ÉLECTRONIQUE DE MULTIPLEXAGES

APPLICATIONS CRYOGÉNIQUES

DÉTECTION DE RAYONNEMENT
À TRÈS BASSE TEMPÉRATURE

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DRTBT2024 - Mars 2024
https://drtbt.neel.cnrs.fr

Arrays of sensors are required for **fast & sensitive maps**

We must be **Cool**ed to be **sensitive**

+

Array are needed to do maps → **images**

AND/OR

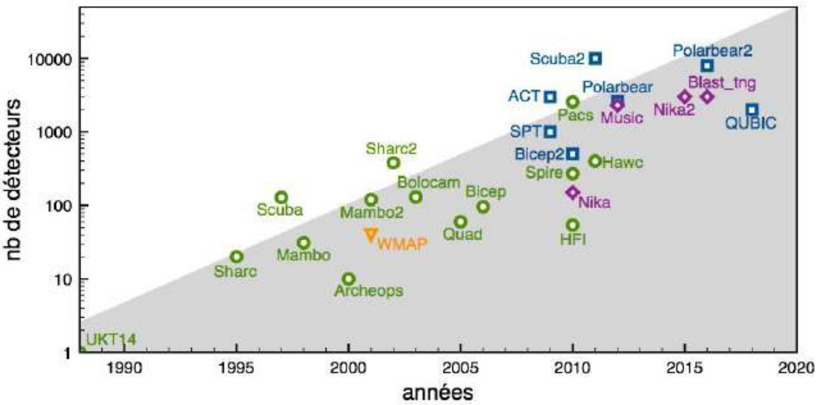
integrate signal → **sensitivity** again

=

Cryogenic Multiplexing

Cryogenic Detectors "Moore's Law"

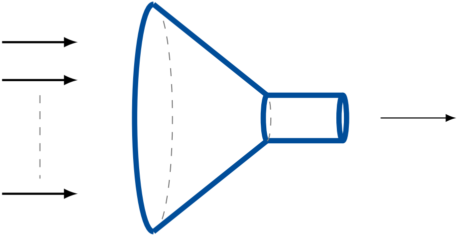
The number of cryogenic detectors is increasing over the past years :



Multiplexing general

Transmission of **N** signals over **1** channel

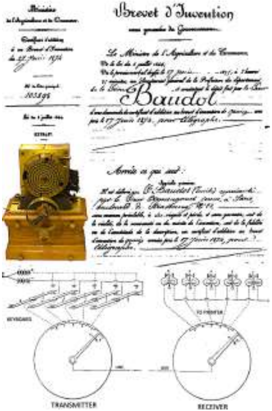
INFORMATION **TRANSMISSION**



Several transmission (analog signals) may be carried using one wire (or one antenna)

First multiplexing systems

Introduced for transmission at the end of the 19^{th} century and widely applied in **MULTIPLEX TELEGRAPHY AND TELEPHONY, as for radio broadcast** during the 20^{th} century

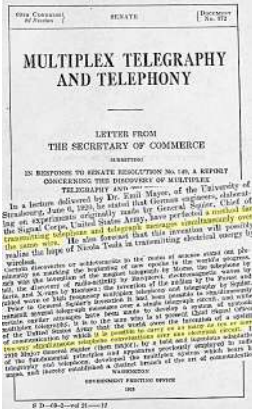


Brevet d'Invention

sans garantie du Gouvernement

Le Ministre de l'Agriculture et du Commerce,

Baudot

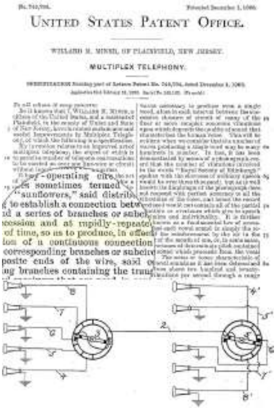


SENATE

MULTIPLEX TELEGRAPHY AND TELEPHONY

LETTER FROM

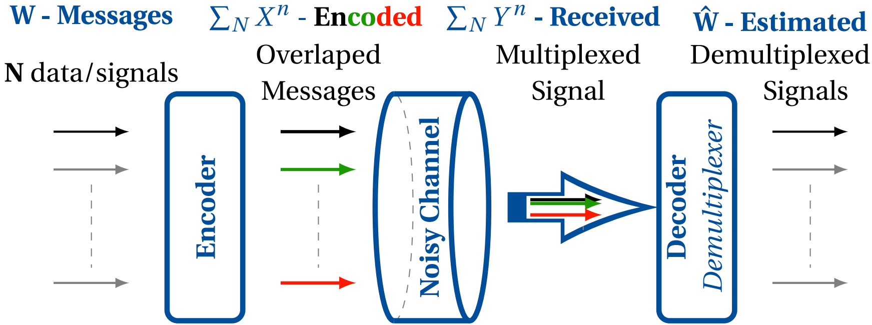
THE SECRETARY OF COMMERCE



UNITED STATES PATENT OFFICE.

MULTIPLEX TELEPHONY.

Channel capacity & Information theory



W - Messages $\sum_N X^n$ - **Encoded** $\sum_N Y^n$ **- Received** **Ŵ - Estimated**

N data/signals

Overlaped Messages

Multiplexed Signal

Demultiplexed Signals

W Signals to be transmitted & multiplexed

X^n Coded Signal with ^{n} showing the "complexity" of coding

Y^n Output of a "noisy" channel : multiplexed signal

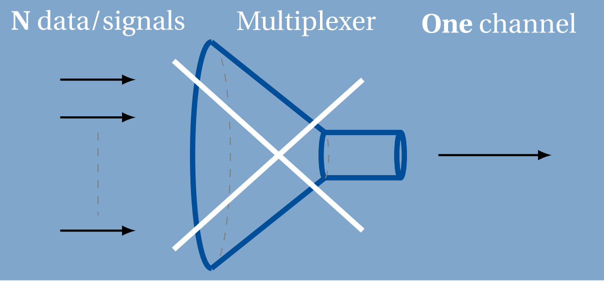
Ŵ Signal reconstruction : demultiplexed signals

☞ *Channel capacity is additive → combined independent channels provides same capacity as used independently*

Multiplexing general

Transmission of **N** signals over **1** channel

INFORMATION **TRANSMISSION**

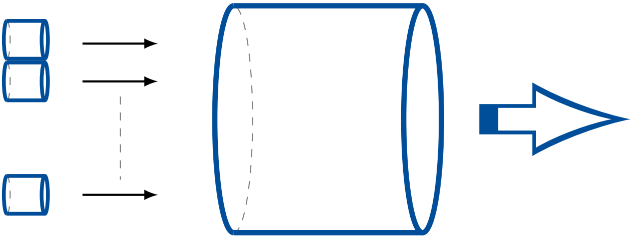


That is **not a real multiplexer***, because this need to reduces -* **Data compression** *- the transmitted informations to use the* **same output channel capacity**

Multiplexing general

Transmission of **N** signals over **1** channel

INFORMATION **TRANSMISSION**



⚠ *To transmit N signals via One channel,* **the "channel" must provides better performances** *than for a single signal transmission.*

Multiplexing notice

⚠ To transmit N signals *via* one channel, **the "channel" must provides better performances** than for a single signal transmission.

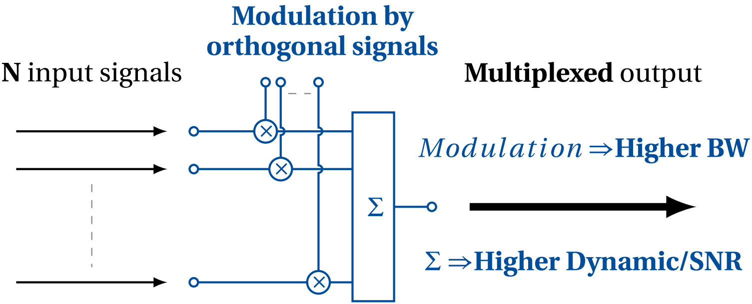
- ⇒ The increasing of the required performances is directly linked to the number N of multiplexed signals.
- ⇒ The affected performances are both :
  - Band Width
  - Dynamic / Signal to Noise Ratio

the multiplexing **divides the capacity of the high-level communication channel** into several **low-level sub-channels**, one for each message, signal or data to be transmited.

Multiplexing as a modulation

There are intersections between modulation and multiplexing

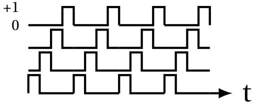
Multiplexing = modulation of input signals by orthogonal signals:



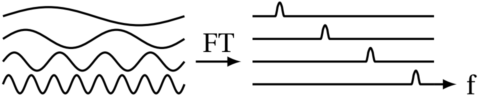
Orthogonal : **boxcar functions** or **carriers at different frequencies**.
Orthogonality ⇒ demultiplexer **able to recover each input signal without interference from the other.**

Example of "orthogonal" functions
sampling, modulation, convolution, coding :

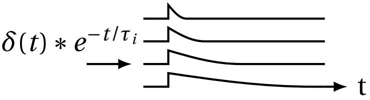
× boxcar functions ≡ **sampling**



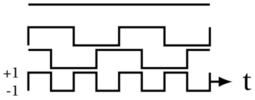
× carriers ≡ **modulation**



∗ time constant ≡ **convolution**



× Walsh Hadamard code ≡ **coding**

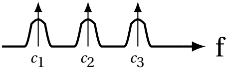


× × row - column **encoding** → 2 functions / "wires" per signal

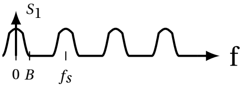
limitations

Multiplexing ≡ **modulation/sampling/coding** + **summation**

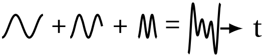
- Frequency modulation → cross-talk between two carriers / **bandwidth margin required**



- Nyquist–Shannon sampling* theorem → aliasing† / **noise margin required** and cross-talk



- Summation → increasing of the amplitude range : **dynamic margin required**



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[*] A time domain multiplexer do not "see" the input signal all the time

[†] High frequencies are mixed with low frequency / White noise increase

Requirement for multiplexing

To multiplex a signal, the readout system (multiplexer) **must have better performances** than to read-out a single pixel.

> *If the readout channel has* **performances better** *than what it is needed for the readout of a single pixel, a multiplexing can be performed* **without signal degradations**.

The multiplexer must have better :

- **bandwidth** ,
- **dynamic** range and/or
- **noise** performances.

