# Frequency-domain Multiplexed Readout of Transition Edge Sensor Bolometers for the POLARBEAR-2 Cosmic Microwave Background Experiment

Kaori Hattori

High Energy Accelerator Research Organization (KEK)

# Outline

- POLARBEAR-2 Cosmic Microwave Background experiment
- Digital frequency-domain multiplexing system
- Improvements on TES bolometer readout for POLARBEAR-2
- Status of developments
- Summary

# Collaborators

## High Energy Accelerator Research Organization (KEK)

*Masashi Hazumi (PB-2, PI)*
*Takayuki Tomaru*
*Yoshiki Akiba*
*Yuji Chinone*
*Masaya Hasegawa*
*Kaori Hattori*
*Yasuto Hori*
*Yuki Inoue*
*Tomotake Matsumura*
*Hideki Morii*
*Takahiro Okamura*
*Jun-ichi Suzuki*
*Hiroshi Yamaguchi*

## NIFS

*Suguru Takada*

## IPMU, Univ. Tokyo

*Nobuhiko Katayama*
*Haruki Nishino*

## Osaka Univ.

*Satoru Takakura*

## Princeton Univ.

*Zigmund Kermish*

## University of California, Berkeley

*Adrian T. Lee (PB, PI)*
*Ari Cukierman*
*William L. Holzapfel*
*Michael J. Myers*
*Christian L. Reichardt*
*Paul L. Richards*
*Michael Sholl*
*Aritoki Suzuki*
*Oliver Zahn*

## University of Colorado, Boulder

*Nils Halverson*
*Greg Jaehnig*

## Laboratoire Astroparticule & Cosmologie (APC)

*Radek Stompor*
*Giulio Fabbian*

## LBNL

*Julian Borrill*
*Josquin Errard*
*Reijo Keskitalo*
*Ted Kisner*

## University of California, San Diego

*Brian Keating (SA, PI)*
*Christopher Aleman*
*Matt Atlas*
*Kam S. Arnold*
*Darcy Barron*
*Tucker Elleflot*
*Guangyuan Feng*
*Frederick Matsuda*
*Stephanie Moyerman*
*Marty Navaroli*
*Praween Siritanasak*
*Nathan Stebor*
*Brandon Wilson*

## Dalhousie University

*Scott Chapman*
*Colin Ross*
*Kaja Rotermund*
*Peter Smith*

## McGill University

*Matt Dobbs*
*Adam Gilbert*
*Graeme Smecher*

## Cardiff University

*Peter Ade*
*William Grainger*

# POLARBEAR-2 CMB experiment

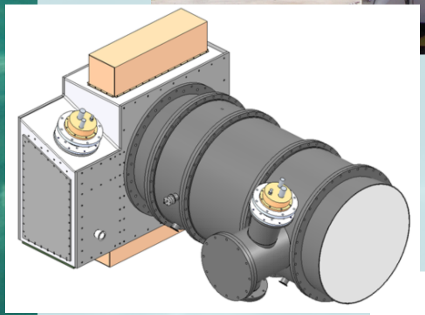
**POLARBEAR-1**

- Aims to observe B-mode polarization pattern imprinted on CMB.
- First light in January 2012.

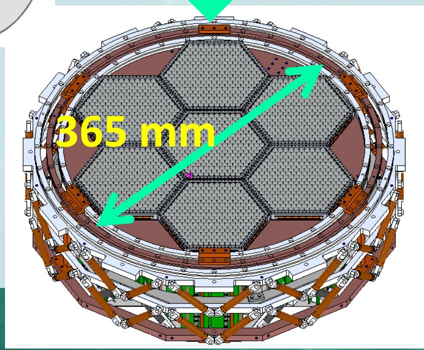
**POLARBEAR-2**

- Upgraded experiment.
- Will be more sensitive to B-mode.

Will be deployed in 2014.

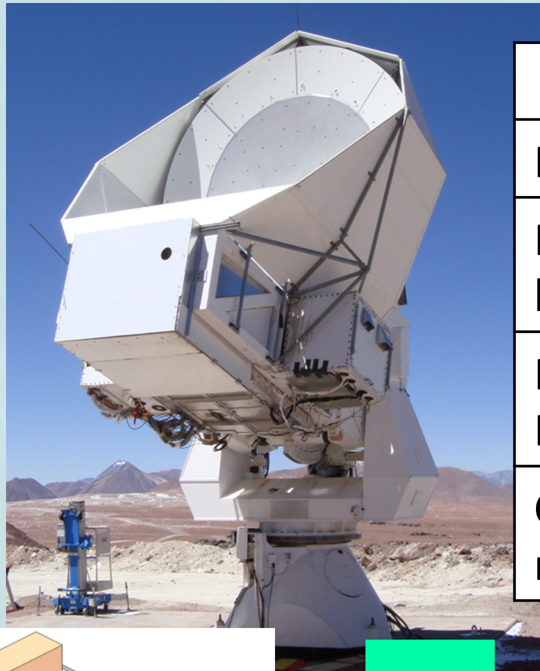


**POLARBEAR-2**

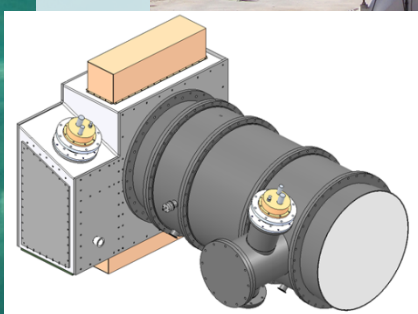



POLARBEAR-1
Darcy Barron, poster, Thursday
POLARBEAR-2
Aritoki Suzuki, poster, Thursday

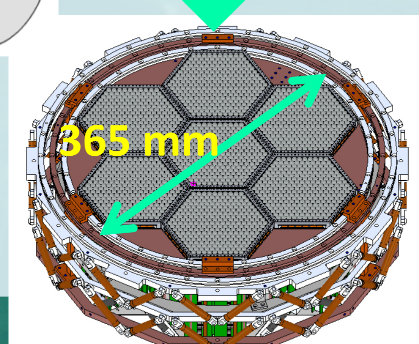
# POLARBEAR-2 CMB experiment



| | POLARBEAR-1 | POLARBEAR-2 |
|---|---|---|
| Frequency | 150 GHz | 95 and 150 GHz |
| Number of TES bolometers | 1,274 | 7,588 |
| Frequency Domain Multiplexing factor | 8 | 32 |
| Carrier frequency range | 1 MHz | 3+ MHz |



