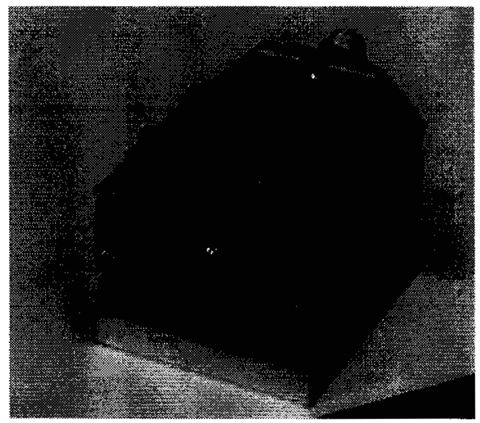
1.8 THz hot electron bolometer mixers for Herschel



Jonathan Kawamura
JPL
Herschel Space Observatory Project
August 28, 2002

People who have contributed to this work:

- Paul Batelaan (CSO effort, microwave components)
- Bruce Bumble (fabrication) ⇦
- Carlos Esproles (CSO effort, FIR laser)
- Paolo Focardi (rf modeling)
- Dennis Harding (Band 6 engineer) ⇦
- John Johnston (Band 6 Technician) ⇦
- Boris Karasik
- Jonathan Kawamura (Band 6 Cognizant Engineer) ⇦
- Rick LeDuc (fabrication)
- Rob McGrath
- Andrea Neto (rf modeling)
- Anders Skalare
- Rolf Wyss

1.8 THz HEB mixers for Herschel HIFI

Outline

- Mixer performance requirements
- Review of results
- Flight Mixer design and progress on Development Model
- Mixer assembly plan
- Mixer performance verification plan
- Facilities, schedule, budget, work-force
- Key risks

HIFI "Band 6H" HEB Mixer Deliverables

• 2 Flight units (to SRON)	Sept '03
• 1 Flight spare (to SRON)	October '03

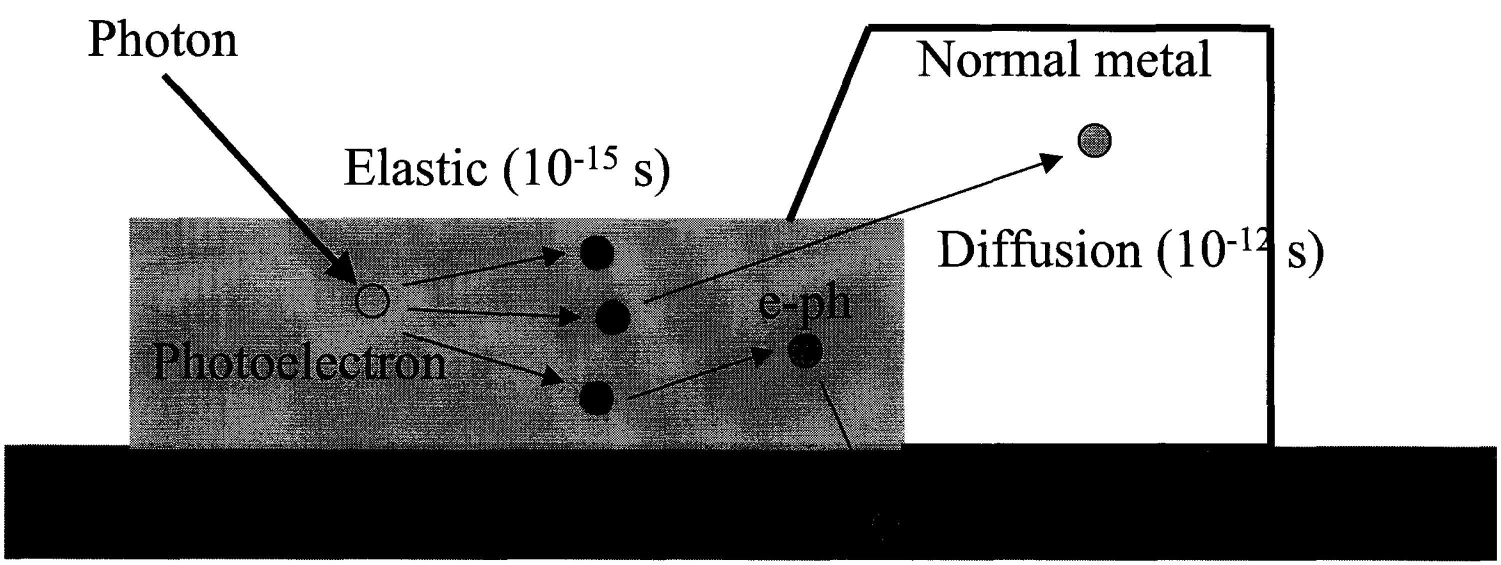
Herschel Space Observatory (FIRST)

•3.5 m primary

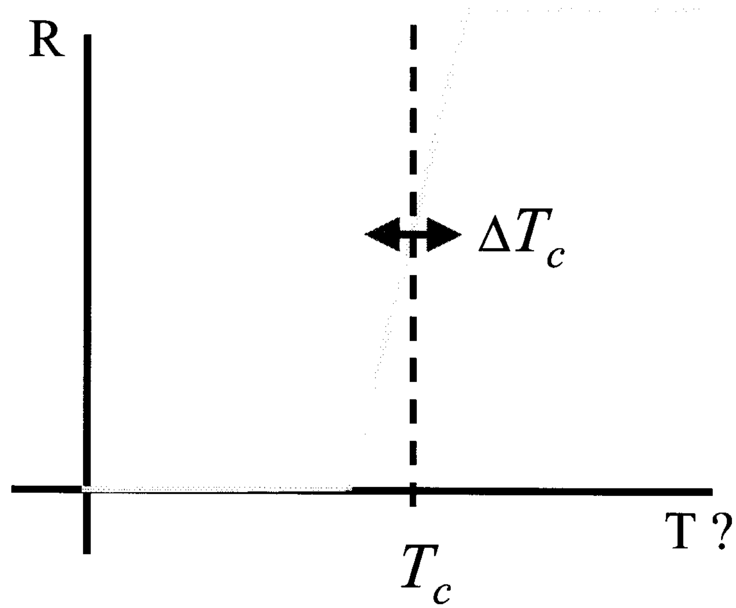
•2007

Hot-electron Bolometer Mixers

- Any thermal sensor can be used a mixer under LO illumination
- Semiconductor version had 1 MHz IF bandwidth (e.g., Phillips)
- Superconductive version, proposed by Gershenzon, Gol'tsman, et al. and by Prober, promised ~10 GHz IF bandwidth
- Simply a strip of superconductor (NbN, Nb, Al, Ti, etc.)
- "Transition-edge sensor" operated in the mixer mode
- First results introduced at the Space Terahertz Symposium at the University of Michigan (1994) --- 8 years ago!

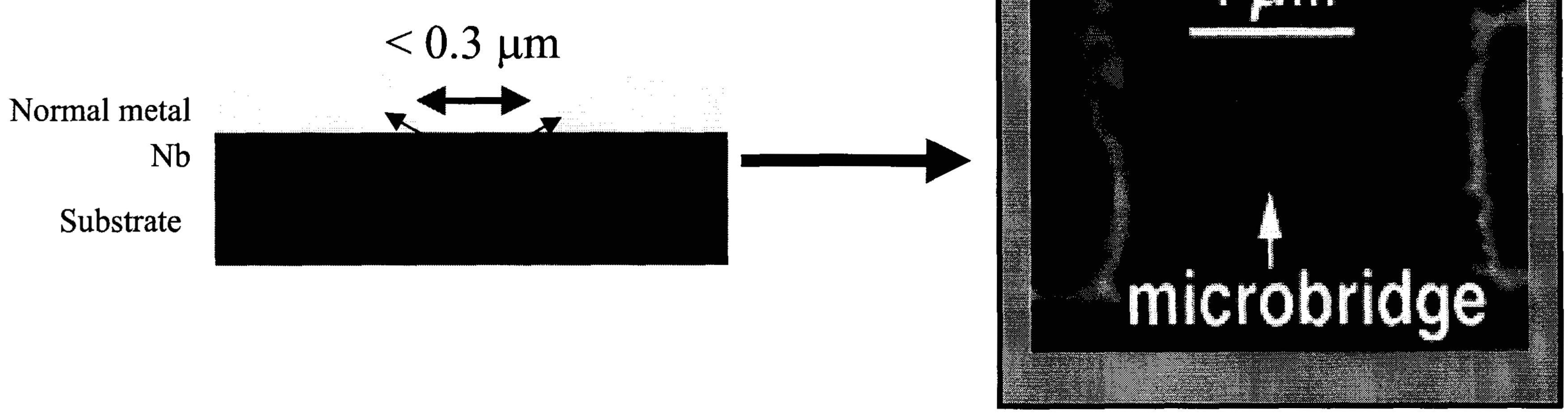


Principle of operation



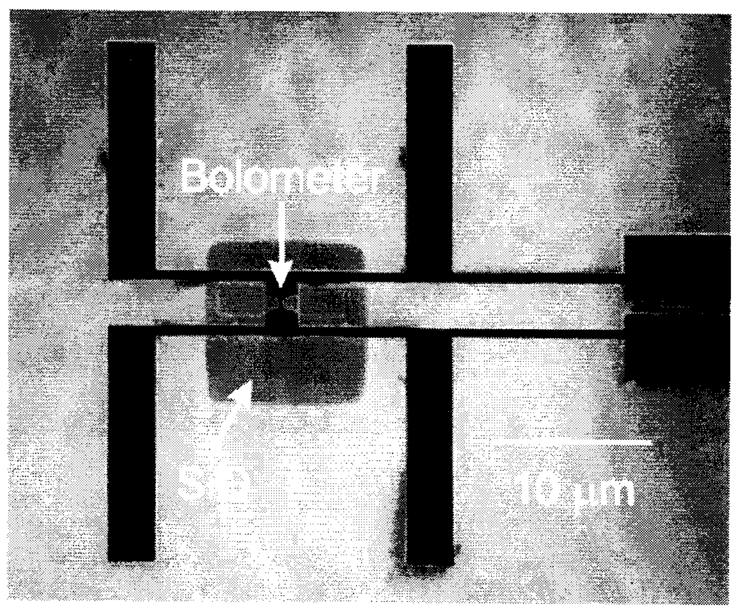
- Any thermal detector can be used as a mixer -> IFBW
- No comprehensive model exists; substantial body of data.
- Figure of merit: $T_{RX} = T_{MIX} + T_{IF} / \eta = (T_{\mathrm{output}} + T_{IF}) / \eta$

- No tuning circuit: entirely resistive above the gap
- Simple fabrication: sub-micron microbridge
- Relaxation limits the IF to up to 10 GHz



Performance Requirements

- RF range: 1.62 - 1.91 THz
- T_{mix} (DSB): 1,800 K (DSB) at 1.80 THz
- IF range: 4 to 8 GHz
- Sensor: diffusion-cooled Nb hot-electron bolometer mixer
- LO Power: need < 0.4 μW incident on Si lens
- Embedding Circuit: quasioptical coupling using a Si lens and twin-slot antennas



Interface Specifications

Operating temperature: 1.8 to 2.5 K

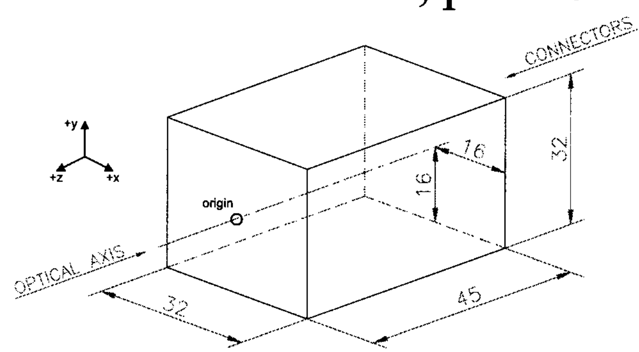
Beam: f/3.9 at -11 dB edge taper, boresight < ±1°

Mixer envelope: 32 x 32 x 45 mm

Mass: not to exceed 75 g

Connectors: 1 female SMA for IF output, one 9-pin micro-D connector for bias lines (5 wires)

Internal bias circuitry: 40 dB isolation between bias and IF, ESD protection, current sense resistor, parallel resistor



High Level Environmental Conditions

ESD: Goal is to withstand >1,000 V HBM

Lifetime: ~5 years shelf / 5 years cold

Ruggedness: Ariane 5 launch, 25 thermal cycles

Cleanliness: survive bake-out, clean room required

Key performance requirements:

1. Sensitivity (~1800 K at 1.800 THz)
2. IF bandwidth (8 GHz)
3. RF bandwidth (0.3 THz)
4. Local oscillator power (0.4 μW)

Summary of past key results

	Frequency [THz]	Trec [K]	PLO [nW]	IFBW [GHz]	RFBW [GHz]
	0.53 [a]	650	20	1.7	10
	0.6 [b]	470	35	9.2	---
Band 6!	1.105 [c]	1670	40	---	780
→	2.522 [b]	1850	22	9 *	1000

*: Bandwidth inferred to be the same as a similar device measured at 600 GHz

Can we meet the baseline

technical requirements for Band 6 for HIFI ?

