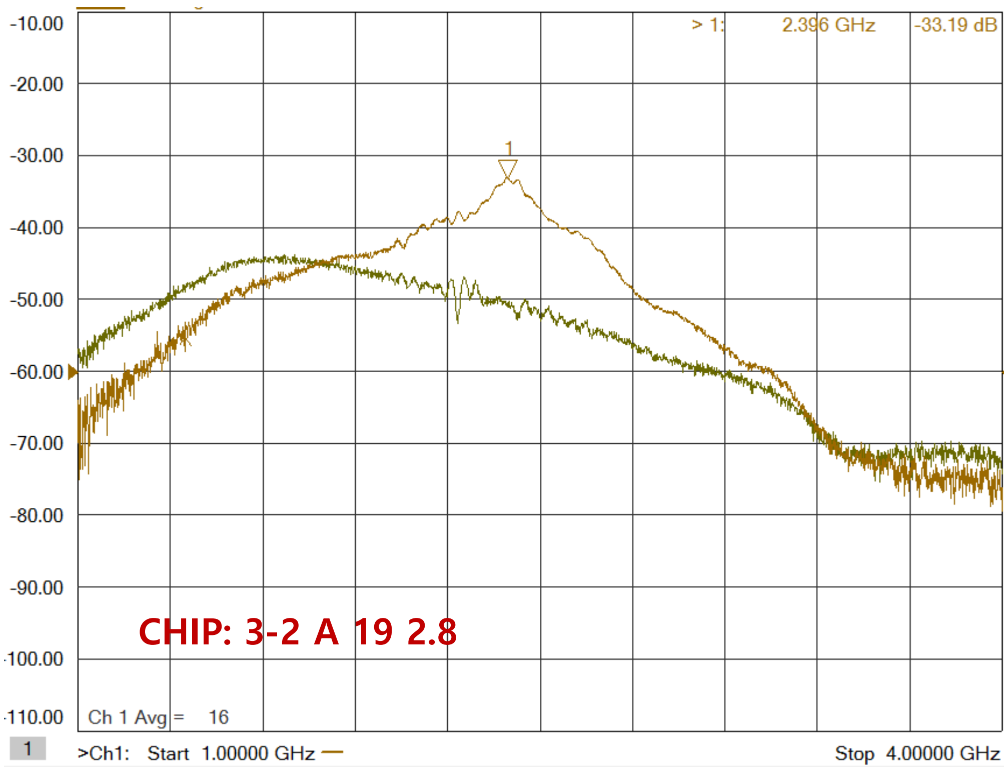
FIG. 4. Gain vs frequency for three microstrip SQUID amplifiers designed for operation in three different modes: $\lambda/2$ mode (left curve), $3\lambda/2$ mode (center curve), and $4\lambda/2$ mode (right curve).

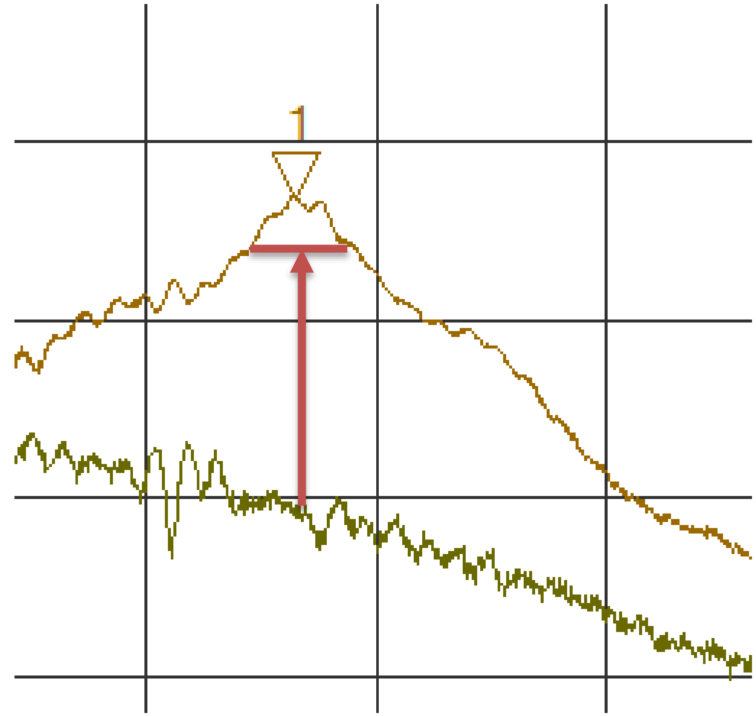




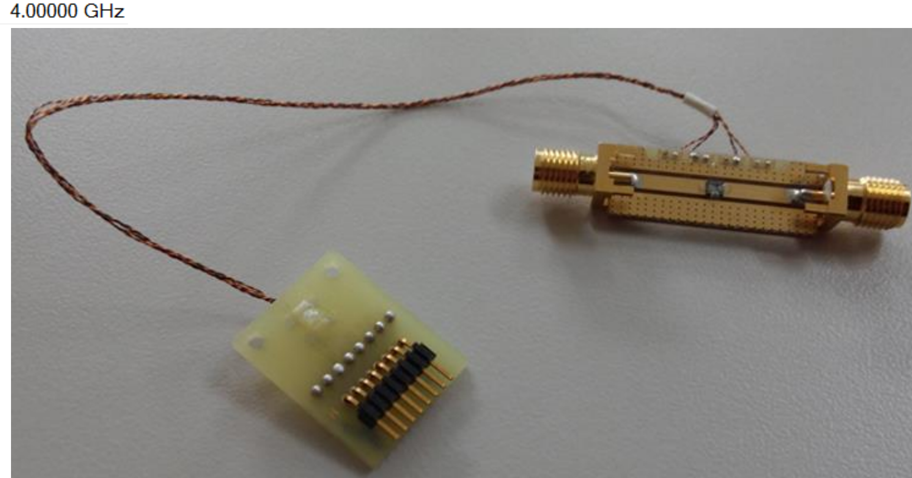
F_0 = 2.43 GHz, ΔF_{15dB} = 100 MHz, Gain = 17 dB

