Coherent Detector Arrays for Continuum and Spectral Line Applications

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CMB Polarization: Requirements

Detection of CMB intensity anisotropy requires good sensitivity, low systematics and (fortunately) minimal foreground removal.

E-mode polarization detection at ~5 μK RMS, requires better sensitivity, systematics and foreground veto or removal (DASI, WMAP)

B-mode polarization detection will require even better systematics, sensitivity and sufficient frequency coverage to remove foregrounds: 30-150 GHz

With detectors approaching fundamental limits, large arrays offer the only path to sensitivity improvement

Coherent Receivers- An Introduction

Coherent detection is fundamentally different from direct detection:
Incoming voltage signals are amplified with the waveform preserved.

This reproduction of signal photons comes with a price:

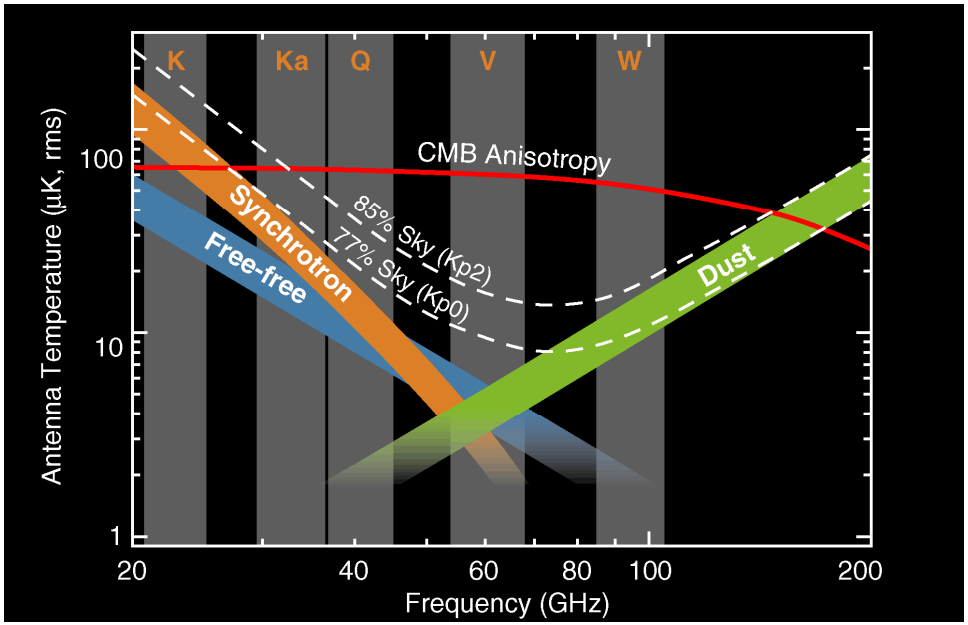
quantum noise: $T > h\nu/k$

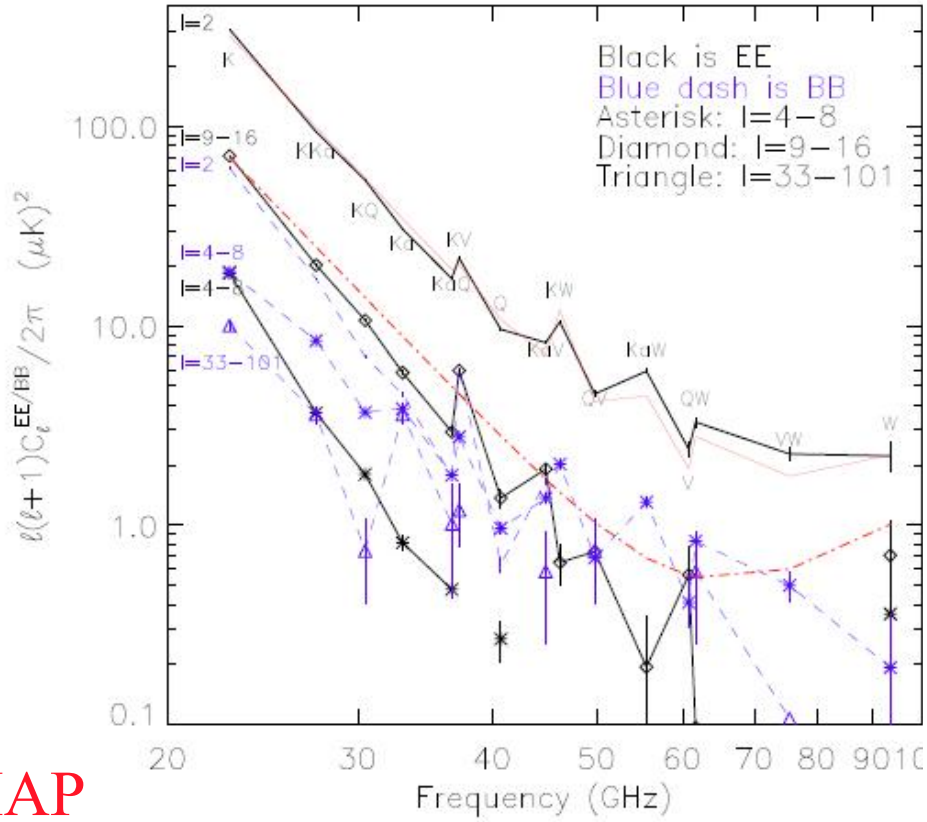
However, the resulting signals can be processed to extract all available information.

This offers unique capabilities for reduction of systematics while sacrificing little in noise performance below 100 GHz

Foregrounds- Minimum between 60-110 GHz

A good match to coherent technology





WMAP

Cryogenic HEMT Amplifiers:State-of-the-art

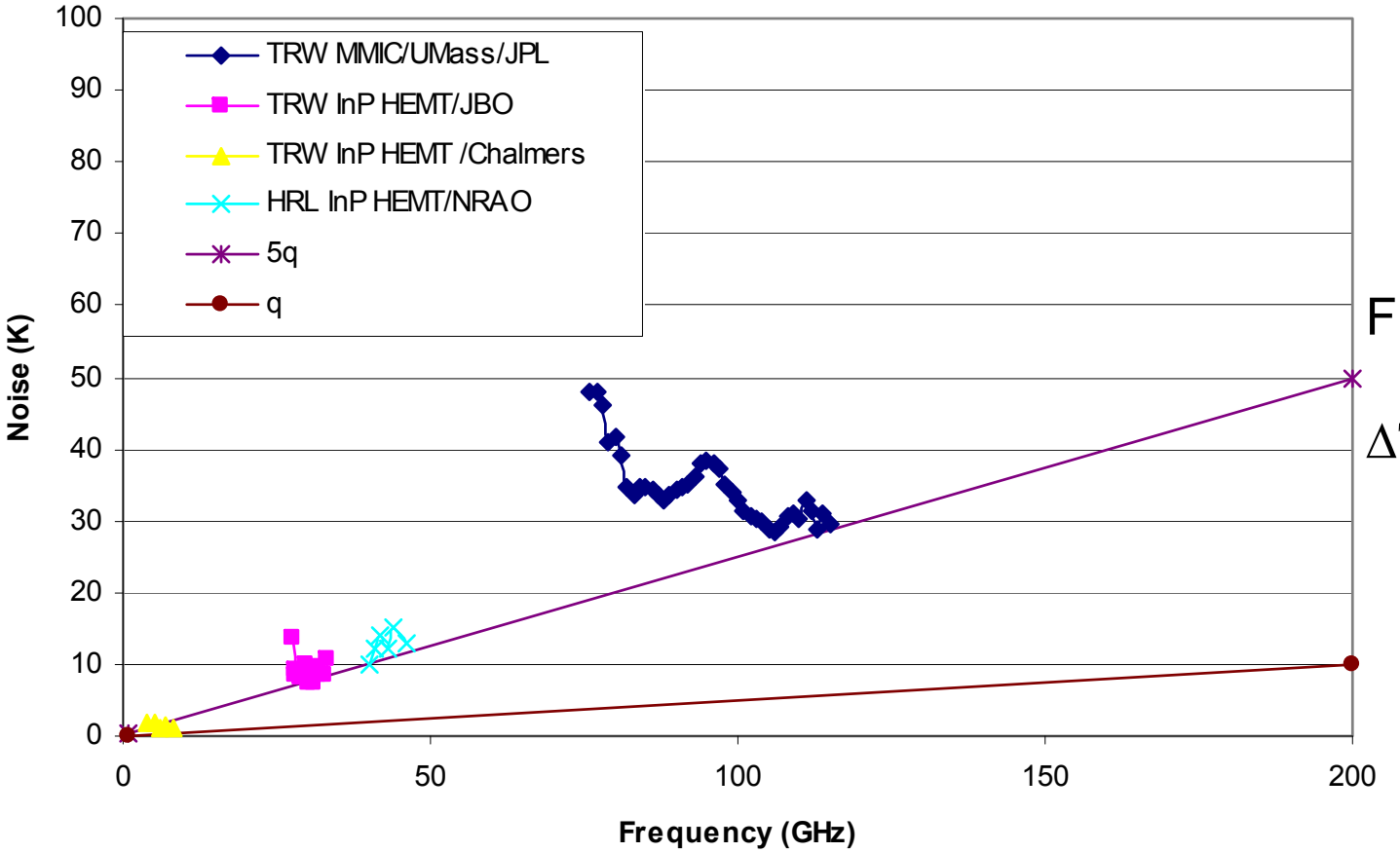
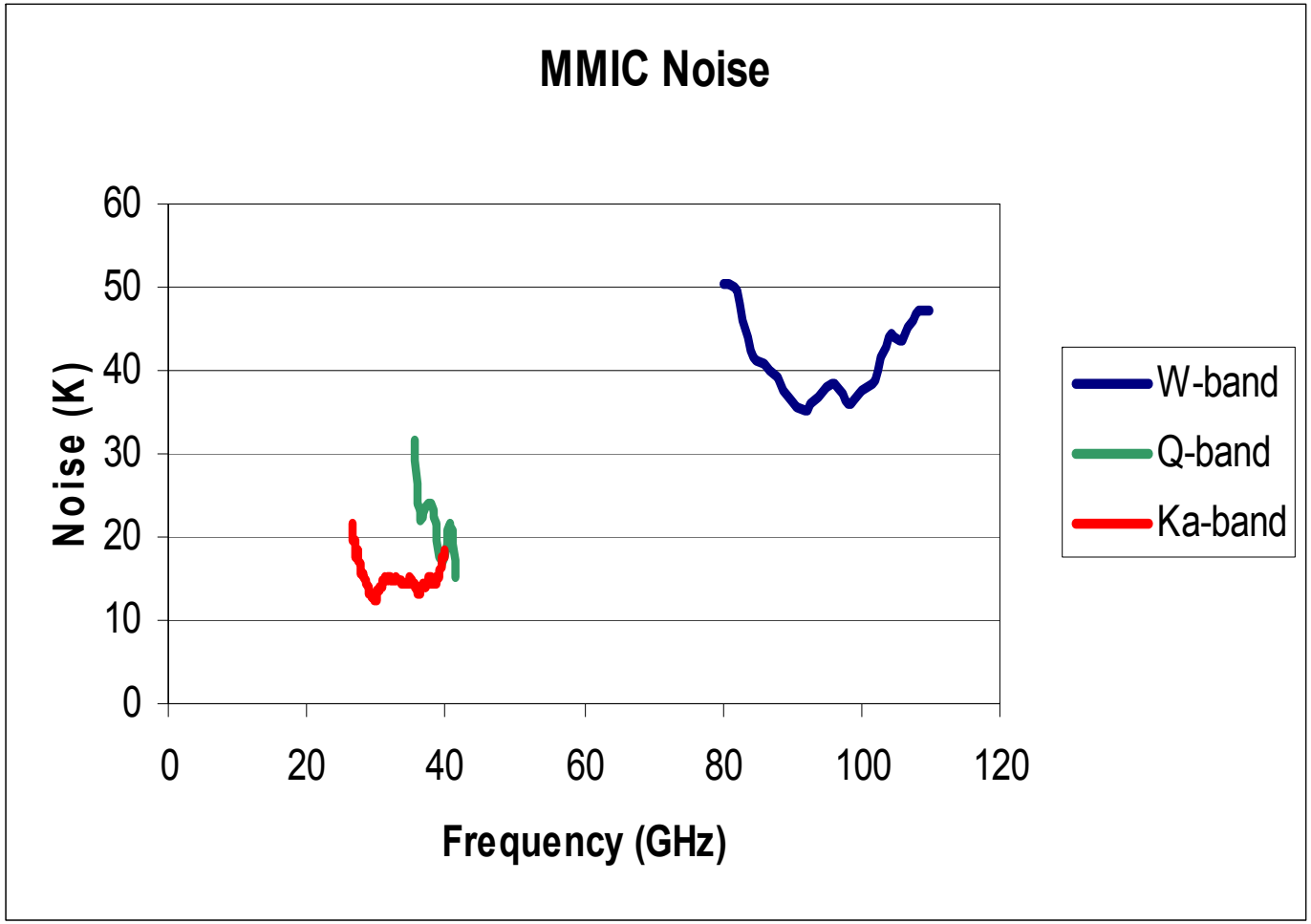


