R&D for CMB instrumentation in Spain

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On behalf of the following teams:
CAB, DICOM (UC), IAC, IFCA (CSIC-UC)

Towards the European Coordination of the CMB programme, APPEC-ASTRONET,
August 31-1 September 2015, Florence

CONTENTS

- Radiometer instrumentation
- KID's developments
- Plans for the next generation of experiments at the low frequency range

CMB experiments

- Tenerife exp., VSA, COSMOSOMAS
- Contribution to Planck LFI (BEMs at 30 and 44 GHz, REBA), and also to HFI.
- QUIJOTE experiment, most of the development produced by the Spanish groups.
- Participation in COrE+

Most of the activities funded by the Ministry of Economy.

Radiometer instrumentation

Eduardo Artal et al.
(Dpt. Communications Engineering, DICOM)

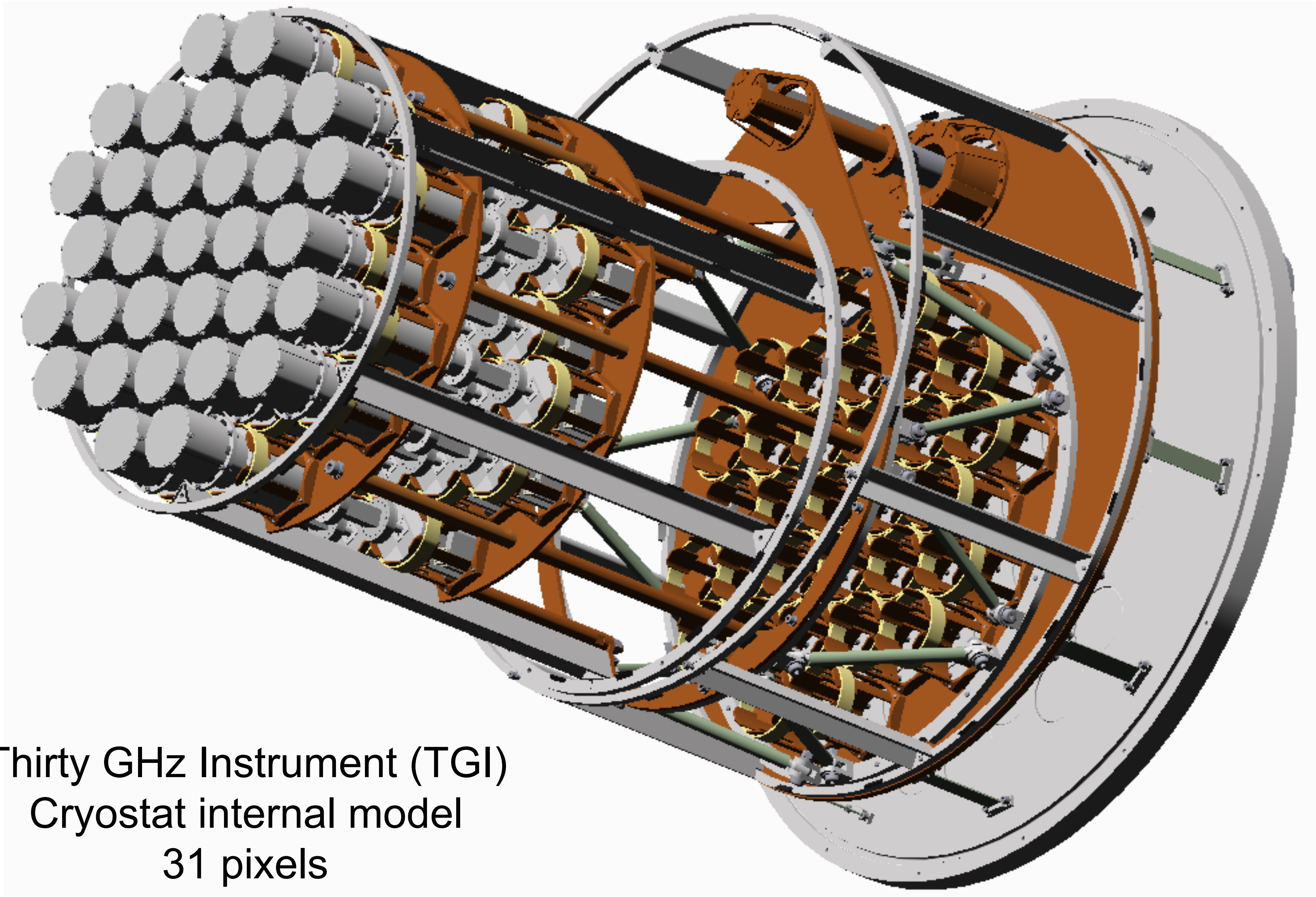
QUIJOTE Experiment

QUIJOTE dome with the two telescopes (Teide Observatory)

QUIJOTE: Project basic features

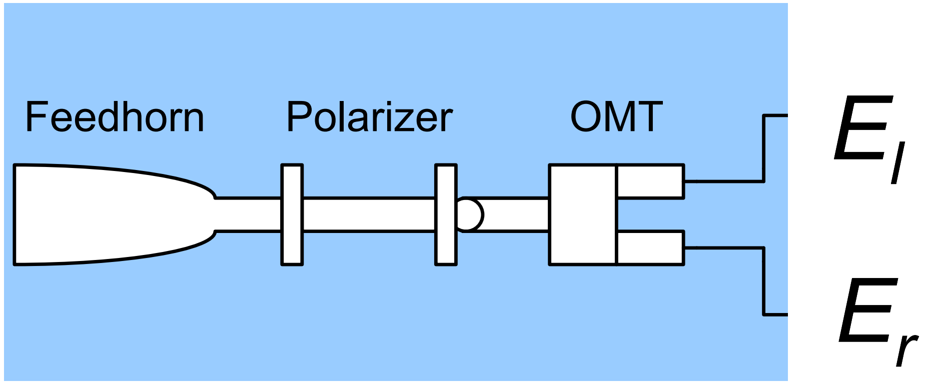
- **Site**: El Teide Observatory, Tenerife, Canary Islands, Spain
- **Frequencies**: 11, 13, 17, 19, 30 and 40 GHz.
- **Angular resolution**: ~1 degree
- **Telescopes and instruments:**
  - **Phase I** First telescope with a multichannel instrument providing 11-20 GHz (in operation).
  - **Phase II** Second telescope, with a second instrument with 31 polarimeters @ 30 GHz (already in the commissioning phase). Third Instrument with 31 polarimeters @ 40 GHz (to be completed at the end of 2016).

QUIJOTE TGI



Thirty GHz Instrument (TGI)
Cryostat internal model
31 pixels

TGI Receiver principle of operation

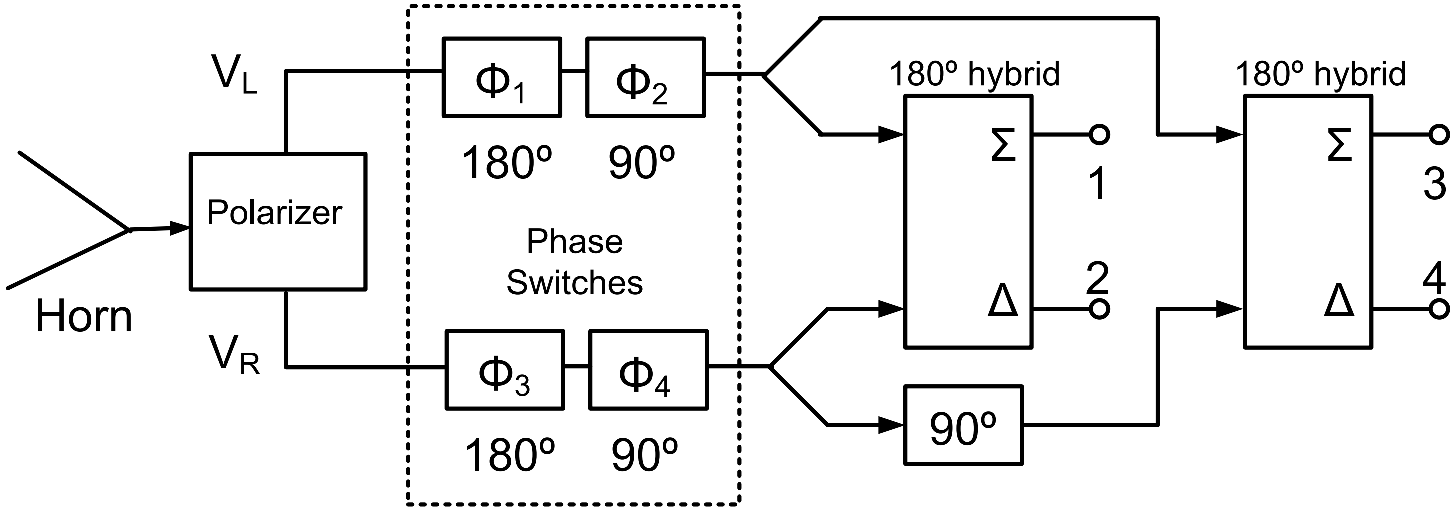


Circular components of electric fields

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} \equiv \begin{pmatrix} |E_l|^2 + |E_r|^2 \\ 2\,\mathrm{Re}\left(E_l^* E_r\right) \\ -2\,\mathrm{Im}\left(E_l^* E_r\right) \end{pmatrix}$$

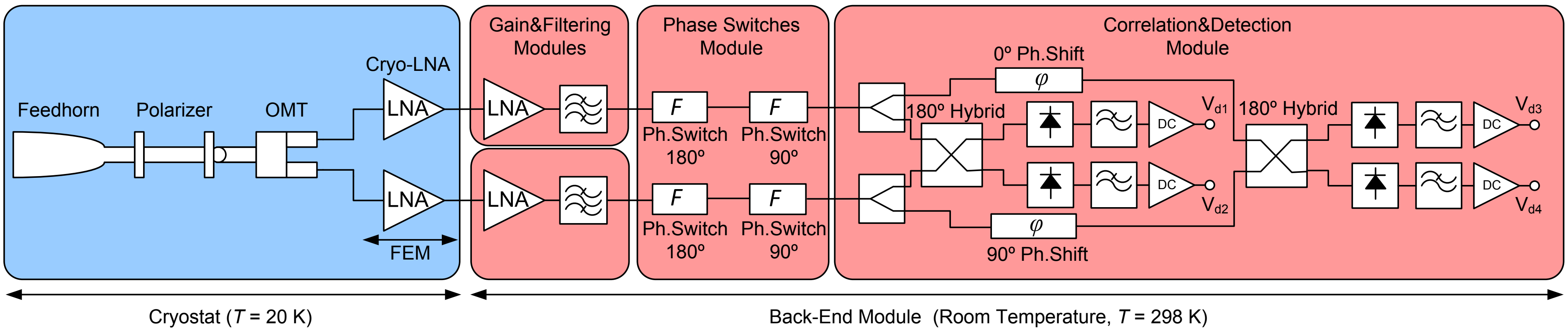
Stokes parameters

Stokes parameters



Φ	I	Q	U
0º	Vd1 + Vd2 = Vd3 + Vd4	Vd1 – Vd2	Vd3 – Vd4
90º	Vd1 + Vd2 = Vd3 + Vd4	Vd3 – Vd4	Vd2 – Vd1
180º	Vd1 + Vd2 = Vd3 + Vd4	Vd2 – Vd1	Vd4 – Vd3
270º	Vd1 + Vd2 = Vd3 + Vd4	Vd4 – Vd3	Vd1 – Vd2

QUIJOTE 30 GHz Instrument (TGI)

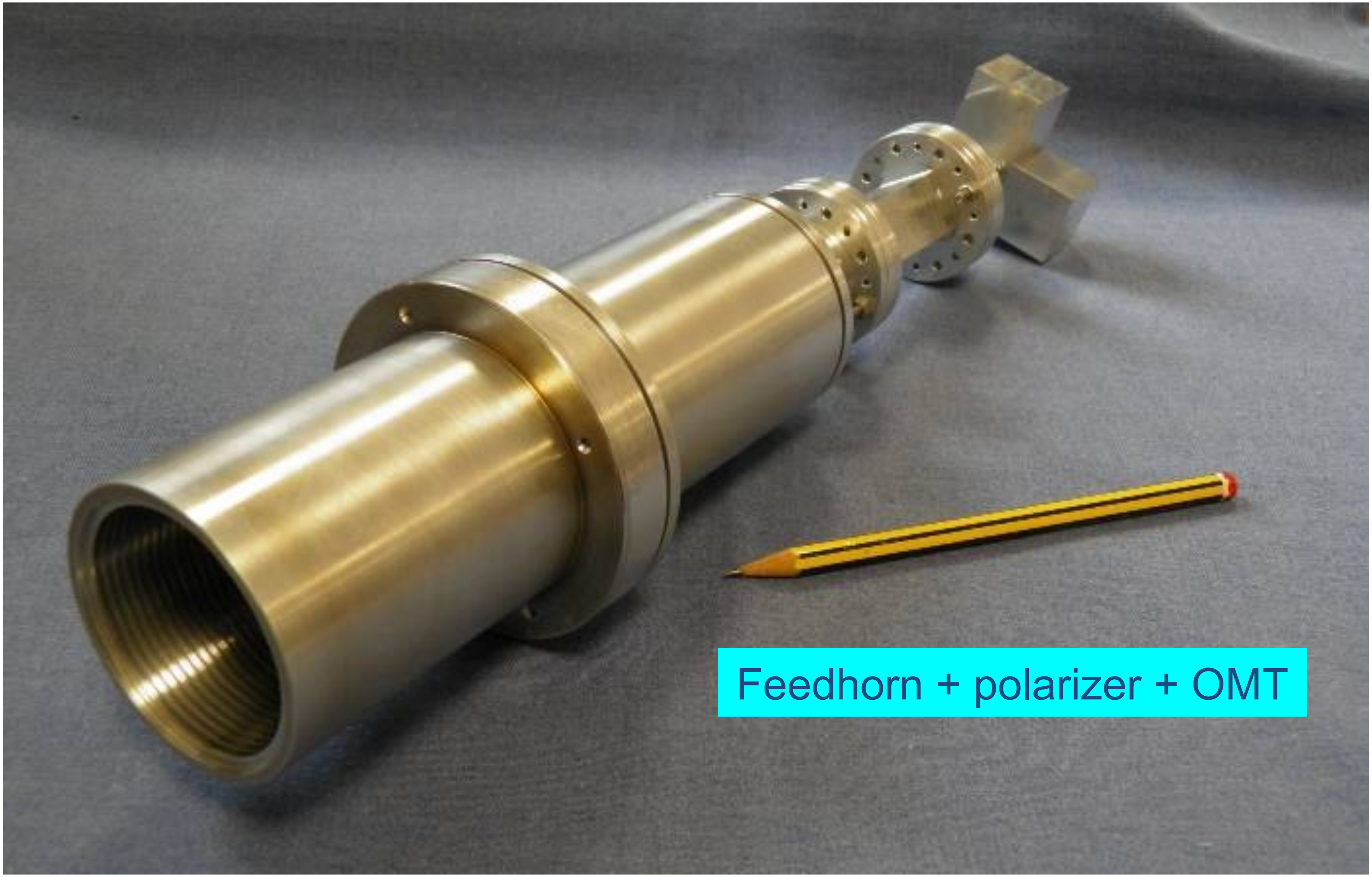


- Phase switches in two balanced branches
- Microwave Correlation (180º hybrids)
- Direct detection (Schottky diode)
- Simultaneous measurement of Stokes parameters (I, Q, U)

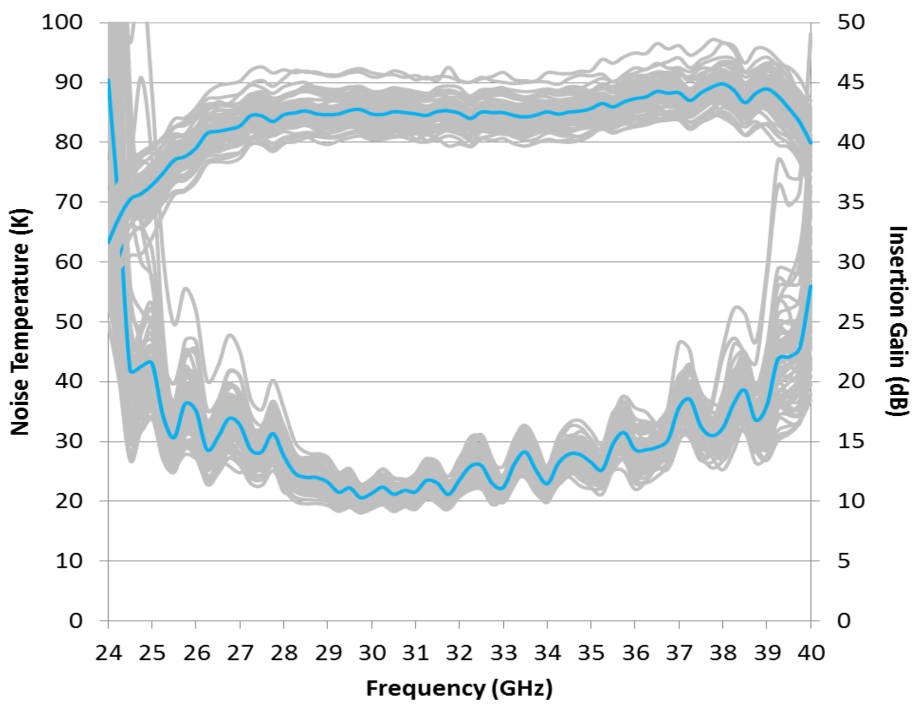
$$I \propto V_{d1} + V_{d2} \;\; \text{or} \;\; V_{d3} + V_{d4}$$

$$Q \propto V_{d1} - V_{d2} \qquad\qquad U \propto V_{d3} - V_{d4}$$

One pixel (TGI)