MSA from KRISS, Korea

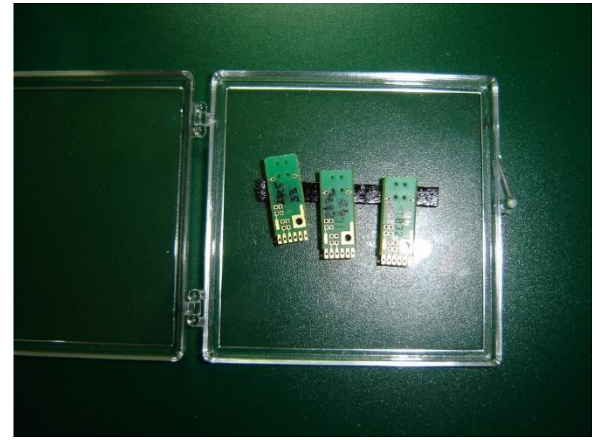


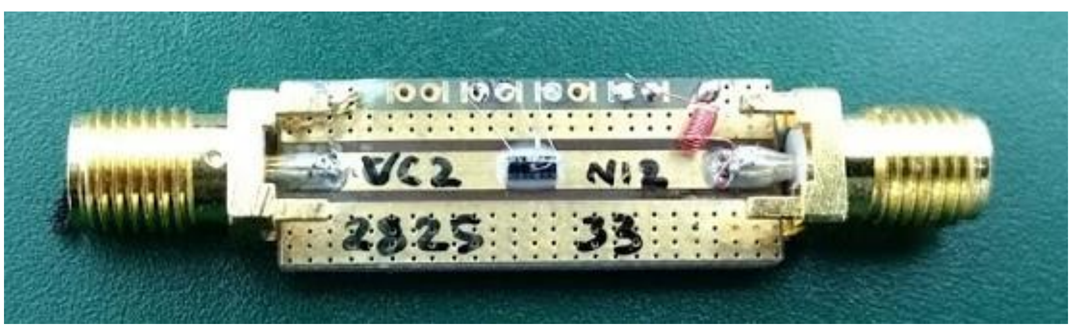


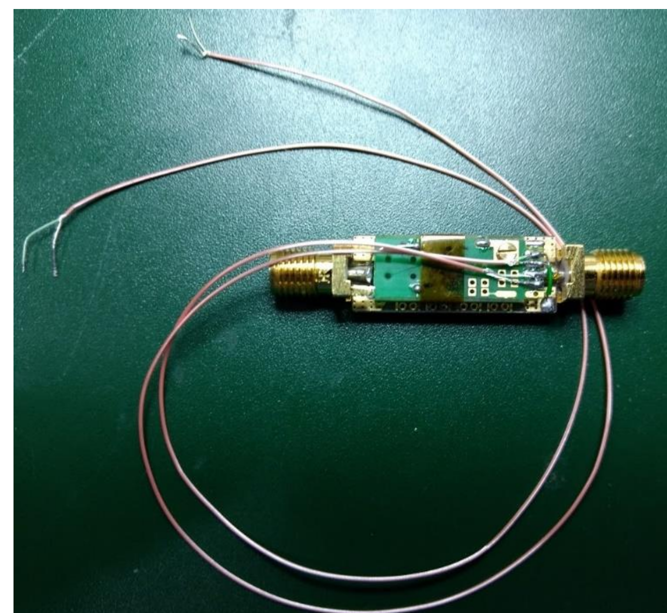
F_0 = 2.4 GHz, $\Delta F15_{dB}$ = 100 MHz,
Gain = 18 dB



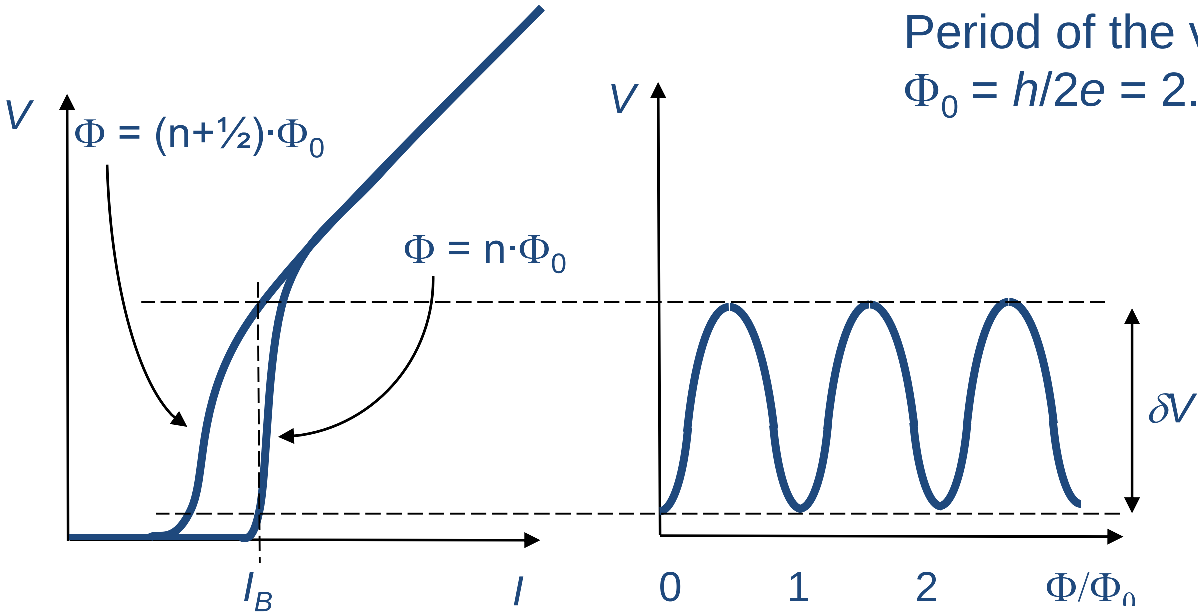
Leibniz Institute of Photonic Technology (IPHT), Jena, Germany