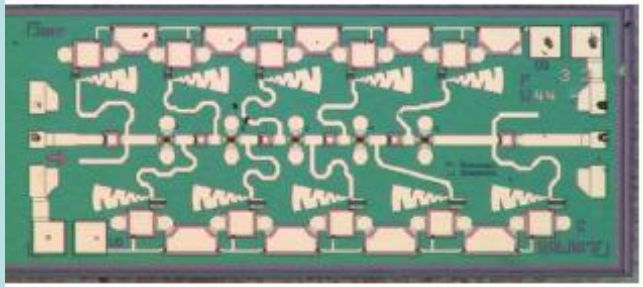
Figure of merit:

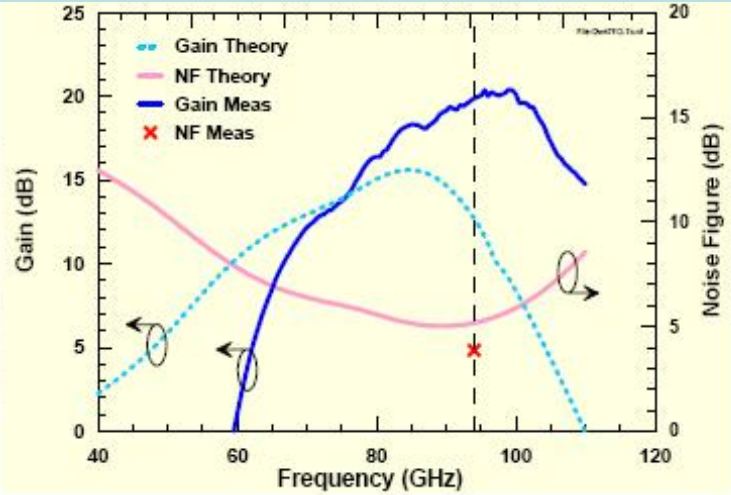
$\Delta T = T_{sys}/\sqrt{\beta\tau}$

MMIC noise is comparable to or better than MICs



High Speed InAs/GaSb HEMT Technology





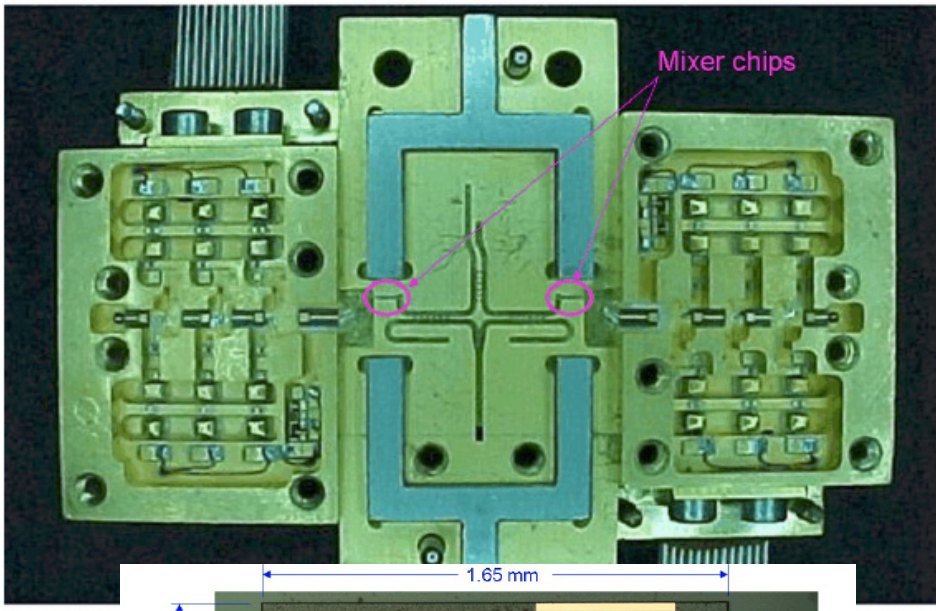
Hacker et al 2005

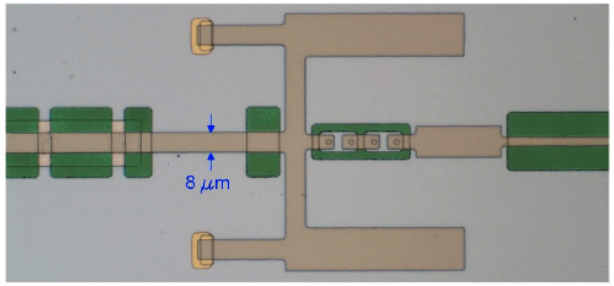
Operating power = 1.5 mW at cryo temps!

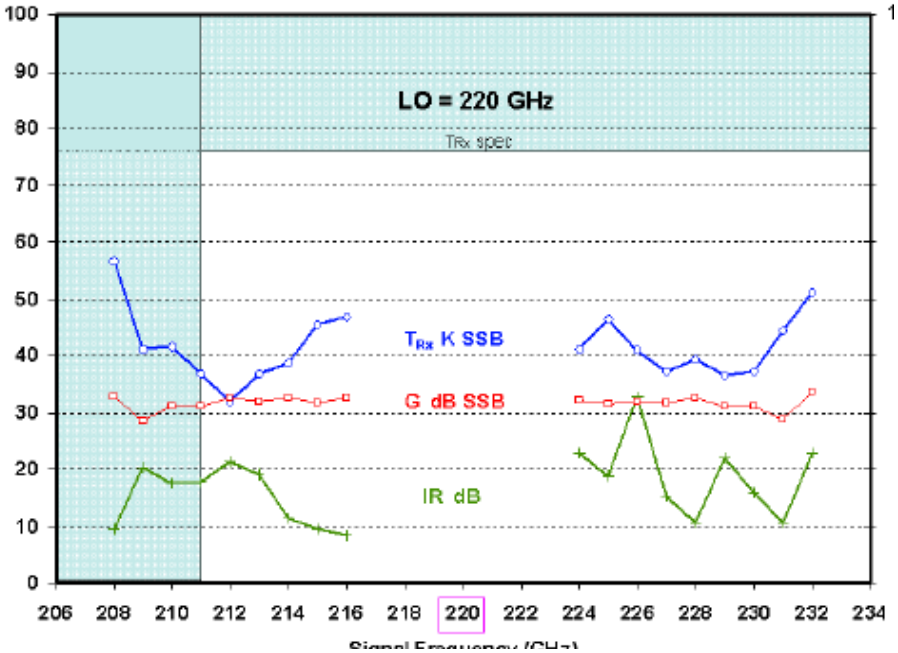
Enormous implications for a future space mission
Operating power ÷ 2

SIS Technology

Essentially a MMIC Mixer… developed for ALMA by NRAO.. planar possible







ALMA Memo 498

14 May 2004

The ALMA Band 6 (211-275 GHz) Sideband-Separating SIS Mixer-Preamplifier

A. R. Kerr [1], S.-K. Pan [1], E. F. Lauria [1], A. W. Lichtenberger [2], J. Zhang [2]
M. W. Pospieszalski [1], N. Horner [1], G. A. Ediss [1], J. E. Effland [1], R. L. Groves [1]

[1] National Radio Astronomy Observatory
Charlottesville, VA 22903

[2] The University of Virginia
Charlottesville, VA 22904

Systematics

All radiometers exhibit excess noise on long times- 1/f

Coherent detectors can utilize phase preservation to reduce 1/f systematics :

Correlation- multiplies independent signal paths separating uncorrelated gain fluctuations from correlated signals

Phase modulation- performed after gain (ie lossless) to reduce correlation offsets

Simultaneous Q/U detection- Provides improved sensitivity and antenna specific systematics check, no loss of signal

Receiver Architectures

Focal plane arrays:

Correlation or pseudocorrelation
Readout easy
Large number of elements
Need very clean optics

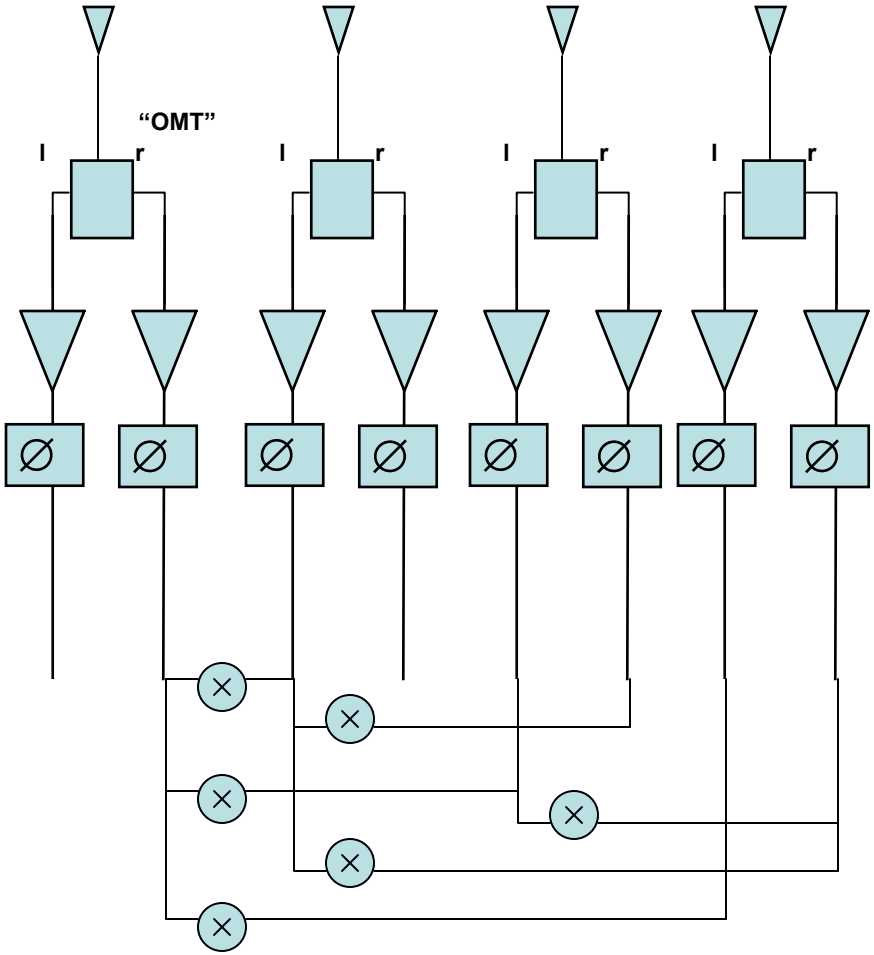
I Difficult
Q, U Easy

Interferometric arrays:

