Multiplier LOs and associated technology

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Acknowledgments

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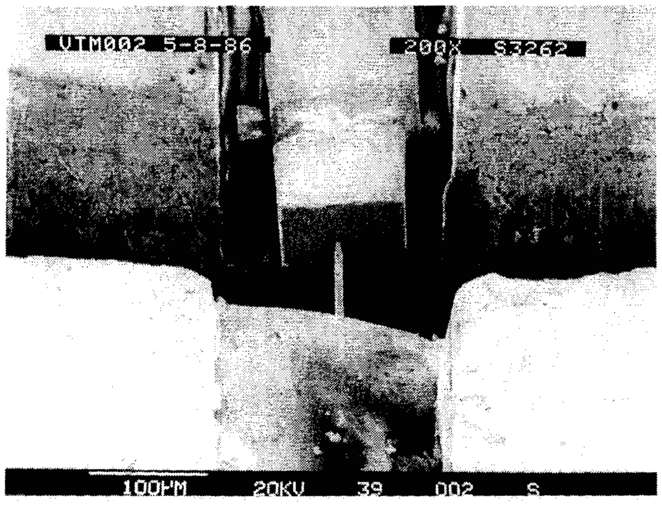
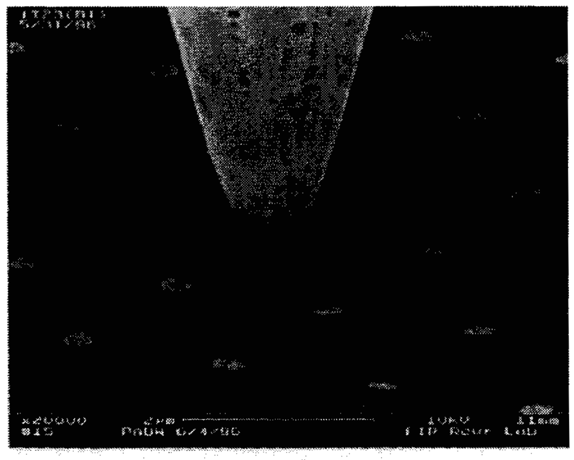
Outline

- Introduction
- Status of THz multiplier sources
- Challenges for next generation multiplier sources
- Concluding remarks

Introduction

- Traditional space borne submillimeter-wave sources
  - Gunn diode + whisker contacted Schottky diode multipliers
- Currently most of the ground and non-ground based heterodyne receivers utilize this technology
- Gunn/transit-time devices
  - 100 GHz InP Gunn, 200 mW (Eisele, UMich)
  - 3.5 mW at 200 GHz, 1 mW at 300 GHz
- Whisker contacted varactors
  - BWO+tripler, 15 **m**W at 1500 GHz (RPGmbH)
  - Gunn+tripler+tripler, 50 **m**W at 1000 GHz





Introduction

- Limitations of Gunn diodes plus whisker contacts
  - Instantaneous bandwidth of Gunn/transit-time devices is limited
  - Power combining is difficult
  - Whisker contacted diodes are extremely difficult to assemble
  - multiple diode configurations are not readily possible
  - complicated phase lock loops are required for frequency stability
  - Commercial viability of Gunn diodes is uncertain
  - Cryogenic operation is risky (thermal cycling specifically)

Multipliers for Space

- Applications
  - Astrophysics--origin of universe, star formation, ...
  - Remote sensing--atmospheric analysis, planetary investigations
- Requirements
  - Performance--high efficiency, bandwidth, stability
  - Milliwatt's of power is required for Schottky diode mixers, 10's of microwatts for SIS mixers, and a couple of microwatts for HEB mixers
  - Mechanical--stability, compact, low mass, thermal viability
  - Environmental--radiation, vibration, thermal

Impetus for recent development

Herschel Space Observatory

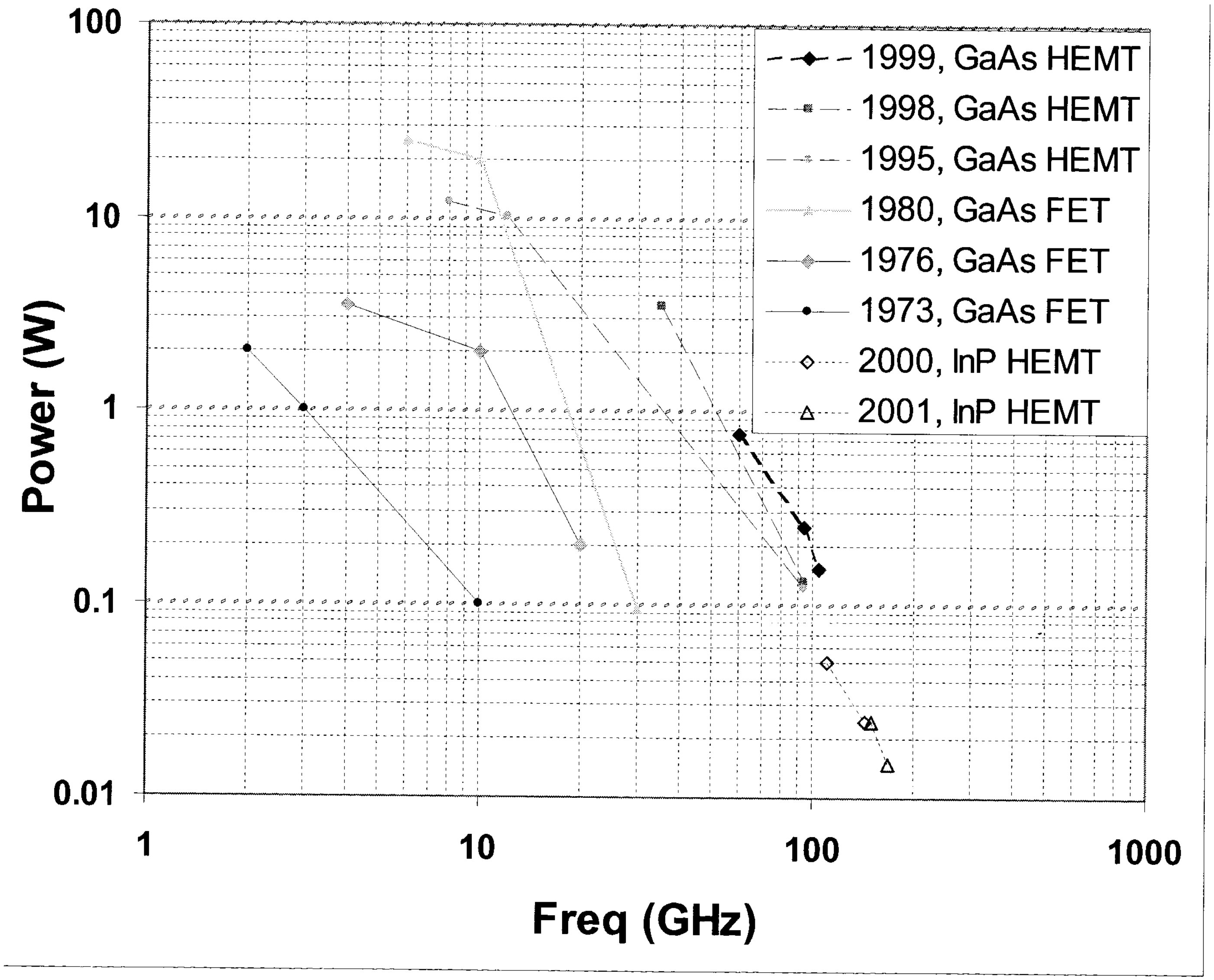
ESA/NASA mission, Launch date: Fall of 2007

Requires local oscillator sources from 400 to 1900 GHz

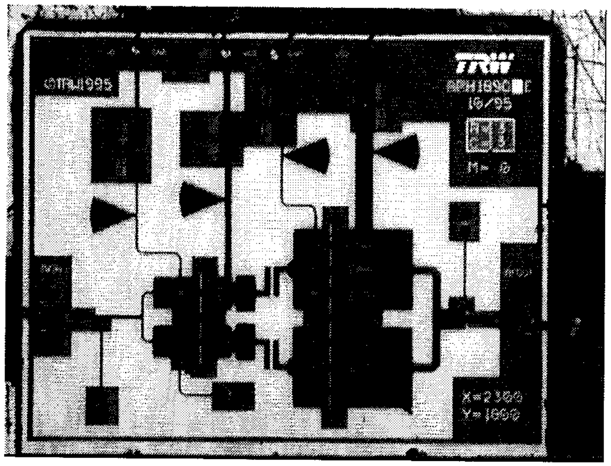
To satisfy HSO needs one must develop:

- Wide band, high input power at 100 GHz
- Balanced, multiple diode designs
- Fully integrated chips
- Waveguide based circuits
- Cryogenic (120 K) operation

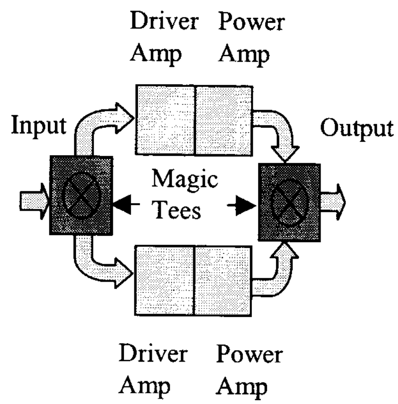
Available Power (PA)



TRW MMIC PA Chip



- 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



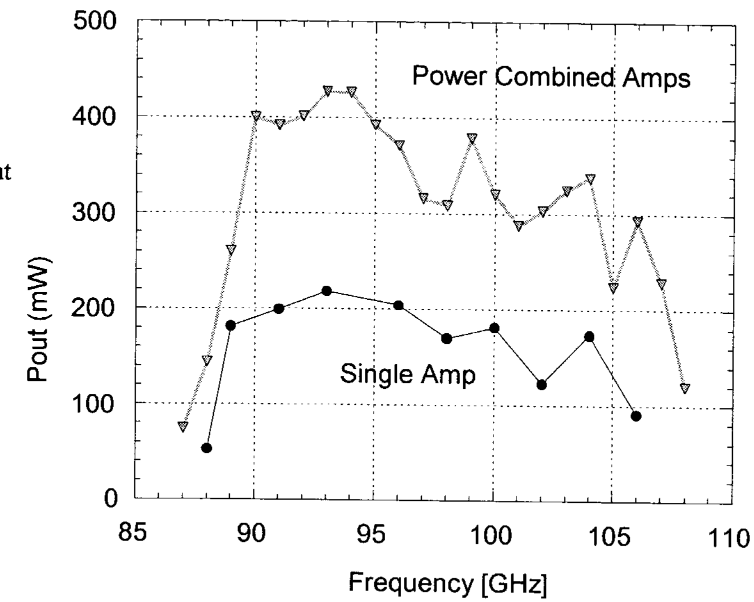
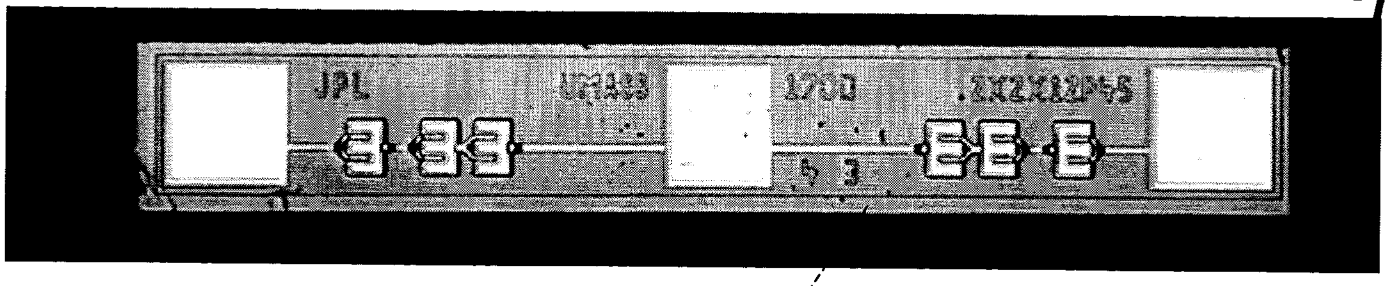


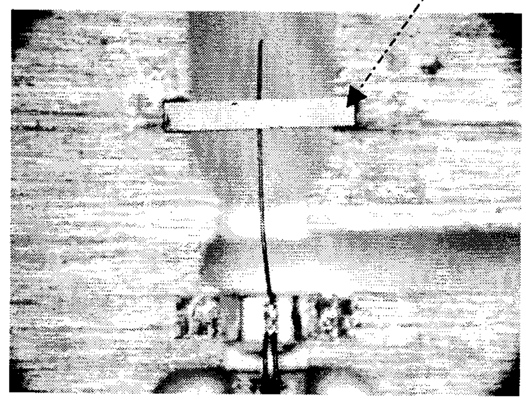
Figure 2. Power output from single and dual power combined packaged TRW MMIC amplifiers at W-band.