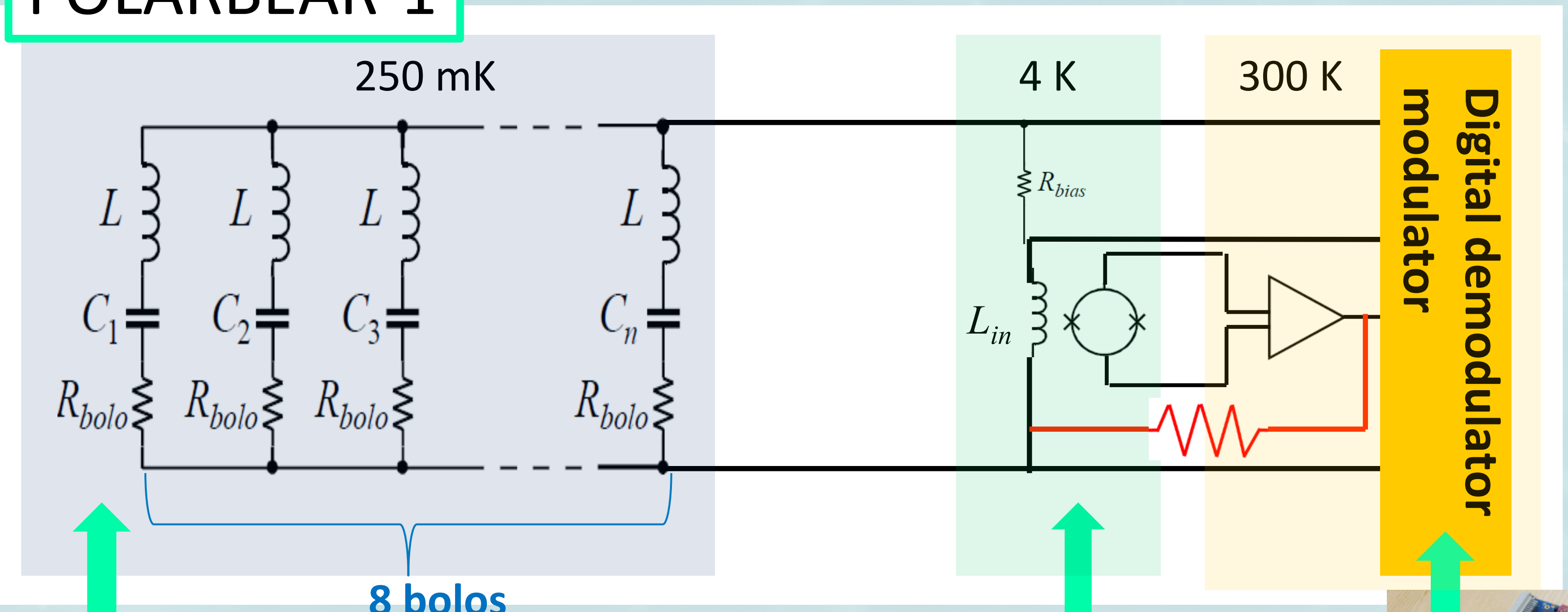
**POLARBEAR-2**

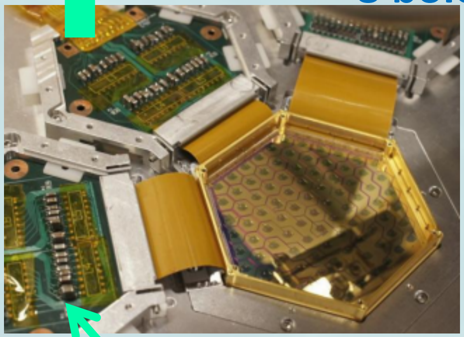



POLARBEAR-1
Darcy Barron, poster, Thursday
POLARBEAR-2
Aritoki Suzuki, poster, Thursday

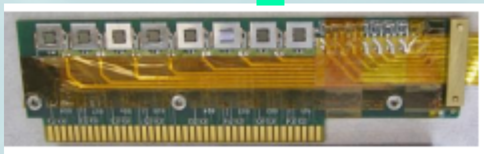
# Digital frequency-domain multiplexing system

**POLARBEAR-1**

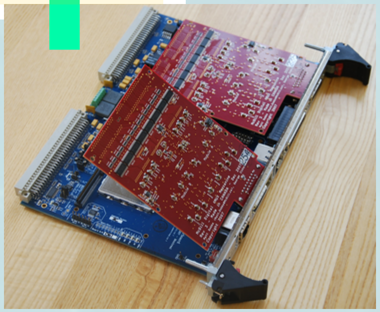


LC board



SQUIDs (NIST)

