MMIC HEMT Radiometry

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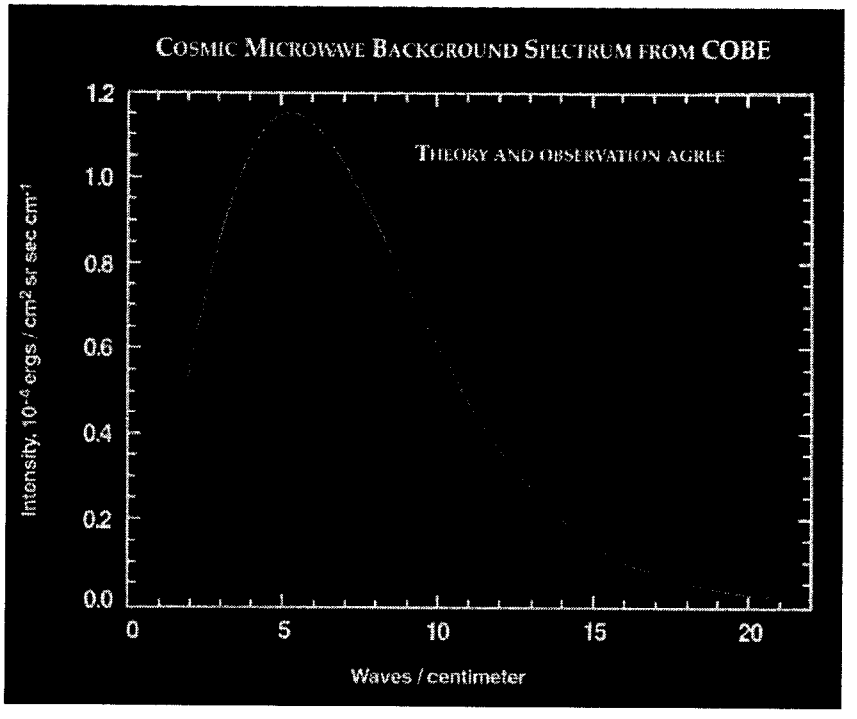
What is radiometry?

All matter emits radiation

In the Rayleigh-Jeans limit ($h\nu \ll kT$) $P=k_b T\beta$

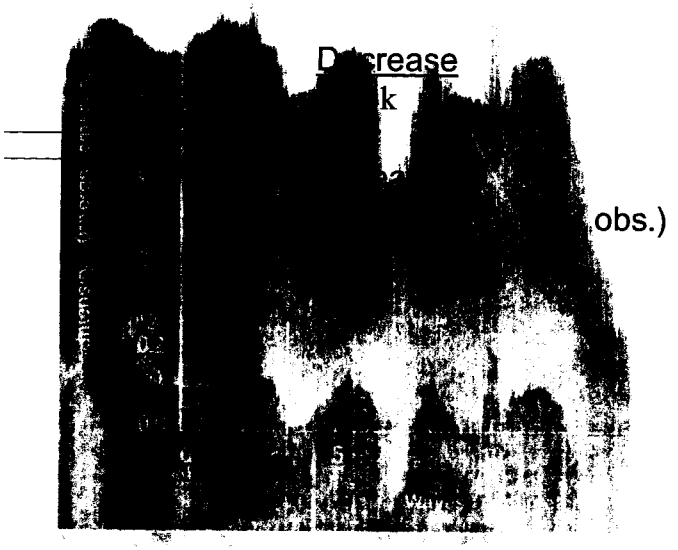
Power measurement at long wavelength measures temperature



Figures of merit:

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

ΔT is measurement uncertainty (noise)
T_{sys} is the receiver noise temperature
β is the receiver bandwidth
τ is the integration (observation) time
k is a constant (for gain stability or chop)

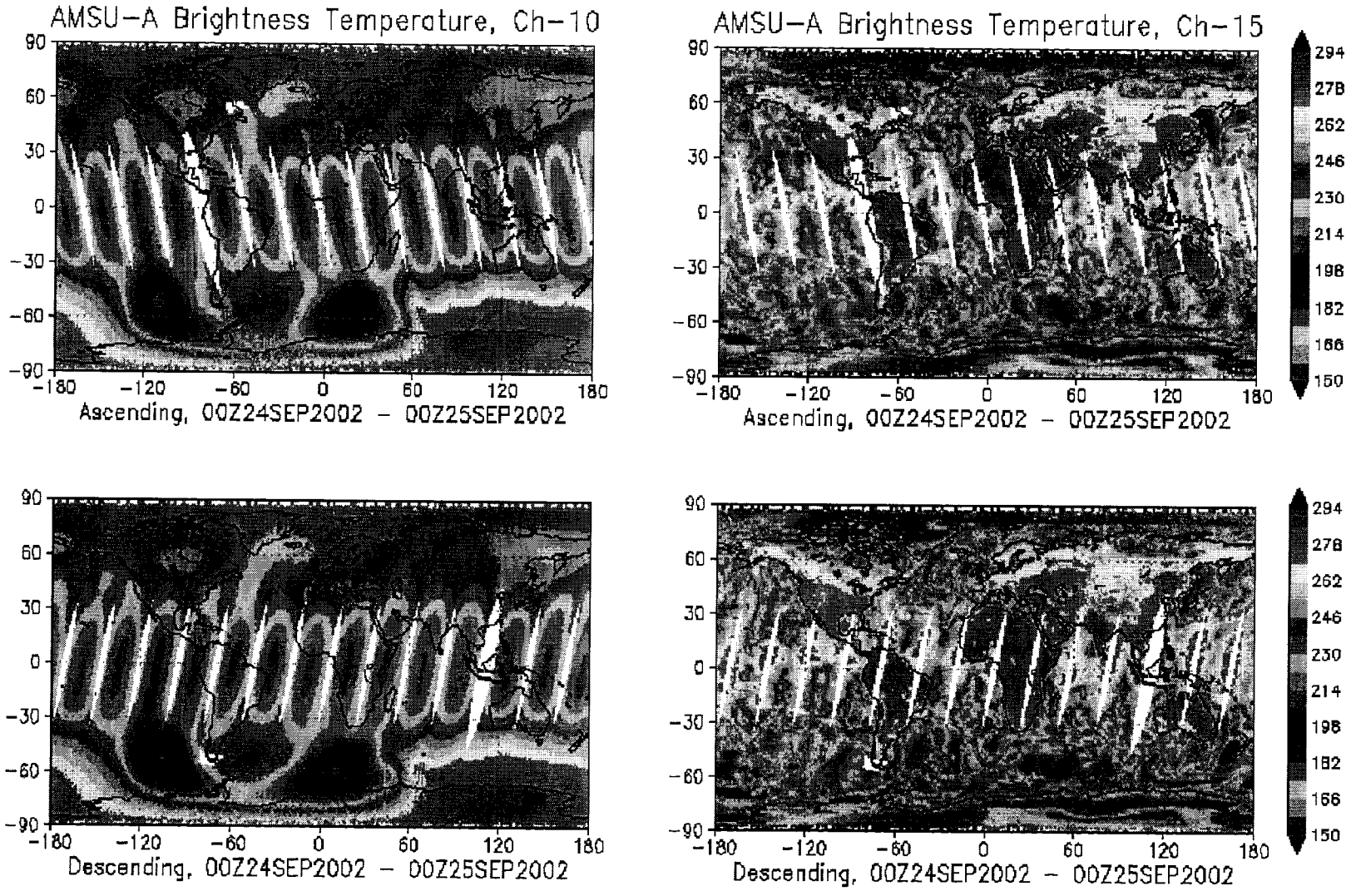


Radiometers can be used to characterize thermal sources of radiation

With broad spectral coverage, radiometry can distinguish thermal from non-thermal emission:

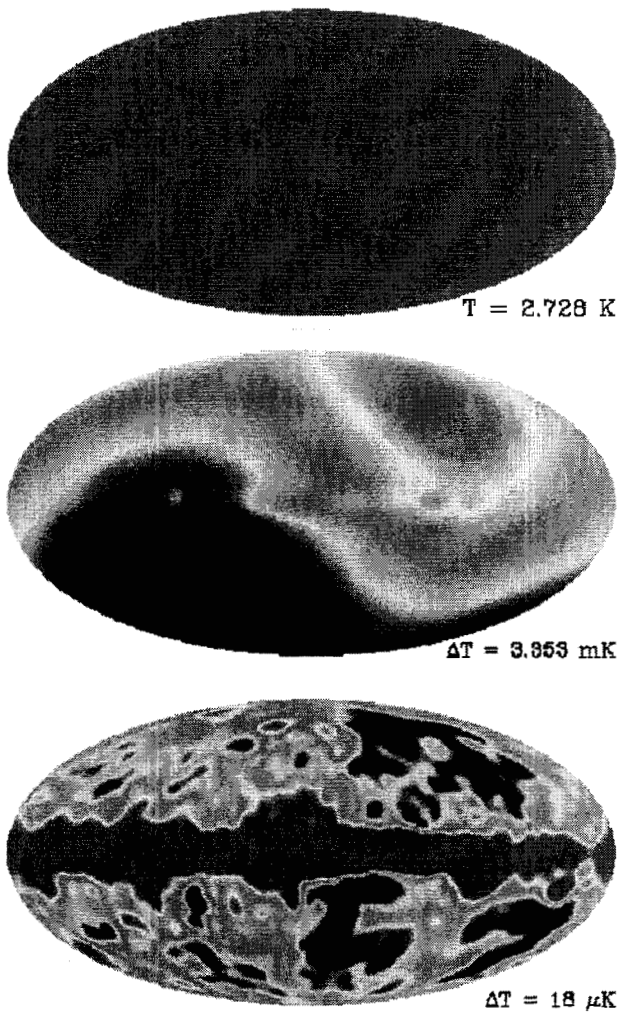
Spectral lines, non-thermal continuum emission, etc

Atmospheric Sounding

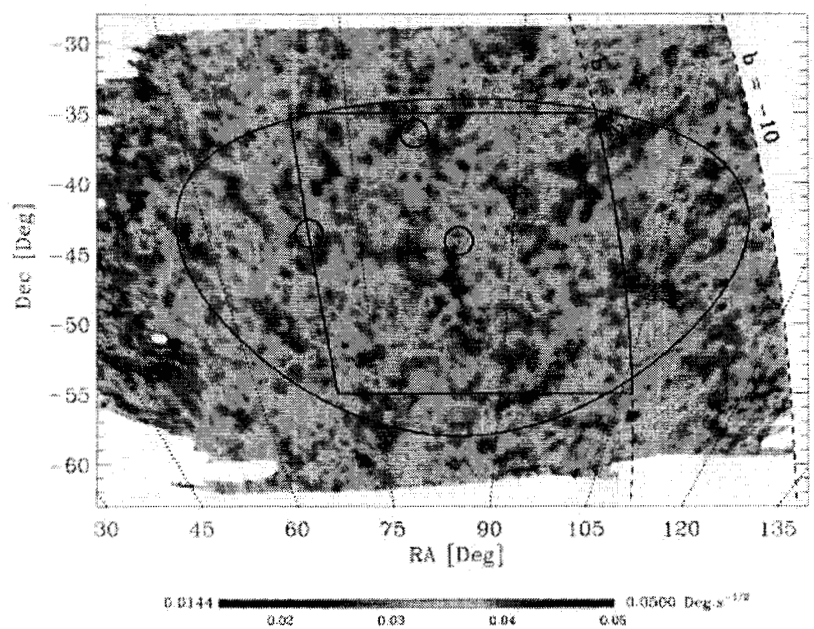


NOAA-NESDIS

The Cosmic Microwave Background, Remnant Radiation from the Early Universe



cobe.gsfc.nasa.gov



Boomerang Experiment, 2001

http://www.physics.ucsb.edu/~boomerang/

Mapping Speed

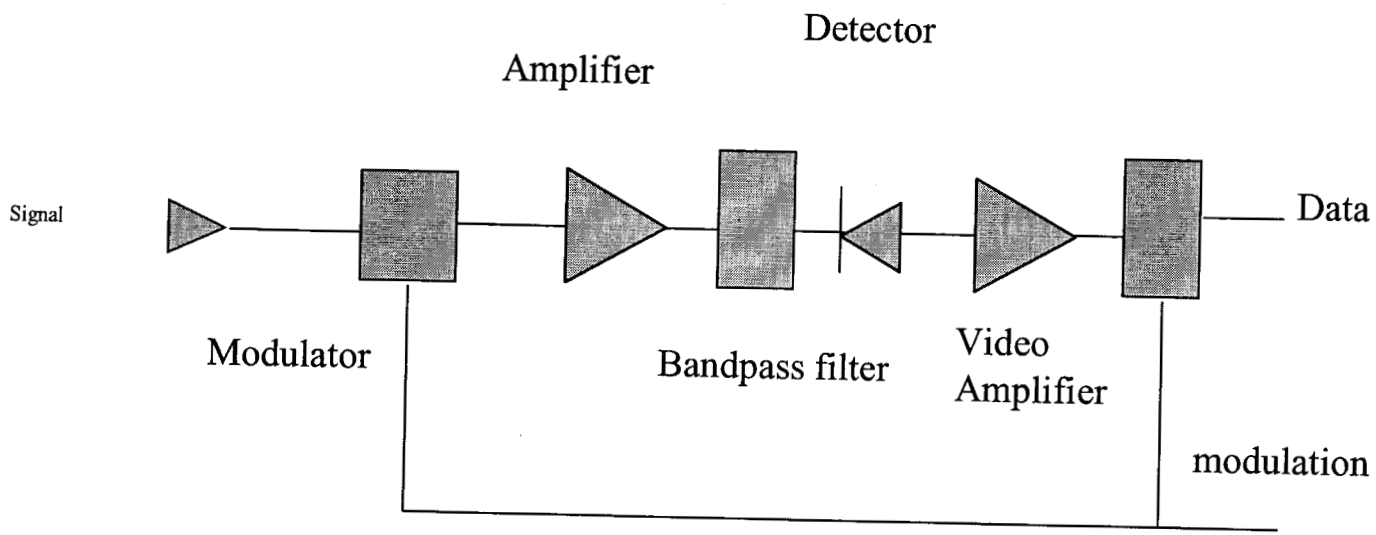
$\Delta T = kT_{sys}/\sqrt{\beta\tau}$ $\tau = k^2 T^2_{sys} / \Delta T^2 \beta$