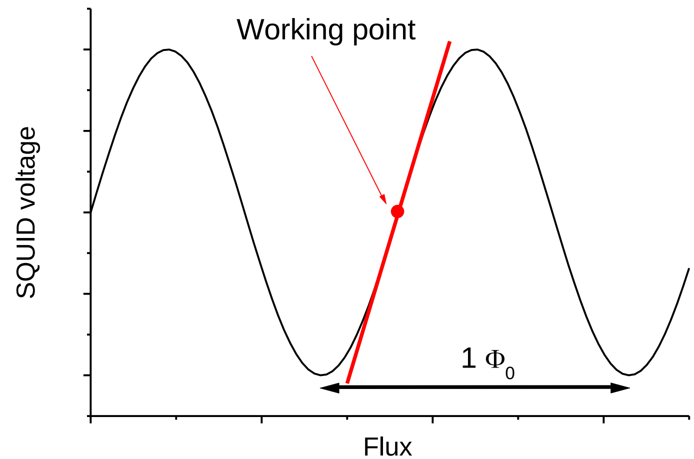
A SQUID Amplifier



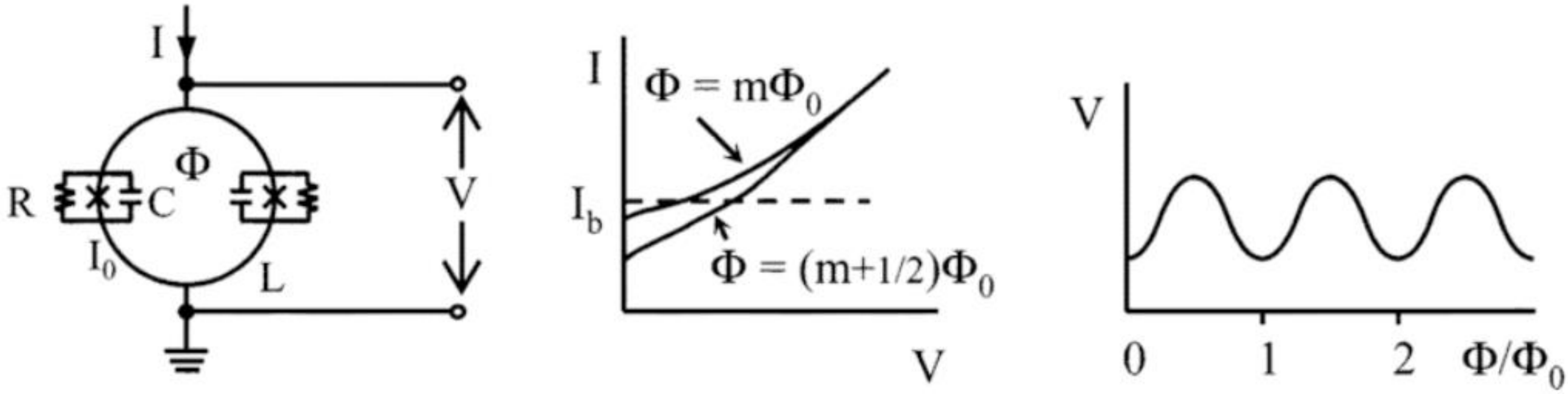
Period of the voltage-flux-dependence

$\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb

$$dV/d\Phi \approx R_{SH}/2L_0$$



A SQUID Amplifier



$dV/d\Phi \approx R_{SH}/2L_0$

McCumber-Stewart parameter $\beta_C = 2\pi I_0 R_{SH}{}^2 C_{JJ}/\Phi_0 < 1$