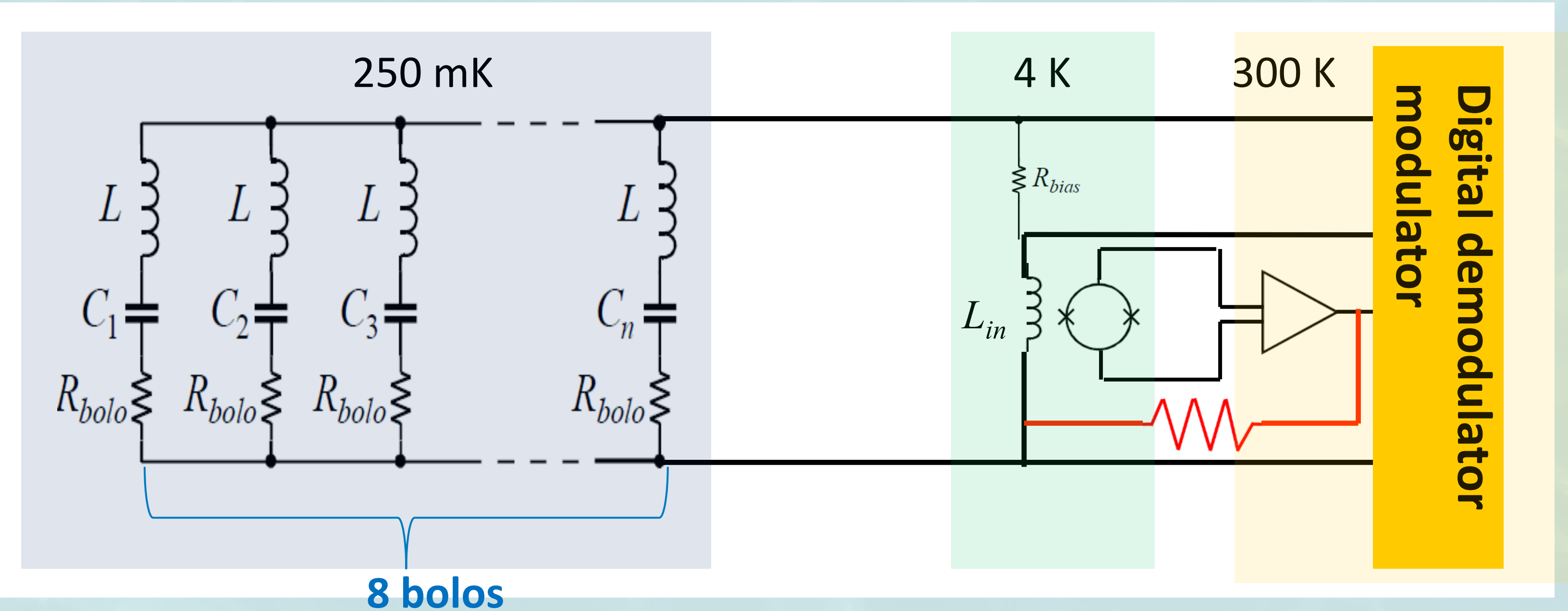


McGill University

**1,274** bolometers
182 / wafer

0.3 – 1 MHz
8xMultiplexing

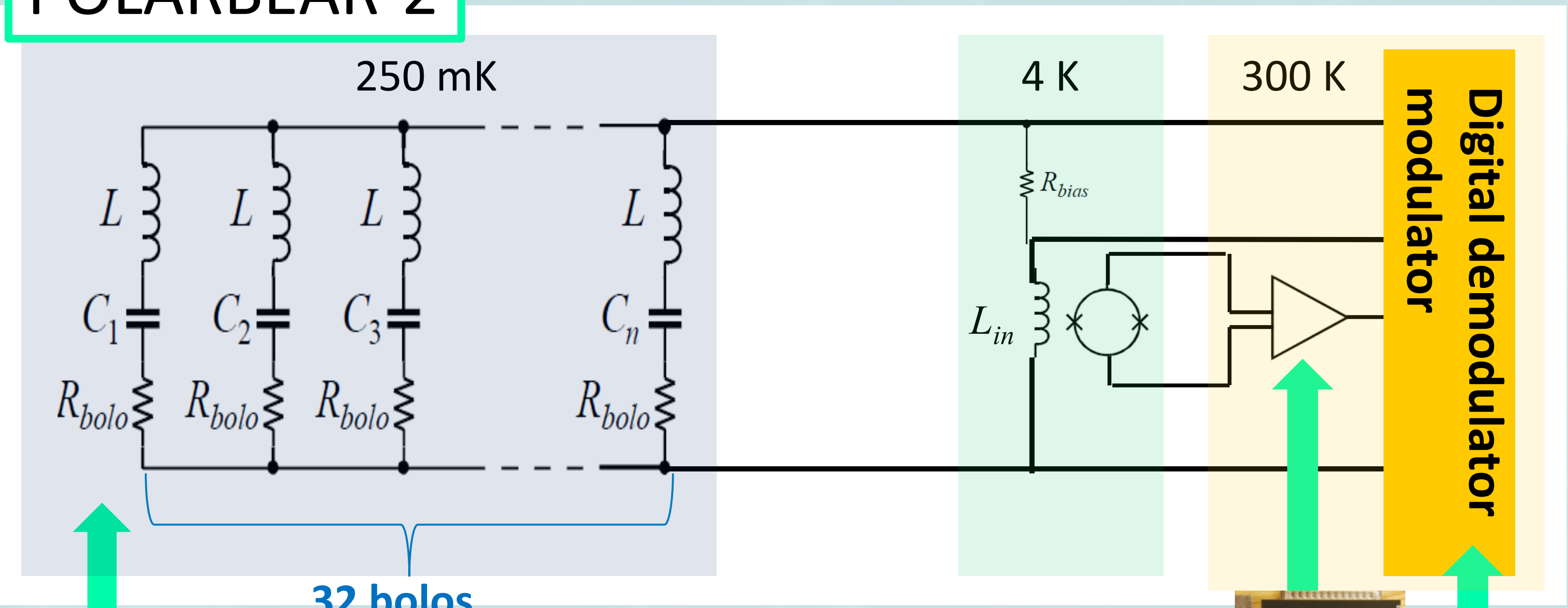
# Digital frequency-domain multiplexing system

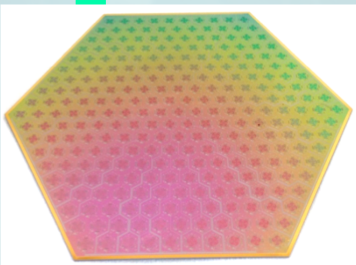



FMUX bias bandwith is limited by SQUID Flux Lock Loop.
Phase delay from the 300 K to 4 K wiring.

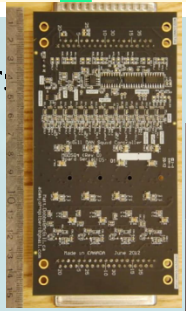
# Digital frequency-domain multiplexing system

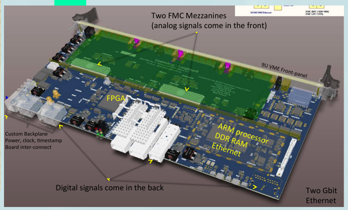
POLARBEAR-2



Multi--chroic dual--polarization bolometric detectors
Aritoki Suzuki
Antenna and mm-Wave Circuits session, Thursday





