THz Local Oscillator Sources: Performance and Capabilities

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Acknowledgments

- Thanks to my many colleagues at JPL, especially from the SWAT team who have made the current progress possible
- Thanks to Dr. Neal Erickson (UMass) & Dr. Jack East (UMich) for many technical discussions and fruitful collaborations

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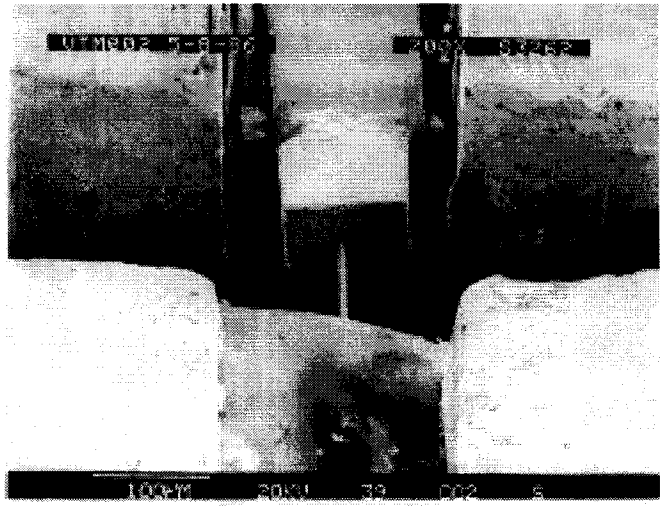
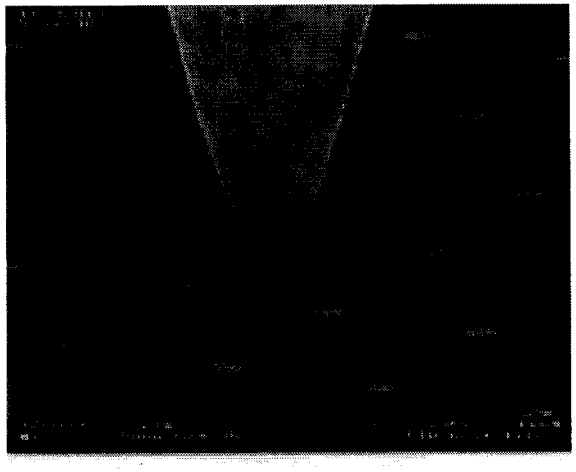
Outline

- Introduction
- Status of THz multiplier sources
- Challenges for next generation multiplier sources
- Emerging technologies
- 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 mW at 1500 GHz (RPGmbH)
  - Gunn+tripler+tripler, 50 mW at 1000 GHz

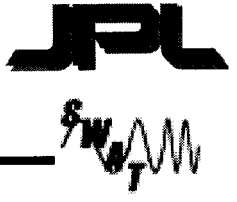




Introduction

- 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

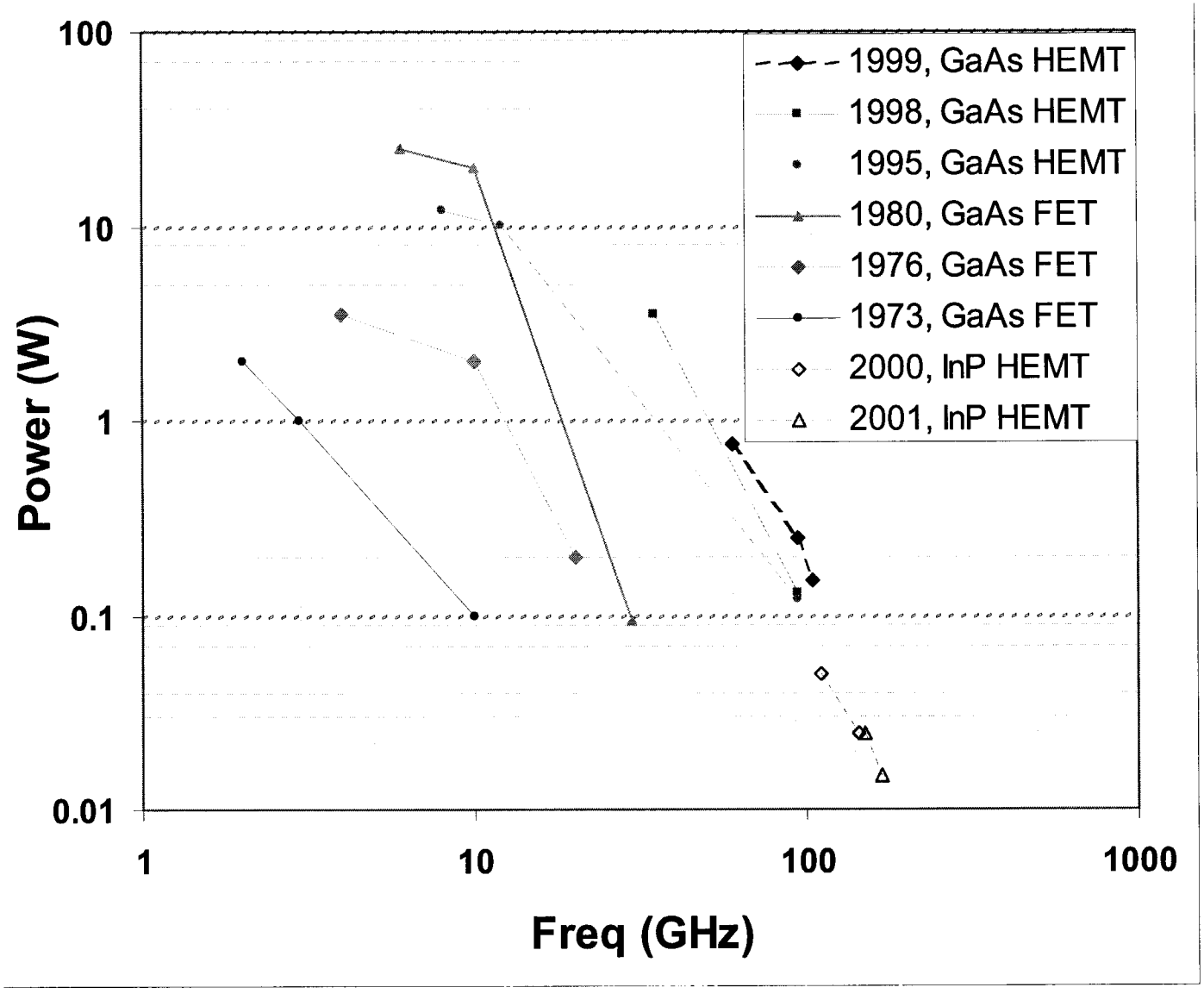
Impetus for recent development

Herschel Space Observatory
ESA/NASA mission, Launch date: Fall of 2007
Requires local oscillator sources from 400 to 1900 GHz

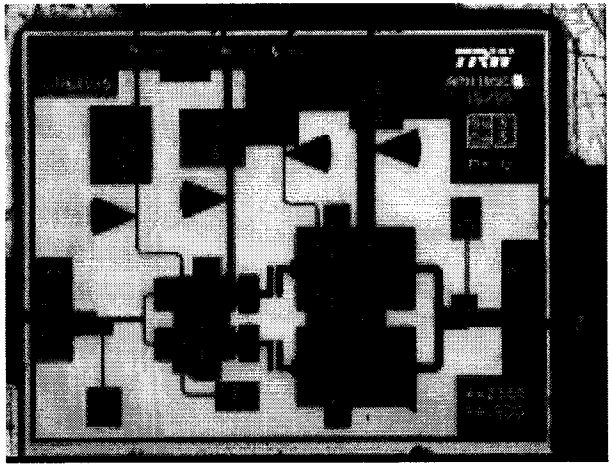
To satisfy HSO needs one must develop:

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

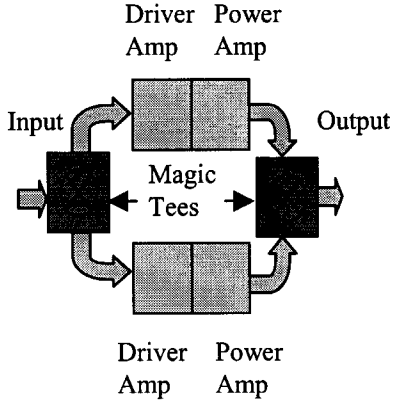
Available Power (PA)



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



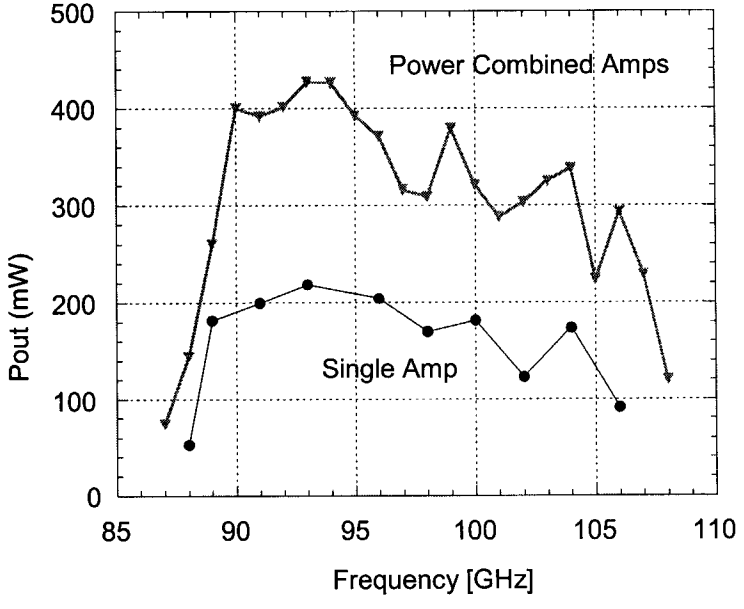


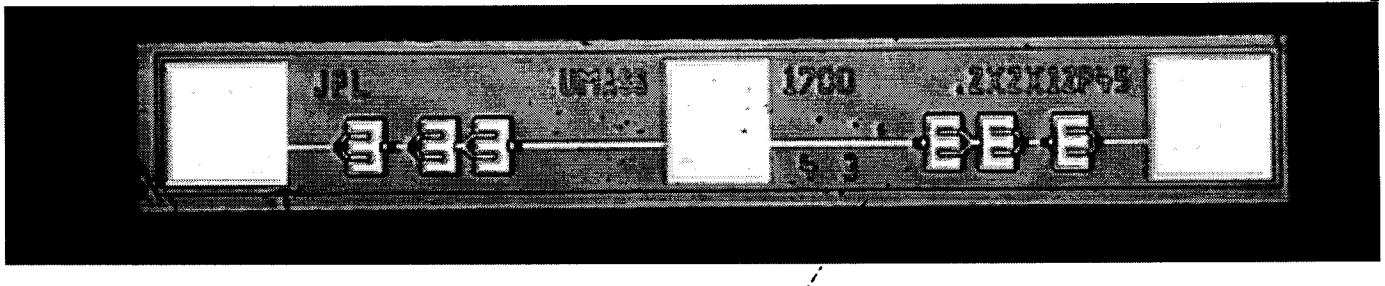
Figure 2. Power output from single and dual power combined packaged TRW MMIC amplifiers at W-band.