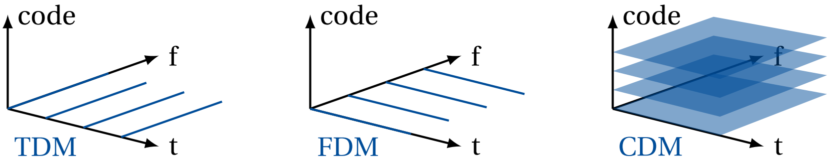
than for a readout of one pixel.

The increasing of the needed performances for a N to 1 multiplexer must be better **by a factor of about** $\sqrt{N}$ *to few N ...*

Multiplexing type *vs* standard modulations

- Multiplexing
  - **Time Domain Multiplexing**
    - **Boxcar modulation (TDM)**
    - **Coded Division Multiplexing (CDM)**
  - **Frequency Domain Multiplexing**
    - **Modulation of the detector biasing itself (FDM)**
    - **Microwave SQUID multiplexing with DC detector bias (μMUX)**
    - **Modulation of the detector "biasing" itself in RF (KIDs)**
    - Wavelength Domain Multiplexing for optical fiber (WDM)
- Coding
  - **Amplitude Shift Keying (ASK)**
    - Binary On-Off Keying
    - − −   − − −   · − ·   · · ·   ·   code
    - **Coded Division Multiple Access (CDMA)**
  - **Frequency Shift Keying (FSK)**

Code as a third dimension ?

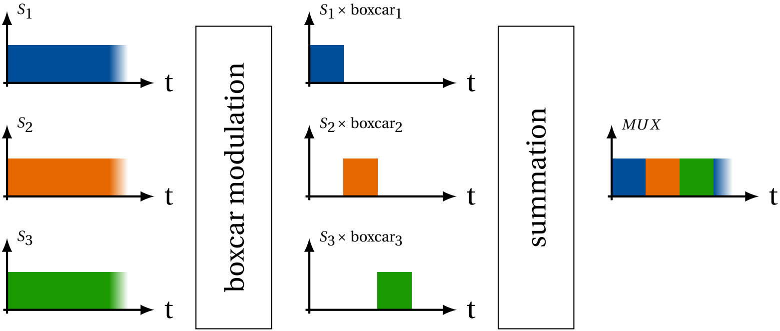


Multiplexing ⇒ spread spectrum

- Code is represented as a third dimension even if this is **not necessarily a physical dimension**.
- CDM is usually used to **spread the spectrum** of the multiplexed signal. But the code dimension is often a repartition both in time, in frequency and some times in amplitude.

Time Domain Multiplexing (TDM)

Time slot of limited duration of each input signal (S_x) is summed

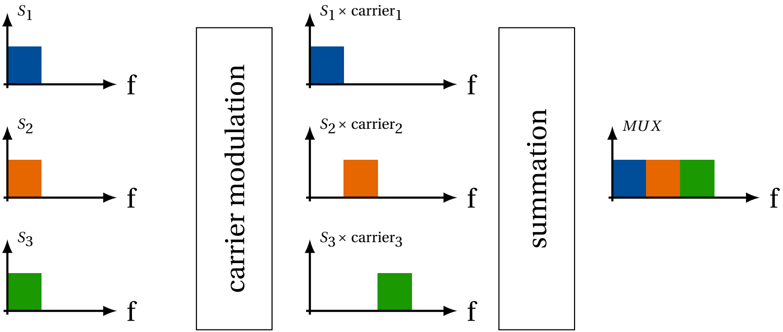


- Requires a specific boxcar (time shifted) modulation / signal
- *Limited duration* ≡ **sampling**

⇒ increasing of the bandwidth
= risk of noise aliasing

Frequency Domain Multiplexing (FDM)

Frequency transposition of each input signal (S_x) is summed

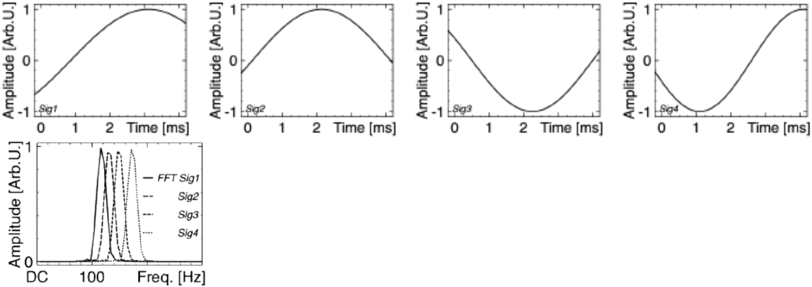


- Requires a specific frequency carrier / signal
- *Summation* ≡ *increasing the* **bandwidth** *and the* **dynamic**

Sine waves multiplexing

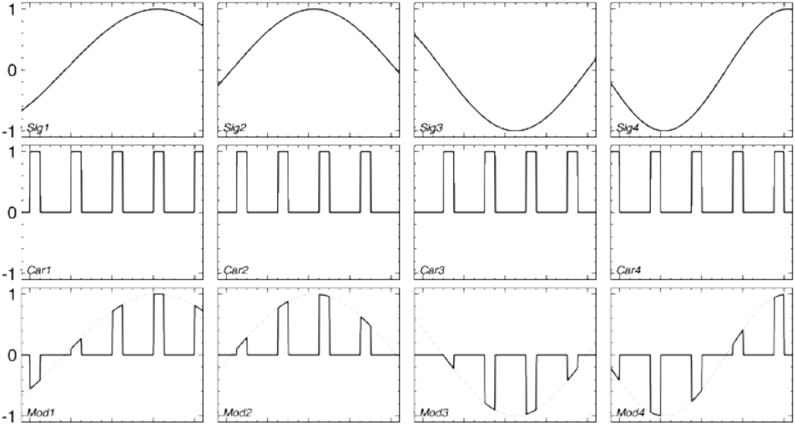
until now, signal has been represented as a time or freq. *"tophat"*