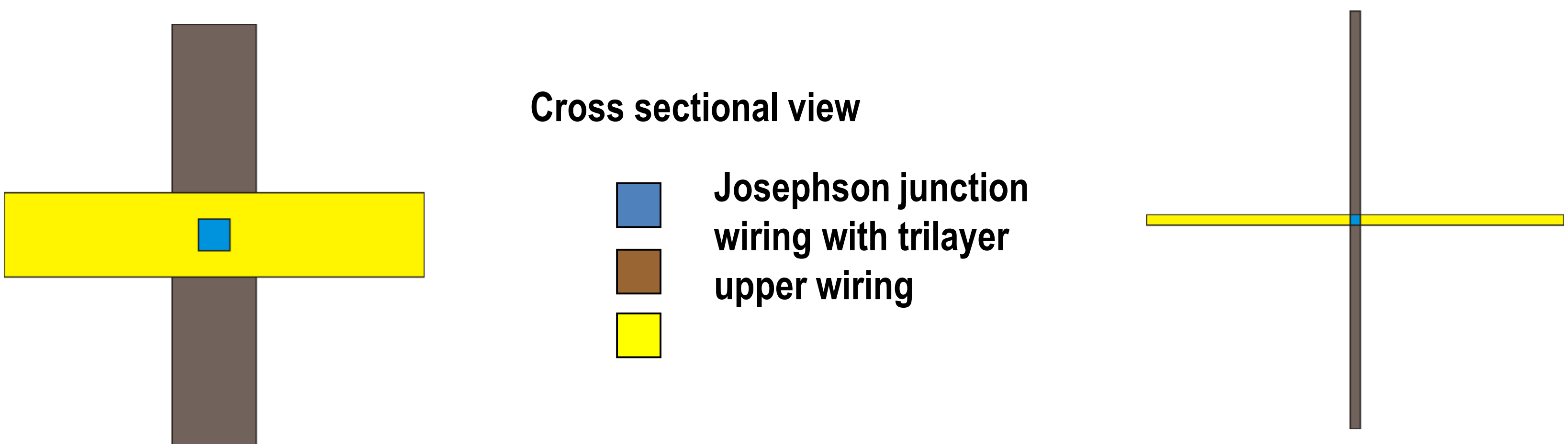
L_0 determines the coupling of the input signal to the SQUID

The most elegant way to increase the transfer function is
to decrease the junction capacitance

A small capacitance Josephson junction

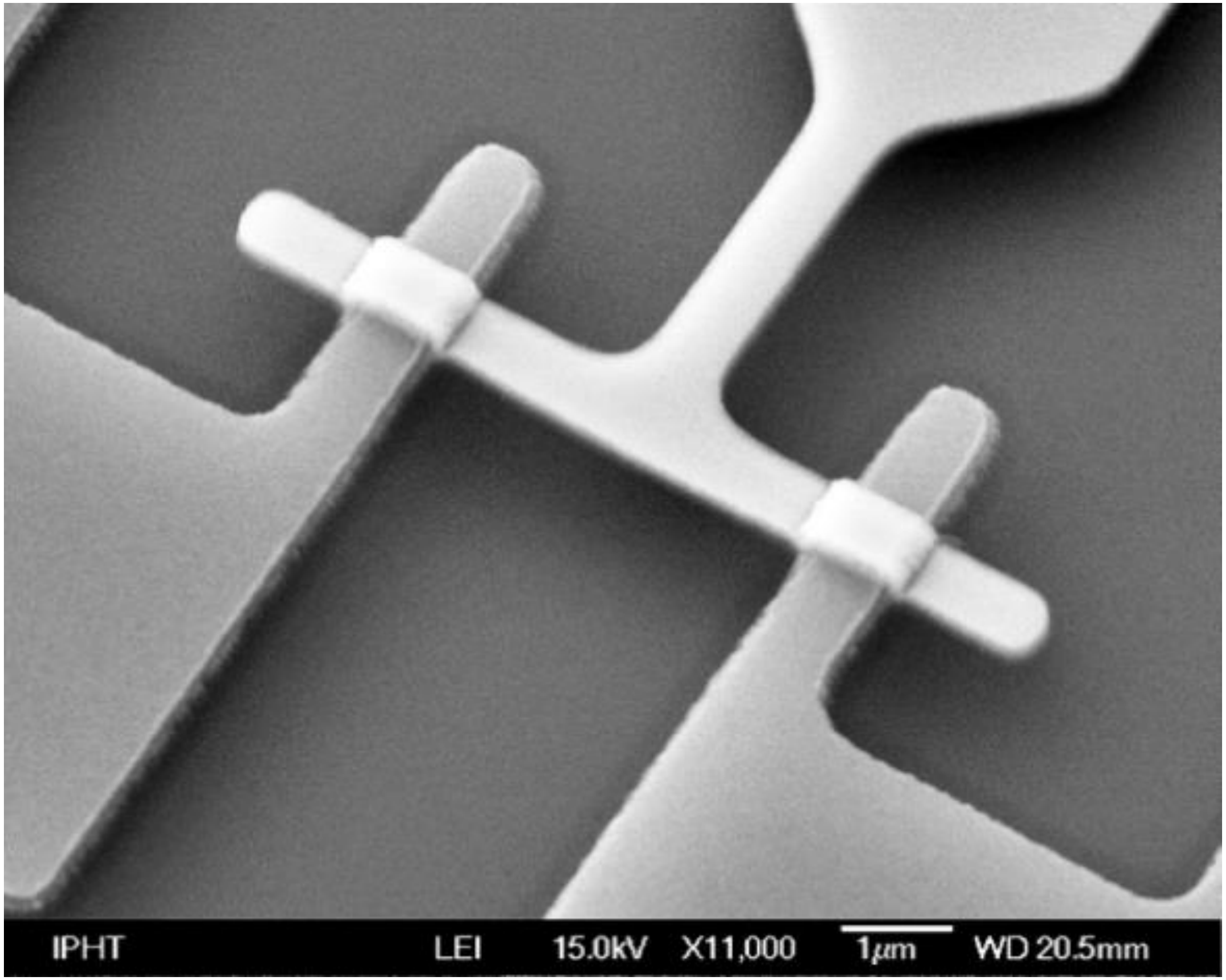
Conventional technology
→ junction area: 10 μm^2,
→ overlap: 60 μm^2,
→ 700 fF,