[a] Skalare et al *Appl. Phys. Lett* **68** 1558 (1996)
[b] Wyss et al *Proc.. 10th Intl. Symp . Space Terahertz Tech*. p215 (1999)
[c] Skalare et al *Proc. 9th Intl. Symp. Space Terahertz Tech.* p115 (1998)

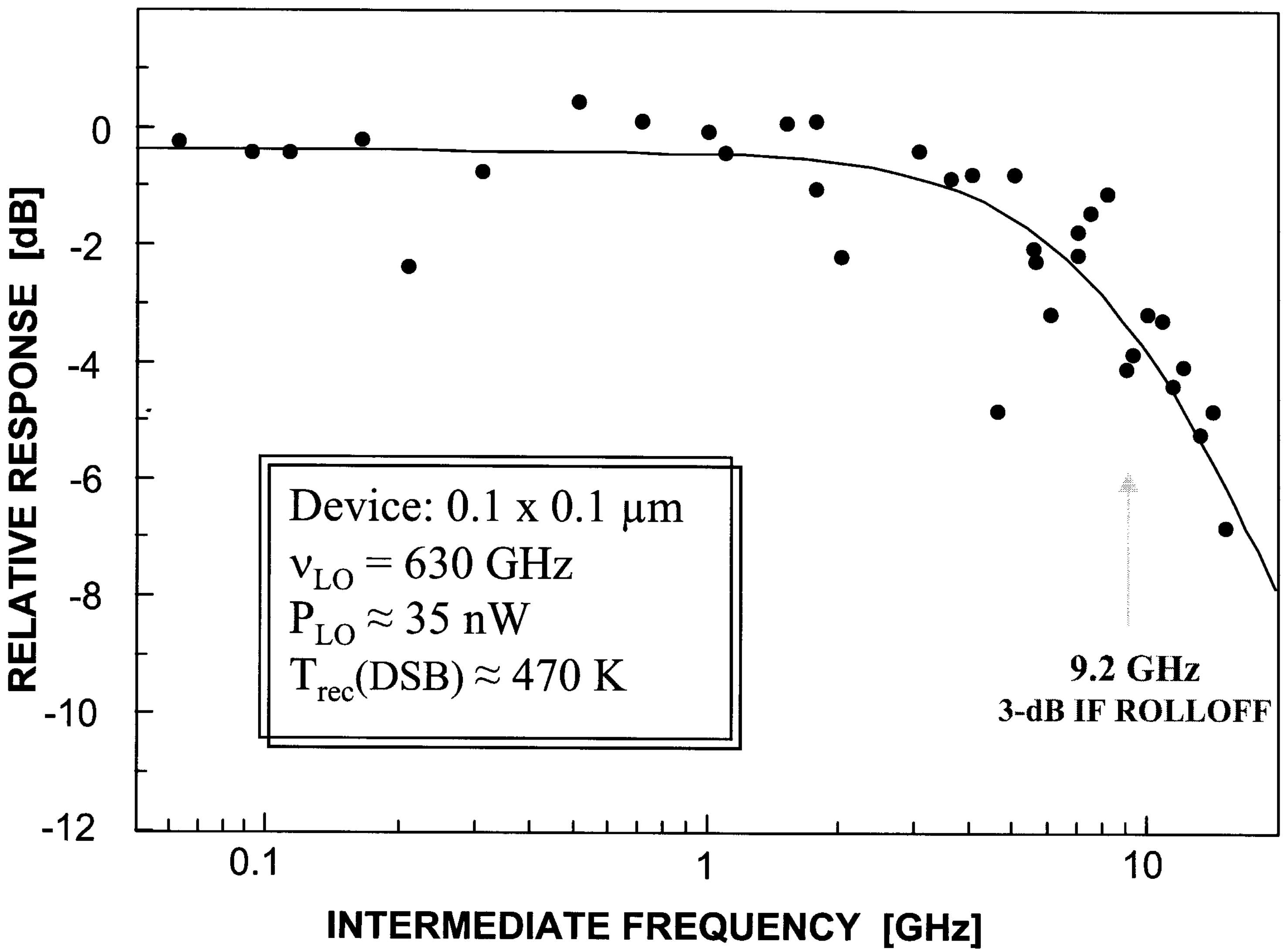
JPL

SUBMILLIMETER WAVE SUPERCONDUCTIVE SENSORS GROUP

CSMT

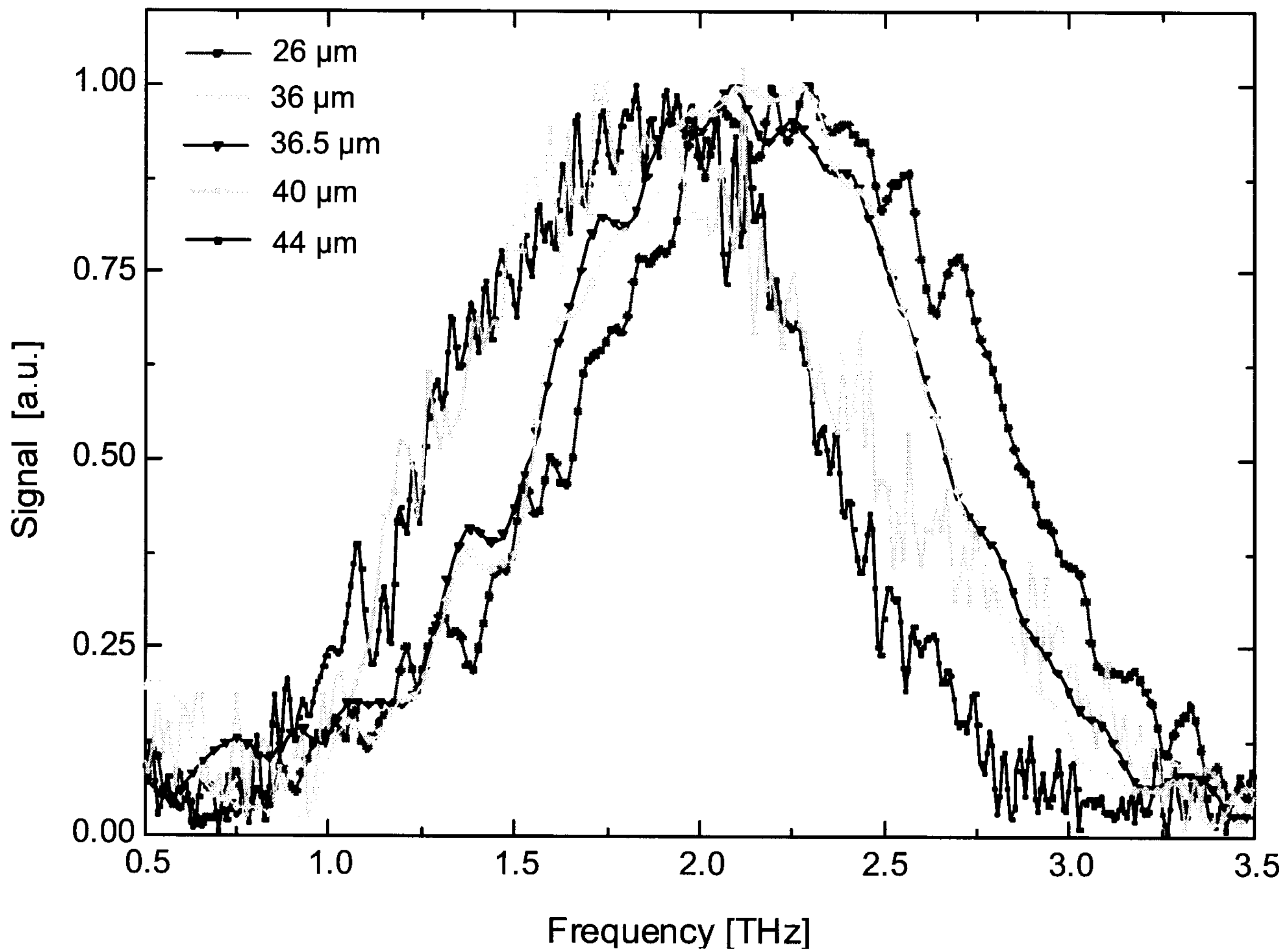
Nb DIFFUSION-COOLED HEB MIXER IF ROLLOFF

Rolf Wyss, Boris Karasik, Rob McGrath, Bruce Bumble, Rick LeDuc

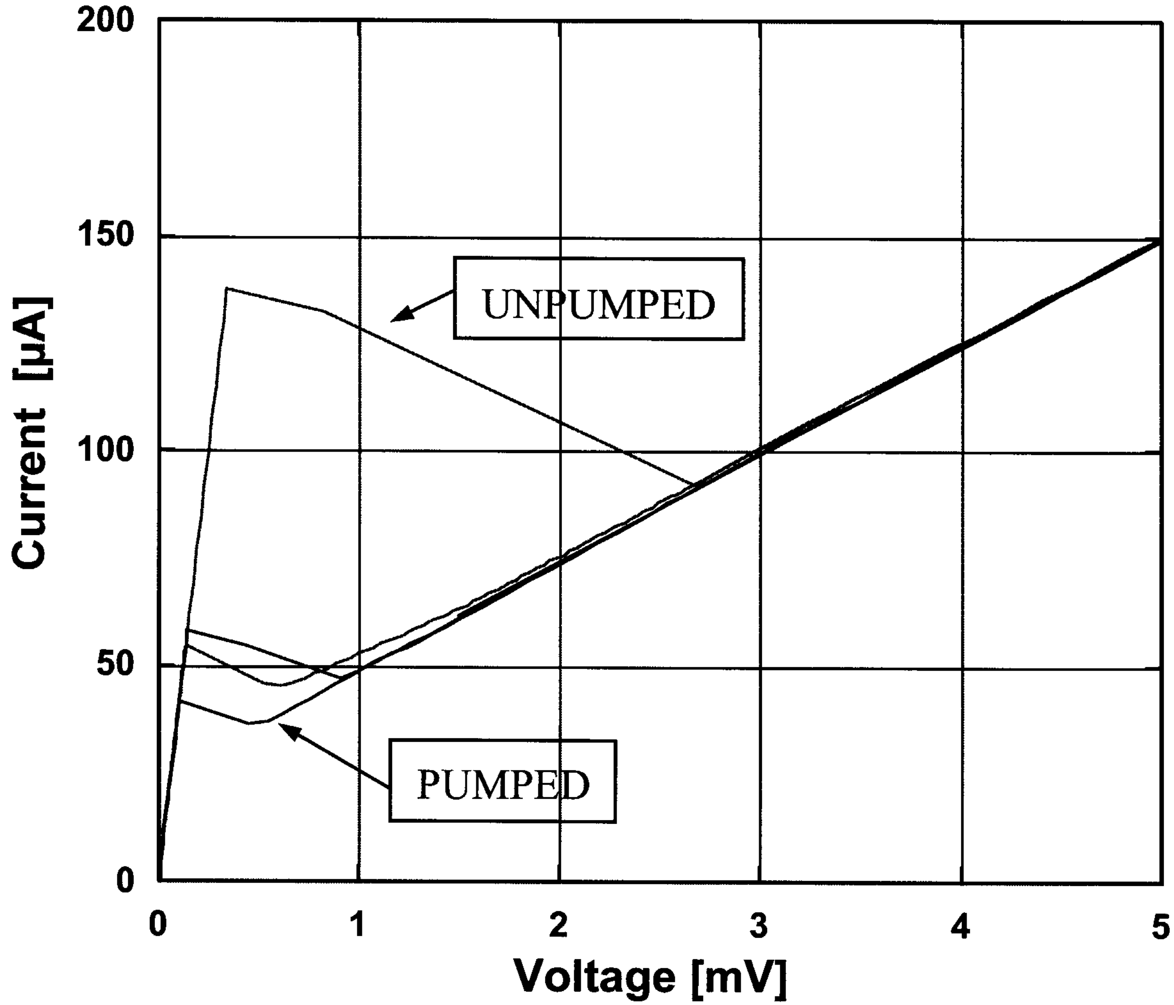


FTS MEASUREMENT OF HEB MIXER RF BANDWIDTH

R. Wyss, B. Karasik, S, Skalare, W. McGrath, B. Bumble, H. LeDuc



SUCCESSFUL DEMONSTRATION OF AN HEB MIXER PUMPED BY A 1.5 THz SOLID-STATE LO SOURCE



ν_{LO} = 1.525 THz

$P_{abs} \approx$ 13 - 16 nW

$P_{inc} \approx$ 80 - 100 nW
(includes mixer and window losses only)

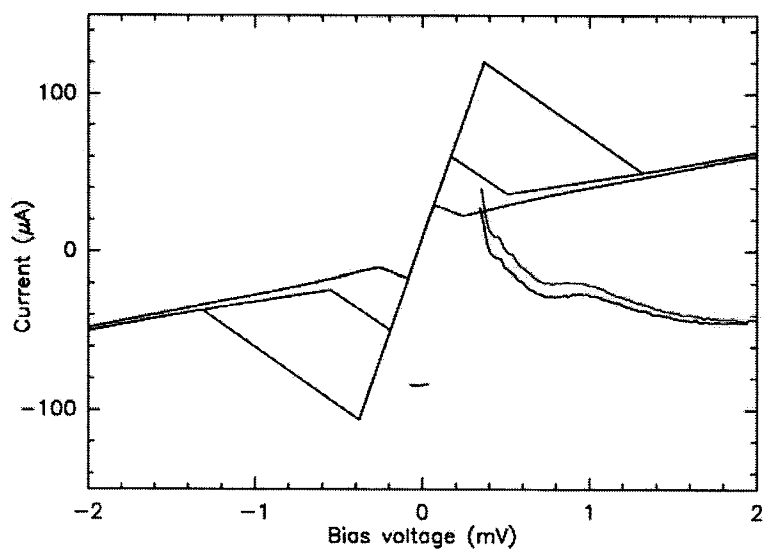
I_C = 137 µA

R_N = 34 Ω

A. Maestrini, W. McGrath, B. Bumble

Current performance:

After difficulty measuring Y-factor at 1.6 THz,
Evaluated mixers at 600 GHz



Trx ~ 1,800 K, but if bandwidth is quite large;
At 1.626 THz, Trx ~ 8-10,000 K

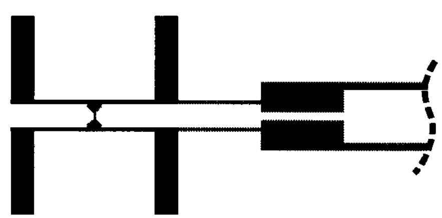
IMPROVED EQUIVALENT NETWORK MODEL

❖ CPW Power Leakage
- k_0 and Z_0 are real ONLY in static approximation

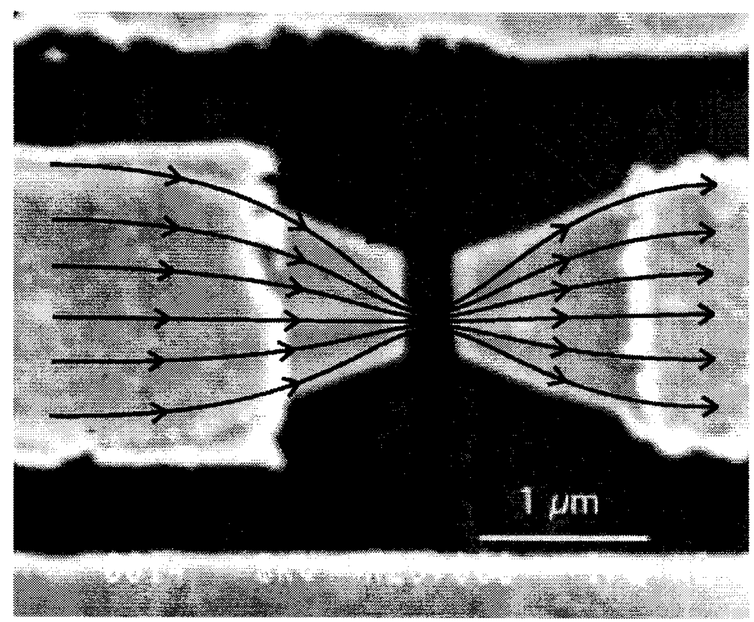
➡ Derivation of k_0 and Z_0 in order to take into account the CPW power leakage.