from now, signals will be represented as 4 sine waves



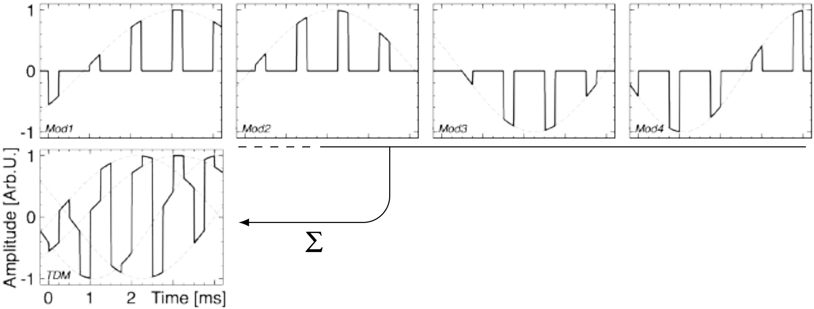
Time Domain/Division Multiplexing - TDM

Modulation - Sampling



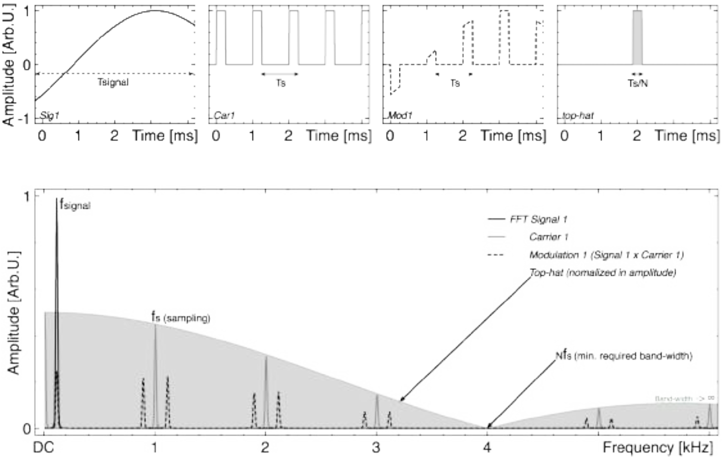
Time Domain/Division Multiplexing - TDM

Summation - multiplexing



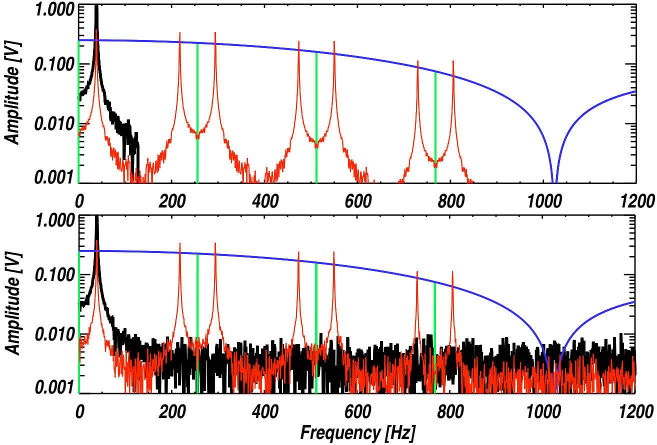
Time Domain/Division Multiplexing - TDM

Spectrum occupancy : $BW_{TDM} > N \times fs > 2 \times N \times BW_{Sig}$



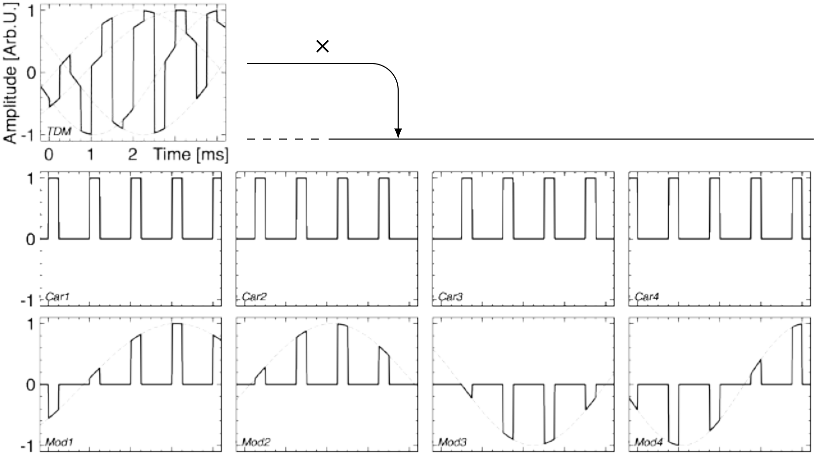
Time Domain/Division Multiplexing - TDM

Shannon-Nyquist Unsatisfied ⇒ Alias the unfiltered white noise



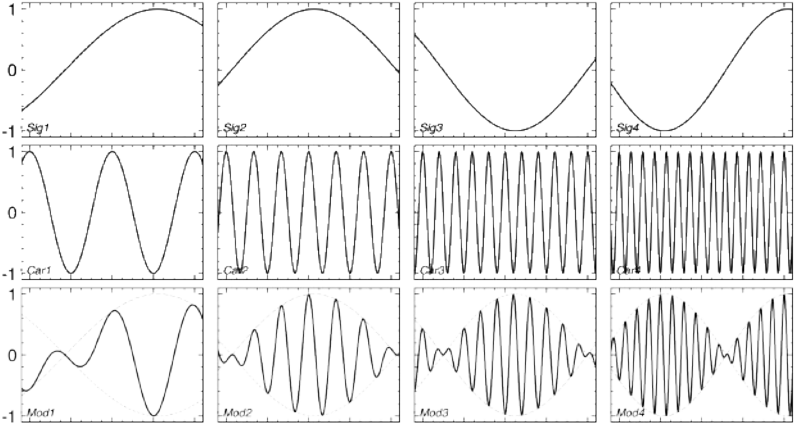
Time Domain/Division Multiplexing - TDM

demultiplexing before sample & hold and filtering



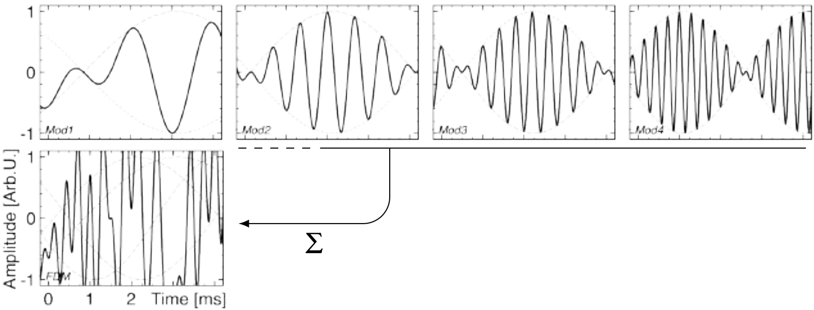
Frequency Domain/Division Multiplexing - FDM

Modulation - Frequency transposition



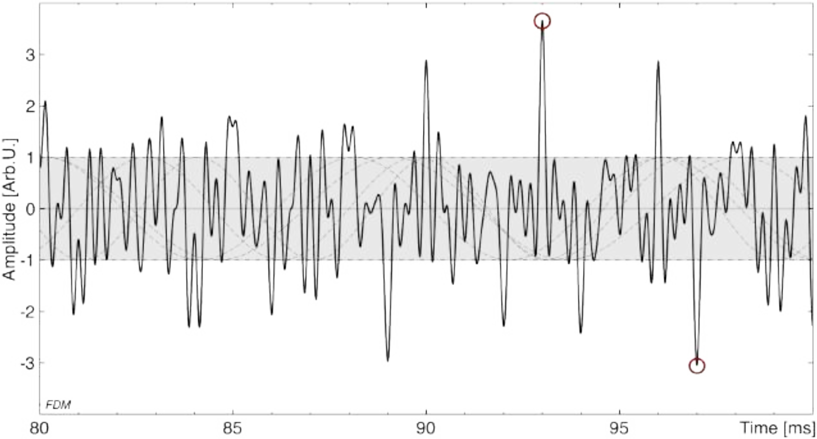
Frequency Domain/Division Multiplexing - FDM

Summation - multiplexing



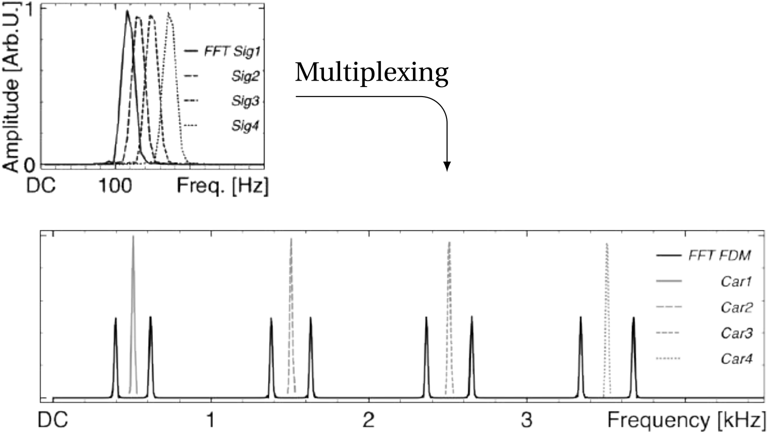
Frequency Domain/Division Multiplexing - FDM

Increasing of the amplitude of the multiplexed signal

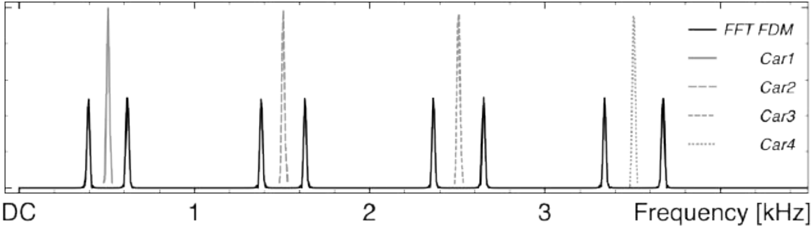


Frequency Domain/Division Multiplexing - FDM

Spectrum occupancy : BW$_{FDM}$ > 2 × N × BW$_{Sig}$



Frequency Domain/Division Multiplexing - FDM

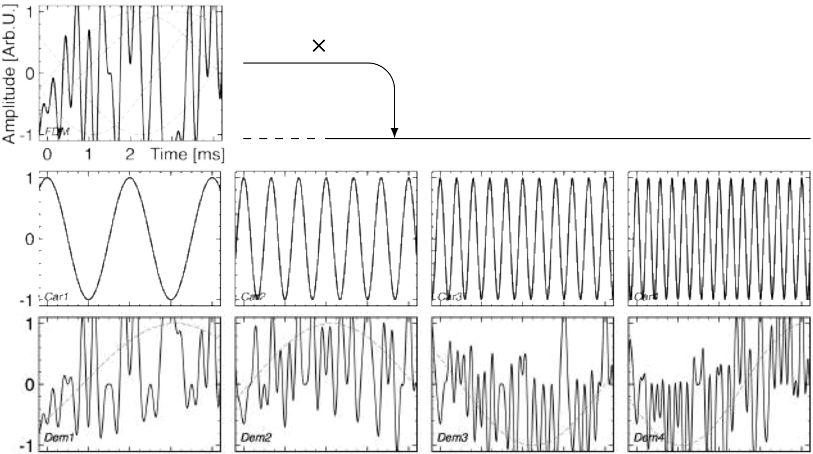


Aliasing of the unfiltered signal and white noise

As for TDM, there is a "Shannon-Nyquist" law (modulation *vs* sampling) which need to limit the signal (and noise) to a bandwidth below an half of the carriers frequency separation

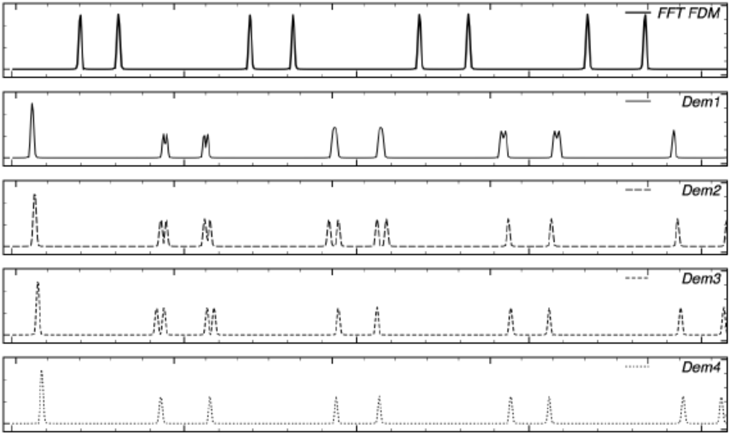
Frequency Domain/Division Multiplexing - FDM

demultiplexing before filtering



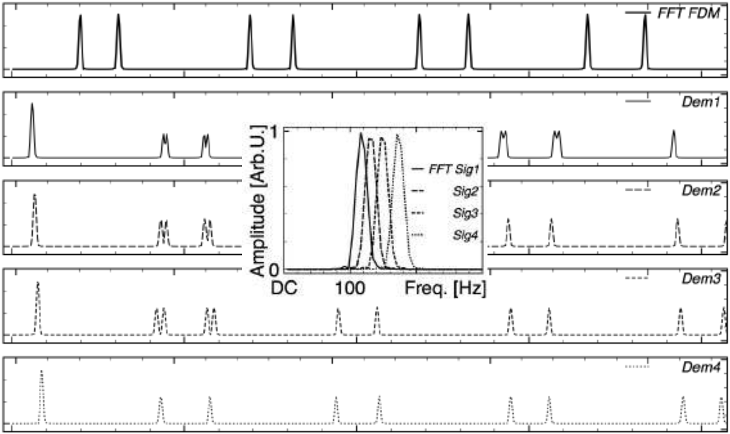
Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



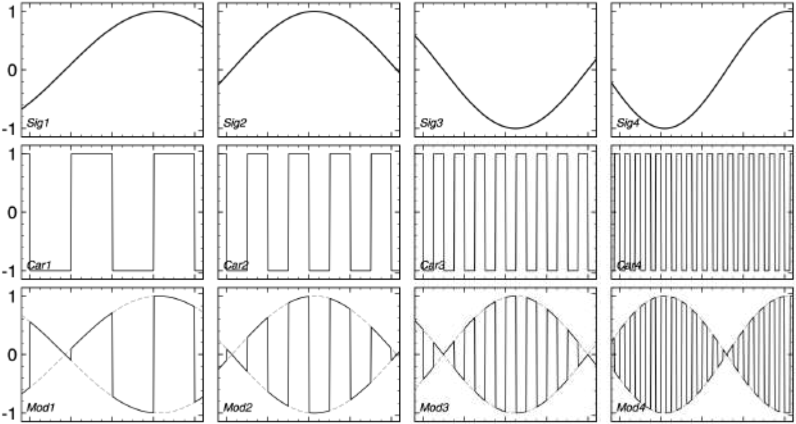
Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