Analog or digital correlation (N^2)
Large number of elements
Excellent systematic rejection

I, Q, U Easy

Interferometric Array Receivers



Synthetic Aperture Interferometer:

Currently in use by DASI, CBI and VSA. Will be used by AMiBA

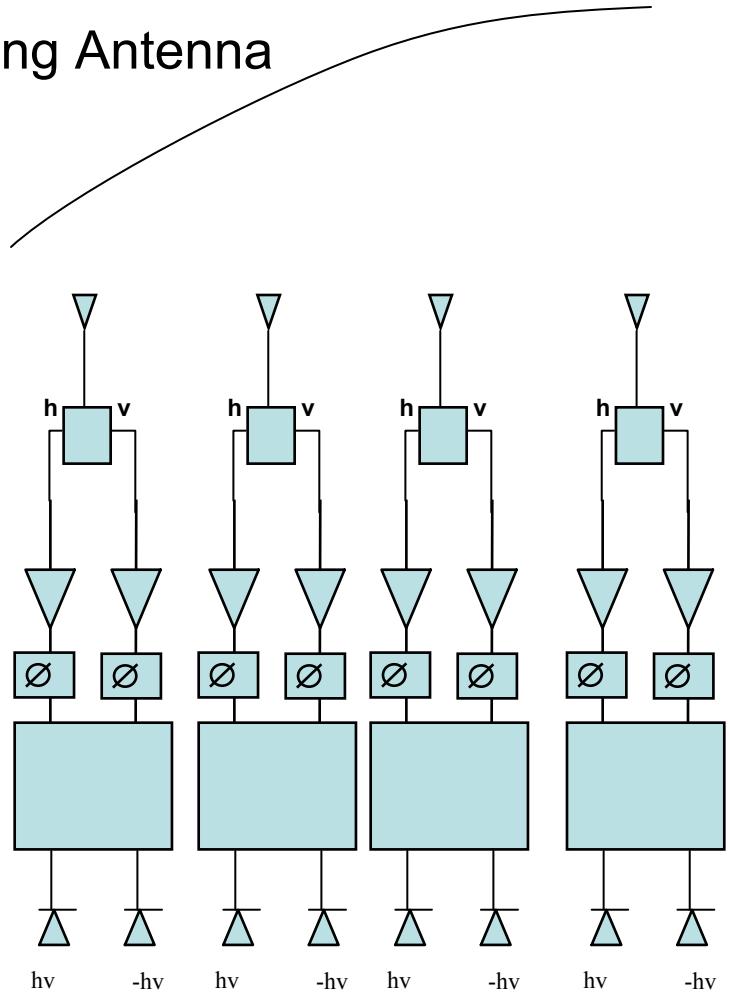
Uses coherent detection to directly map sky brightness distribution.

Amplification has been used very effectively. I,Q,U simultaneously

N(N-1) Correlations

Focal Plance Arrays- Correlation or Dicke-Switched

Imaging Antenna



Focal-plane array polarimeters
CAPMAP, COMPASS, QUIET, COFE

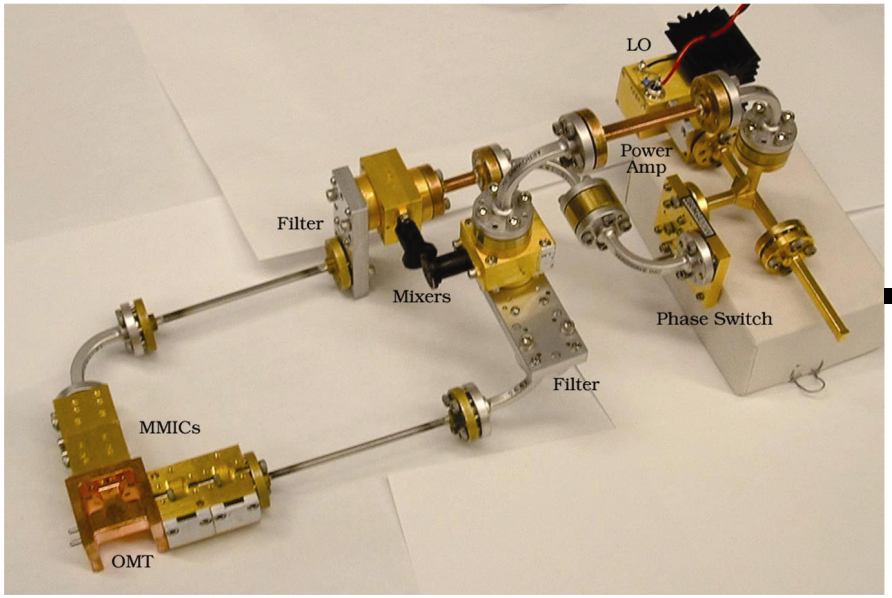
This concept increases mapping speed by N, the number of receiver elements.

QUIET approach- Focal Plane Arrays

JPL- Seiffert, Lawrence, Kangaslahti,Gorski, Dragovan, Imbriale, TG
Princeton- Staggs, Bannister
Chicago- Winstein
Miami- Gundersen
Columbia-Miller
Stanford-Church
NASA/GSFC-Wollack
Oxford- Jones
Berkeley-White
Harvard-Smithsonian-Wilson