❖ Reactances introduced by:
- Strong concentration of electromagnetic field
- Steep variation of field direction

❖ Input impedance alteration due to:
- Impact of the RF band stop filter

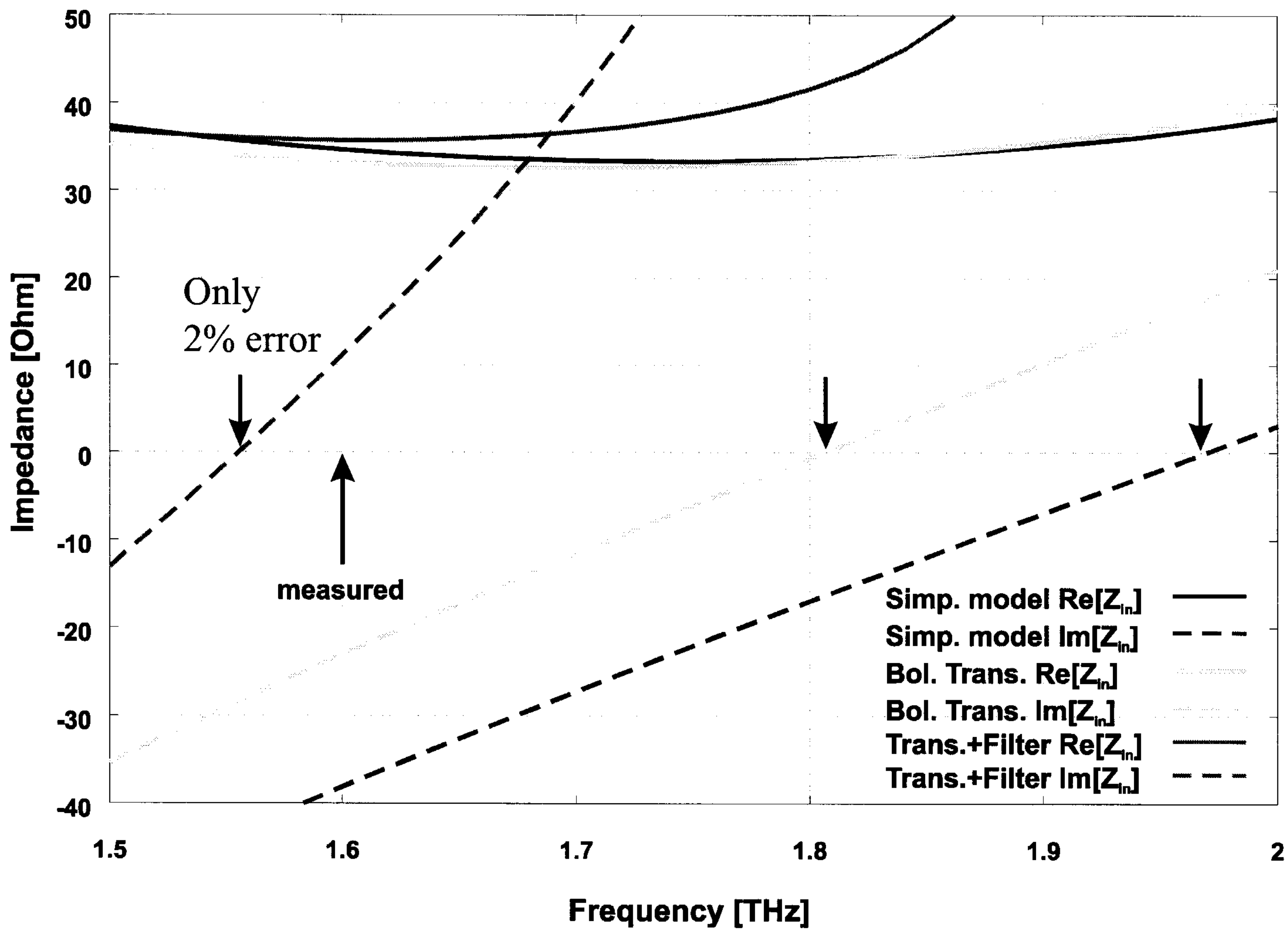


Complete mixer embedding circuit modeled using method of moments and uniquely derived analytical formulas. P. Focardi, A. Neto, W. McGrath Submitted to IEEE MTT August, 2001.