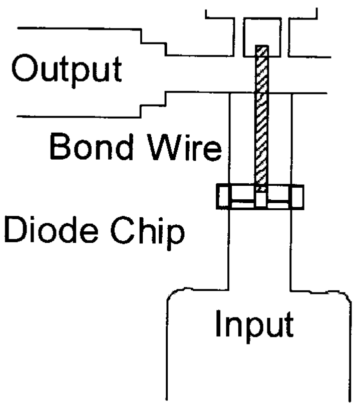
Ref: R. Lai et. al, "A high efficiency 0.15 um 2-mil thick InGaAs/AlGaAs/GaAs V-band power HEMT MMIC," IEEE GaAs IC Symposium Digest, Nov. 1996.
M. D. Biedenbender et al, "A 0.1 um W-band HEMT production process for high yield and high performance low noise and power MMIC's," 16th GaAs IC Symposium,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

1st Multiplier stage, Discrete Chips

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

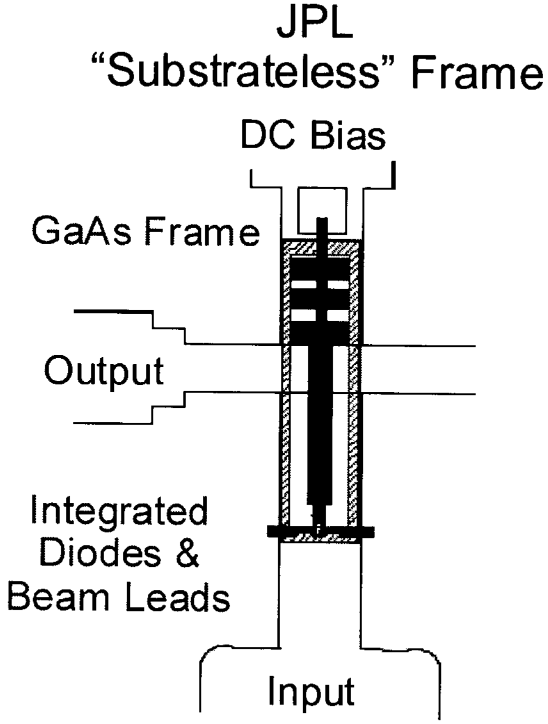
- Chip soldered to block
- Bondwire connects chip to DC Bias Cap

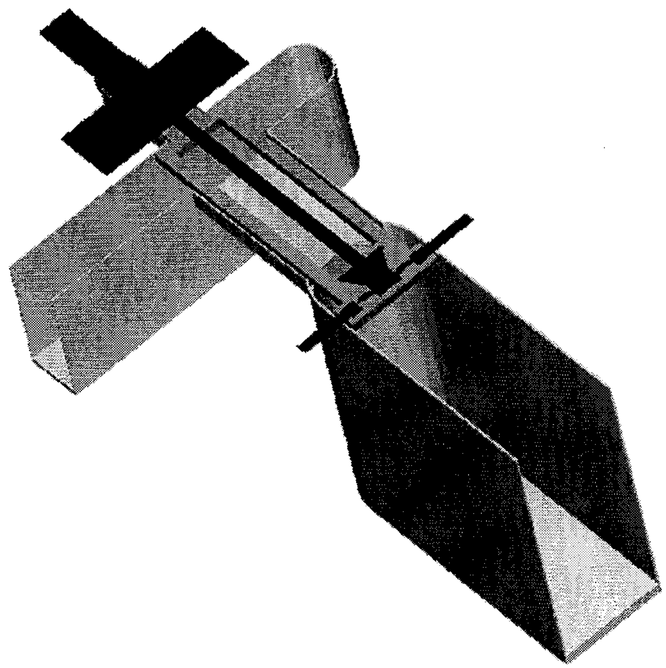
Q: Can this approach be extended in frequency?

2nd stage multiplier

A: Yes—but it gets very difficult to implement

Solution: Integrate circuitry with device !





- All chip connections to block made with beam leads
- Diodes integrated into circuit
- GaAs under metal removed for low loss

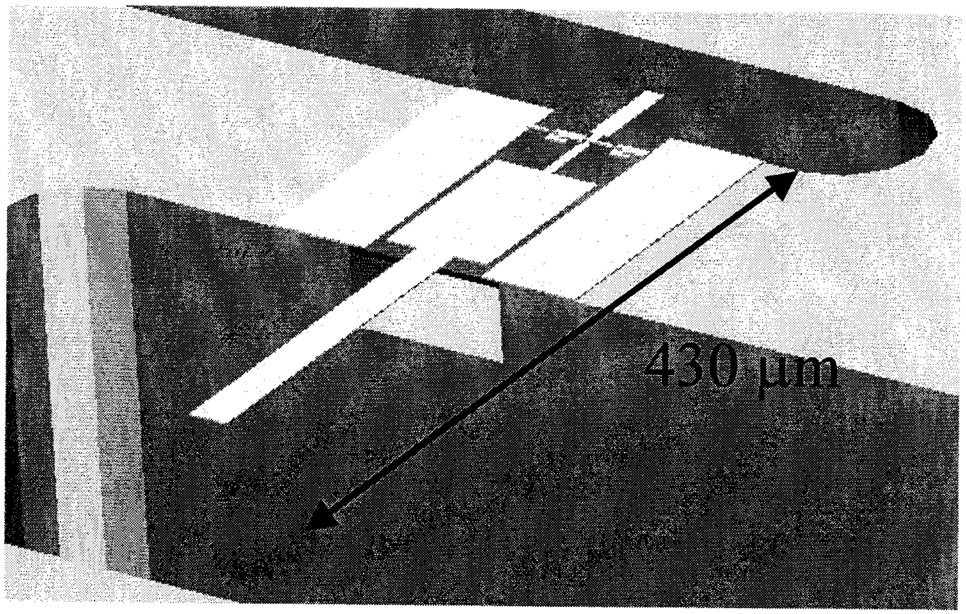
Q: Can this technology be scaled higher?

Devices beyond 1 THz

A: Yes—but GaAs thickness difficult to scale

Solution: remove all of the GaAs substrate !

Membrane Devices

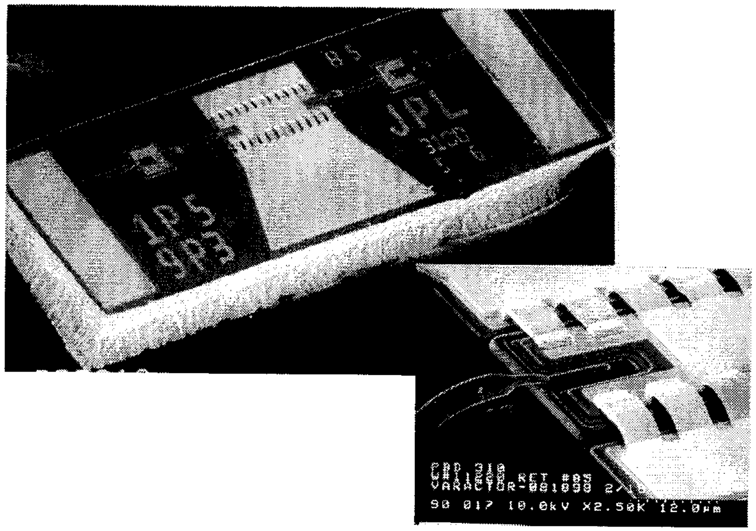


- Membrane is 3 microns thick
- Extensive use of beam-leads
- Extremely simplified assembly
- Bias less design

Q: Can this technology be scaled higher?

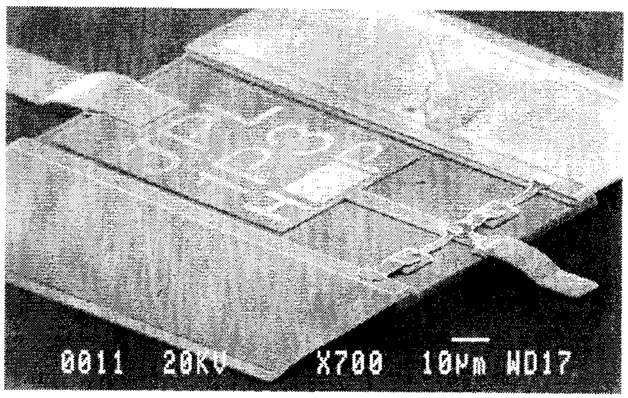
A: Demonstrated up to 2700 GHz!