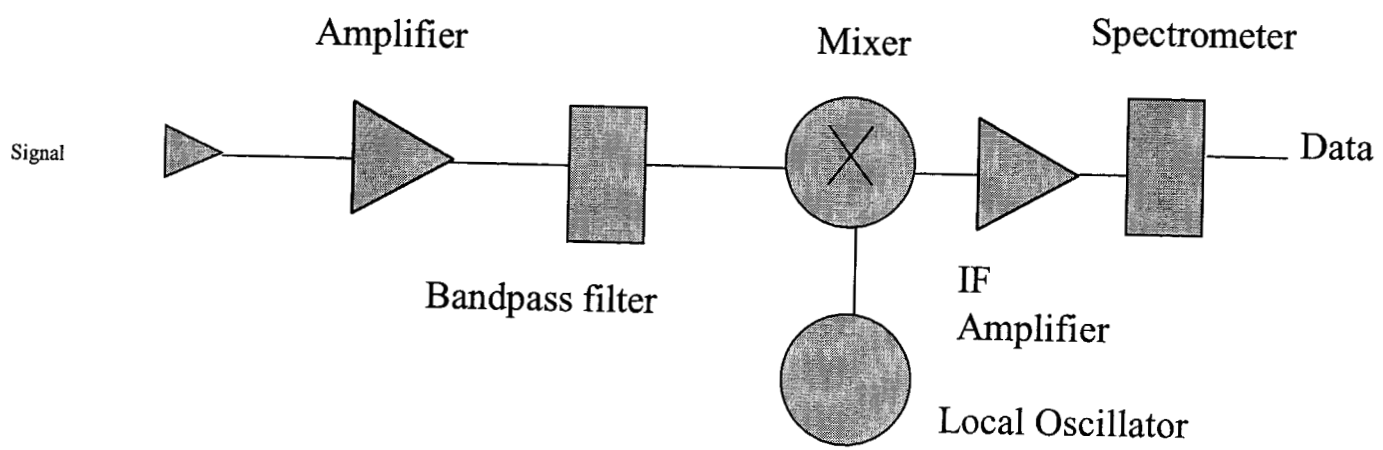
For continuum sources and mapping area larger than the beam mapping speed is increased by N, the number of receivers in a focal plane array (non-interferometric).

$\longrightarrow$ compact modules in a dense focal plane maximize sensitivity

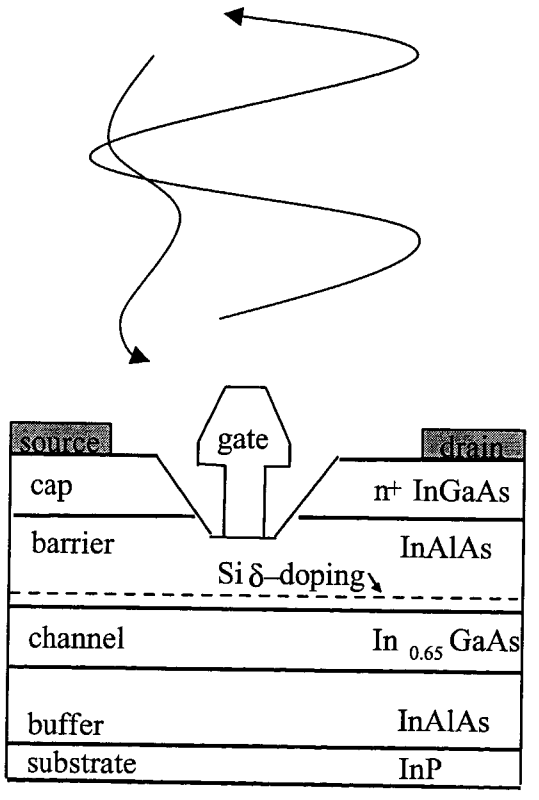
Need to develop the building blocks for these modules

The architecture of the module depends upon the function





HEMT Amplifiers



Coherent Gain:

For low noise applications this adds noise limited ultimately by : $T>h\nu/k$

Low noise devices operate at low voltage and current with high gain.

Will generate power limited by the gain and breakdown of the Device

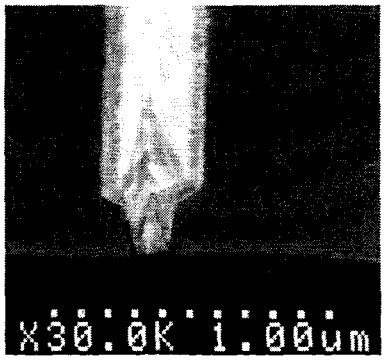
InP HEMT Technology

InP High Electron Mobility Transistors offer the lowest noise, highest operating frequency and lowest power consumption of any current millimeter wave transistor:

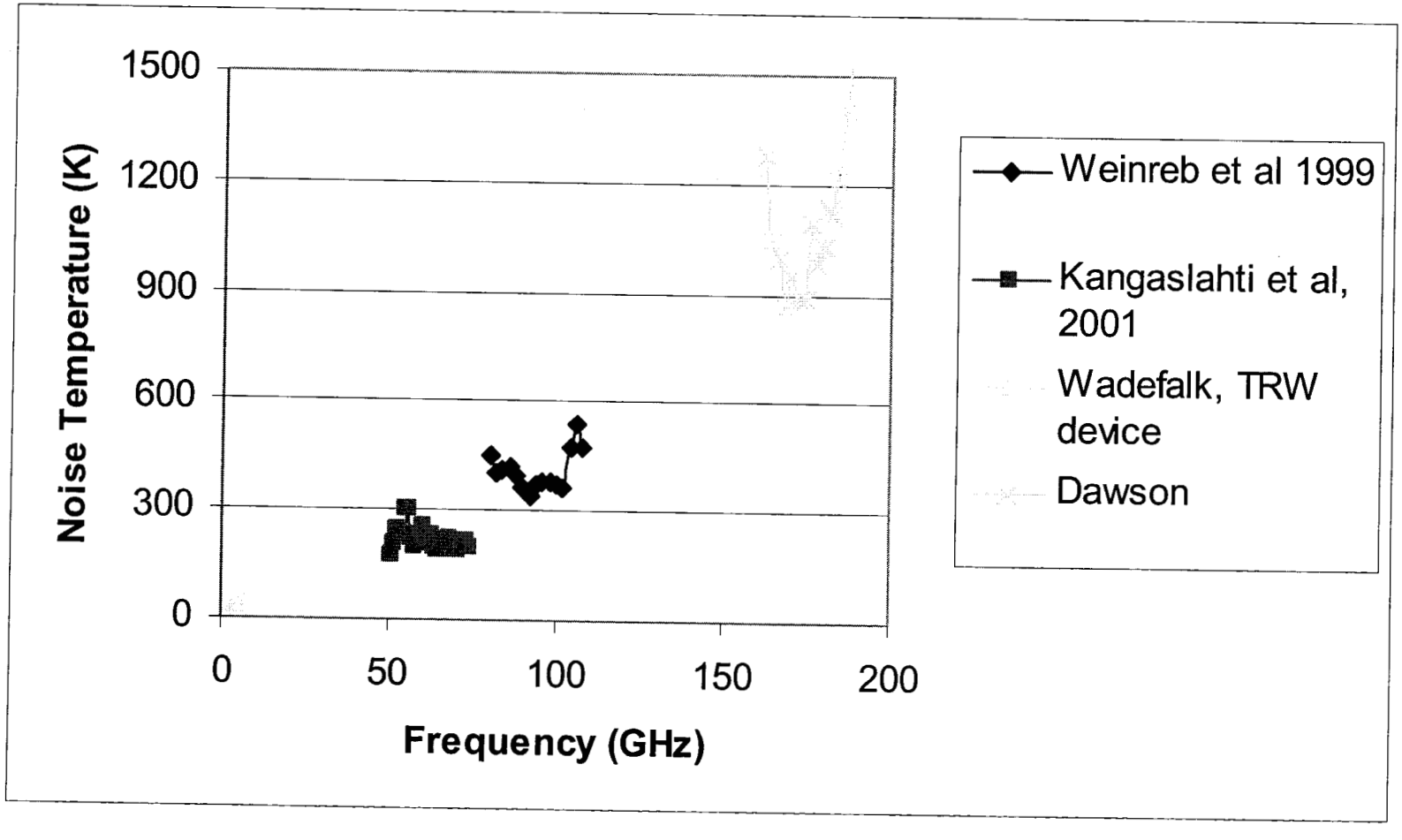
These advances have been driven by military and commercial applications and spearheaded by:

- Processing improvements in epixatial materials
- Short gate lengths using e-beam lithography
- Monolithic millimeter-wave integrated circuit (MMIC) processing advances:
  - repeatability
  - low parasitics

MMIC process iteration is slow and expensive, but already mass producible

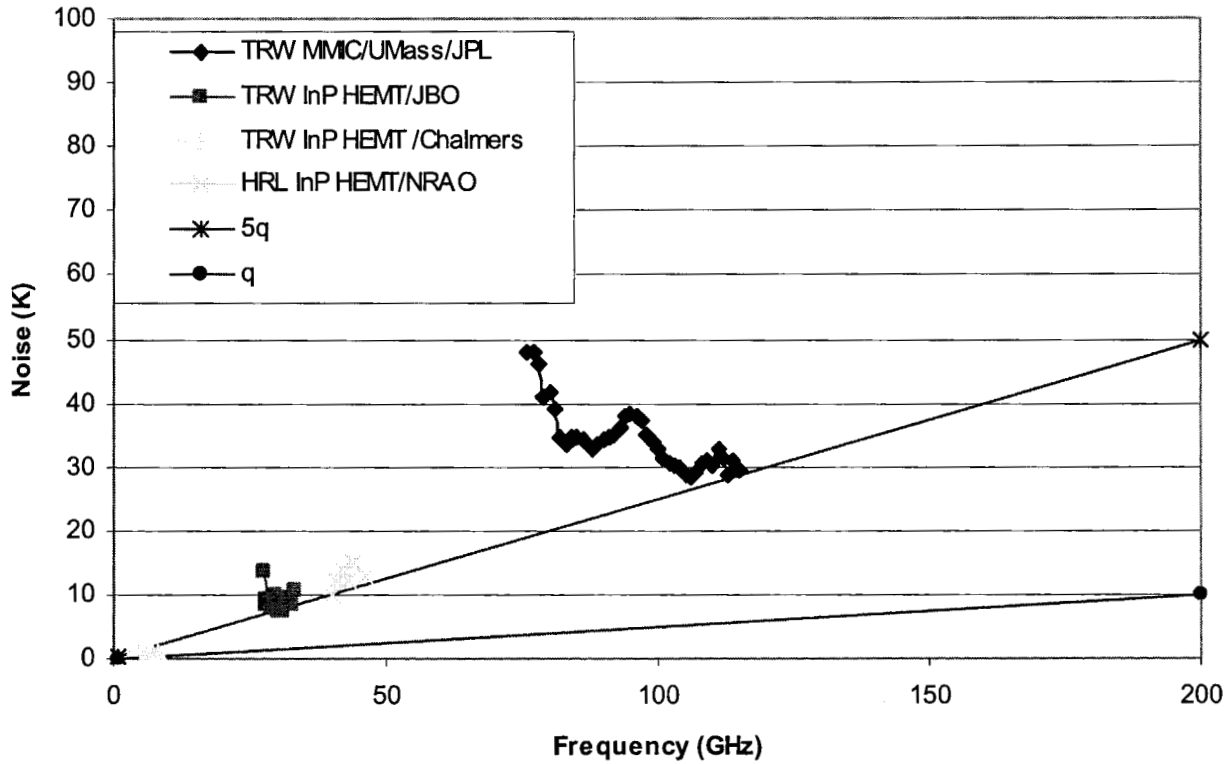


Low Noise Amplifiers

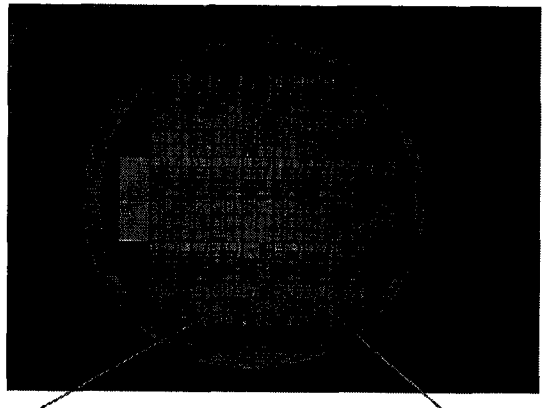


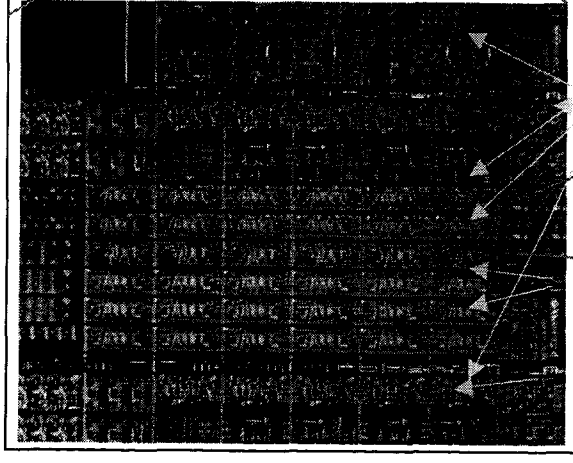
Cryogenic Low Noise Amplifiers

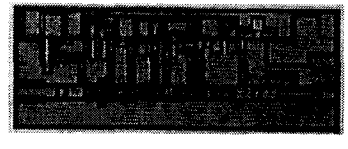
Low Noise Amplifiers (LNAs) can be used as receiver front ends for systems at operating frequencies as high as 240 GHz. Cryogenic LNAs are competitive with other low noise technologies at frequencies as high as 200 GHz. They play a critical role in IF amplification for SIS heterodyne receivers, with insertion loss multiplying the amplifier noise.