Cross type technology
→ junction area: < 1 μm^2,
→ overlap: no
→ below 50 fF,



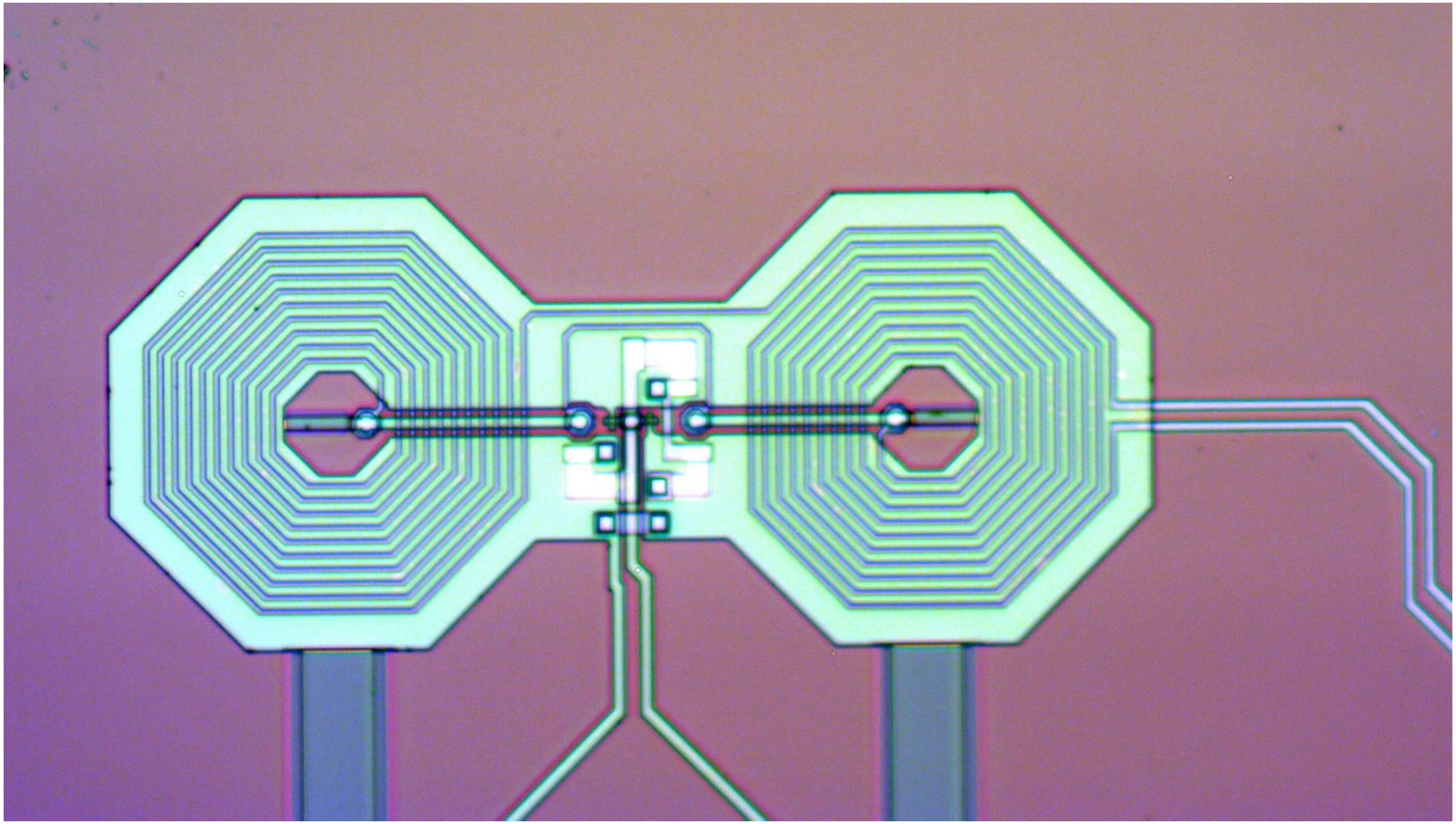
* R. Stolz, PhD thesis, Isle, Ilmenau, 2006

Small capacitance Josephson junctions



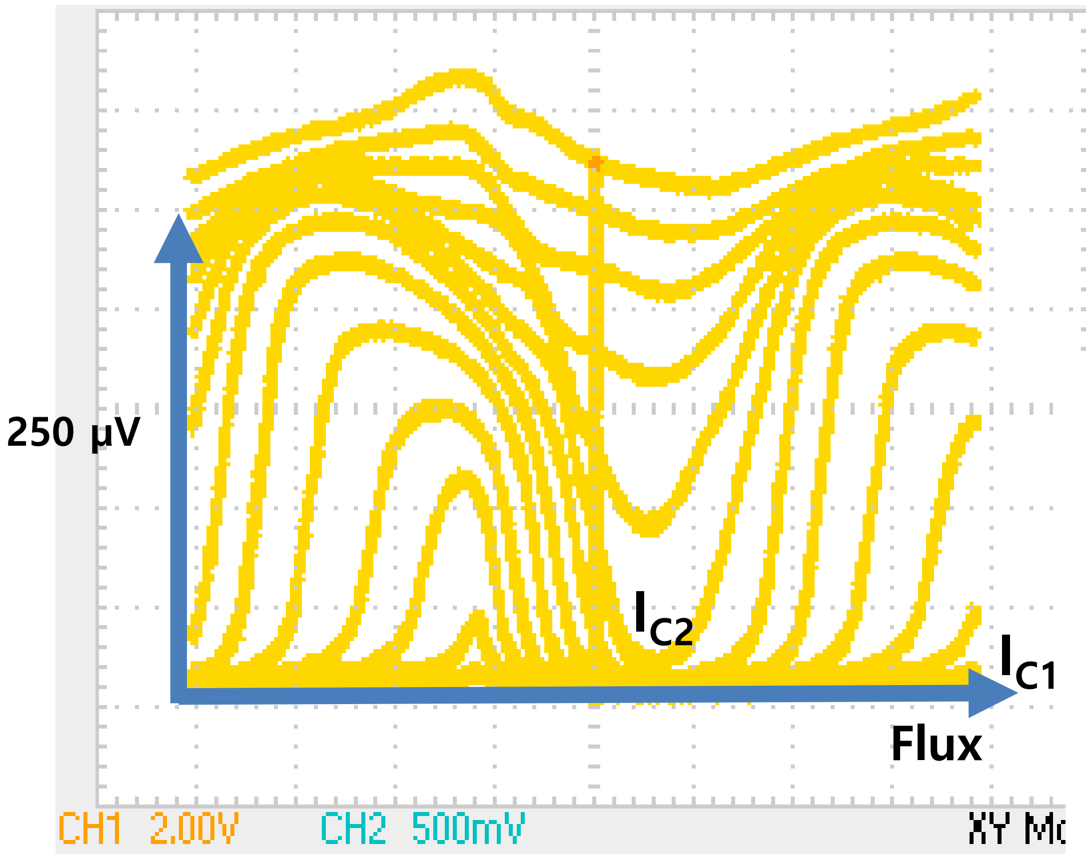
Scanning electron microscope image of a Josephson tunnel junction with an area of (0.6x0.6) µm^2.