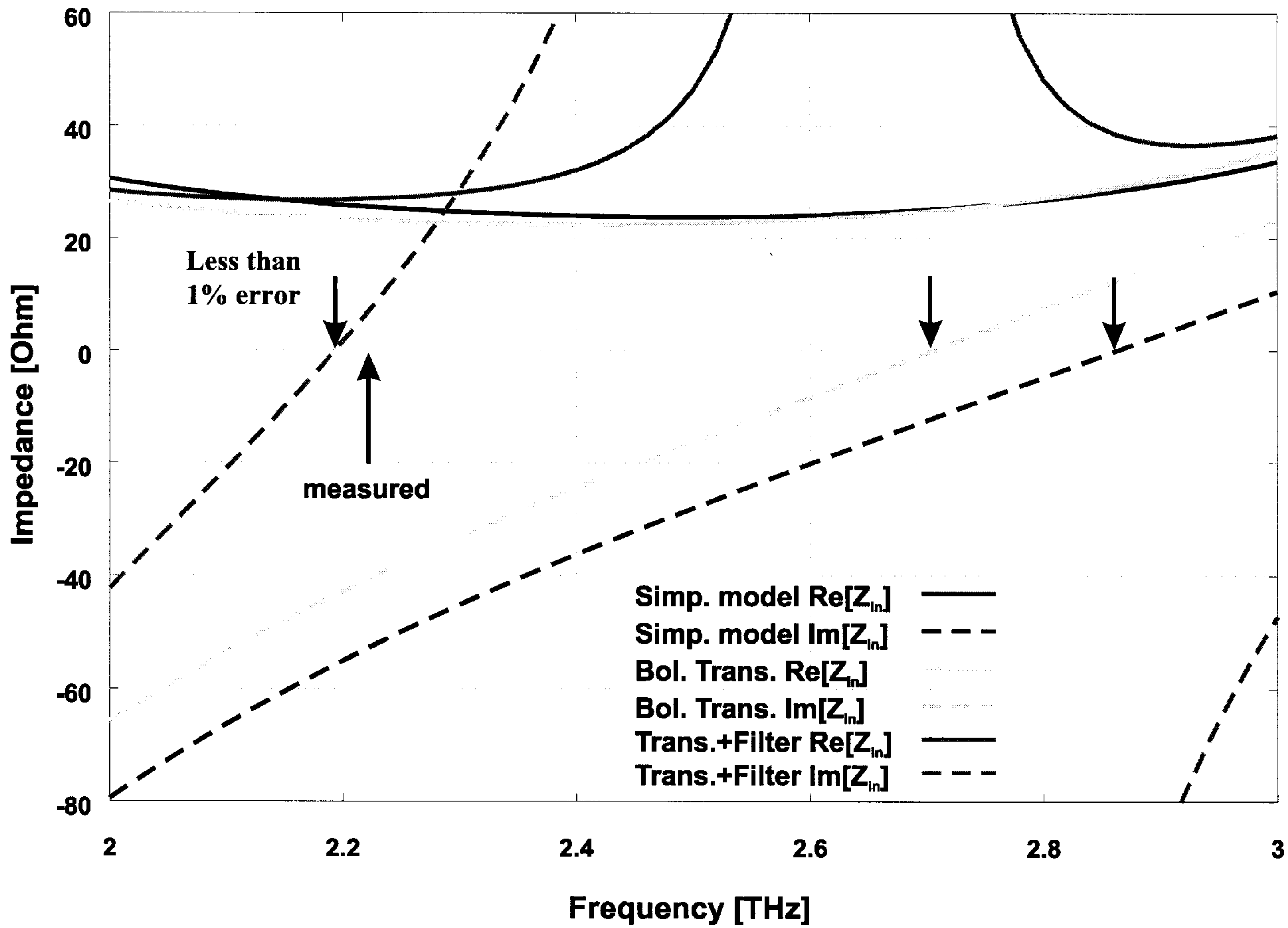
INPUT IMPEDANCE OF 1.6 THz HEB MIXER

P. Focardi, A. Neto, W. McGrath



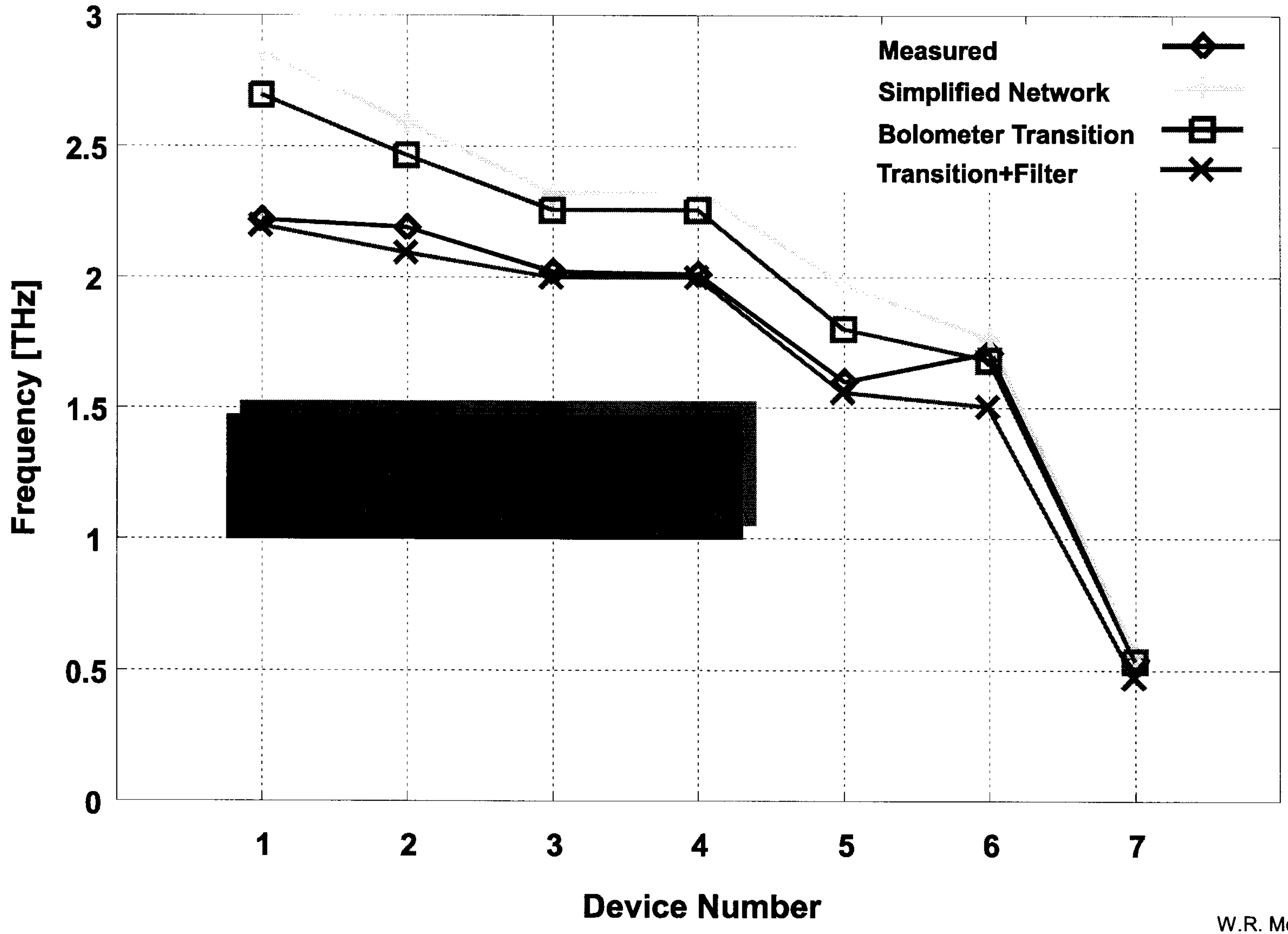
INPUT IMPEDANCE OF 2.2 THz HEB MIXER

P. Focardi, A. Neto, W. McGrath



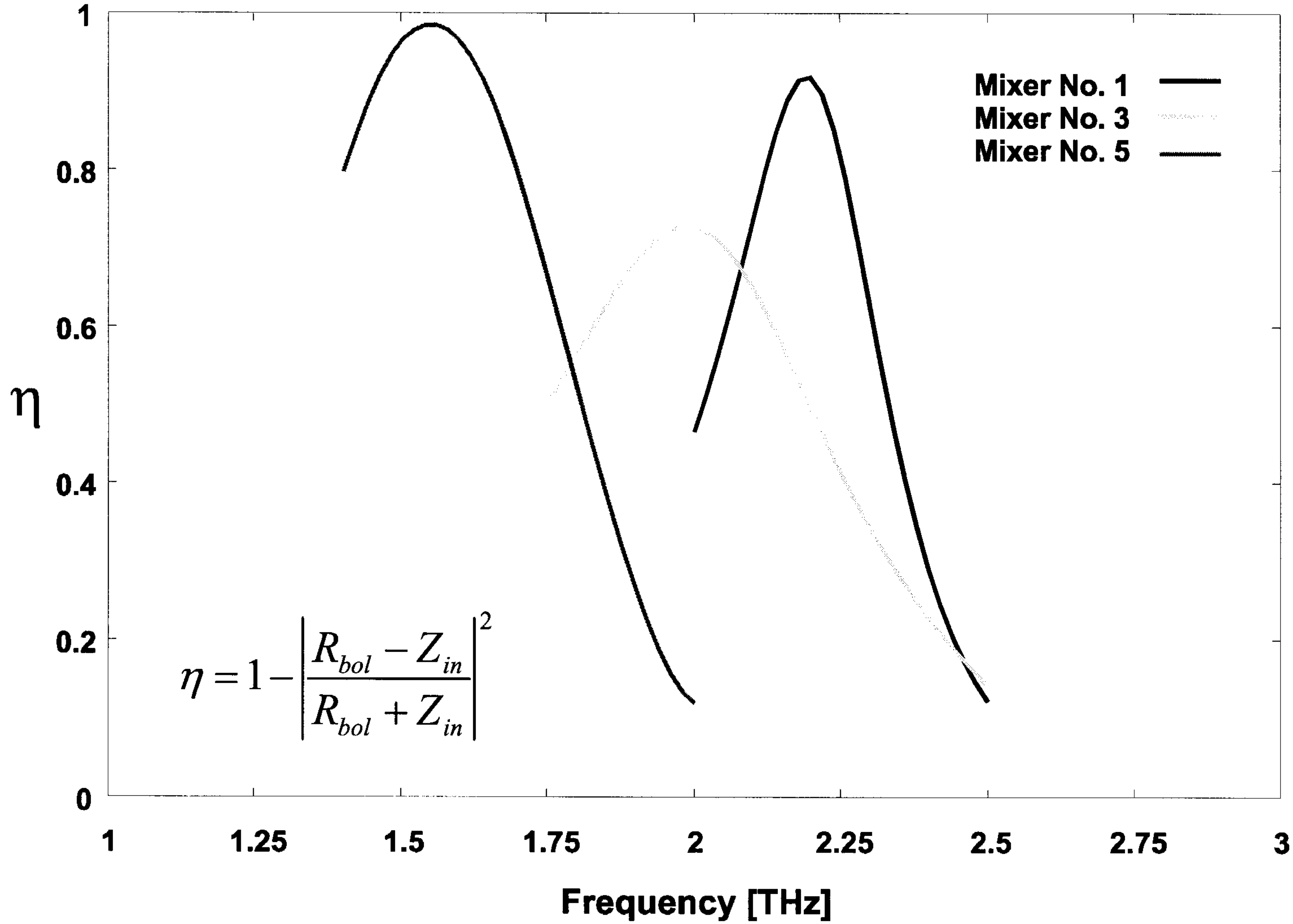
RESONANT FREQUENCY SUMMARY

P. Focardi, A. Neto, W. McGrath



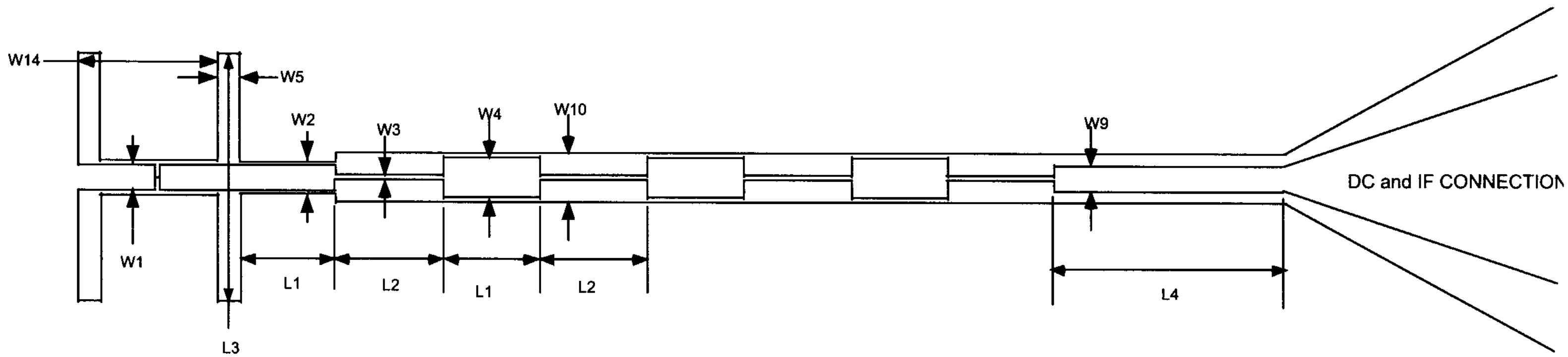
RF COUPLING EFFICIENCY

P. Focardi, A. Neto, W. McGrath



$$\eta = 1 - \left| \frac{R_{bol} - Z_{in}}{R_{bol} + Z_{in}} \right|^2$$

IMPROVED 1.6 THz HEB MIXER DESIGN



FEATURES:

- CPW-to-HEB transition changed from tapered to abrupt.
- Slot antenna length and impedance adjusted for best rf match.
- Length of first rf filter section adjusted for best rf match.

EXPECTED IMPROVEMENTS:

- Better control of resonant frequency.
- Better impedance match to device.

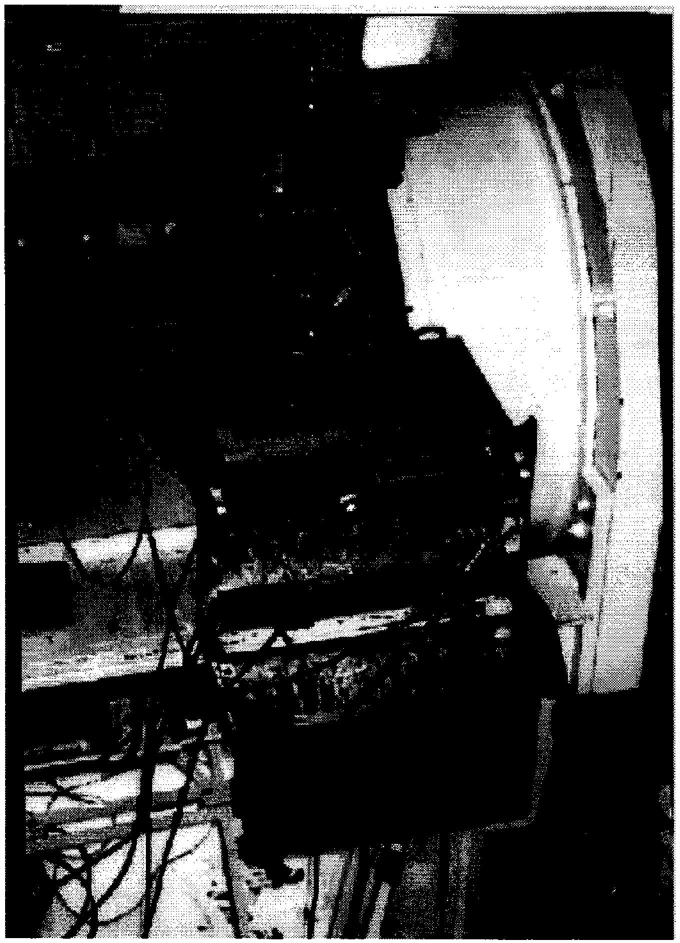
Observing Run at the Caltech Submillimeter Observatory

View of CSO, JCMT and SMA atop Mauna Kea

- Starting October '00, designed & built a 650 GHz test receiver
- CSO observing run carried out January 28-31, 2001

Kawamura, Esproles, Batelaan, McGrath, Karasik

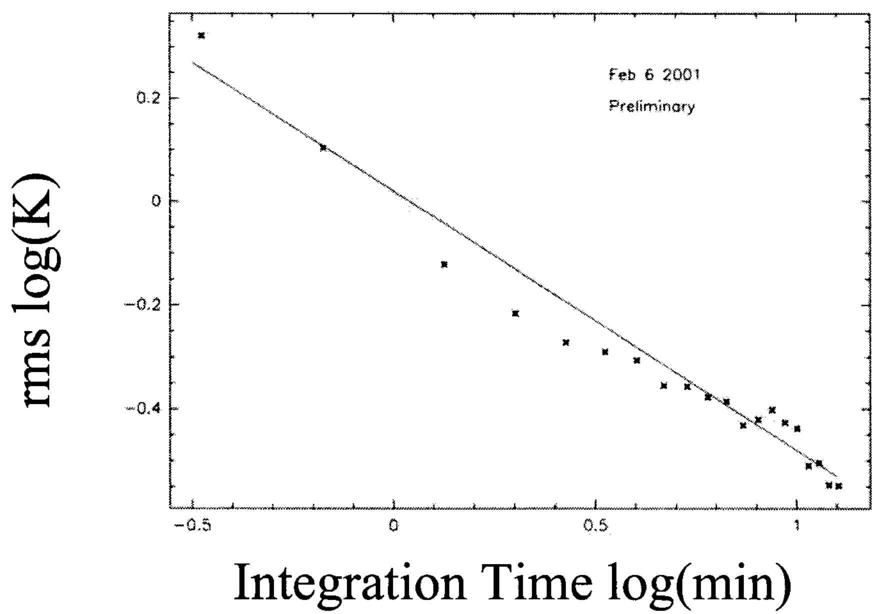
Observing Run at the Caltech Submillimeter Observatory



HEB receiver the CSO Cassegrain relay optics cage

- Receiver on telescope for 5 days, with no change in mixer characteristics
- Receiver was stable to 1 part in 800 over several hours

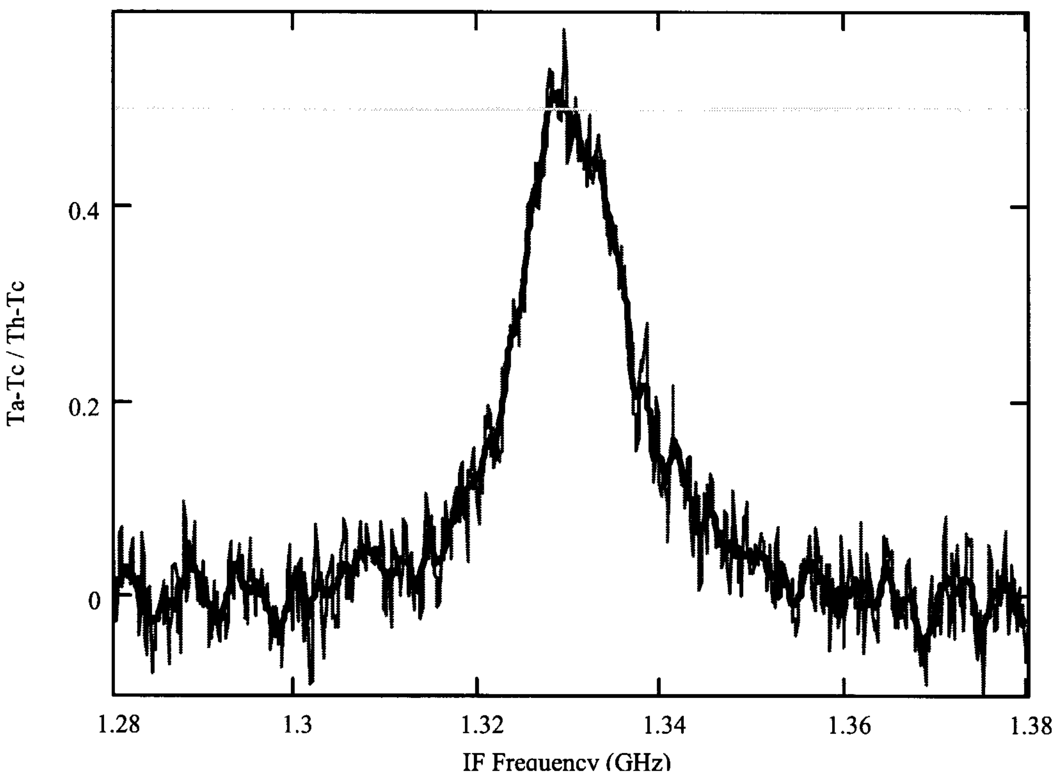
The receiver worked very well, but there was no opportunity to observe a spectrum

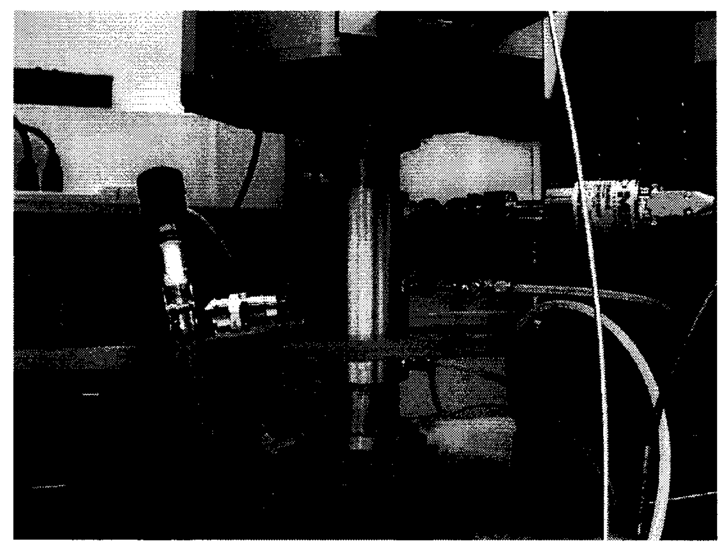


Blank sky integration using the facility 500 MHz AOS. (red line is $1/\sqrt{t}$; Vertical axis is uncalibrated)