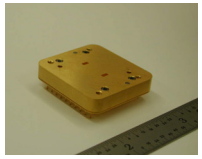
MMIC packaging makes arrays possible

CAPMAP 90 GHz Polarimeter

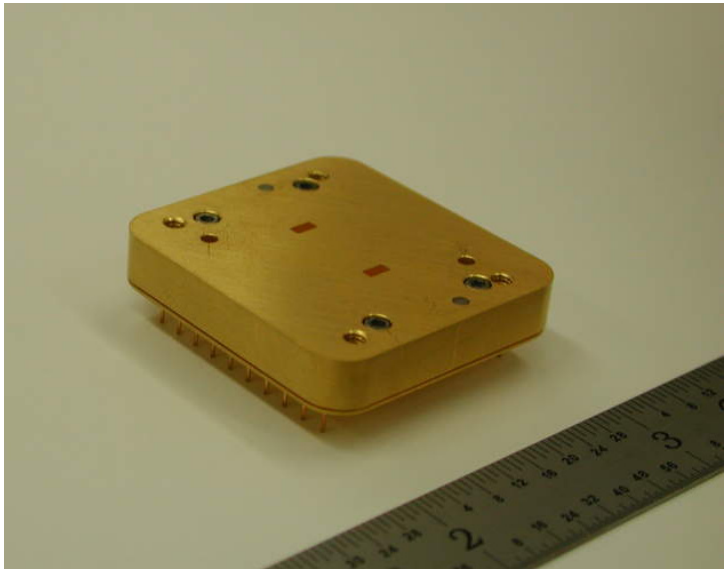


X-Y Polarizer

~ $40K and 50 physicist-hours for checking, characterizing, etc

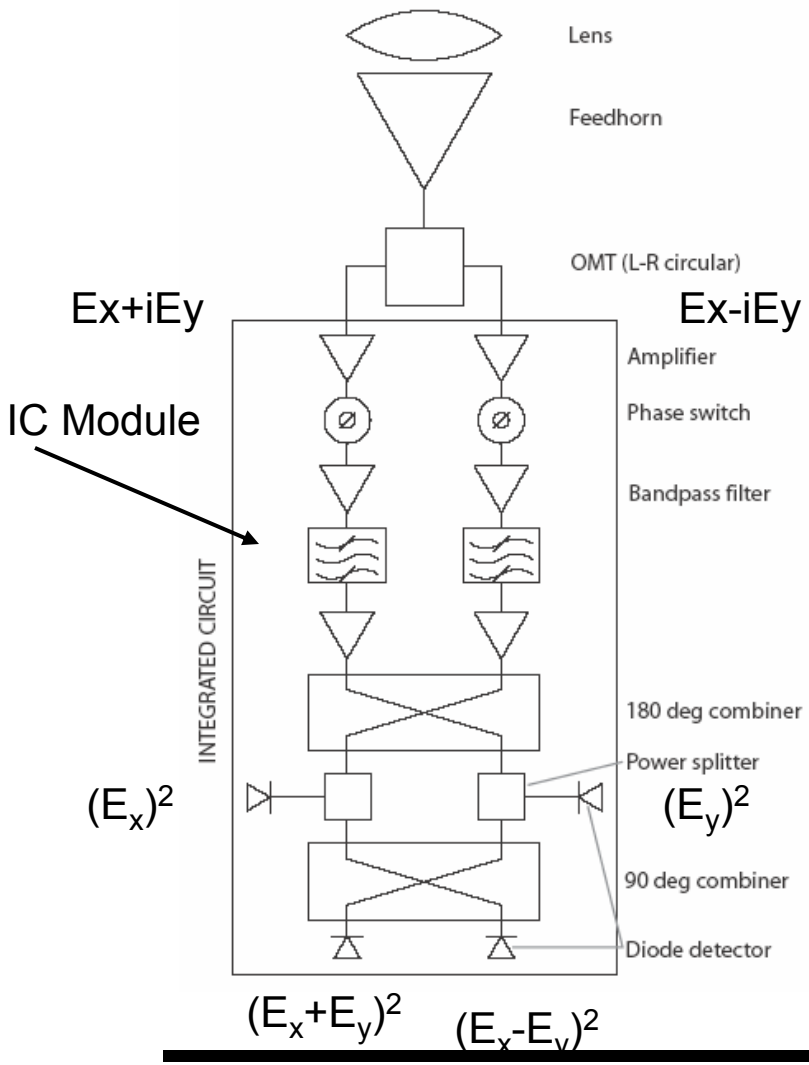


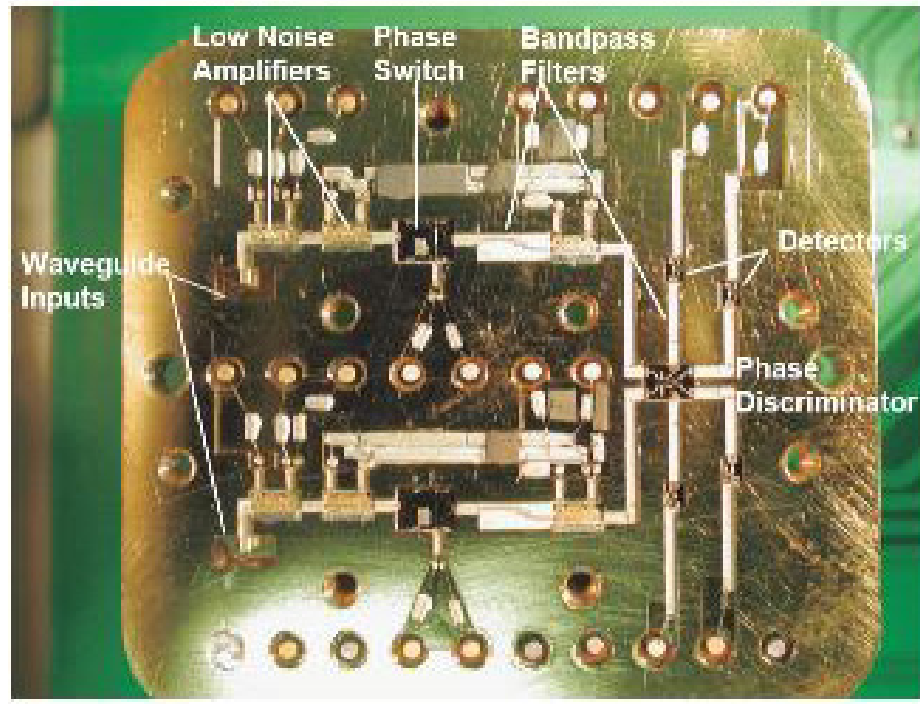
QUIET Polarimeter IC



~ $500 and automated assembly and test, completely scalable

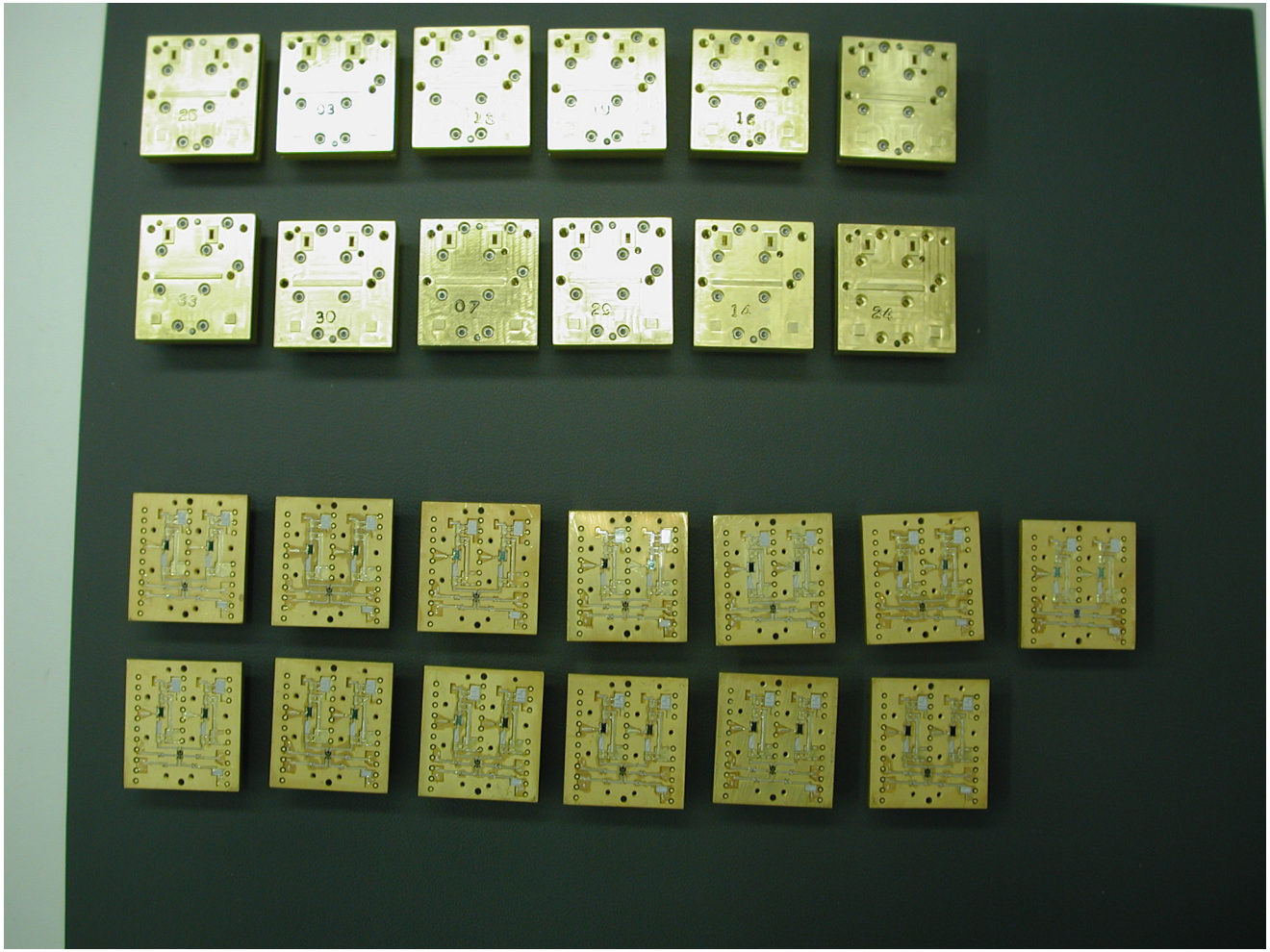
90 GHz Pseudocorrelation Receiver



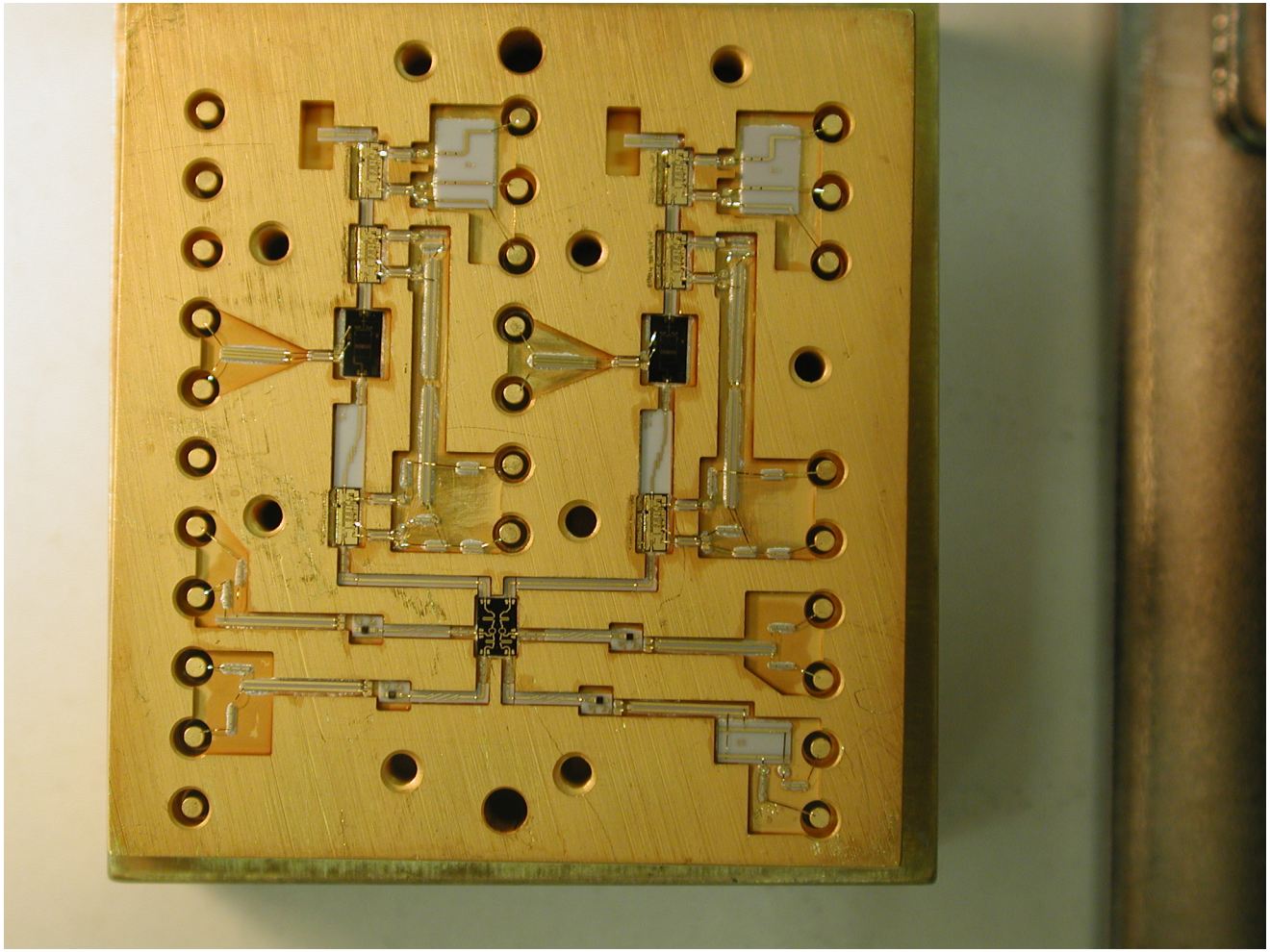


T_{sys}=60K at cryo temps

90 GHz Pseudocorrelation Receiver- Array Production



Robotically Assembled Module



40 GHz Pseudocorrelation Receivers

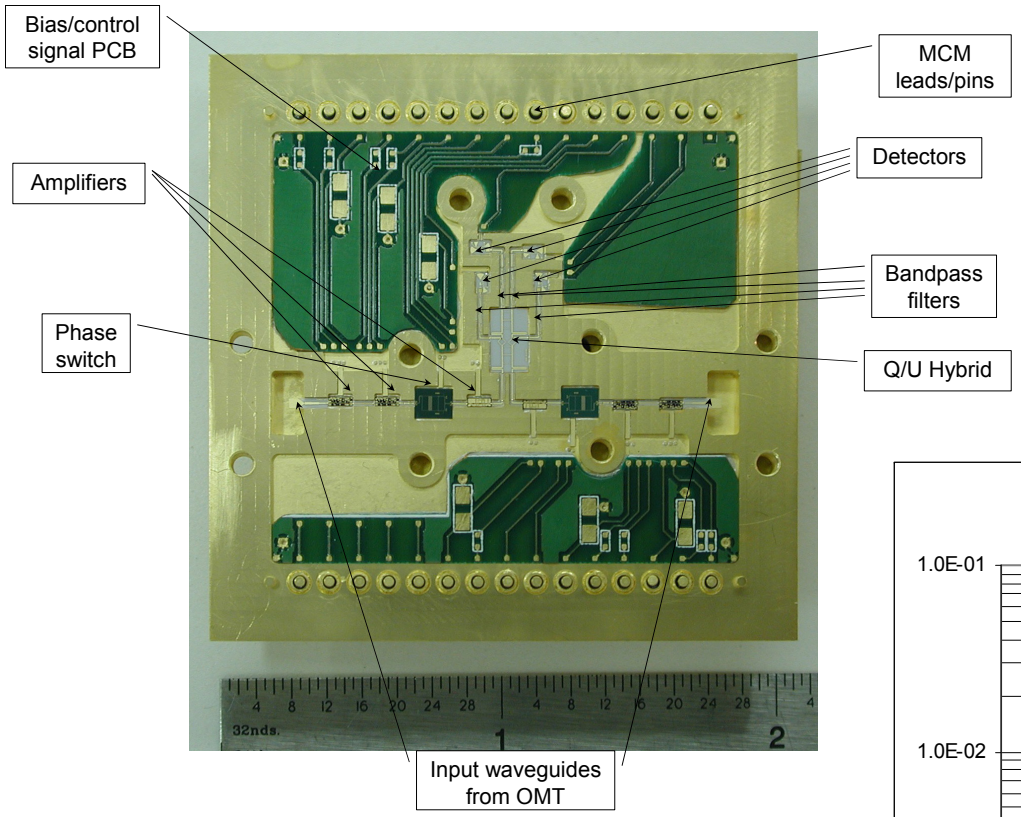
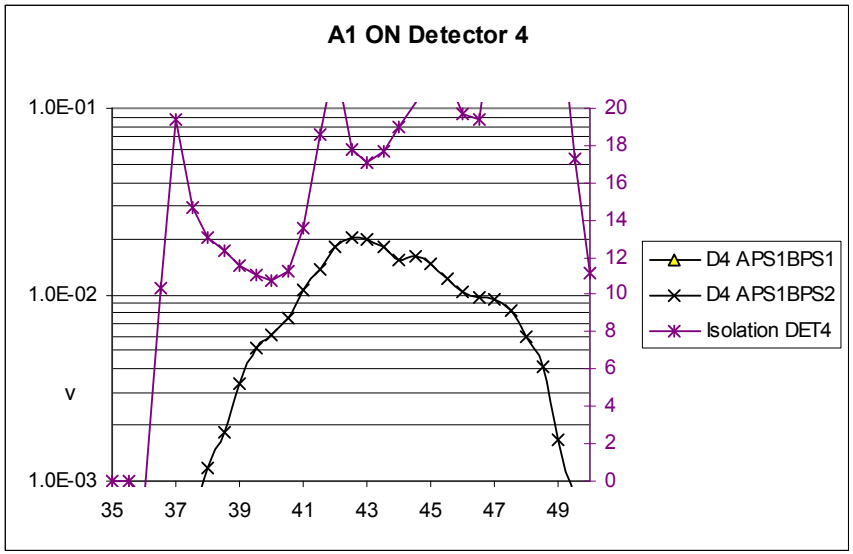
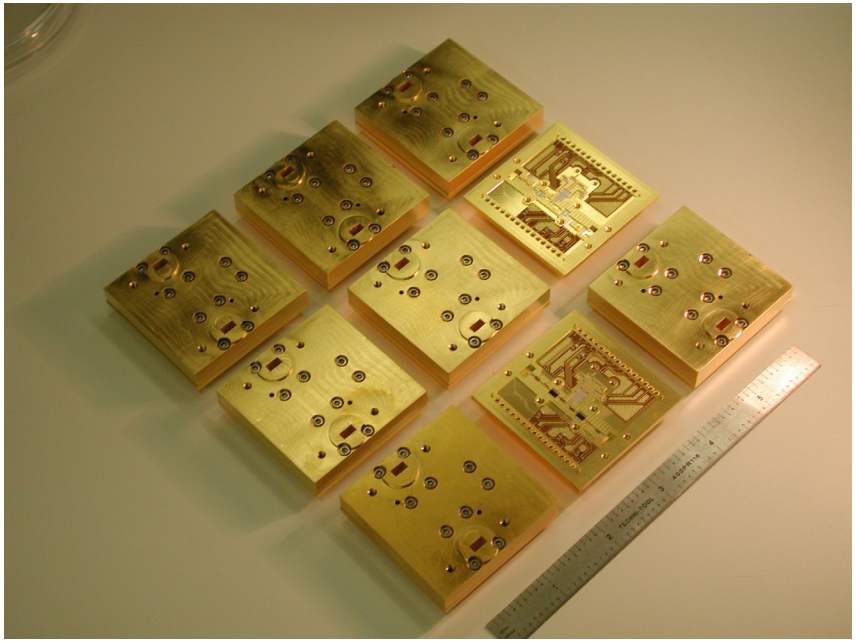


Fig 1. 40GHz polarimeter integrated as a MultiChip Module (MCM). The module contains all the functions of the polarimeter, including the detection of Stokes parameters Q and U. The module has two WR-22 waveguide inputs from the OMT through the lid and DC connections to the back-end electronics