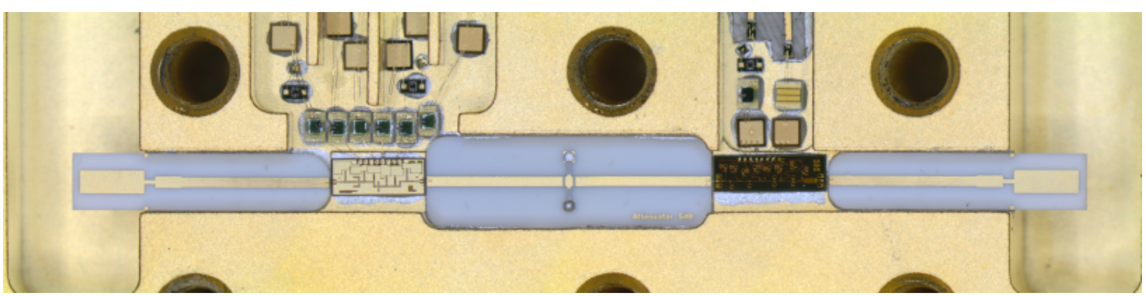


Cryo-LNA (FEM) 26-36 GHz – IAF MMIC Ka V2 BA



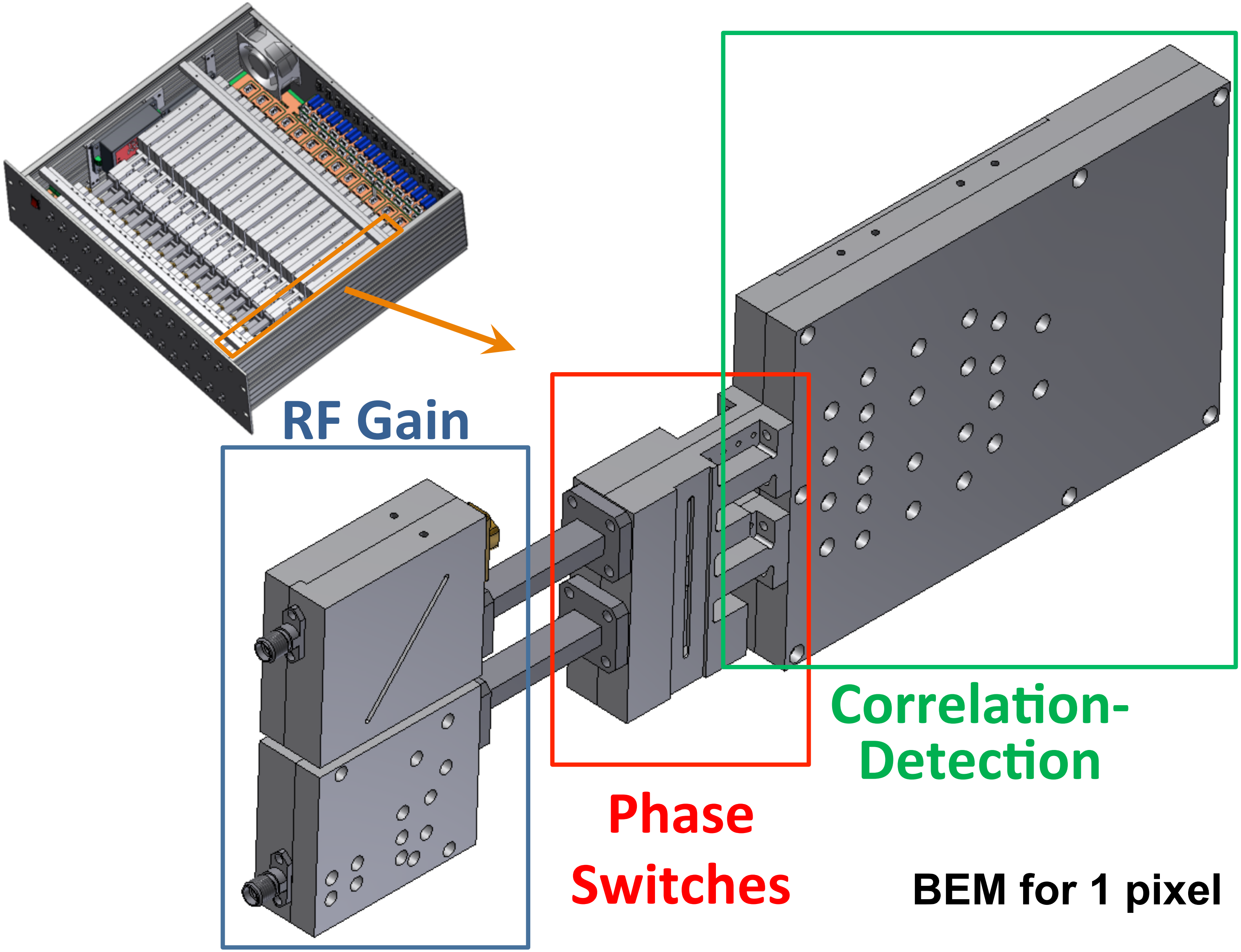
Performance of the 62 cryogenic-Low Noise Amplifier (LNA) units at 12 K
(Gain and Noise Temperature)

Average values (26-36 GHz):
Gain ≈ 43 dB
Noise temperature ≈ 25 K



Internal view:
Two MMIC chips

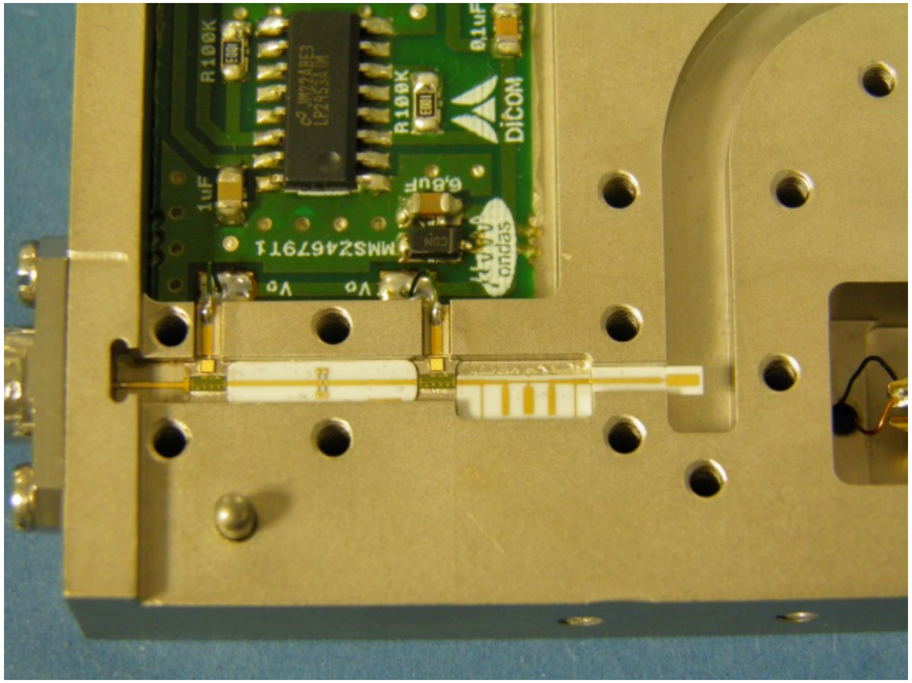
TGI BEM rack assembly: 1 unit of 16

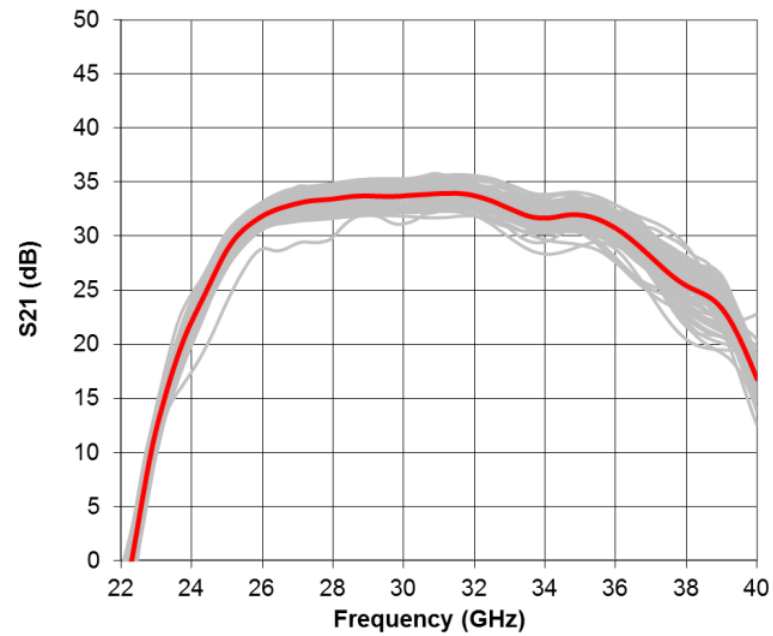


BEM for 1 pixel

BEM rack TGI (16 pixels)

RF Gain BEM - QUIJOTE TGI



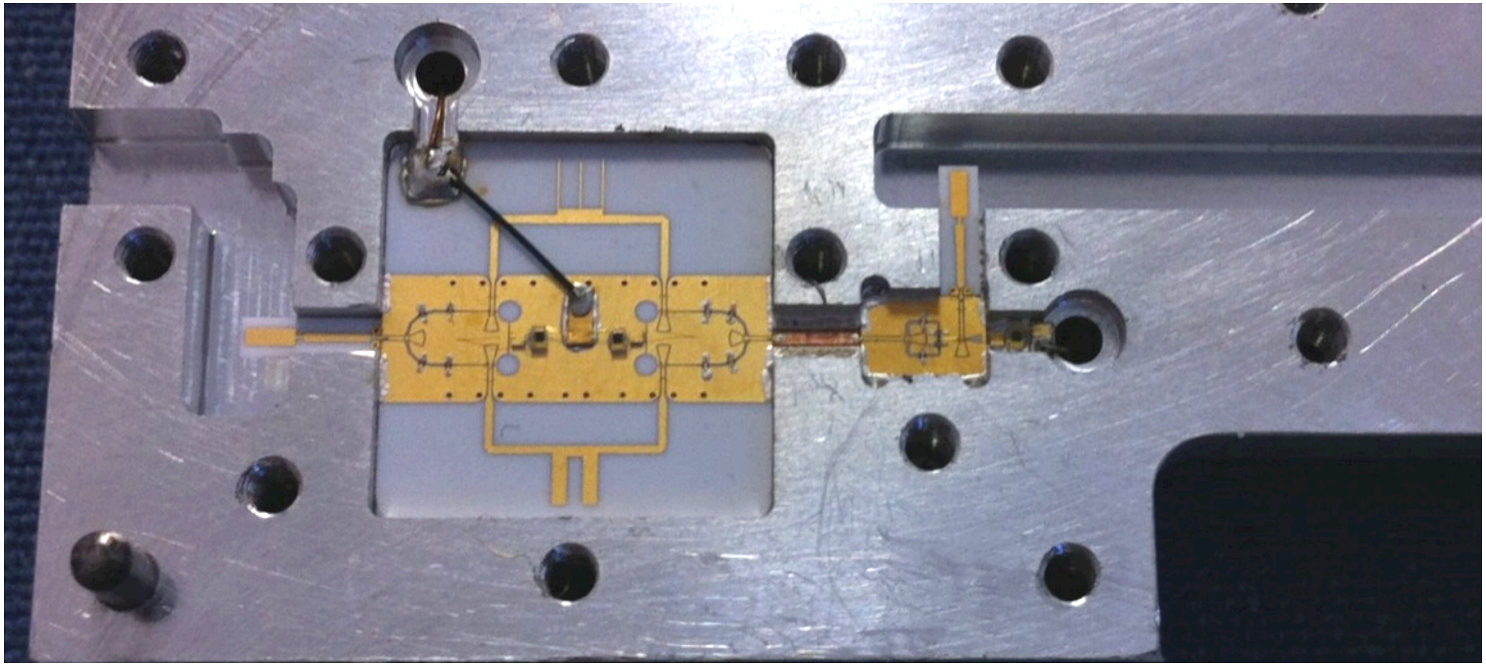


Internal view:
 Two MMIC LNA
 + 10 dB attenuator
 + Band Pass Filter

Performance of the 66 units at room temperature (298 K)

Average values (26-36 GHz):
 Gain = S21 (dB) ≈ 32 dB
 Noise Figure < 4 dB

Phase Switches - QUIJOTE TGI



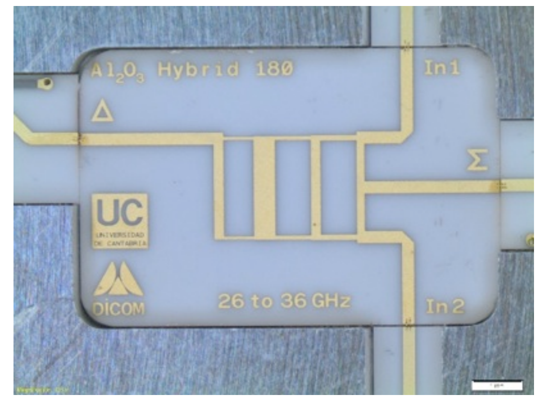
View of the 90° (left part) and 180° (right part) phase switches, only one branch.

Coplanar waveguide, slotline and microstrip transmission lines

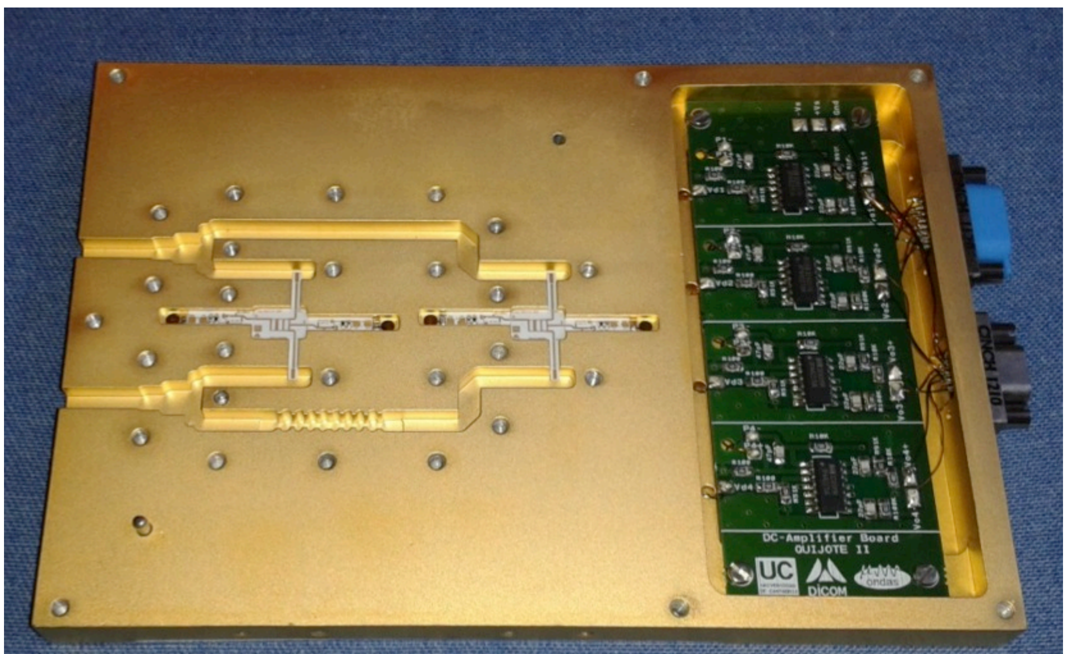
Switching devices: PIN diodes

Correlation and detection - QUIJOTE TGI

- Two input signals
- Combination of waveguide and microstrip circuits
- Correlation with 180 degrees hybrids (two units)
- Schottky diode detection (4 outputs)
- Post-detection DC amplifiers