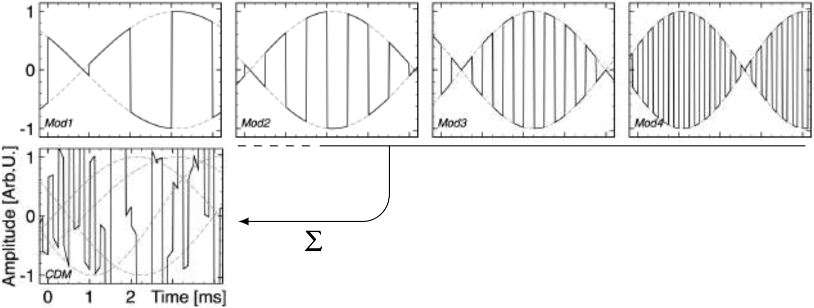
Coded Domain/Division Multiplexing - CDM

Modulation - "Coding" (not the Walsh code)



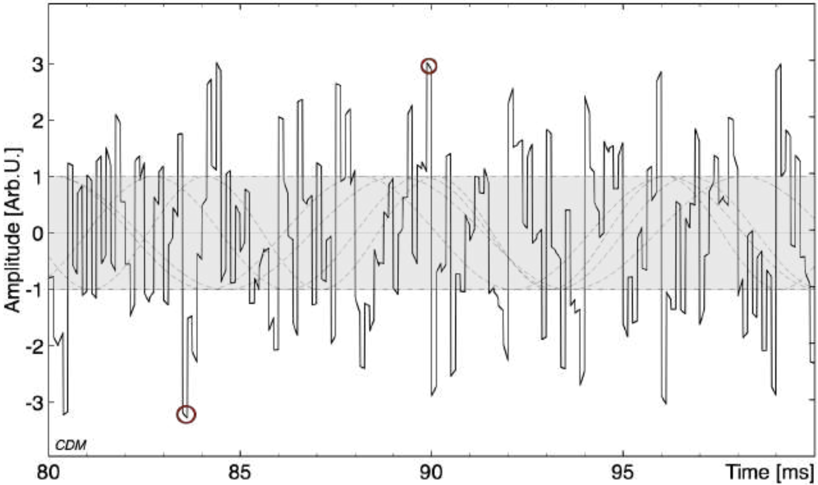
Coded Domain/Division Multiplexing - CDM

Summation - multiplexing



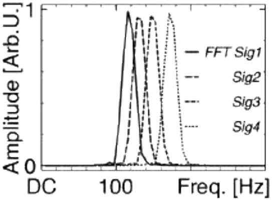
Coded Domain/Division Multiplexing - CDM

Increasing of the amplitude of the multiplexed signal

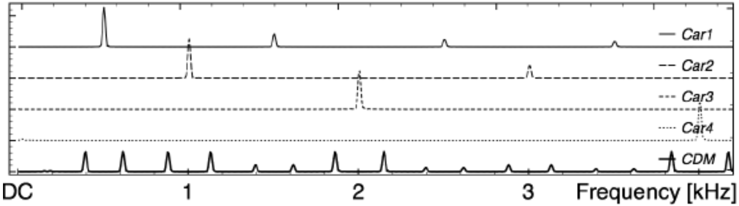


Coded Domain/Division Multiplexing - CDM

Spectrum occupancy : BW$_{FDM}$ > 2 × N × BW$_{Sig}$

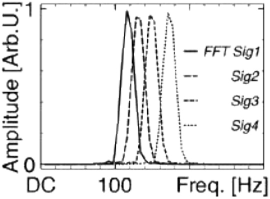


Multiplexing

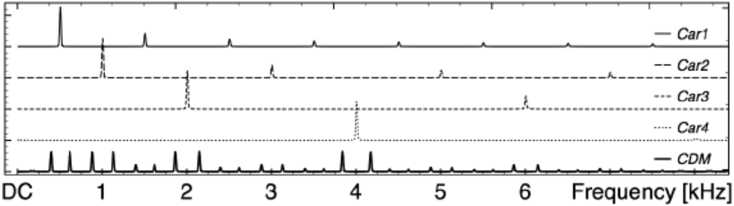


Coded Domain/Division Multiplexing - CDM

Spectrum occupancy : wide "spread" spectrum

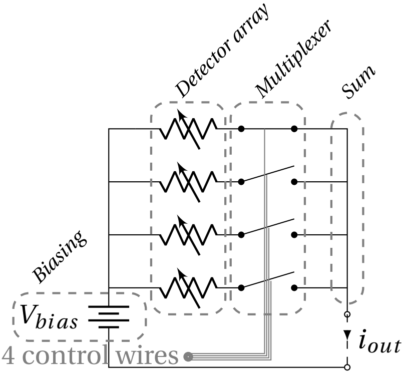


Multiplexing



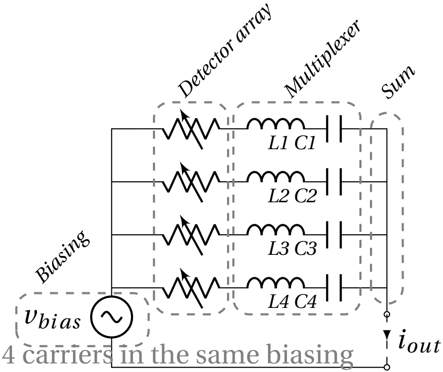
TDM vs FDM "ultra basic" principle

Multiplexer 1D



4 control wires

Car1, Car2, Car3 and Car4

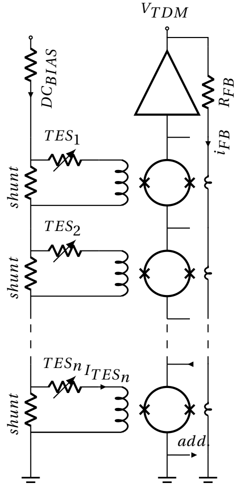


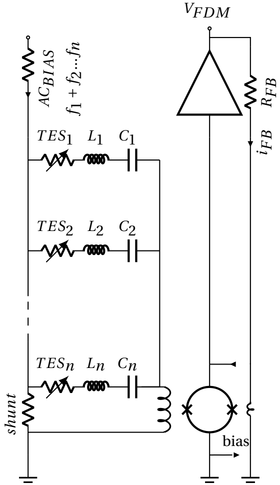
4 carriers in the same biasing

Car1 + Car2 + Car3 + Car4

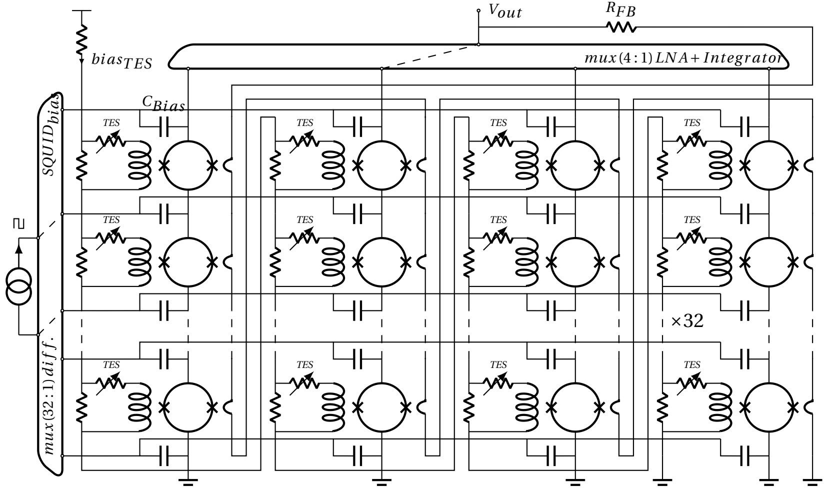
TDM vs FDM with SQUID 1D

Multiplexer 1D



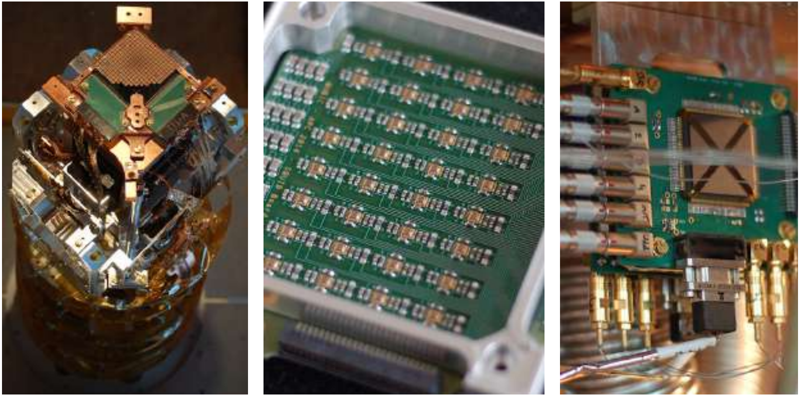


Cryogenic TES time domain multiplexer - QUBIC



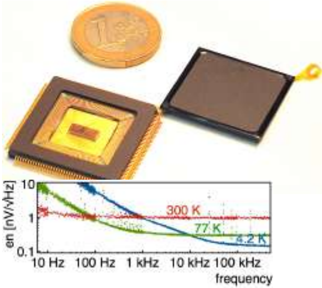
Cryogenic TES time domain multiplexer - QUBIC

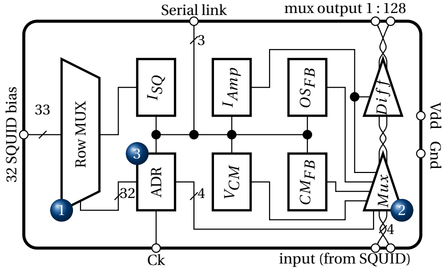
QUBIC readout chaine : TES (300 mK) + SQUID (1K) + ASIC (77K)