SQUIDs with small capacitance JJs



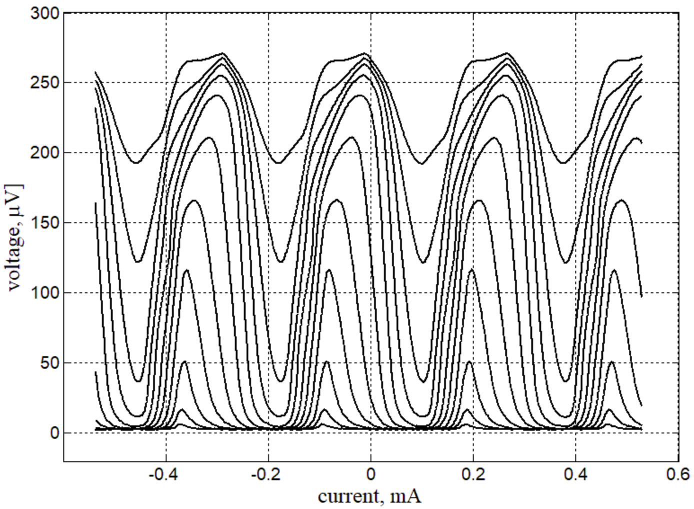
VC2 SQUID current amplifier was tested as a microwave amplifier