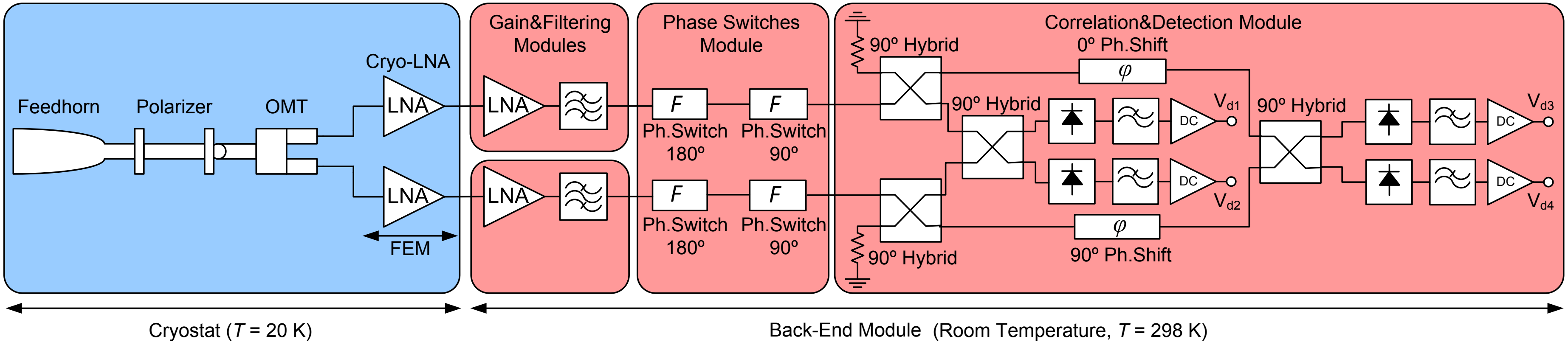


180 degrees hybrid



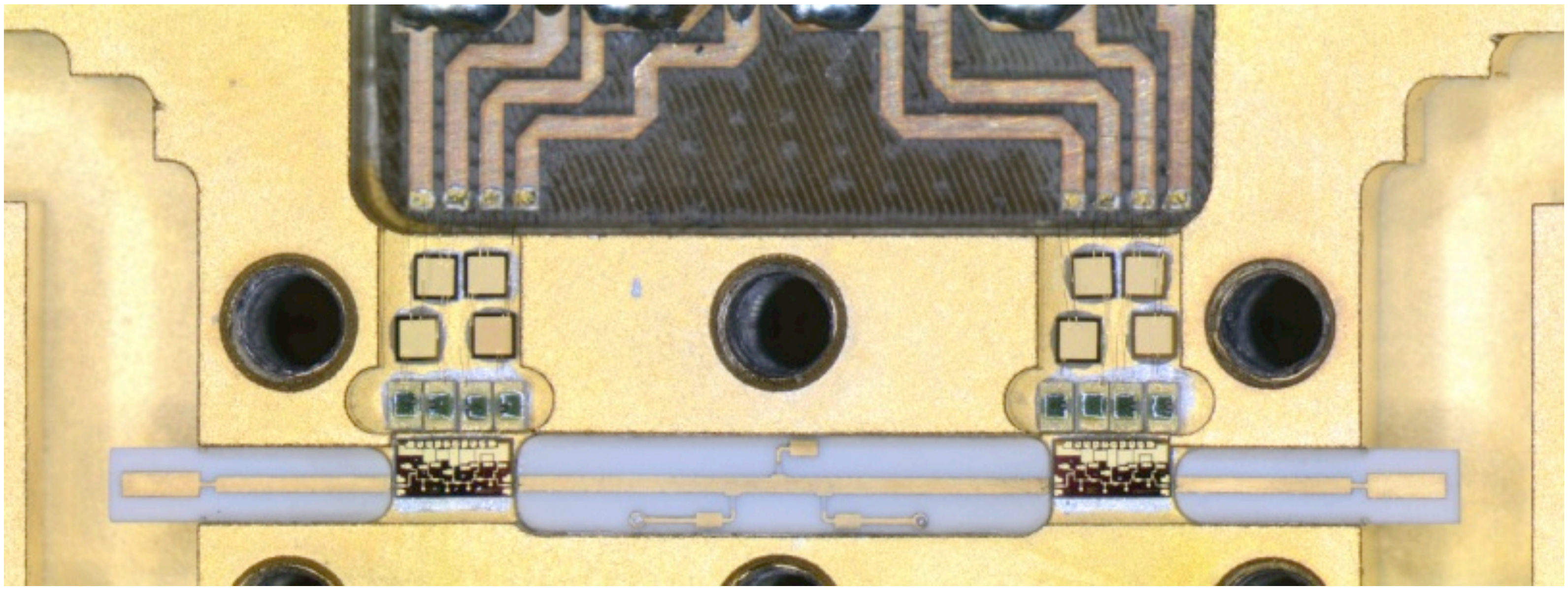
Module open view:
Left side: microwaves
Right side: DC amplifiers

Receiver scheme QUIJOTE 40 GHz (35-47 GHz) Forty GHz Instrument (FGI)



Same main architecture as 30 GHz receiver

Cryogenic Low-Noise Amplifier (FGI) (35-47 GHz)



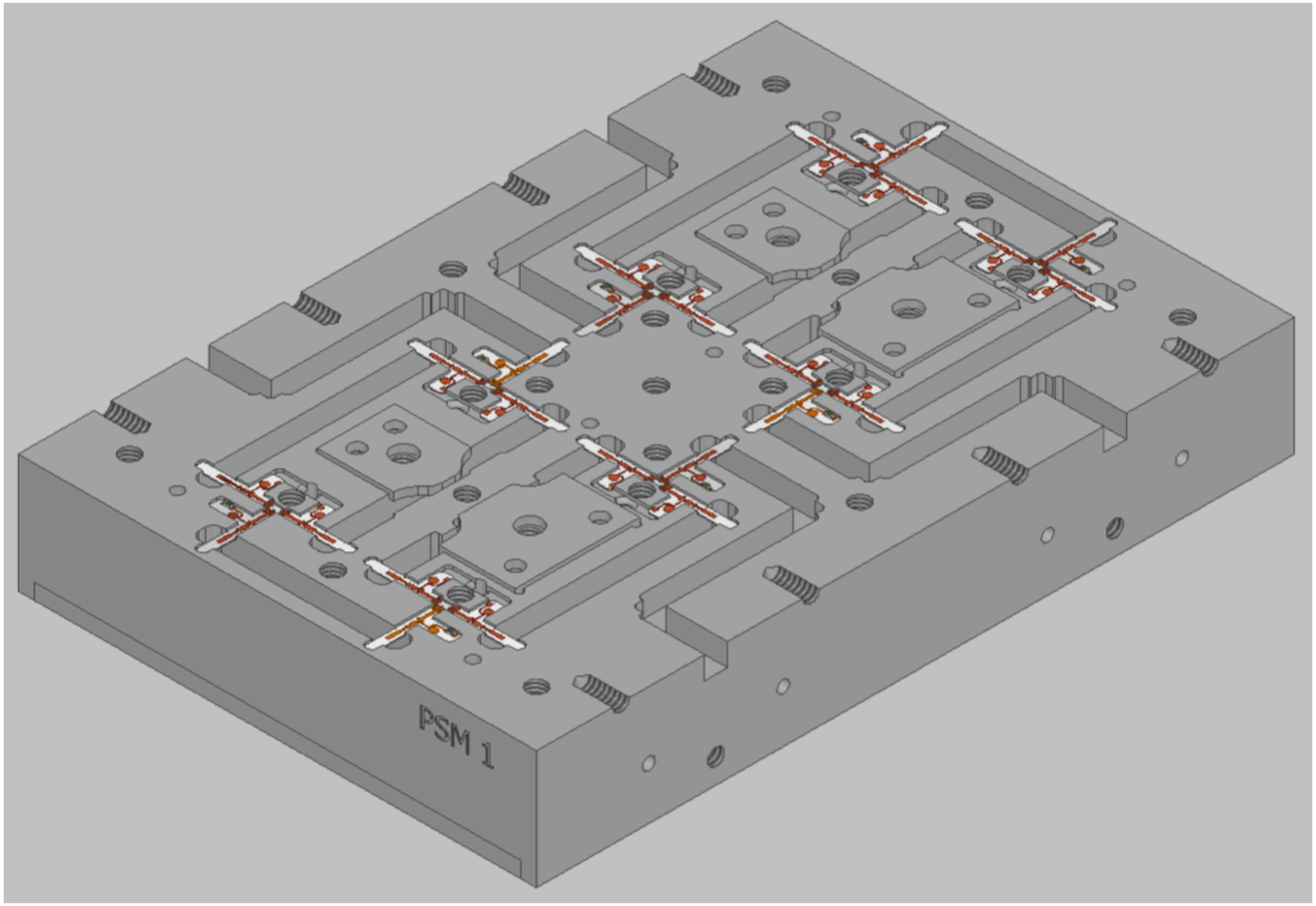
Cryo-Q-Band LNA MMIC (two units) from IAF-Fraunhofer + gain equalizer

Prototype results:

Gain ≈ 41 dB at 15 K

Noise temperature ≈ 22 K at 15 K

Phase Switches - QUIJOTE FGI



FGI phase-switches module (180 and 90 degrees). Two branches.
Based on SPDT MMIC chips and waveguide phase-shifters.

UC-DICOM capabilities

Design and manufacturing of:

Radiofrequency and microwave systems for radio astronomy.

- Cryogenic LNA Monolithic Microwave Integrated Circuits (MMIC):
  - IAF-Fraunhofer 100 nm and 50 nm mHEMT technologies (two collaboration projects since 2008 with Observatorio de Yebes), cryo-LNA in several bands from 2 to 110 GHz
  - OMMIC (France) mHEMT 70 nm, Ka and Q-band LNA
- Horn antennas, Orthomode Transducers (OMT), Polarizers, Couplers:
  - Several frequency bands, from 10 to 110 GHz
  - Broadband performance (10-14 GHz, 14-20 GHz, 26-36 GHz, 35-47 GHz, 81-99 GHz)
- Radiometers and polarimeters:
  - Planck-LFI: 30 and 44 GHz Back End Modules
  - QUIJOTE TGI and FGI (30 and 40 GHz): horns, OMT, polarizers, receivers (Front End and Back End Modules) (31 pixels)
  - Polarimeter demonstrator at 90 GHz: horns, OMT, polarizers, receivers (Front End and Back End Modules) (2 pixels)
- Broadband subsystems:
  - Cryogenic and ambient LNA
  - Phase-switches, microwave correlators, filters, Schottky diode detectors, …

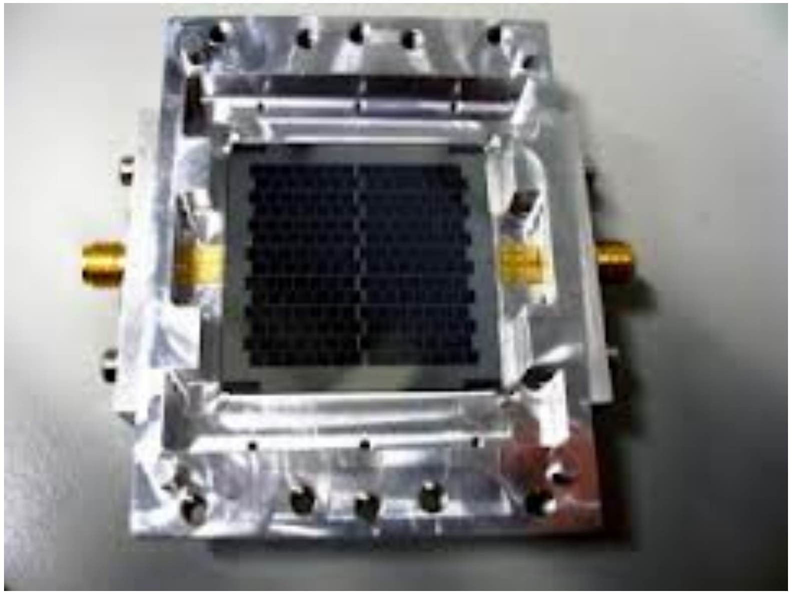
KID's developments

CENTRO DE ASTROBIOLOGÍA
Asociado al NASA Astrobiology Institute

Alicia Gómez Gutiérrez
Jesús Martín-Pintado

CENTRO DE ASTROBIOLOGÍA
Asociado al NASA Astrobiology Institute

Kinectic Inductance Detectors

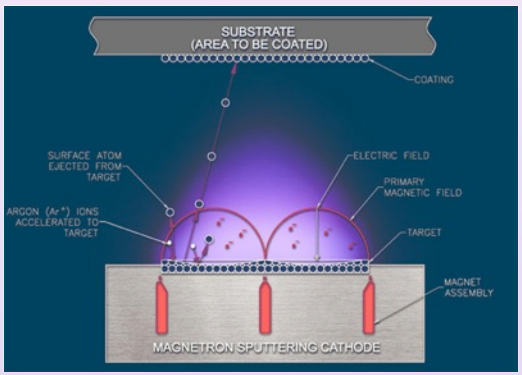


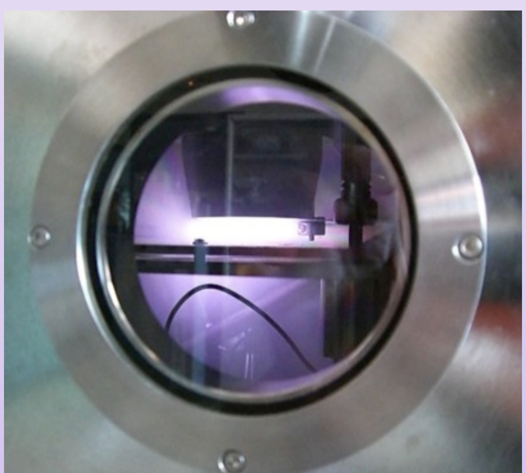
- Sensitivity performance comparable to the state-of-art bolometers
- Intrinsically multiplexable