Correlated sampling on blind thermometers to remove 1/f noise

SiGe ASIC for cryogenic 1:128 TD SQUID M





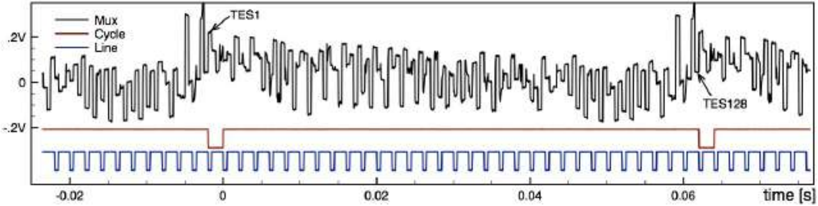
BiCMOS SiGe ASIC

350nm AMS technology

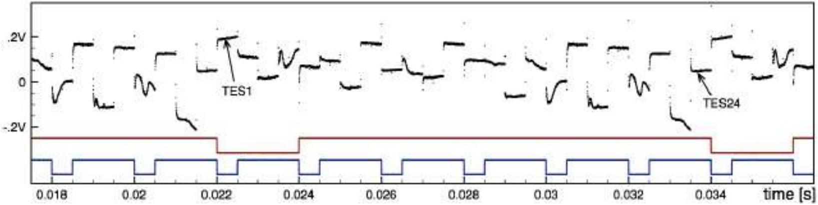
1. SQUID rows addressing:
   Biasing through capacitors with AC multiplexed current sources (1 : 32)
2. Low noise amplifier with multiplexed inputs:
   FLL preamplifier column mux. (1 : 4)
3. Digital addressing circuit controlled by external Ck

Multiplexed time line

1:128 multiplexing rate

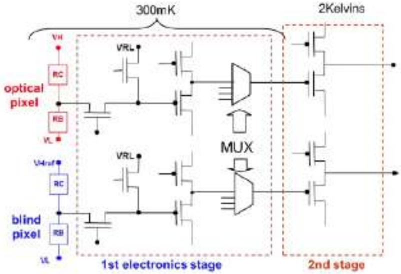


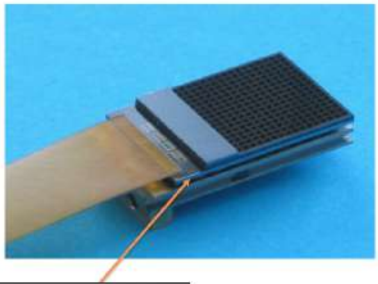
The ASIC allows to reduce the part of the array readout



300 mK CMOS 1:16 TDM - PACS/Herschel satellite

- **Double correlated sampling** to remove 1/f readout noise
- **Differential** measurement with blind pixels to remove the external collective perturbations.



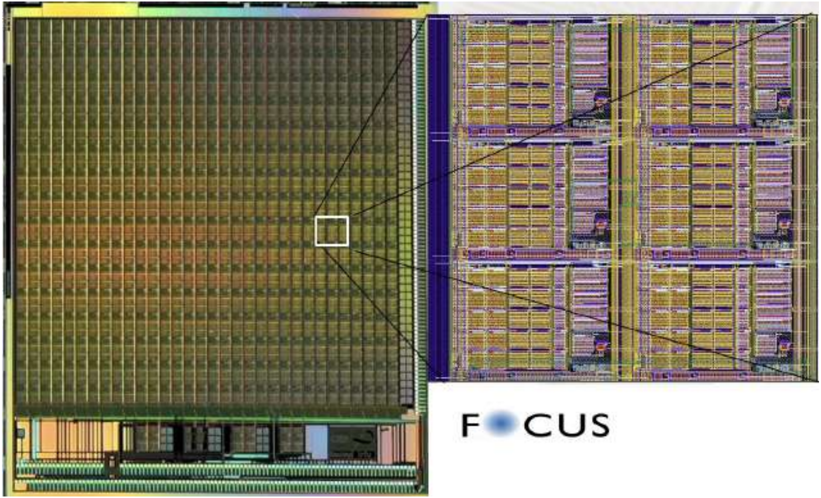


cold electronics layer

P. Agnèse, L. Rodriguez, L. Vigroux et al. - CEA

16*16 50 mK CMOS 16->1 TDM

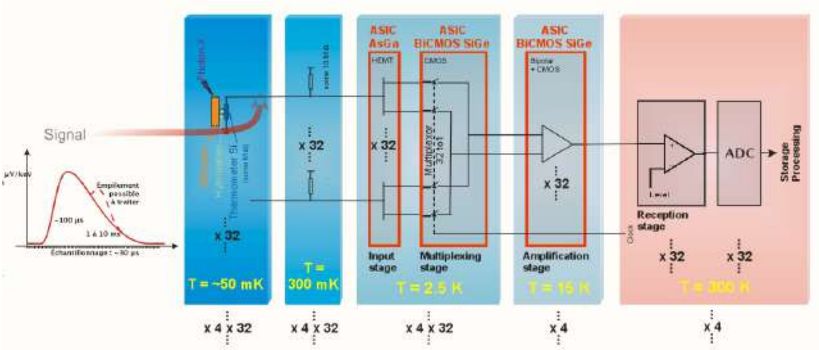
256 pixels / array , 4 readouts / pixel for polarization

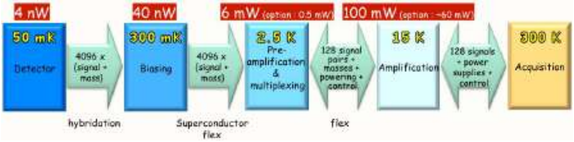


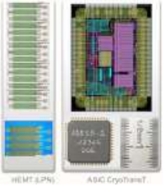
The readout circuit is the base of the detector structure

sensors, absorbers, suspension beams added layer by layer on IC wafer `L. Rodriguez et al. - CEA`

Xray microcalorimeter + TDM (HEMT + SiGe)



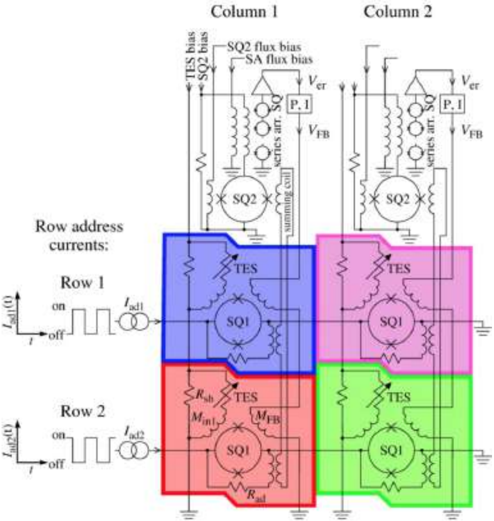




X. de le Broïse et al. - CEA SEDI

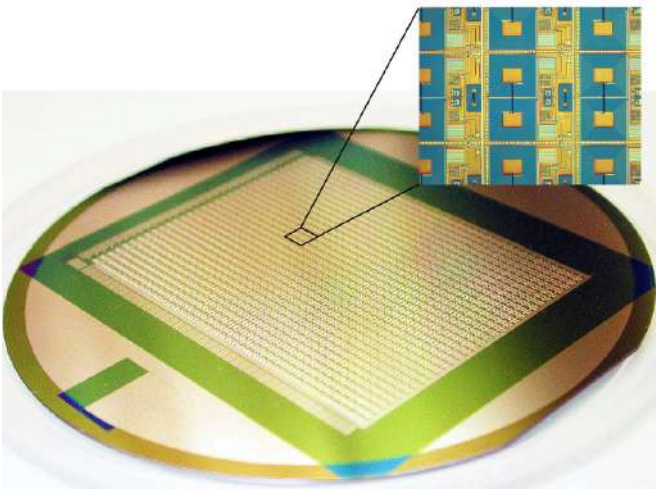
TDM by NIST 2D

`SQUID Multiplexer`
`- G. Hilton, R. Doriese, et al - 2006`



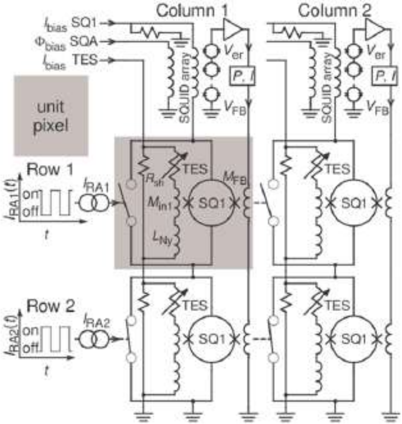
TDM SCUBA2 SQUID Chip - 1300 channels

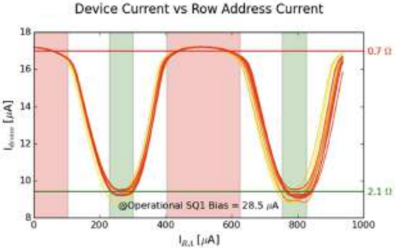
Wafer-scale processing assembled with indium bump-bonding on a TES array of 40x32 pixels



TDM with flux activated switch (FAS)

SQUID turned on applying a row address current IRA "opening" the flux actuated switches





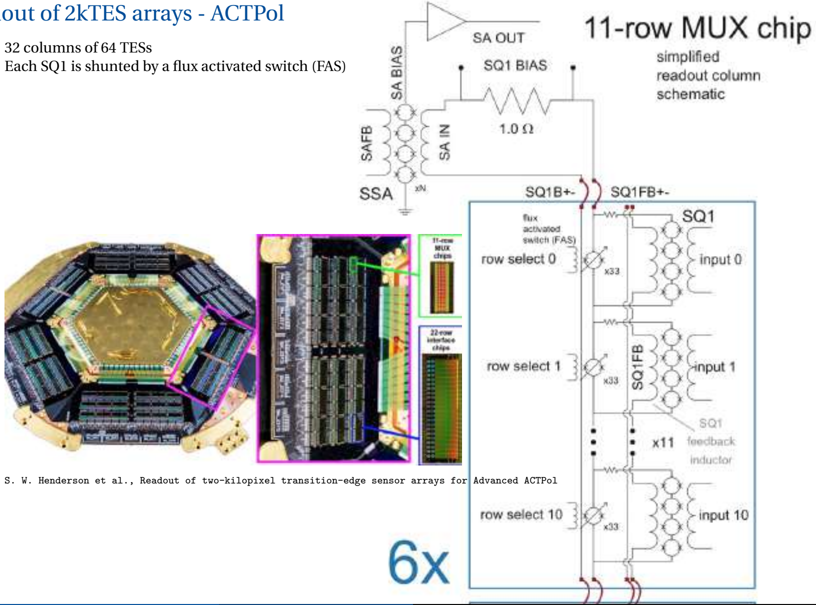
M. Durkin et al., Demonstration of Athena X-IFU Compatible 40-Row Time-Division-Multiplexed Readout

C. Reintsema et al., High-Throughput, DC-Parametric Evaluation of Flux-Activated-Switch-Based TDM and CDM SQUID Multiplexers - IEEETAS2019