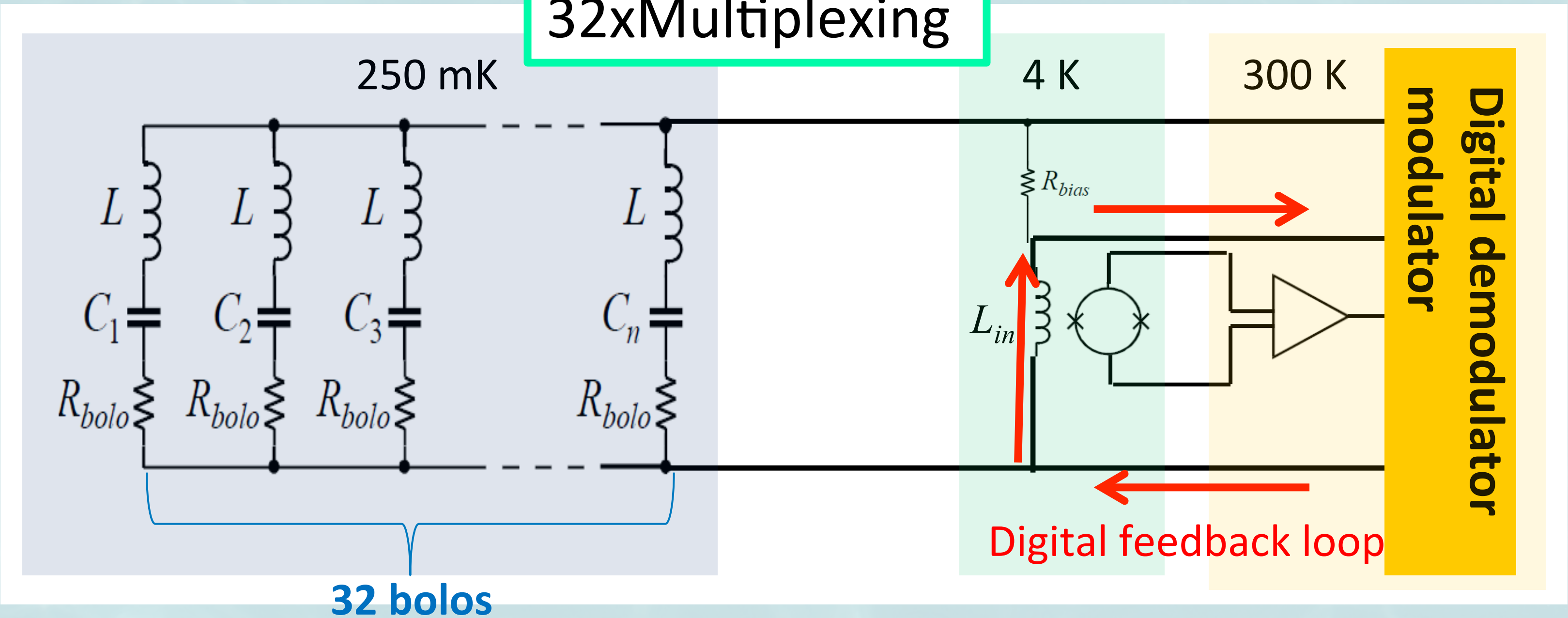
**7,588** bolometers
1,084 / wafer

3+ MHz
32xMultiplexing

Being developed
by McGill University

# Digital frequency-domain multiplexing system

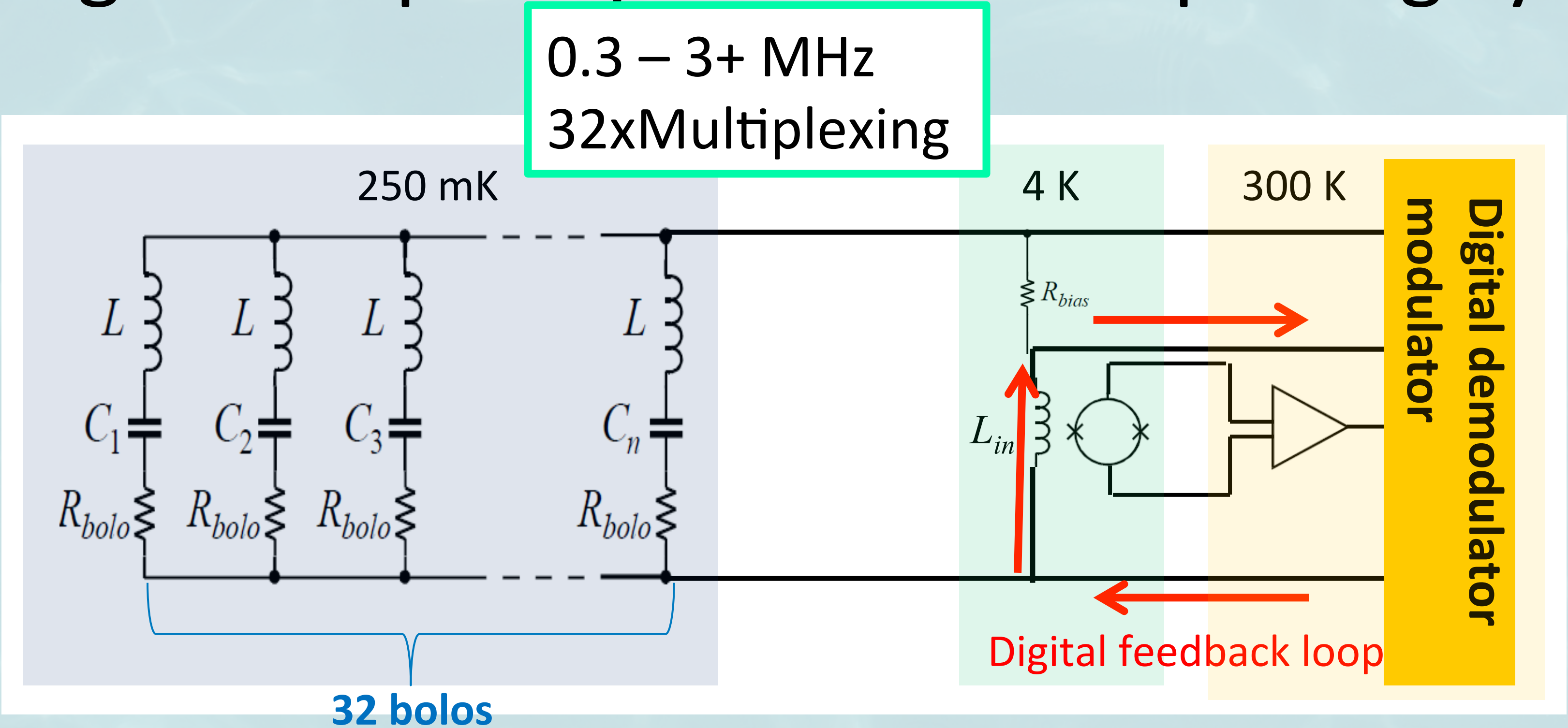
0.3 – 3+ MHz
32xMultiplexing




Increase in the bandwidth of the SQUID electronics is required.

- Instead of analog Flux Lock Loop, use digital SQUID feedback
  Digital Active Nulling *T. de Haan, Proc. SPIE (2012) 8452-13.*
- Feedback over a small frequency range around each of carrier frequencies.