Cryogenic HEMT Optimization Program







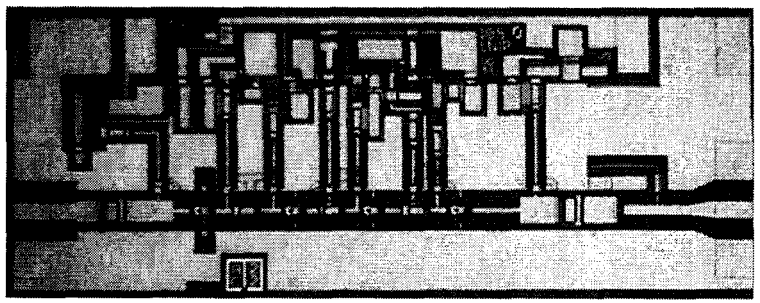
CHOP has produced thousands of low-noise InP devices which are being used for a radio astronomy including:

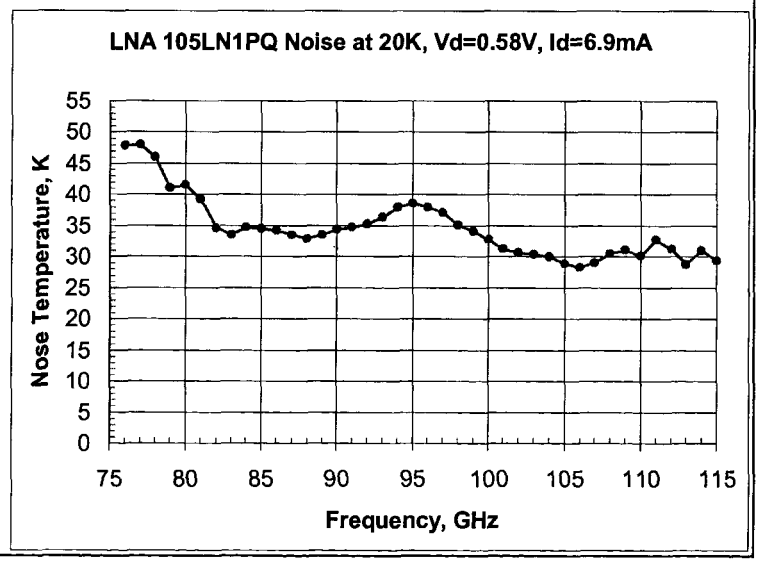
- UMass Sequoia Array
- 90 GHz VLBI on Effelsberg Telescope
- UCSB/JPL BEAST Telescope
- DSN
- Princeton University CMB polarization
- Planck and FIRST prototype development
- IF amplifiers for CSO, SOFIA receivers
- Amplifiers for Metsahovi Radio Obs.

CHOP/TRW 4-Stage LNA for Planck LFI

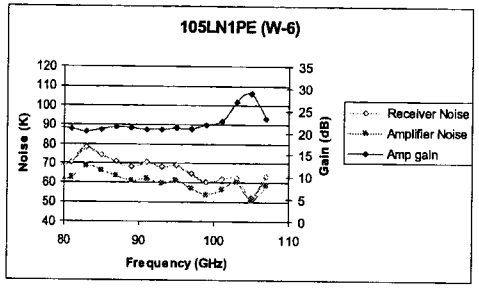
- 80-110 GHz >25 dB gain
- NF~ 3-4 dB at room temp
- Record low noise atc ryo temps:
  - → 34 K average 80-110 GHz
  - → < 40 K from 85-115 GHz
  - → 30 K noise at 105 GHz
- Yield:105 chips per wafer
- Ultra-low power operation
  - 20 dB gain at 1.4 mW
  - 15 dB gain at 0.54 mW
- Excellent Gain and Phase match

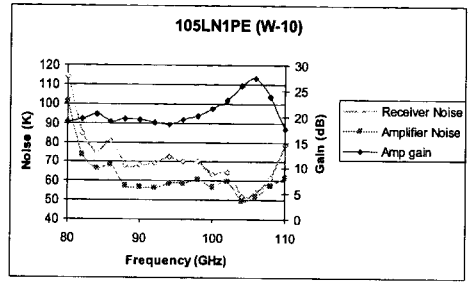
(data courtesy UMass FCRAO)