VC2 Flux–Voltage characteristics family

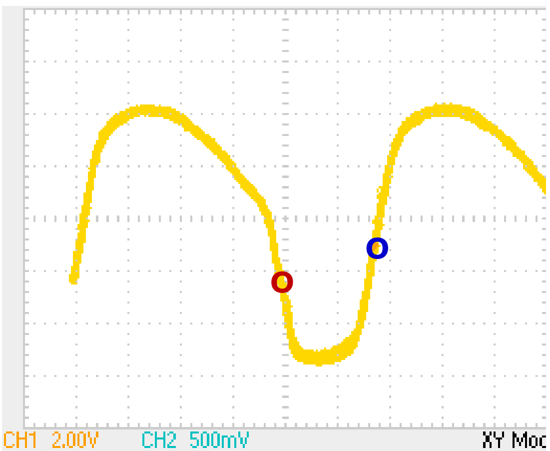


I_{C1} = 62.4 µA
I_{C2} = 87.0 µA

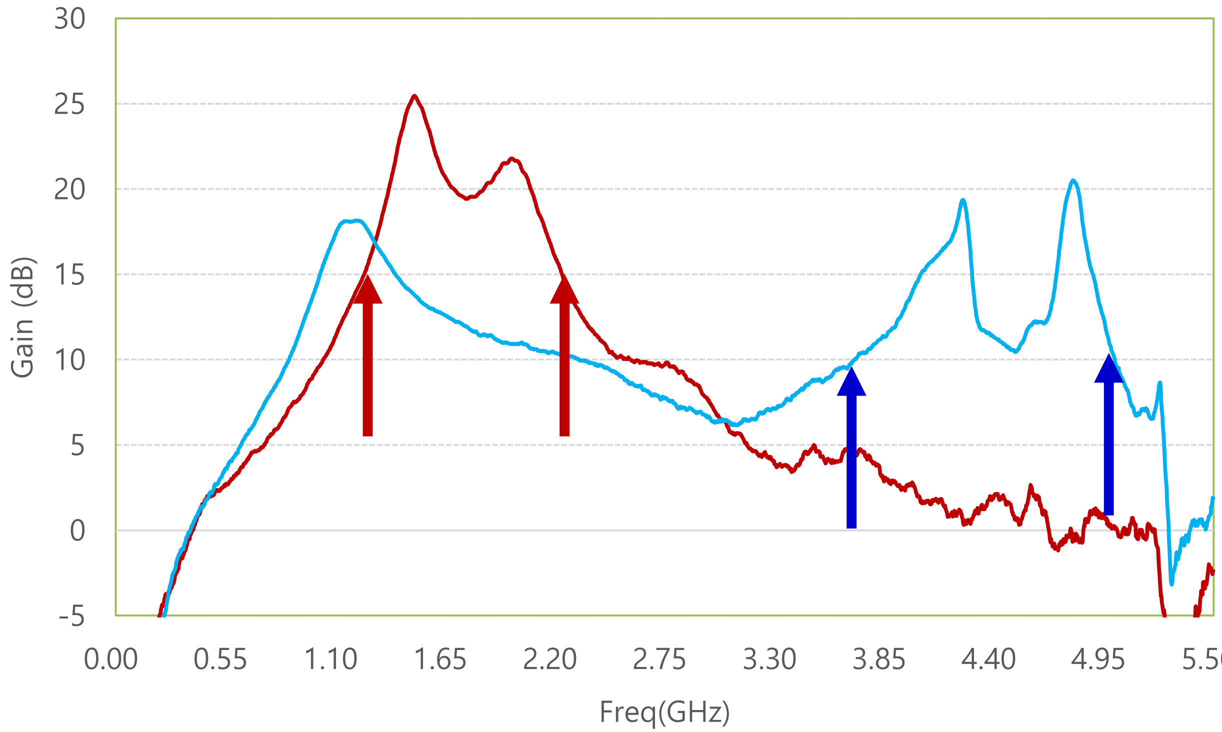
ΔI = 4.0 µA



VC2 as a Microwave Amplifier



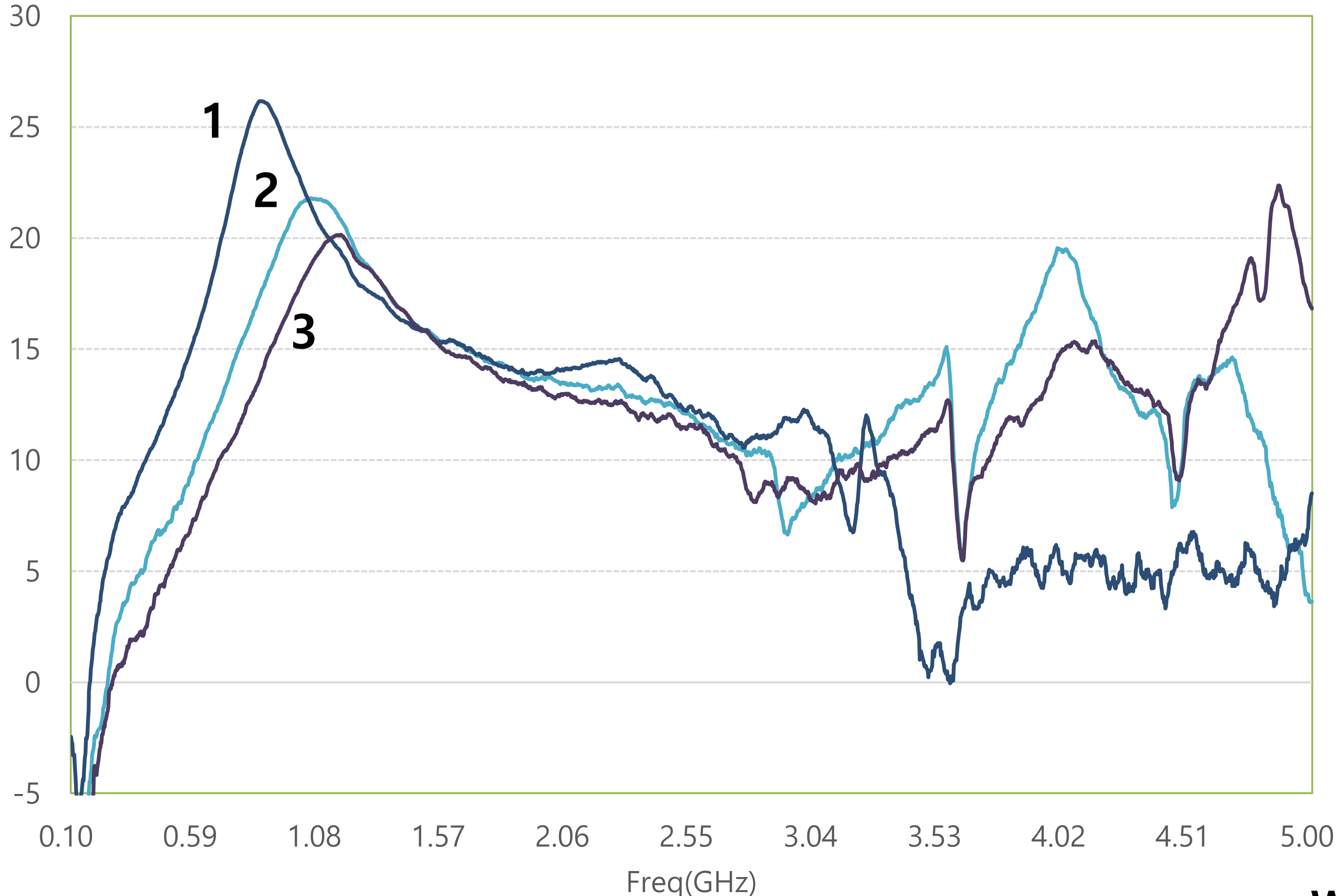
Working point positions
I_{BIAS} = 87.0 µA