→ KIDs provide a viable alternative to traditional detectors

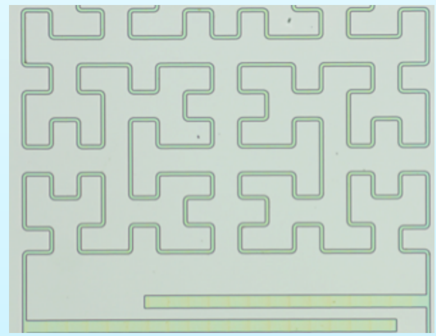
KIDs: Fabrication

Sputtering:
Deposition of superconducting films

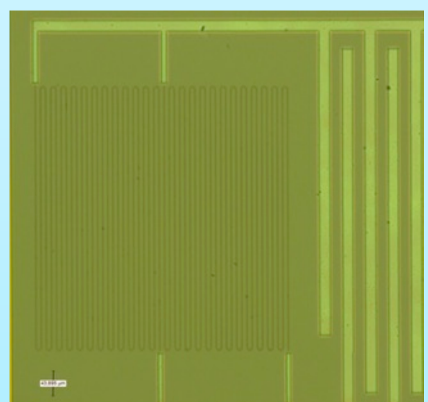




Nano and micro lithography

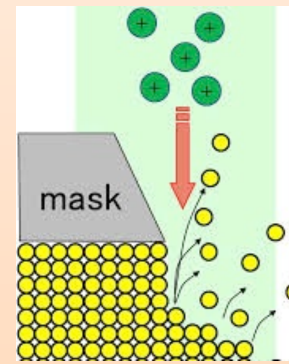


Laser writer

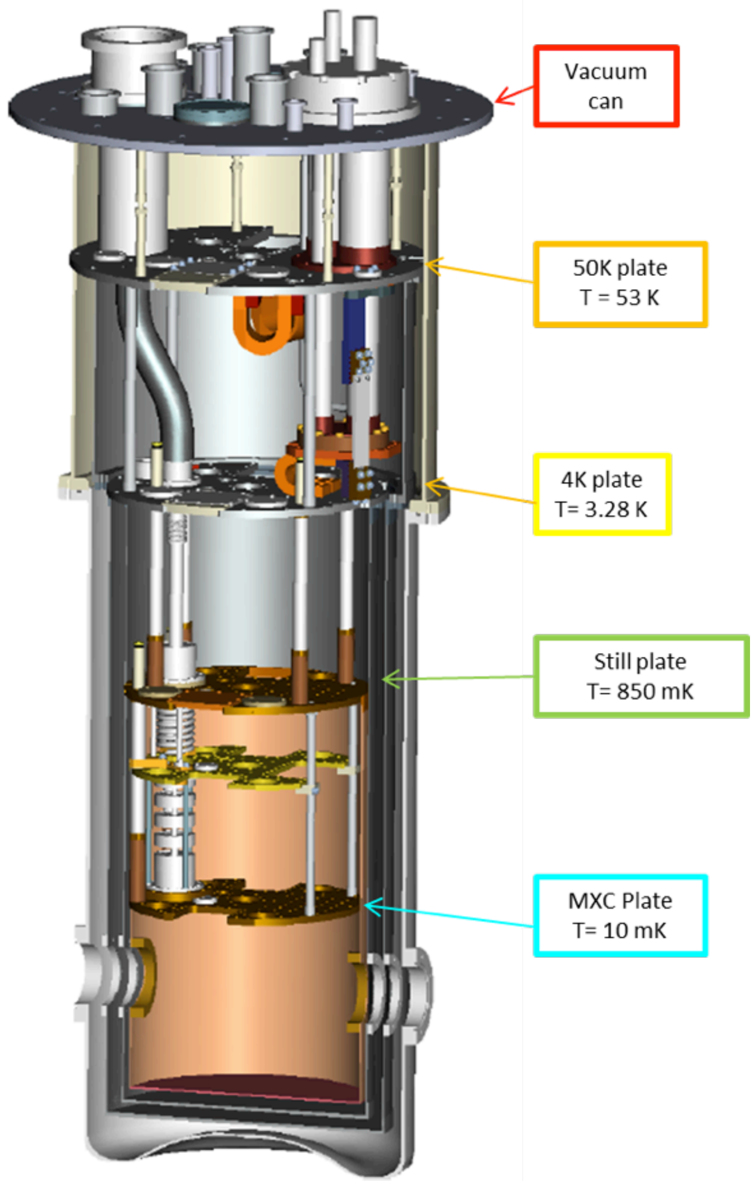


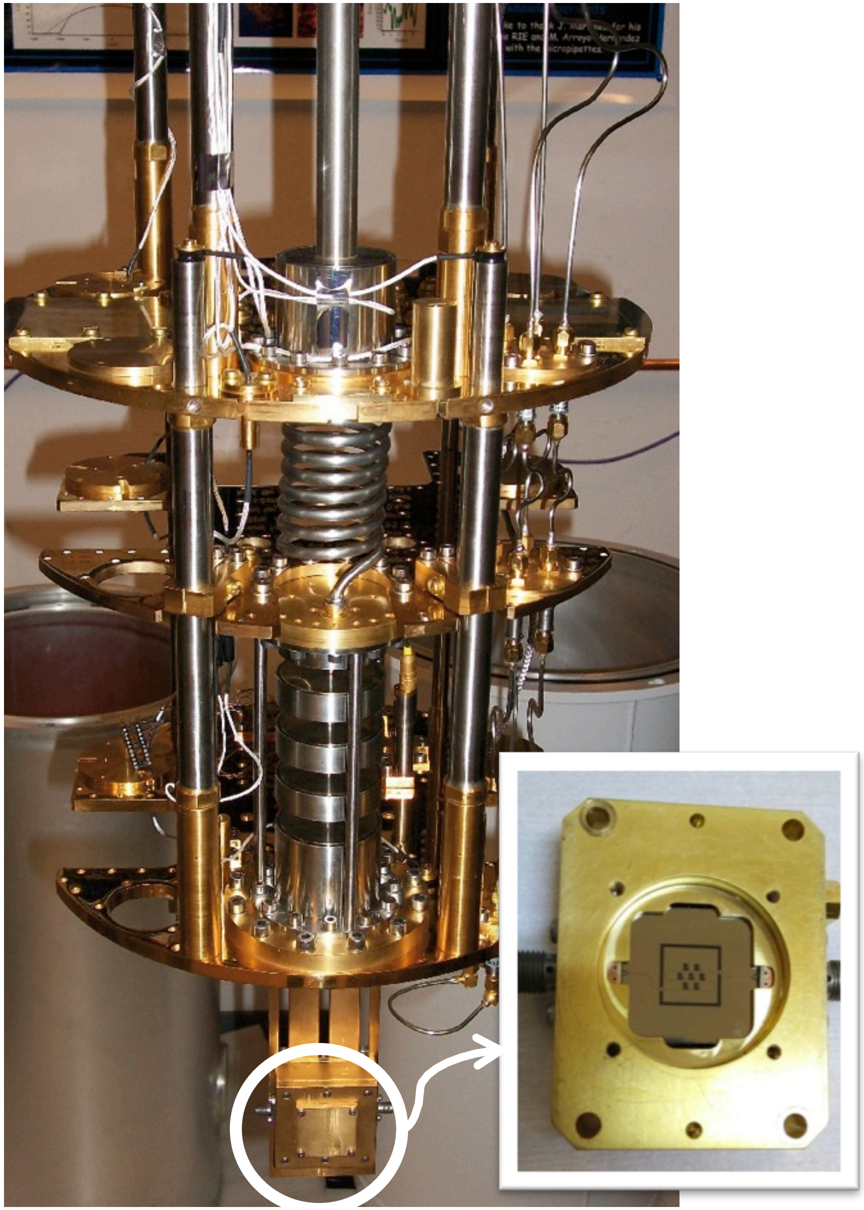
e-beam lithography

Etching:
Wet etching,
ion milling and RIE



KIDs: Characterization





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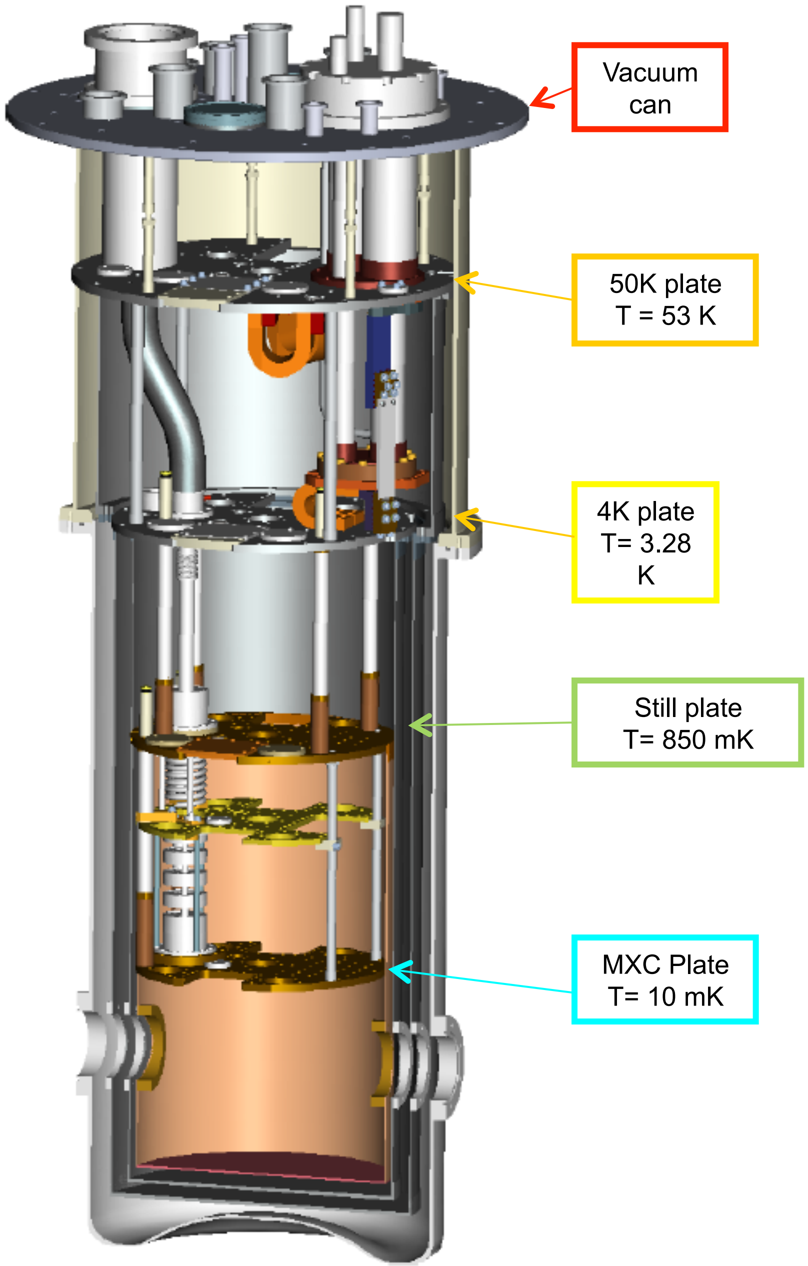
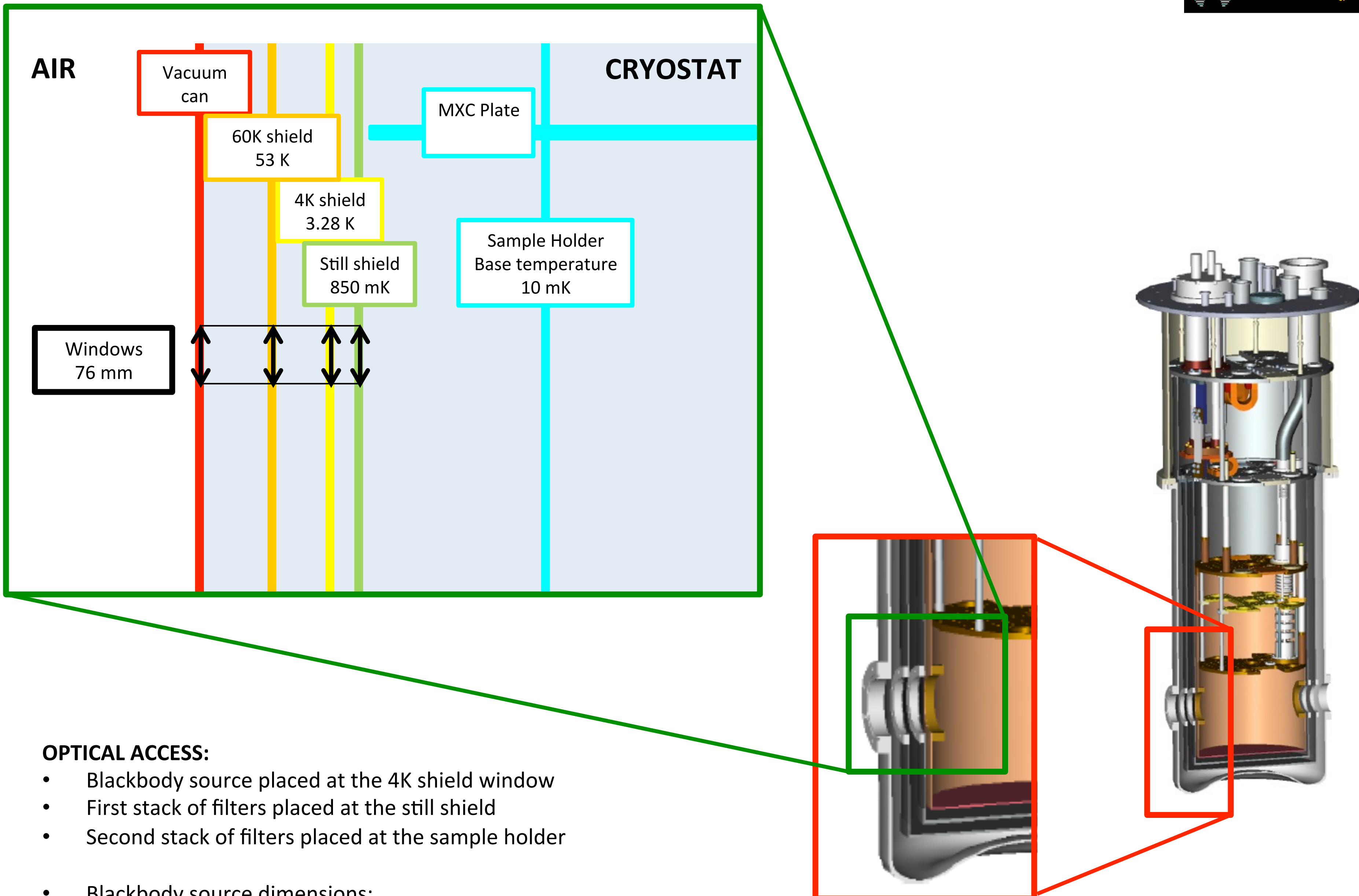


- Dilution refrigerator cryostat with base temperature below 10mK
- Cooling power: 350uW @ 100mK and 1W @ 4K
- Optical access to mixing chamber flange
- Two SQUID channels
- 2 RF lines (up to 10GHz)

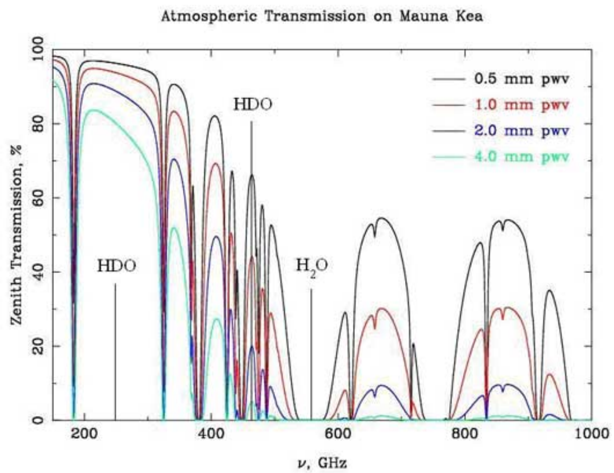


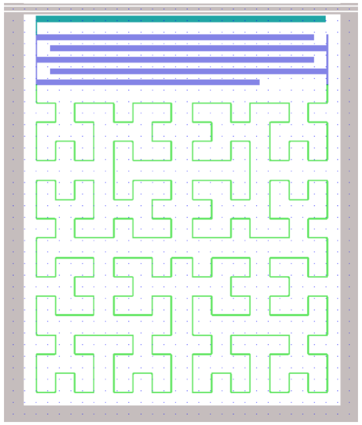
OPTICAL ACCESS:

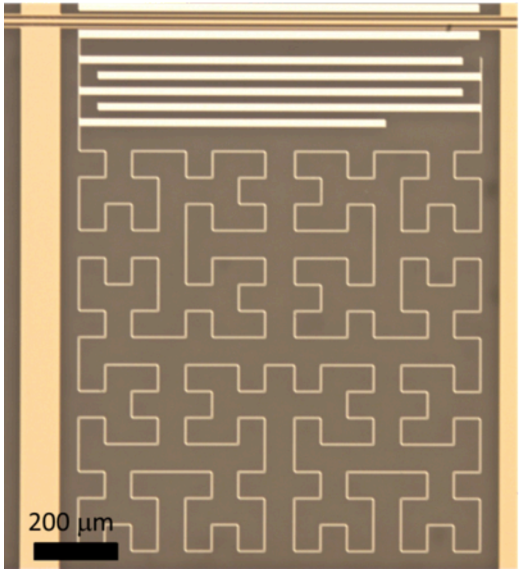
- Blackbody source placed at the 4K shield window
- First stack of filters placed at the still shield
- Second stack of filters placed at the sample holder

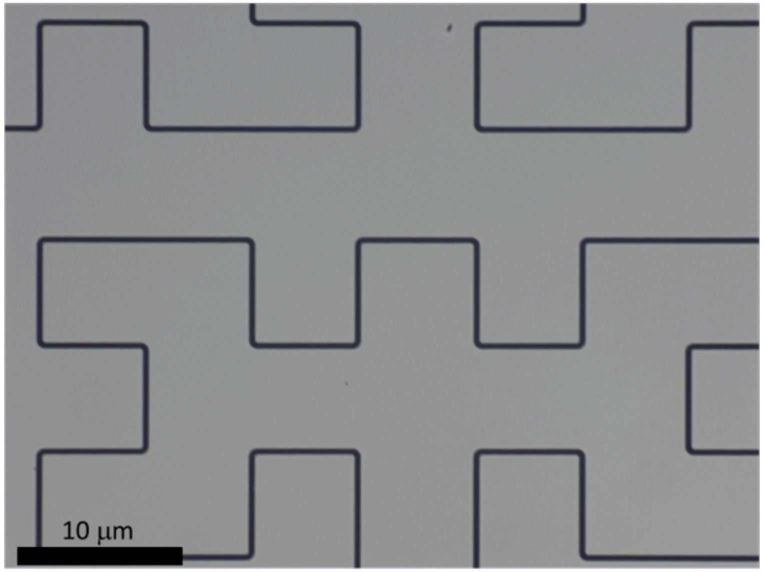
- Blackbody source dimensions:
  - Diameter = 50mm
  - Thickness = 8mm
  - It does not stick out of the 4K shield window

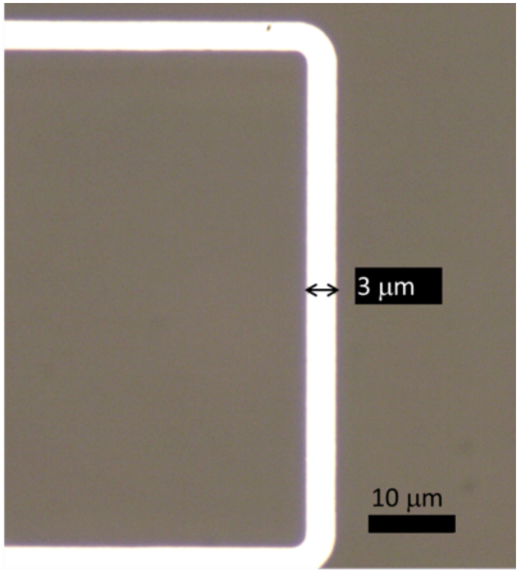
Earth Observation: Narrow band Hybrid KIDs