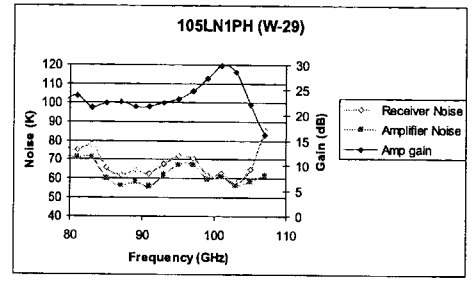


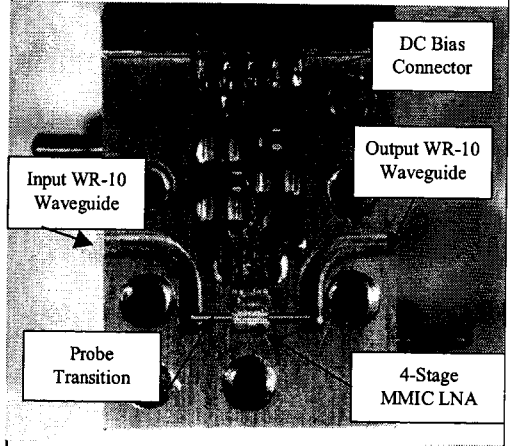


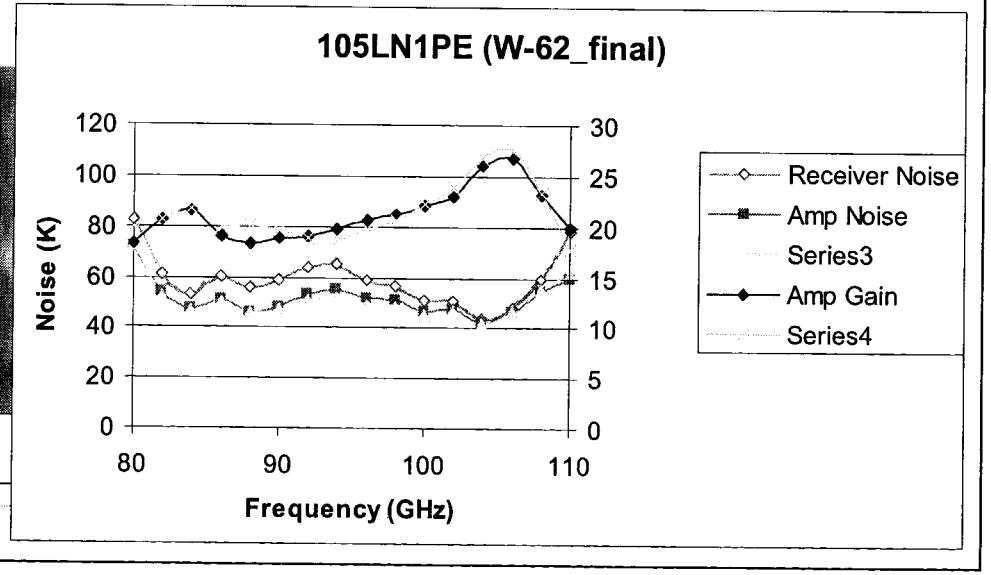
Repeatable Amplifiers are Easily Built



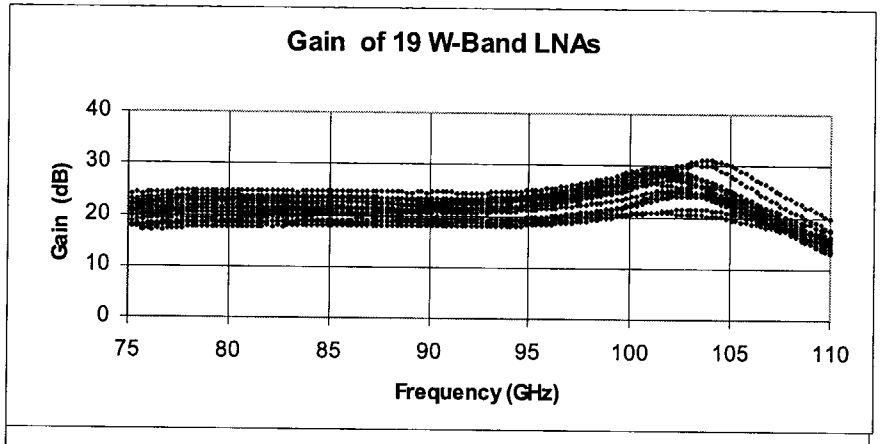


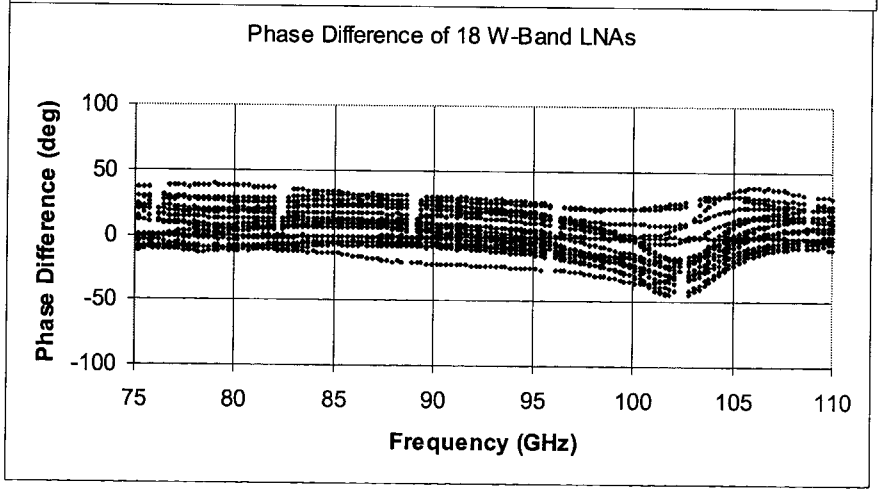




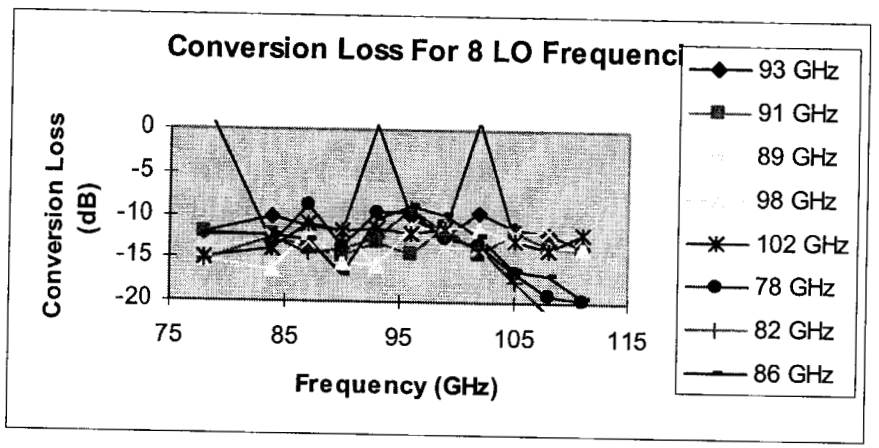


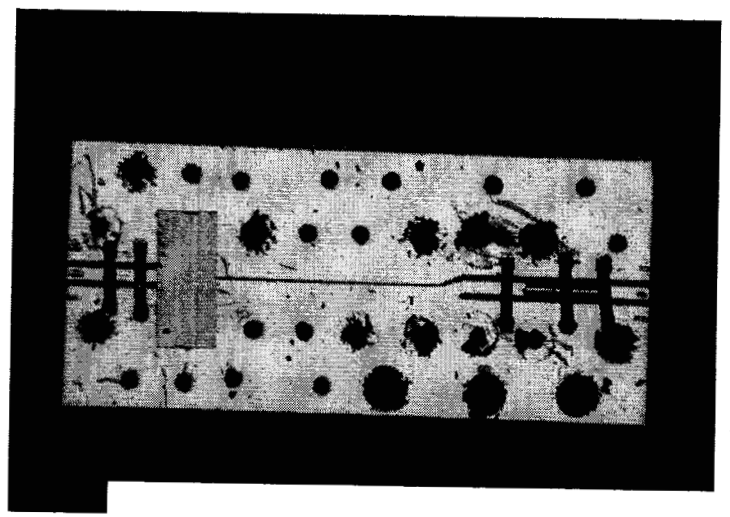
MMIC Module Repeatability

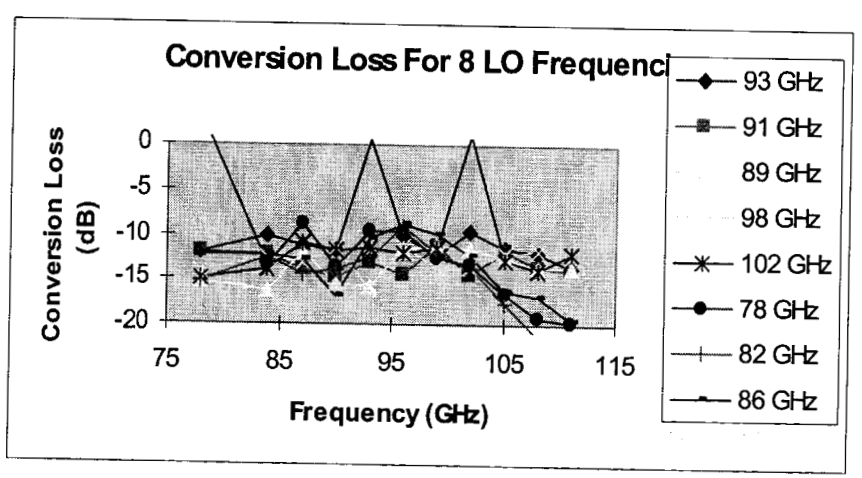


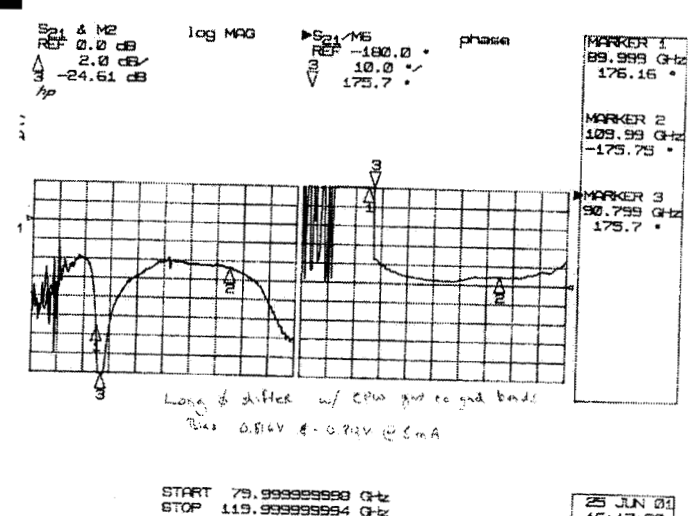


Multi-function designs





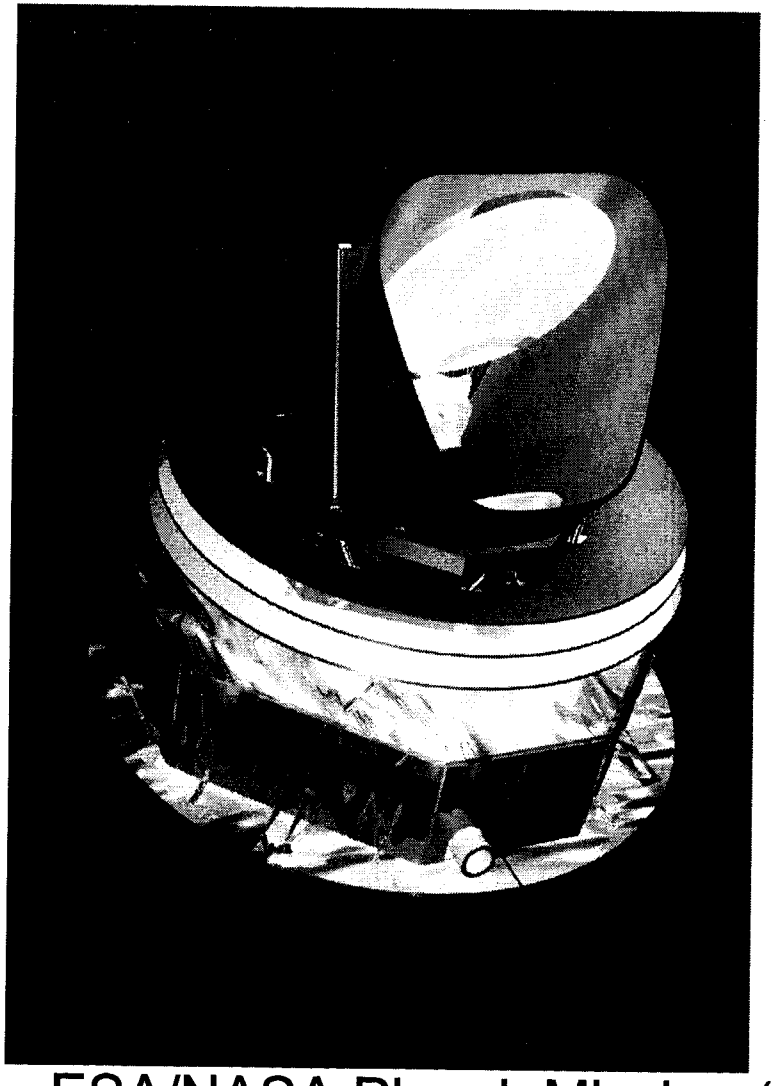


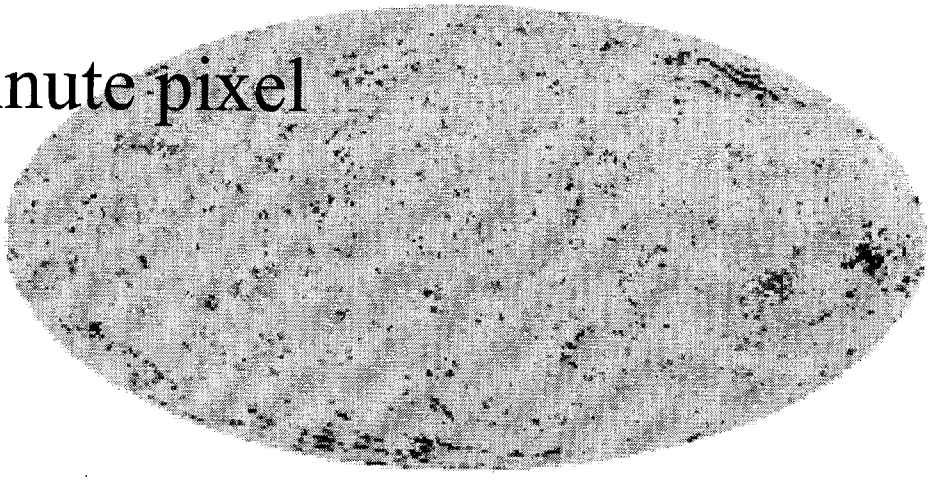


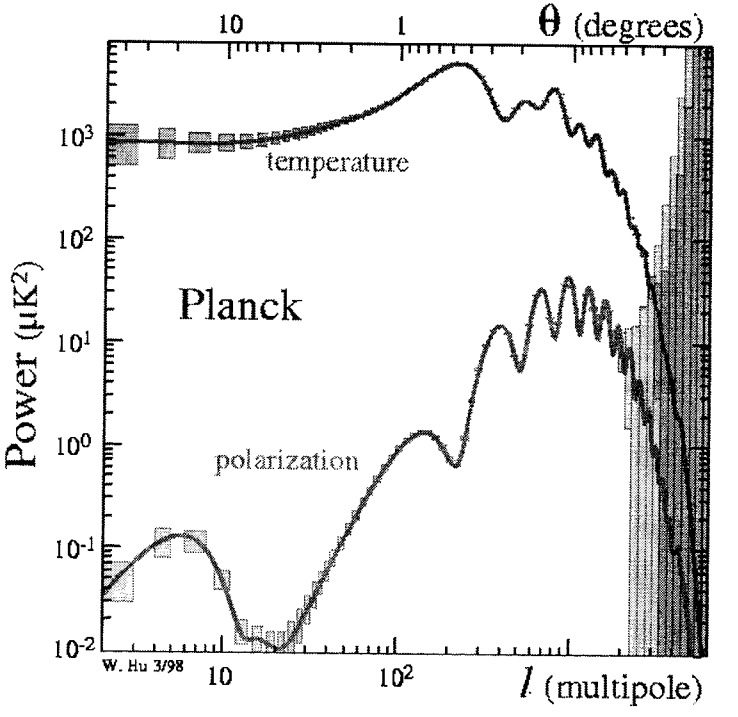
Once the component chips are developed…

Multi-function Modules

10 microKelvin/10 arcminute pixel

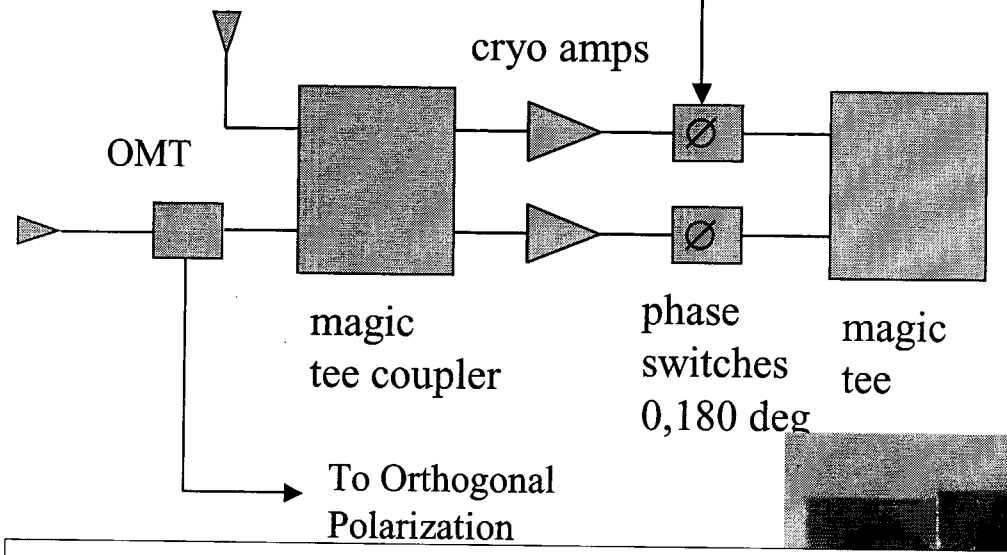


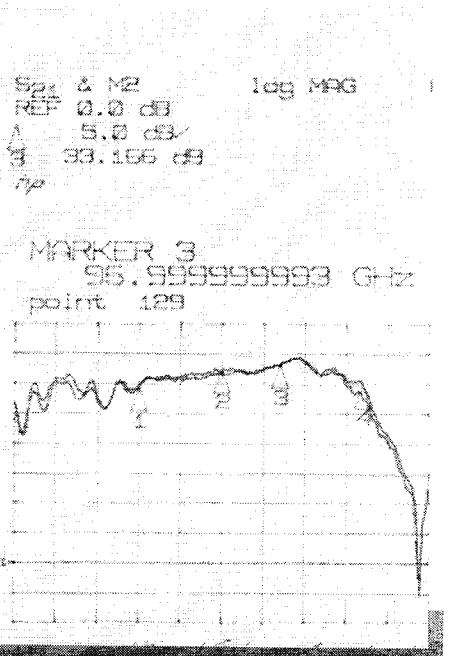


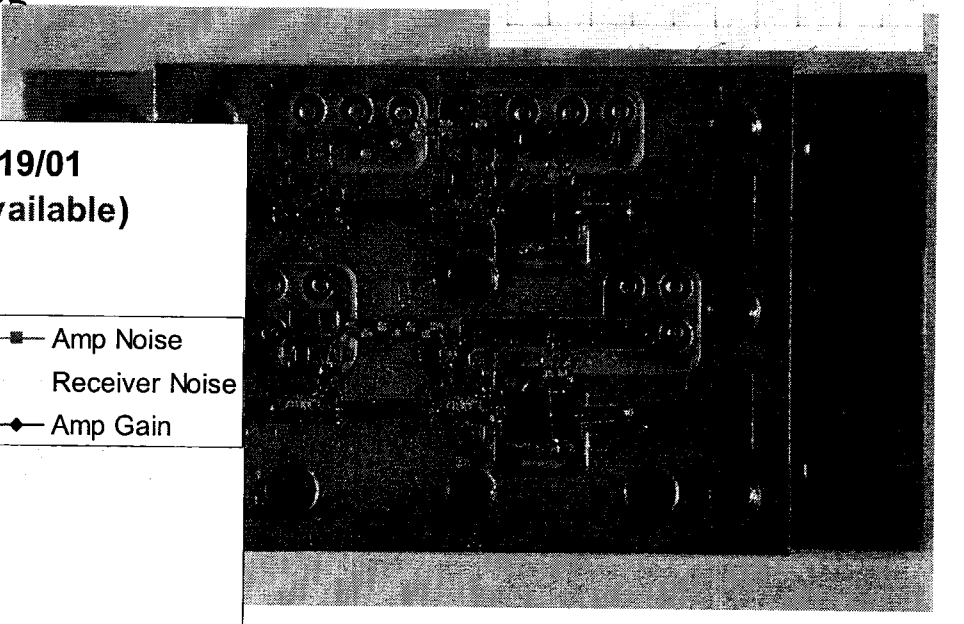


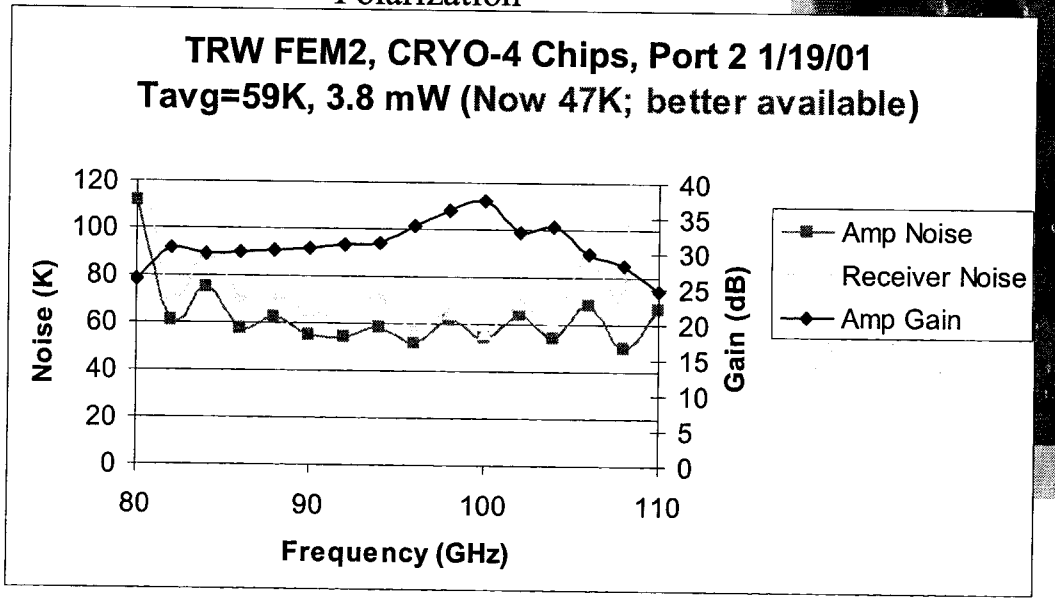
ESA/NASA Planck Mission (to be launched 2007)