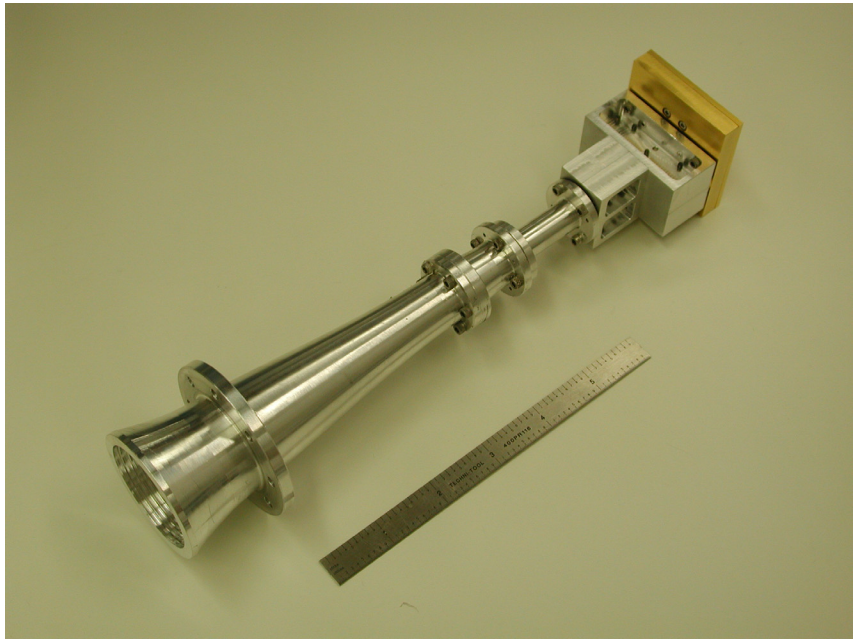
16-20 K Noise
38-47 GHz BW
30 mW DC



40 GHz Receivers



19 Element Array in Fabrication
9shown

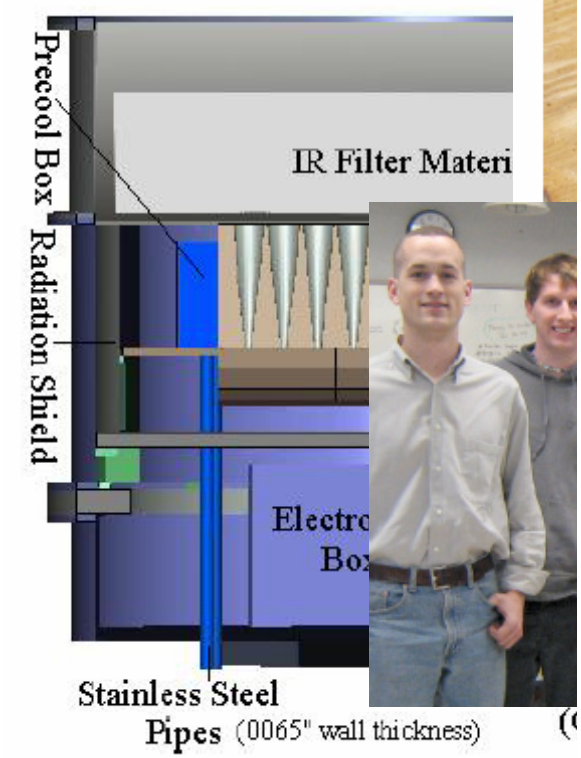


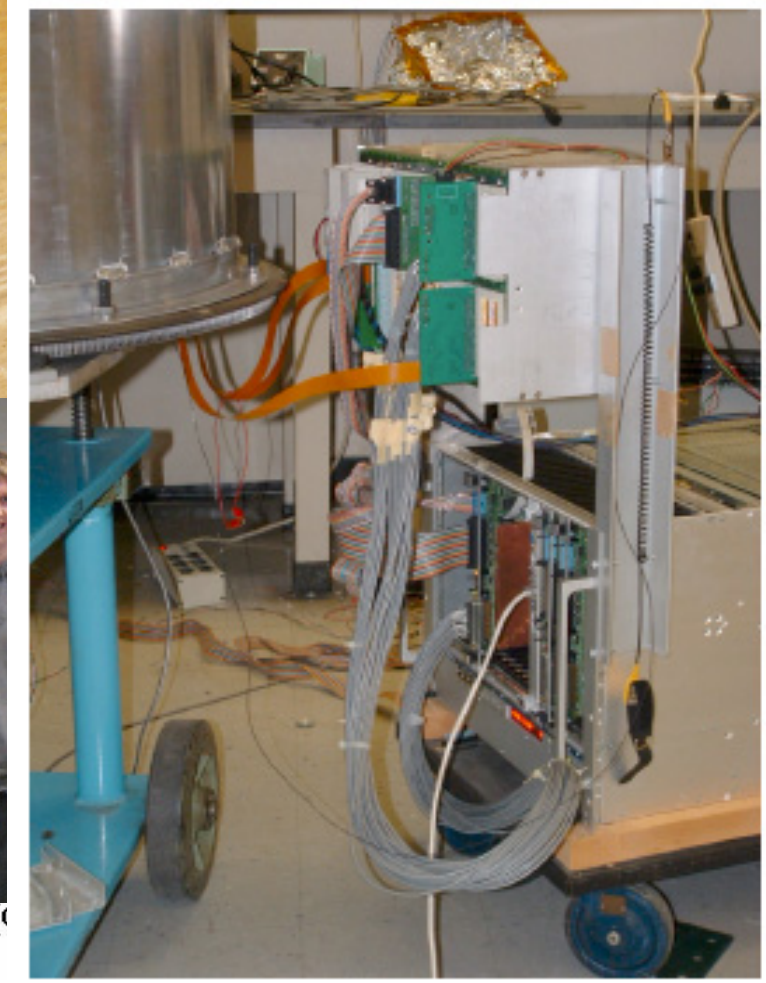
Assembled Polarimeter

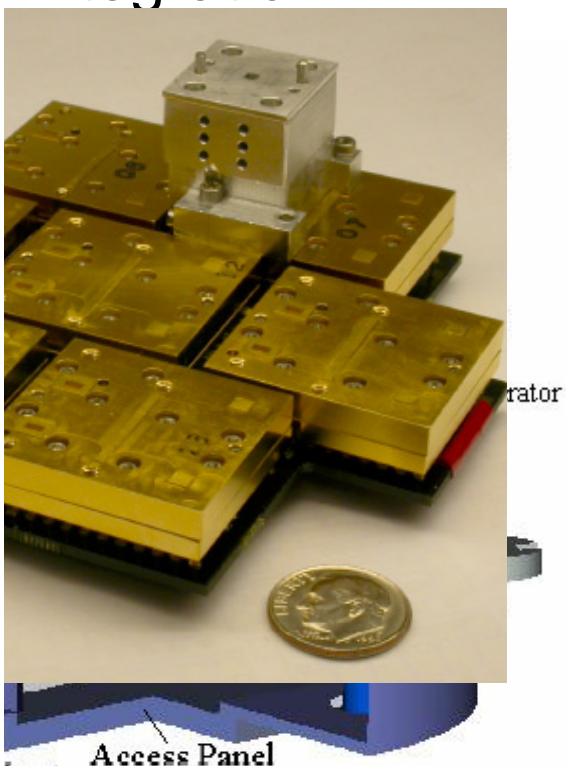
91 Element W-band Array

91-Elem

integration







QUIET-Experiment Parameters

CHARACTERISTICS OF QUIET — Q/U SENSITIVITY

Experiment	ν [GHz]	FWHM [′]	FOV [deg]	$N_{\rm feeds}$	$T_{\rm rcrv}$ [a] [K]	$T_{\rm sys}$ [b] [K]	$\Delta\nu$ [GHz]	Feed Sens[c] [μK s$^{1/2}$]	Q+U Array Sens[d] [μK s$^{1/2}$]
QUIET Phase I									
1m	40	41	11	17	19	27	8	159	39
1m	90	18	12	83	45	54	18	248	27
QUIET Phase II									
2m	40	23	13	166	19	27	8	159	12
7m	40	9	6	83	19	27	8	159	17
2m	90	10	12	714	45	54	18	248	9
7m	90	3-8	5	357	45	54	18	248	13