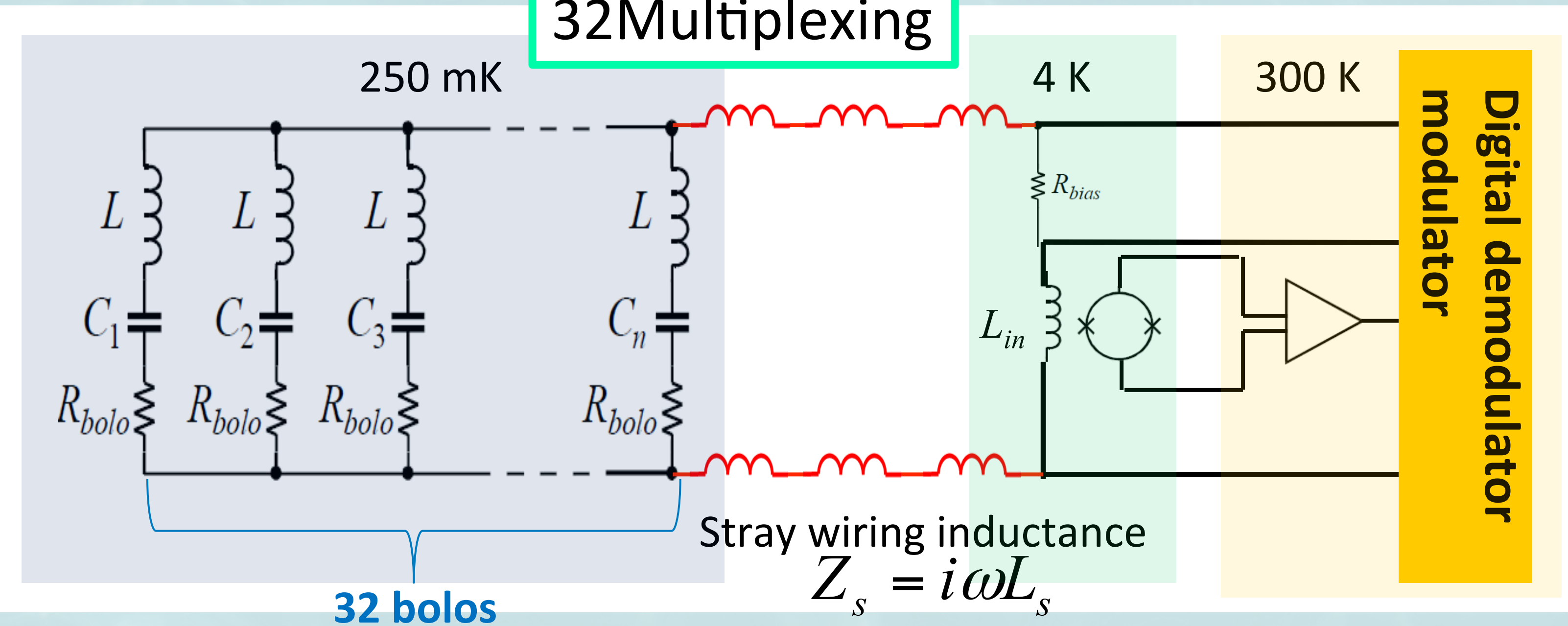
# Digital frequency-domain multiplexing system




- Shunt feedback.
- Feedback signal is injected to the same SQUID input coil as TES bolometers.
- Can null impedance of SQUID coil.

# Digital frequency-domain multiplexing system

0.3 – 3+ MHz
32Multiplexing

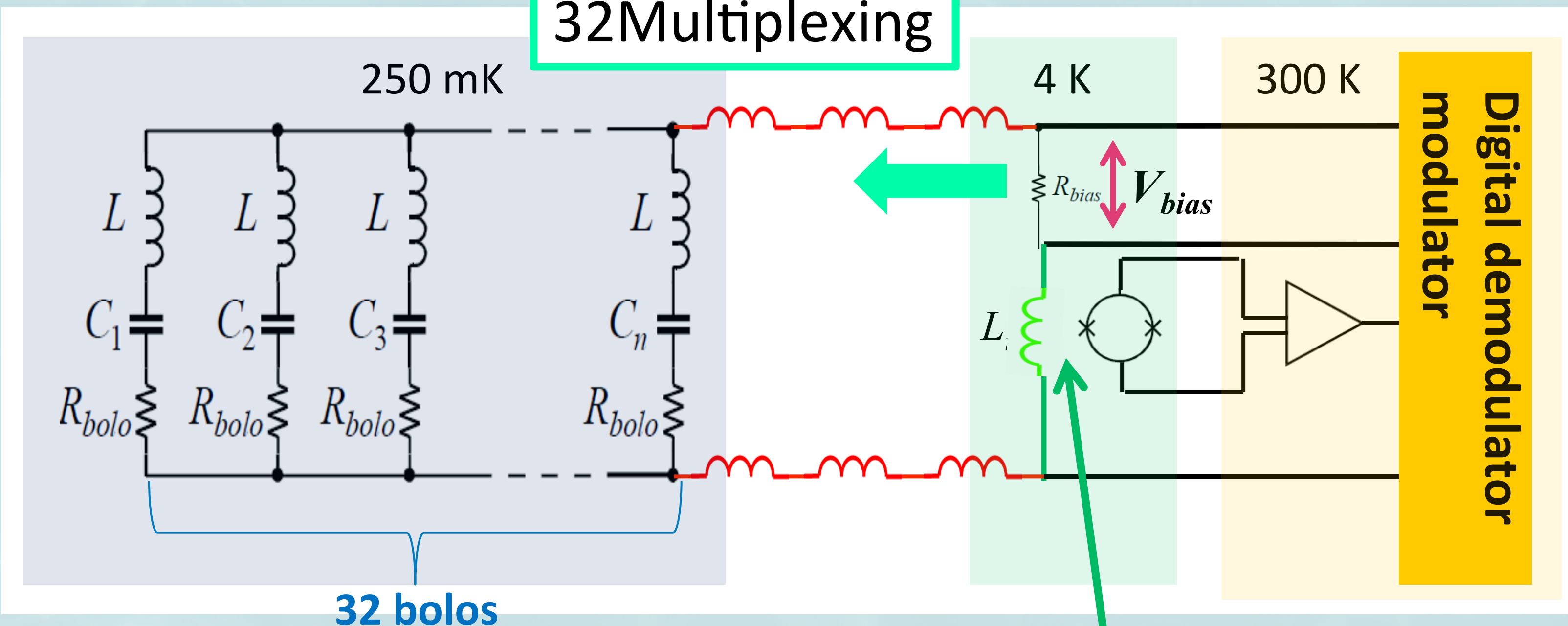



$$Z_s = i\omega L_s$$

Stray wiring impedance is proportional to carrier frequency.
Reduces detector stability and produces crosstalk.
POLARBEAR-1 : 160 nH