Planck-LFI 100 GHz Breadboard



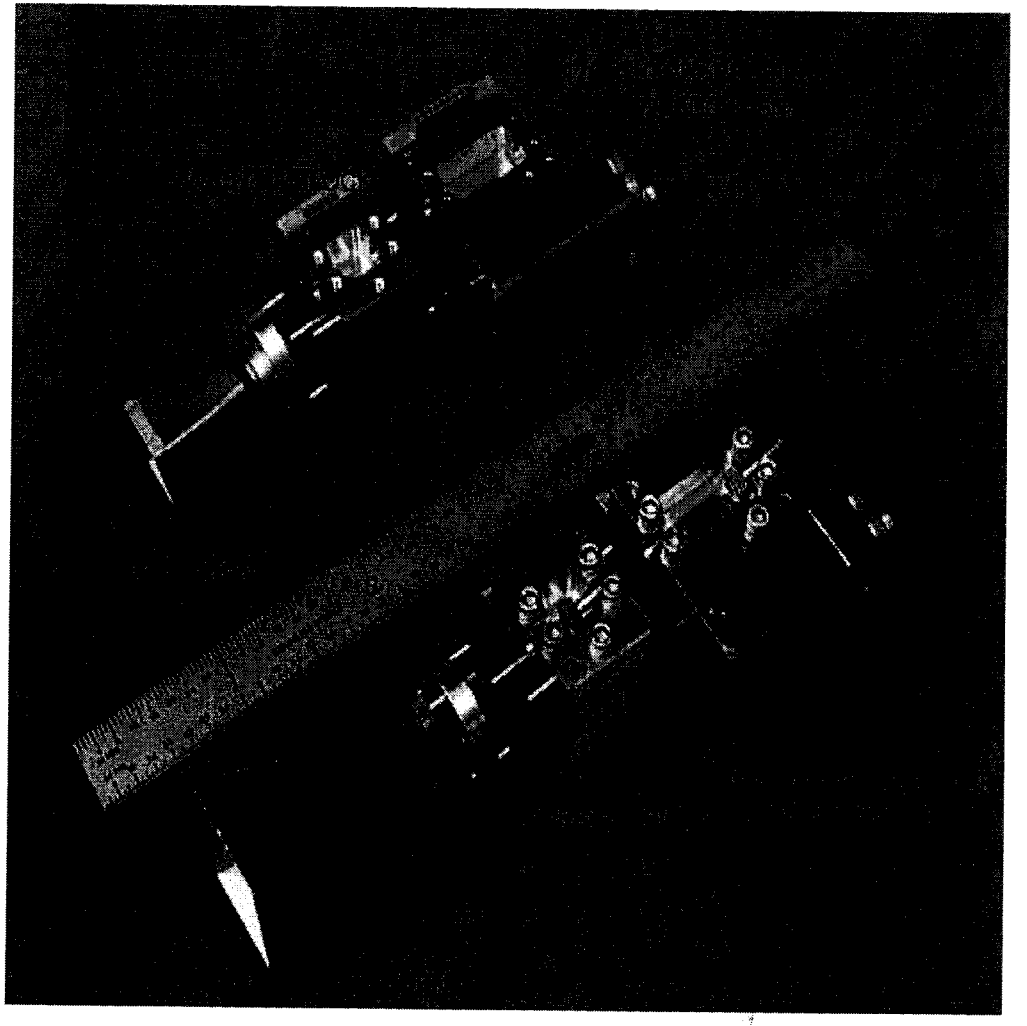






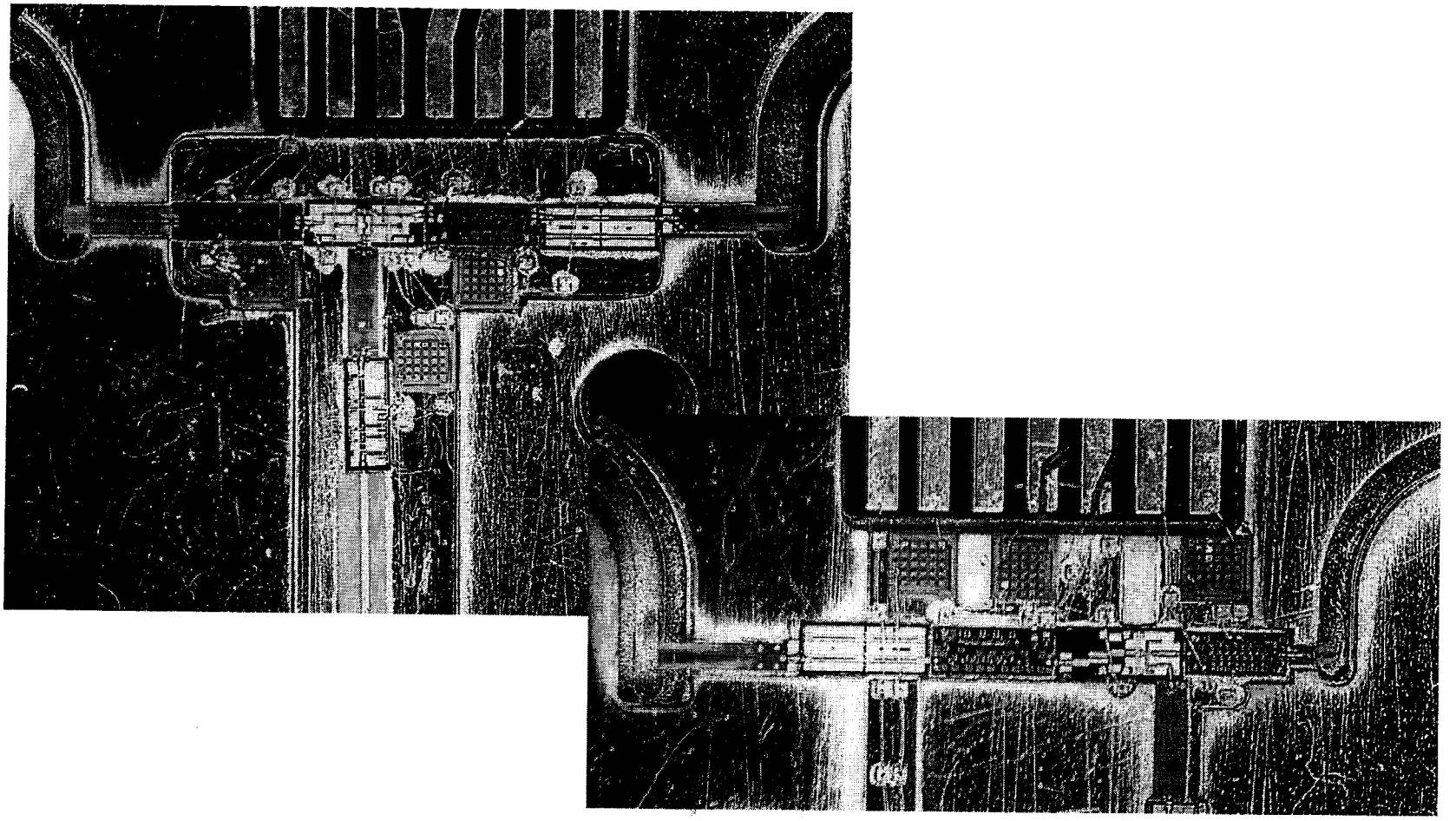
Planck 100 GHz Prototype Receiver in Cryostat

Microwave Atmospheric Temperature and Humidity Sounders

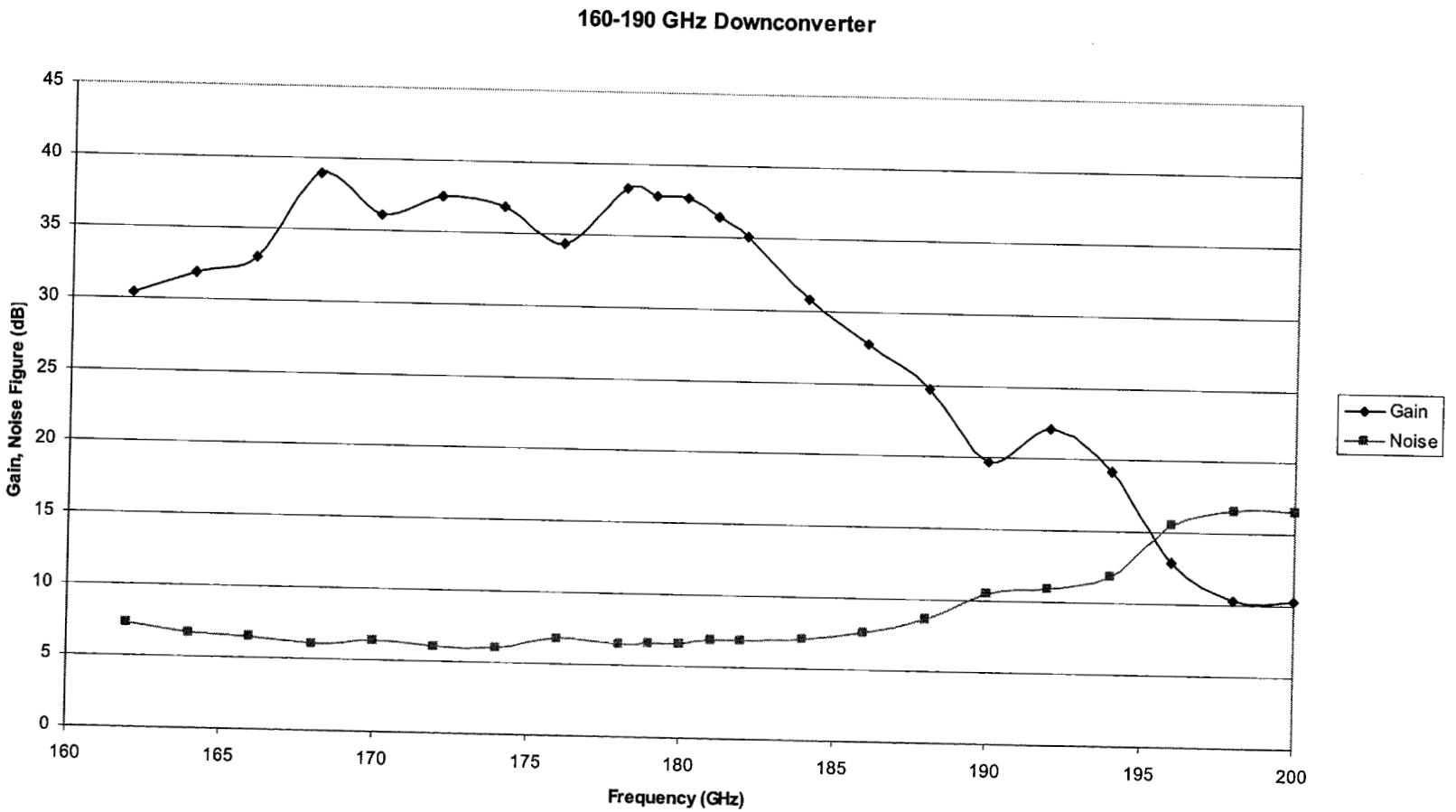


Compact heterodyne receivers

Douglas Dawson

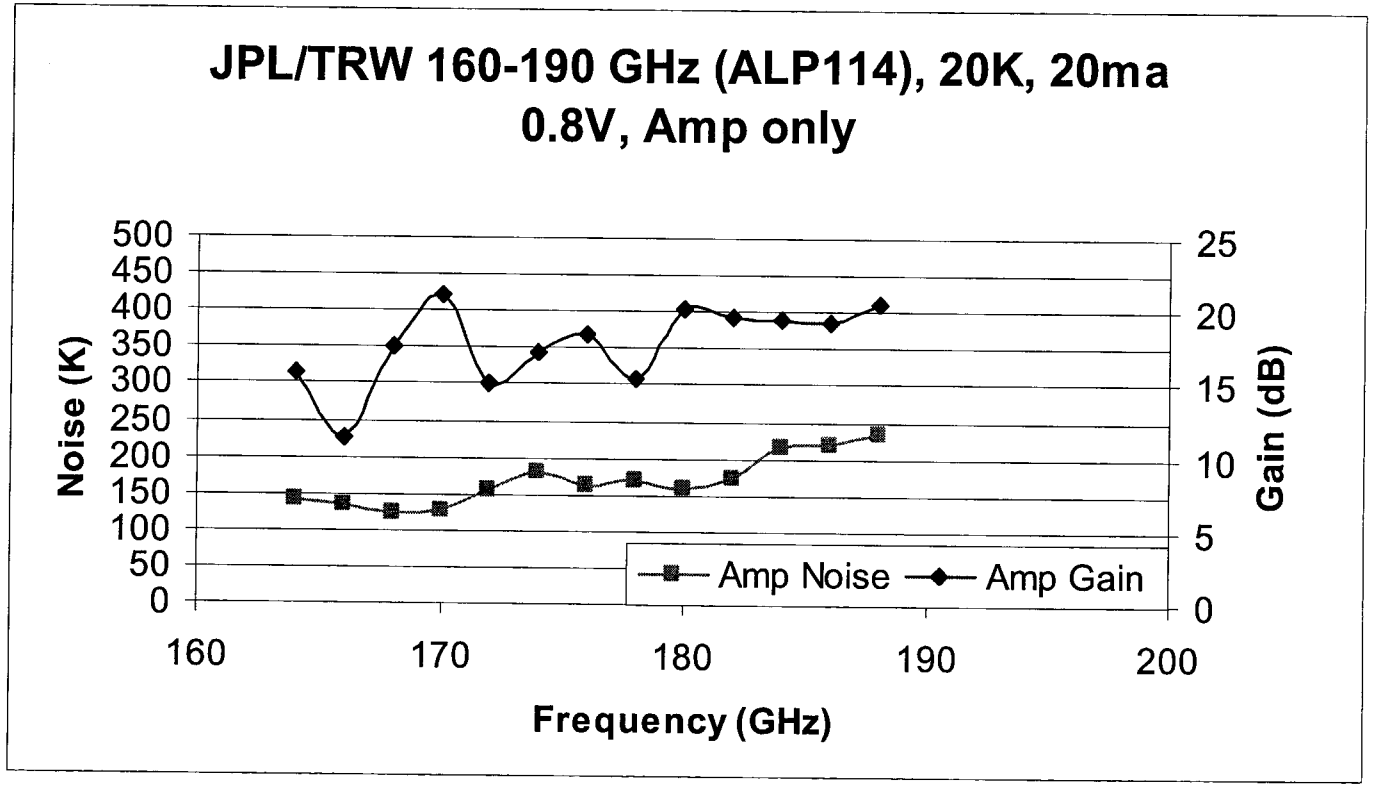


D. Dawson



Courtesy D. Dawson

Cryogenic Data



Massive Array Technologies for the Future

Driven by the science need to get a few μK per arcminute pixel over large portions of the sky.