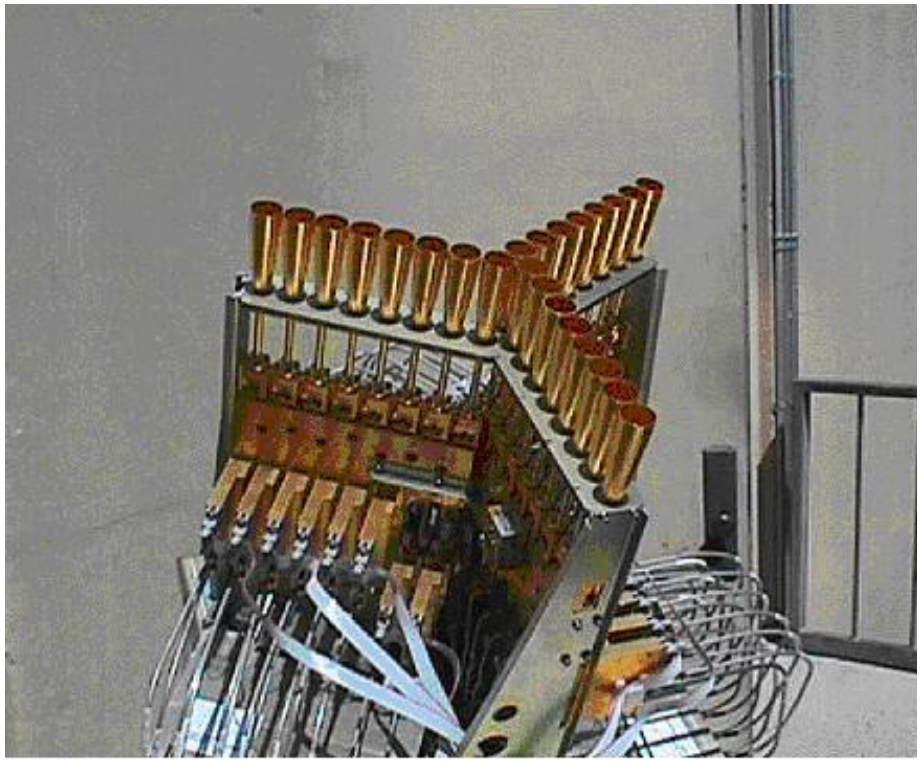
[a]Receiver noise temperature (antenna temperature units) — based on field-tested MMIC amplifiers

[b]Total system temperature (antenna temperature units) including 2.73 K for the background itself and NRAO model for atmospheric emission at 45 deg elevation.

[c]Per feed, corrected to thermodynamic units, including both Q & U from correlation polarimeter, with normalization $Q = (T_x - T_y)/2$.

[d]QUIET will be configured with 90% polarimeters, 10% intensity receivers.

The interferometric approach



GeoSTAR compact aperture synthesis interferometer

Compact modules reduce front-end cost (This could be MMIC or SIS)
LO distribution can be via PCB+multiplier

The correlator is the tall tent pole.

Sobering Rough Order Correlator Realities

CMB requirement: 20 GHz Bandwidth, N=100-1000, dual pol

ALMA/EVLA Correlator
16 GHz, N~50 (~2500 correlations)
Cost~>$10M

GeoSTAR Correlator
110 MHz, N~24 (IQ)
Cost ~$0.1M

FPGA based correlator for CMB-

Virtex-4 chip 200,000 logic cells, ~80 logic cells/mult-accum

For N=100, ~40,000 mult-accum (w/pol) → need ~16/500 MHz band or 1000 chips+distribution (Costly, but not impossible)

Interconnections may dominate!

ASIC might result x5 reduction in chips (200 chips)

Moore's Law would project:
50 chips in 3 years
12 chips in 7 years

How About an Analog Correlator?

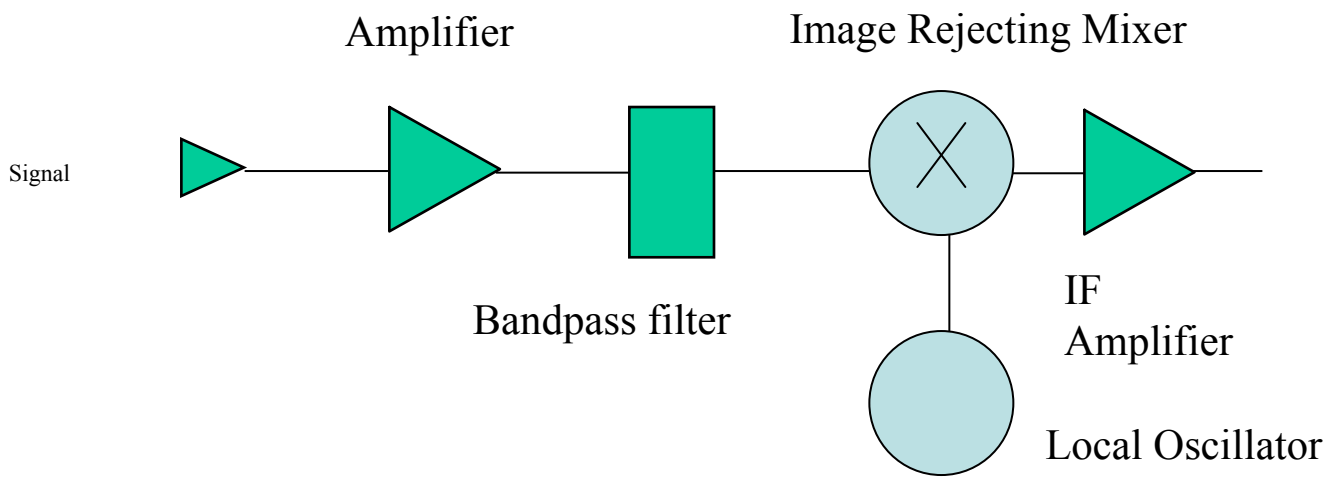
For N=100 , Bandwidth=2 GHz
Assume Multiply-Amplify chip is 4 mm^2, accumulate is 4mm^2
10^4 pairs are required or ~1 m per side (with interconnects)

But…

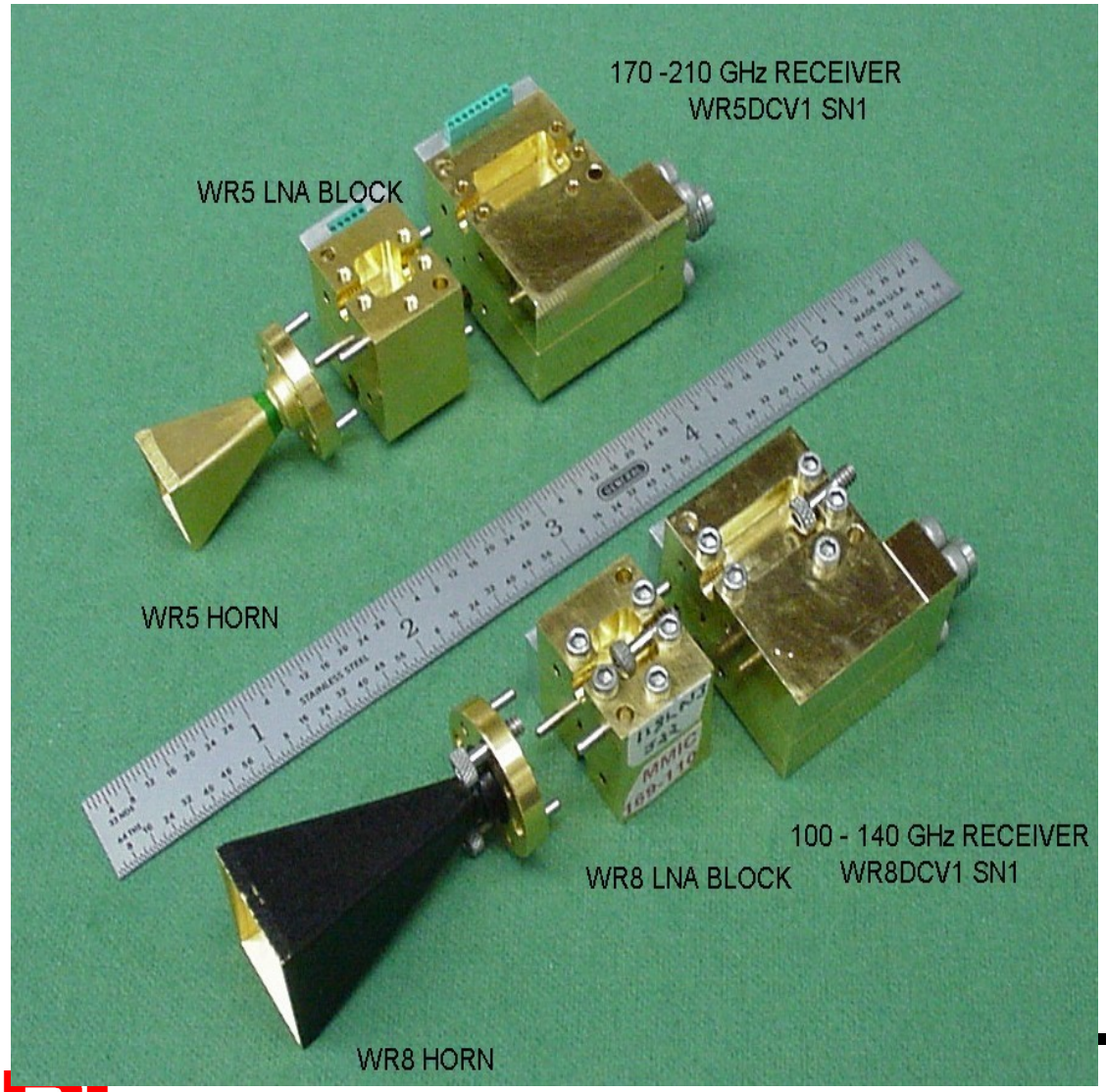
The power consumed might be a few hundred watts (nothing new)
Also, the IF processor becomes a huge driver- decimate 20 GHz BW into 10x 2 GHz BW xNx2- costly, big, heavy

….Although it looks possible!