# Digital frequency-domain multiplexing system

0.3 – 3+ MHz
32Multiplexing

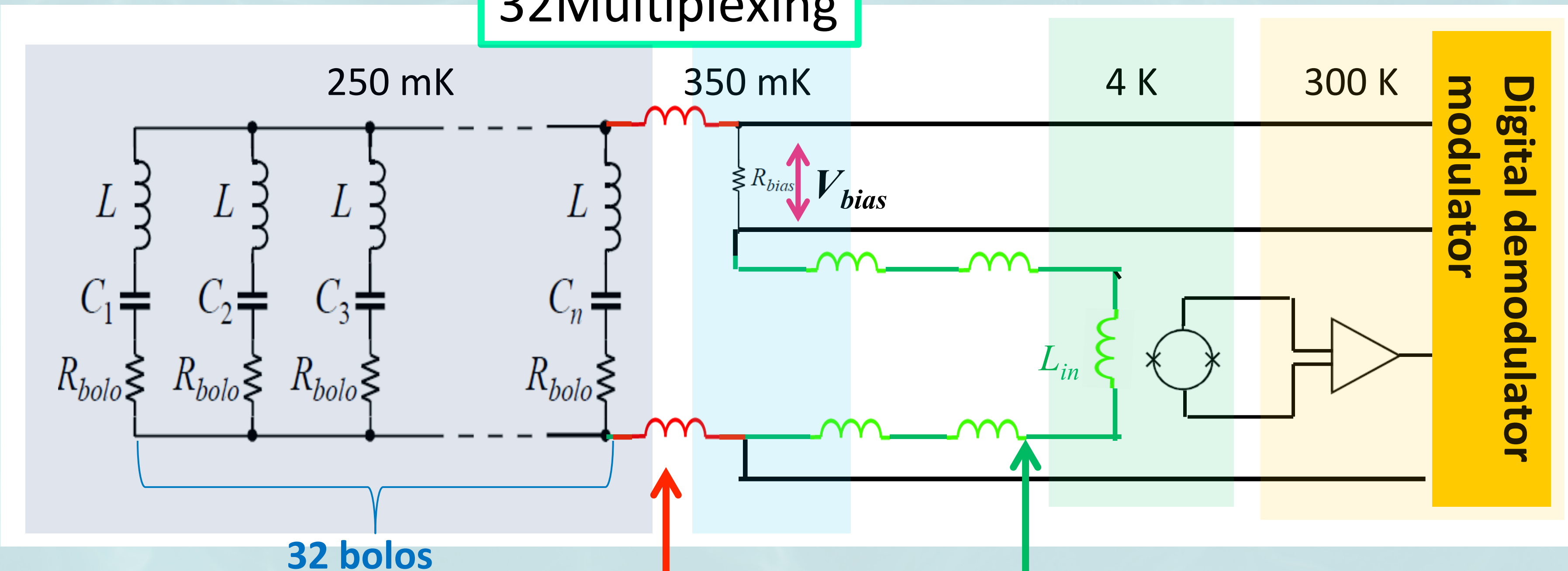



Stray inductance nulled by digital feedback.

- Enclose cables in digital feedback loop.
- Move resistor applying voltage bias across TES bolometers closer to cold stage.

# Minimizing Stray Inductance

0.3 – 3+ MHz
32Multiplexing

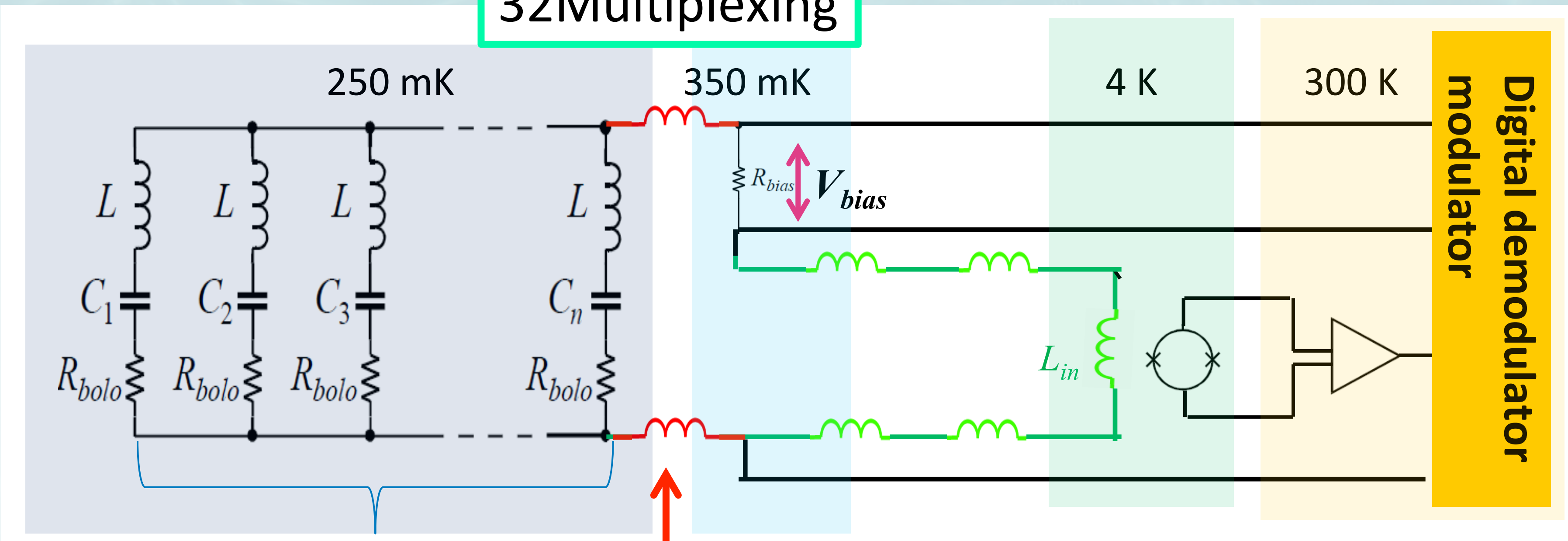


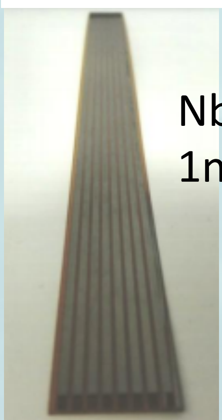

Make stray wiring inductance smaller.