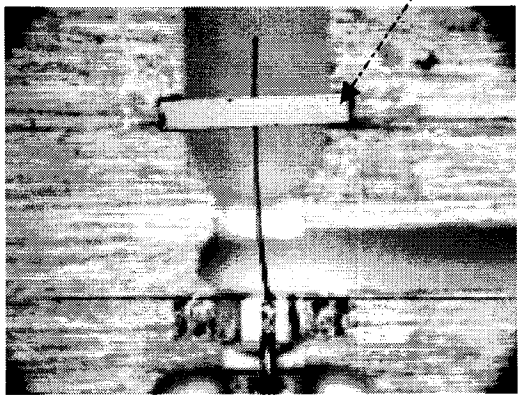
Ref: R. Lai et. al, "A high efficiency 0.15 um 2-mil thick InGaAs/AlGaAs/GaAs V-band power HEMT MMIC," IEEE GaAs IC Symposium Digest, Nov. 1996.

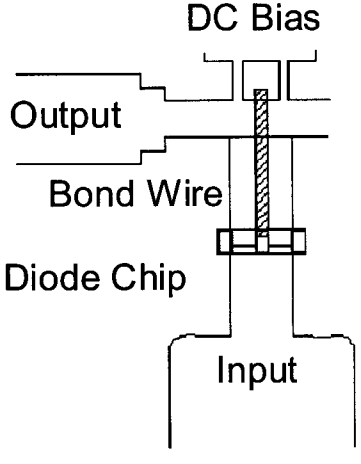
M. D. Biedenbender et al, "A 0.1 um W-band HEMT production process for high yield and high performance low noise and power MMIC's," 16th GaAs IC Symposium, 1994.

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

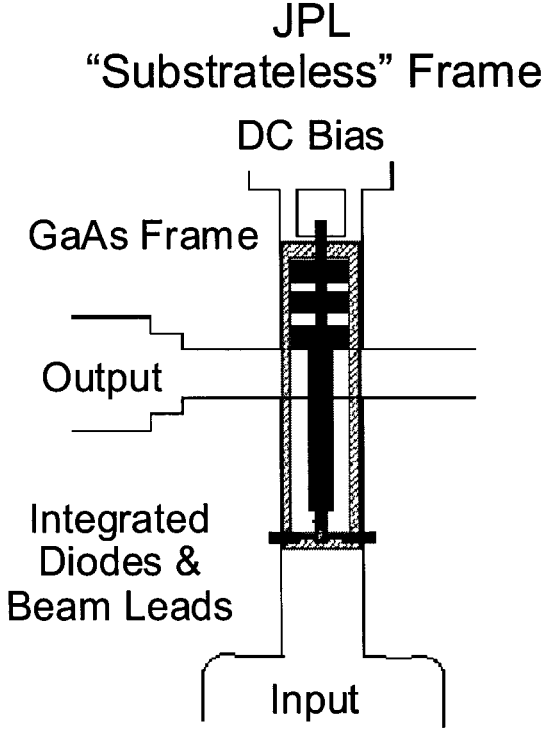
- Chip soldered to block
- Bondwire connects chip to DC Bias Cap

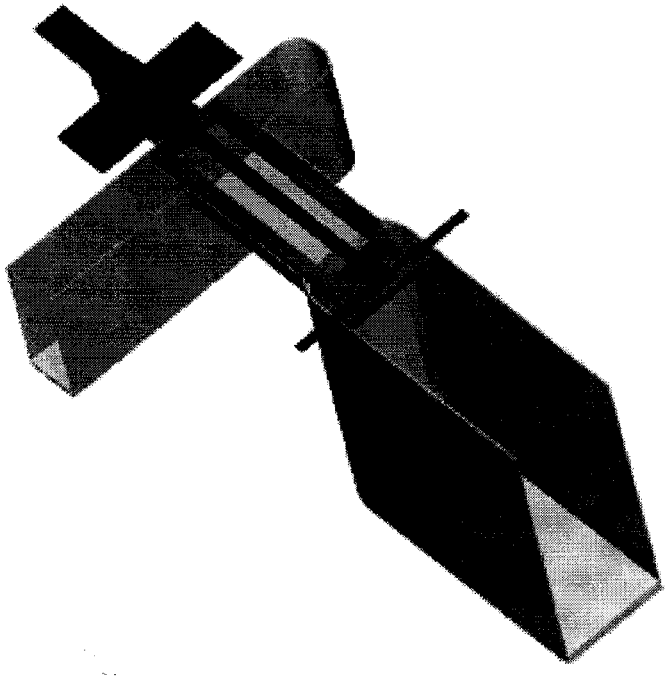
Q: Can this approach be extended in frequency?

2nd stage multiplier

A: **Yes**—but it gets very difficult to implement

Solution: Integrate circuitry with device !





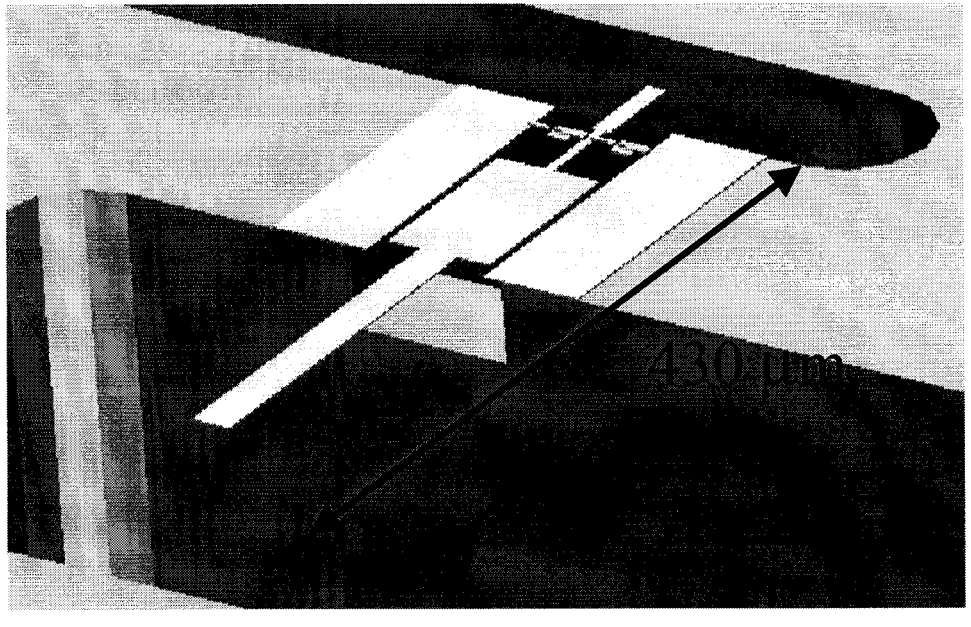
- All chip connections to block made with beam leads
- Diodes integrated into circuit
- GaAs under metal removed for low loss

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!

JPL supported Device Processes

LF

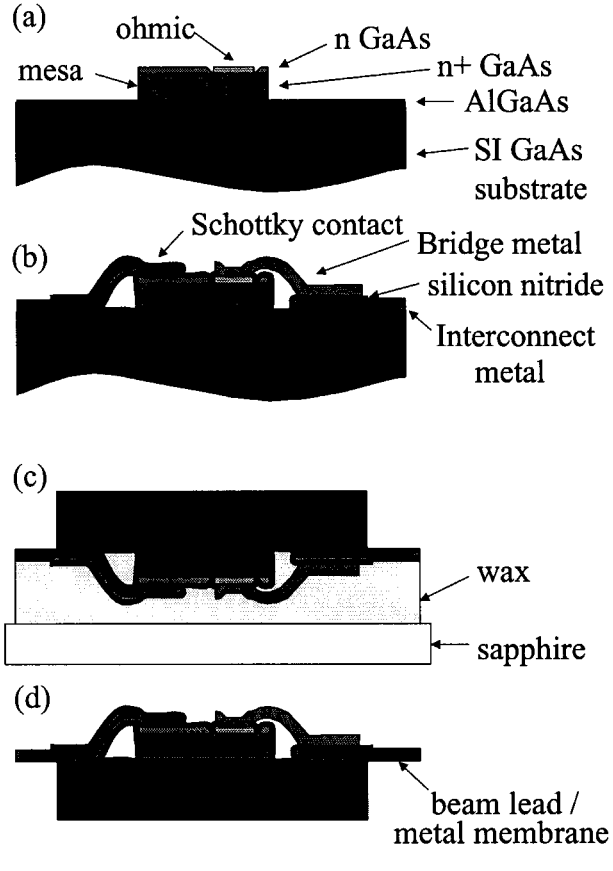


Fig. 1 Low Frequency process. (a) Ohmic and mesa definition. (b) Interconnect metal and air-bridged Schottky deposition, followed by passivation and bridge metal definition. (d) Backside thinning and device separation. (e) Release of device from carrier wafer.

