ESA workshop
NEW PERSPECTIVES FOR POST-HERSCHEL FAR INFRARED ASTRONOMY FROM SPACE
Madrid , 1-4 September 2003

(Invited presentation)

LO Sources for 1-3 THz: present status and future prospective

Imran Mehdi

Jet Propulsion Laboratory
California Institute of Technology
M/S 168-314, 4800 Oak Grove Drive, Pasadena CA 91109
Email: imran@merlin.jpl.nasa.gov

Abstract

For many practical THz applications robust, agile and powerful sources are a must. The last decade has seen an impressive development in terms of generating THz signals largely in response to space based needs. MMIC power amplifiers with impressive gain in the Ka- to-W band have enabled the use of microwave synthesizers which can then be actively multiplied to provide a frequency agile power source beyond 100 GHz. This medium power millimeter source can then be amplified to enable efficient pumping of follow-on balanced multiplier stages. Input power to the multipliers can be further enhanced by power combining to achieve close to half a Watt at W-band. An 800 GHz three-stage multiplier chain, implemented this way has demonstrated a peak output power of 1 mW.

A second advance in LO generation lies in the Schottky diode varactor technology. Planar Schottky diode multipliers have now been demonstrated up to 1500 GHz and it can be assumed that most of the future multiplier chains will be based on these robust devices rather than the whisker contacted diode of the past. The ability to produce planar GaAs diode chips deep into the THz range, with submicron dimensions, has opened up a wide range of circuit design space which can be taken advantage of to improve efficiency, bandwidth, and power handling capability of the multipliers.

This talk will present an overview of the current technologies that are available for implementing local oscillator sources for 1-3 THz applications. Progress to date on specific components will be discussed in some detail. Outstanding issues and concerns regarding practical implementation of these new technologies will also be discussed.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with National Aeronautics and Space Administration.

LO Sources for 1-3 THz:

Present Status and Future Prospective

Imran Mehdi

Submillimeter-Wave Advanced Technology (SWAT) Team
Jet Propulsion Laboratory
California Institute of Technology

ESA Workshop

Outline

- Introduction
- Status of THz multiplier sources
- Future goals
- Concluding remarks

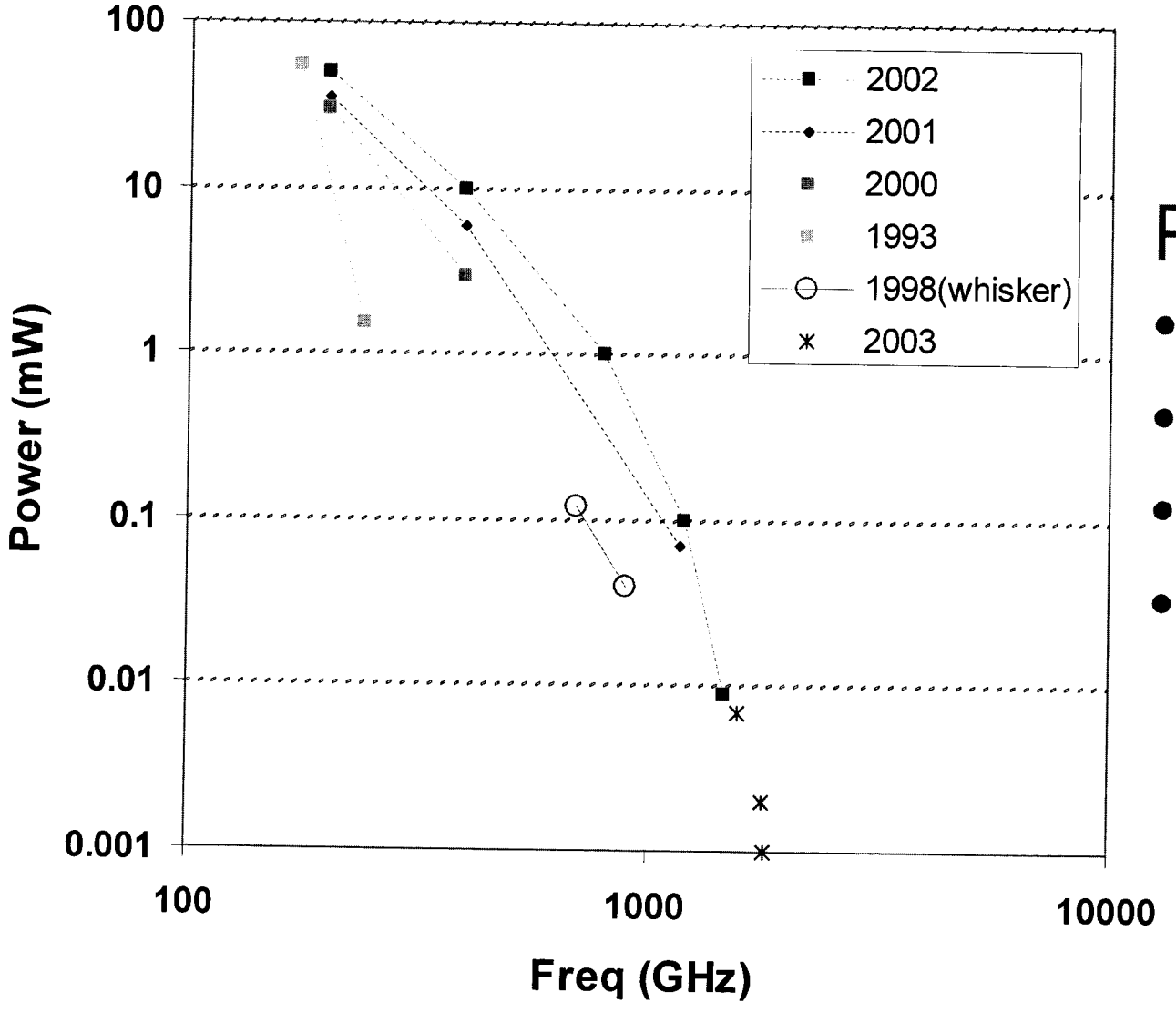
Multipliers for Space

Requirements

- Figure of merit
  - Frequency
  - Power
  - Bandwidth
  - Efficiency
- Output power:
  - Milliwatt's for Schottky mixers
  - 10's of microwatts for SIS mixers,
  - 1-2 microwatts for HEB mixers
- Mechanical--stability, compact, low mass, thermal viability
- Environmental--radiation, vibration, thermal

How far have we come?

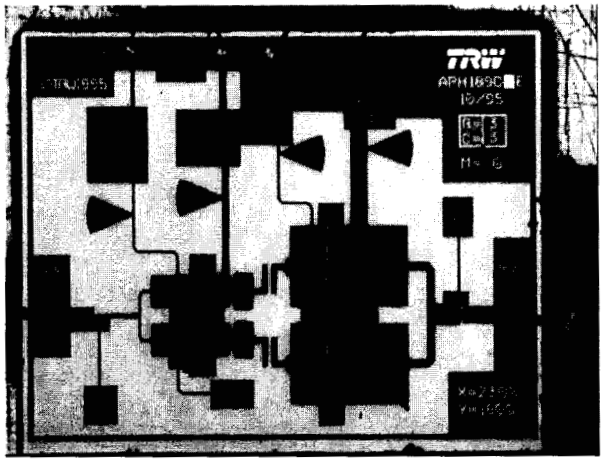
multiplied sources at 300 K

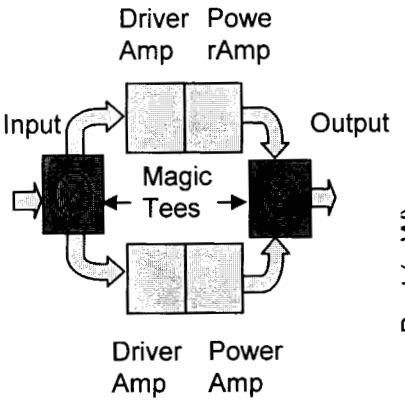


Progress due to:

- MMIC PA
- Modeling
- Machining
- Planar diodes

TRW MMIC PA Chip





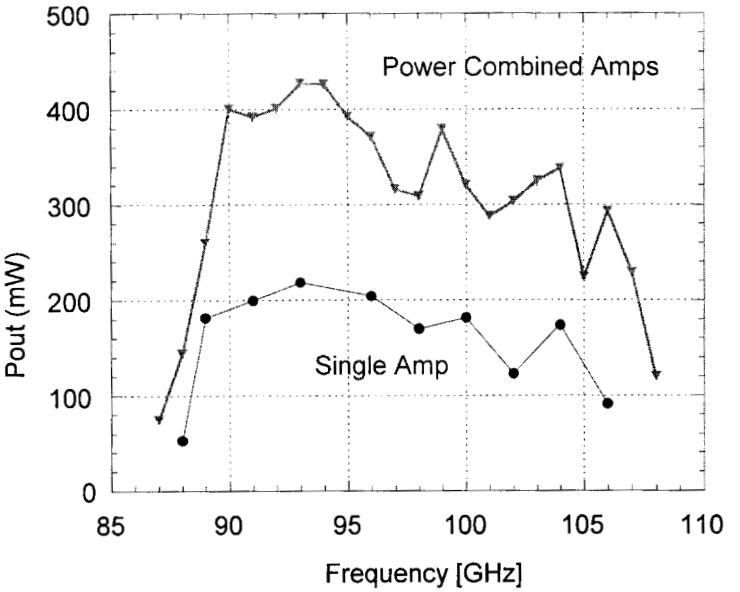
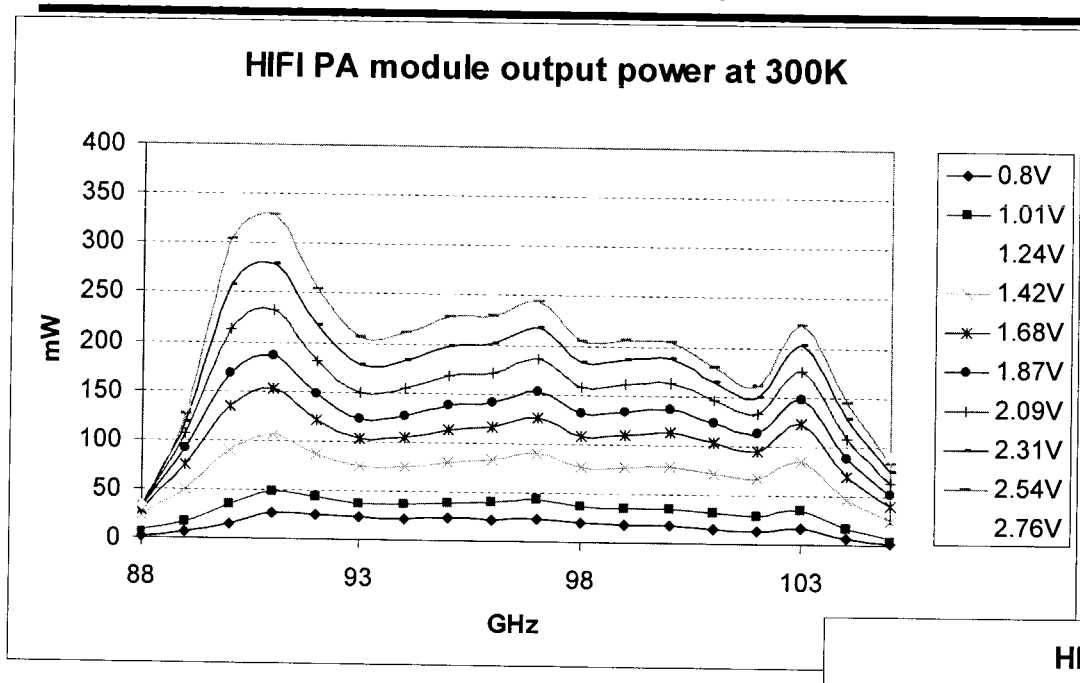


Figure 2. Power output from single and dual power combined packaged TRW MMIC amplifiers at W-band.