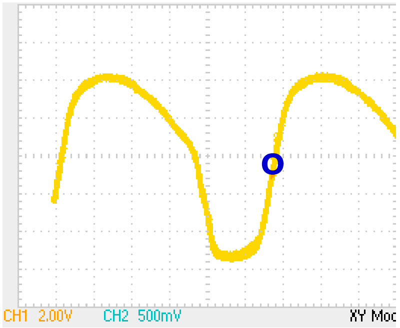


ΔF_{15dB} = 2.2 – 1.2 = 1.0 GHz

ΔF_{10dB} = 5.0 – 3.7 = 1.3 GHz

VC2 as a Microwave Amplifier

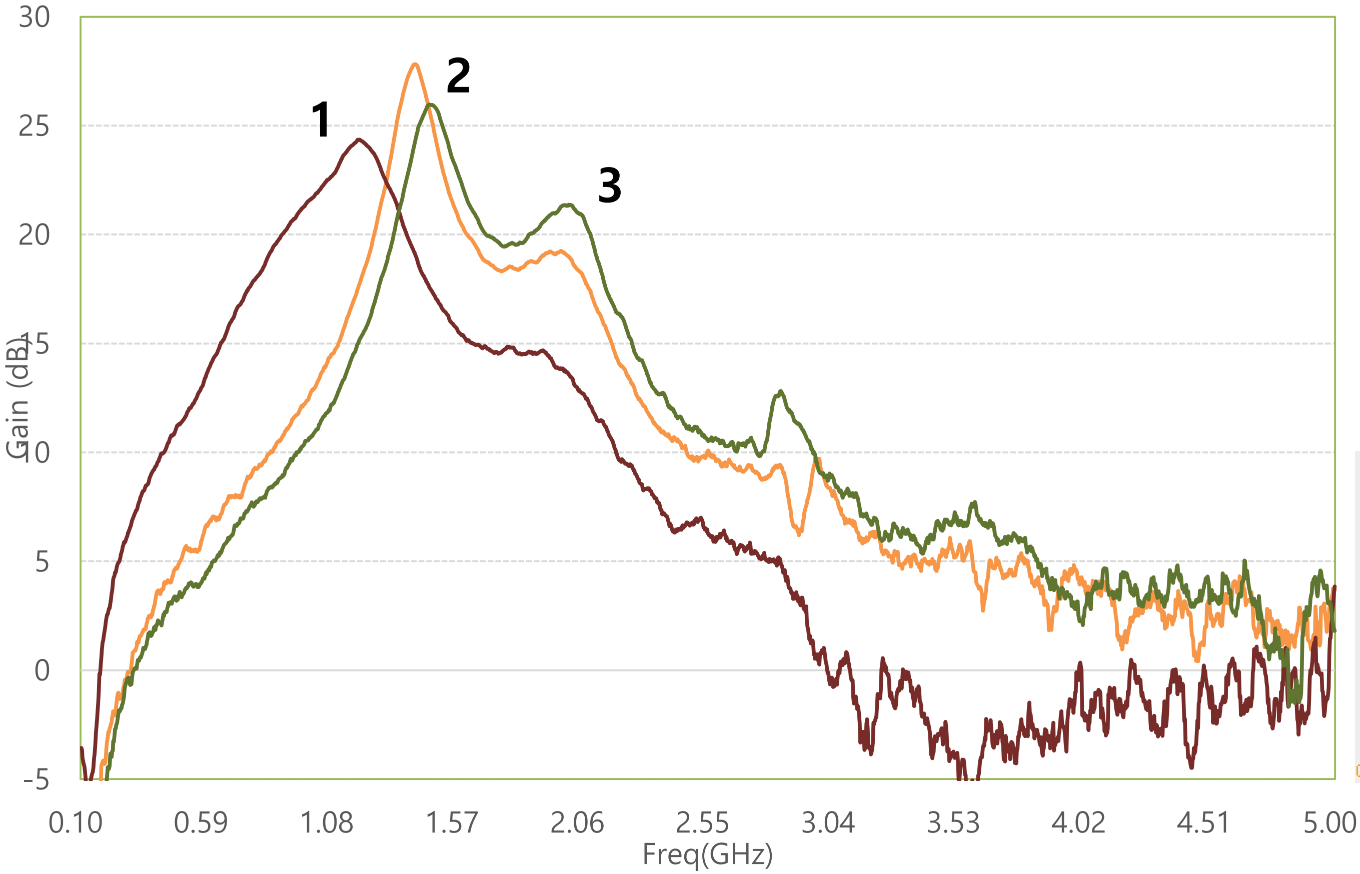


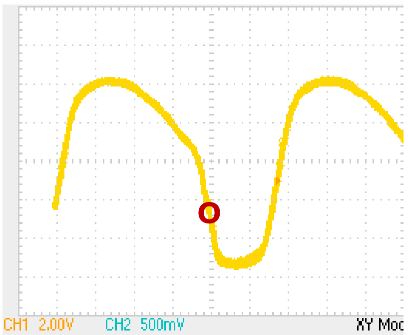


Working point position
I_{BIAS} = 87.0 μA

1. **4 mm bond connected from L_{IN} on the chip to a pad on PCB**
2. **4 mm bond connected only to L_{IN} on the chip**
3. **No bond connected to the second pad of L_{IN}**

VC2 as a Microwave Amplifier





Working point position
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3. **No bond connected to the second pad of L_{IN}**

Summary

- **The nature of the dark matter – one of the most important questions in modern science**
- **The axion – the most attractive particle dark-matter candidate**
- **The axion detection – converting Milky Way halo axions into microwave photons inside high-Q cavity in presence a very strong magnetic field**
- **CULTASK: CAPP Ultra-Low Temperature Axion Search in Korea**
- **Microstrip SQUID Amplifiers can reach <u>quantum limited noise level</u>**
- **Resonant MSAs from UC Berkeley, ezSQUID and KRISS**
- **It was experimentally proven that extremely wideband microwave SQUID amplifiers can be made using low capacitance Josephson junctions**
- **New SQUID amplifiers from IPHT can work in 0.5 – 5.0 GHz bandwidth**

THANKS FOR YOUR ATTENTION !