Kawamura, Esproles, Batelaan, McGrath, Karasik

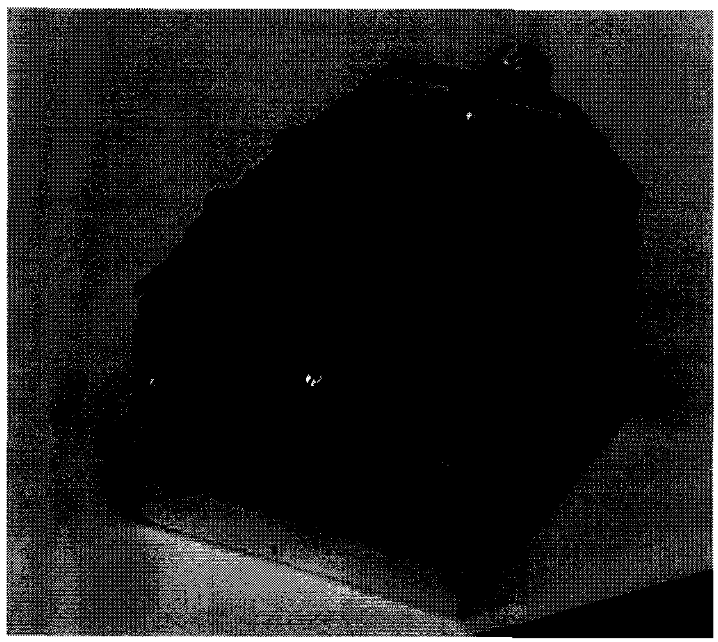
Gascell measurement





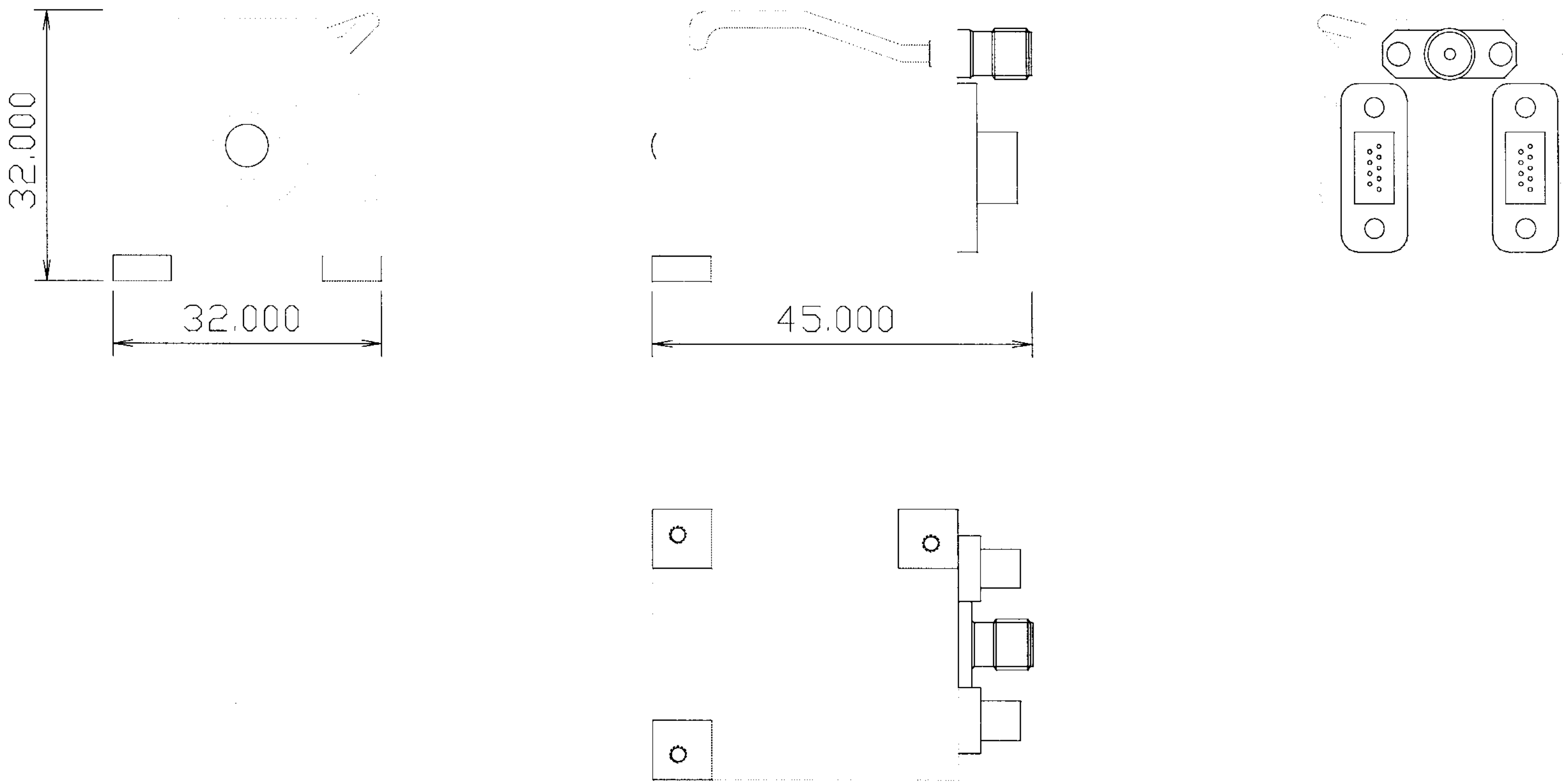
FLIGHT MIXER CONCEPT

Focus for flight mixer development is a robust, reliable design



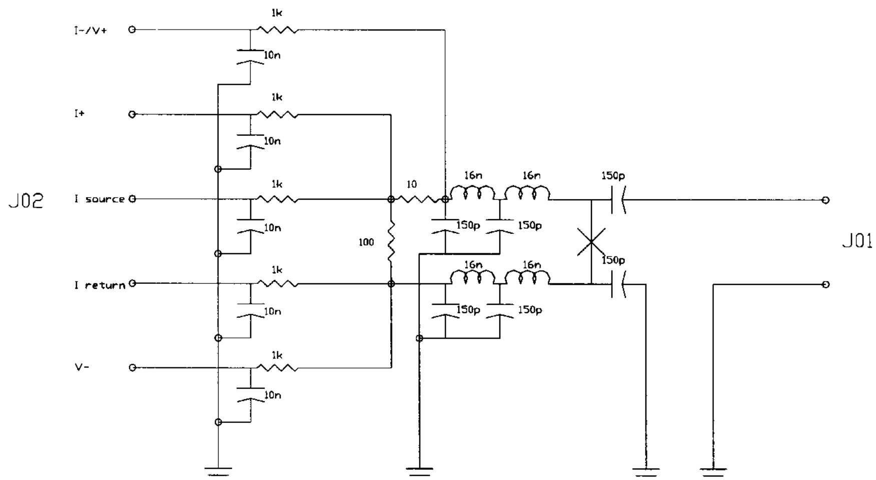
Flight-style mixer block

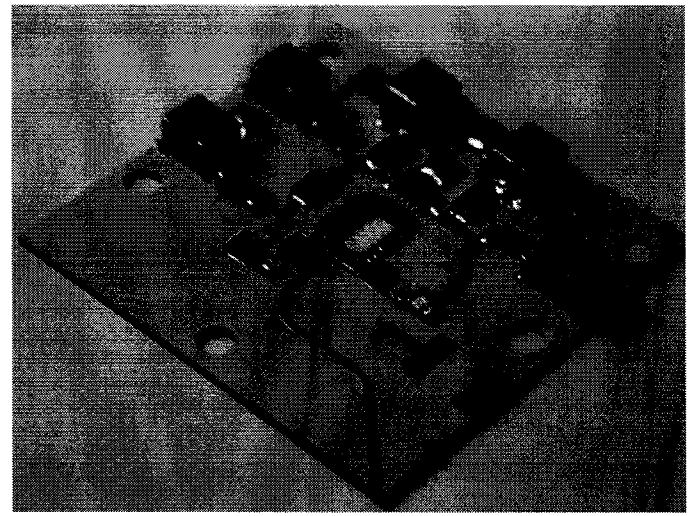
Outside view of mixer block



- Aluminum body T7075
- Bias board is completely enclosed
- Microstrip to coax transition with 90-deg bend
- As-built mass = 57 g

Internal bias circuitry





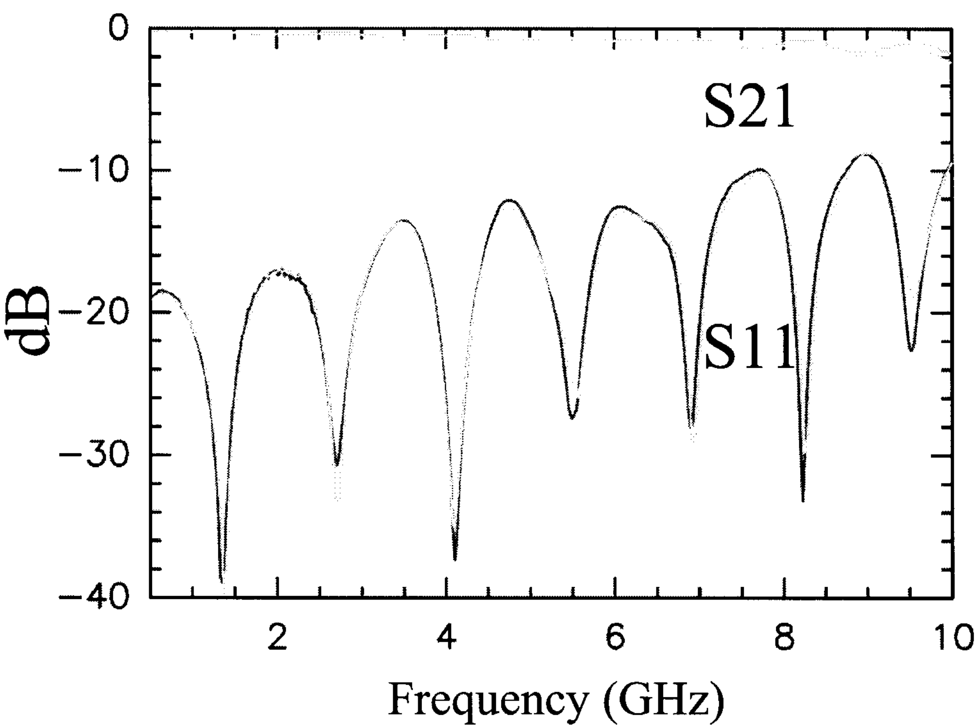
Photograph of populated bias board

Functions:

- Bias-tee
- ESD Protection (1,000 V HBM on any bias line ⇒ 70 mV (peak) across mixer
- Isolation between bias and IF (>40 dB required)
- Current sense resistor
- 16 kHz bias bandwidth
- Total dissipated power at nominal bias point: <100 μW

Properties of microstrip-to-coax transition with 90-degree bend

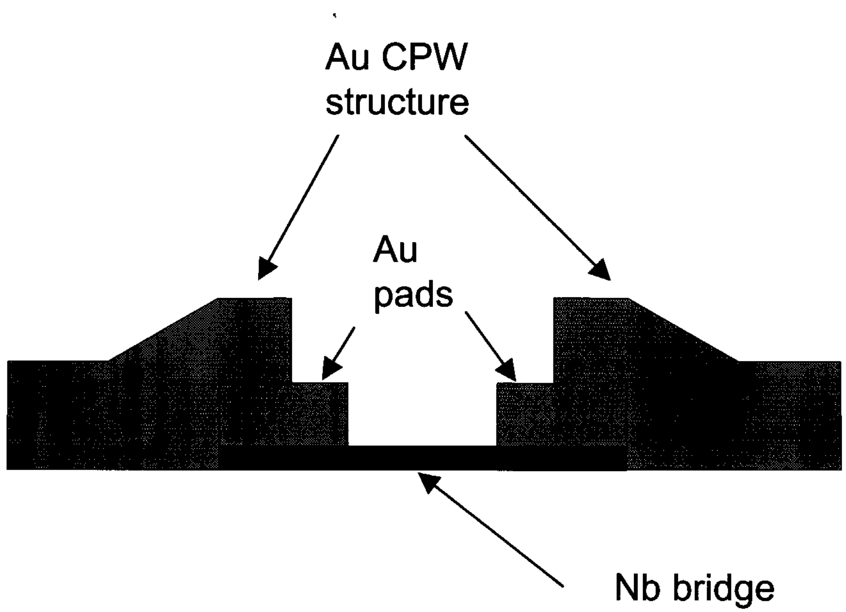
Microstrip-to-coax
Clamped capture
5 mm radius 90-degree bend



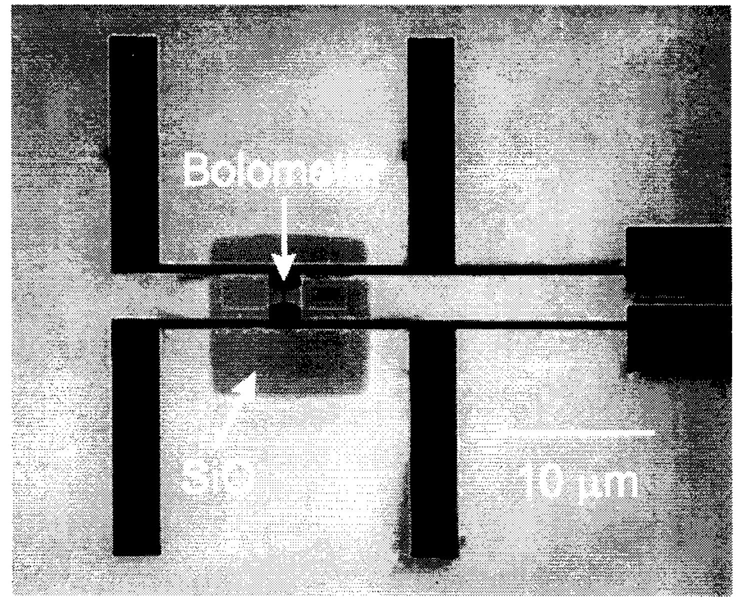
- Measured better than 20 dB return loss at 1-2 GHz
- Presently better than ~10 dB at 4-8 GHz (will improve)
- Soldered version remains stable after at least 12 thermal cycles