HF

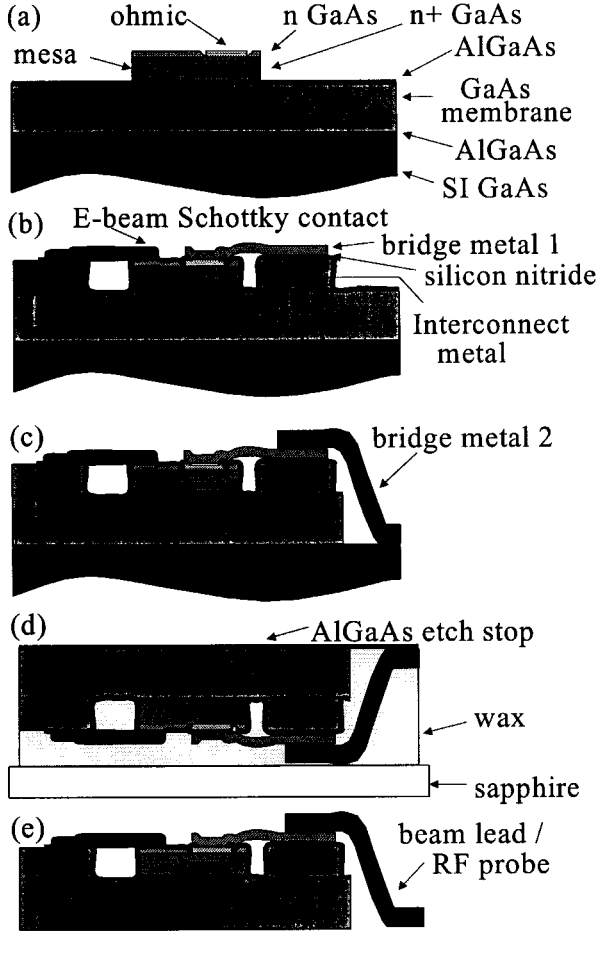
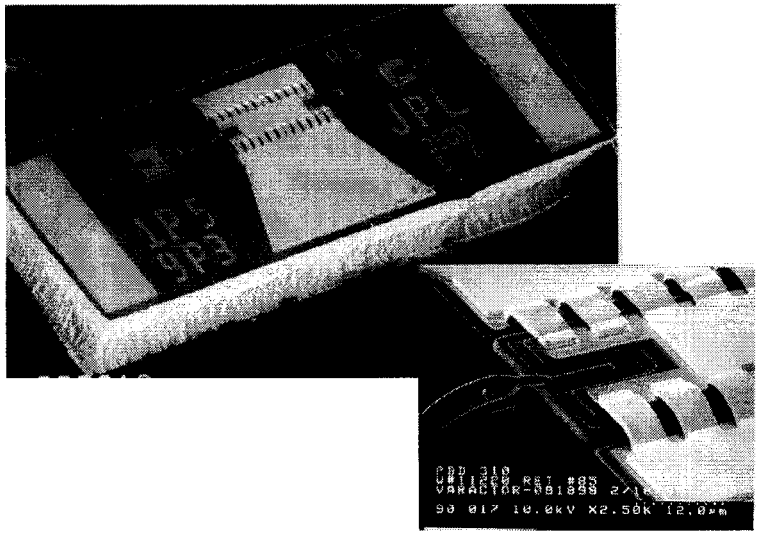
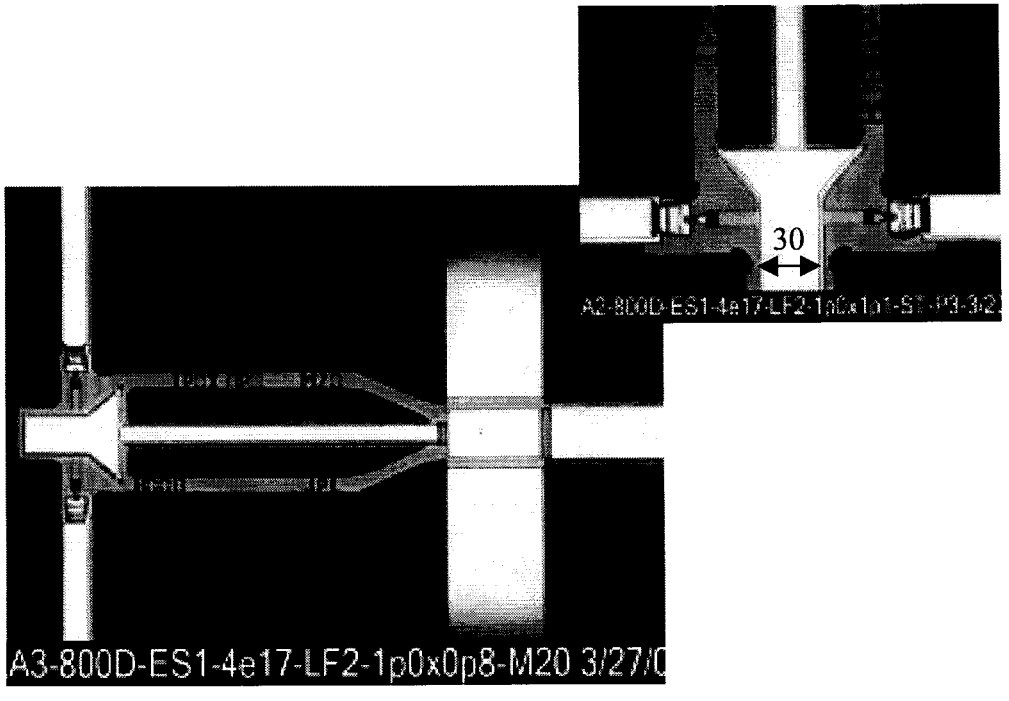


Fig. 2 High Frequency process. (a) Ohmic and mesa definition. (b) Interconnect metal and e-beam-defined Schottky deposition, followed by passivation and bridge metal 1 definition. (c) Membrane layer etch and bridge metal 2 deposition. (d) Removal of substrate with selective etch. (e) Release of device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