TDM with SQ1/FAS 1level

Readout of 2kTES arrays - ACTPol

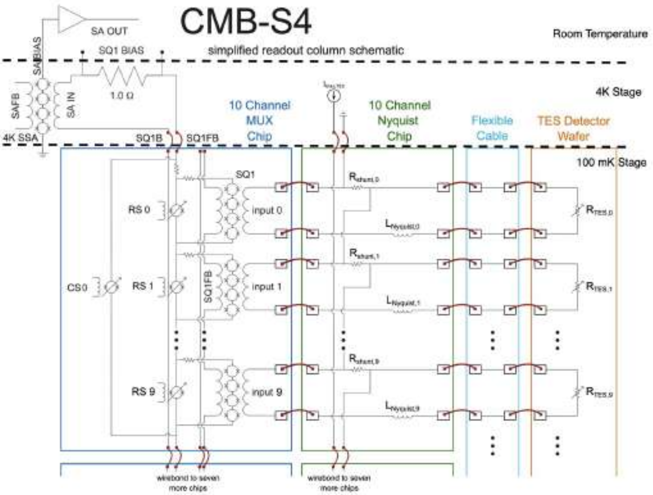
32 columns of 64 TESs
Each SQ1 is shunted by a flux activated switch (FAS)



`S. W. Henderson et al., Readout of two-kilopixel transition-edge sensor arrays for Advanced ACTPol`

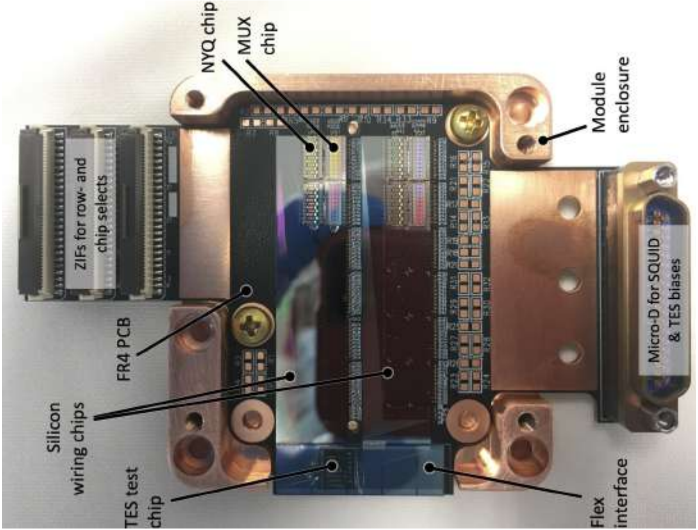
TDM with SQ1/FAS 2levels: 10+8 address lines for 80rows

Readout of half a million of TES for CMB-S4
Each SQ1 is shunted by 2 FAS



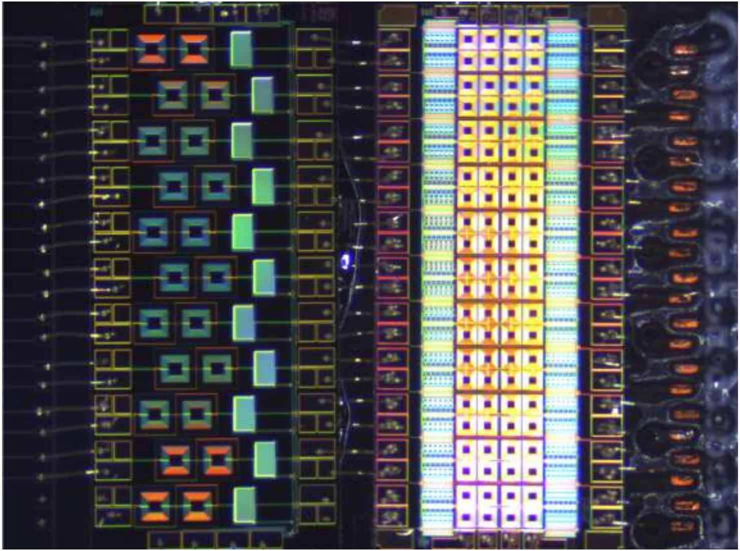
D. Barron et al., Conceptual Design of the Modular Detector and Readout System for the CMB-S4 survey experiment

TDM with SQ1/FAS 2levels: 10+8 address lines for 80rows



D. Barron et al., Conceptual Design of the Modular Detector and Readout System for the CMB-S4 survey experiment

TDM with SQ1/FAS 2levels: 10+8 address lines for 80rows



D. Barron et al., Conceptual Design of the Modular Detector and Readout System for the CMB-S4 survey experiment

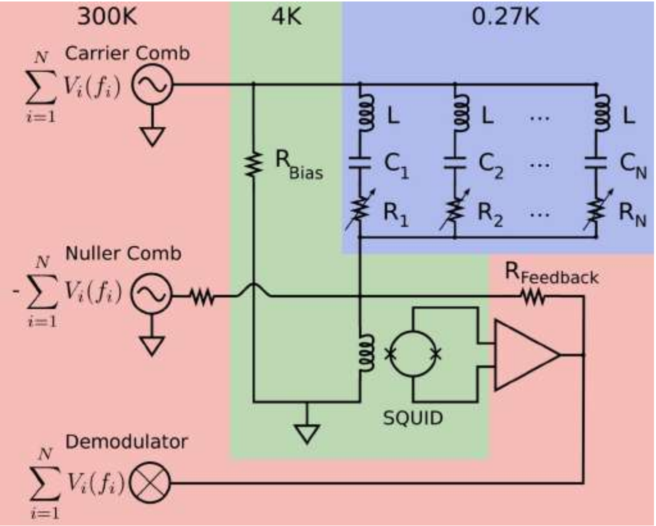
TDM control and front-end electronics using SiGe IC

`S. Chen et al., Warm ASIC for the SQUID/TES Readout of ATHENA?s X-IFU Instrument LTD2021`

`D. Prêle et al. , X-IFU Warm Front End Electronic Demonstrator Model measured performance, SPIE 2024`

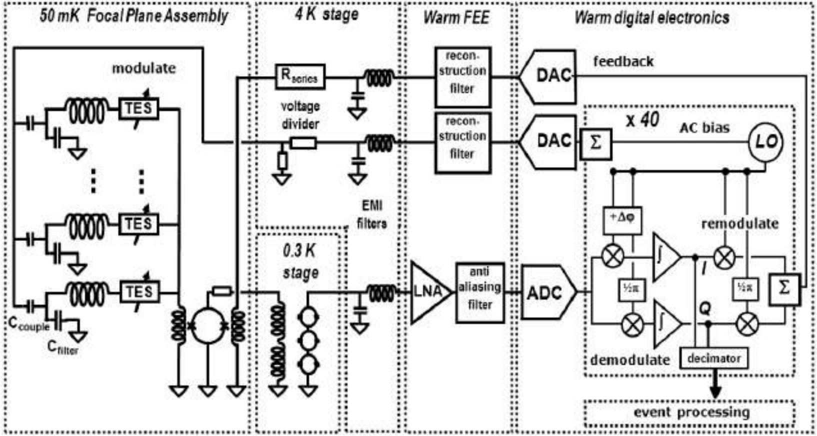
`M. Gonzalez et al. CMB-S4 SiGe ASIC-based daughter board for low temperature detectors front-end analog readout, SPIE2024`

FDM with BaseBand FeedBack



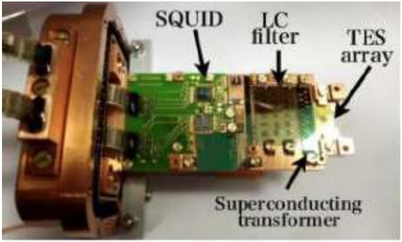
K. Mac Dermid et al. The performance of the bolometer array and readout system during the 2012/2013 flight of the E and B experiment - 2014

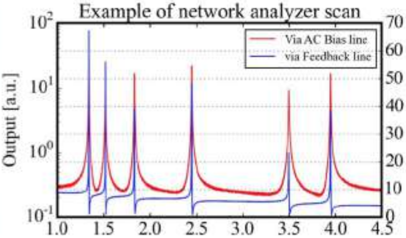
FDM with BaseBand FeedBack



SRON for SAFARI SPICA and ATHENA X-IFU

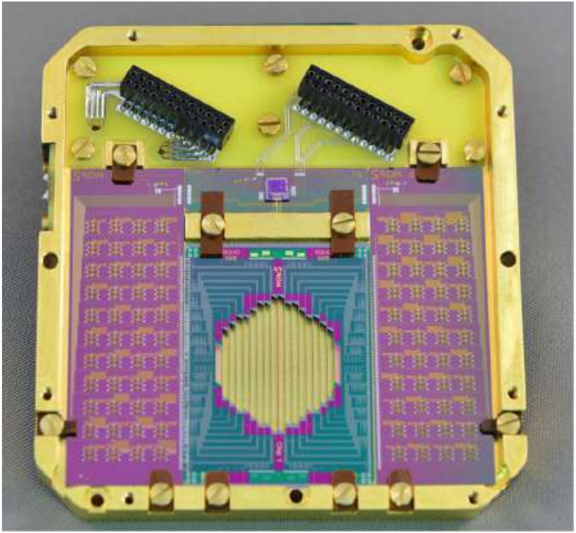
FDM with BaseBand FeedBack ATHENA X-IFU demonstrator





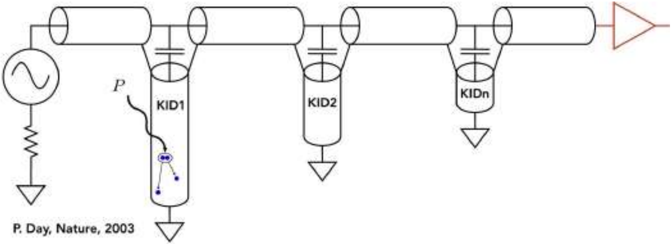
`Development of FDM for the X-ray Integral Field Unit (X-IFU) on the Athena - H. Akamatsu et al. - 2016`