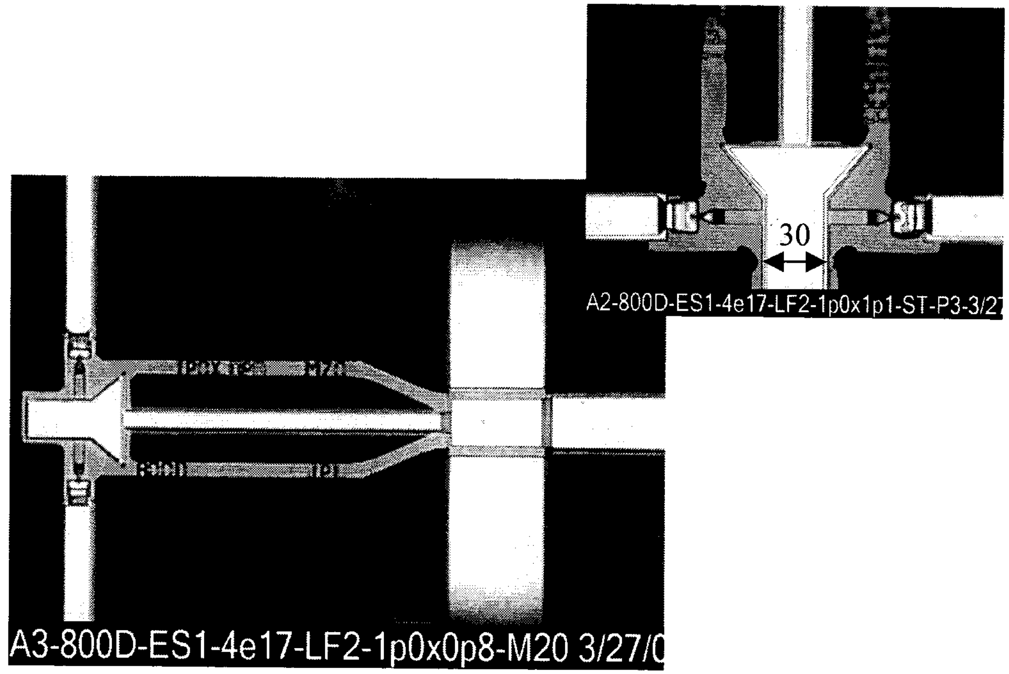
Planar device alternatives



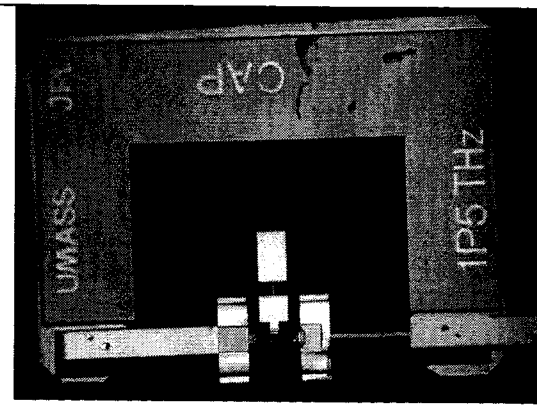
Discrete devices

Frameless membrane devices



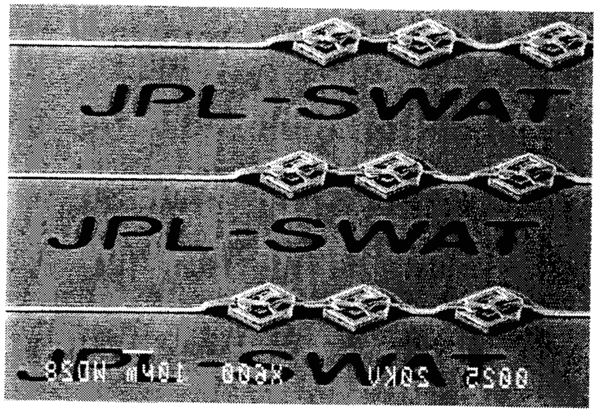


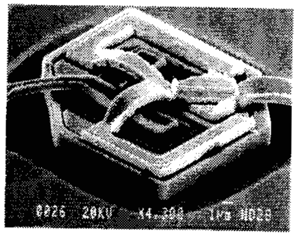
Monolithic substrateless devices



Framed membrane based devices

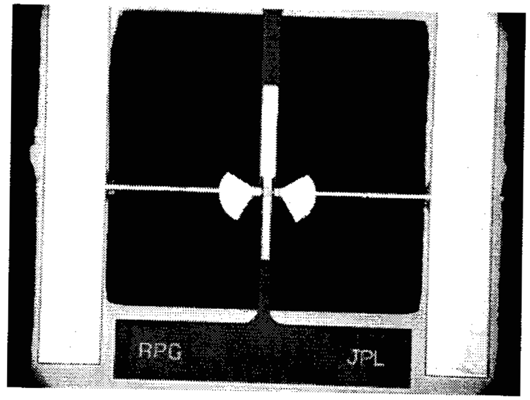
Some more devices…



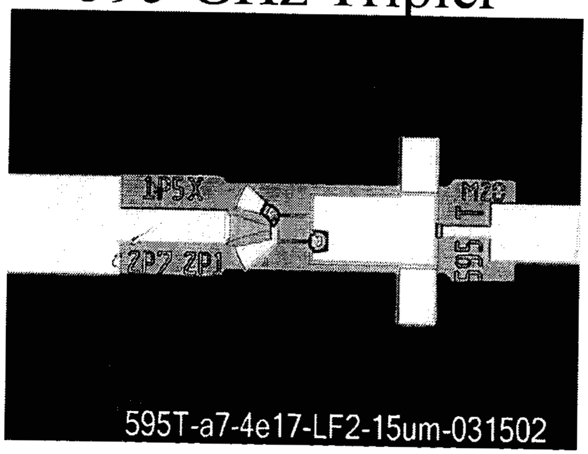


140 GHz chip

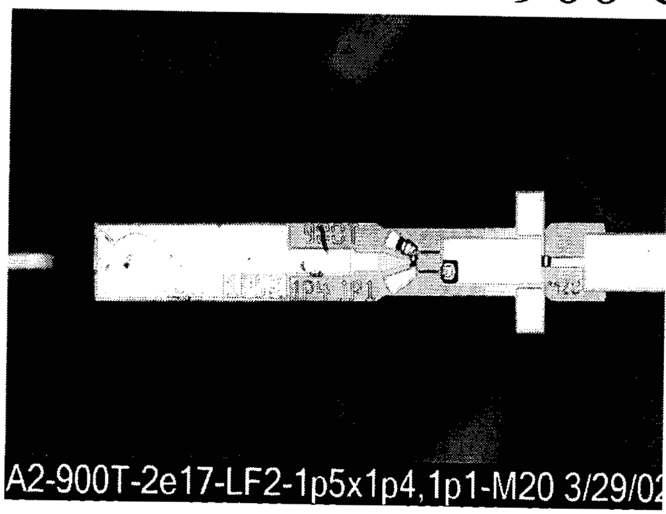
1100 GHz Tripler

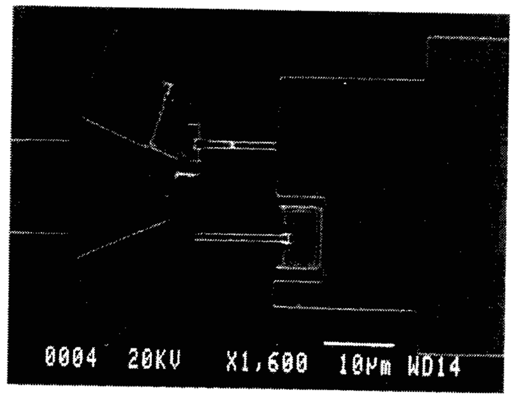


595 GHz Tripler



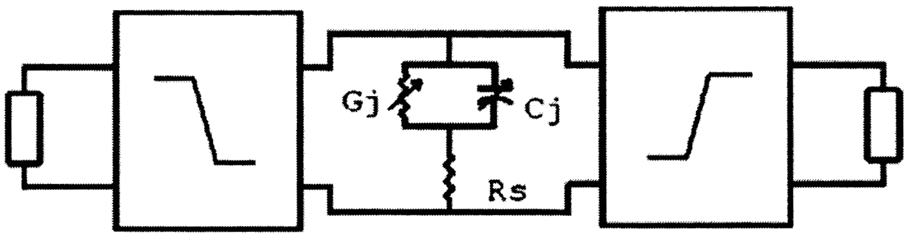
900 GHz tripler





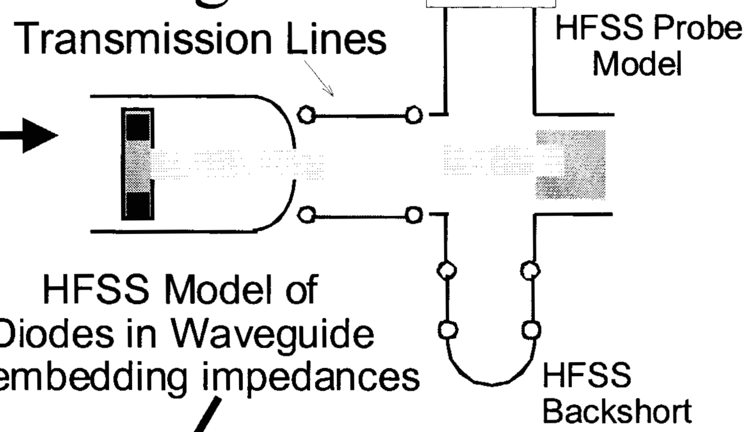
Three-Step Multiplier Design Strategy

1. Optimize Diode



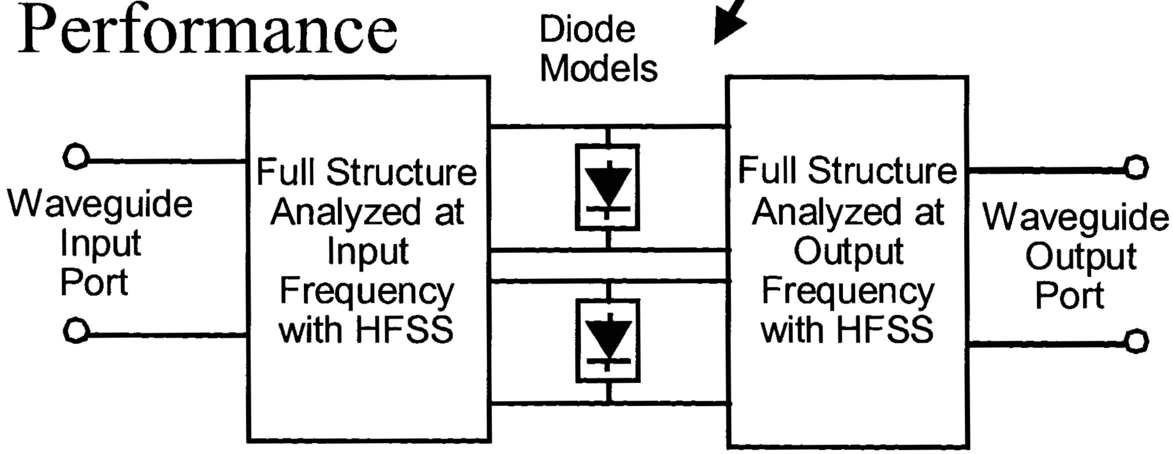
Optimize diode size and find embedding impedances using harmonic balance simulator and diode model.

2. Design Linear Circuit



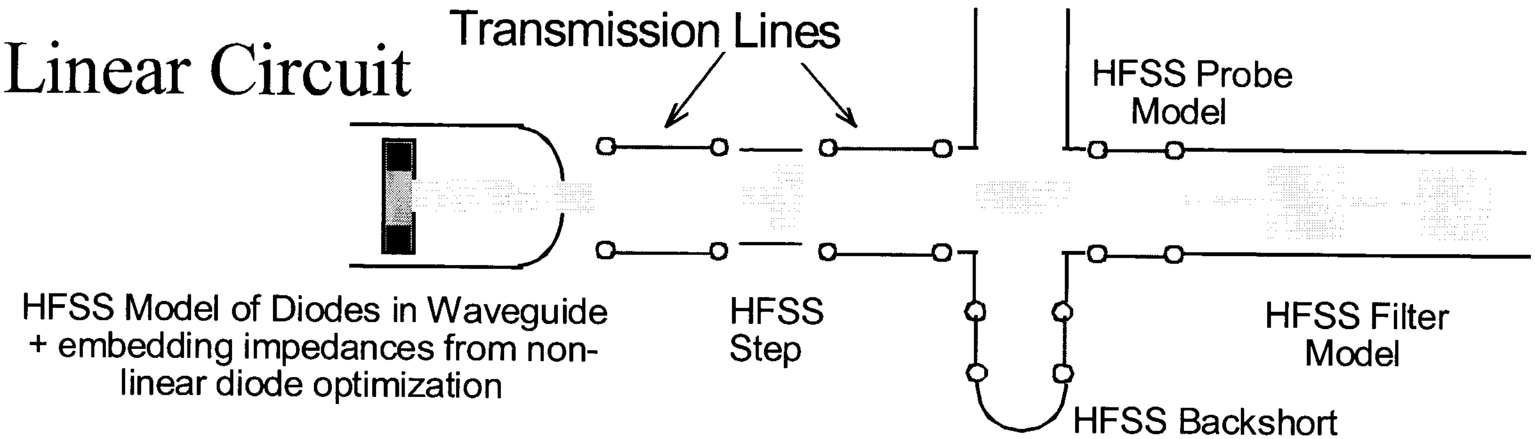
HFSS Model of Diodes in Waveguide + embedding impedances

3. Calculate Performance

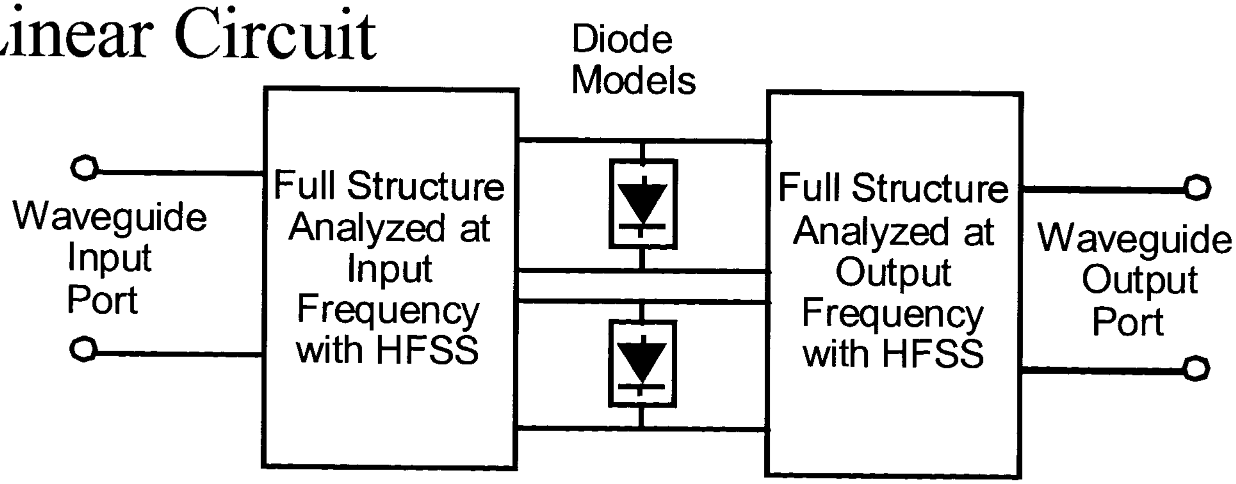


Multiplier Design Strategy

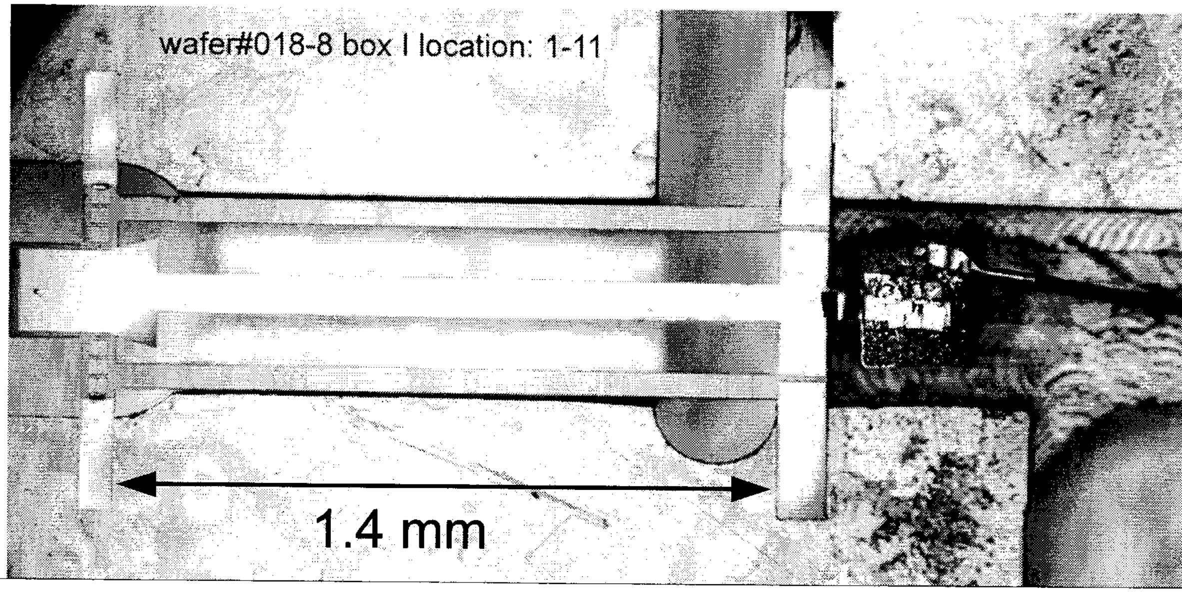
Linear Circuit



Non-Linear Circuit



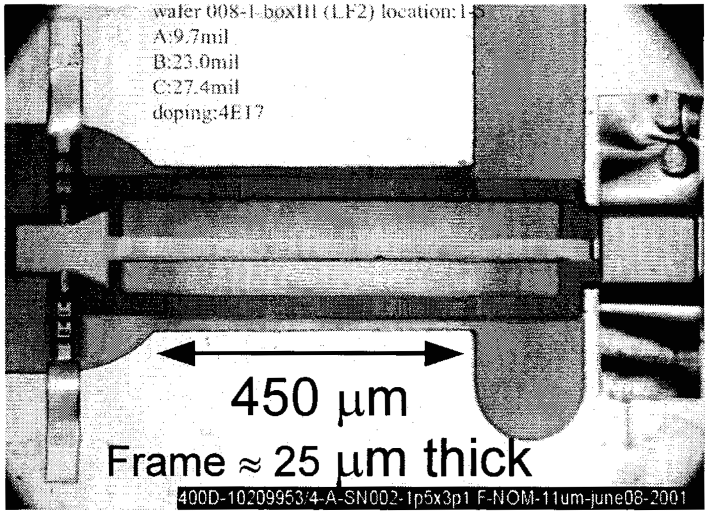
Particulars of 200 GHz Doubler Design



Chip in block, uses 6 diodes

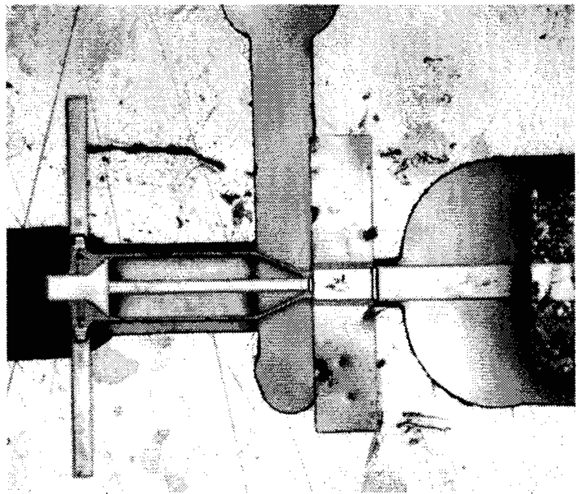
200 GHz doubler requires:
Lower doping — 1-2 X10^{17} cm^{-3} for higher breakdown voltage
Can use off chip bypass capacitor
6 diodes for high power handling
Thick frame ($\approx$ 25 μm) for thermal conduction
Tuning stub for first pole output tuning
All have been demonstrated.