Planar device alternatives

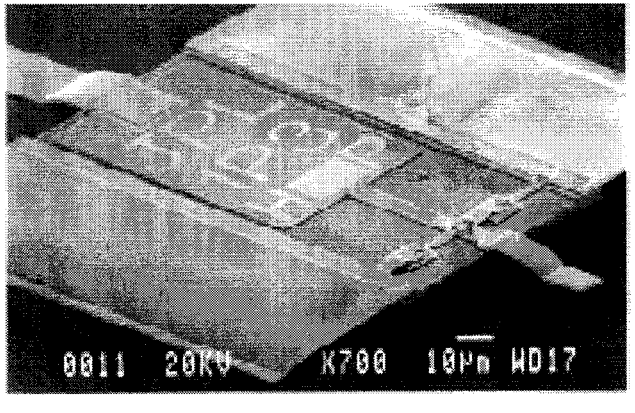


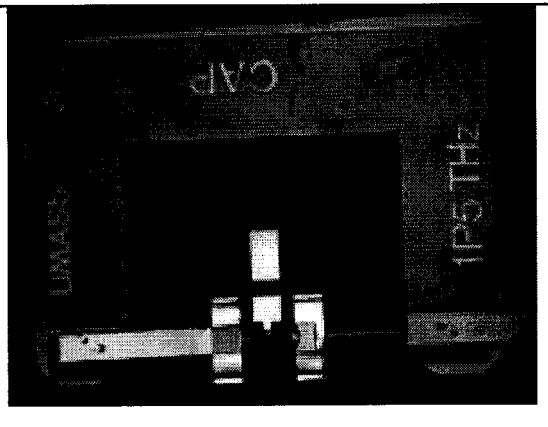
Discrete devices



Monolithic substrateless devices

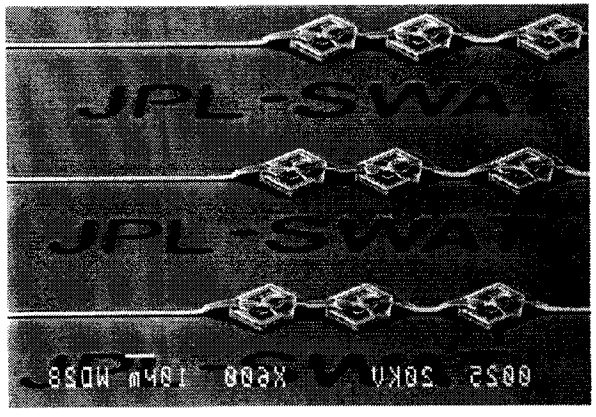
Frameless membrane devices



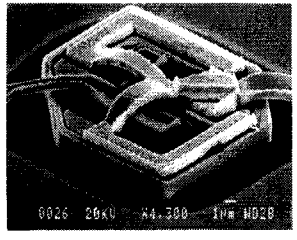


Framed membrane based devices

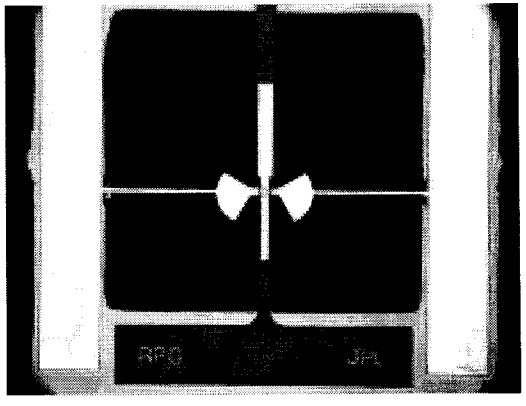
Some more devices…



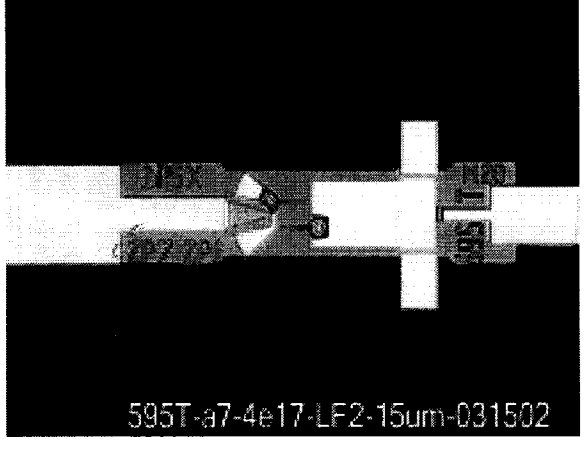
140 GHz chip



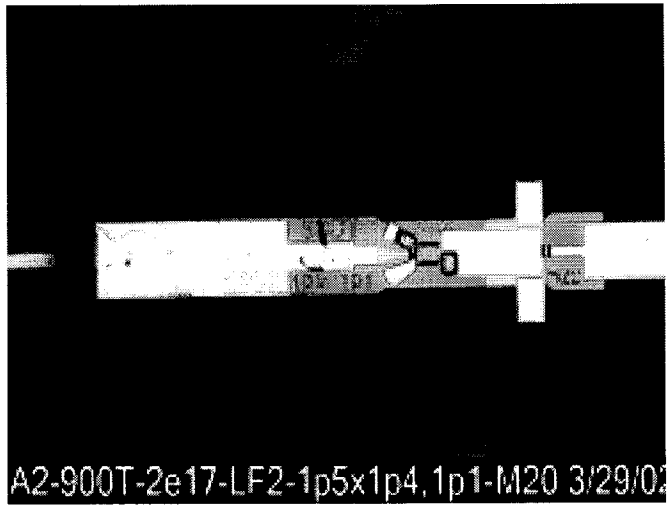
1100 GHz Tripler

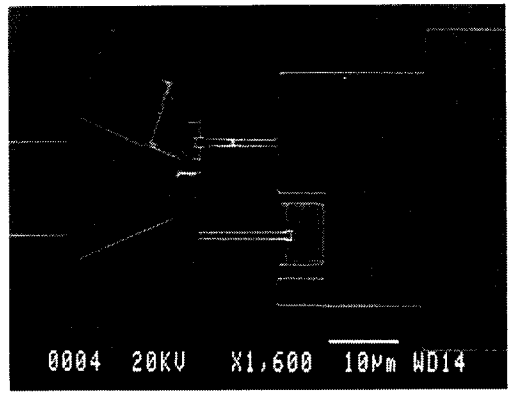


595 GHz Tripler



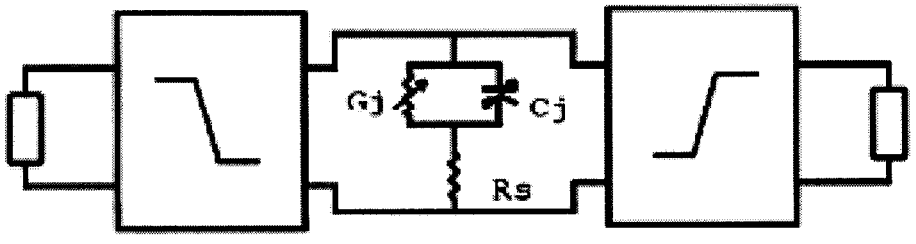
900 GHz tripler





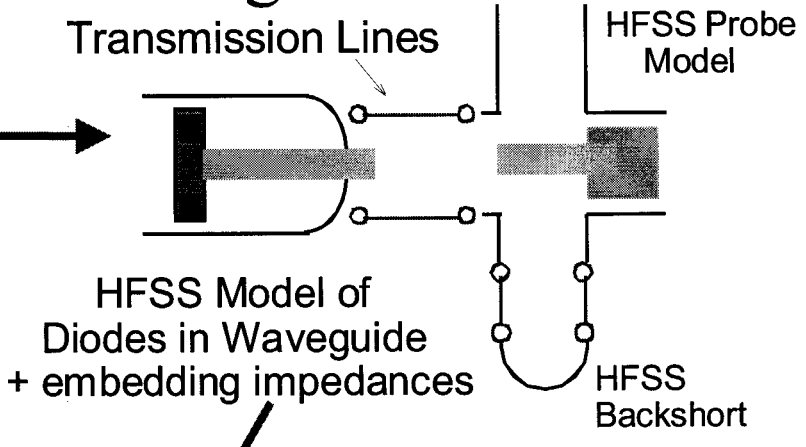
Three-Step Multiplier Design Strategy

1. Optimize Diode

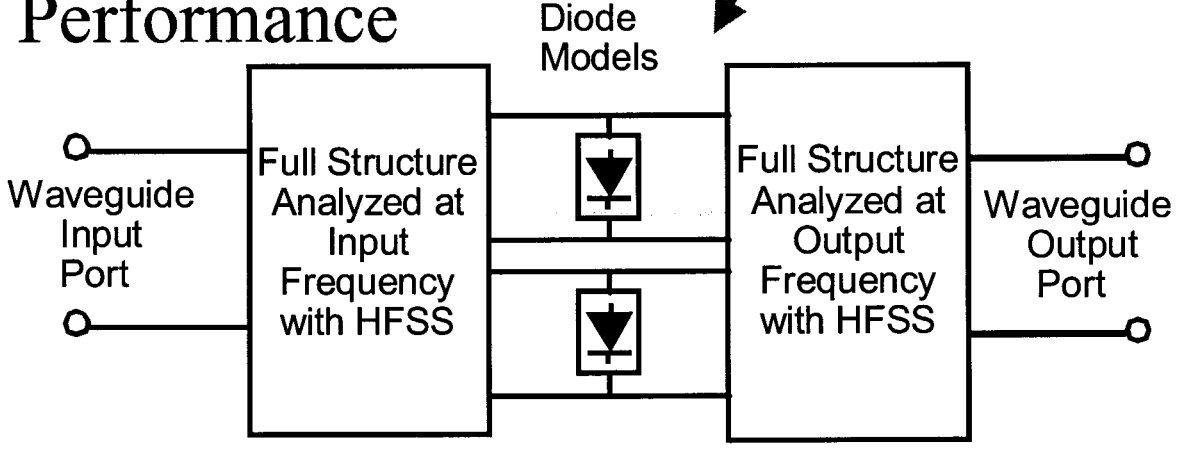


Optimize diode size and find embedding impedances using harmonic balance simulator and diode model.

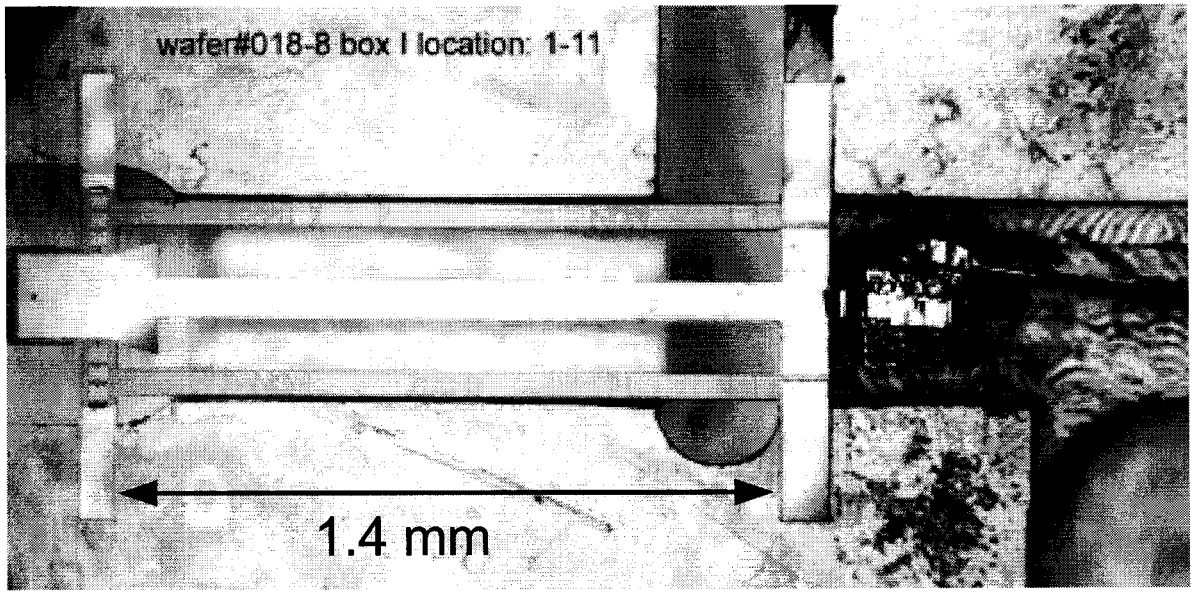
2. Design Linear Circuit



3. Calculate Performance



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

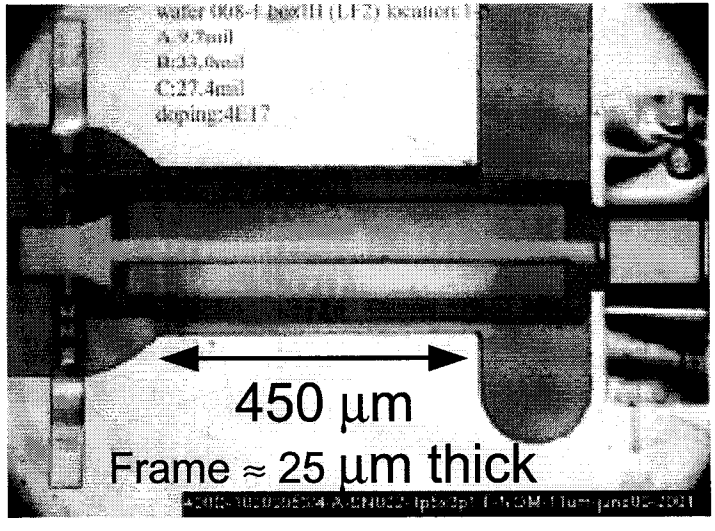
6 diodes for high power handling

Thick frame ($\approx$ 25 μm) for thermal conduction

Tuning stub for first pole output tuning

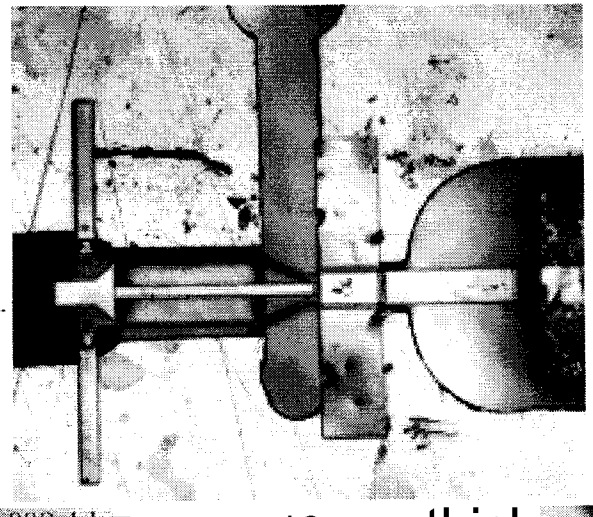
All have been demonstrated.