HEB device deliveries

HEB device cross section

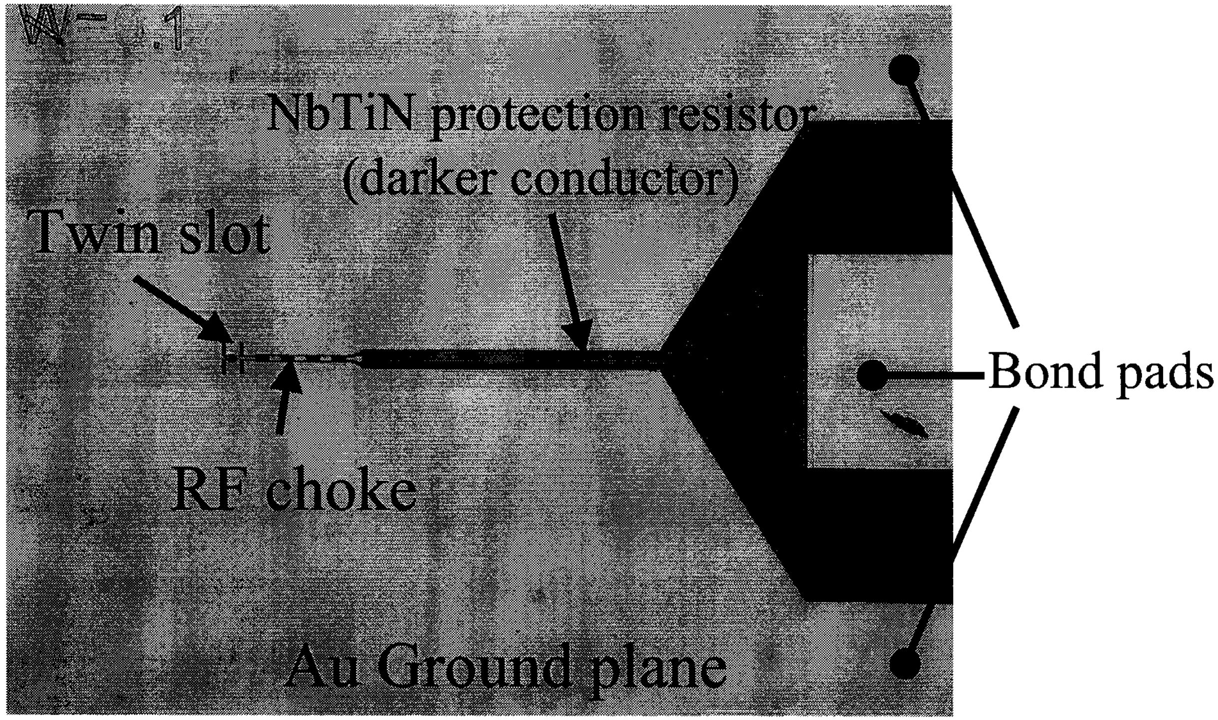


- Nb submicron bridge
- Au contact pads
- Au CPW structure



SEM of an HEB mixer

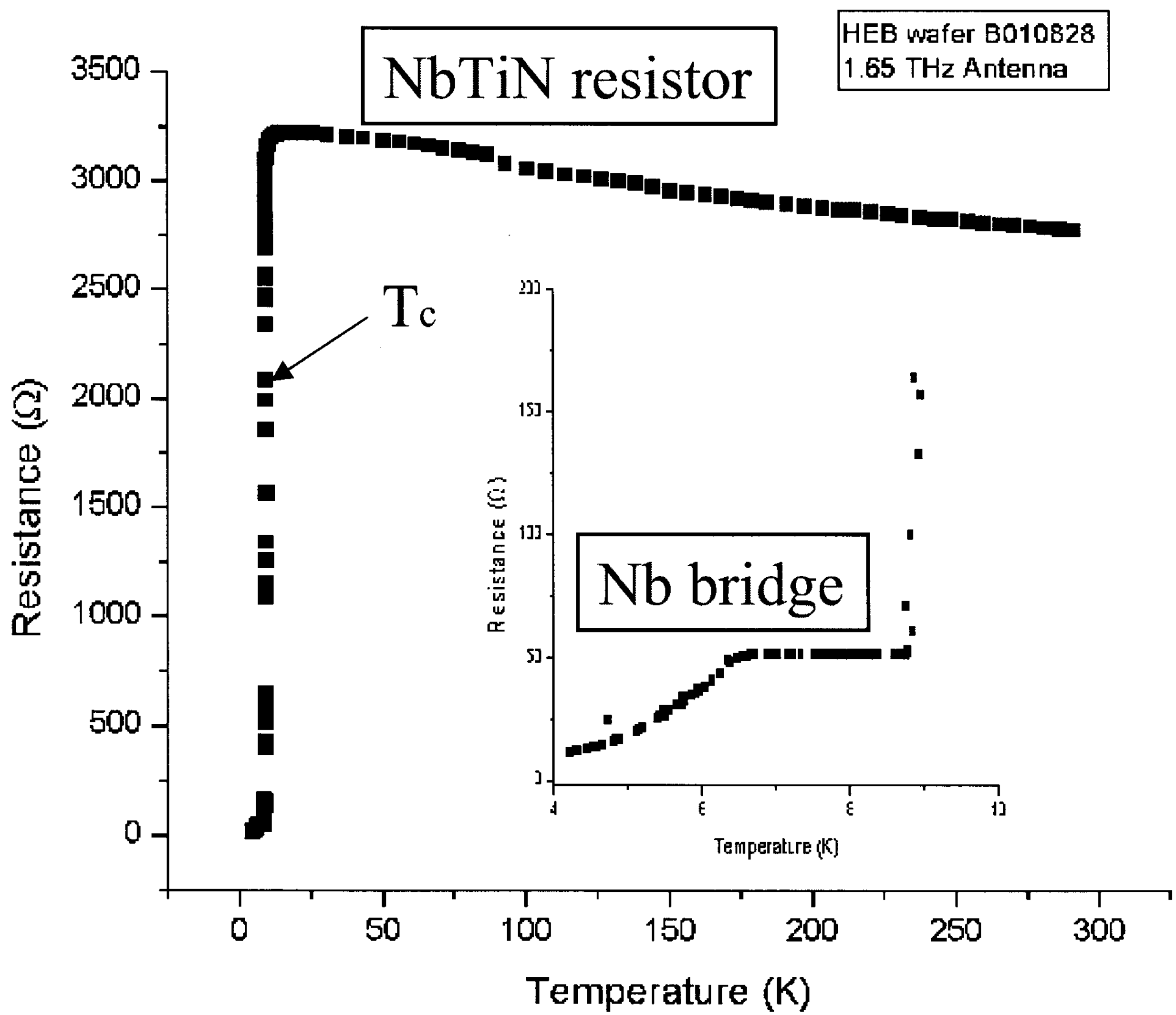
Die level improvements



- SiO etchmask for excellent uniformity
- Thicker SiO passivation layer on Ti to improve adhesion
- NbTiN ESD protection resistor (3 kΩ at RT, 0 Ω at <9 K)
- AlN etch stop (Improves ground plane quality)

⇒ Excellent run-to-run uniformity,
Yield improved from 10-30% to > 90%

Resistance versus Temperature for actual device



Reliability of device?

History: Unpassivated devices have a shelf-life of ~1 month. Passivated devices observed to degrade or fail some time after use.

Symptoms: Increase in R_N, reduced I_c, degraded system performance. Complete failure: open circuit.

Potential causes: Exposure to moisture and/or oxygen, thermal cycling, ESD

⇒ Device degradation was usually attributed to air penetrating ineffective passivation, but recent experience suggests *handling* is largely to blame.

Action: Isolate failure modes, quantify threshold

- Field testing
- ESD testing
- Perform accelerated aging tests with different passivation techniques
- Thermal cycling tests

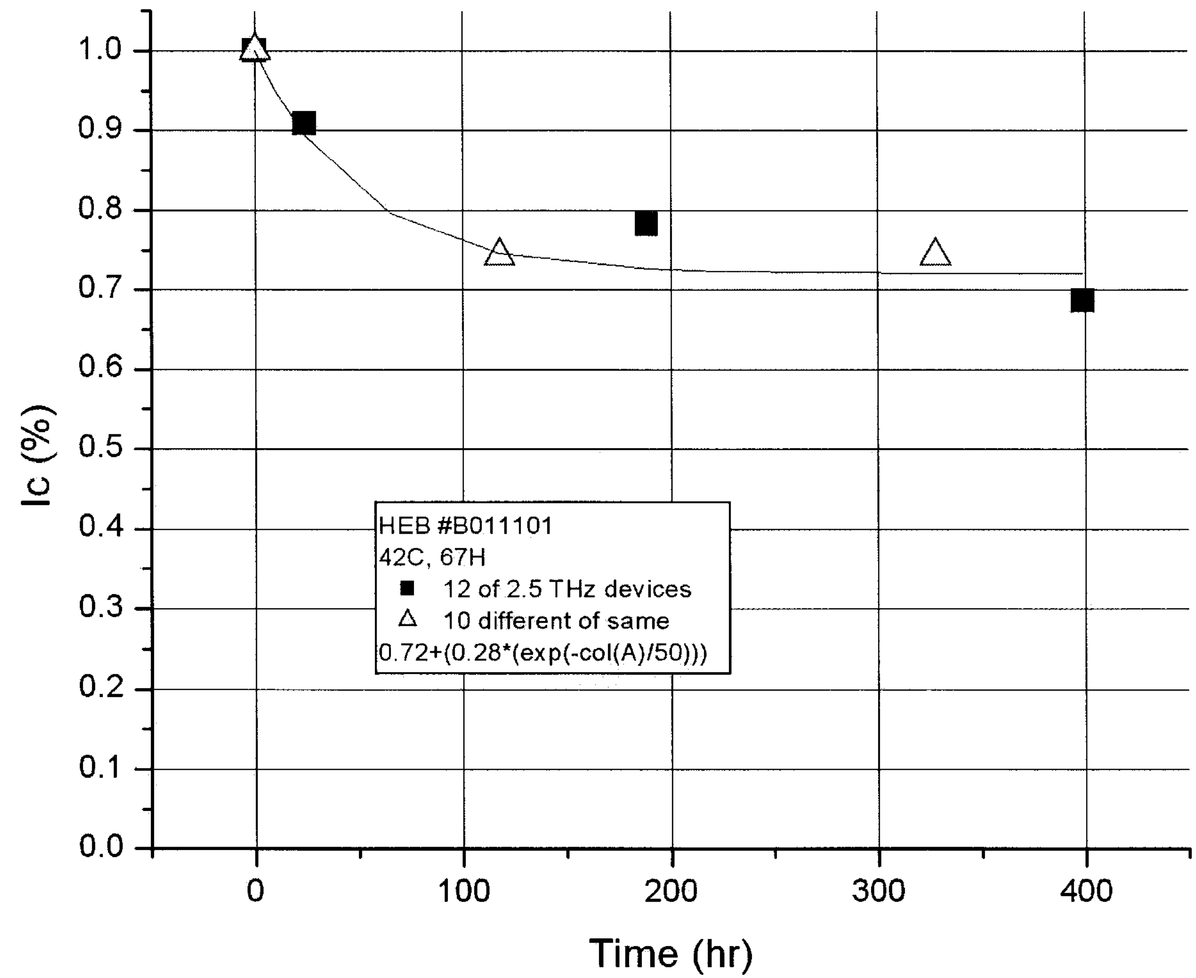
HEB reliability tests

- Passivated devices with 400 Å SiO last at least 5 years with no thermal cycling
- Current Passivation: 10 Å Ti, 2000 Å SiO. Appears to mitigate problems stemming from thermal cycling
- 200 hr / 80 C bake-out test. No apparent degradation.
- Accelerated lifetime tests are on-going. Devices do age, but degradation appears to flatten out in a characteristic time of 200 hours after exposure.

⇒ Device shelf-life is adequate. Thermal cycling does not affect aging

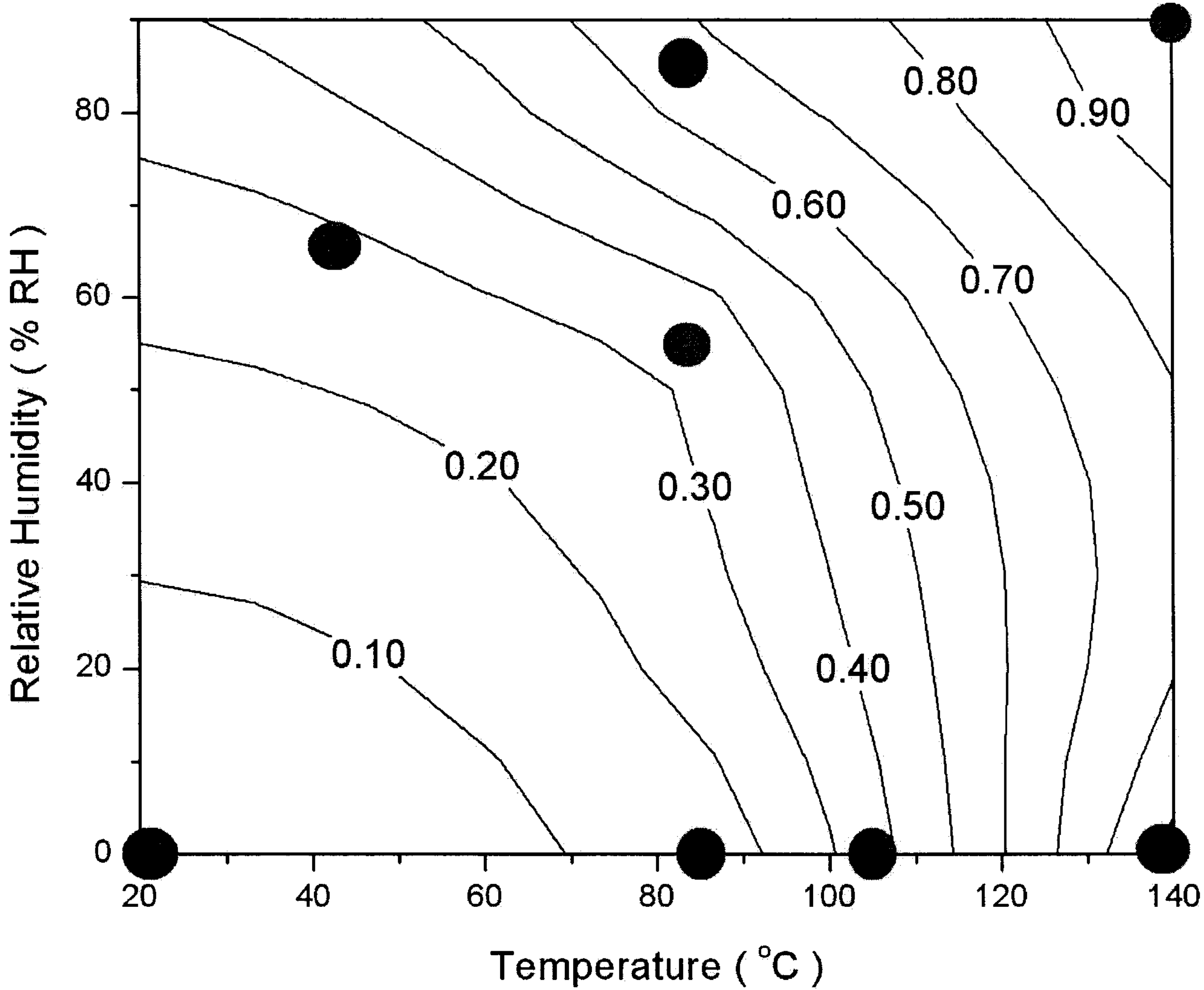
HEB reliability tests

Dies subjected to 42 C and 67% RH



HEB reliability tests

Critical current degrades by % if exposed to….