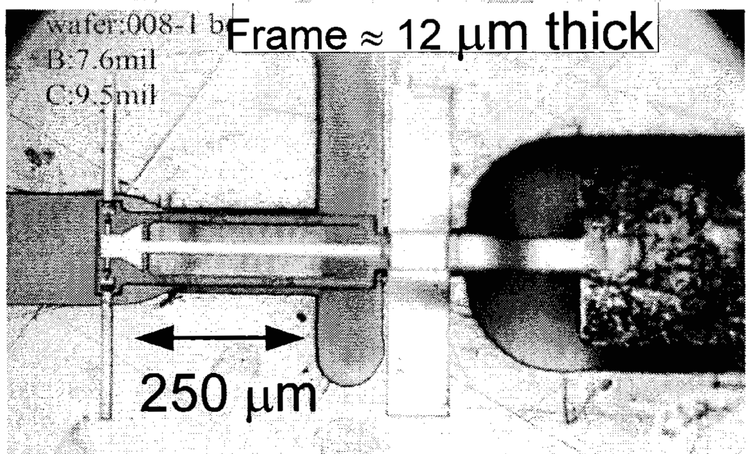
Particulars of 400 and 800 GHz Doubler Designs



400 GHz Doubler, uses 4 diodes

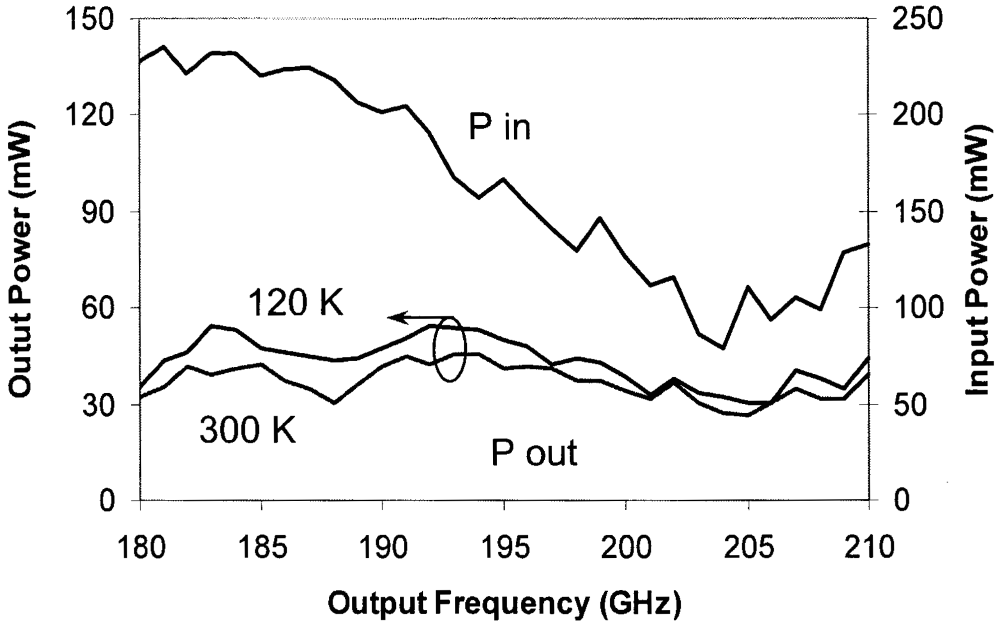
Higher frequencies require:
Higher precision machining
Higher doping — 2-4X10^{17}
On chip DC bias Capacitor
All have been demonstrated.



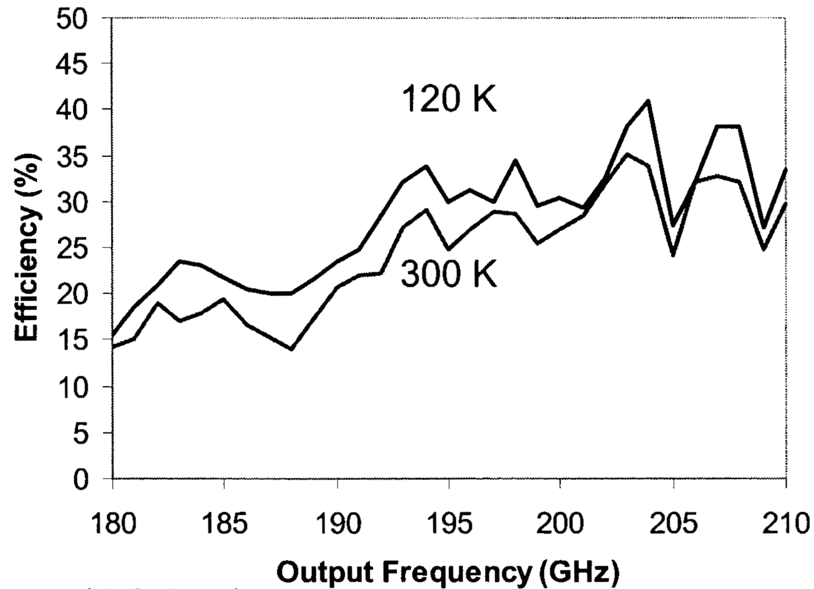


800 GHz Doublers, 2 diodes

200 GHz Doubler Performance

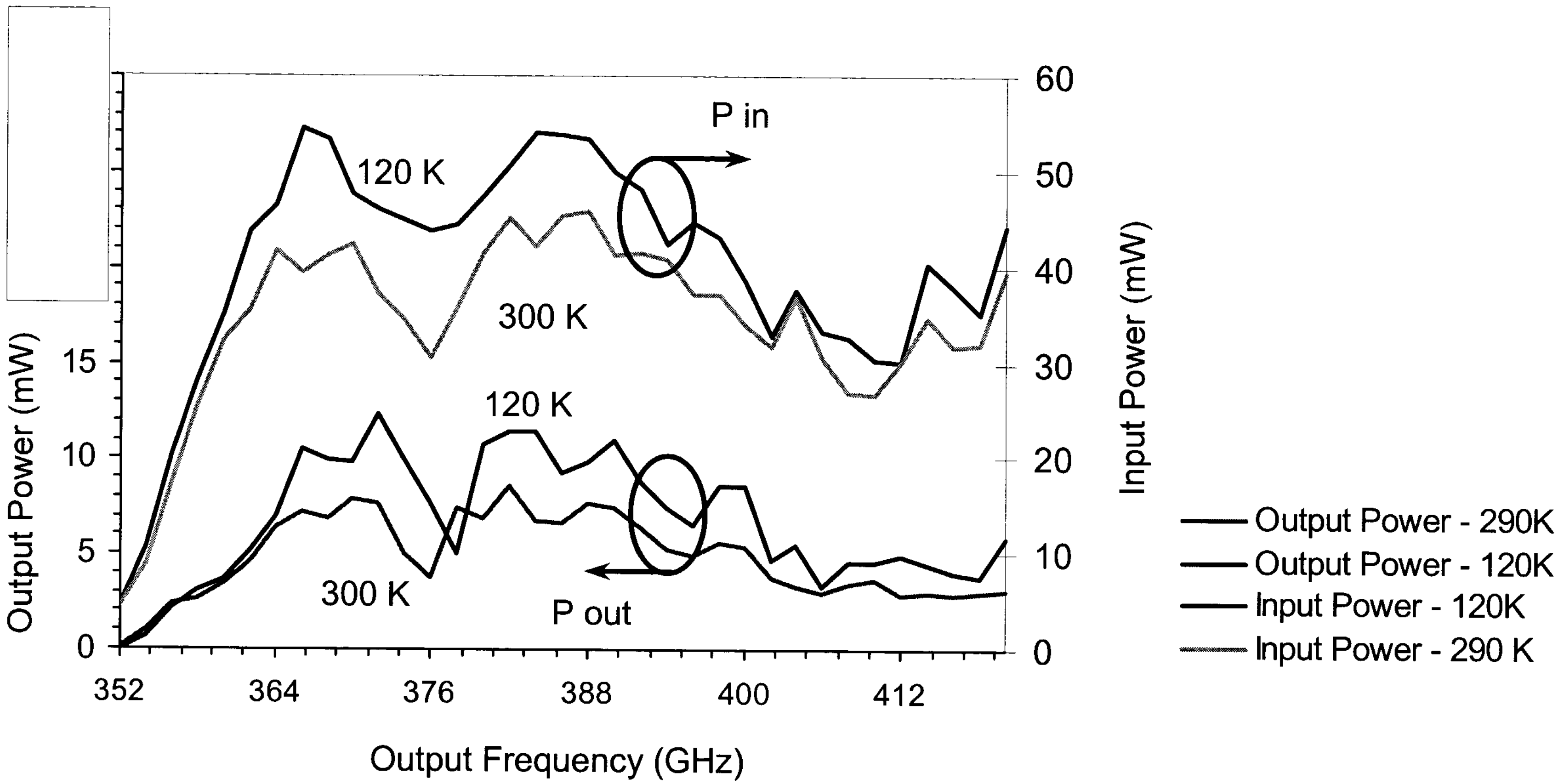


6 anode chip
3 X12 μm^2 (2e17) diode



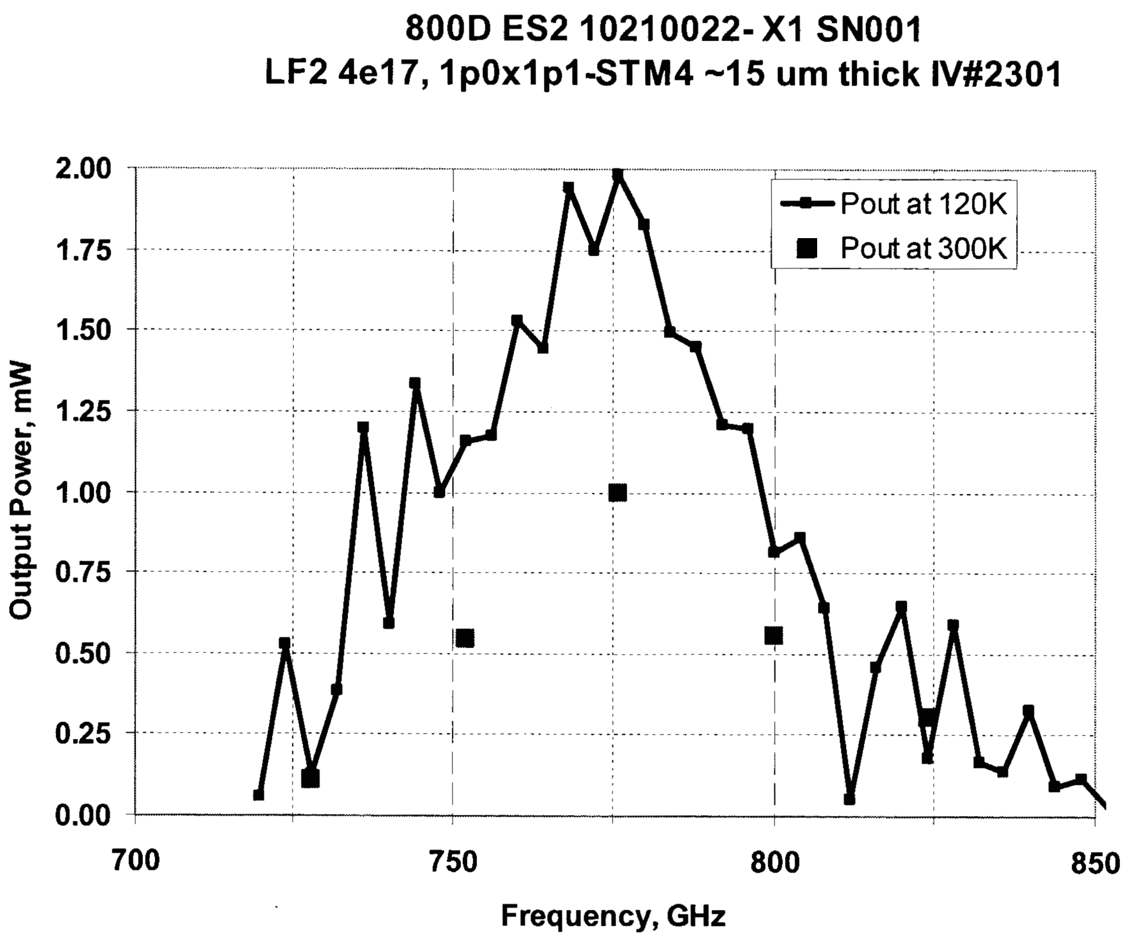
- Peak Power of 45 mW(300K) and 55 mW(120K)
- 3dB BW of >12%

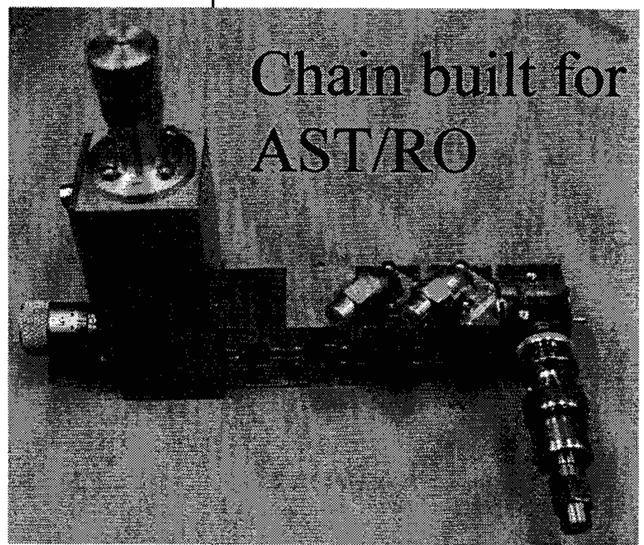
400 GHz Doubler Performance



- At 300K peak power of 8mW, 3dB BW ~10%
- At 120K peak power of 12 mW, 3dB BW ~10%