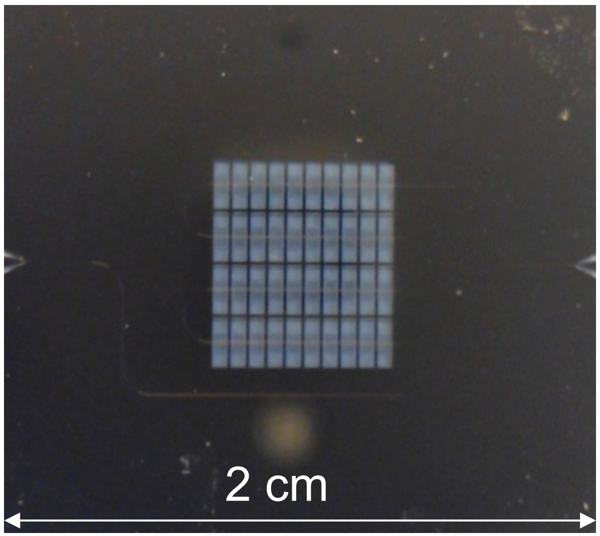


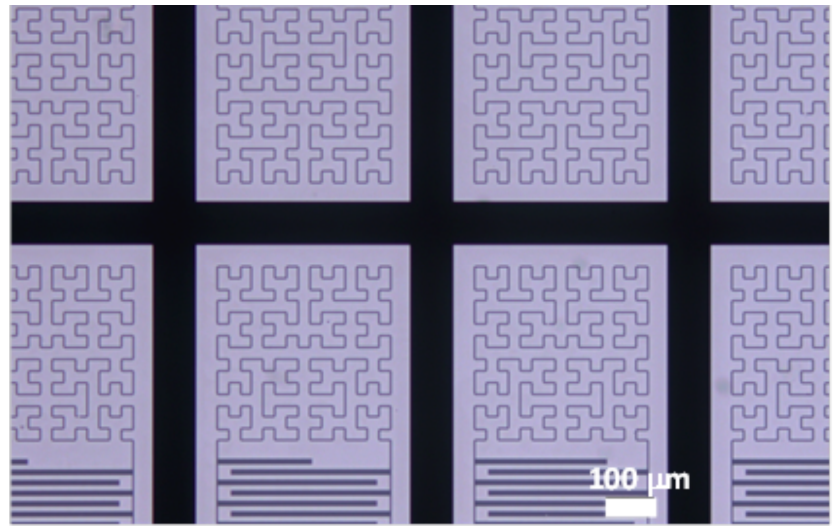


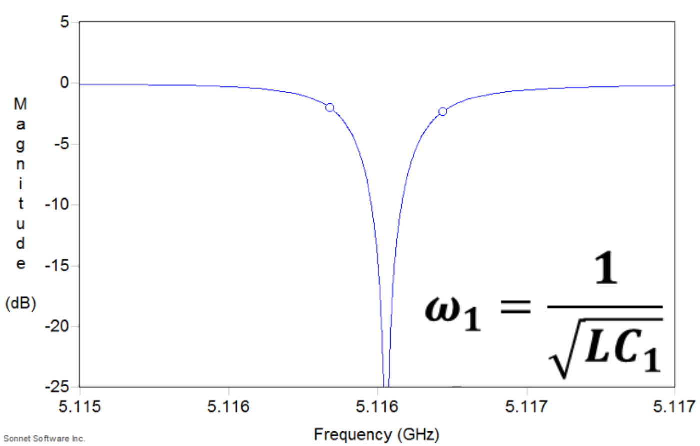




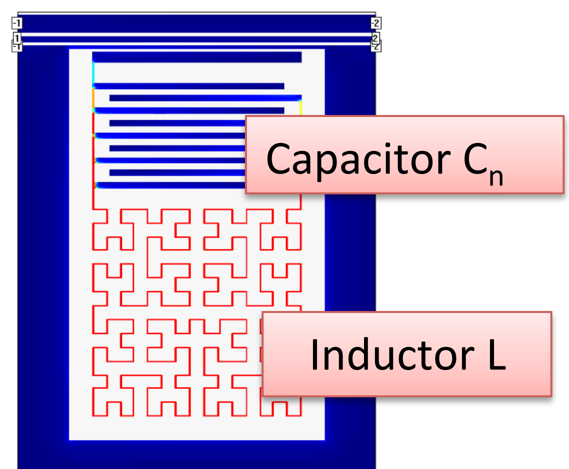
Earth Observation: Narrow band Hybrid KIDs







$$\omega_1 = \frac{1}{\sqrt{LC_1}}$$



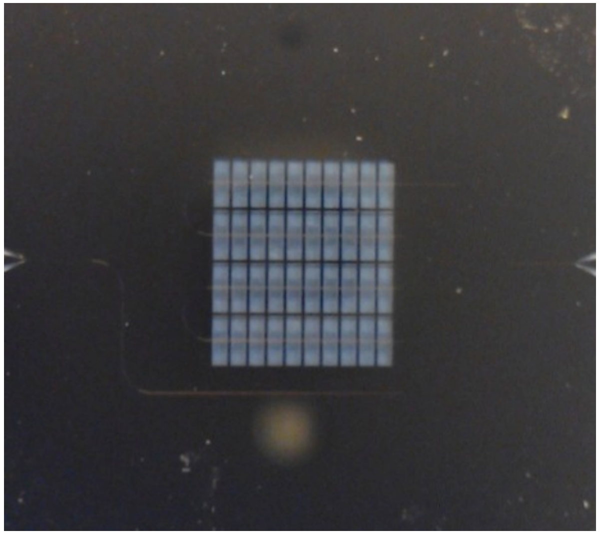
$$\omega_2 = \frac{1}{\sqrt{LC_2}}$$

EASY TO MULTIPLEX

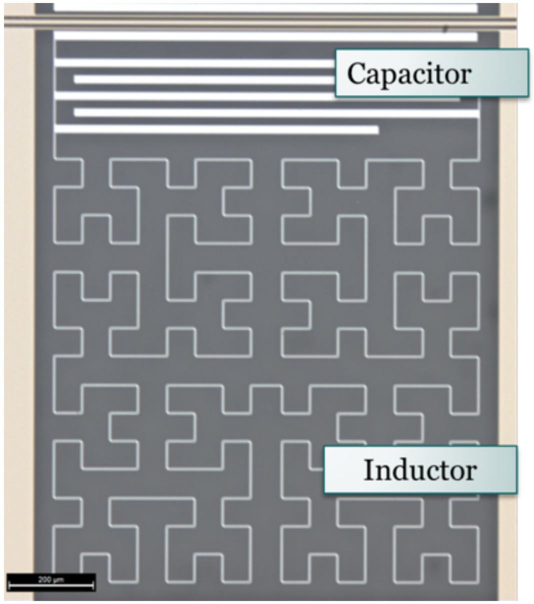
$$\omega_n = \frac{1}{\sqrt{LC_n}}$$

Earth Observation: Narrow band Hybrid KIDs

Vac $_{IN}$

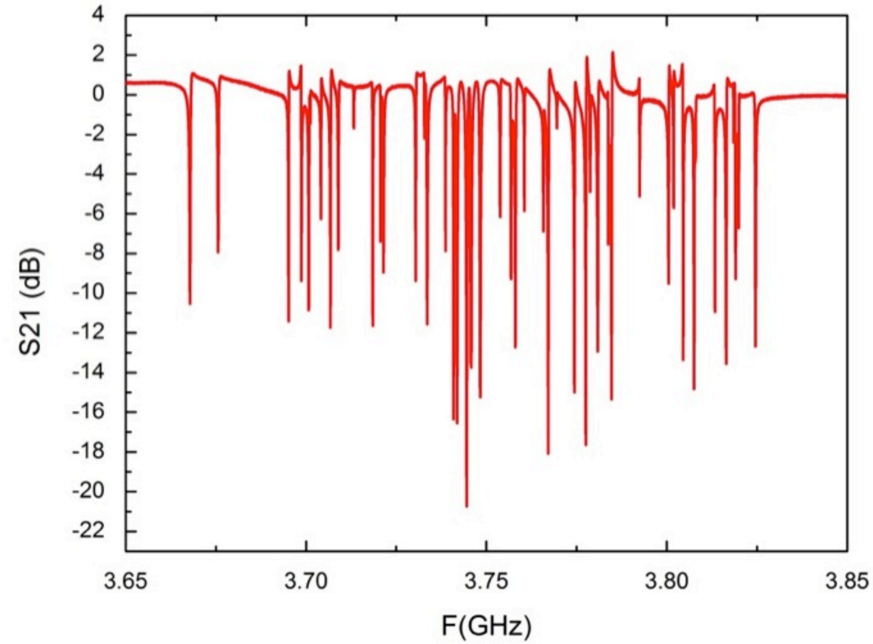


Vout $_{IN}$



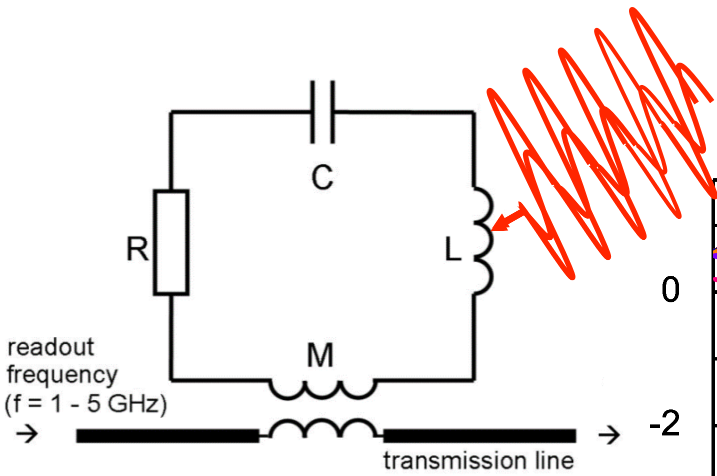
$$\omega_n = \frac{1}{\sqrt{LC_n}}$$

Vac $_{OUT}$ / Vac $_{IN}$



40 Al KIDs on Sapphire
350 GHz radiation

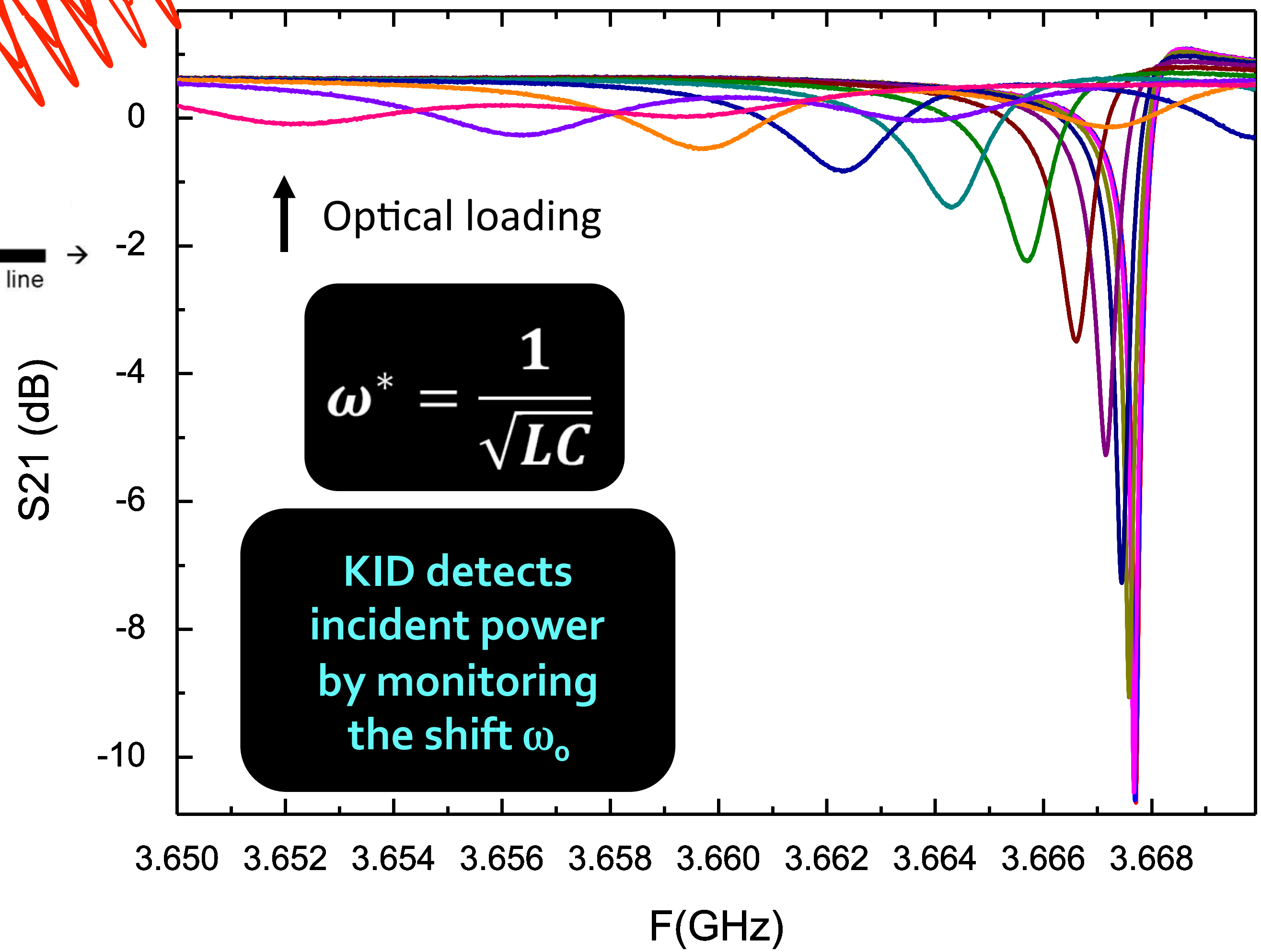
Earth Observation: Narrow band Hybrid KIDs



$\downarrow n_s$

$\Downarrow$

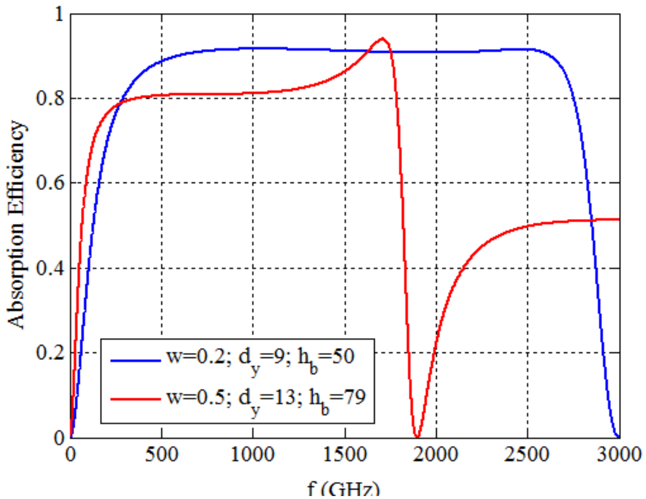
$\uparrow L_K$



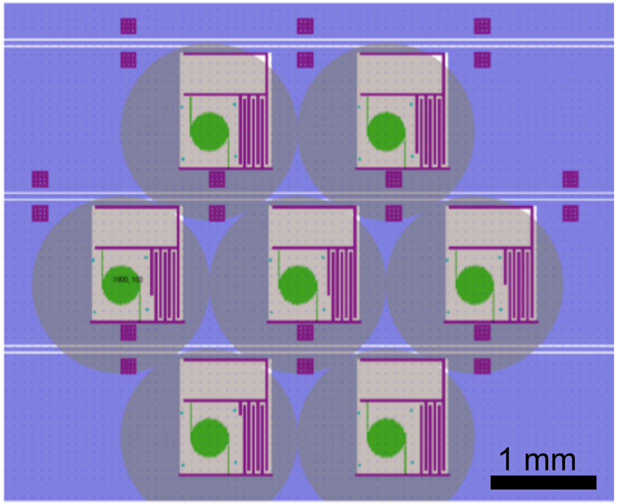
$$\omega^* = \frac{1}{\sqrt{LC}}$$

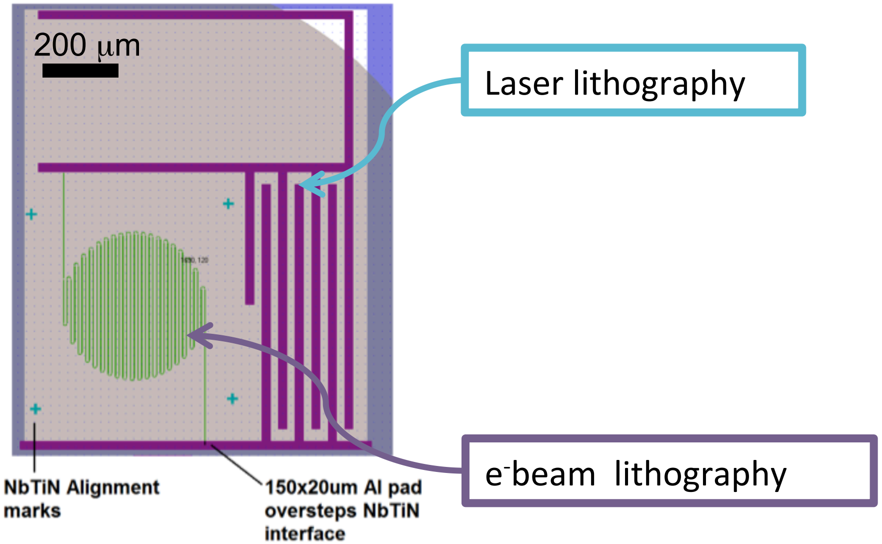
KID detects incident power by monitoring the shift ω_o