FDM with BaseBand FeedBack for the far-infrared satellite mission SPICA

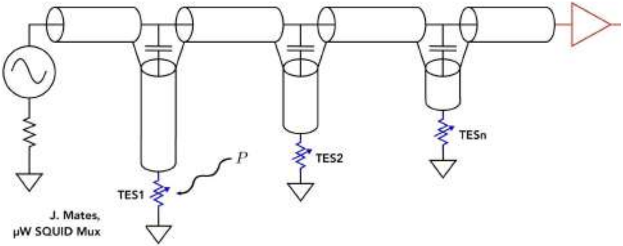


Micro-wave multiplexing

KID vs TES Multiplexer



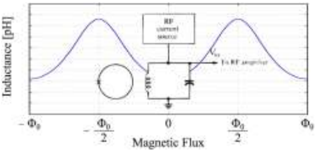
P. Day, Nature, 2003

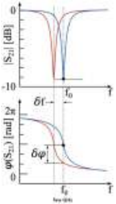


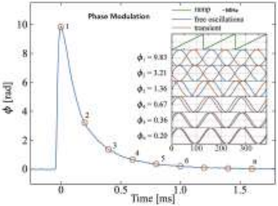
J. Mates, µW SQUID Mux

Micro-wave multiplexing … in real

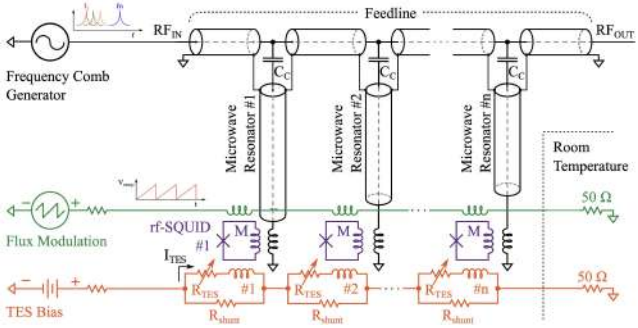
with RF SQUID & common flux-bias line





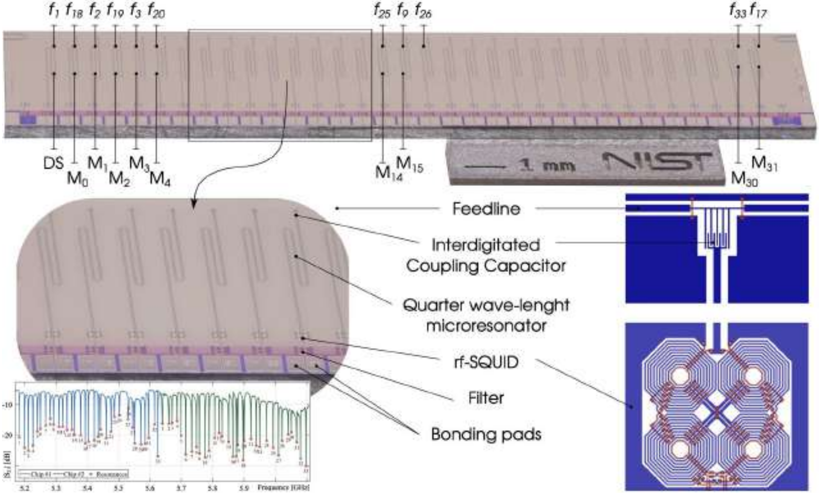


`Kraft et al., Superconducting Quantum Interference Device, 2017`



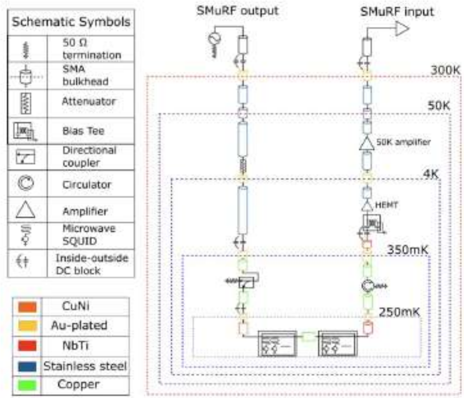
`Beckera, Bennett et al., Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment micro-calorimeters - JINST 2019`

Micro-wave multiplexing takes advantage **large BW** to combine signals of hundreds of sensors



Beckera, Bennett et al., Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment micro-calorimeters - JINST 2019

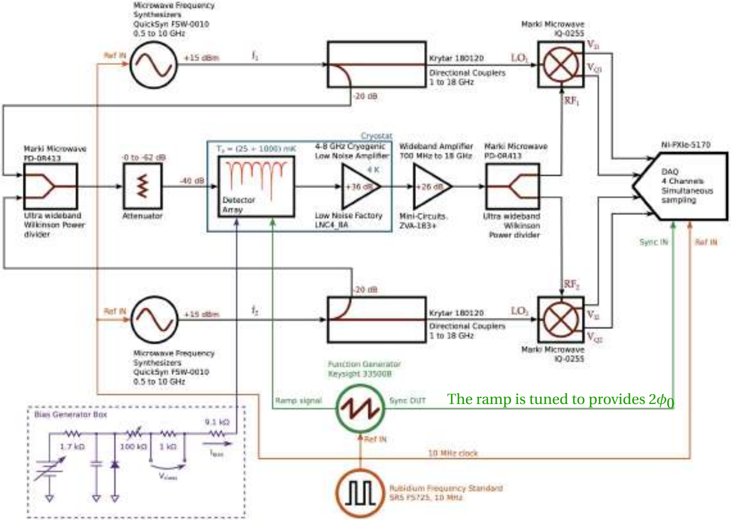
a Micro-wave multiplexing **Cryogenic detection chain**



Cukierman, Ahmed et al., Microwave Multiplexing on the Keck Array - JLTP2020

20 dB HEMT 4 K + 10 dB 50 K (2 amplifiers : better linearity allow more tones). Bias tee heat sinks HEMT to 4 K. Room-temperature amplifier boosts the gain 20 dB

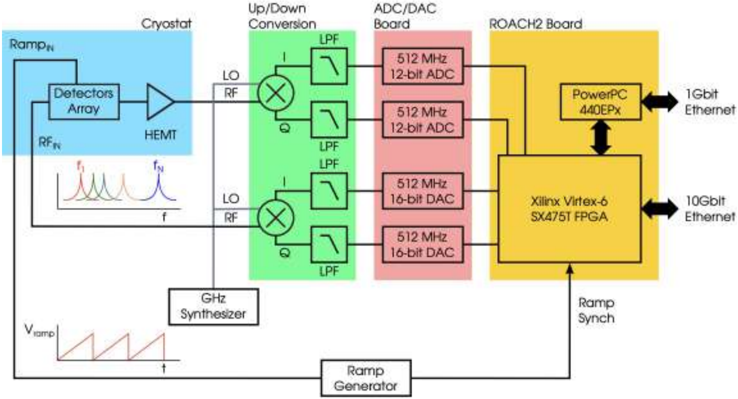
a Micro-wave multiplexing **homodyne** readout - 2 Channels



The ramp is tuned to provides $2\phi_0$

Beckera, Bennett et al., Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment micro-calorimeters - JINST 2019

a Micro-wave multiplexing **heterodyne**

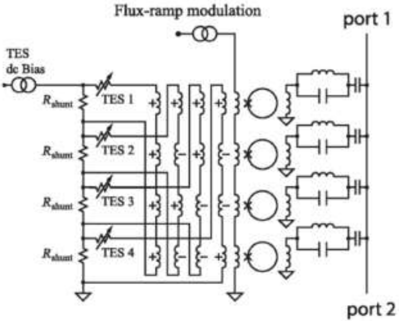


`Beckera, Bennett et al., Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment micro-calorimeters - JINST 2019`

software-defined radio techniques also used for MKIDs readout

a Micro-wave multiplexing

with four-pixel implementation of spread-spectrum SQUID multiplexer (SSMux).



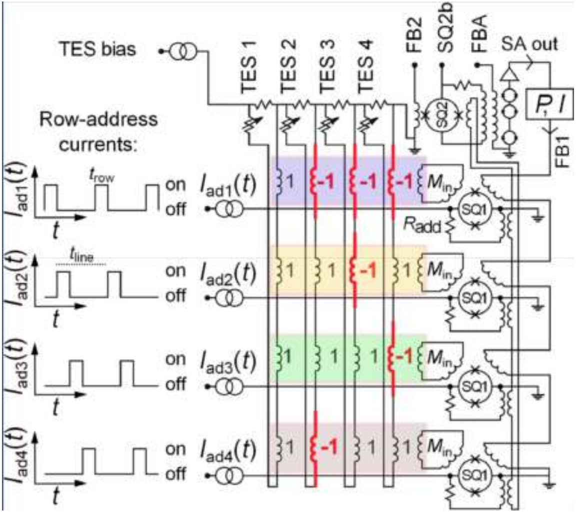
D. Bennett et al., Microwave SQUID multiplexing for the Lynx x-ray microcalorimeter, 2019

The current from each TES couple to all four SQUIDs shown, with coupling polarities modulating in a Walsh code ≡ CDM topology.

Improve the BW efficiency bandwidth utilization under low count rate conditions by the implementation of a spread-spectrum multiplexing

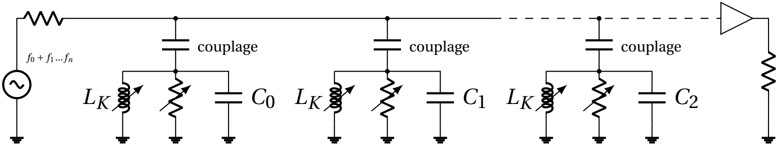
prele@apc.in2p3.fr

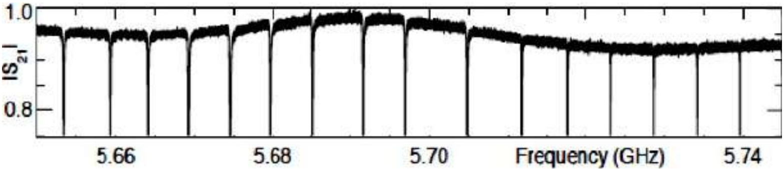
CDM with "TDM"



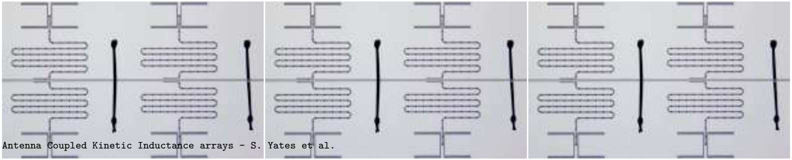
G. M. Stiehl et al., Code-division multiplexing for x-ray microcalorimeters