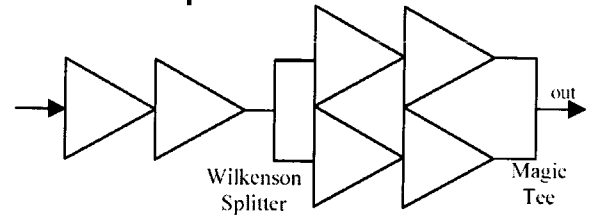
- 0.1 um PHEMT process
- 50 um thick substrate
- f_t = 200 GHz
- 64 finger device cell (output)
- on-chip bias network
- 50 ohm matching in/out
- 2.3 mm x 1.8 mm

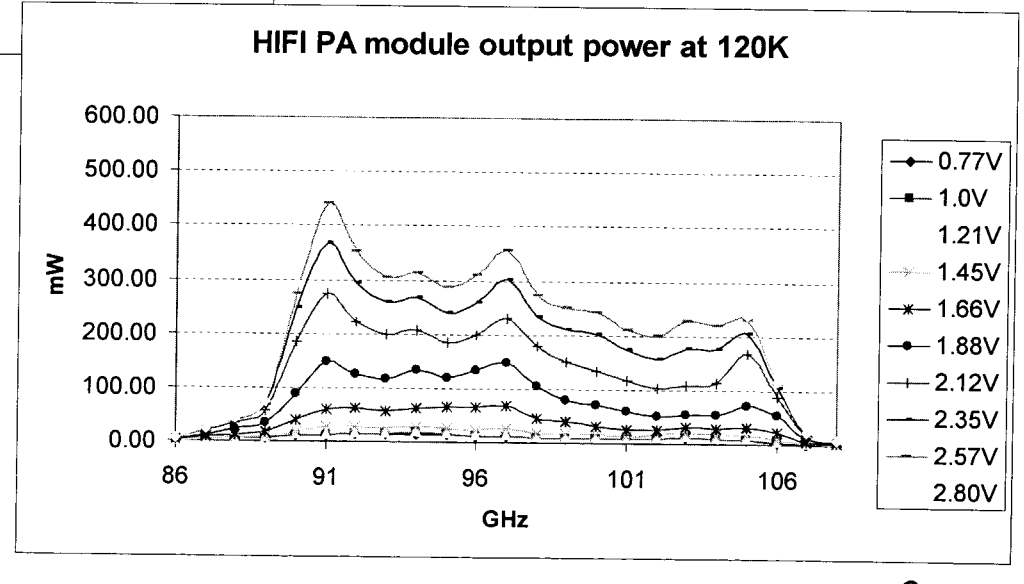
Ref: R. Lai et. al, "A high efficiency 0.15 um 2-mil thick InGaAs/AlGaAs/GaAs V-band power HEMT MMIC," IEEE GaAs IC Symposium Digest, Nov. 1996.
M. D. Biedenbender et al, "A 0.1 um W-band HEMT production process for high yield and high performance low noise and power MMIC's," 16th GaAs IC Symposium, 1994.

Power Amplifier Modules from heaven!



+0 dBm input



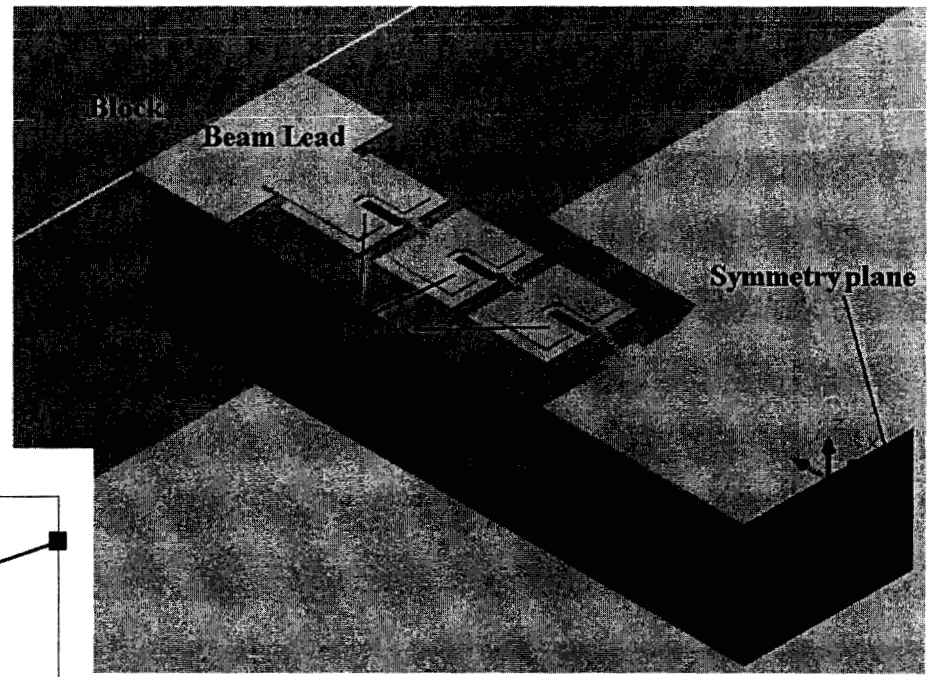


JPL Schottky Diode Model

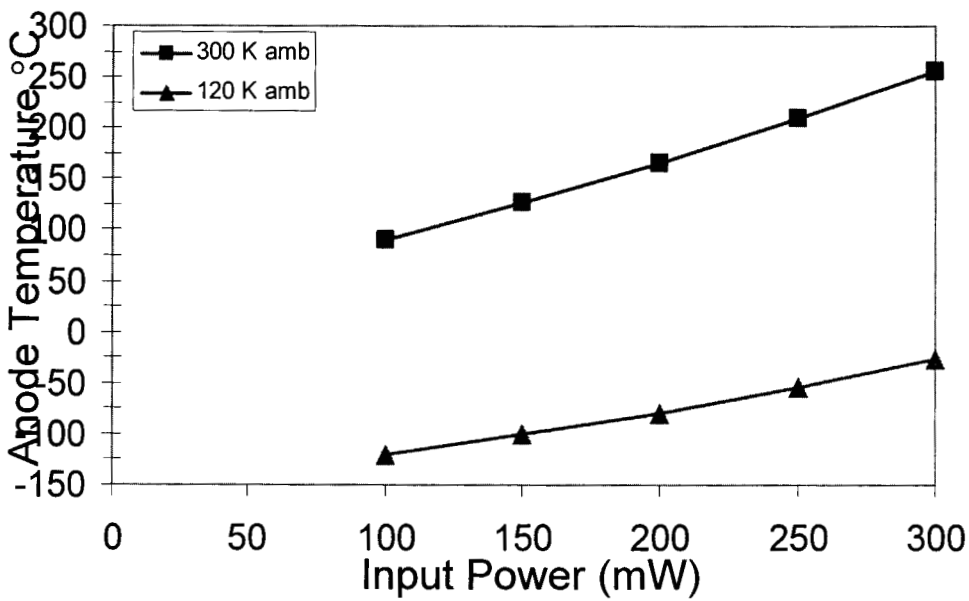
- Builds on work done by groups at University of Virginia, University of Michigan, Chalmers University, and Helsinki
- Model includes time-dependent velocity saturation, carrier inertia and shunt capacitance in the undepleted active layer, tunneling through the Schottky barrier and heating of the junction at high powers. The model is calibrated using ensemble Monte Carlo calculations of material parameters, but otherwise no parameters are fitted other than to DC I-V measurements
- Chip temperature and diode transport properties are solved iteratively
- Diode model for given input power and temperature is used in a harmonic balance technique

Thermal Modeling

$$T = T_{BLOCK} + R_{T1}P_{DISS} + R_{T2}P_{DISS}^2$$



Hottest anode temperature

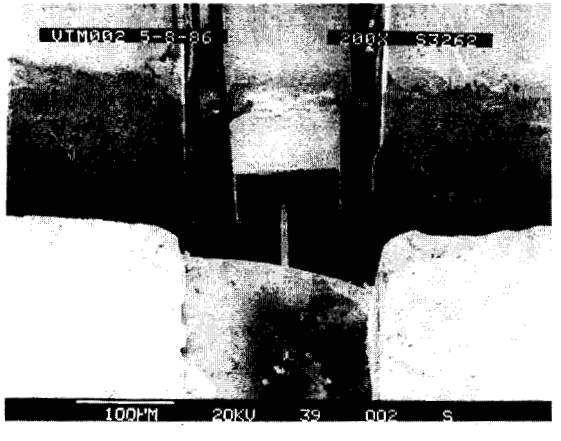


Modeled system has:

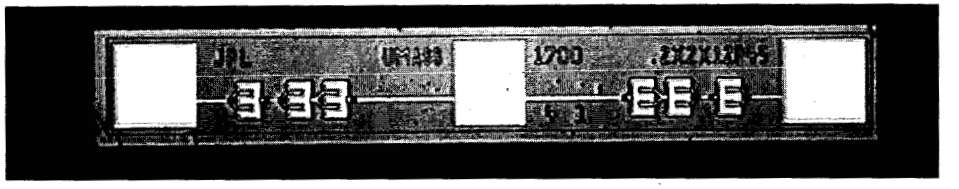
1. No convection, heat escapes through beam leads only.
2. Temperature dependent GaAs thermal conductivity.
3. Assumes dissipated power is 75% of input power

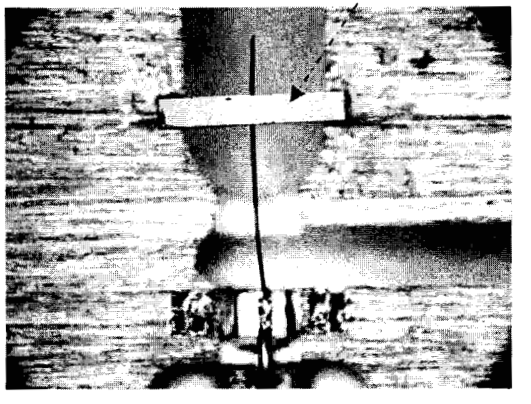
First generation discrete chips

Whisker contacted anode



6-anode 170 GHz chip





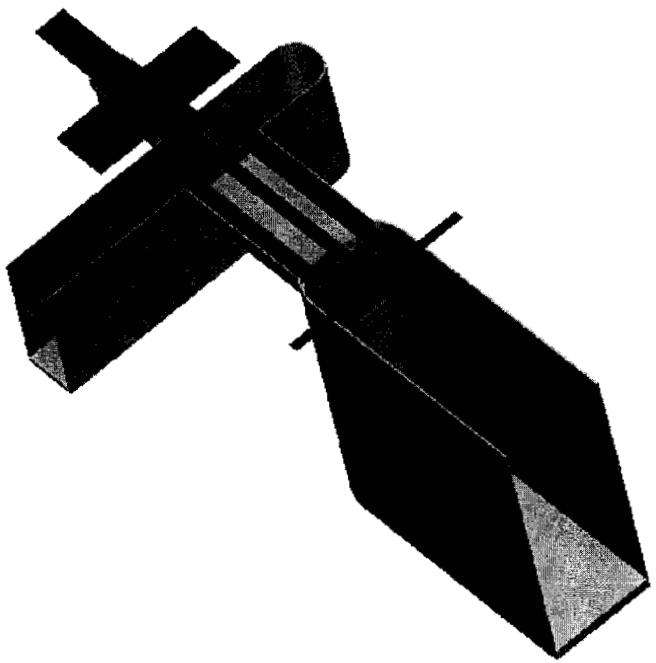
Performance at room temperature
(Erickson, STT 2000)
- Able to handle 220 mW of input power
- > 30% efficiency, 65 mW at 150 GHz