Space Observation:Broadband Hybrid KIDs

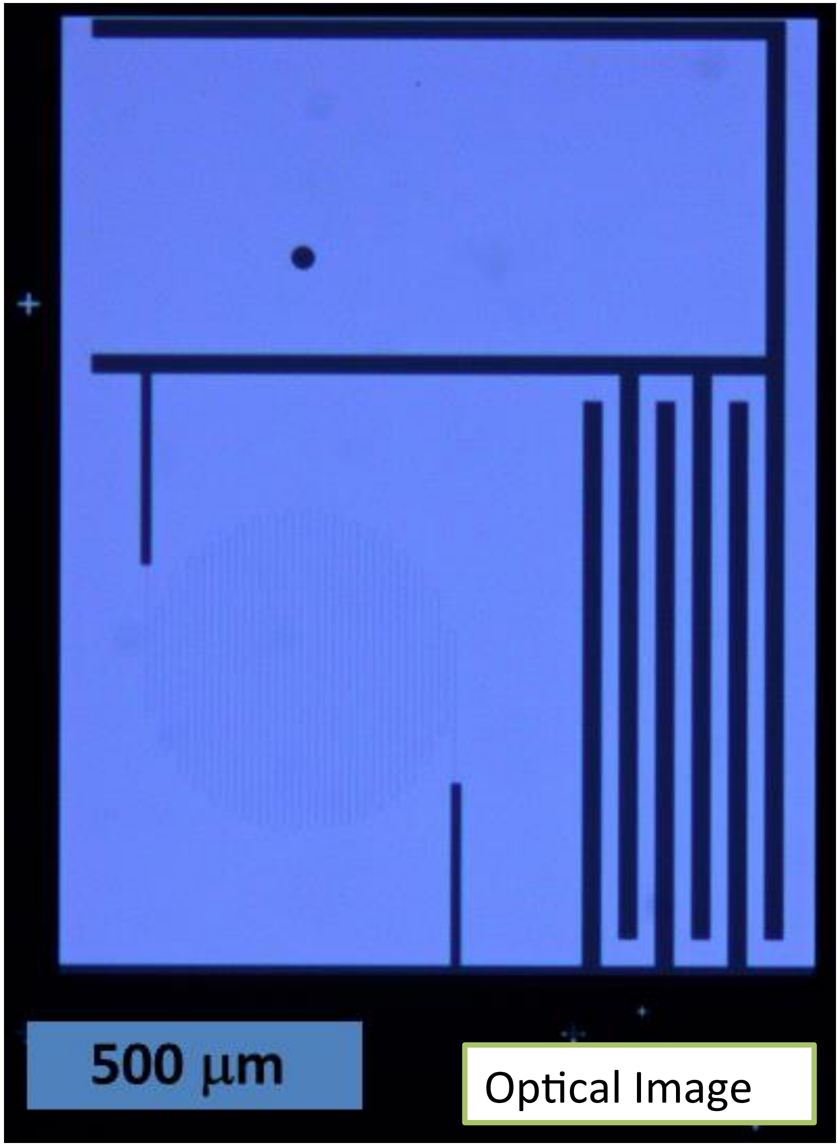


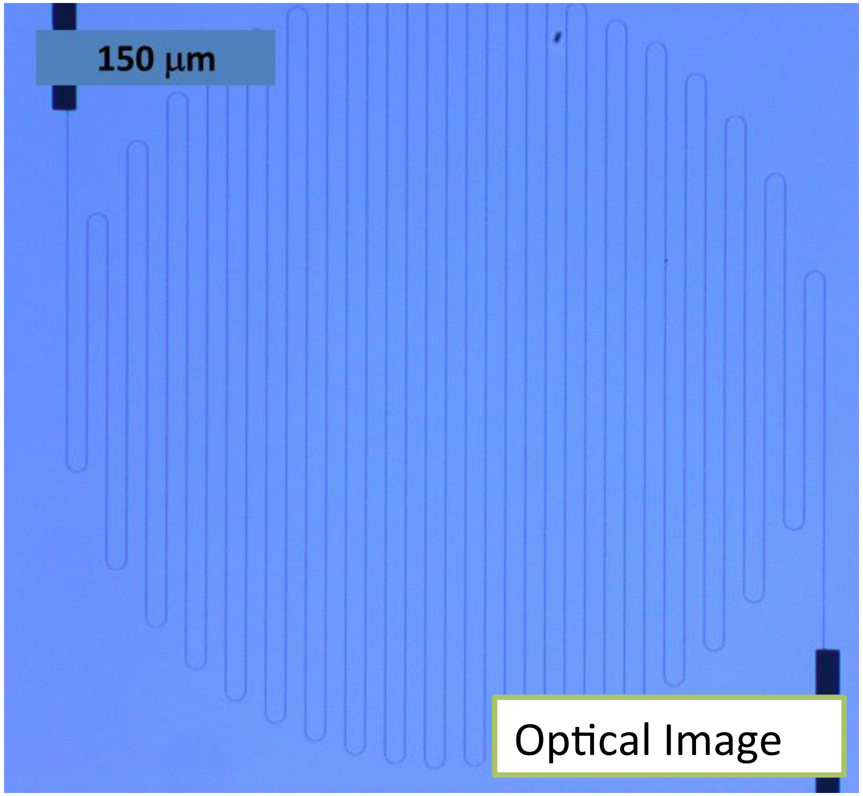
Broadband detector
0.5 THz – 2.5 THz

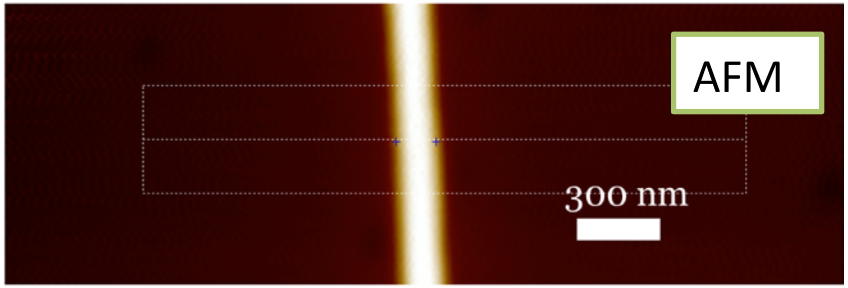




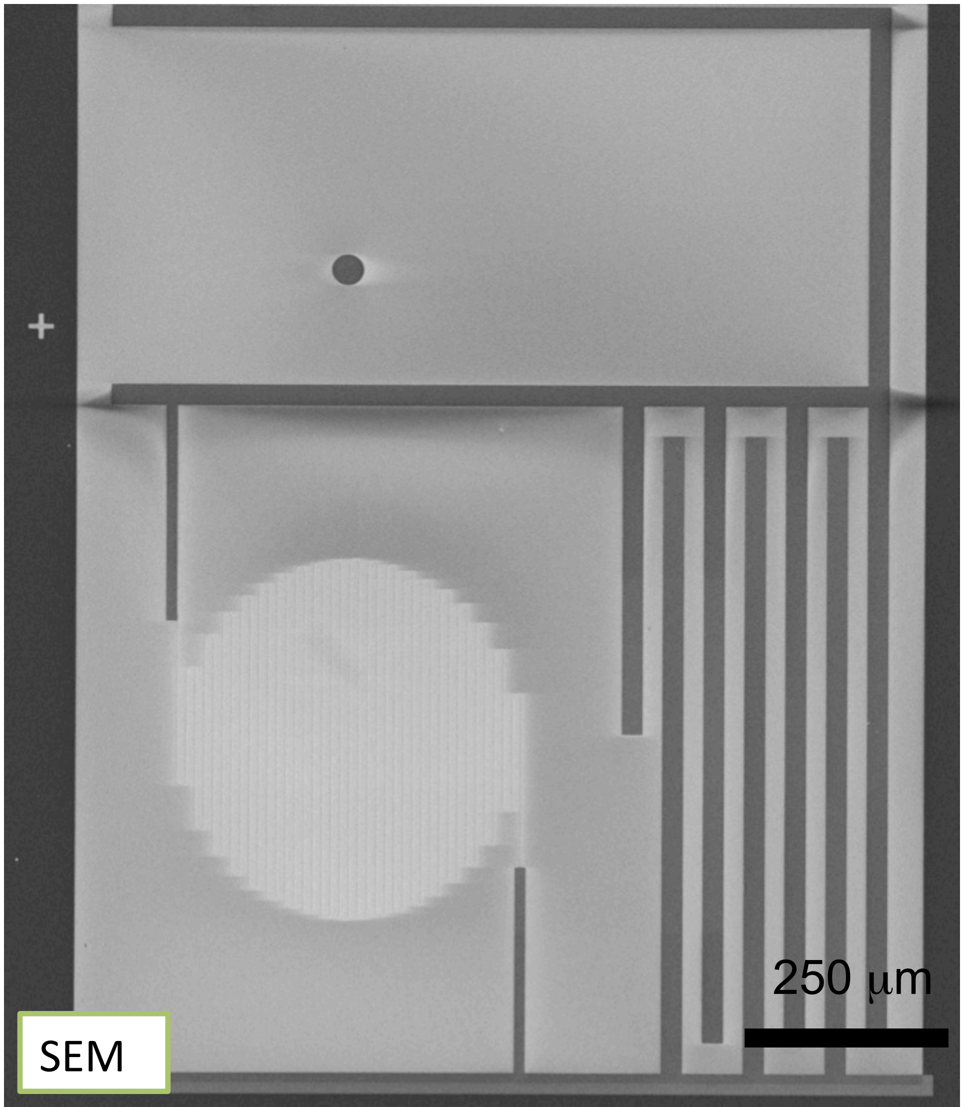
Space Observation:Broadband Hybrid KIDs

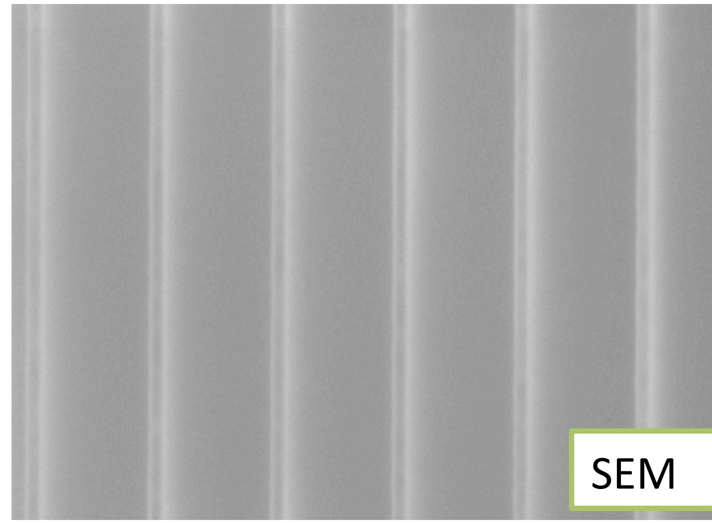


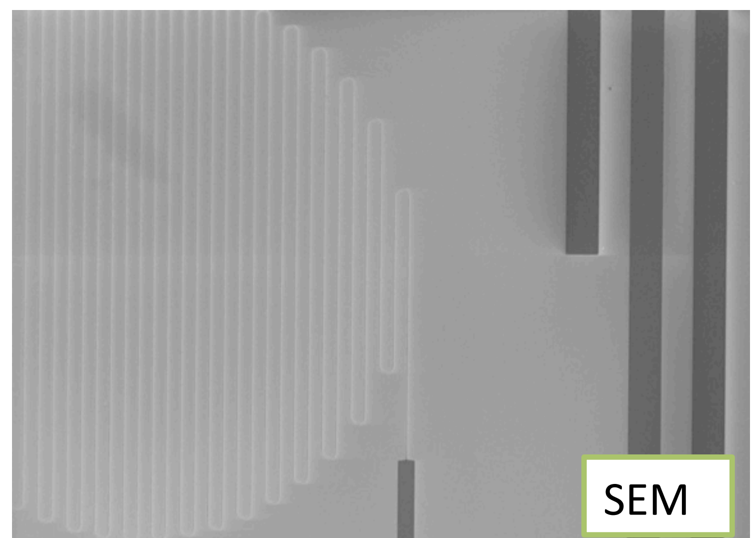




Space Observation:Broadband Hybrid KIDs







IR Electro-Optical Correlator for a Large Format Interferometer

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Francisco J. Casas
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Instituto de Astrofísica de Canarias · IAC ·

Roger Hoyland

With contributions from Bob Watson (JBO, U. Manchester)

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-Introduction

-MZM based Optical Correlator

-Instrumental precedents

-MW to IR Up-Conversion Application Example

-Interferometer Implementation Proposal

-Next steps

Introduction

-***Goal:*** *Develop an instrument to measure polarization with high sensitivity at 10-20 and 30 GHz.*

-***Detection Technology:*** *Bolometers are not optimal in this frequency range. Ultra Low Noise receiver-based polarimeters can be used.*

-***Opto-Mechanics:*** *Size limiting factor for direct imaging instruments due to the restricted focal plane area of the required telescope.*

-***Large Format Interferometer****: Not limited by the focal plane area. Potentially hundreds or even thousands of receivers to have optimal sensitivity*

Introduction

-***<u>Main Challenge:</u>*** *Develop a correlator for hundreds of wideband microwave (MW) signals. The routing, combination and detection result complex and very expensive.*

-***<u>Proposal:</u>*** *Use Electro-Optical (EO) modulators to up-convert MW signals to the Infra Red (IR) wavelength (1550 nm).*

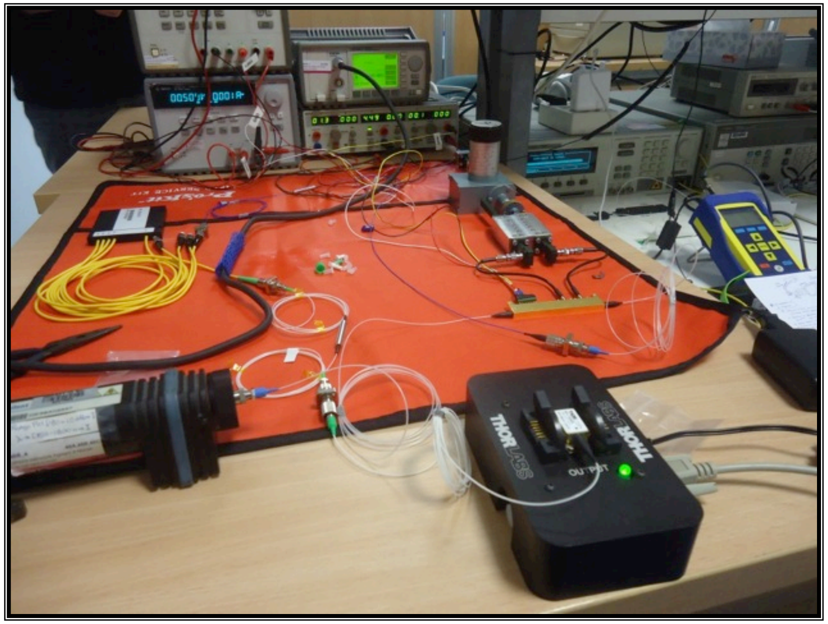
-The correlation and detection can be performed using optical fibers, lenses and IR cameras.

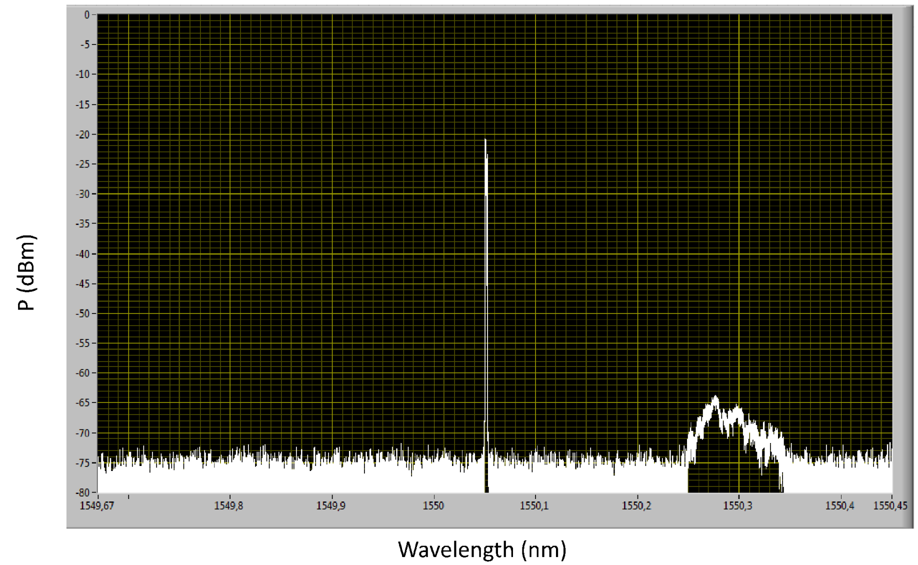
-High density detection and low cost.