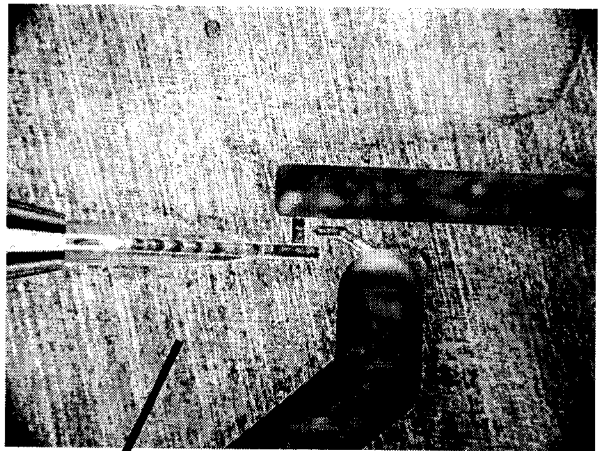
x2x2x2 Chain to 800 GHz

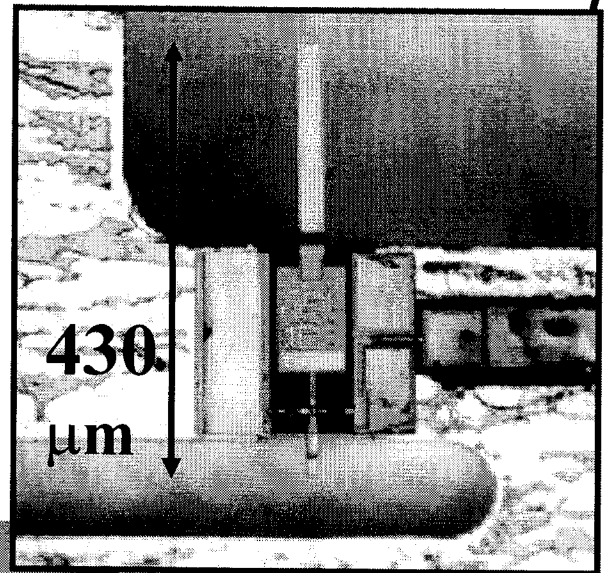


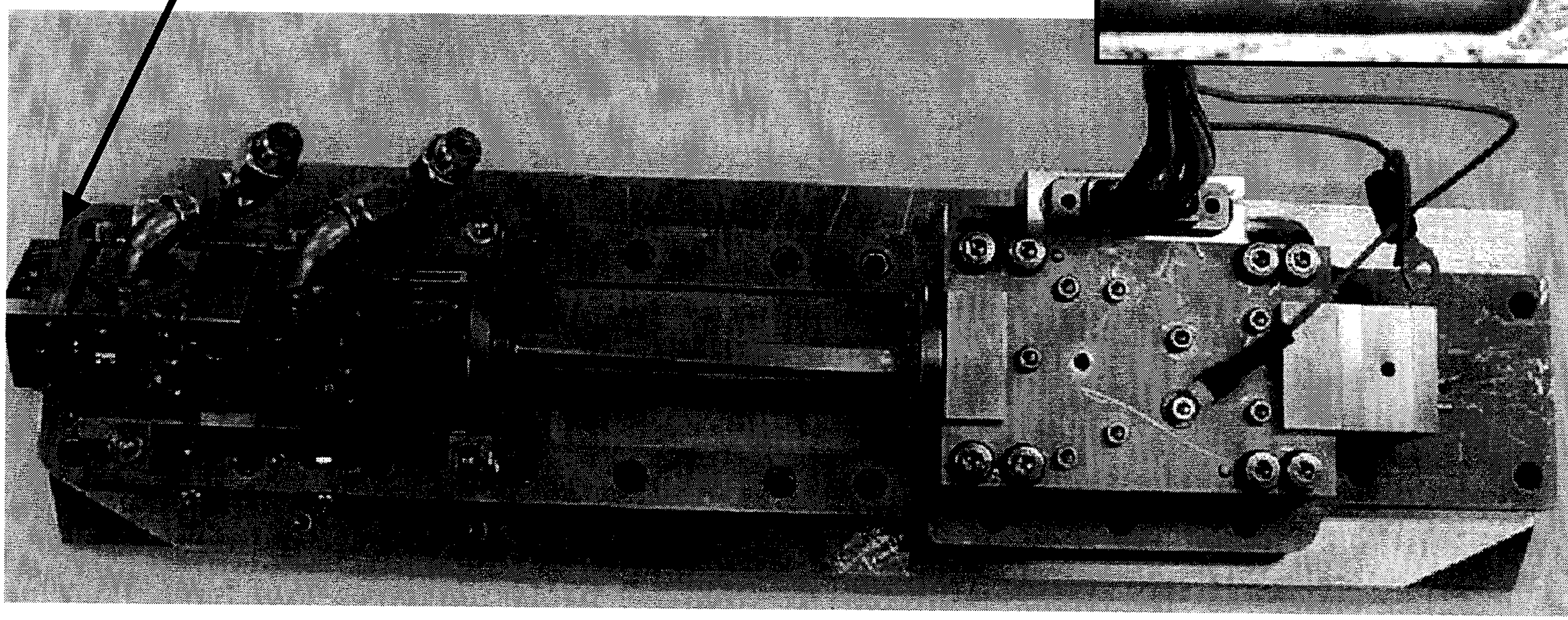


- At 120K peak power of 2mW, 3dB BW of >6%

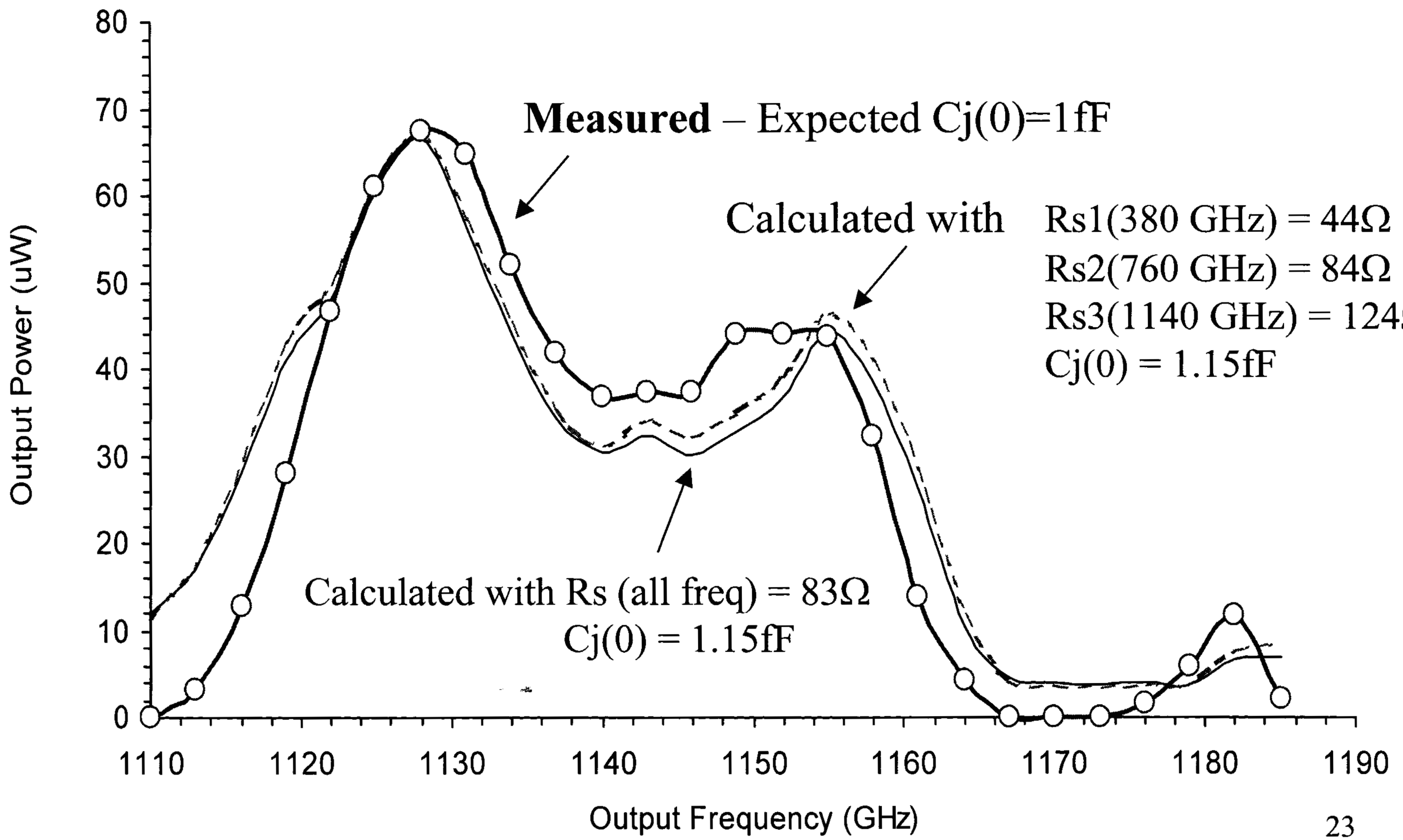
Planar LO chain at 1200 GHz



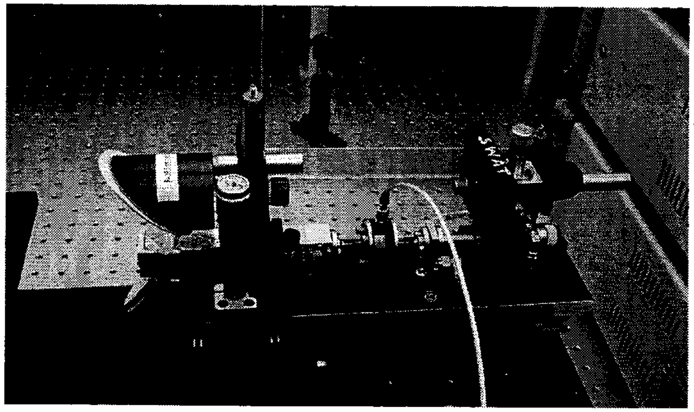




Measured *vs* Calculated Output Power of the 1.2 THz balanced tripler

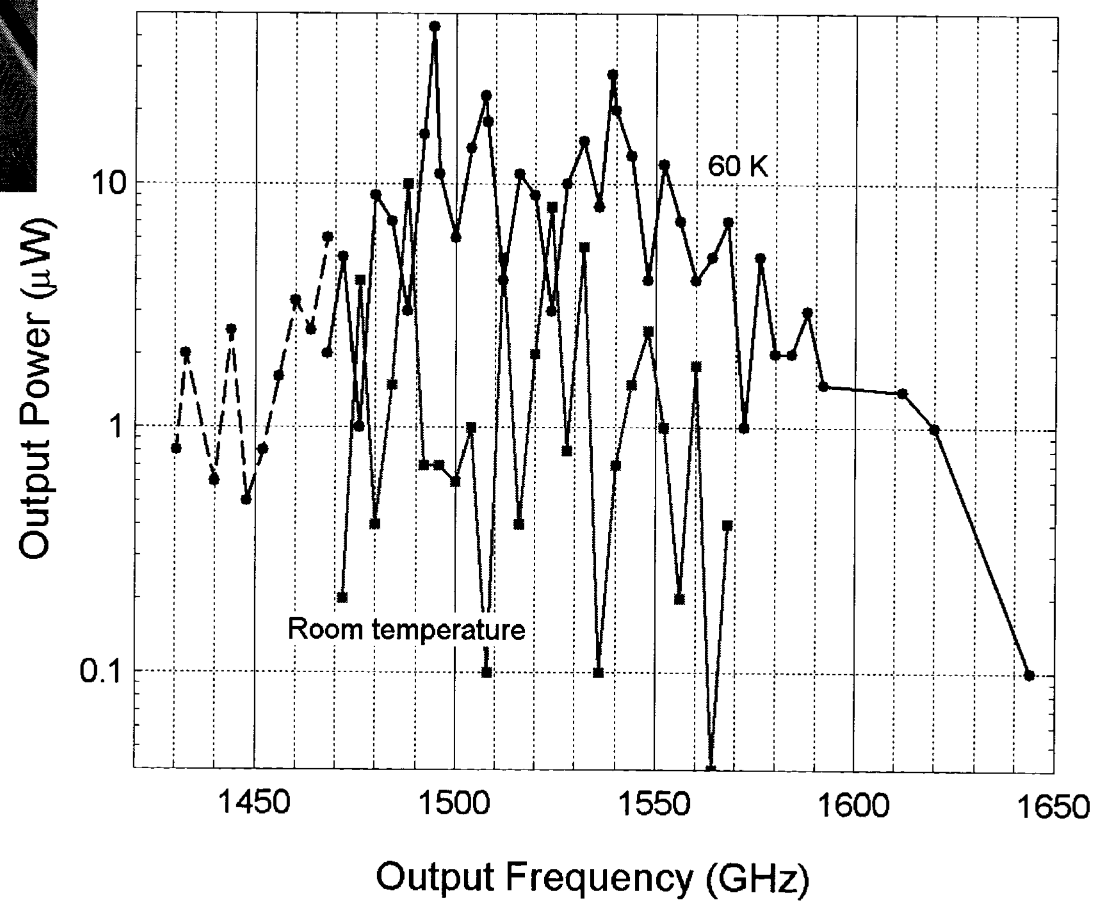


LO Source to 1600 GHz

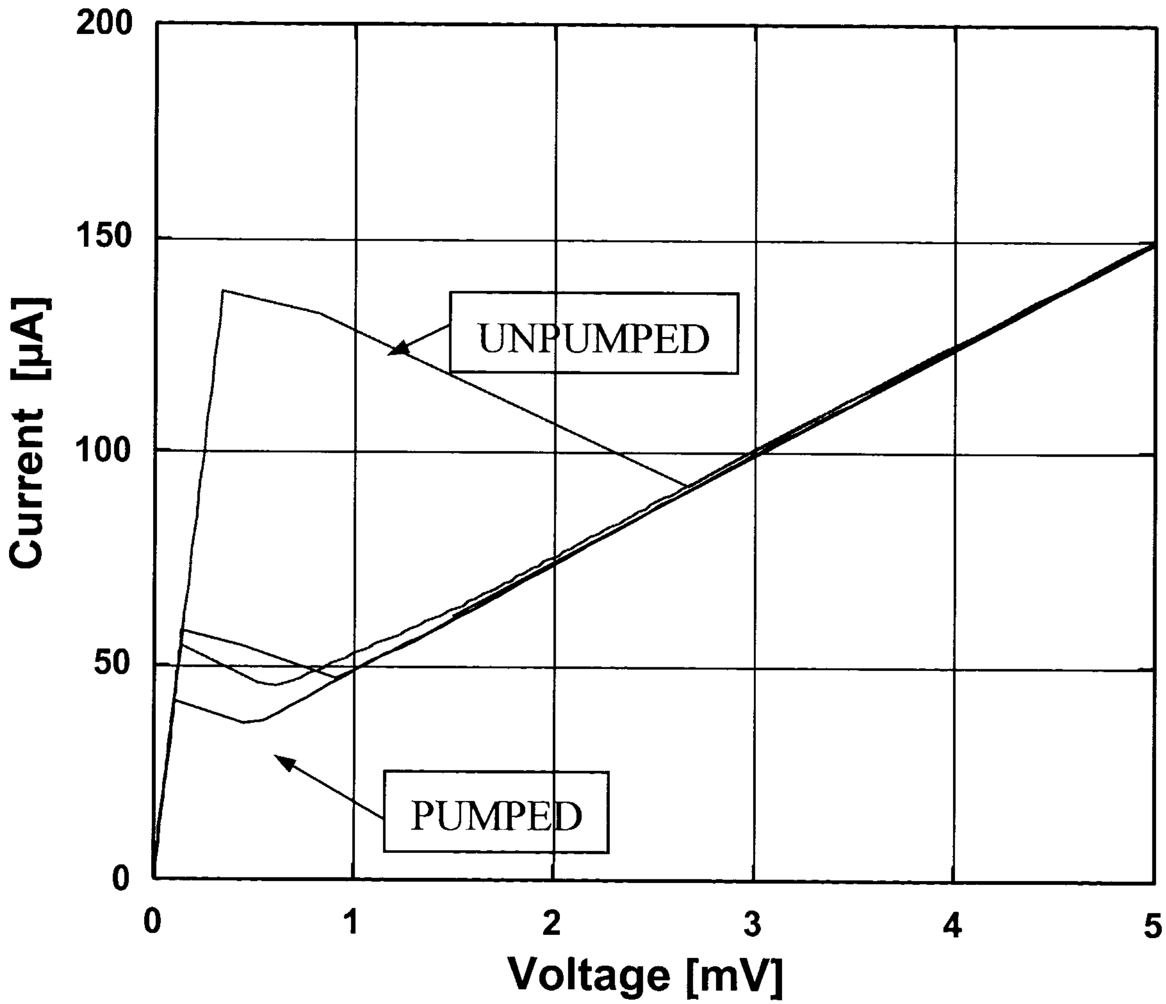


525 GHz LO Chain

X2x2x2x2 Chain Pout



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



$\nu_{LO} = 1.525$ THz

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

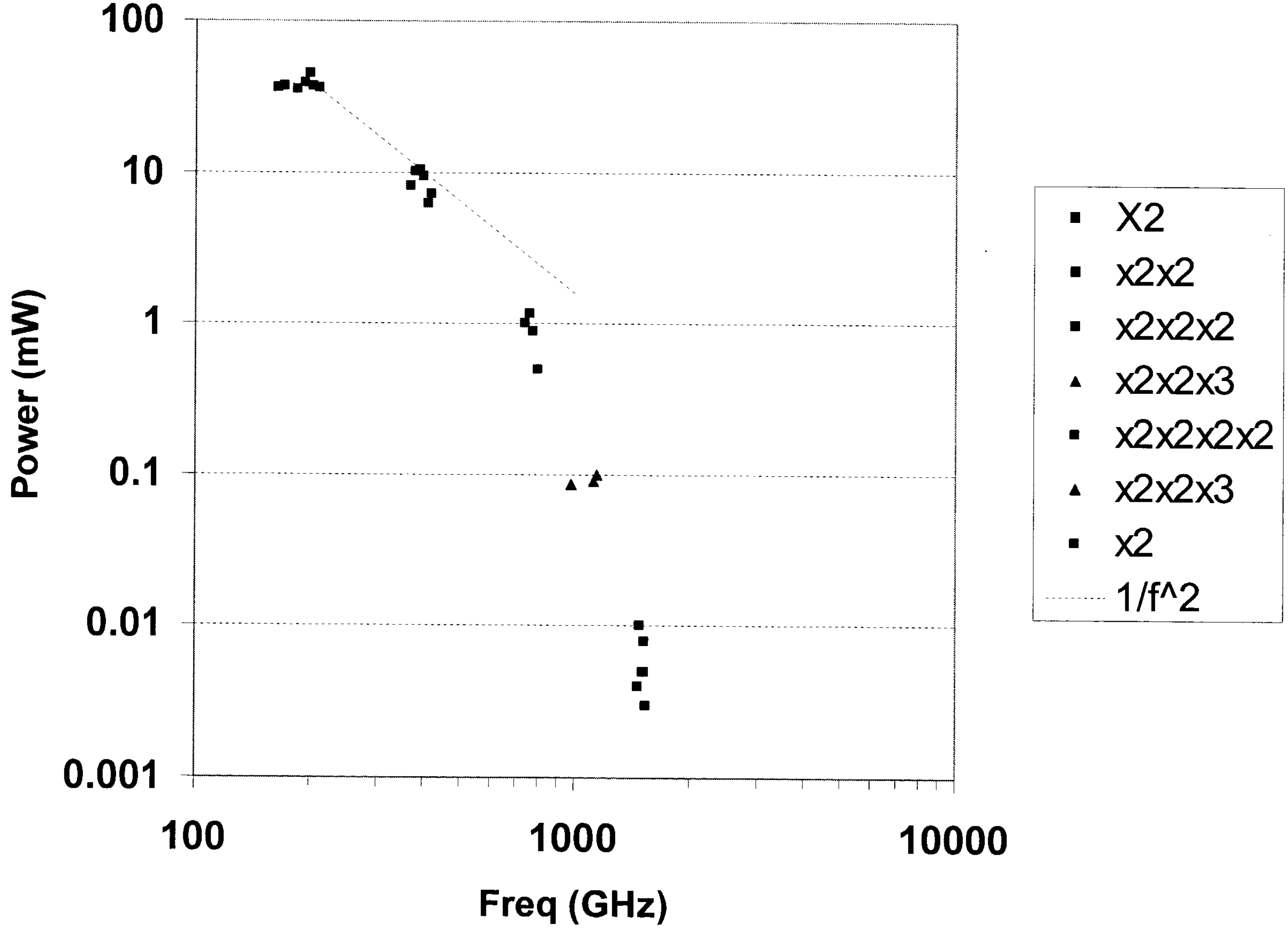
$P_{inc} \approx 80 - 100$ nW (includes mixer and window losses only)