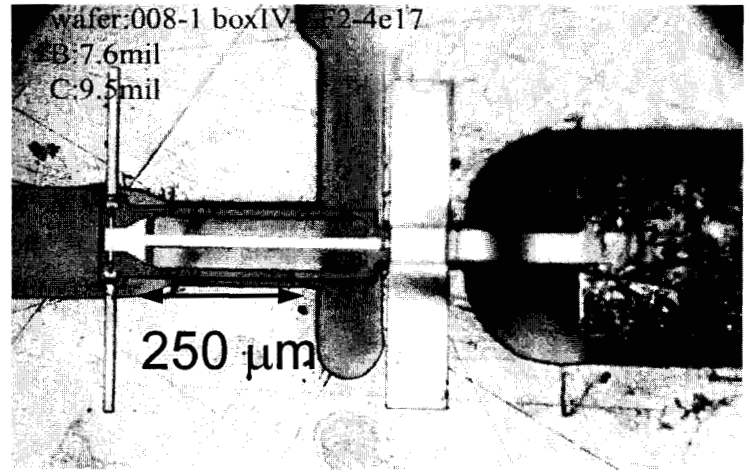
Q: Can this approach be extended in frequency?

Substrateless Technology

A: Yes—but it gets very difficult to implement

Solution: Integrate circuitry with device !





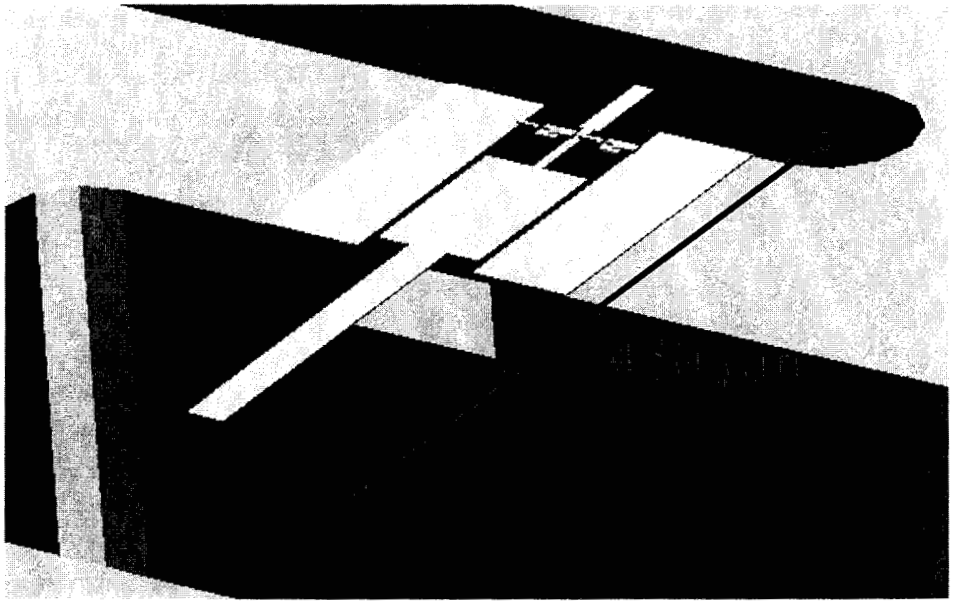
Frame ≈ 12 μm thick

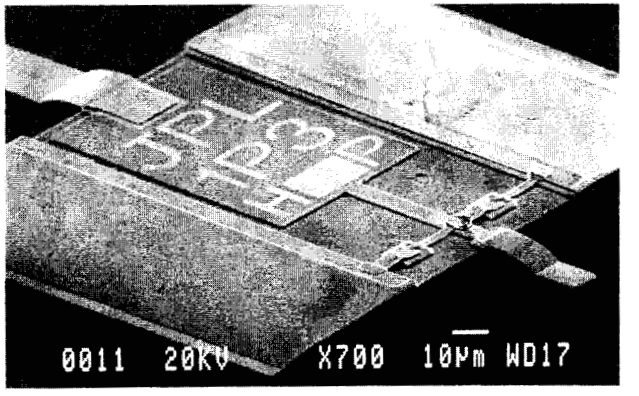
Q: Can this technology be scaled higher?

Devices beyond 1 THz

A: Yes—but GaAs thickness difficult to scale

Solution: remove most of the GaAs substrate→membrane devices





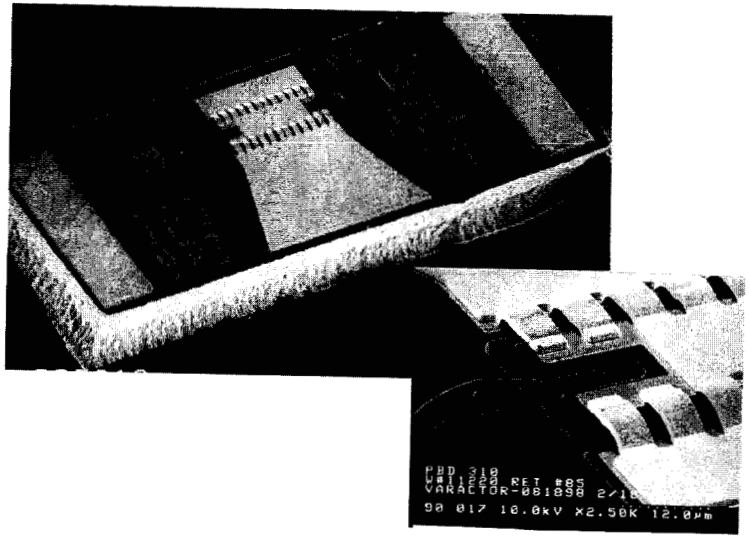
1200 GHz tripler chip

- Membrane is 3 microns thick
- Extensive use of beam-leads
- Extremely simplified assembly
- Bias less design

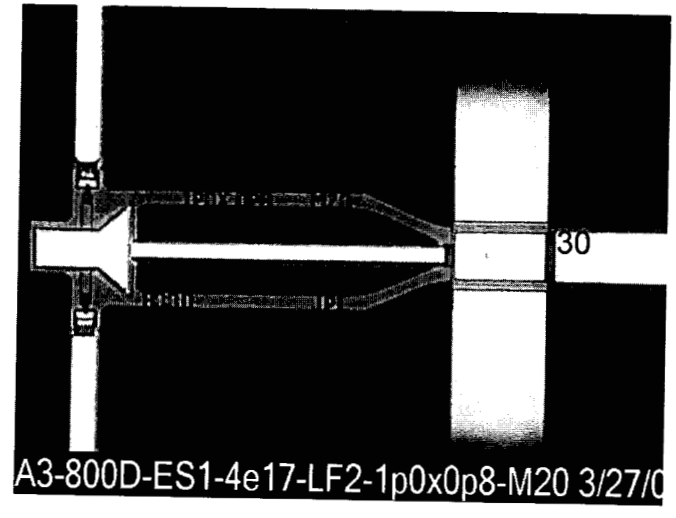
Q: Can this technology be scaled higher?

A: Demonstrated up to 2700 GHz!