Stray inductance nulled by digital feedback.

# Minimizing Stray Inductance

0.3 – 3+ MHz
32Multiplexing



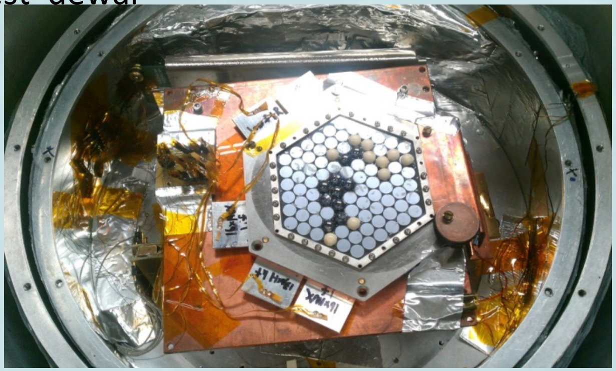



NbTi stripline
1nH / cm

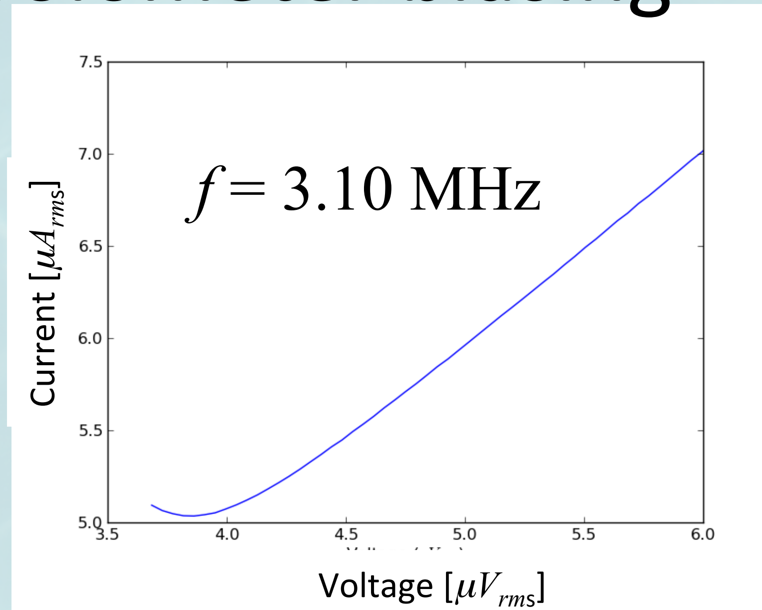
160 nH (POLARBEAR-1)
→12 nH

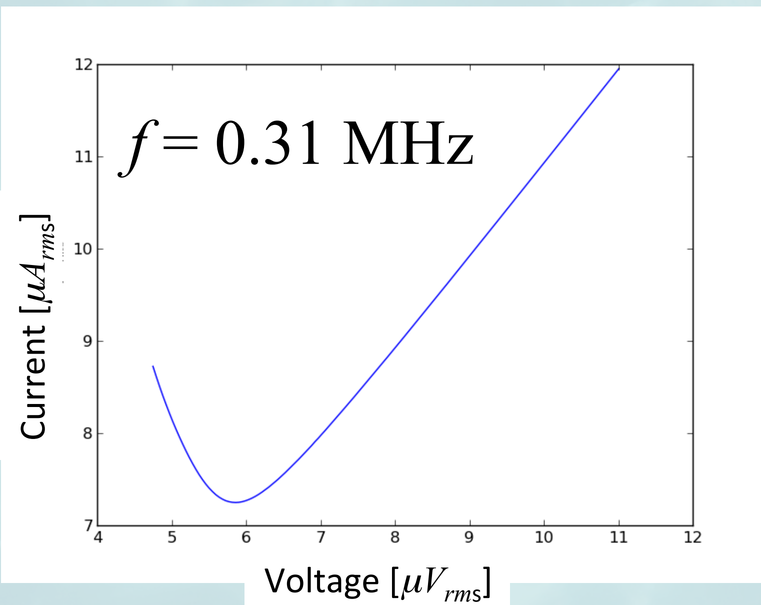
# High frequency bolometer biasing

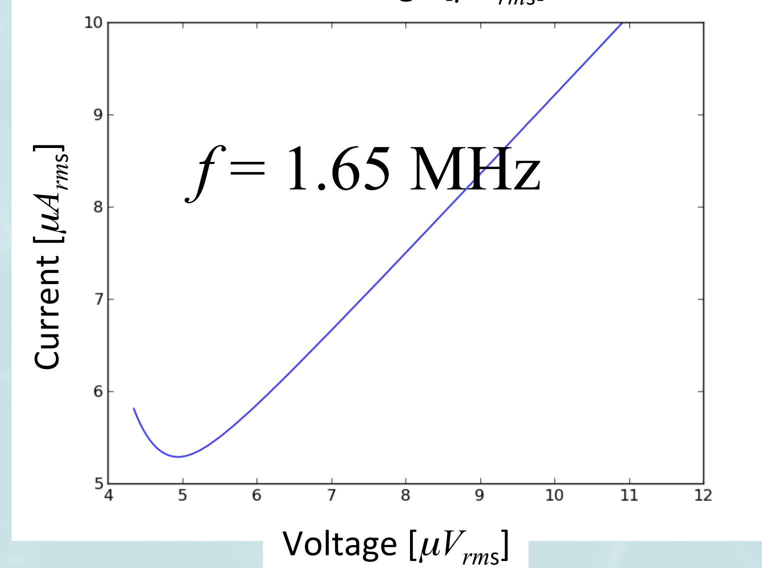
Test dewar



- multi-layer ceramic capacitor
- L = 24 μH




Can't get a bolometer deeper in transition at 3MHz than at a lower frequency.