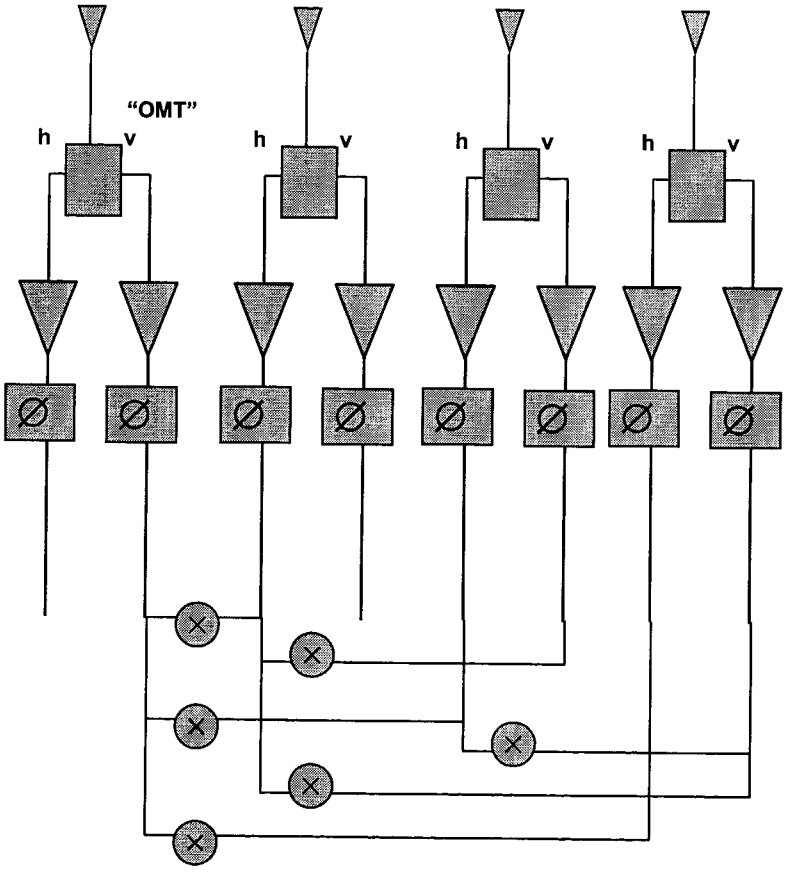
- Develop end-to-end design

- Multi-chip modules can be mass produced – 1000 element array is feasible. We need to develop mass producible design and packaging techniques.

- Amplifier technology is evolving- We are <u>not</u> at the quantum limit and new materials are being explored. We need to push harder.

- Prototypes need to be developed and field tested with real experiments.

Synthetic Aperture Array Receivers



Synthetic Aperture Interferometer:

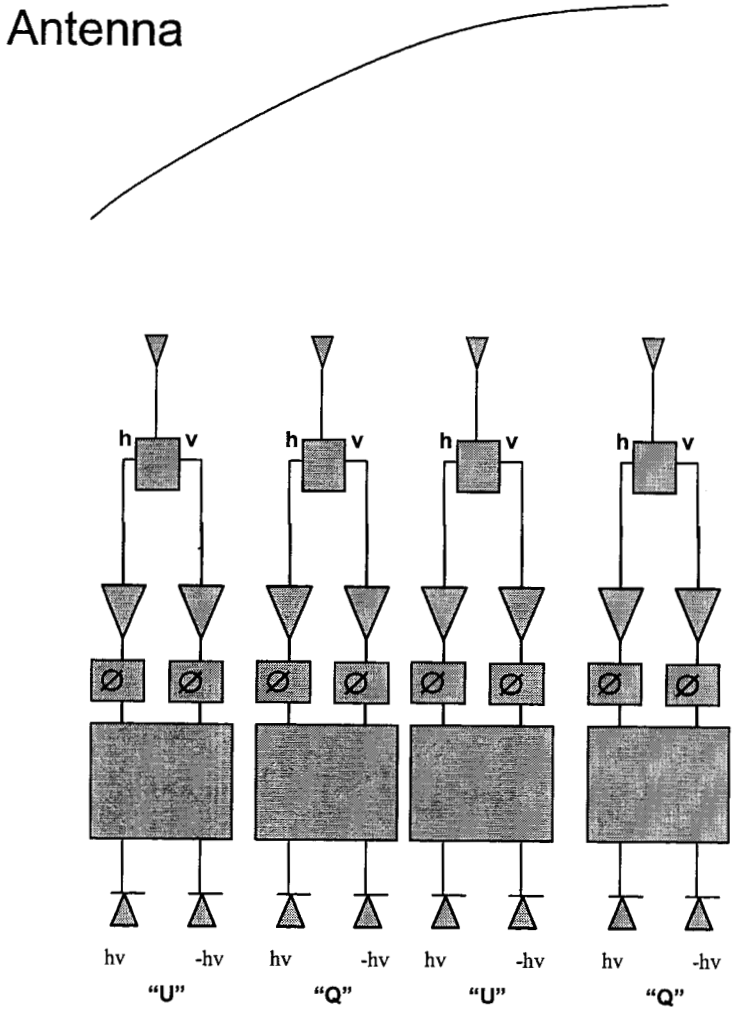
Currently in use by DASI, CBI and VSA?. Will be used by AMiBA

Uses coherent detection to directly map sky brightness distribution.

Amplification has been used very effectively.

~2.5 mK√s/Q/pixel for 12 elements
And 100 pixels (30 GHz)

Focal Plane Array Receivers



Focal-plane array polarimeters
CAPMAP, COMPASS

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

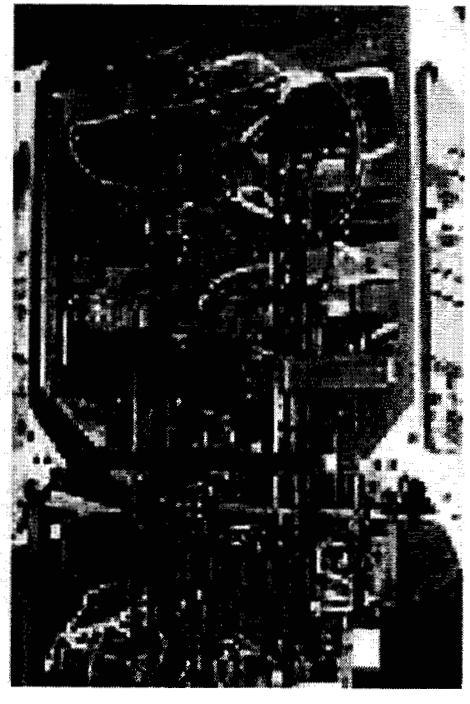
~100 μK√s/Q for 10 elements (100 GHz)

The Good, The Bad and The Ugly

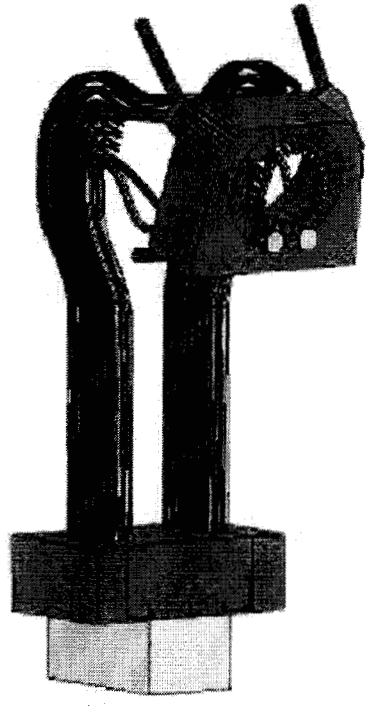
Interferometer	Filled-aperture focal plane array
$\Delta T \approx (A/BN) T_{sys} / \sqrt{\beta\tau}$	$\Delta T \approx T_{sys} / \sqrt{(\beta\tau NB/A)}$
I,Q & U	Q, U & degraded I
Robust against systematics	
	Needs beam steering
Few moving parts	
High resolution at long λ	Large apertures are expensive
<u>$N^2/2$ correlators</u>	Large N, has potential optical challenges

Map solid angle A, pixel solid angle B, N>>1 receiver elements

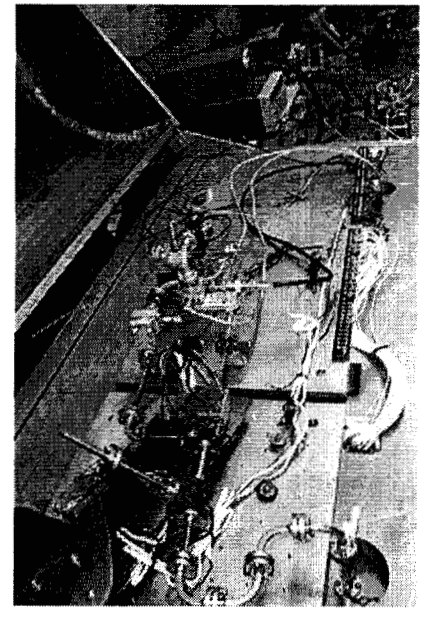
We need a new way of integrating…



WMAP



LFI



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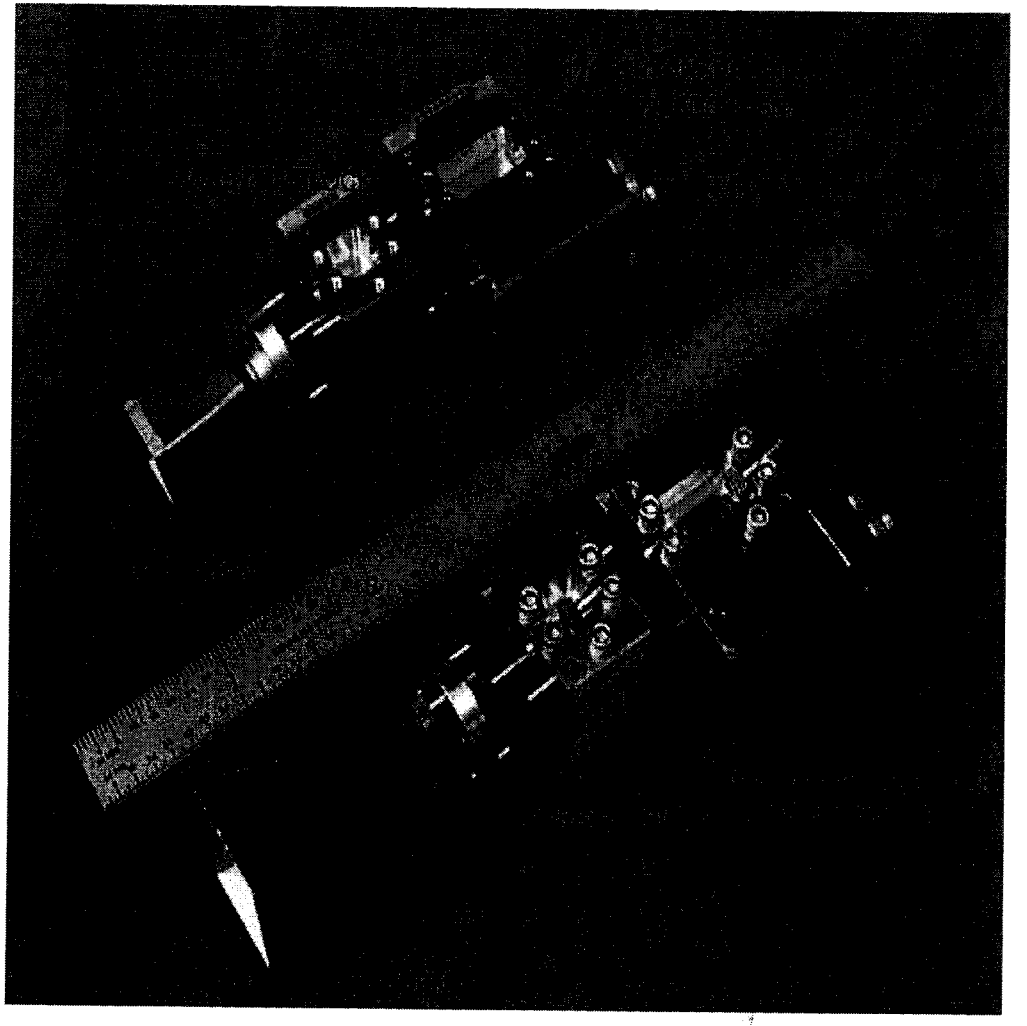

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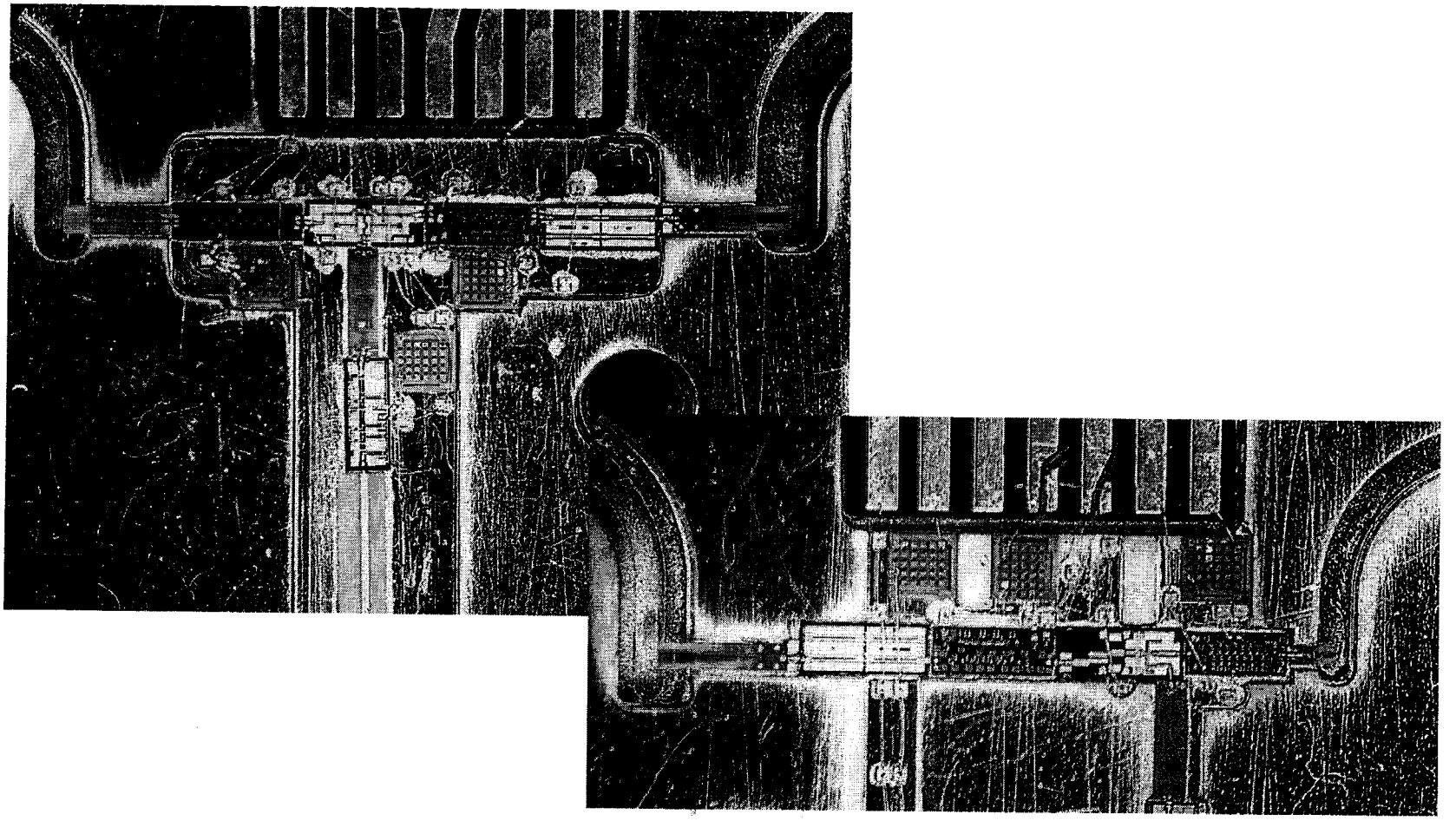