Planar device alternatives

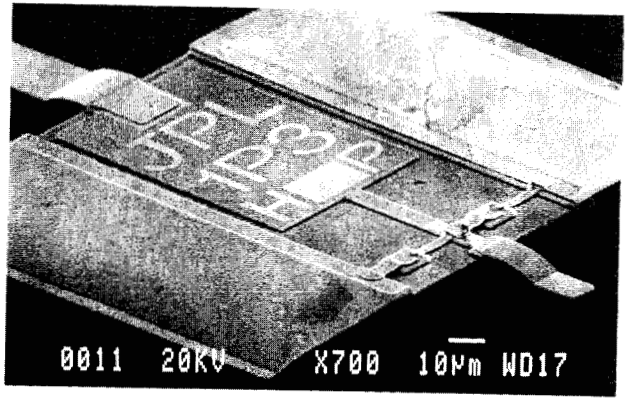


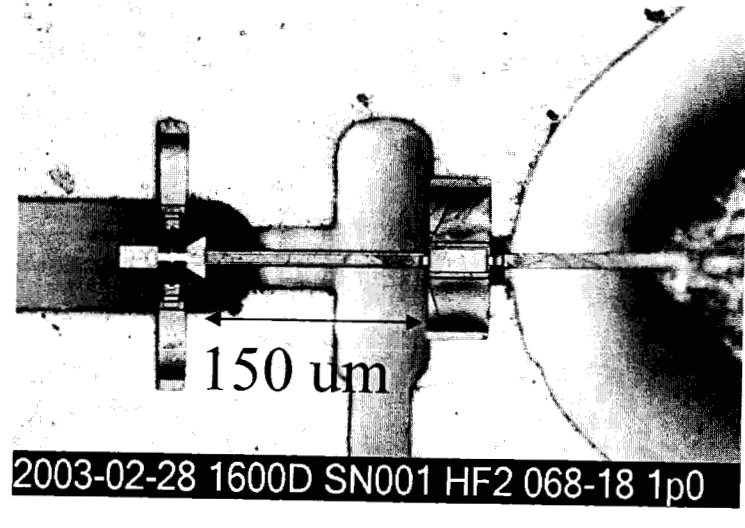
Discrete devices



Monolithic substrateless devices

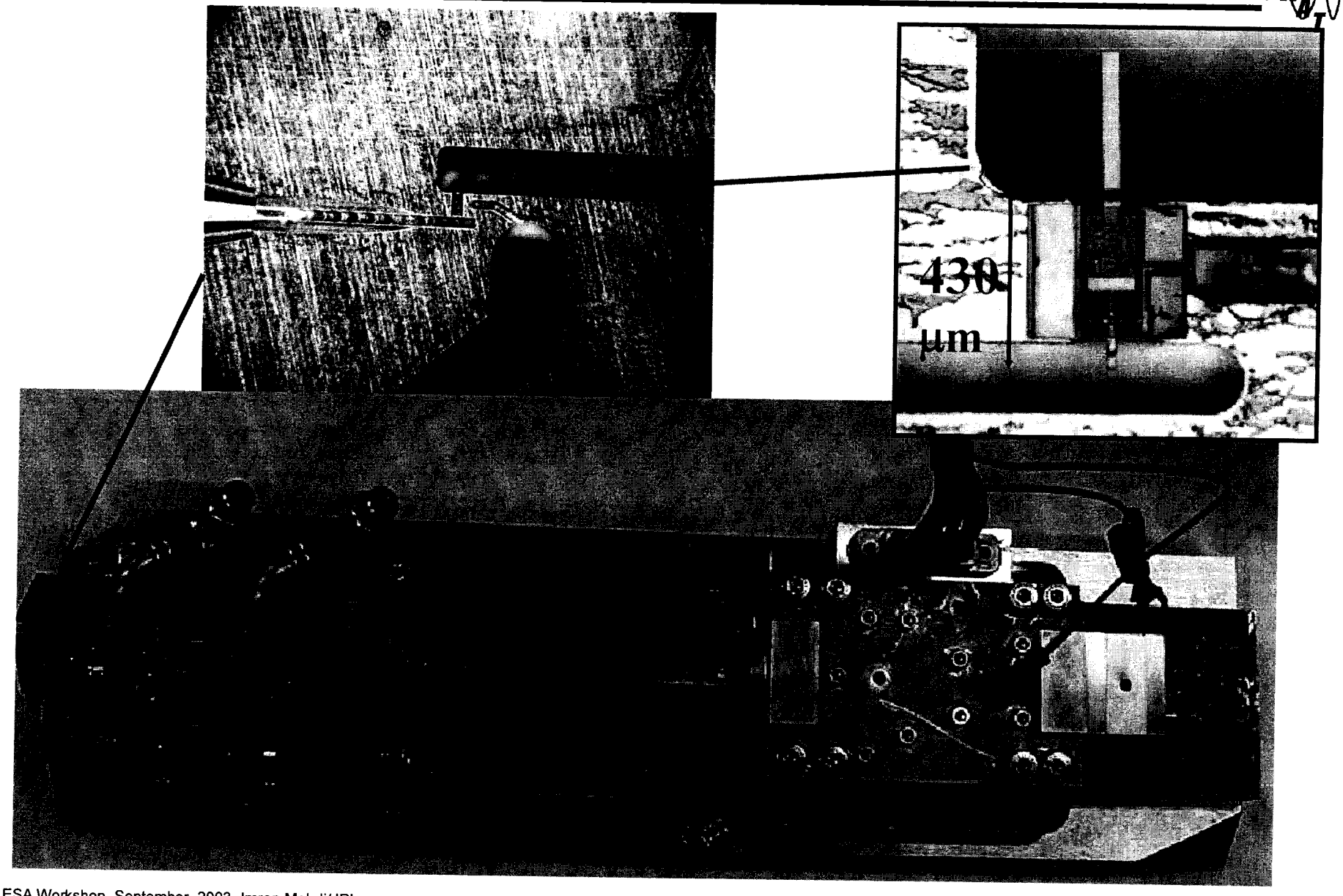
Frameless membrane devices



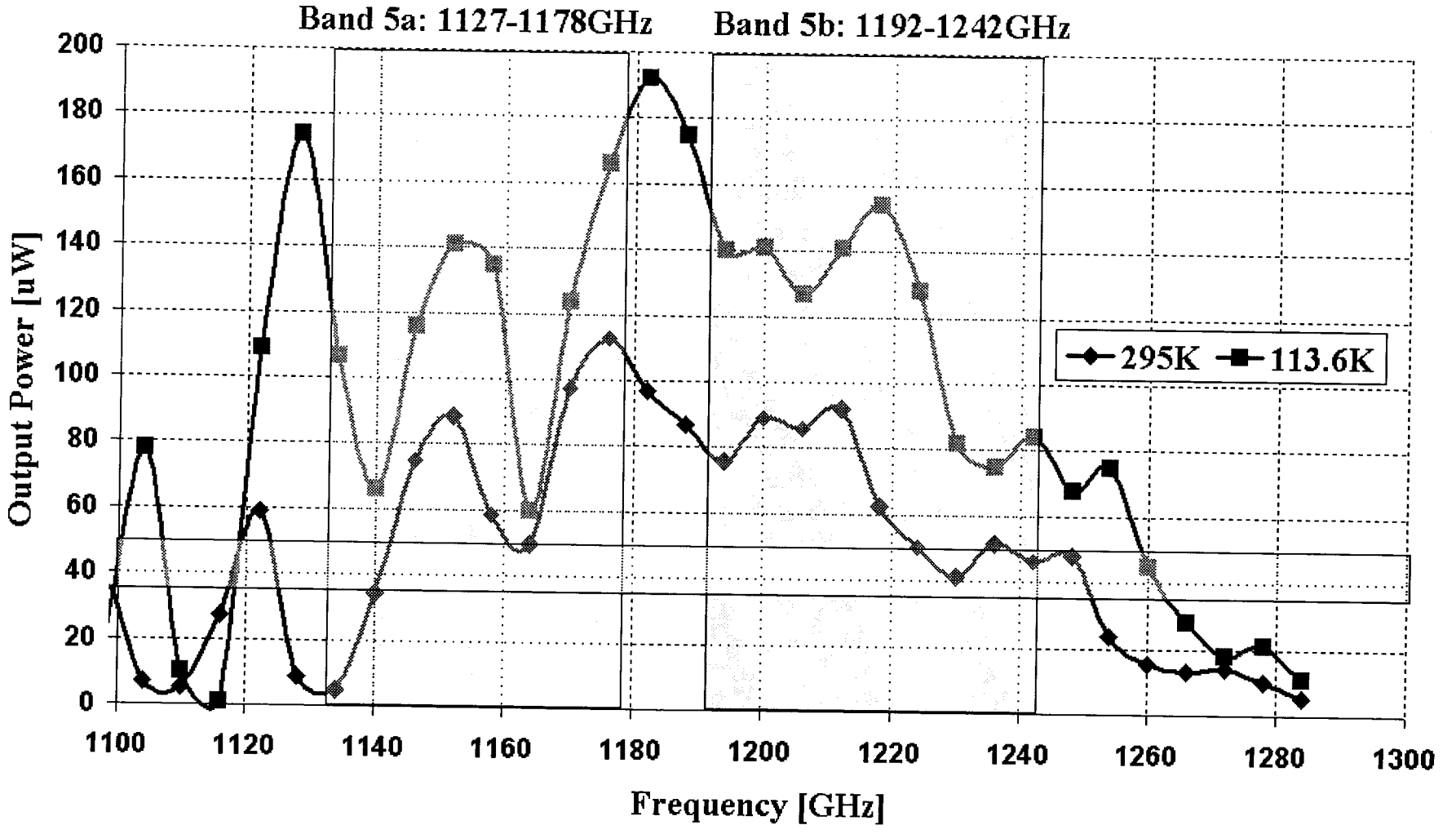


Frameless membrane based devices

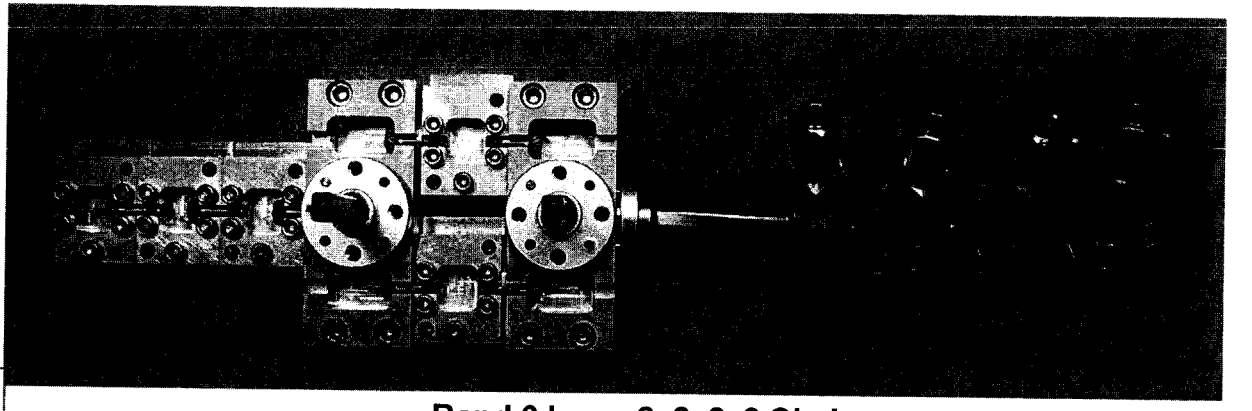
Planar LO chain at 1200 GHz

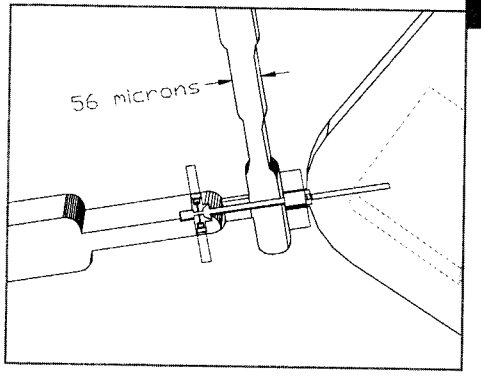


Broad Band Chain at 1200 GHz



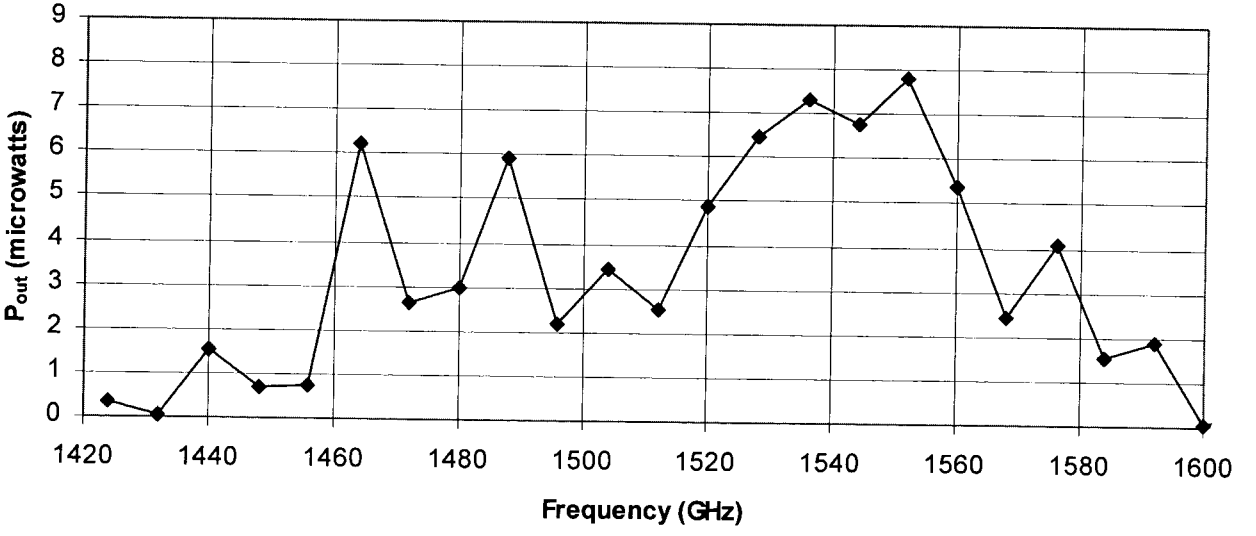
1600 GHz chain (x2x2x2x2)