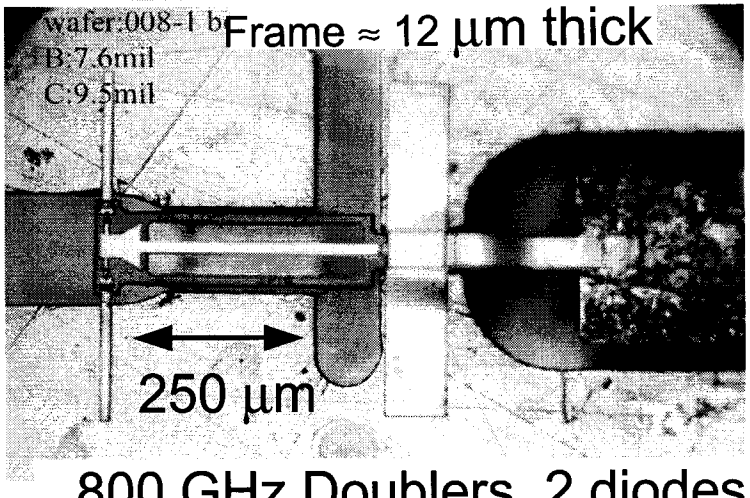
Particulars of 400 and 800 GHz Doubler Designs



400 GHz Doubler, uses 4 diodes

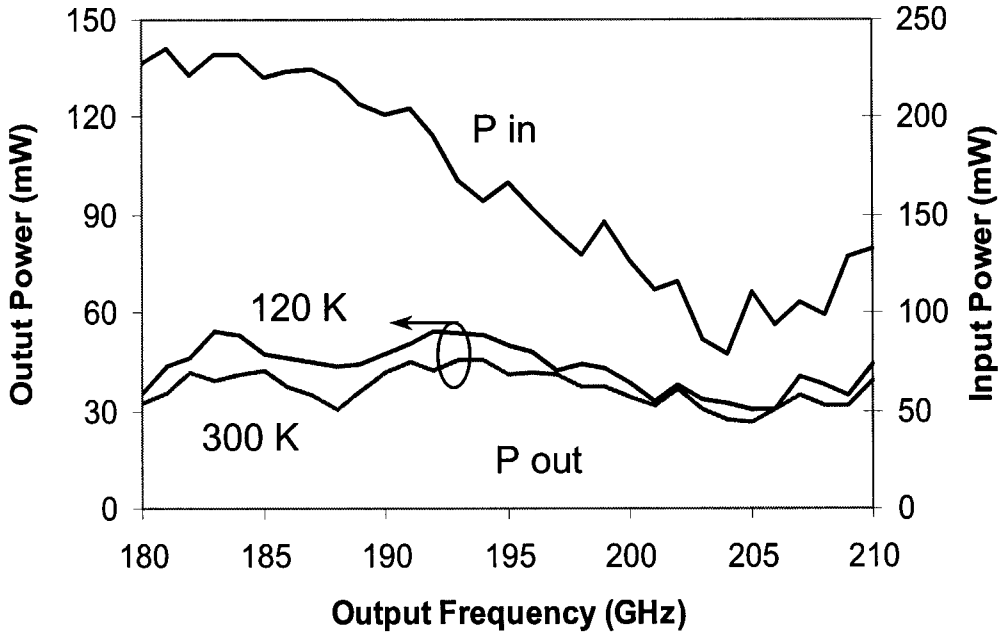
Higher frequencies require:
Higher precision machining
Higher doping — 2-4X10^{17}
On chip DC bias Capacitor
All have been demonstrated.



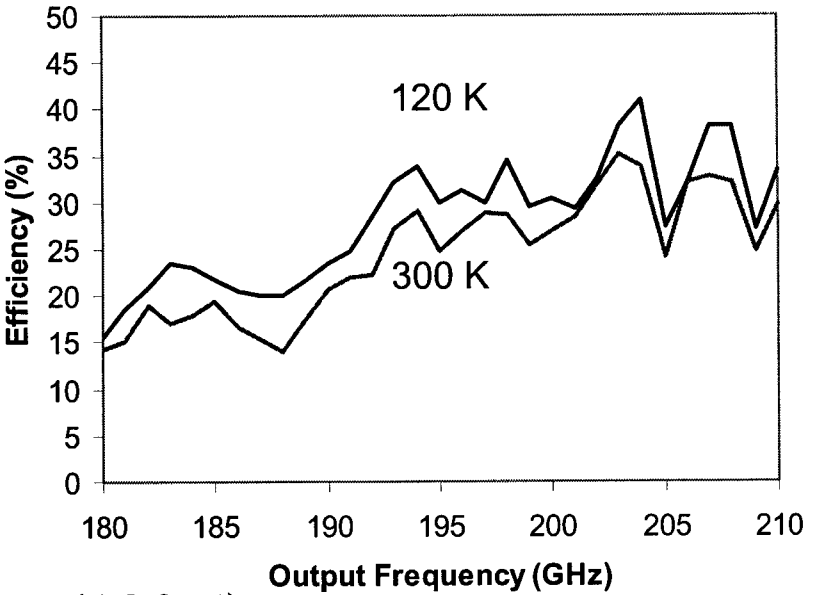


800 GHz Doublers, 2 diodes

200 GHz Doubler Performance

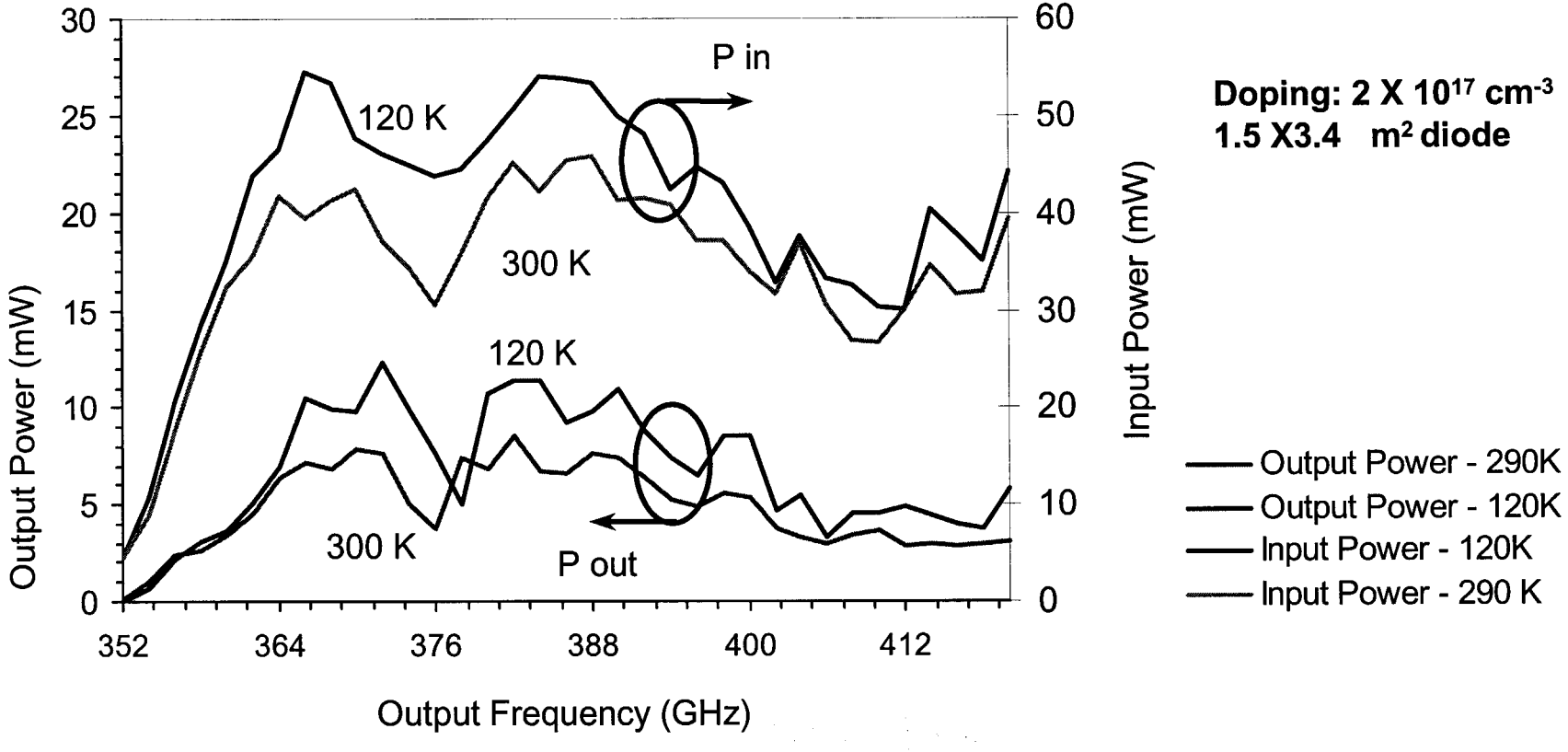


6 anode chip
3 X12 μm^2 (2e17) diode



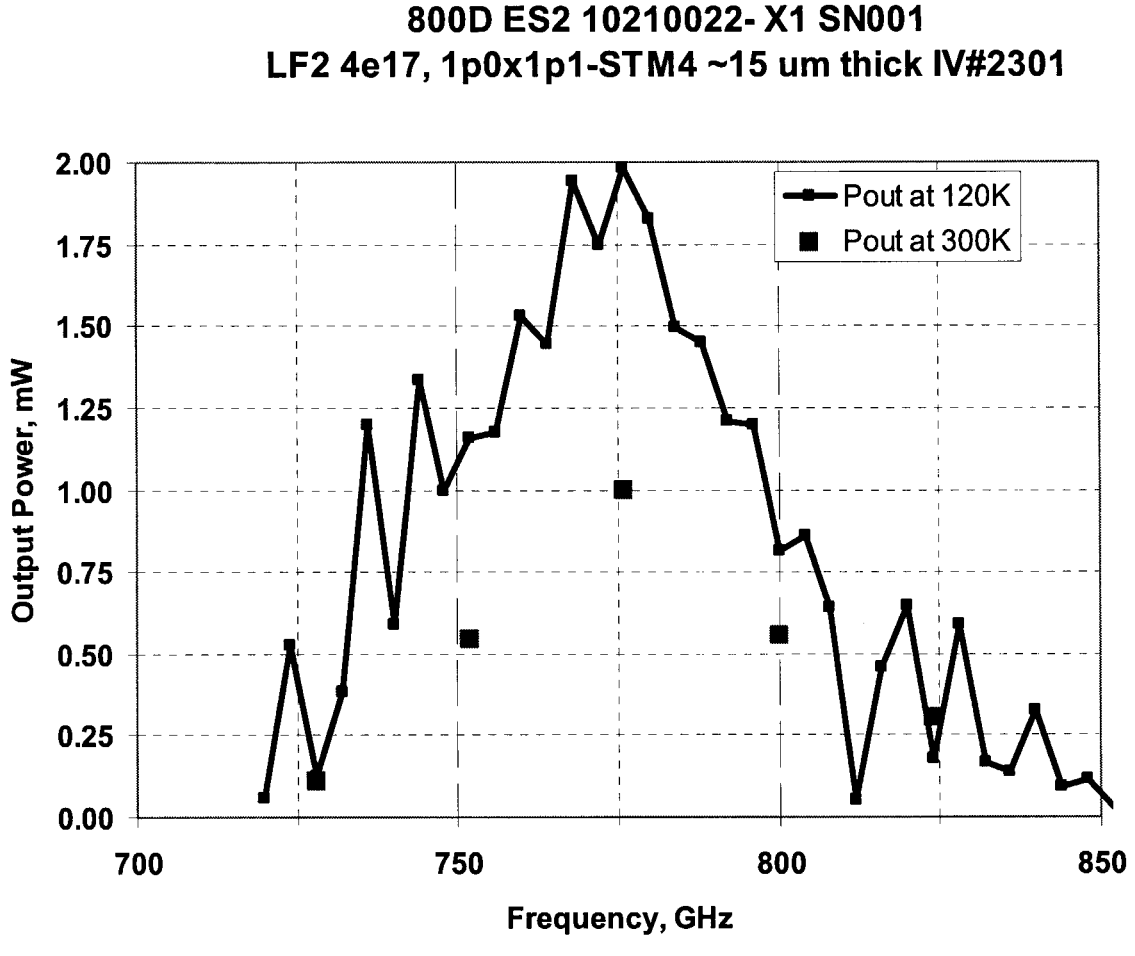
- Peak Power of 45 mW(300K) and 55 mW(120K)
- 3dB BW of >12%