What about heterodyne spectroscopic receivers?

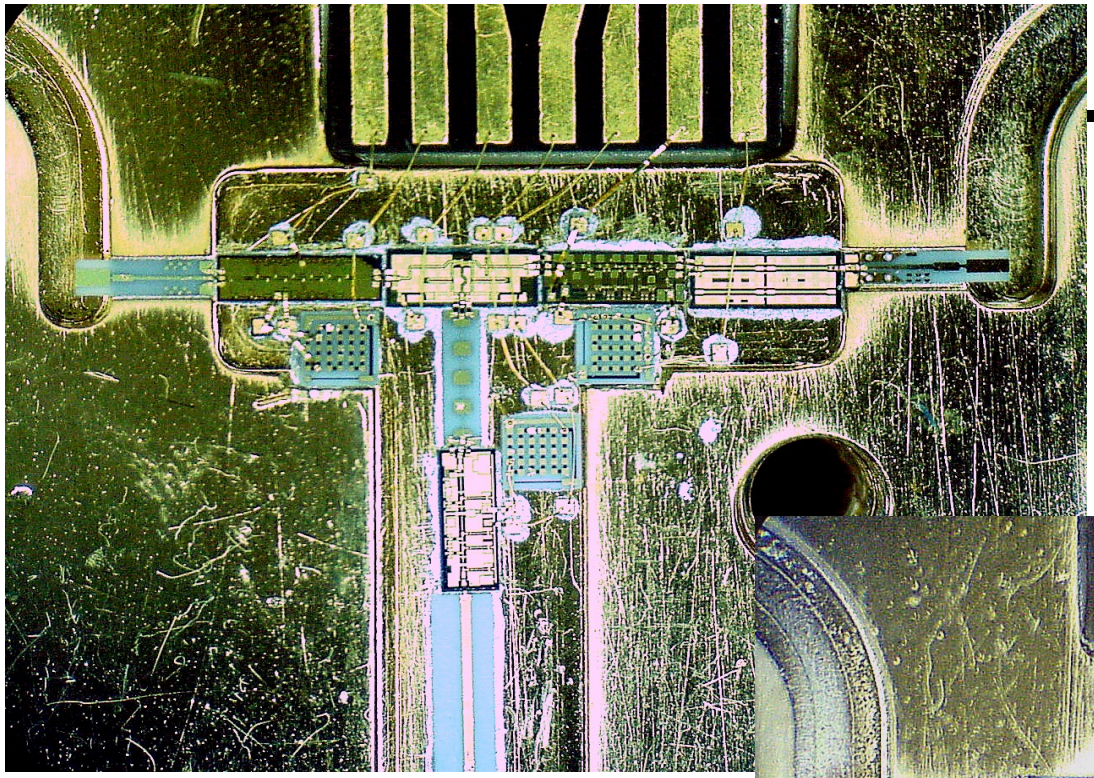


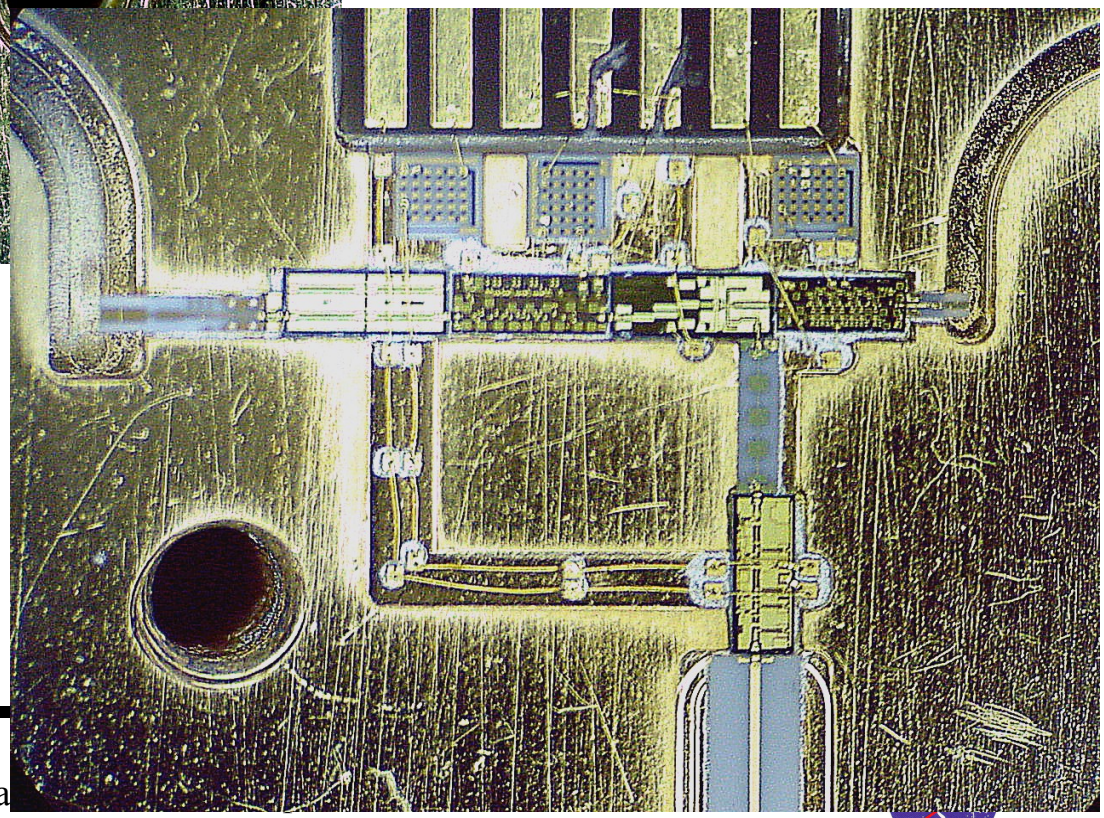
Microwave Atmospheric Temperature and Humidity Sounders