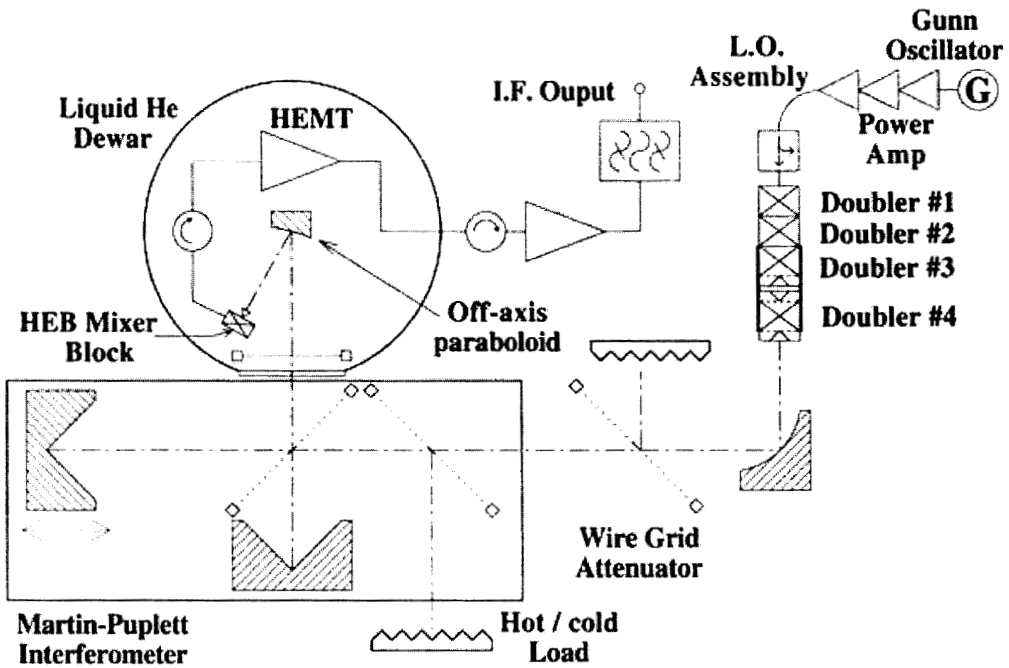


Band 6 Low x2x2x2x2 Chain

295 K, 150 mW input power - February 28, 2003

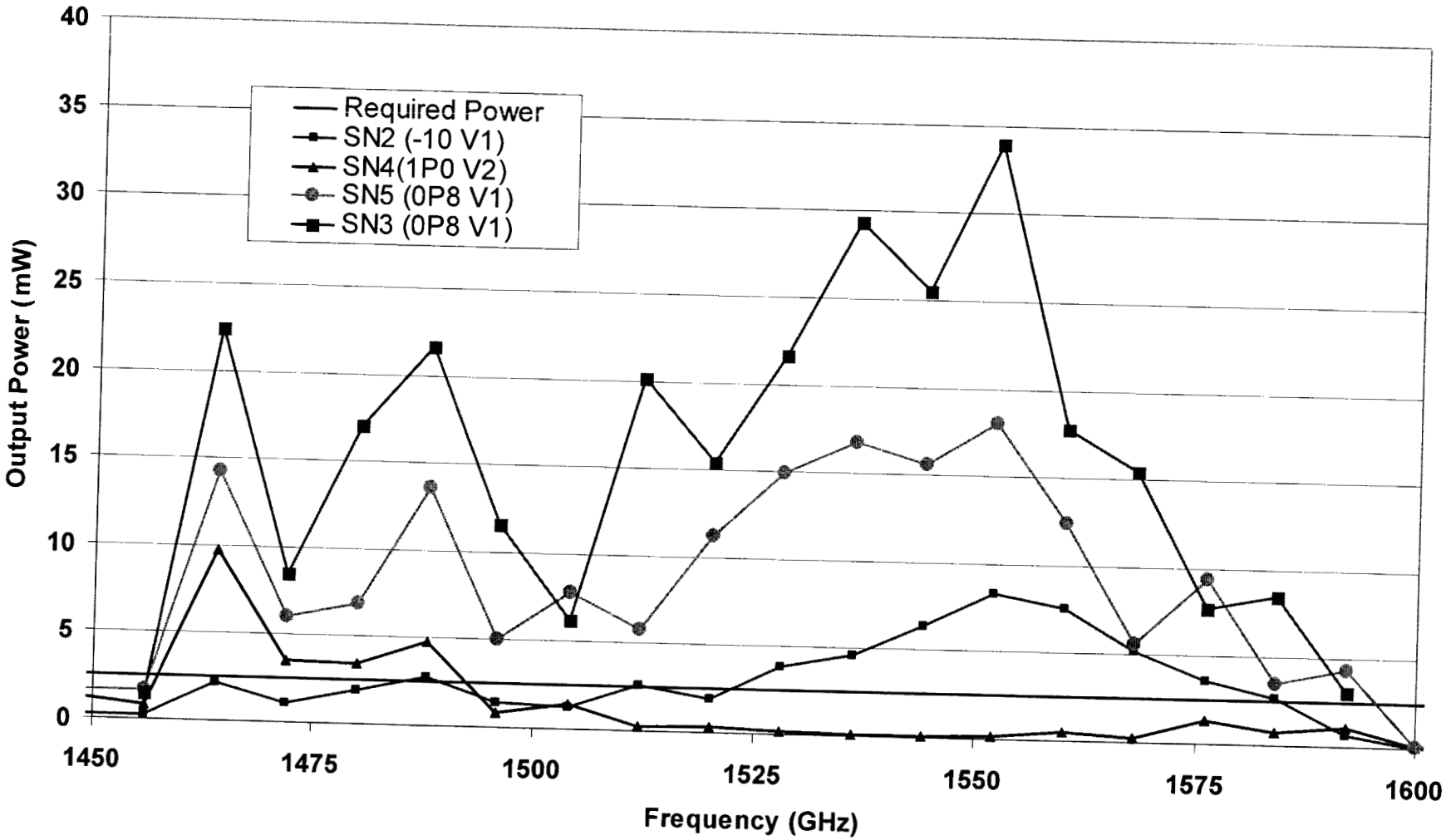


Can we pump HEBs? (courtesy E. Tong, J. Kawamura et al)

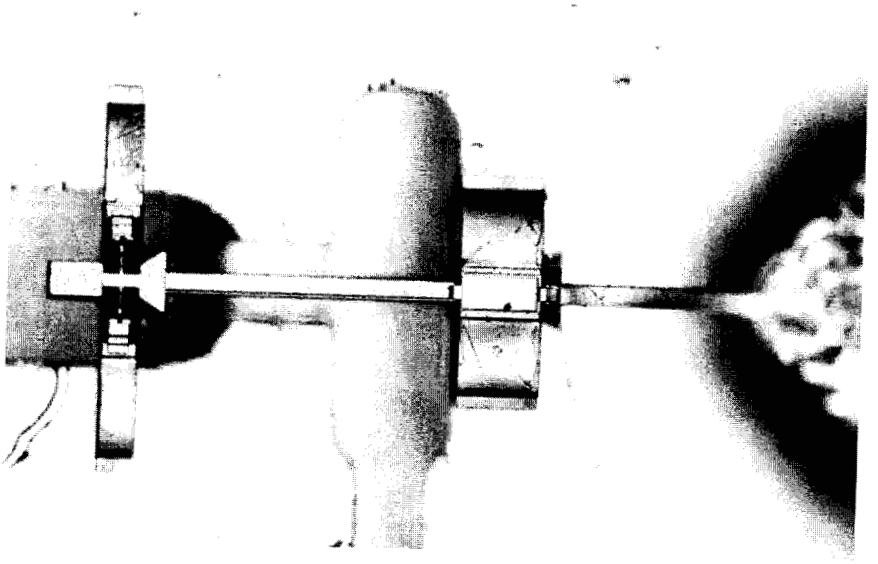


- NbN devices, 1.45 to 1.55 THz
- Threshold power ~ 1 uW (measured with Calorimeter)
- Tr~1460K @ 1.476 THz (IF was 3 GHz)
- LO coupling efficiency ~ 70%
- Isotherm model predicts 70nW at device (120 nW after correction)

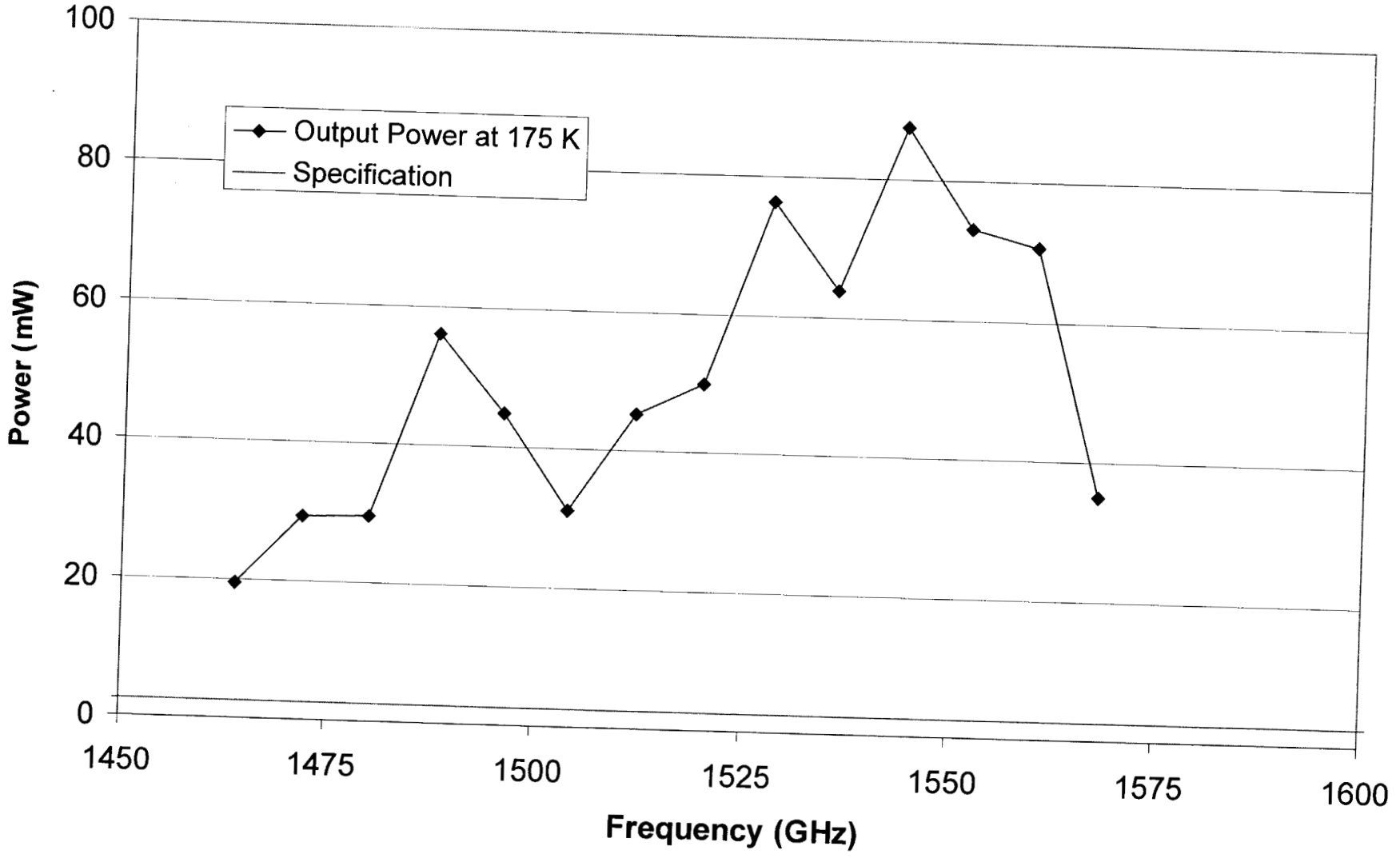
1500 GHz Results (295 K)