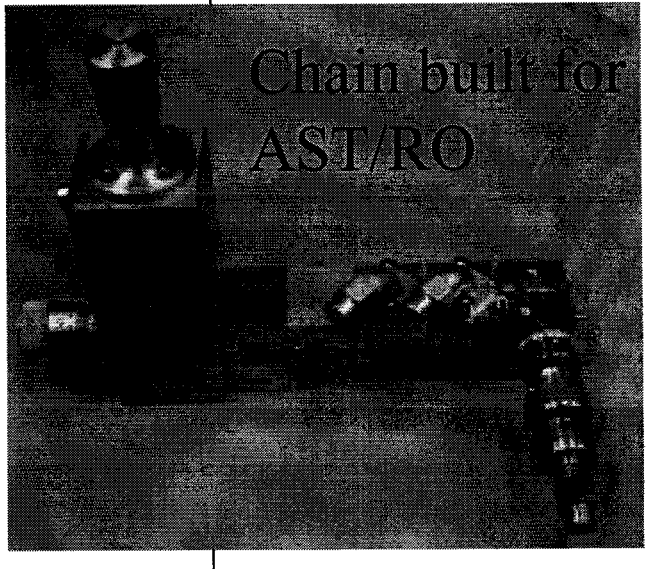
400 GHz Doubler Performance



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

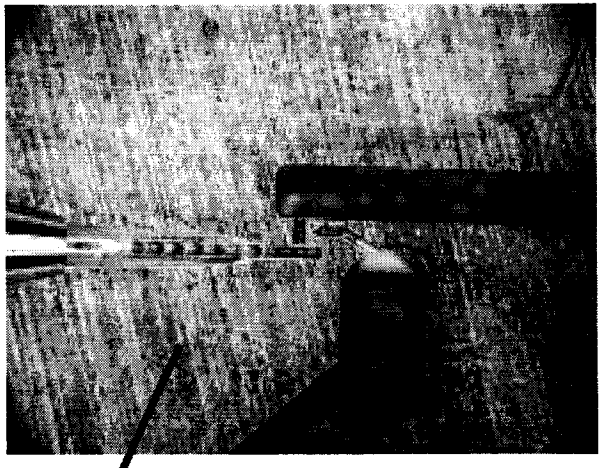
x2x2x2 Chain to 800 GHz

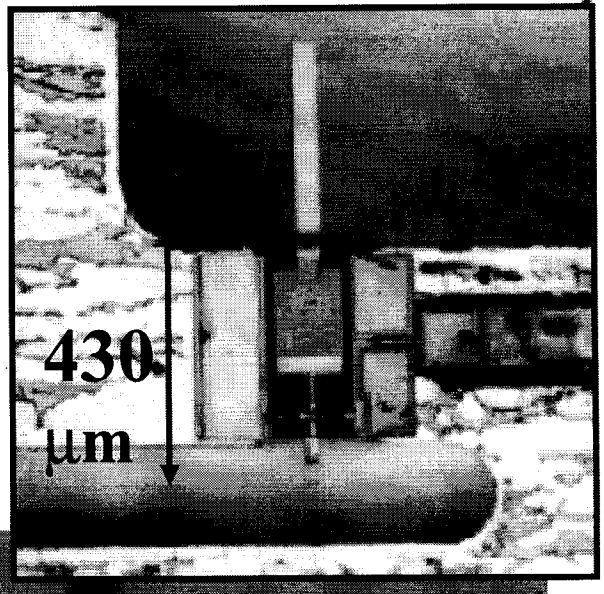


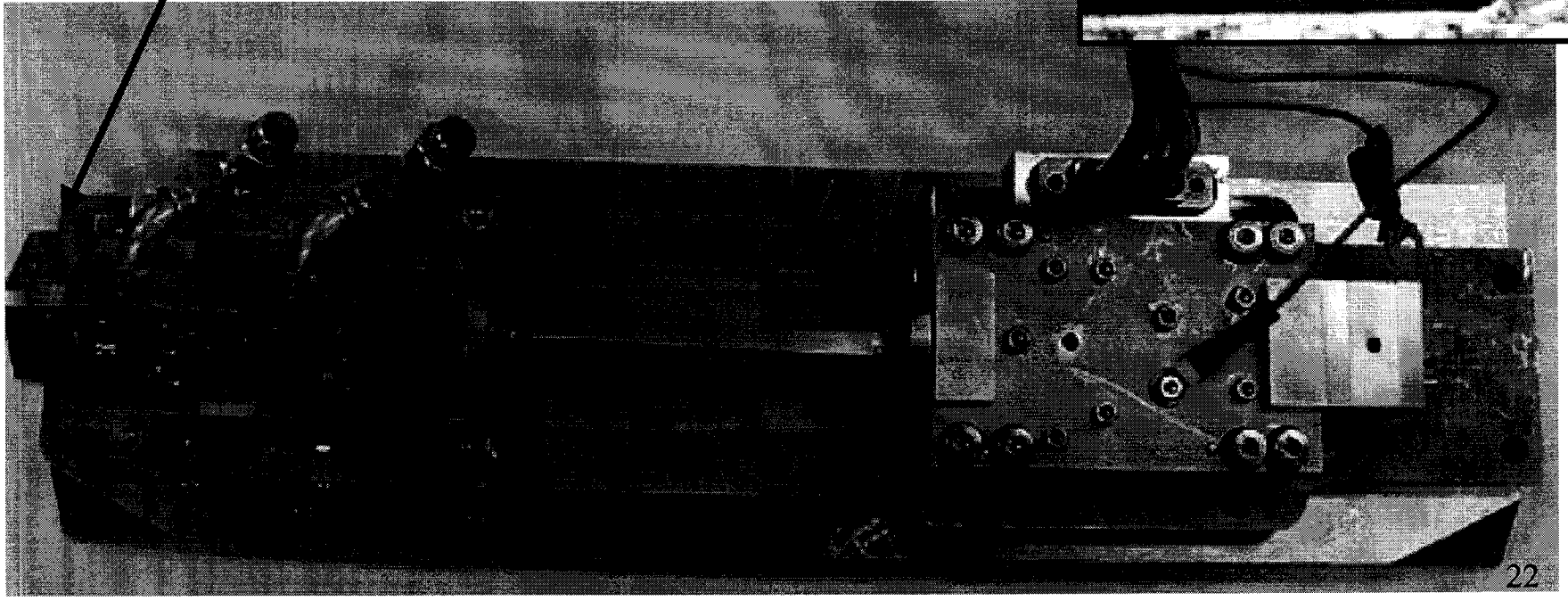


- At 120K peak power of 2mW, 3dB BW of >6%