Compact heterodyne receivers

Room temperature

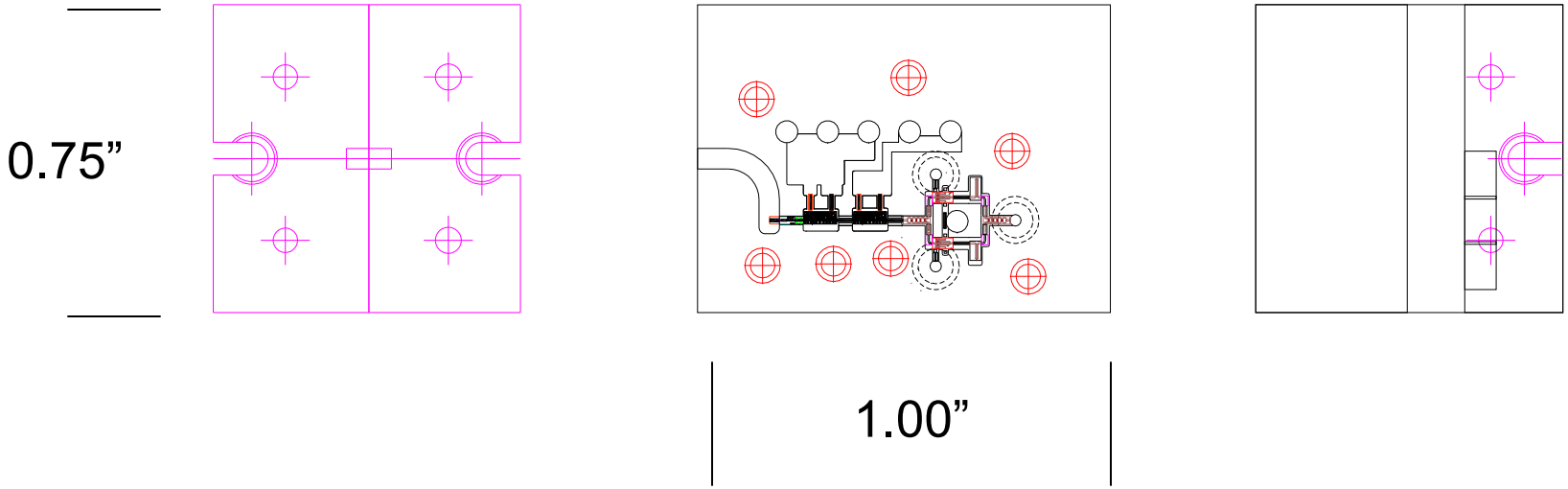




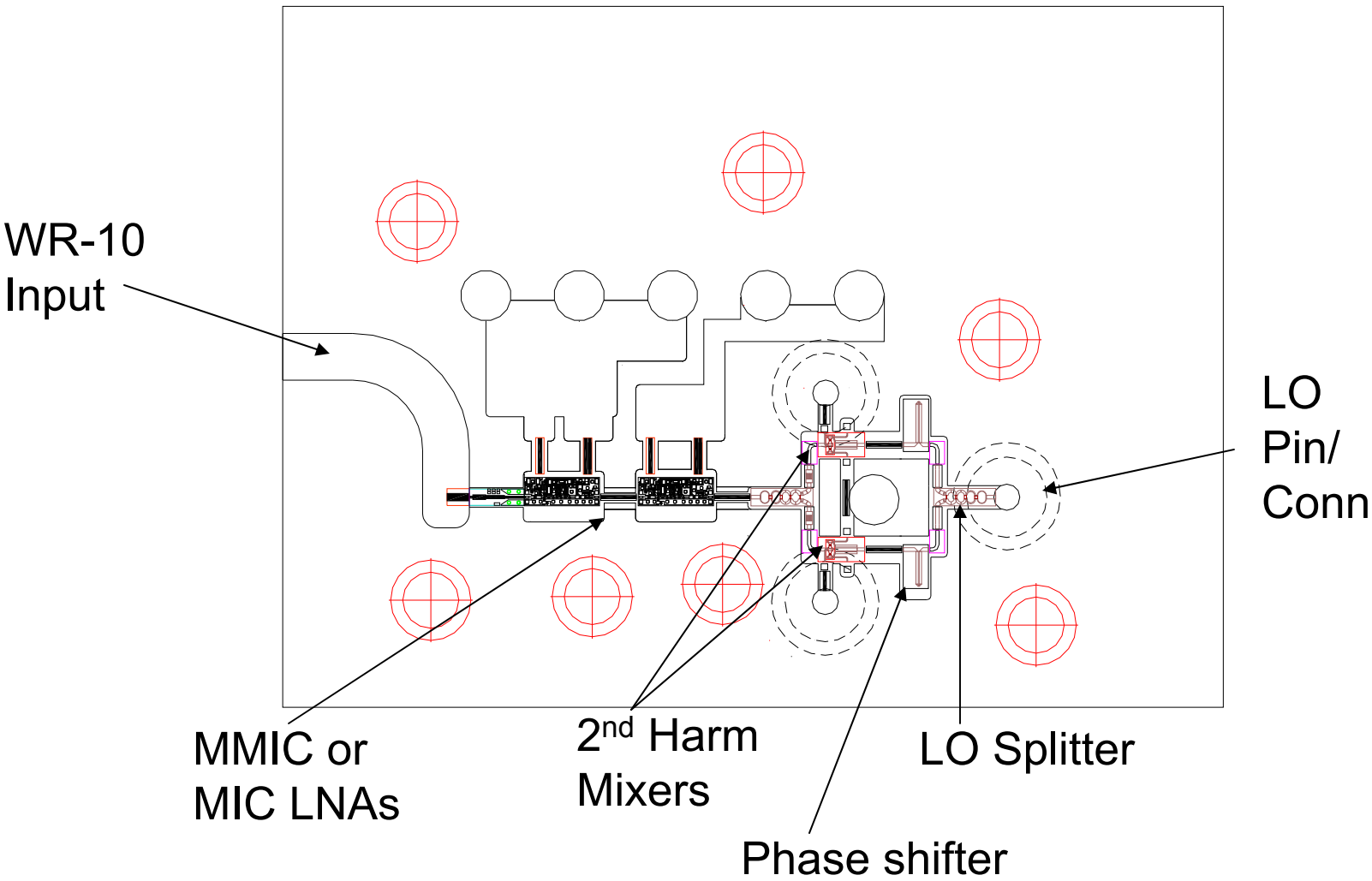
D. Dawson

T. Ga

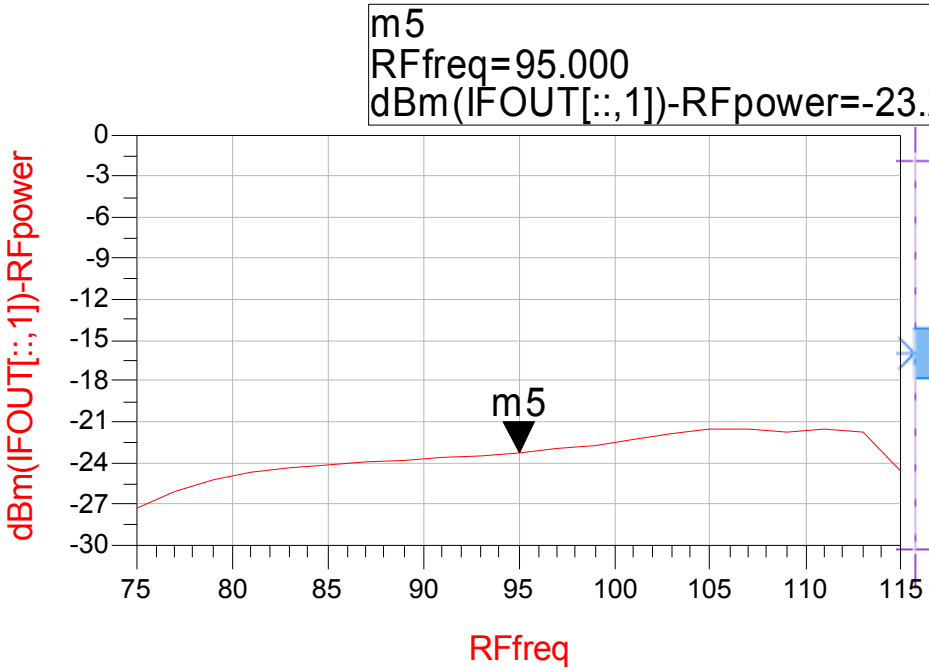
GBT W-Band Spectral Line Receiver Module Concept

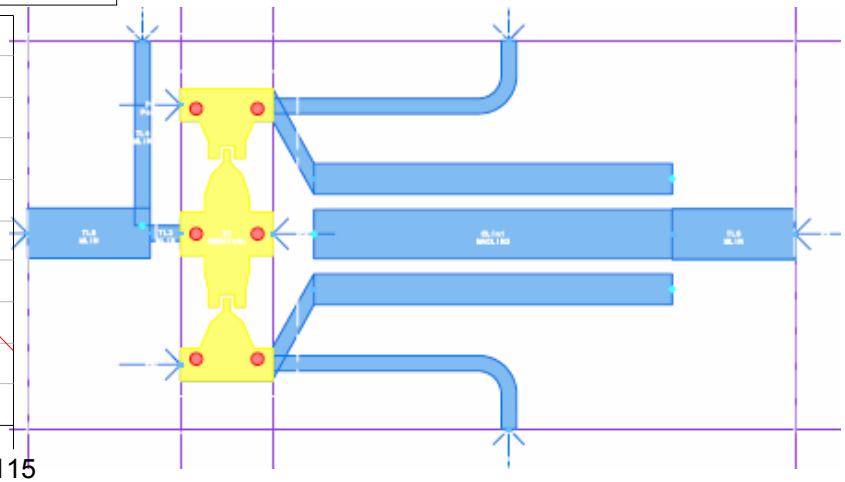


GBT W-Band Module Functions

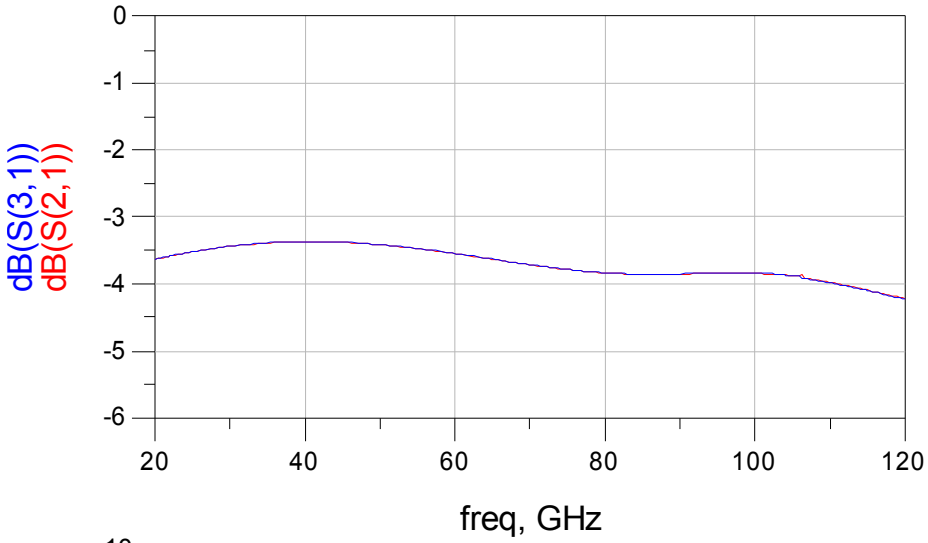


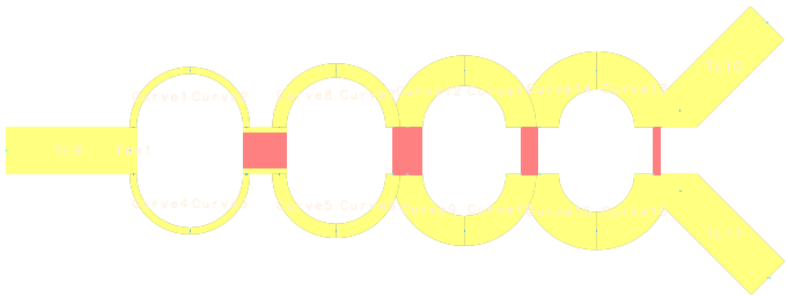
2nd Harmonic Mixer Modeled Performance

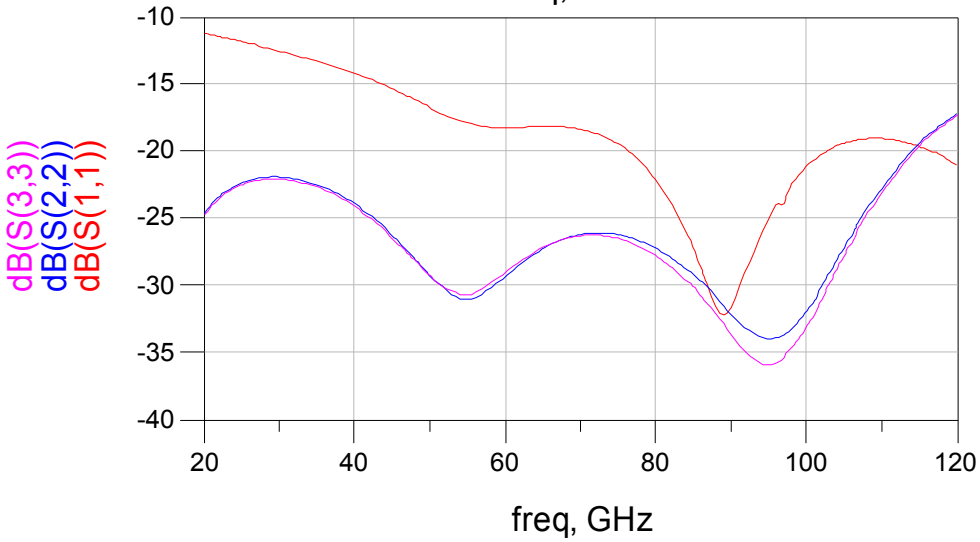


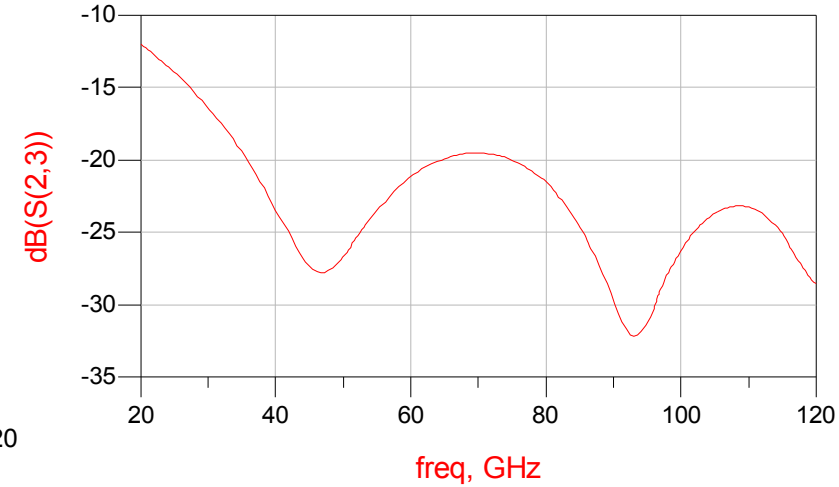


Wilkinson Splitter Modeled Performance









Conclusion

MMIC technology offers a straightforward path to massive focal plane millimeter wave arrays:

The technology will readily support continuum imagers, polarimeters and spectral line receivers from 30-110 GHz.

Science programs, particularly large field blind surveys will benefit from simultaneous observations of hundreds or thousands of pixels

1000 element array is competitive with a cost less than $2M.

Conclusions

•Coherent detectors are competitive at frequencies below 100 GHz from the ground. SIS MMICs may make compact modules receiver possible up to 250 GHz. Sb devices may enable a space mission

•We are poised to demonstrate large arrays of pseudocorrelation polarimeters in focal plane arrays

•Aperture synthesis interferometric arrays with N>100 are possible now from the front-end perspective and maybe a few years away on the correlators