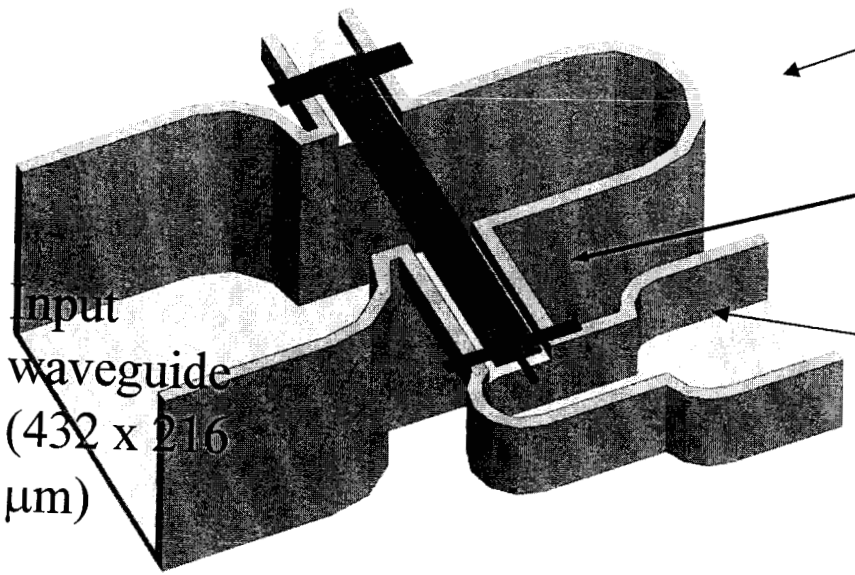
JPL 1500 GHz Doubler



1500 GHz Results (175 K)



1.9 THz Balanced Tripler

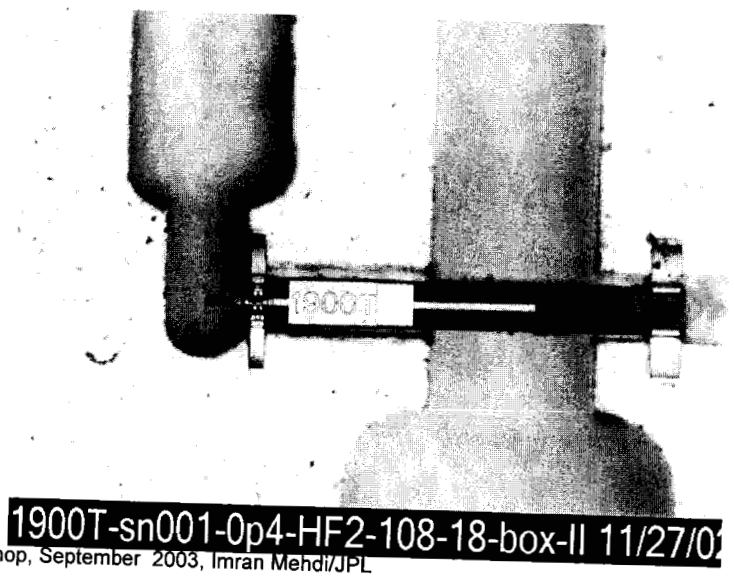


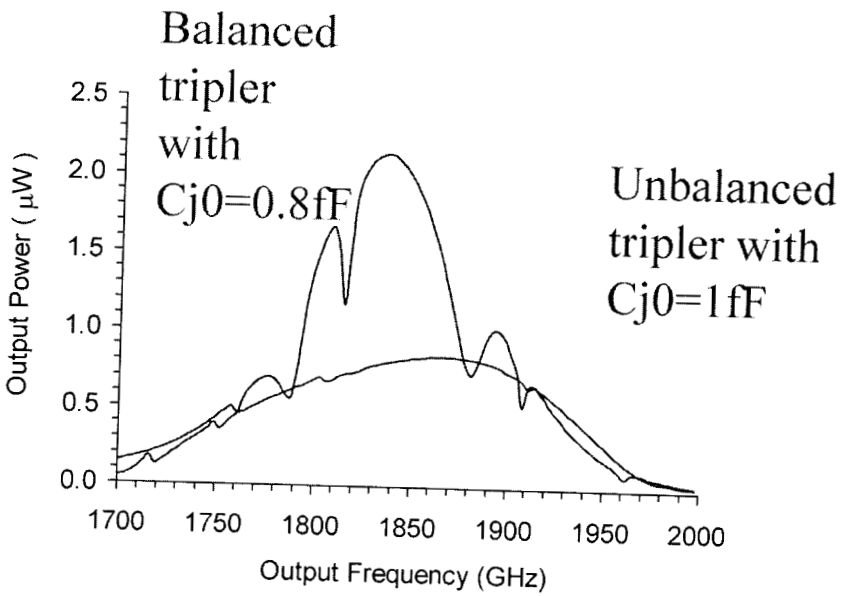
Reduced height waveguide (432 x 108 μm)

Chip channel (46 x 25 μm)

Input waveguide (432 x 216 μm)

Output waveguide (106 x 106 μm)