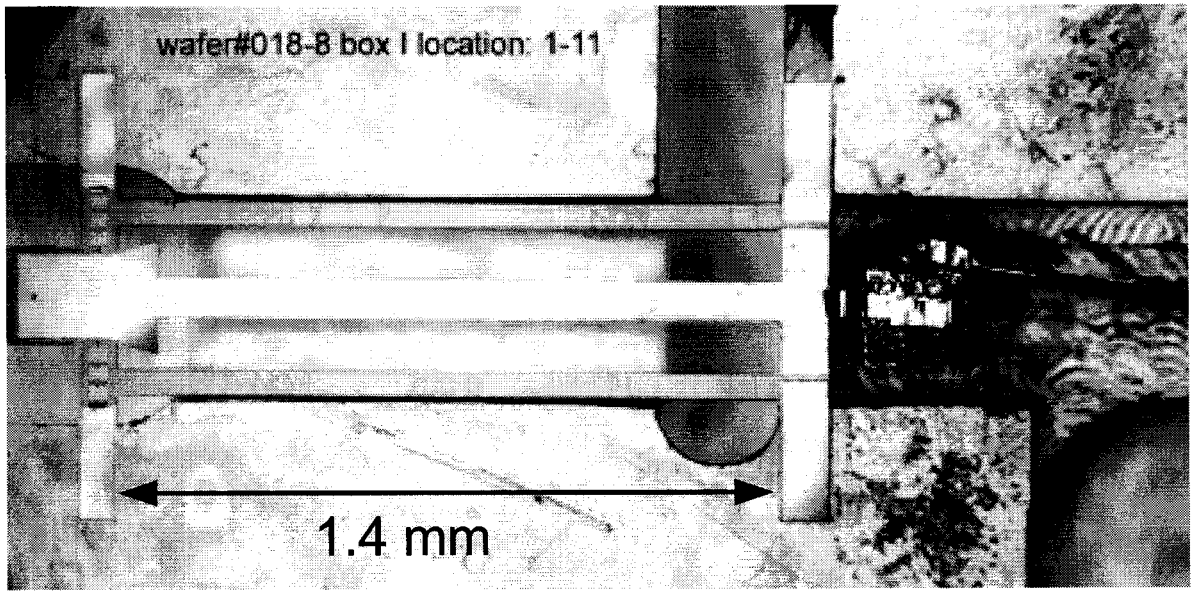
Planar LO chain at 1200 GHz







Particulars of 200 GHz Doubler Design



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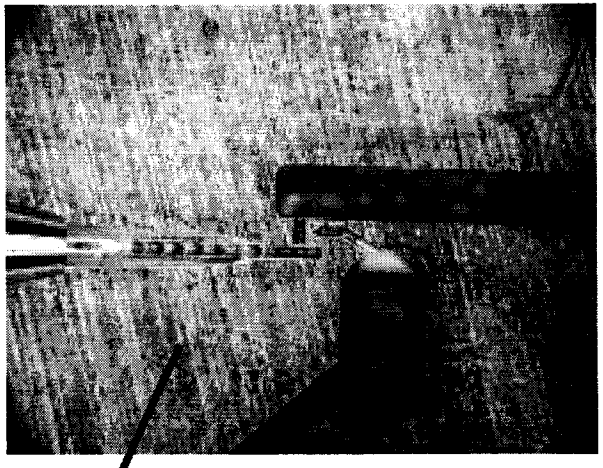
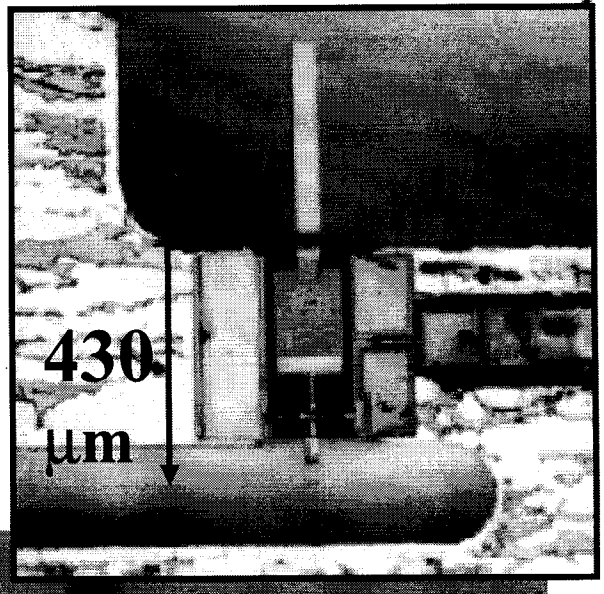
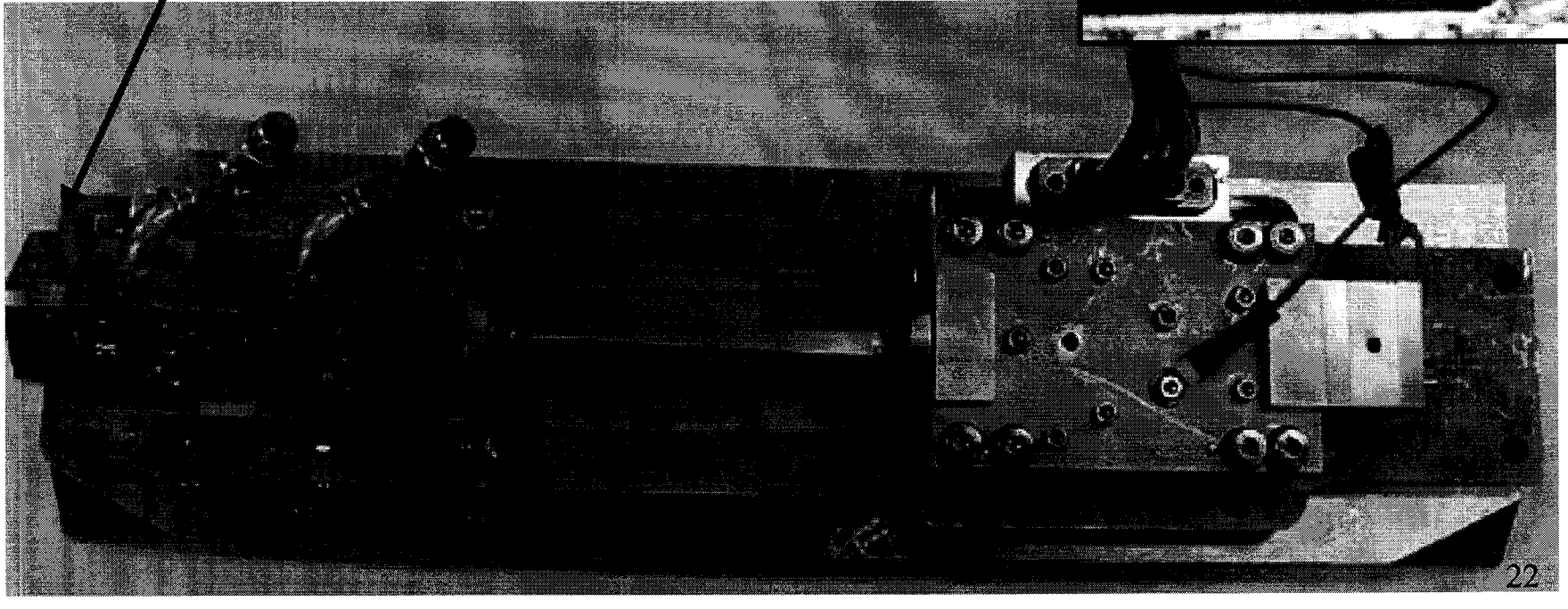
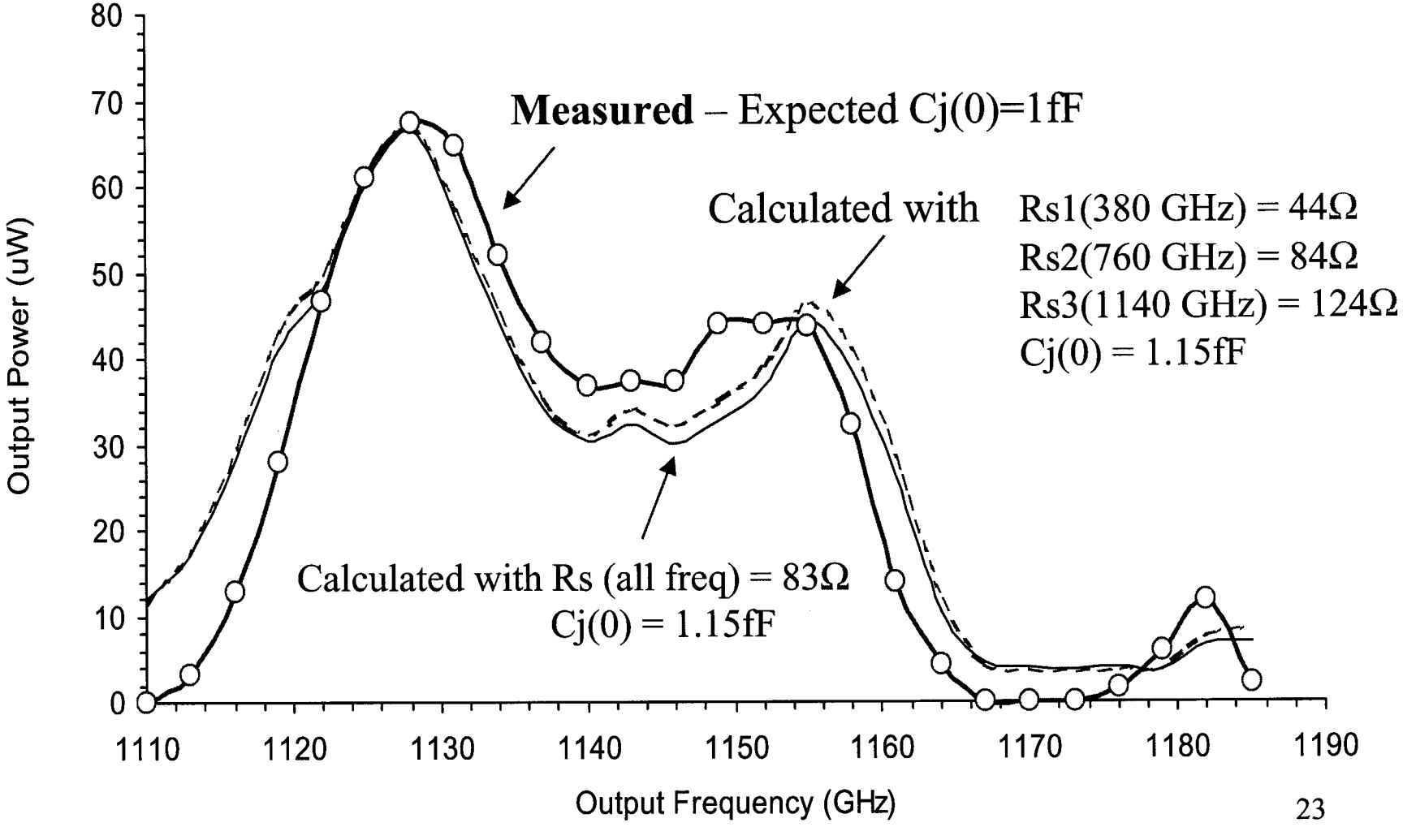