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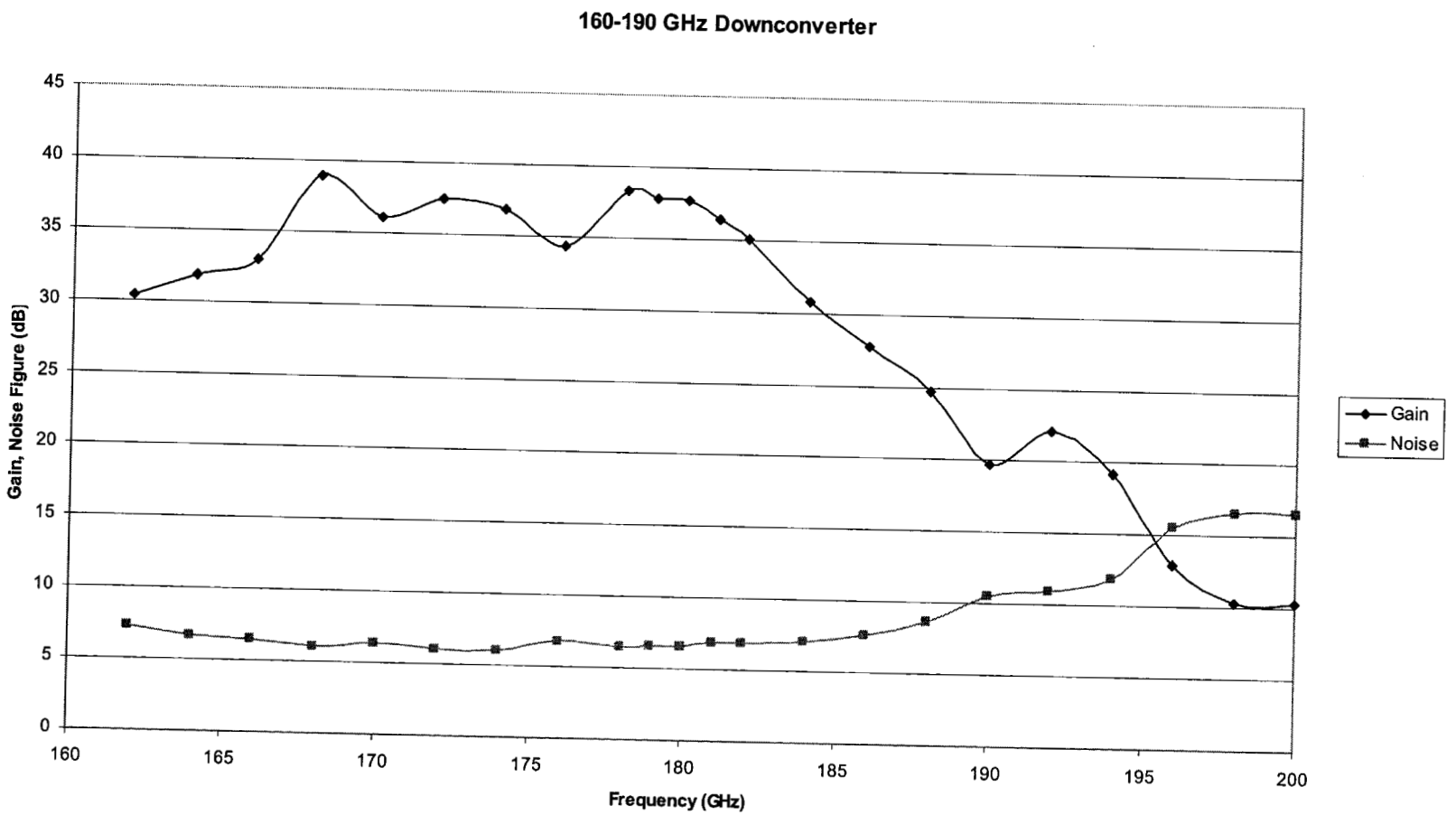

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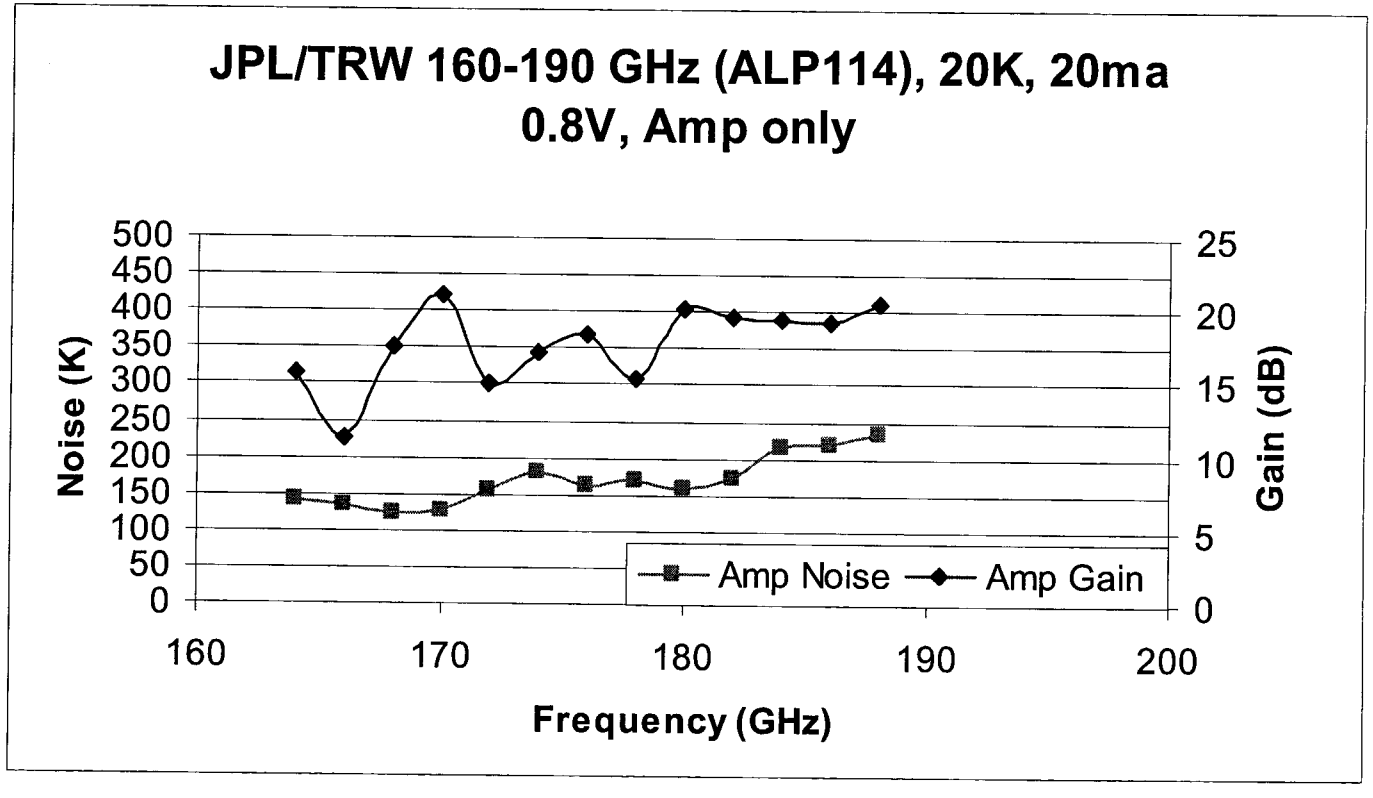

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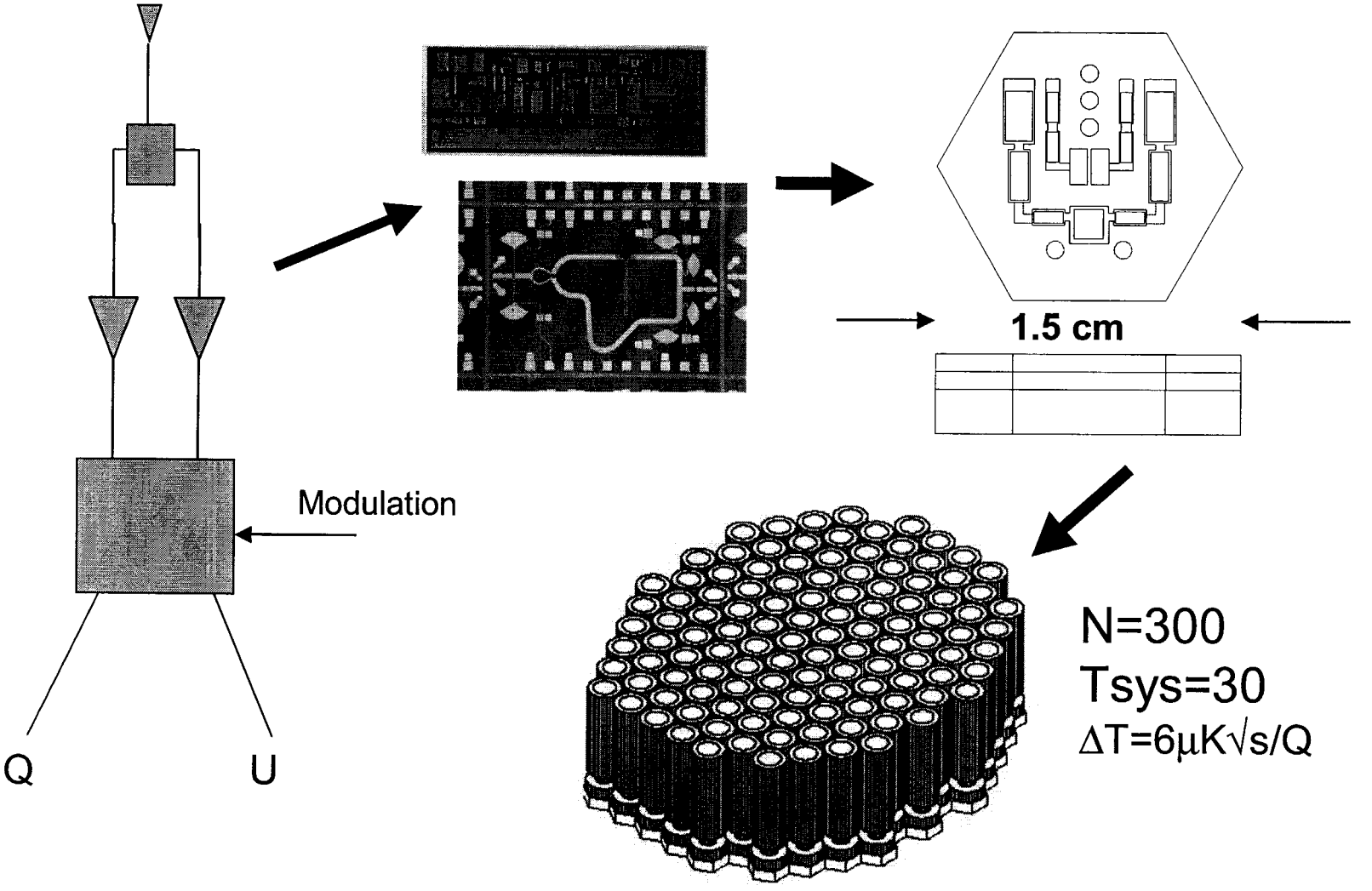
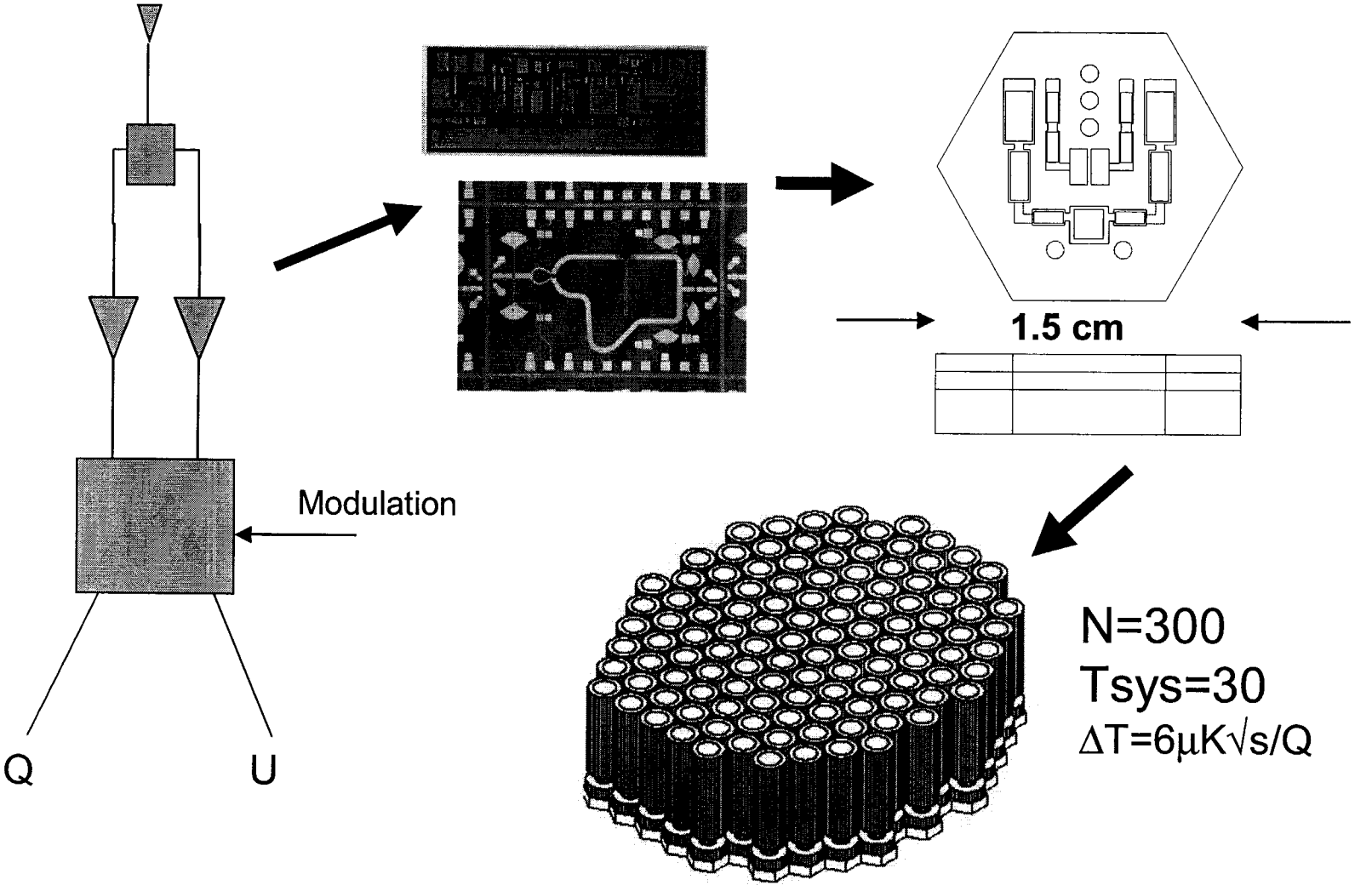
An order of magnitude better than Planck?