KID multiplexing





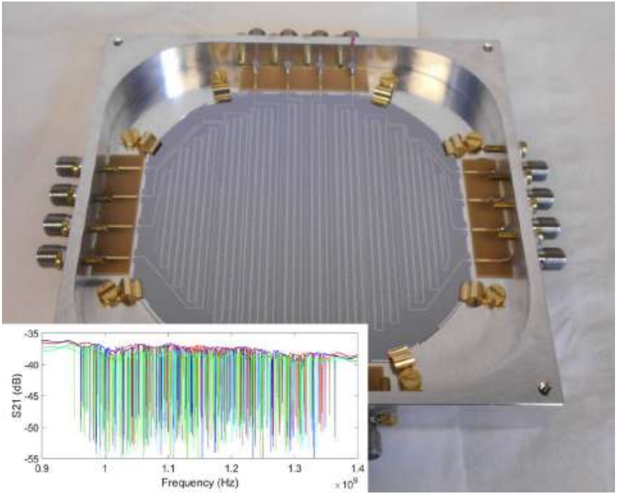
`B. Mazin, Microwave Kinetic Inductance Detectors: The First Decade`



`Antenna Coupled Kinetic Inductance arrays - S. Yates et al.`

NIKA2

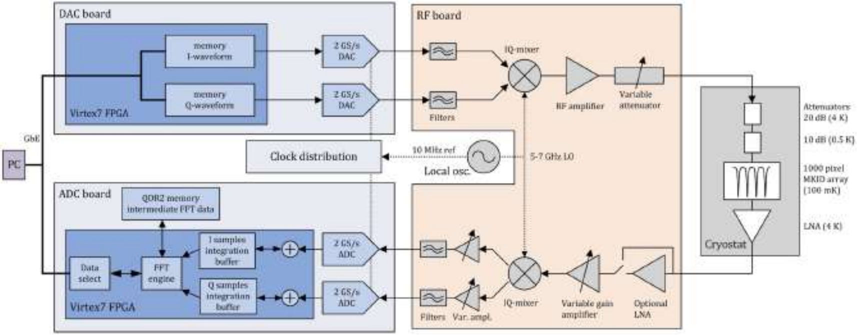
260 GHz NIKA2 arrays, 1140 KIDs via eight feed-lines
Sweep over four feedlines of the 150 GHz array



R. Adam et al., The NIKA2 large-field-of-view millimetre continuum camera for the 30 m IRAM telescope - A&A2018

KIDs readout

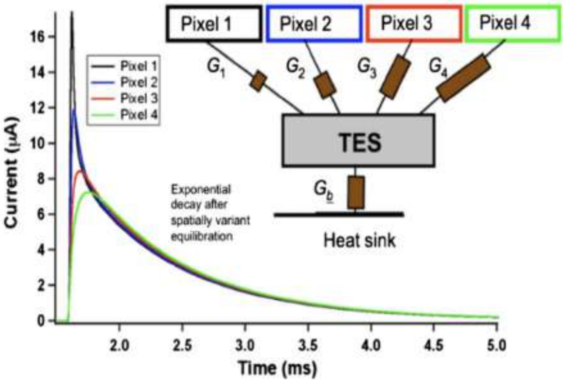
including digital electronics, RF electronics and cryostat with MKID array

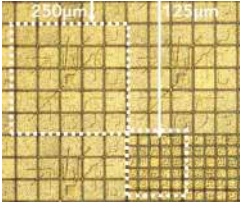


J. van Rantwijk et al., Multiplexed Readout for 1000-pixel Arrays of Microwave Kinetic Inductance Detectors - TMTT2016

Thermal Mux with TES- "hydra"

Absorbers connected to a single TES via varied thermal conductance G1, 2, ...n ... then the TES is weakly thermally coupled to a heatsink via a common conductance Gb



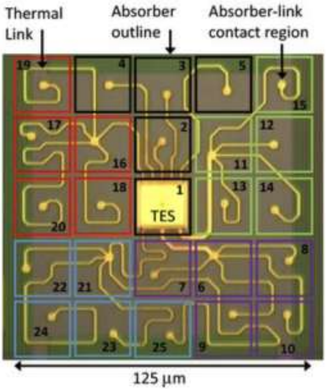


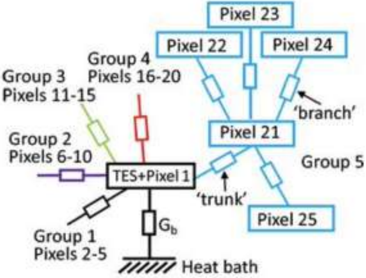
X-ray Microcalorimeter Technology Roadmap

Allows dense pitch pixels in the center of the focal plan, where routing is particularly complicated

Thermal Mux with TES- "hydra"

Absorbers connected to a single TES via varied thermal conductance G1, 2, ...n ... then the TES is weakly thermally coupled to a heatsink via a common conductance Gb

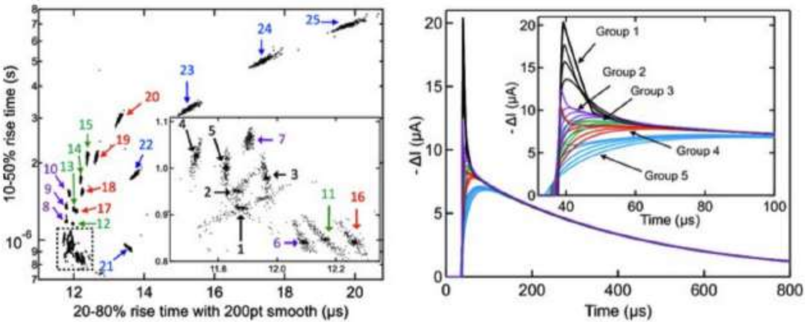




S. Smith et al., Toward 100,000-Pixel Microcalorimeter Arrays Using Multi-absorber Transition-Edge Sensors

Thermal Mux with TES- "hydra"

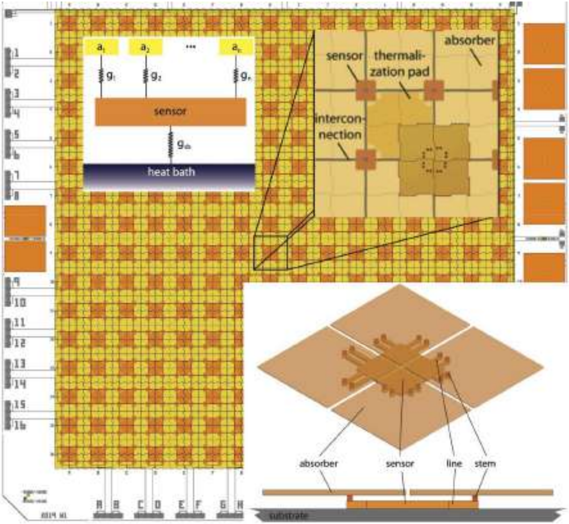
Absorbers connected to a single TES via varied thermal conductance G1, 2, ...n ... then the TES is weakly thermally coupled to a heatsink via a common conductance Gb



S. Smith et al., Toward 100,000-Pixel Microcalorimeter Arrays Using Multi-absorber Transition-Edge Sensors Rise-time scatter showing 25 separate regions with the different groups of pixels identified

Thermal Mux "hydra" with MMC

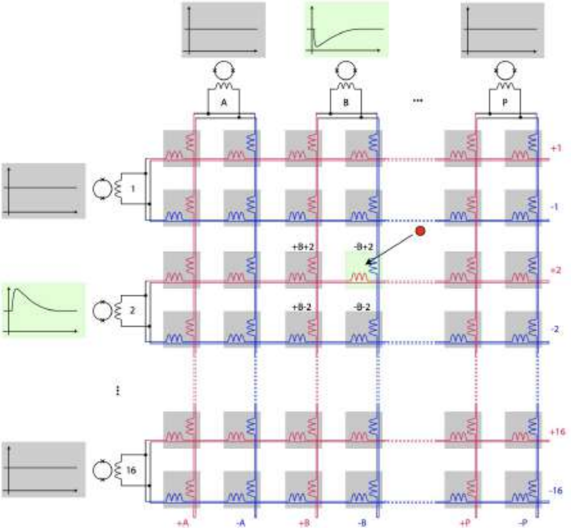
One sensor with four absorbers, connected with four different thermal links



D. Schulz, Development and characterization of MOCCA, a 4k-pixel molecule camera for the energy-resolved detection of neutral molecule fragments

Row and column SQUID readout

+ 2 polarity in the SQUID + hydra with four different thermal links



D. Schulz, Development and characterization of MOCCA, a 4k-pixel molecule camera for the energy-resolved detection of neutral molecule fragments

Conclusion

- Multiplexing for the readout of large arrays

  Reduction of the wiring

- The multiplexer must have better :
  - **bandwidth** $> 2 \times N \times BW_{Sig}$,
  - **dynamic** range and/or
  - **noise** performances $\propto \sqrt{N}$.

  than for a readout of one pixel

- Multiplexing is like a modulation + summation
  - **TDM is based on "boxcar" modulation**

    Switchs or shift
  - **FDM is based carrier modulation**

    LC filters
  - + lot of "new" Mux as CDM, μMux, Thermal Mux ...

☞ Many new applications mix different "multiplexing" technics

- *SQUID multiplexers for TES* - K. D. Irwin - Physica C 2002
- *Shannon Limits for LowT Detector Readout* - K. D. Irwin - 2009
- *Dev. of FDM for the X-IFU* - H. Akamatsu et al. - 2016
- *Microwave SQUID mux for the Lynx x-ray μCalo.* D. Bennett 2019
- *Multiplexed readout for kMKIDs arrays* J van Rantwijk - IEEE 2016
- *SQUID readout multiplexers for TES arrays* - A.T. Lee - NIMA 2006
- *High-resolution γ-ray spectro. μMux TES array* - O. Noroozian - 2013
- *Readout of 2kTES arrays for Advanced ACTPol* - S.W. Henderson
- *Le bolomètre résistif* - L. Rodriguez - DRTBT 2009
- *SQUID et Multiplexage* - D. Prêle - DRTBT 2009
- *Front-end Multiplexing* - D. Prêle - INFIERI 2014
- *Readout systems for space applications* - A. Tartari CMB Day 2023
- *Front-end Multiplexing applied to SQUID* - D. Prêle - JLTP 2015
- *Multiplexage signaux analogiques - cryo. app* - D. Prêle - DRTBT 2018
- *Cryo Read-Out Review & TD SQUID M with SiGe IC* - D. Prêle - BI 2008
- *Supercon. mux for arrays of TESs* - JA. Chervenak - APL1999