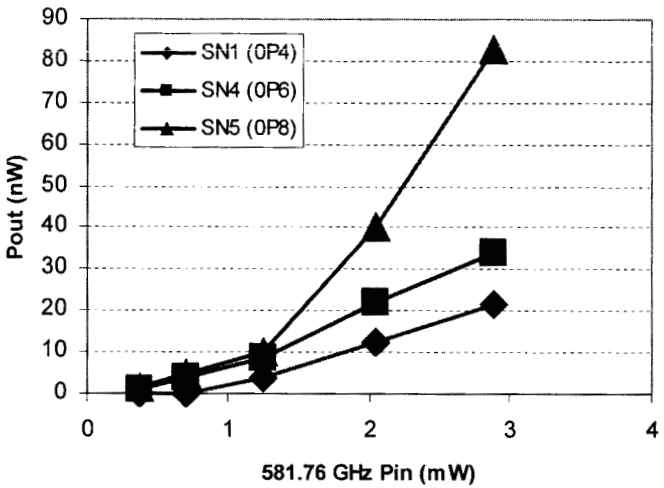




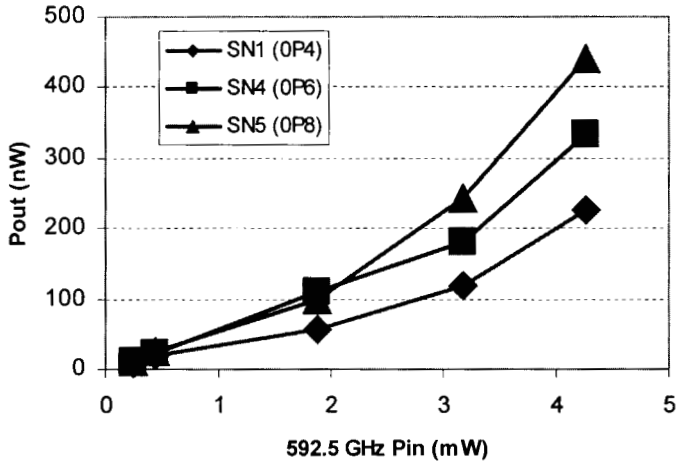
Input power = 2.5 mW

1.9THz Tripler w/ BWO Results

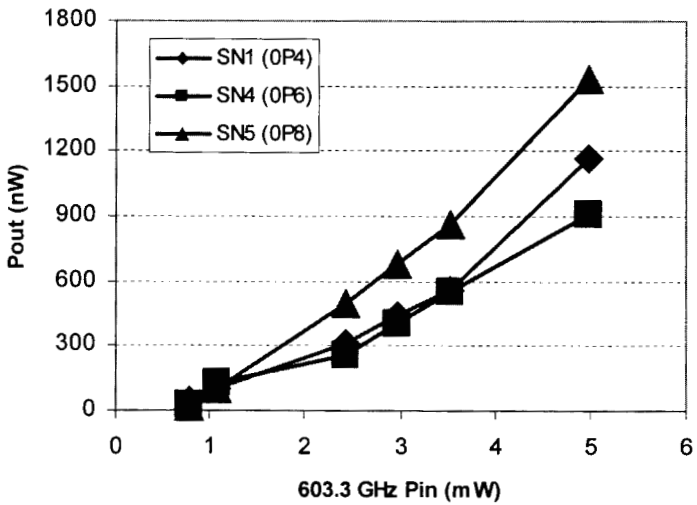
1745.3 GHz Power Sweeps



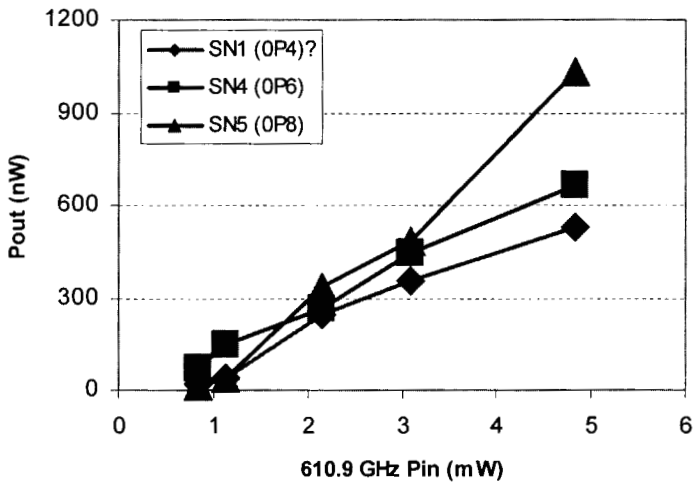
1777.5 GHz Power Sweeps



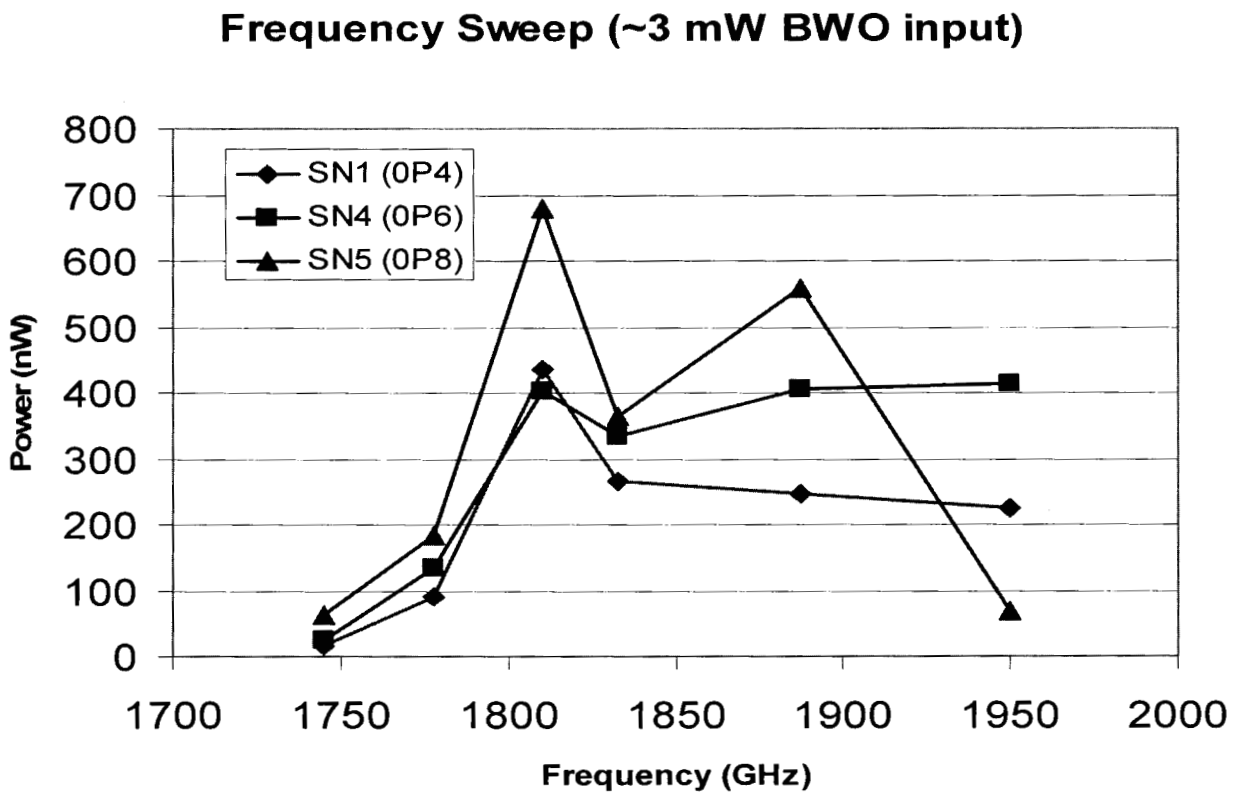
1810 GHz Power Sweeps



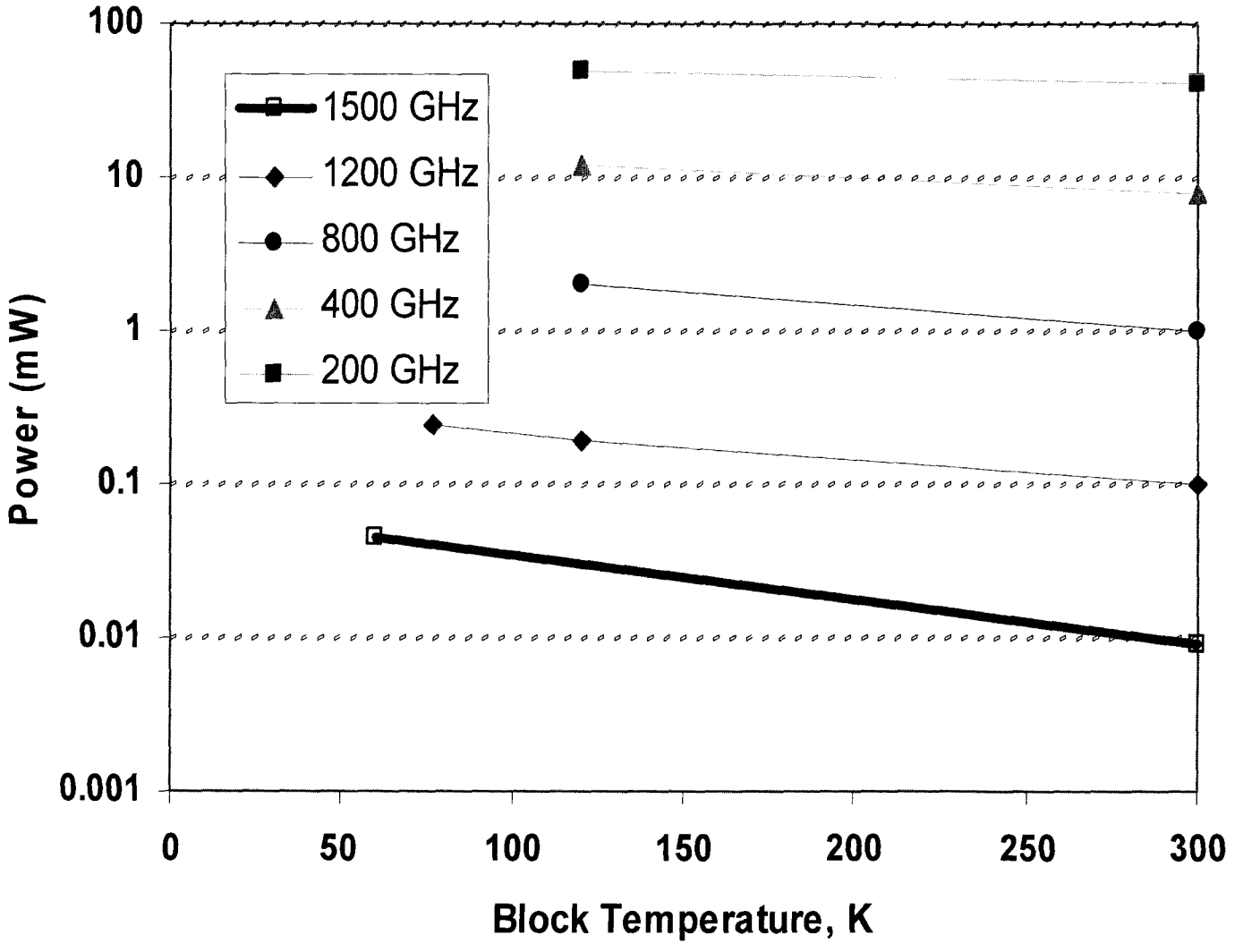
1832.8 GHz Power Sweeps



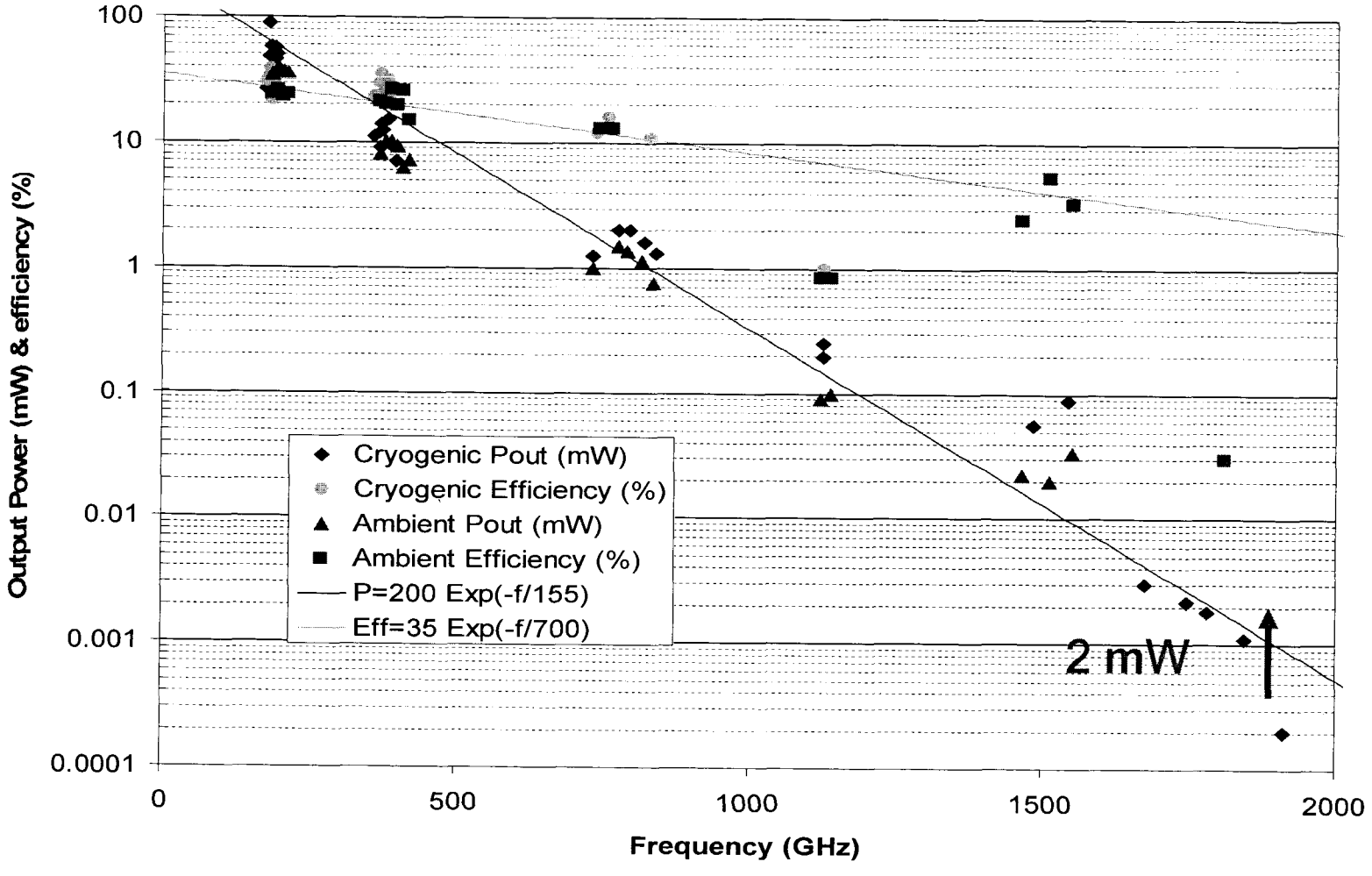
1900T Frequency sweep (RT)



Output Power vs Block Temperature



The State of the Art



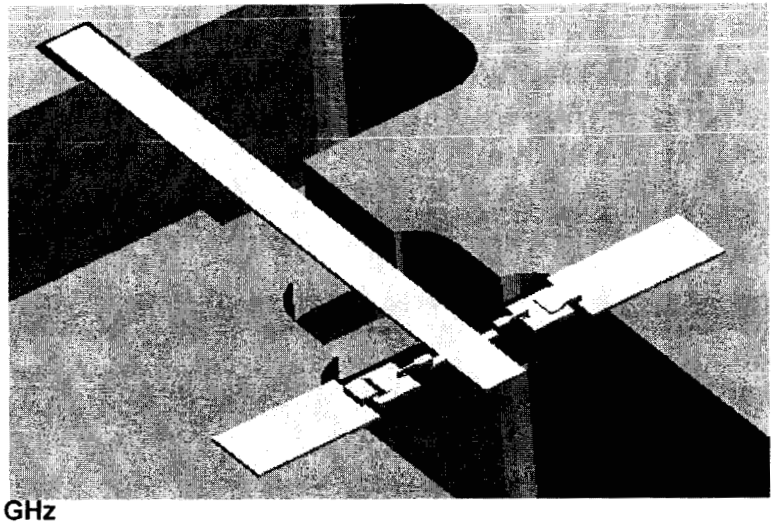
Note: Includes points from Band 5 (~1120) & UMass (~1800 GHz)

Other Challenges

- More efficient higher freq power amps? InP, pHEMT
- Improve bandwidth—better designs, re-configurable
- Simplify chain construction—micro-machined blocks, increased integration
- Planar device/modeling—increase yield, increase throughput and uniformity, reduce time to completion

Challenge: increase output frequency

Planar Diode properties:
Membrane thickness: 3 micron
doping: 5×10^{17} cm^{-3}
Anode dimensions: 0.14 x 0.6 um