$I_C = 137\ \mu A$

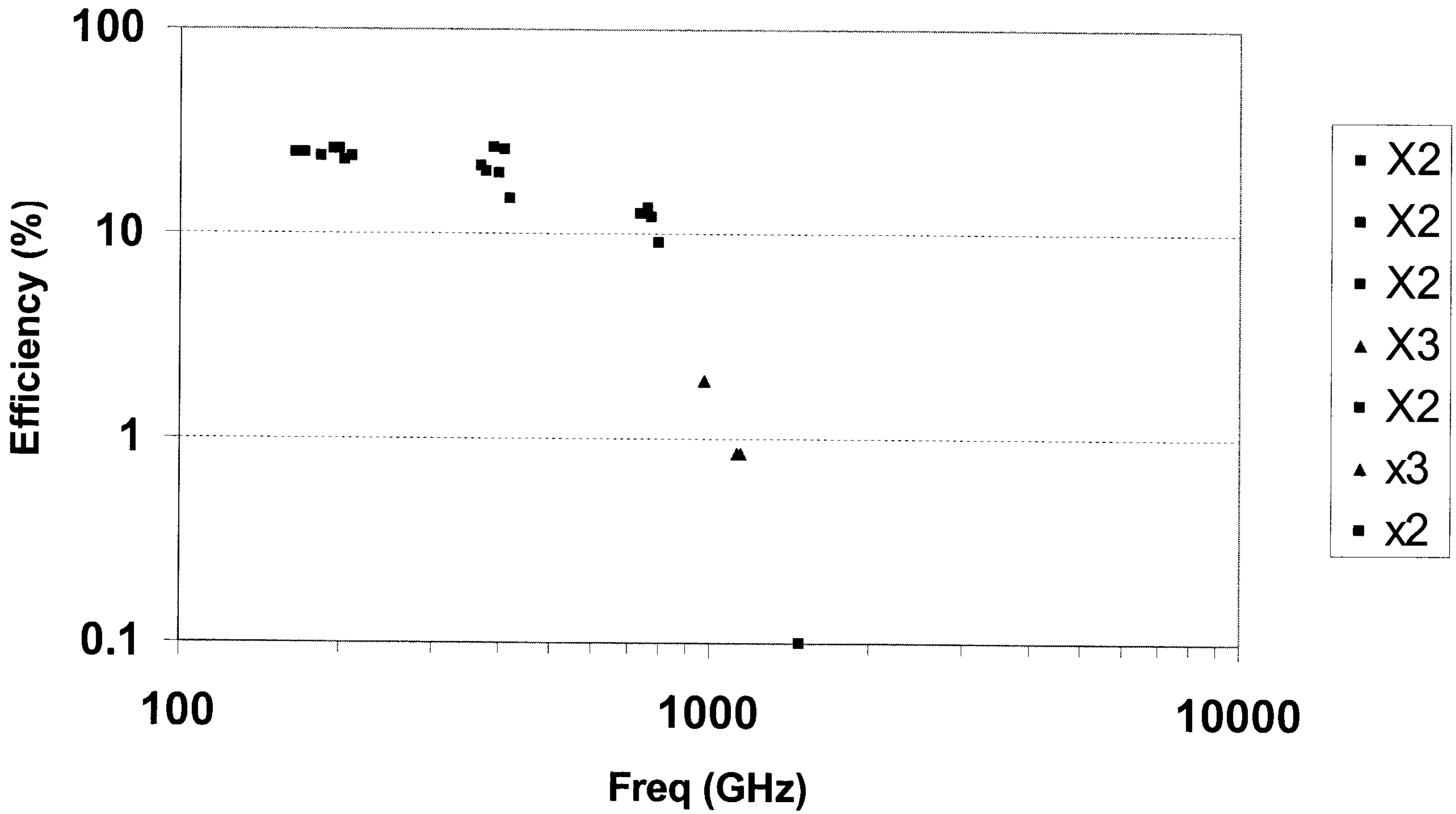
$R_N = 34\ \Omega$

A. Maestrini, W. McGrath, I. Mehdi, J. Kawamura, N. Erickson, B. Bumble,

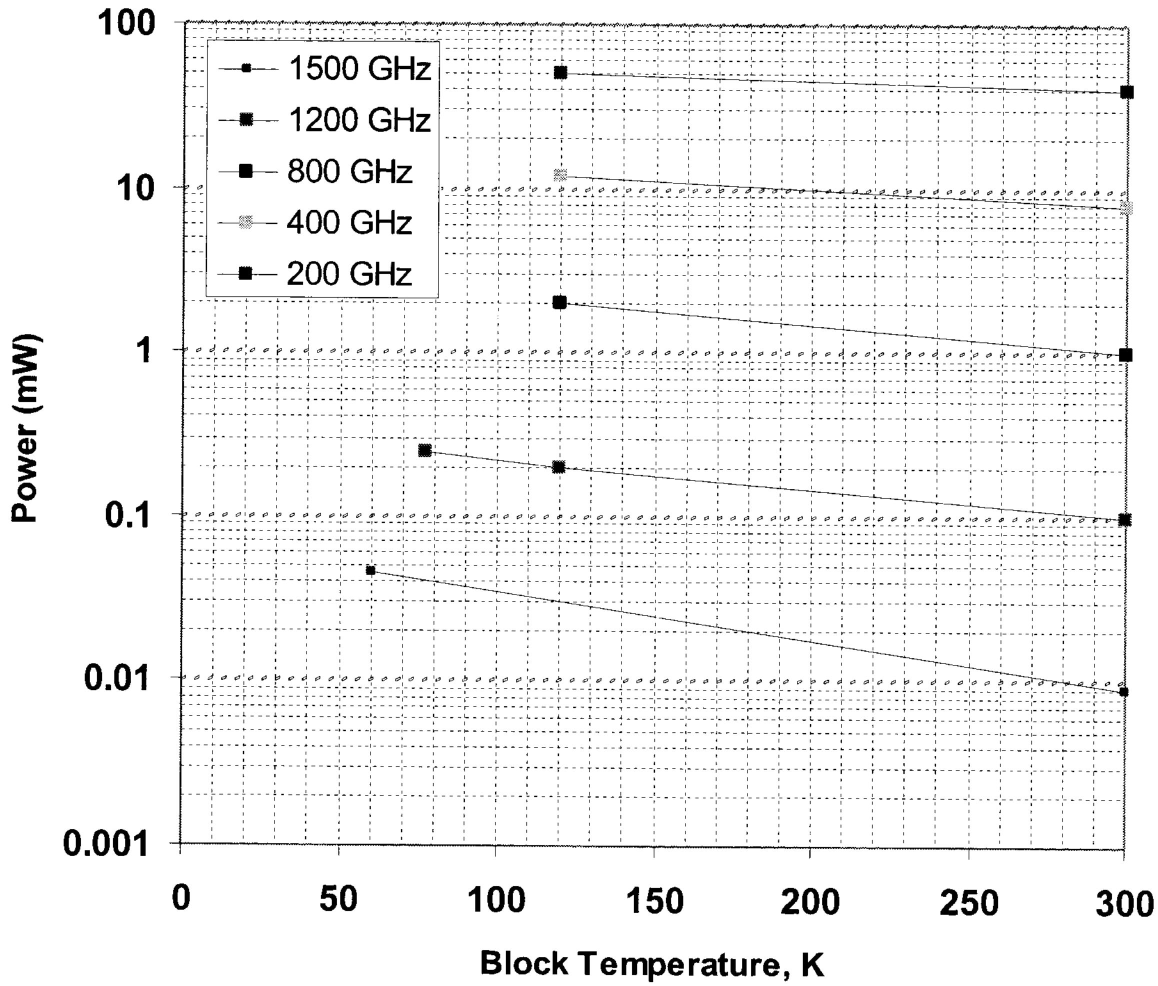
Current status of LO Sources at 300K



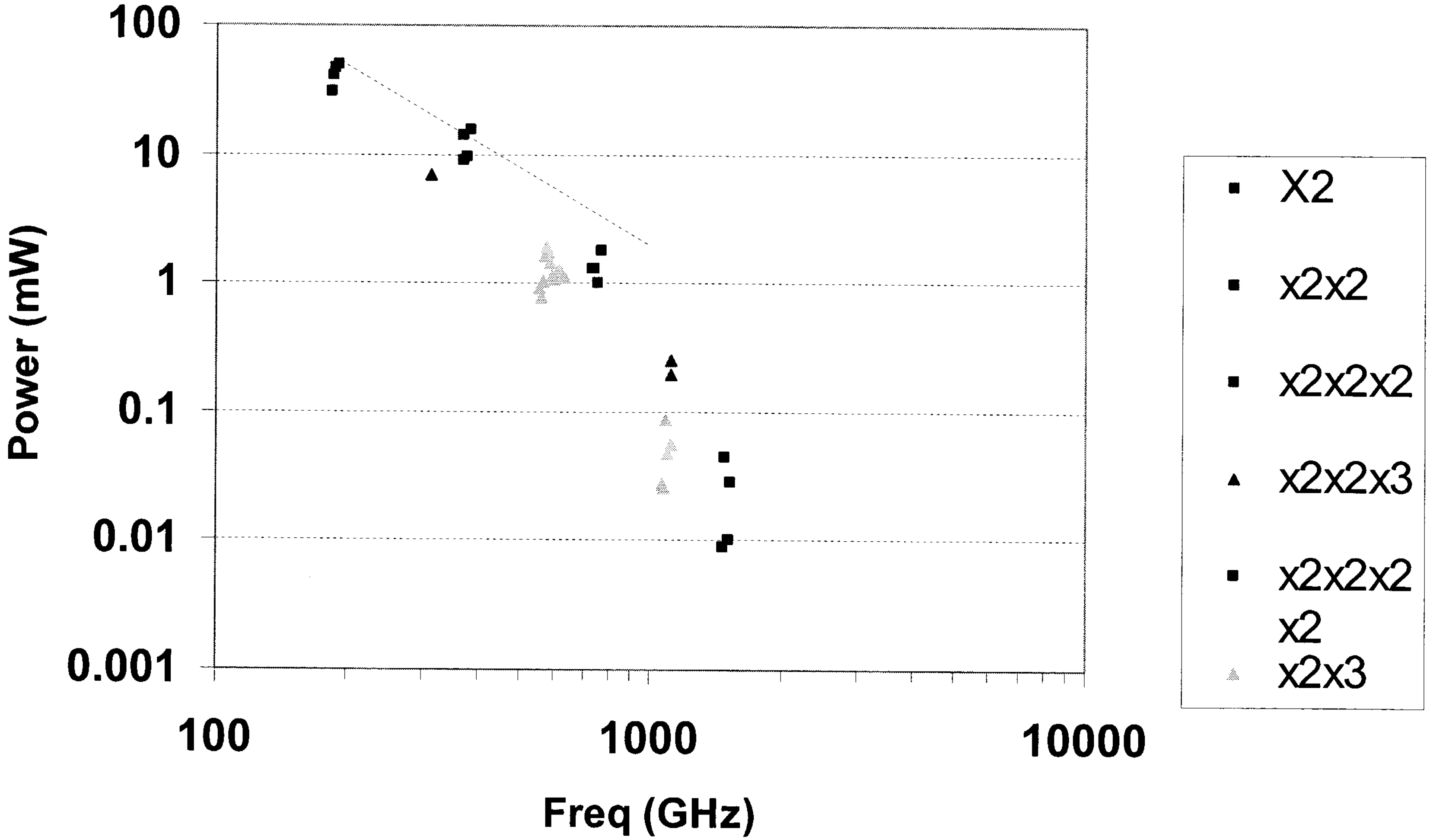
Current status of LO Sources at 300K



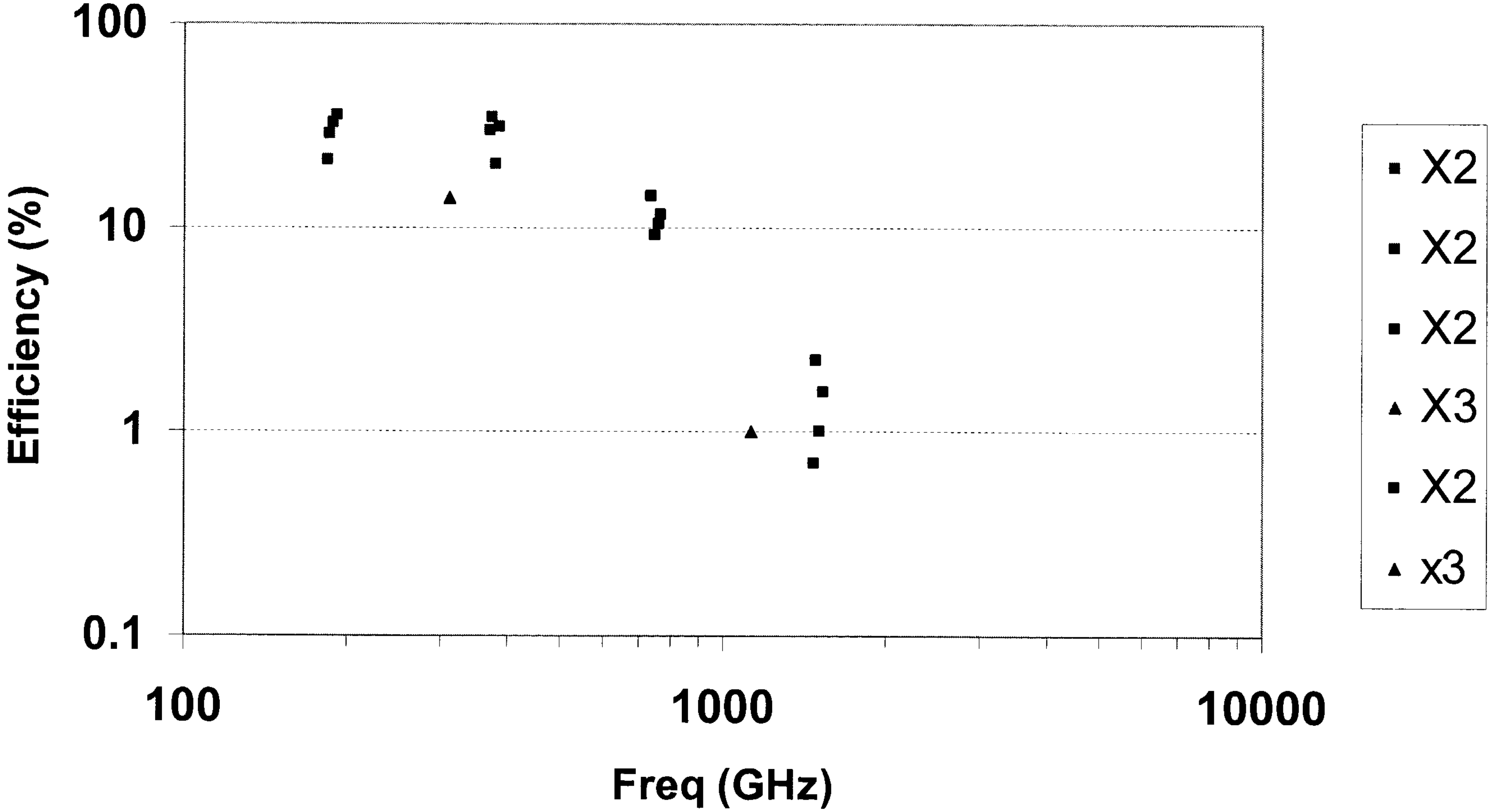
Output Power vs Block Temperature



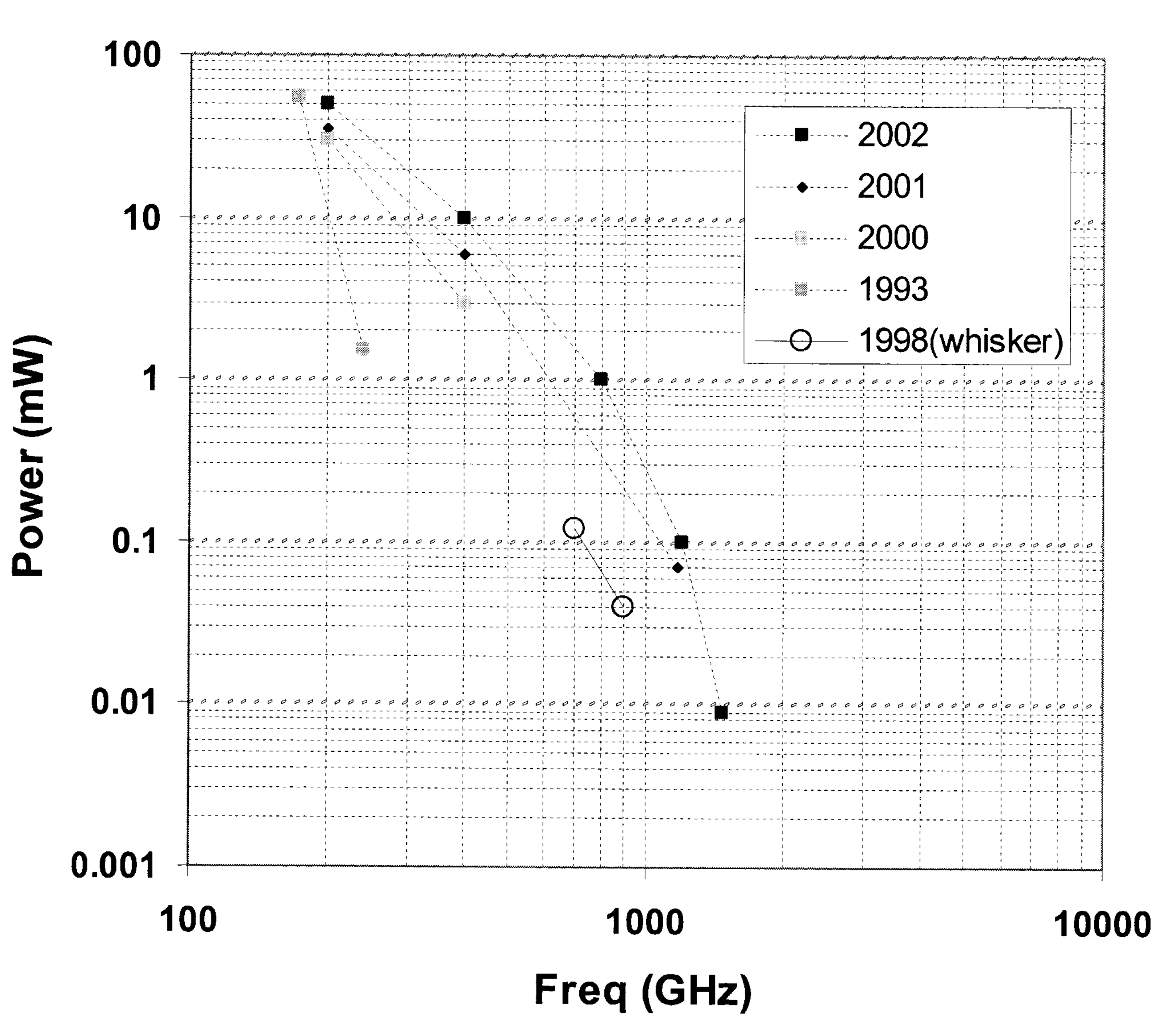
Current status of LO Sources at 60-120K



Current status of LO Sources at 60-120K



How far have we come?