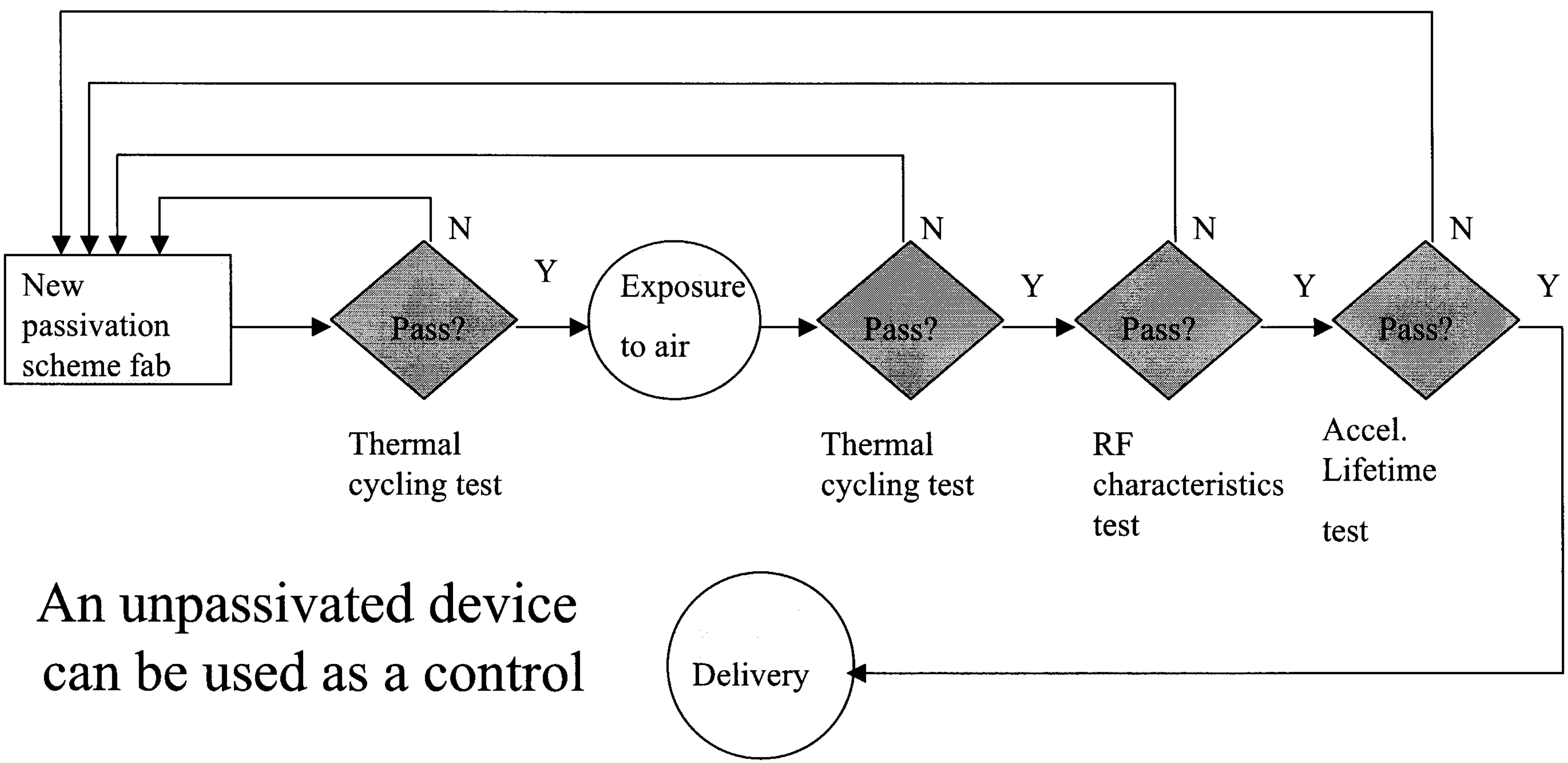


HEB passivation issues: plans

- Develop a more effective passivation scheme
  - Thicker SiO ?
  - Alternative Materials
    - Si_3N_4, SiO_2
    - Polyimide
    - Oxidized metals
    - Multilayers
    - Parylene
- Each scheme must pass
  - Thermal cycling test
  - Post thermal cycling exposure to air/moisture
  - RF characteristics test
  - Accelerated lifetime tests

B. Bumble, P. Echternach, R. Leduc

New passivation scheme development



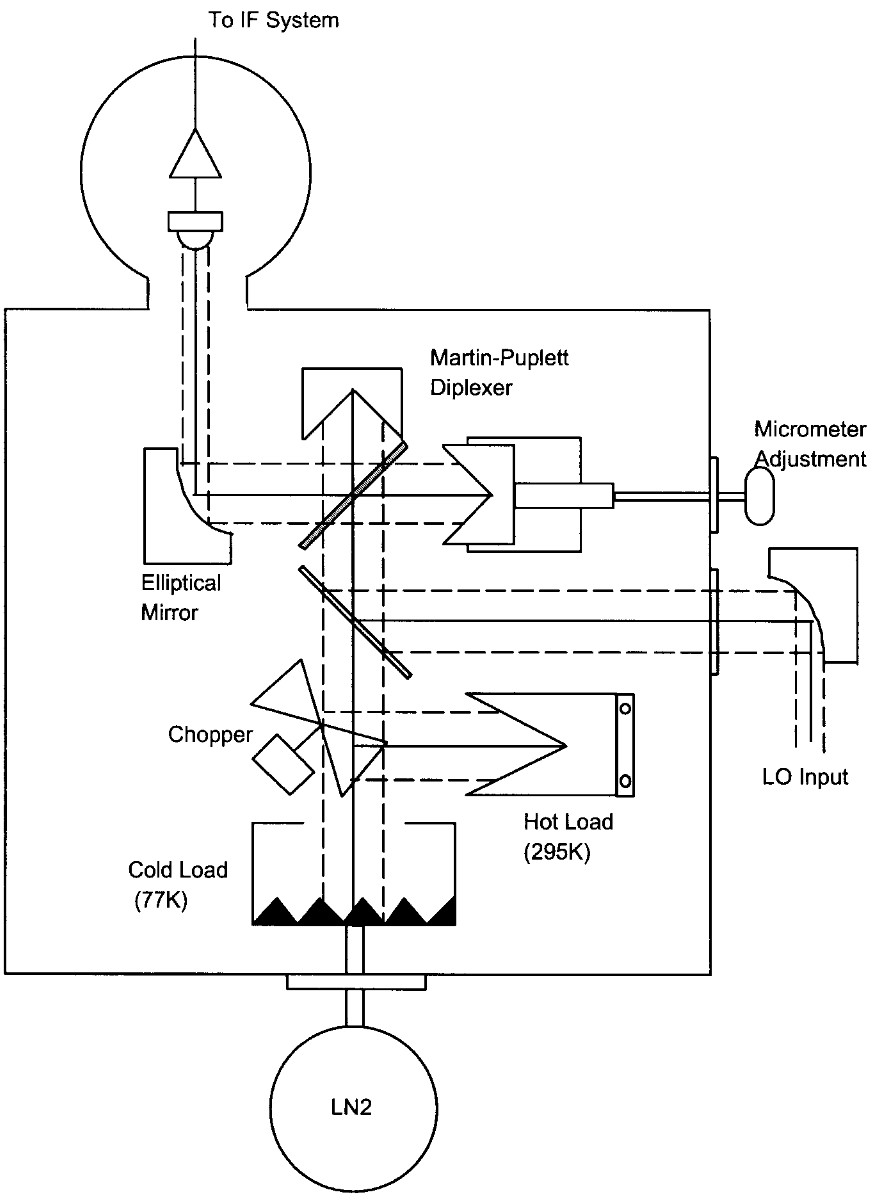
An unpassivated device can be used as a control

P. Echternach, R. Leduc

FLIGHT TEST SYSTEM and GROUND SUPPORT EQUIPMENT

- "Reference Receiver" is to be built. Measurements are to be conducted within a vacuum test chamber containing 300K and 77K loads, a mechanical chopper, a Martin-Puplett diplexer or simple beam-splitter, with optical access for LO injection. The reference receiver will emulate a full Mixer Assembly.
- Verify correct operation of microwave circuits, e.g., the microstrip-to-coax transition and bias-tee
- T_{rec} / IFBW measurement: Y-factor method using sweepable YIG filter or spectrum analyzer to get noise temperature as a function of IF.
- Beam Pattern Measurement: A pair of computer-controlled rotation stages to rotate cryostat about beam waist in order to measure beam profiles. Rotate source for Co- and Cross-polarization. Boresight will only be measured to ± 1-degree.

Test system (performance specification)

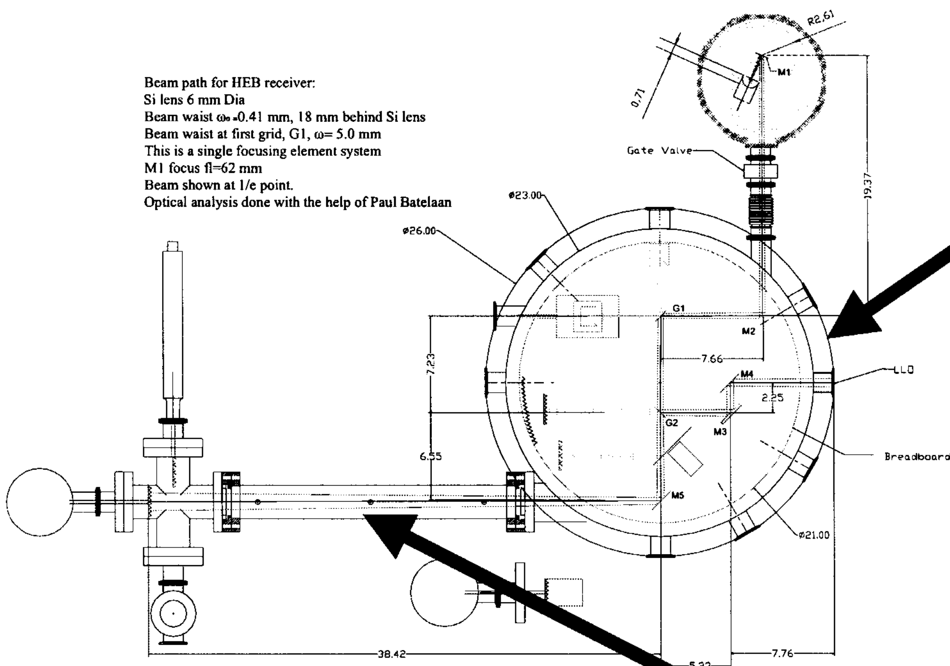


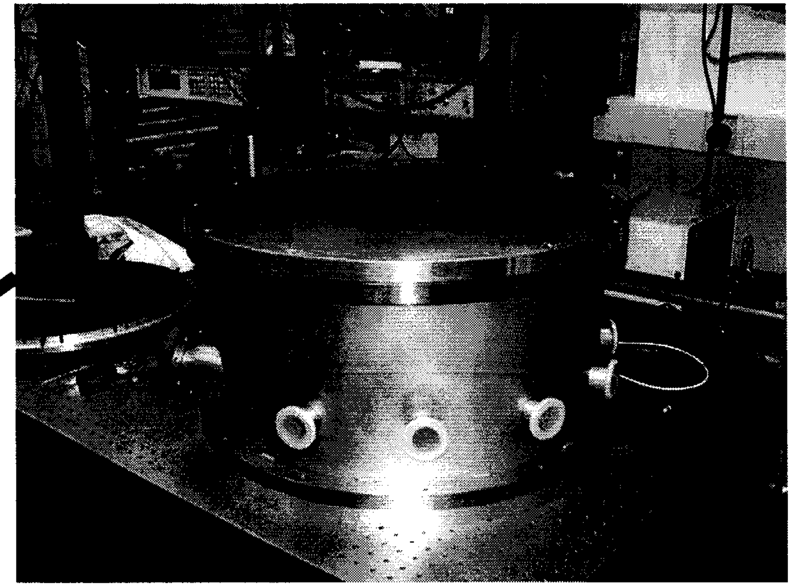
"REFERENCE RECEIVER"

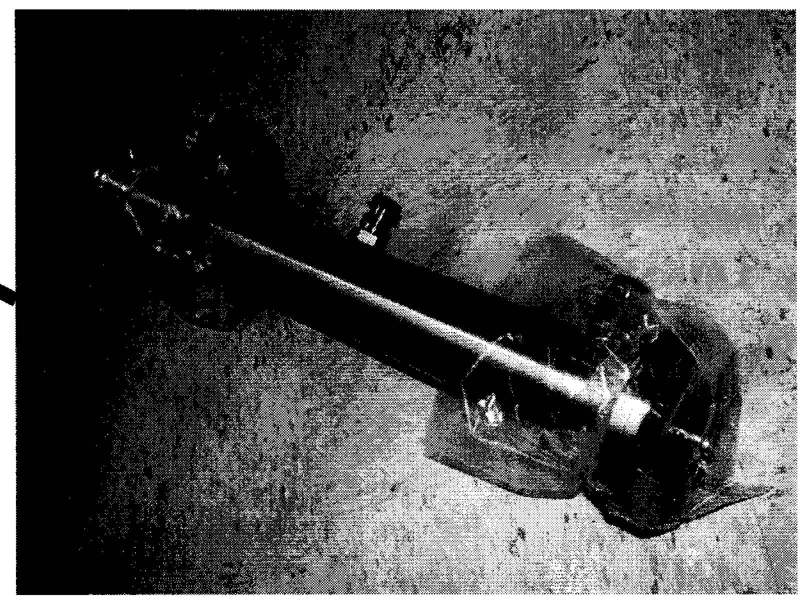
Measurements in vacuum of

- Mixer noise temperature
- IF bandwidth
- Conversion efficiency

- Test system (performance specification)