-Very well understood technology to implement a synthesized imager.

MZM-Based Optical Correlator

Up-conversion of MW Signals to the IR



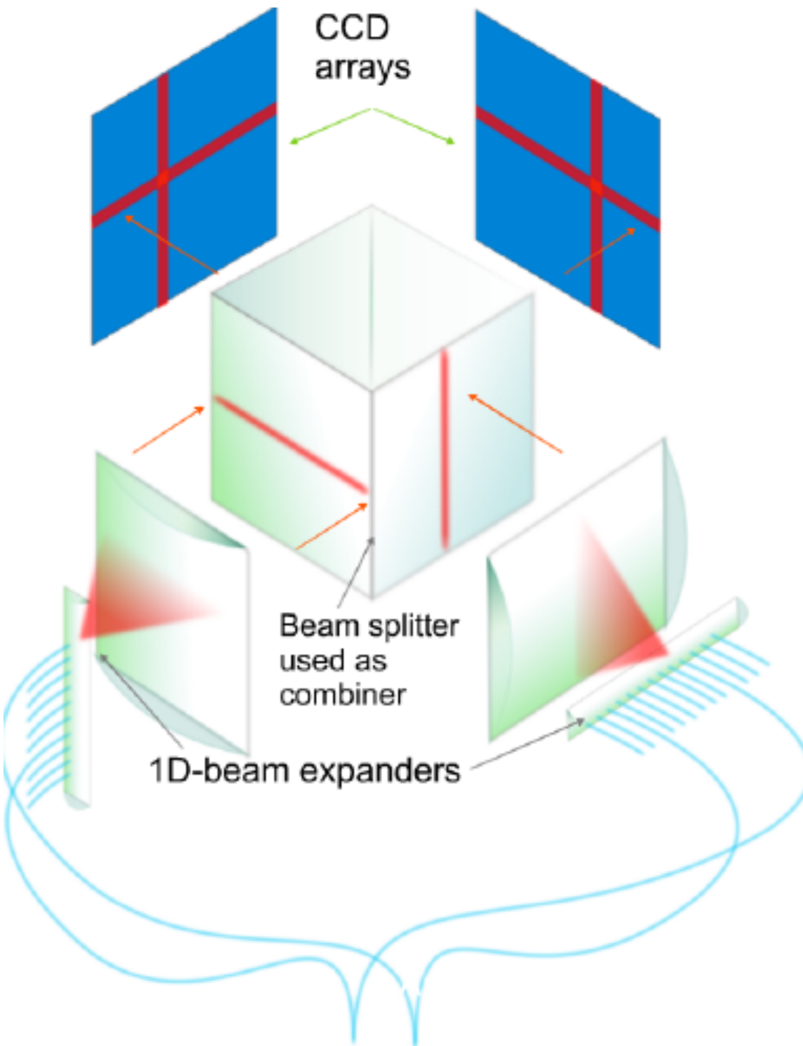


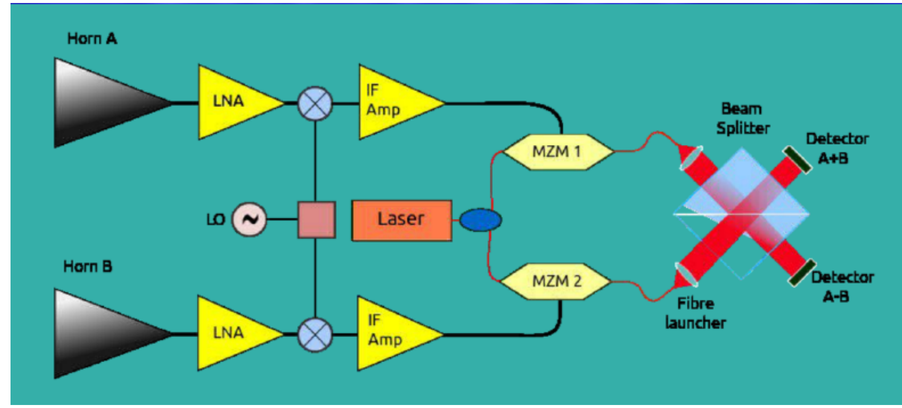
-Use of Mach-Zehnder Optical Modulator to perform the frequency range conversion.

-Optical carrier needs to be filtered.

MZM-Based Optical Correlator

Michelson type correlator:





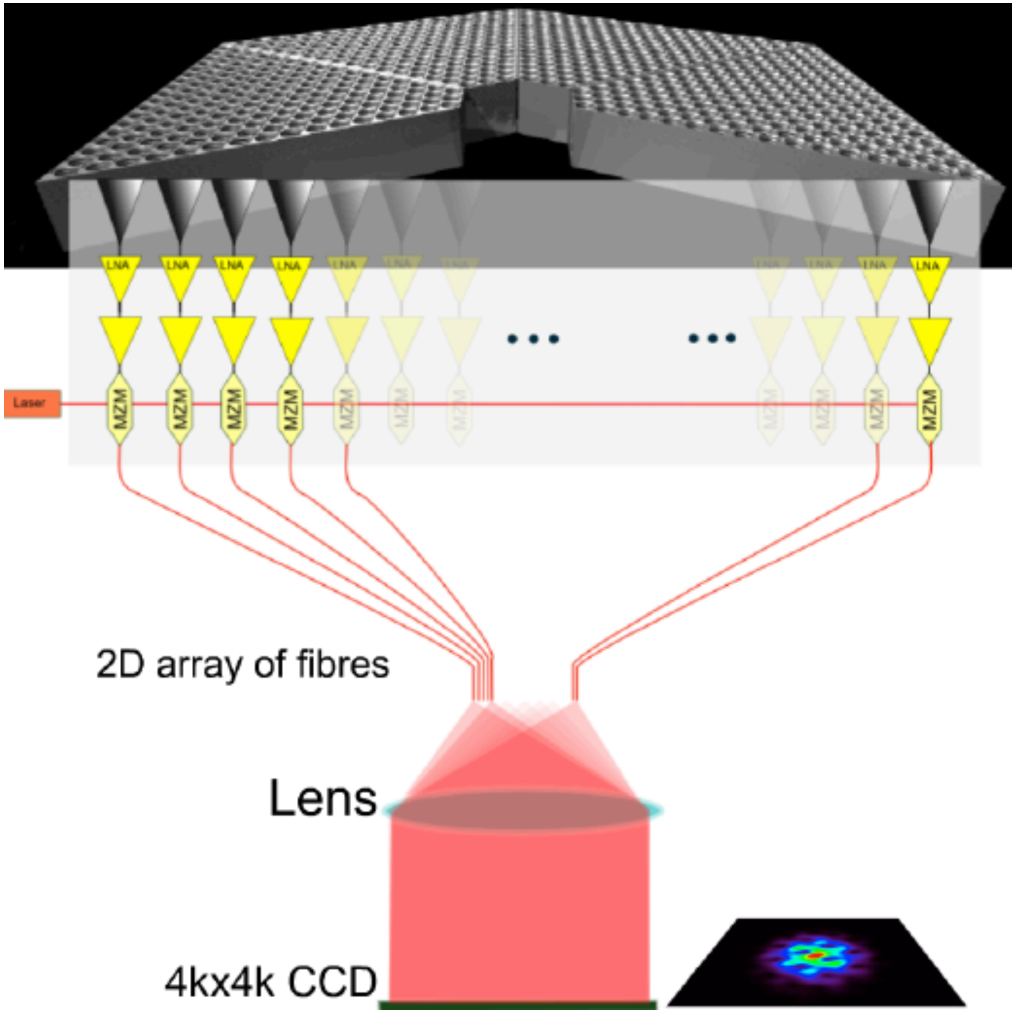
-Visibilities from combination of horizontal and vertical fringes.

- Projection on to a CCD.

- Number of baselines (n(n-1)/2) not a problem. 1K x 1K CCD arrays are easily available.

MZM-Based Optical Correlator

Fizeau type correlator:



- Phased array of Young's slits.

- Less flexible.

- Systematics probably not as good as Michelson.

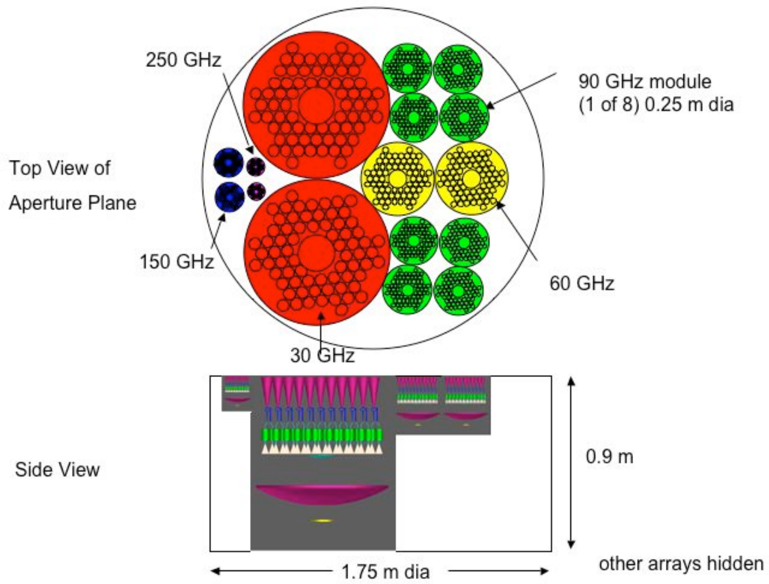
- Radically simpler design.

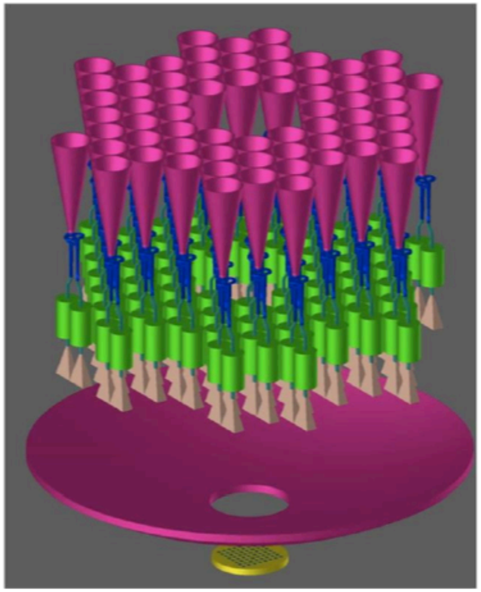
- Polarization modulation, by complex phase switching, can be implemented in both the MW or IR domain.

- A good option for big arrays of receivers.

Instrumental Precedents

EPIC: Space mission concept





The Einstein Polarization Interferometer for Cosmology or EPIC is a proposed space probe to measure the B-modes of the CMB Polarization. It consists of a series of interferometric arrays tuned to various frequencies to precisely measure the CMB and to remove galactic foregrounds from infrared dust emission and syncrotron radiation. Each array as shown below has a set of 64 conical

- From 30 to 300 GHz.

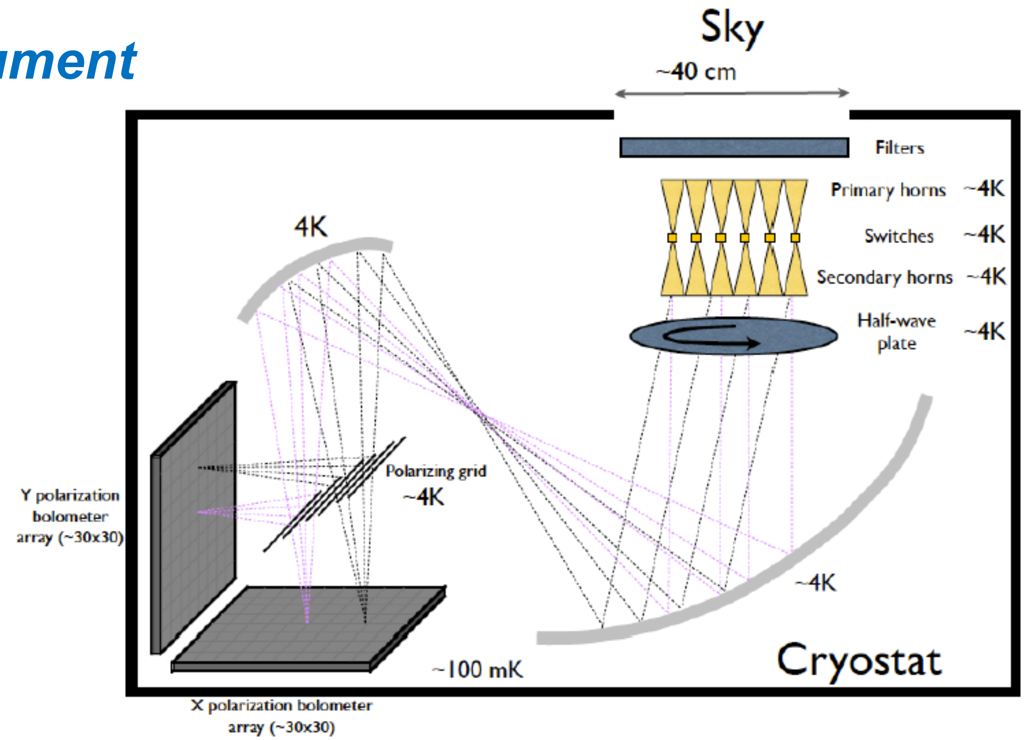
- Bolometric Interferometer

- Fizzeau Beam Combiner

Instrumental Precedents

QUBIC: Ground-based Instrument

- *Synthetized Imager*
- *97, 150 and 220 GHz*
- *Antarctica Concordia Station*
- *Fizzeau Beam Combiner*



The signal on the bolometers as a function of time is[2]:

$$R(\vec{d}_p, t) = S_I(\vec{d}_p) \pm \cos(4\omega t) S_Q(\vec{d}_p) \pm \sin(4\omega t) S_U(\vec{d}_p)$$

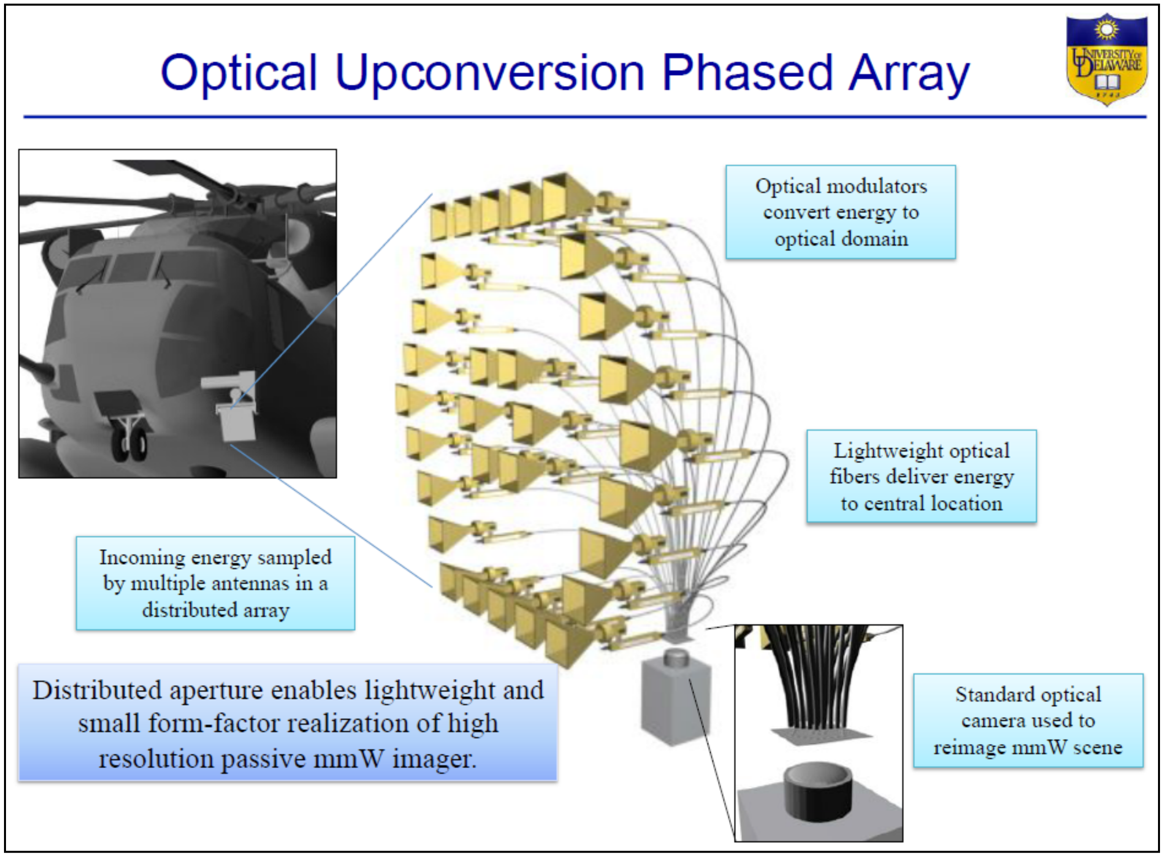
where the ± is + for one of the focal planes (polarized in one direction) and – for the other one polarized in the other direction.