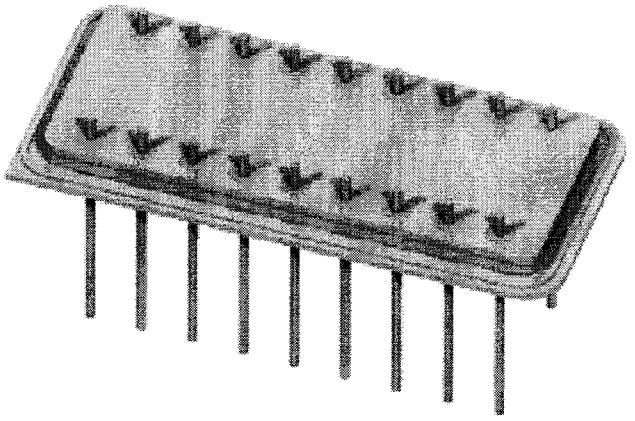


An order of magnitude better than Planck?

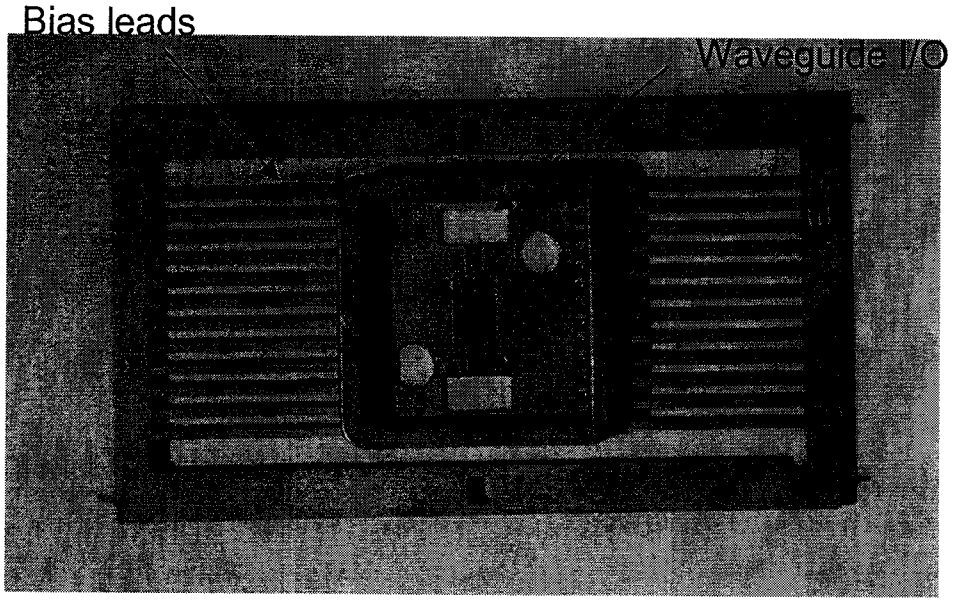


Packaging Technologies for Massive Arrays

Eliminate connectors
Reduce DC functionality
Utilize automation



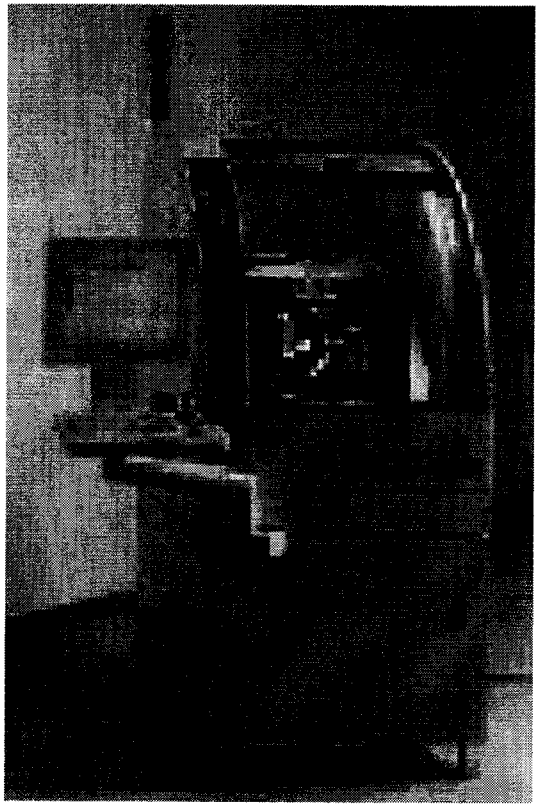
→ < $300/element



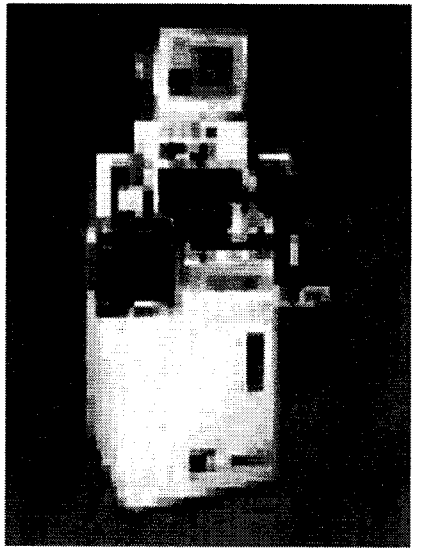
Modules Reside on a "motherboard" which provides all DC functions (eg bias, A/D)

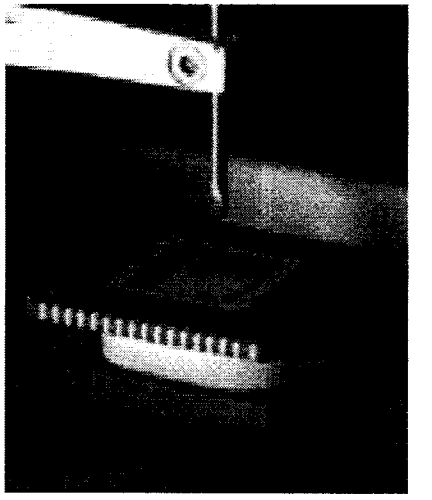
Test board automatically bias tunes and tests.

Crack Team of Assemblers…



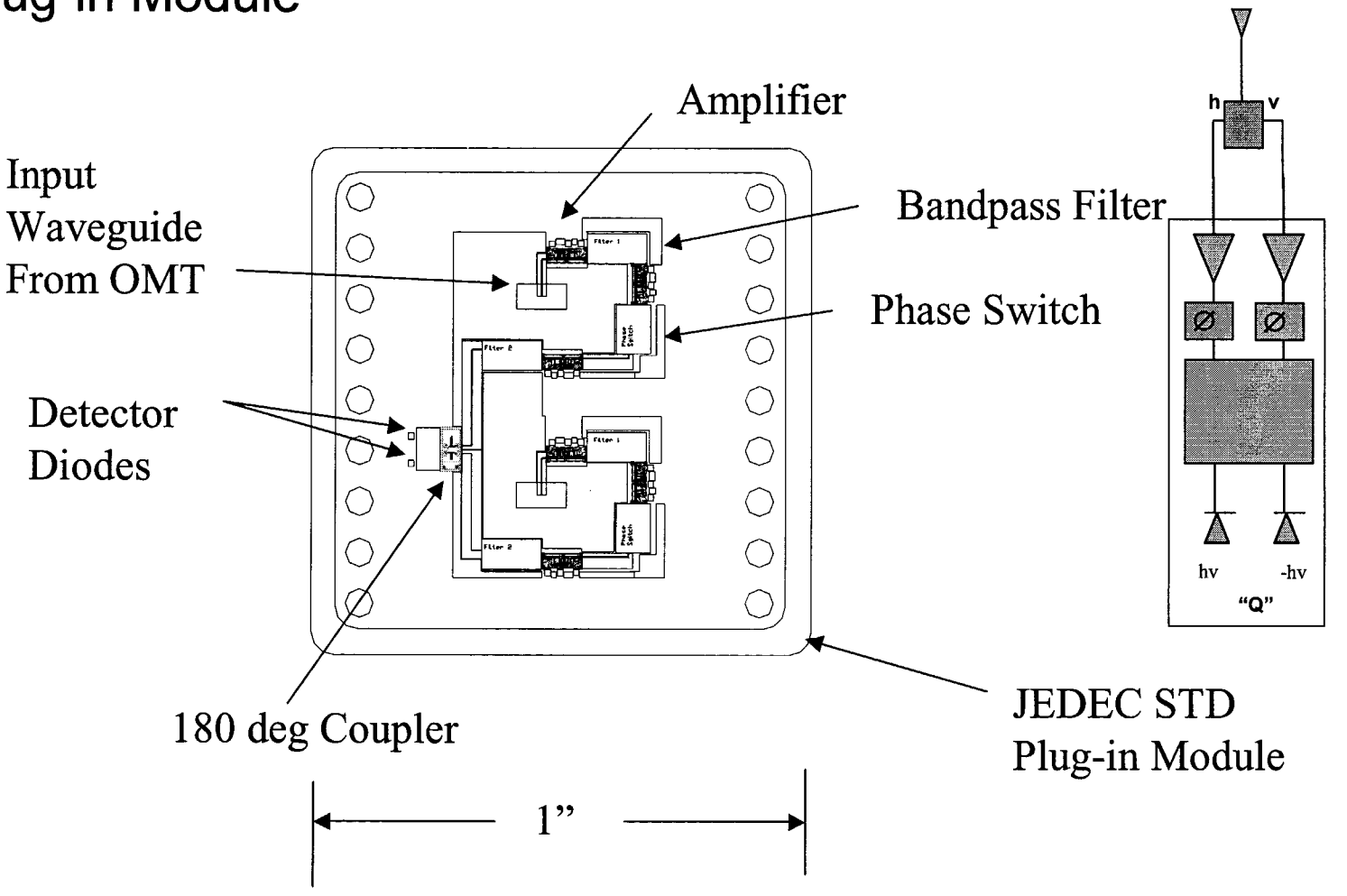
Automatic die-attach
Datacon Inc



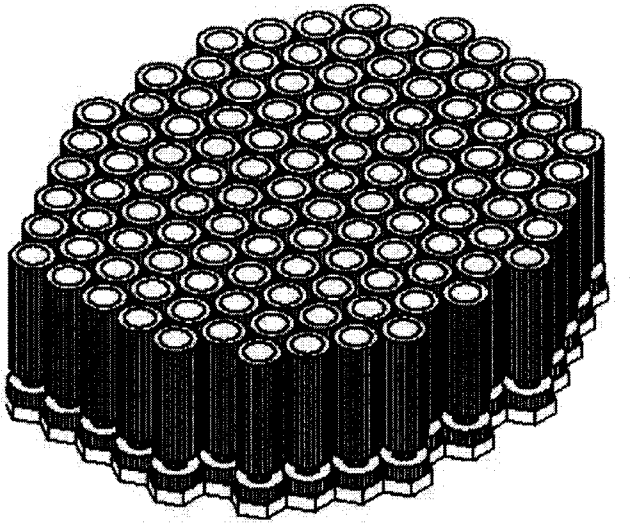


Automatic Ribbon Bonder
K&S

Array element:Complete 100 GHz Polarimeter receiver in a Plug-in Module



Q/U Imaging ExperimenT (QUIET) Array Development Schedule



Functional 100 GHz "Q" Element Prototype: 10/03 ~500 μK√s/Q

100 Element Array: 9/04 ~50 μK√s/Q

1000 Element Q/UArrays: '05 ~10 μK√s/Q