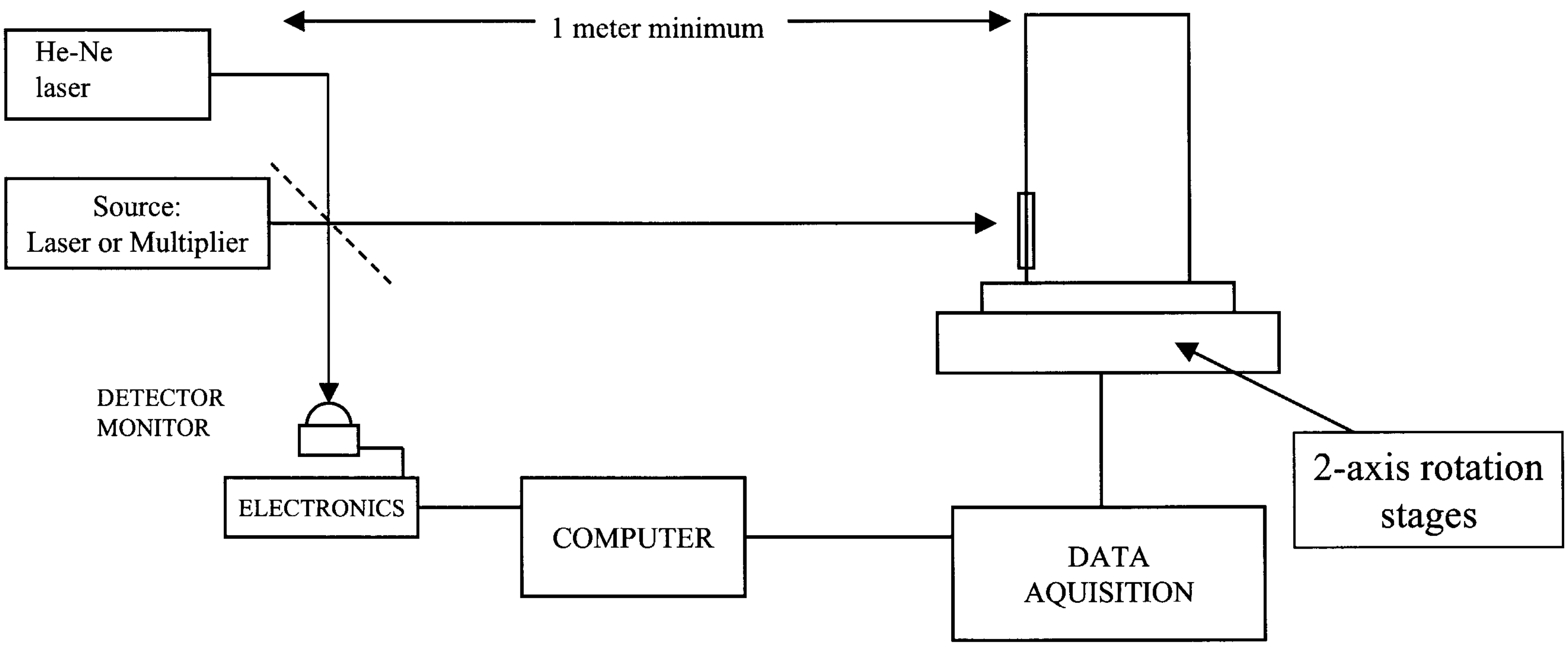




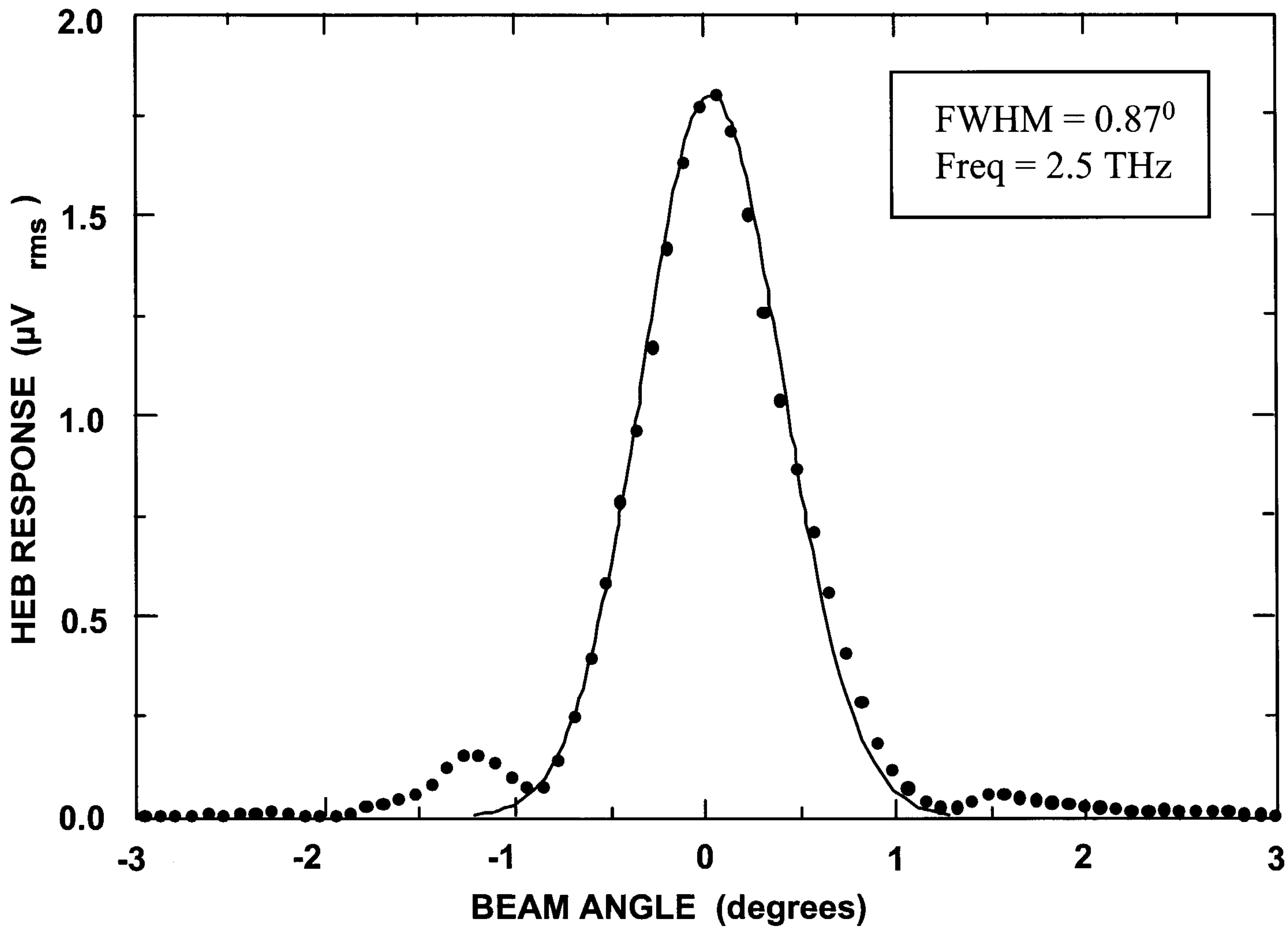


Beam measurement system (interface specification)

Alignment Procedure:
- Co-align (parallel) optical laser with submm source.
- Mount optical surface to mixer reference planes.
- Measure beam pattern relative to optical surface.

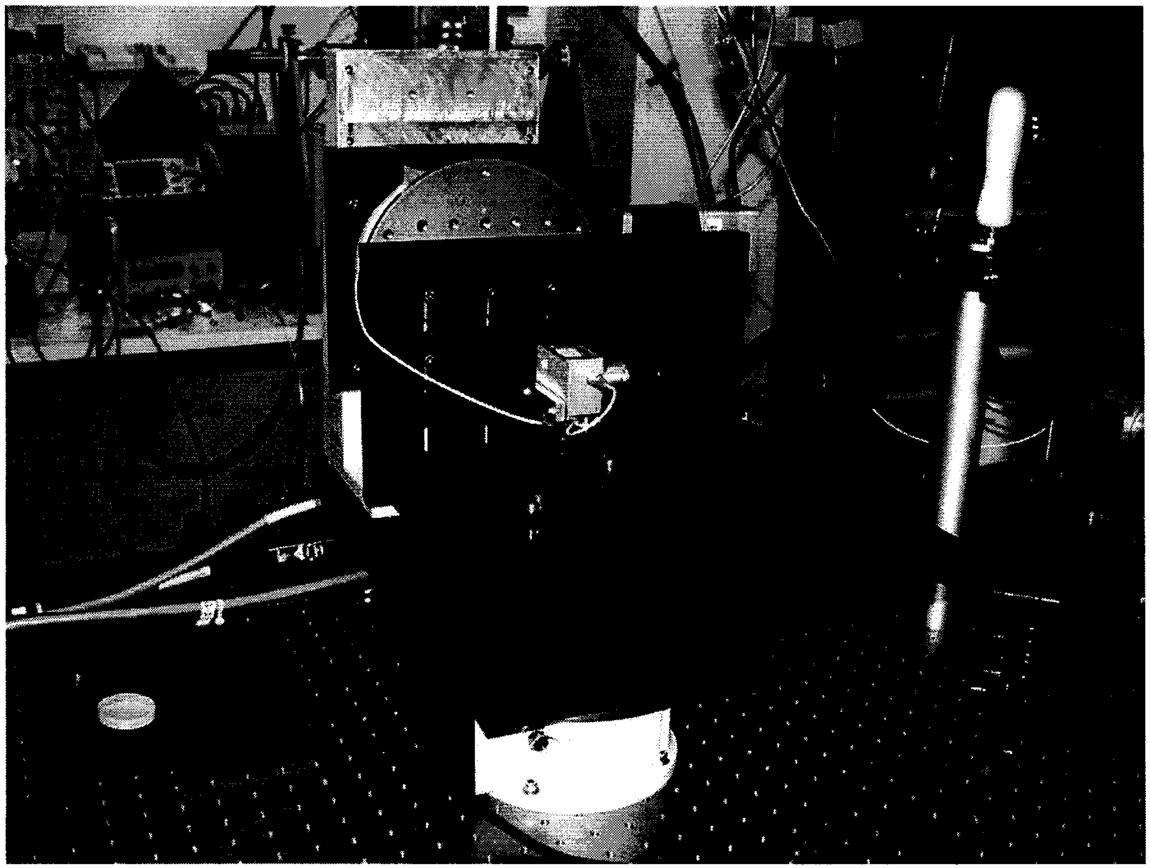


BEAM PATTERN MEASUREMENT



R. Wyss, W. McGrath, B. Bumble, R. LeDuc

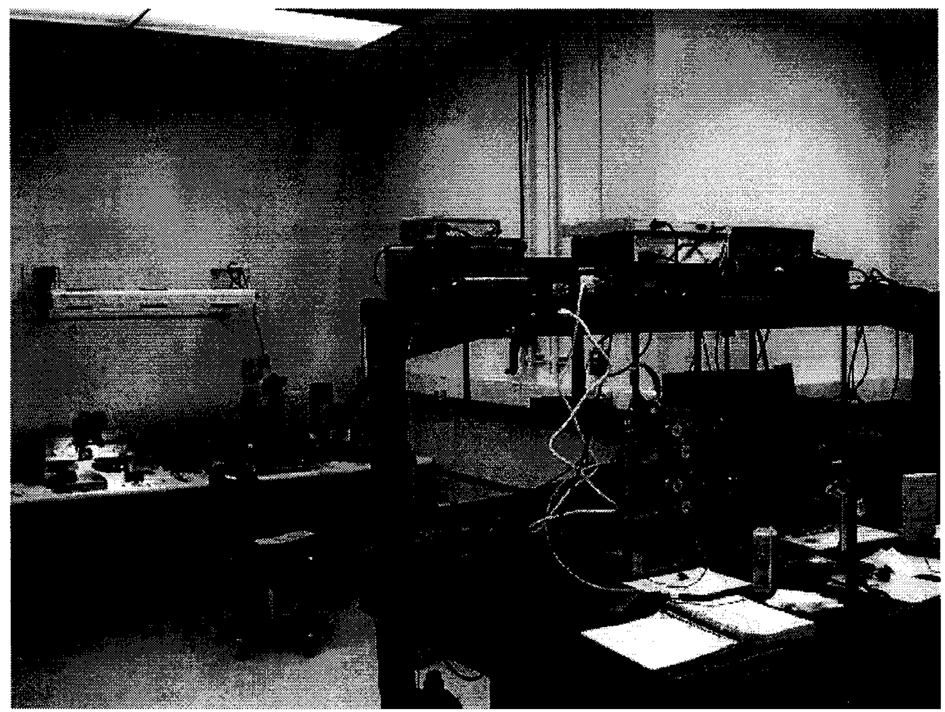
- BEAM PATTERN MEASUREMENT



Facility

Flight Assembly and Test Lab (Bldg 169-108/109)

- Renovations commenced Feb 01', completed Aug '01.
- Class 100,000 clean room: HEPA filtration, gown-up room, shoe mats.
- Extensive ESD precautions: static-dissipative bench-tops, chairs, flooring and smocks, copper ground-rail, air-ionizers, humidifier.
- Westbond bonder, Nikon microscope
- FIR Laser operational
- Access to Microdevices Laboratory, research lab equipped with other FIR lasers, network analyzer, etc.



Qualification plan (environmental)

Device level

- Wafer screening
  - ✓ Visual inspection under optical microscope
  - ✓ SEM inspection of random bolometers on wafer prior to final etch
- Device screening
  - ✓ Resistance vs. Temperature measurements
  - ✓ Current vs. Voltage measurements at 4.2K
- Reliability (shelf life/accelerated lifetime tests)
  - ✓ Thermal cycling between 300 and 4.2 K
  - ✓ 200 hr @ 86 C in vacuum (bakeout)
  - ✓ ESD testing
  - ✓ Accelerated lifetime testing
- Metal adhesion/bond pad integrity
  - ✓ Bond pull tests on selected dies.

Qualification plan (environmental)

Mixer level

- Static / Quasi-static (analysis)
- Cold vibration test
- Thermal cycling in vacuum:
  - 60 times between 4.2 K and RT (6 daily)
  - 5 times between RT and 86 C
- EMC (higher level)
- Bond tests
- Bake test (80 C for 96 hours)
- FMECA
- Worst-case analysis

Risks

- ESD damage — low
  - ⇒Addition of NbTiN resistor has mitigated risk. Strictly adhere to prescribed precautions: i.e., all personnel are trained in ESD control and areas where unit is handled are surveyed.

- Lifetime — low
  - ⇒Device shelf-life being investigated

- Repeatability of fabrication process — low
  - ⇒New SiO etchmask process *appears* to have solved this problem

- Choice of materials parameters to optimize mixer performance — high
  - ⇒Plan de-scoped last FY.

- Measurement of LO power
  - ⇒Not a serious issue if LOs are available to test with