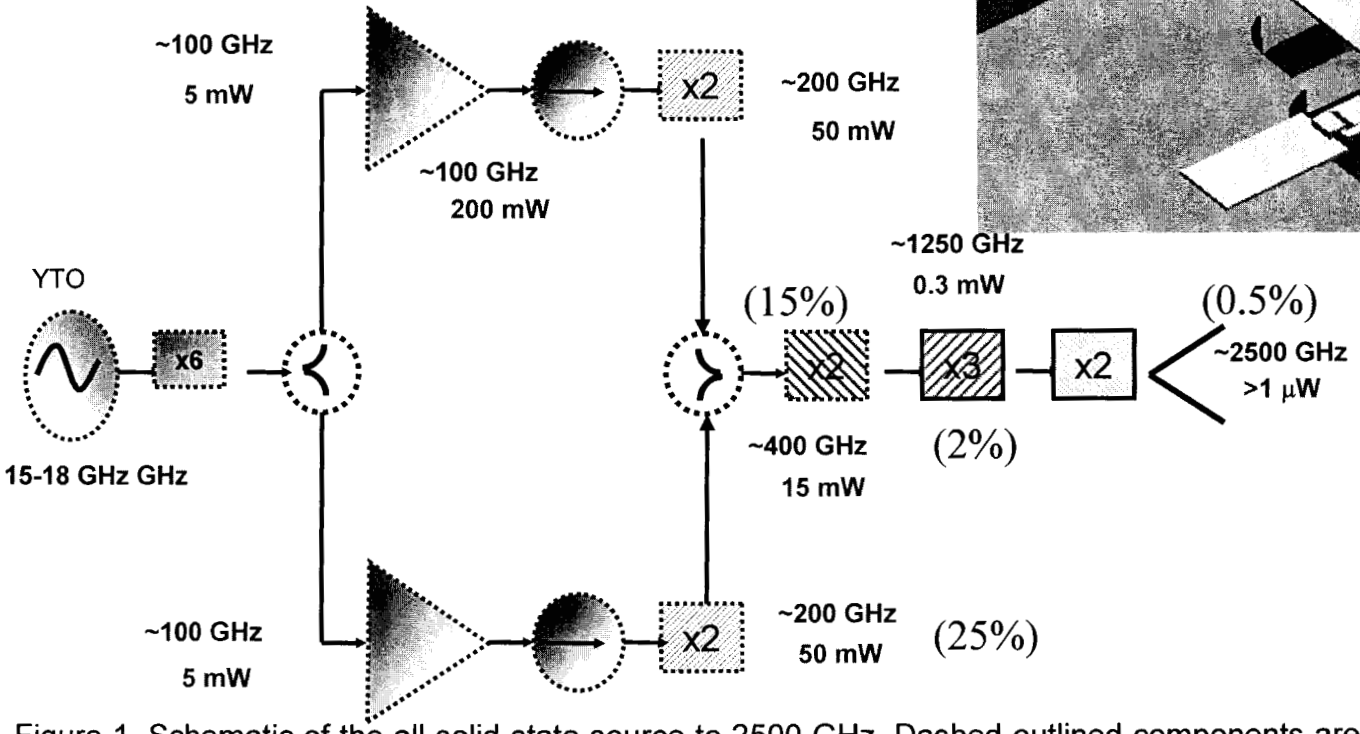
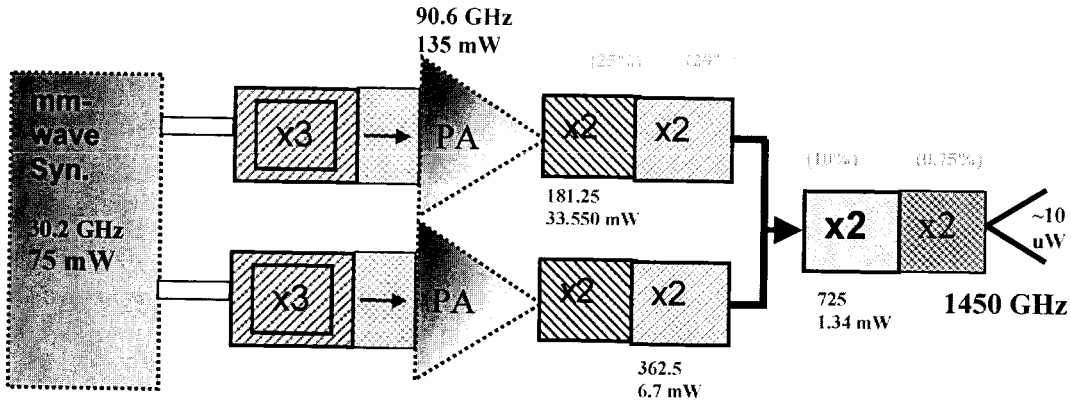
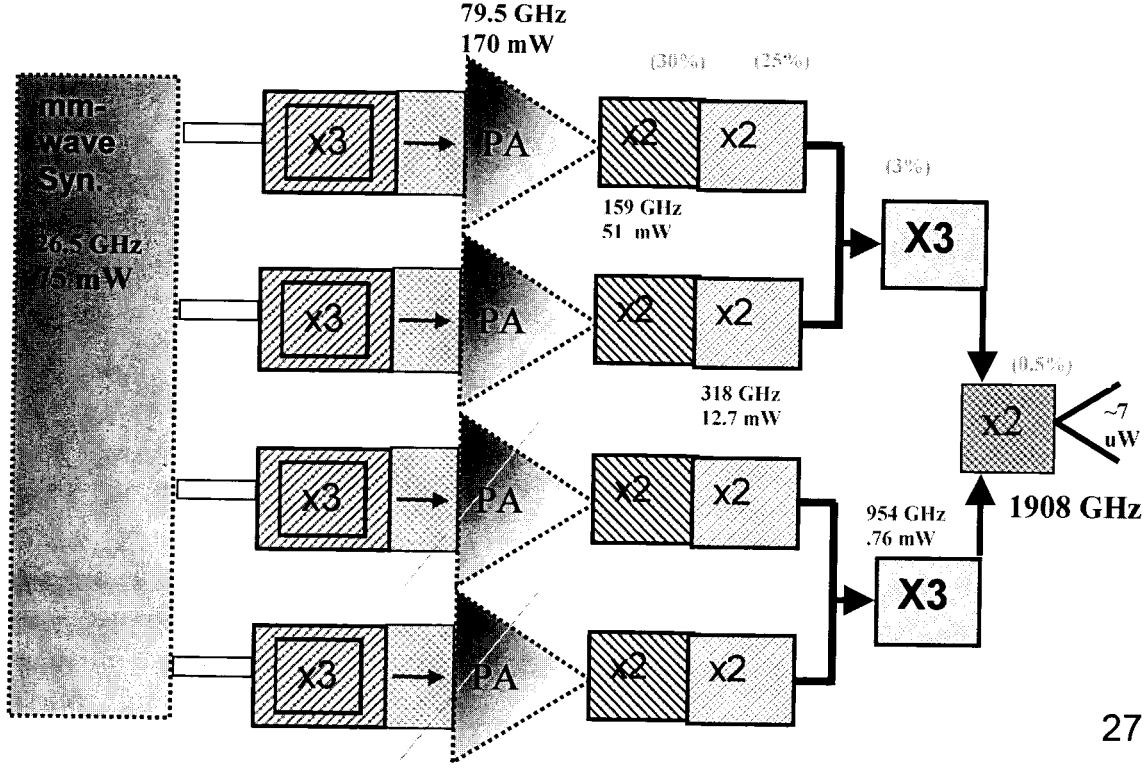


Figure 1. Schematic of the all-solid-state source to 2500 GHz. Dashed outlined components are either commercially available or have already been demonstrated in our laboratory. Solid outlined components are to be developed under this proposal.

Challenge: Increase output power?

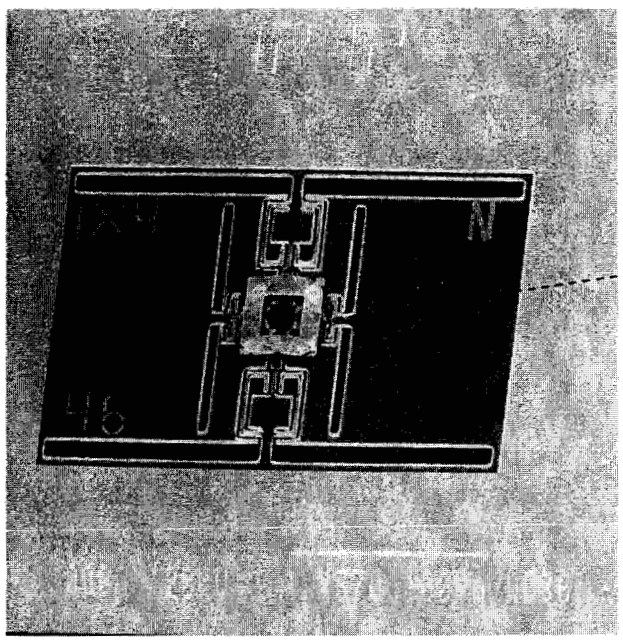


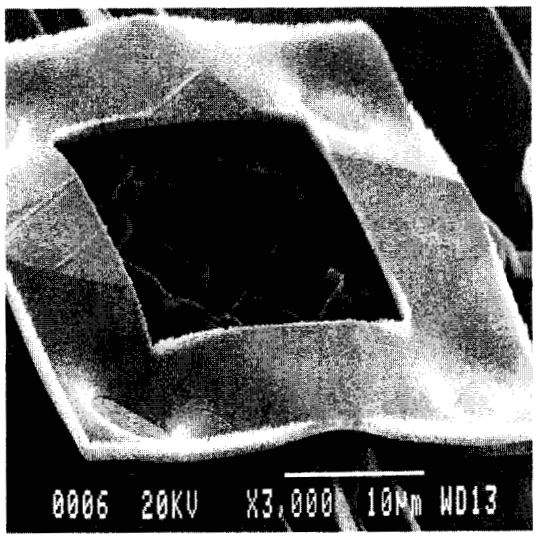


Challenge: multipixel receivers

- To increase output power
- Multiple frequency coverage
- Multiple pixel coverage

Components available, architecture, system issues need to be studied





Kim et al
1 mW at 600 GHz

Concluding Remarks

- Multiplier chains (200 to 1200 GHz) are now possible that are
  - Robust
  - Broadband (5 to 10 %)
  - Cool-able
  - Sufficient to pump SIS and HEBs
- Chains in the 1.2 to 1.9 THz range are being developed
- Frequency range of 2-3 THz is attainable
- Wider bandwidths (>10%) are attainable
- Higher output power is possible with power combining techniques

Acknowledgments

- Many thanks to colleagues at JPL (past and present) who have made the current progress possible:
  - Dr. Lorene Samoska, Dr. Peter Siegel, Dave Pukala, Dr. Frank Maiwald, Dr. John Ward, Dr. John Pearson, Robert Lin, Ray Tsang, Alex Peralta, Suzi Martin, John Gill, Dr. Peter Smith, Dr. Alain Maestrini, Dr. Jean Bruston, Peter Bruneau
- Much of the progress is also due to the pioneering work by the following:
  - Dr. Neal Erickson (University of Massachusetts)
  - Dr. Jack East (University of Michigan)
  - Dr. Tom Crowe (University of Virginia)
  - Dr. Peter Zimmermann, et al (Radiometer Physics, GmbH)

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THz Power Measurement

- Several power meter technologies available
  - Golay cell, Keating meter, Erickson calorimeter, Bolometer
- Each meter brings specific calibration challenges
  - Impedance mismatch / standing waves
  - Waveguide losses
  - Optical losses / coupling
  - Atmospheric absorption
  - Drift
  - Sensitivity
  - Maximum power limits
- Factor of 2 discrepancies are common
- Agreement to 30% may be possible with care

➔ The ultimate figure of merit is to pump a mixer.
See Jon Kawamura's talk Thursday for pumped mixer results.