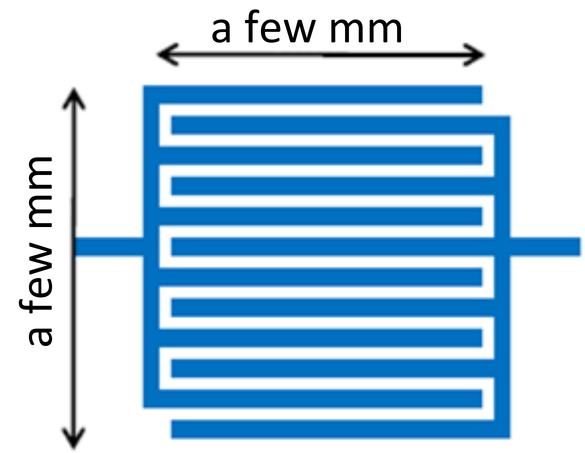
# Capacitor Equivalent Series Resistance

- Can't get a bolometer deeper in transition at a high frequency than at a lower frequency.
- Equivalent Series Resistance (ESR) of ceramic capacitors is 0.3 – 0.4 $\Omega$ at 3 MHz.
- Should reduce ESR, thus improving bolometer stability.
- Goal : 10 % of bolometer operating resistance < ∼0.1 $\Omega$
- Need capacitors with low-loss dielectric.
- Required capacitance accuracy < 0.5 %

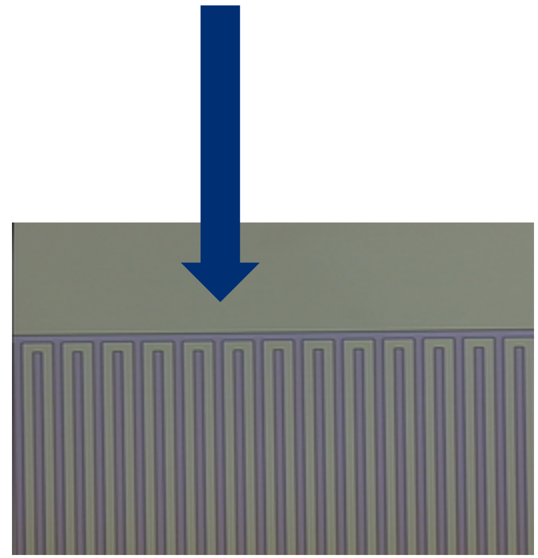
# Inter-digitated capacitor on Si

Aritoki Suzuki UC Berkeley


Undoped high resistivity Si
for low loss dielectric

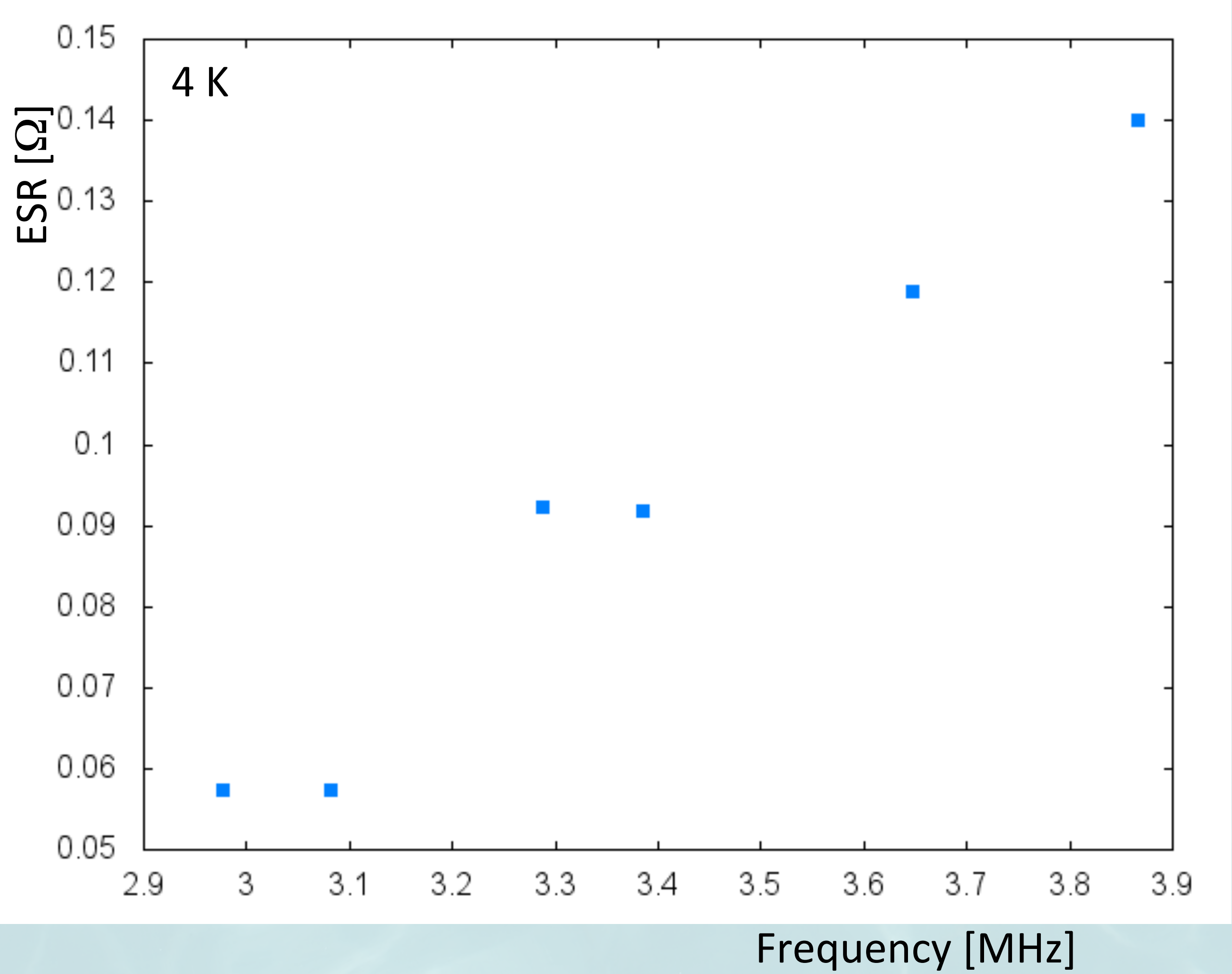



Line / space : 2 -5 μm



# Equivalent Series Resistance

Full demonstration of circuit.
Series resistance including loss of an inductor, Al wirebonds and copper traces.



# Summary

- POLARBEAR-2 will be deployed in 2014.

- For POLARBEAR-2 challenges are
  1. Frequency range of fMUX bias bandwith is 3+ MHz.
     → We have used digital SQUID feedback.
  2. Stray wiring inductance
     → Enclose most of strays in feedback loop.
     → Voltage-biased a bolometer at 3 MHz.
  3. Capacitor ESR
     → ESR of inter-digitated capacitors is about 10% of bolometer resistance.