This kind of interferometers act as imagers

(Battistelli et al., Astroparticle Physics 34, 2011, 705-716)

MW to IR Up-Conversion Application Example

Distributed Aperture Millimeter-Wave Imaging System using Optical Up-conversion



- Collaboration: University of Delaware and Phase Sensitive Innovations.

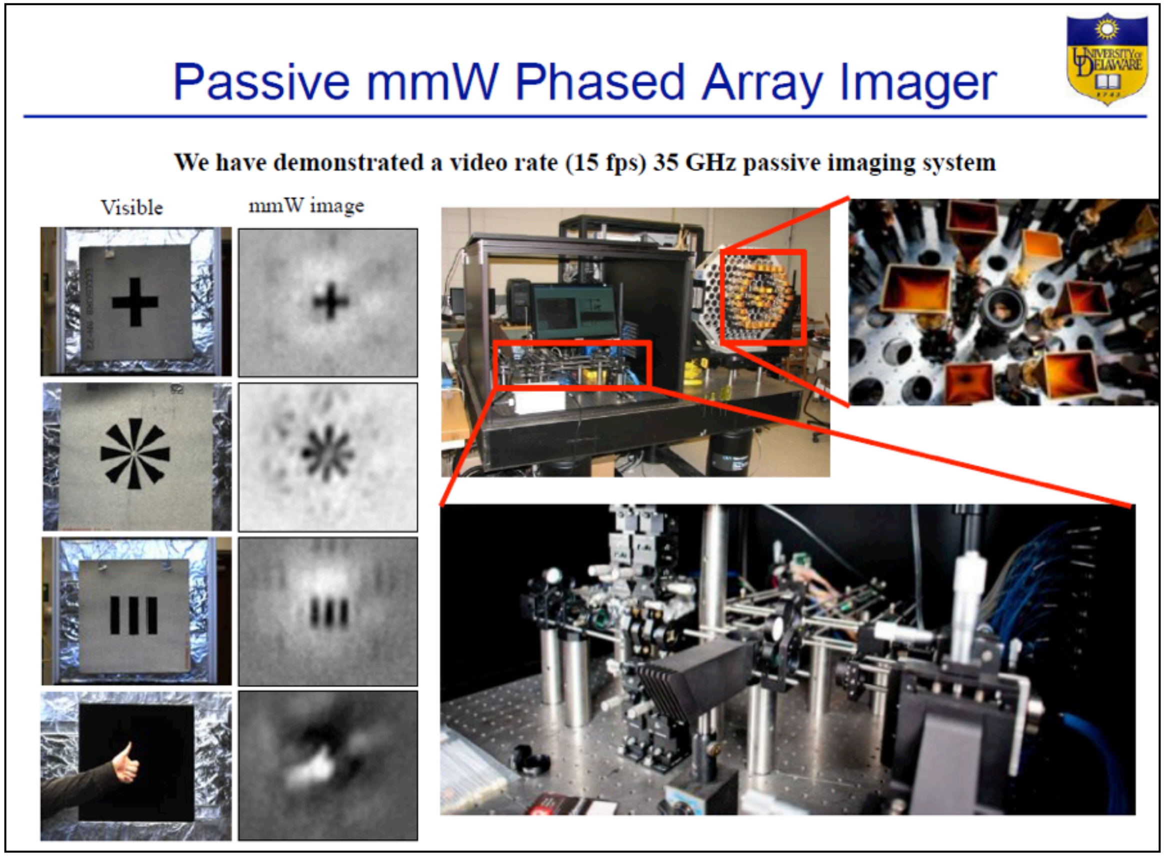
- 30 elements at 35 GHz.

- Optical processor stabilizes phase of each channel.

- Also enables electronic image enhancement techniques.

MW to IR Up-Conversion Application Example

Distributed Aperture Millimeter-Wave Imaging System using Optical Up-conversion



- Collaboration: University of Delaware and Phase Sensitive Innovations.

- 30 elements at 35 GHz.

- Optical processor stabilizes phase of each channel.

- Also enables electronic image enhancement techniques.

MW to IR Up-Conversion Application Example

220 Elements at 75 GHz:

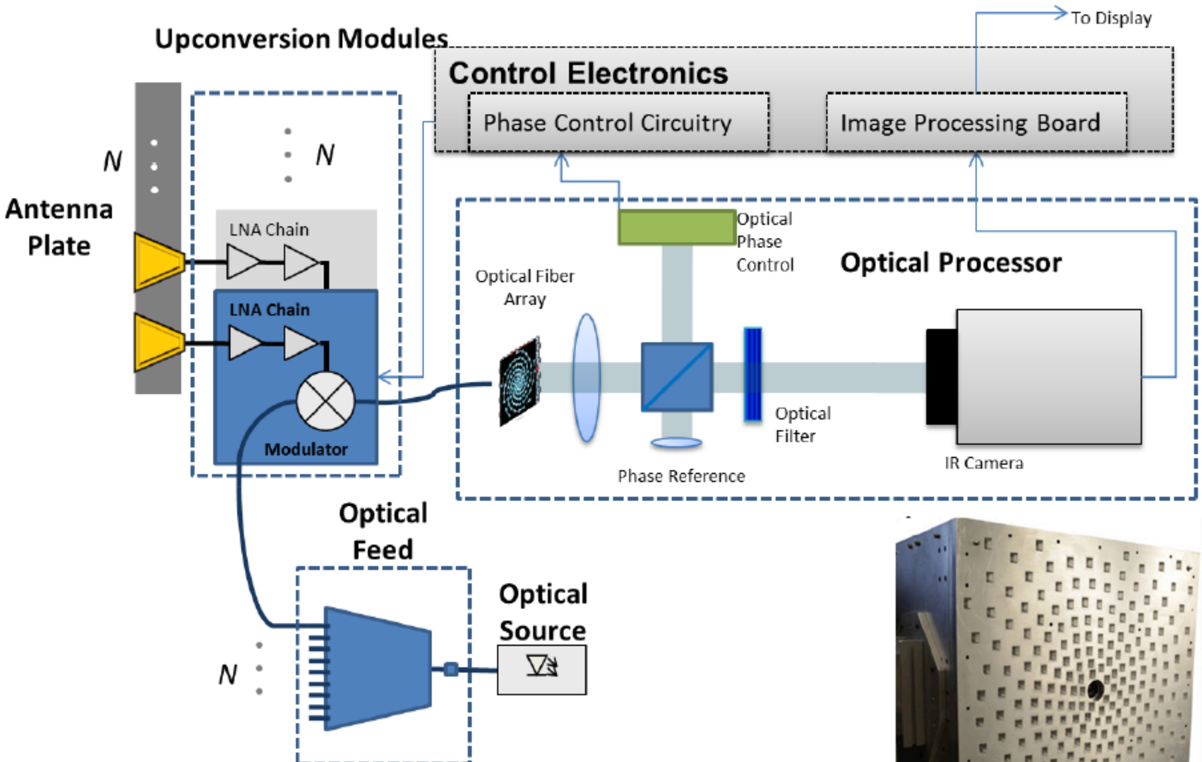
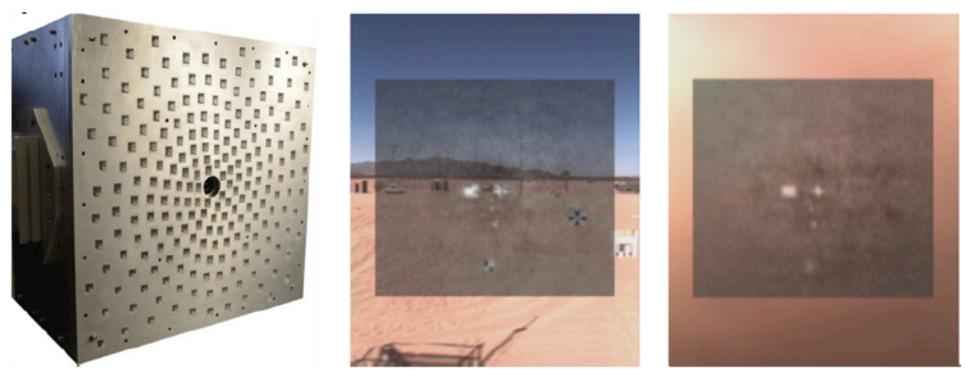


Figure 3. Block diagram of system components within the optical upconversion imager.

-A SWIR InGaAs CCD camera.

-Active phase control (to control vibrations from an helicopter!)

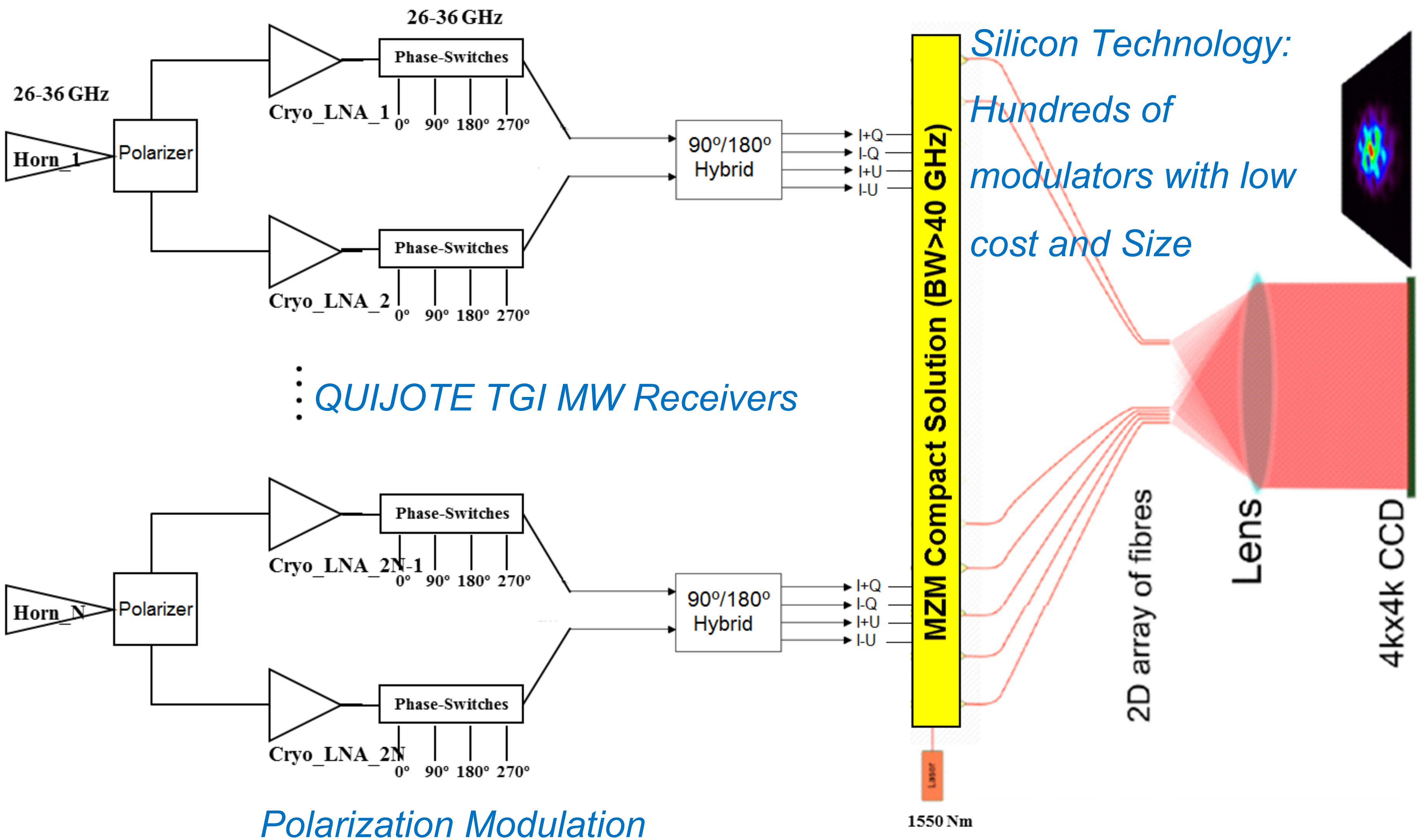


(a) (b) (c)

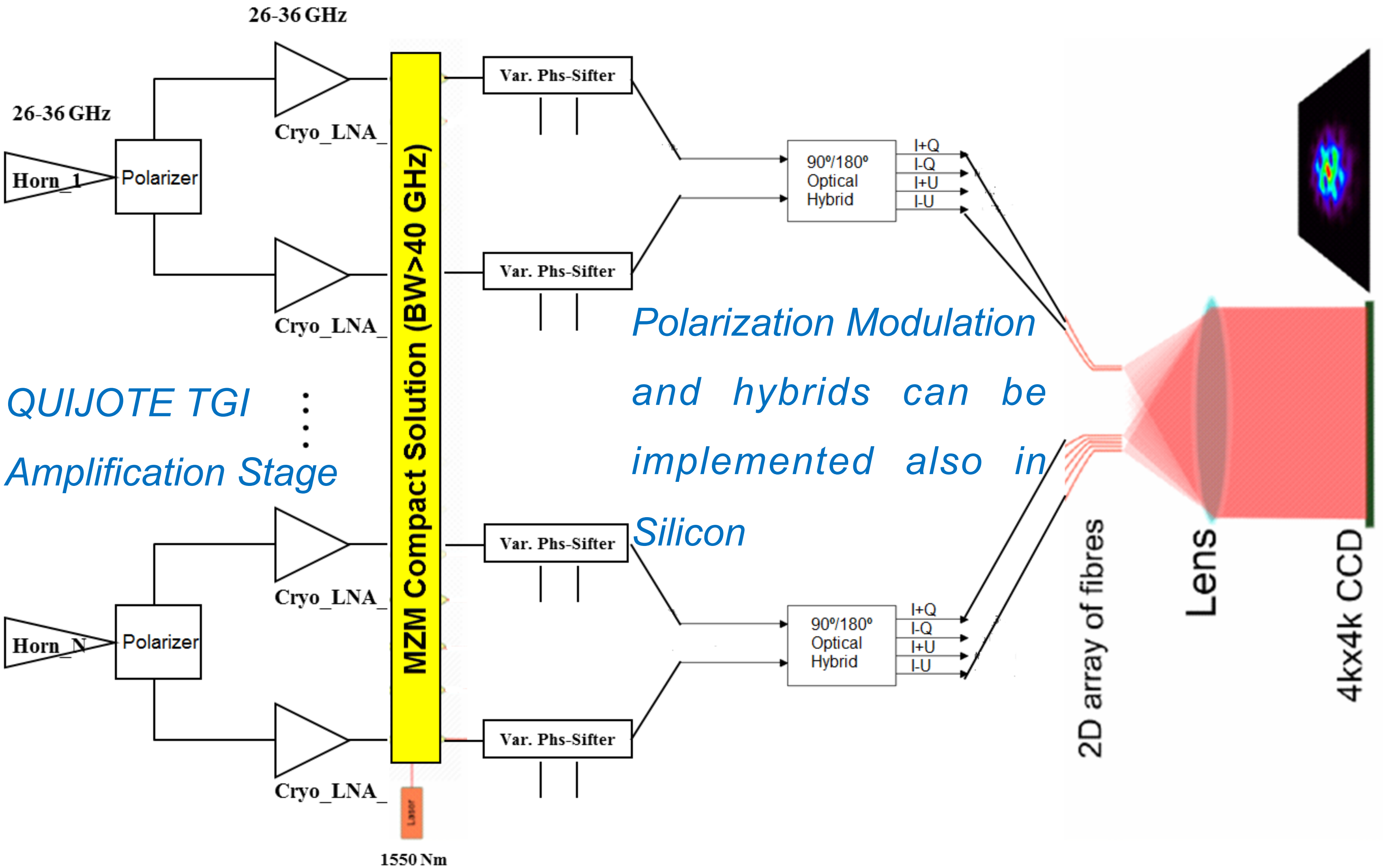
Figure 2. Showing (a) picture of the 220-channel, 75-GHz imager as well as snapshots from visible with passive millimeter-wave video overlaid taken during a recent field testing event for rotorcraft brownout mitigation in both (b)clear air and (c)in brownout. Distance to the central cross target is approximately 250'.

-1W and 1558nm fiber laser

Interferometer Implementation Proposal



Interferometer Implementation Proposal



QUIJOTE TGI Amplification Stage

Polarization Modulation and hybrids can be implemented also in Silicon

NEXT STEPS

· An optical correlator using MW to IR up-conversion is proposed to implement large format interferometers at 10-20 and 30 GHz.

· With the reported technology Michelson but also Fizeau type interferometers can be implemented. This work focus in Fizeau.

· The proposed interferometer uses the receiver scheme of the QUIJOTE TGI to achieve images of the polarization parameters I, Q and U. In a first stage we plan to develop a 9 pixels array covering the 10-20 GHZ band.

· Polarization modulation and signal combination functions can be implemented in the MW or IR domain. The latter would be the optimal solution in terms of integration and cost by using Silicon technology, being this technology also preferred to the MZM implementation.