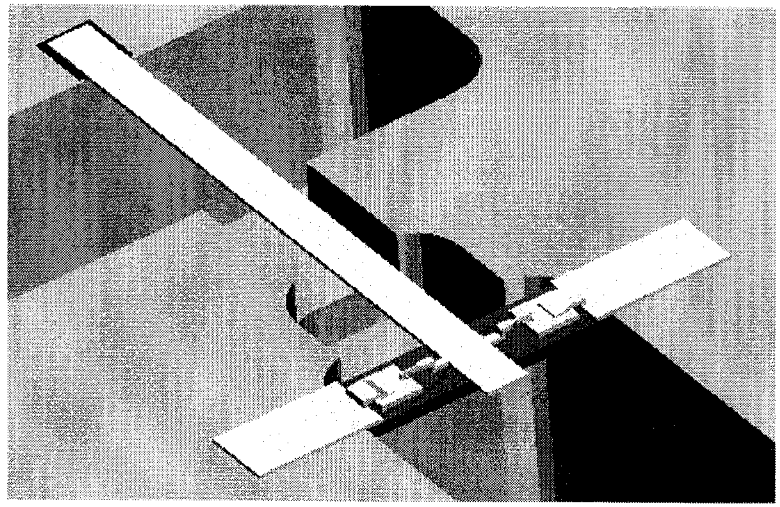
Challenges

- Higher frequency ?
- Higher Output power
- Higher frequency power amplifiers
- Higher PAE amplifiers
- Improve bandwidth—better designs, re-configurable
- Simplify chain construction—micro-machined blocks, increased integration
- Arrays—quasi optical techniques, leverage MEMs knowledge
- Implementation—diversified skill mix, better machining, better testing procedures
- Planar devices—increase yield, increase throughput and uniformity, reduce time to completion

Prospective source to 2400 GHz

Planar Diode properties:

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



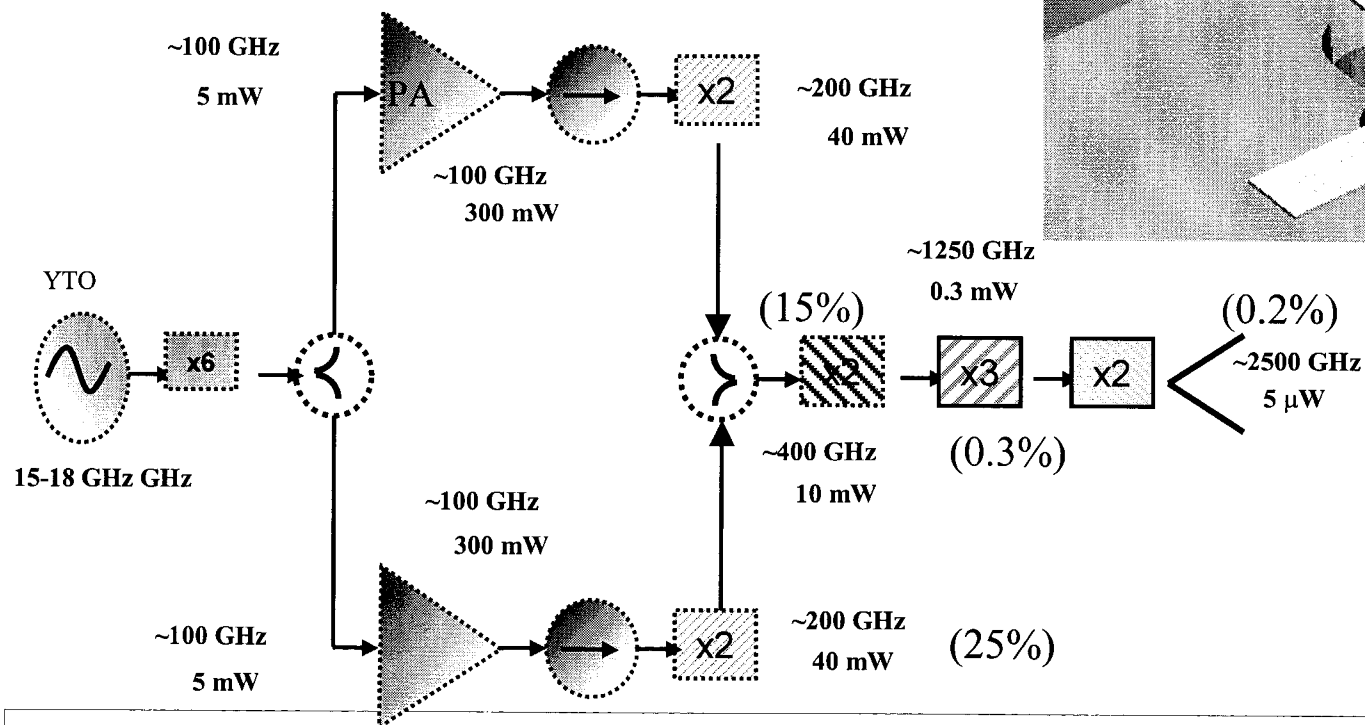
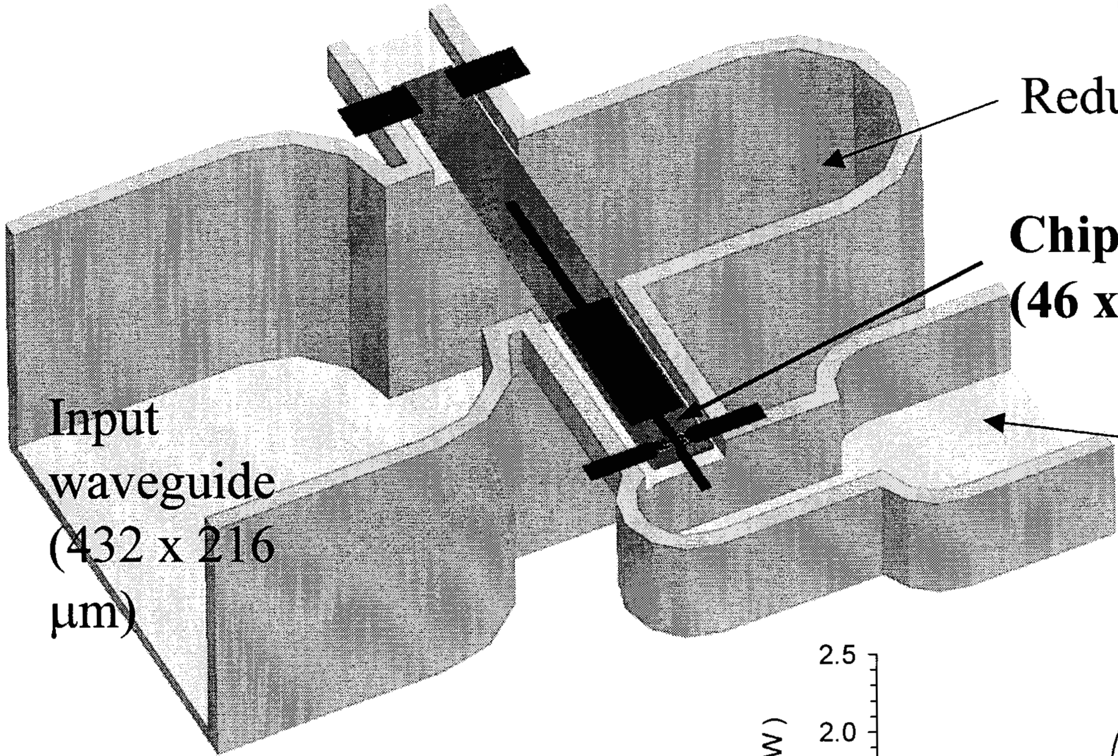
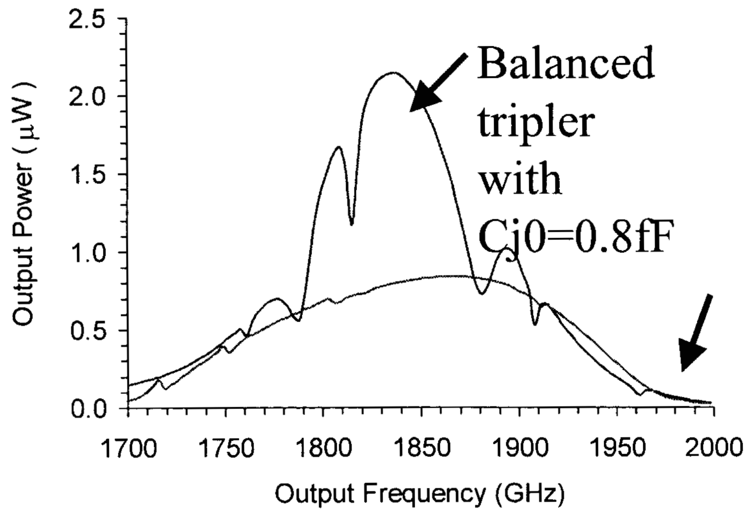


Figure 1. Schematic of the all-solid-state source to 2500 GHz. Dashed outlined components are either commercially available or have already been demonstrated in our laboratory. Solid outlined components are to be developed under this proposal.

[redacted]



Input power = 2.5 mW



Emerging Technologies

- **InP based PA**
  - Higher PAE, faster speeds, lower DC power
- **Active multipliers for <100 GHz**
  - lower conversion loss
  - robust synthesizers
- **InGaAs multipliers**
  - lower resistivity
- **Vacuum based electronics**

Monolithic THz Vacuum Tube Source: Nanoklystron

DESCRIPTION:
Monolithically fabricated Nano-Reflex Klystron tube with operating frequency above 1 THz!!!

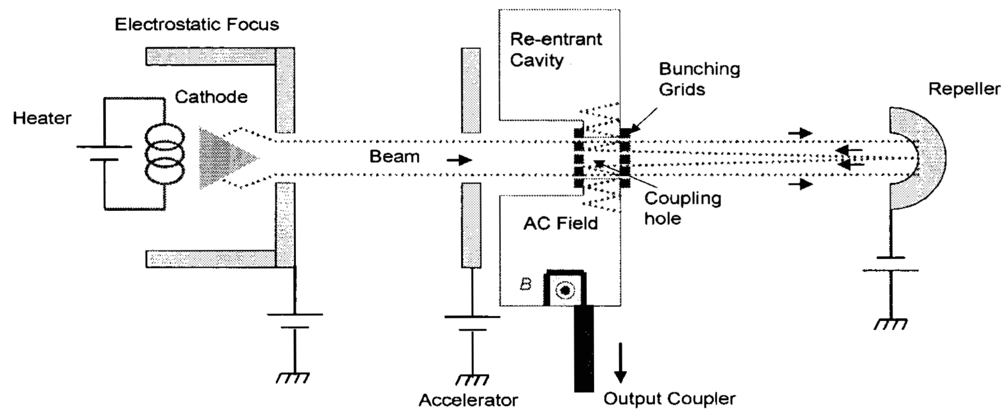
PRODUCT FUNCTION:
- Provides milliwatts of power at THz frequencies – no other solid state sources exist at these frequencies!
- Monolithically fabricated and tailorable to any frequency from 100-3000 GHz.
- Demonstrates first ever klystron above 200 GHz. First oscillator/amplifier of any kind above 600 GHz.
- Uses novel highly ordered carbon nanotube array cathode – radiation hard, temperature insensitive.
- Critical for passive downconverters, comm. & radars.
- Potential operation at high power levels via arrays.

UNDERLYING TECHNOLOGIES:
New highly ordered carbon nanotube array cathodes
Nanofabrication, MEMs and micromachining
Ultra high vacuum assembly & sealing in silicon

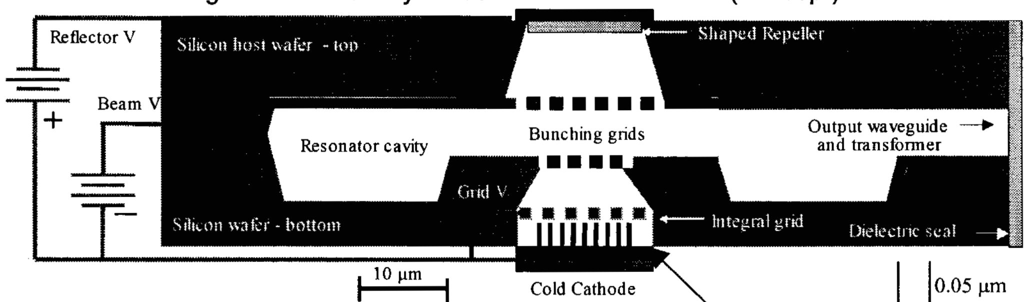
POTENTIAL USES:
Compact, low power, phase-lockable THz sources for heterodyne sensor systems, radar, comm., diagnostics etc.
Potential deployment for wide range of NASA remote sensors

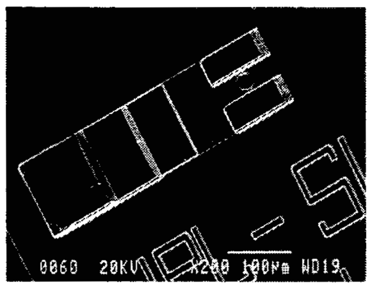
CURRENT STATUS
CNT's demonstrated on silicon substrate (Brown U.)
300, 600 GHz & 1.2 THz MEMS cavities fabricated (JPL)
UHV nanotube/hot cathode test chamber being fab'd (JPL)
Self-focusing CNT cold cathodes being developed (JPL)
Self--focusing hot-cathode being developed (HeatWave/JPL)

SCHEMATIC OF A SIMPLE REFLEX KLYSTRON



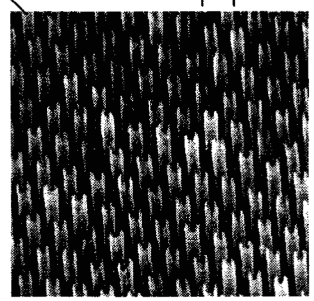
BELOW: Revolutionary monolithic *Nanoklystron* formed from two bonded silicon wafers and high current density carbon nanotube cathode (concept).





Left: 1200 GHz MEMS fabricated nanoklystron circuit in Silicon (lower half)

Right: Brown University highly ordered carbon nanotube array.



Concluding Remarks

- Planar diode chains driven with high power PAs are capable of pumping mixers well into the THz range.
- Robust chains that can be cooled have been successfully demonstrated.
- Emerging technologies show potential and can complement Schottky diode chains

Finally…

NASA led concerted effort of the last three years has now made it possible to realistically baseline solid state LO sources well into the THz range. However, it continues to be a niche technology highly dependent on NASA sponsorship. After Herschel further technology development will be directly proportional to the quality and quantity of NASA support.

Even to sustain the current capability NASA support will be required

Supplementary slides

JPL supported Device Processes

LF

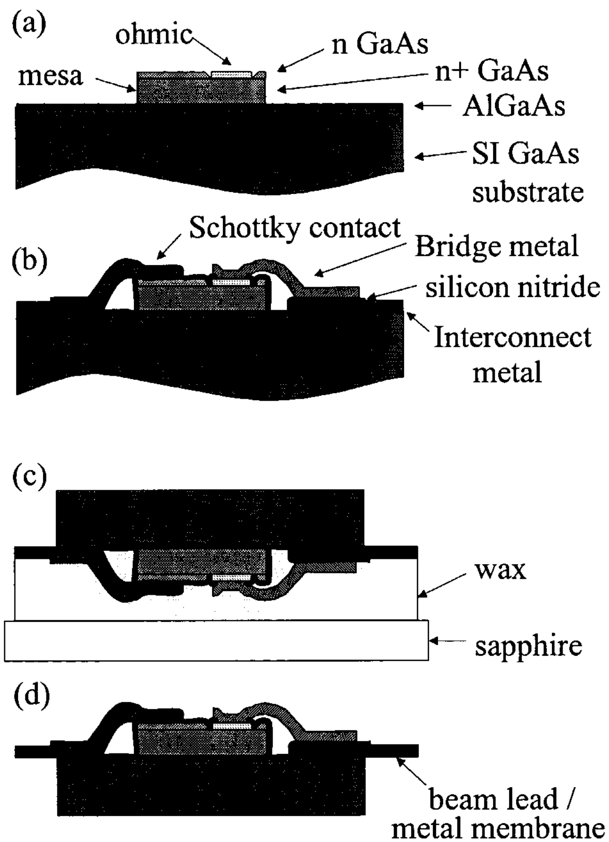


Fig. 1 Low Frequency process. (a) Ohmic and mesa definition.
(b) Interconnect metal and air-bridged Schottky deposition,
followed by passivation and bridge metal definition.
(d) Backside thinning and device separation. (e) Release of device from carrier wafer.

HF

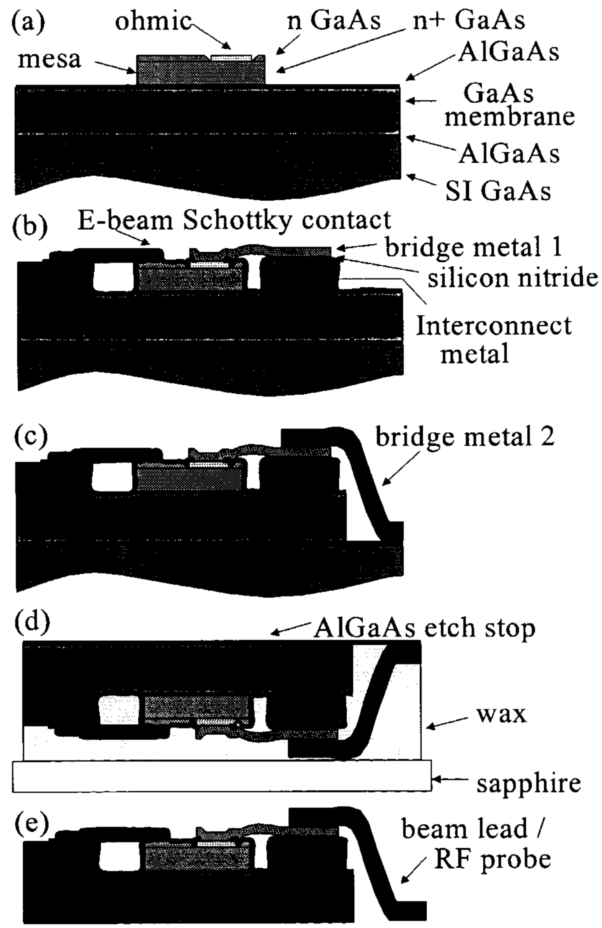


Fig. 2 High Frequency process. (a) Ohmic and mesa definition. (b)_ Interconnect metal and e-beam-defined Schottky deposition, followed by passivation and bridge metal 1 definition. (c) Membrane layer etch and bridge metal 2 deposition. (d) Removal of substrate with selective etch. (e) Release of device from carrier wafer.