Measured *vs* Calculated Output Power of the 1.2 THz balanced tripler



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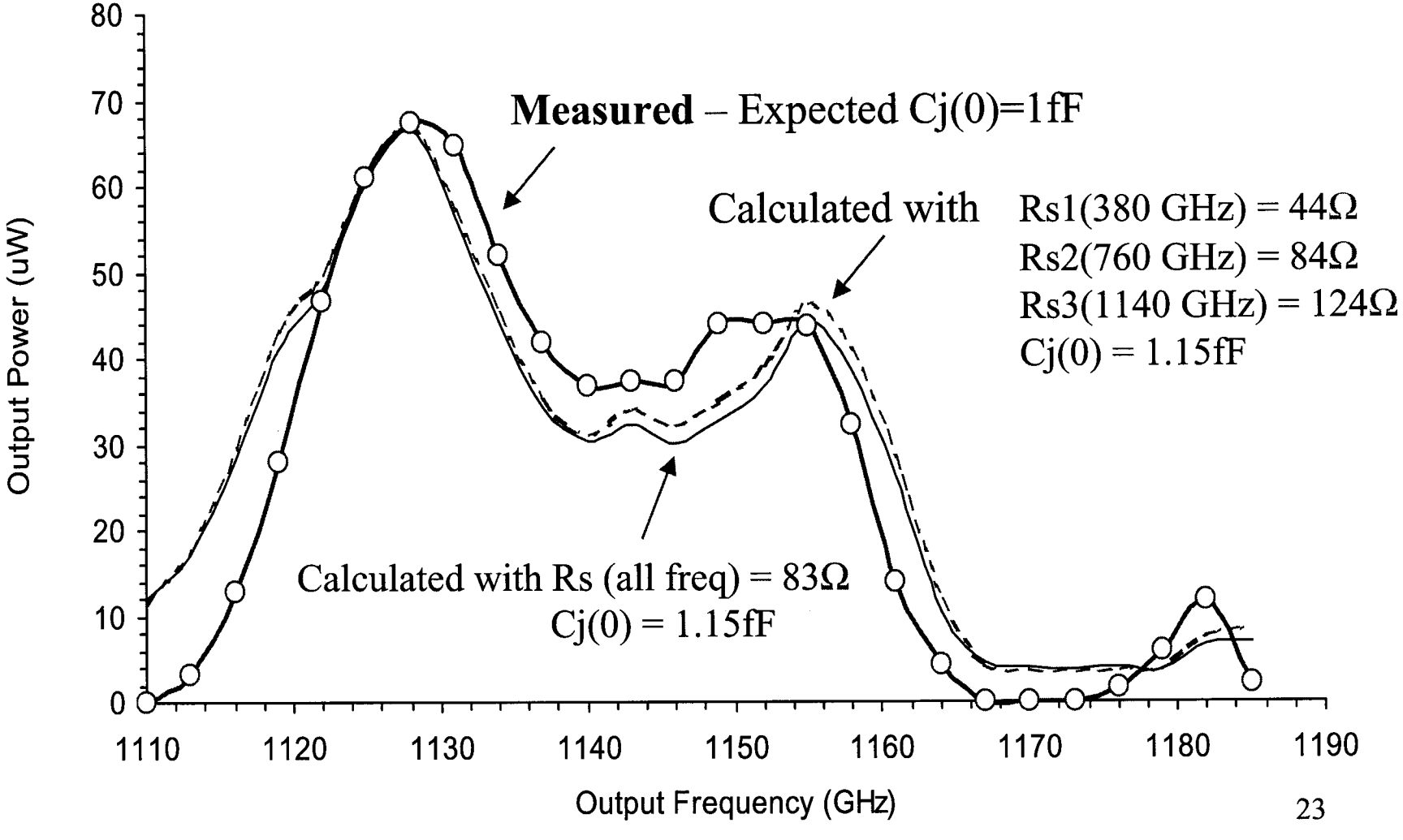
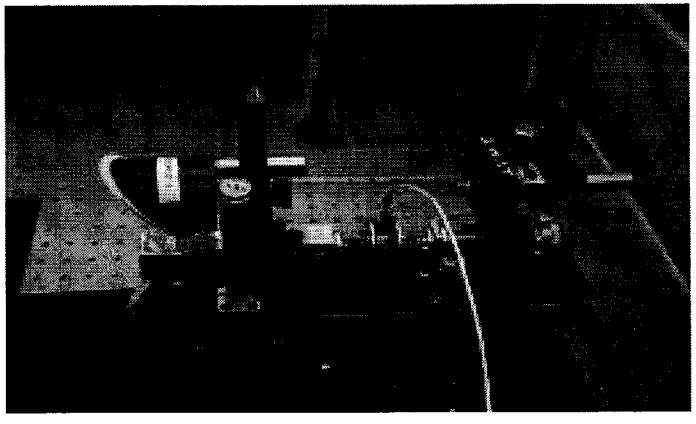
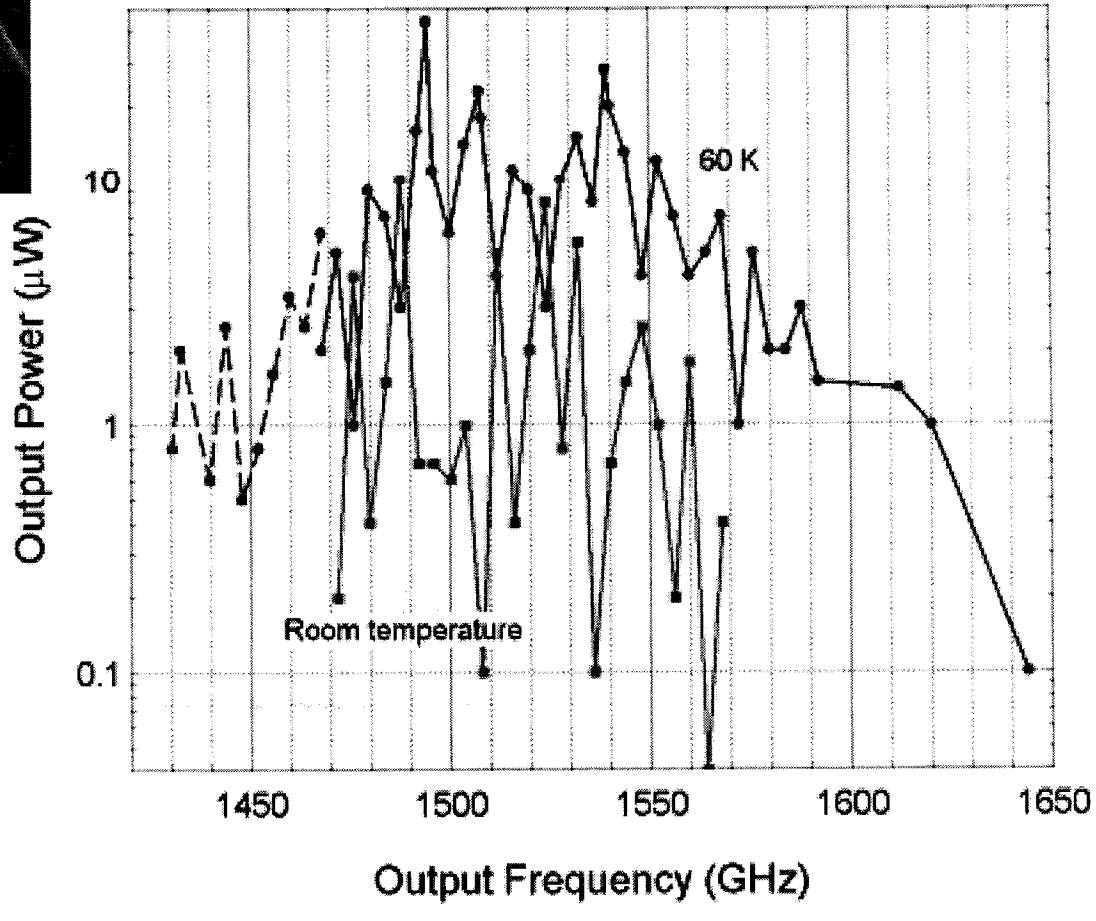


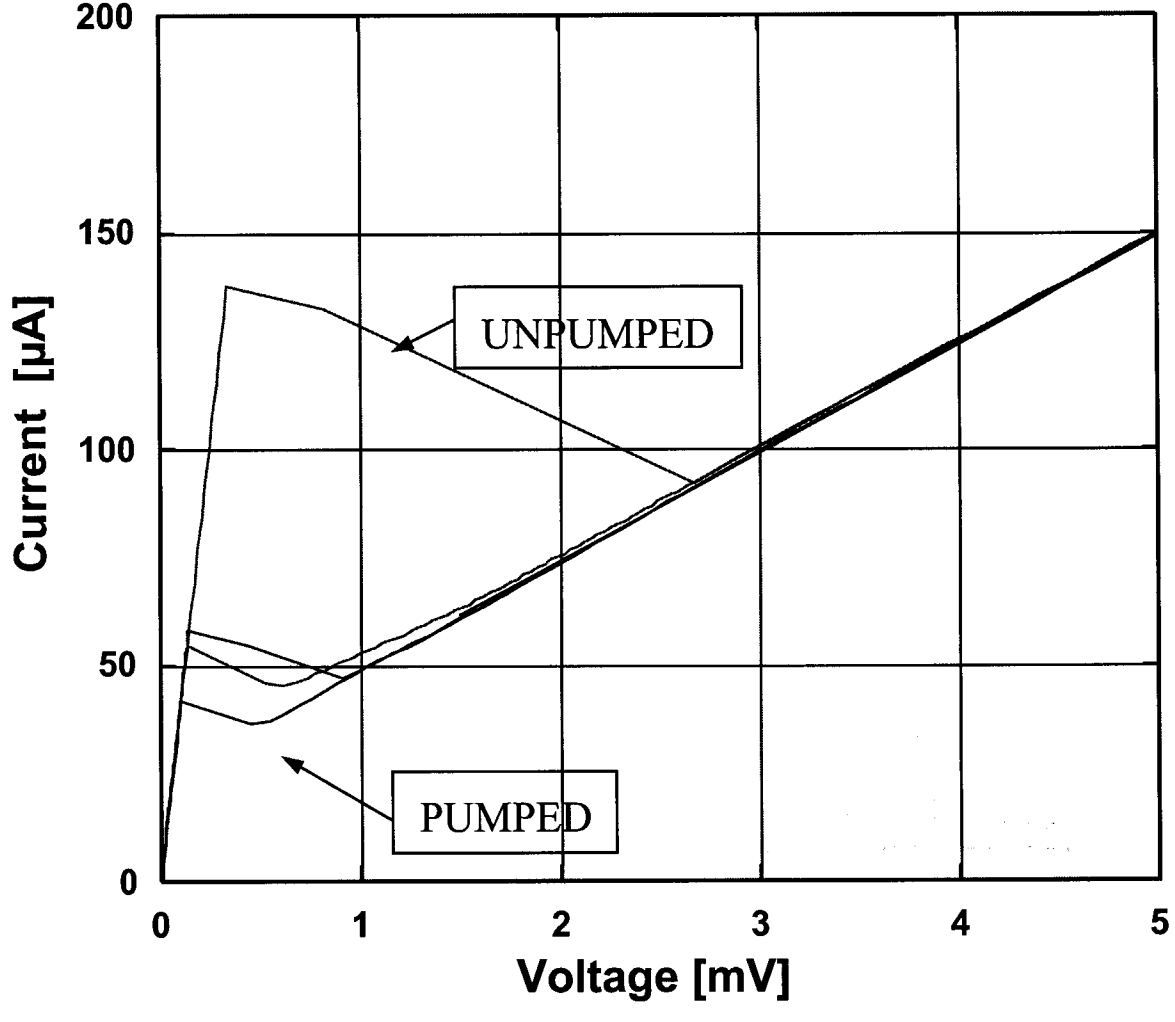
LO Source to 1600 GHz



X2x2x2x2 Chain Pout



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

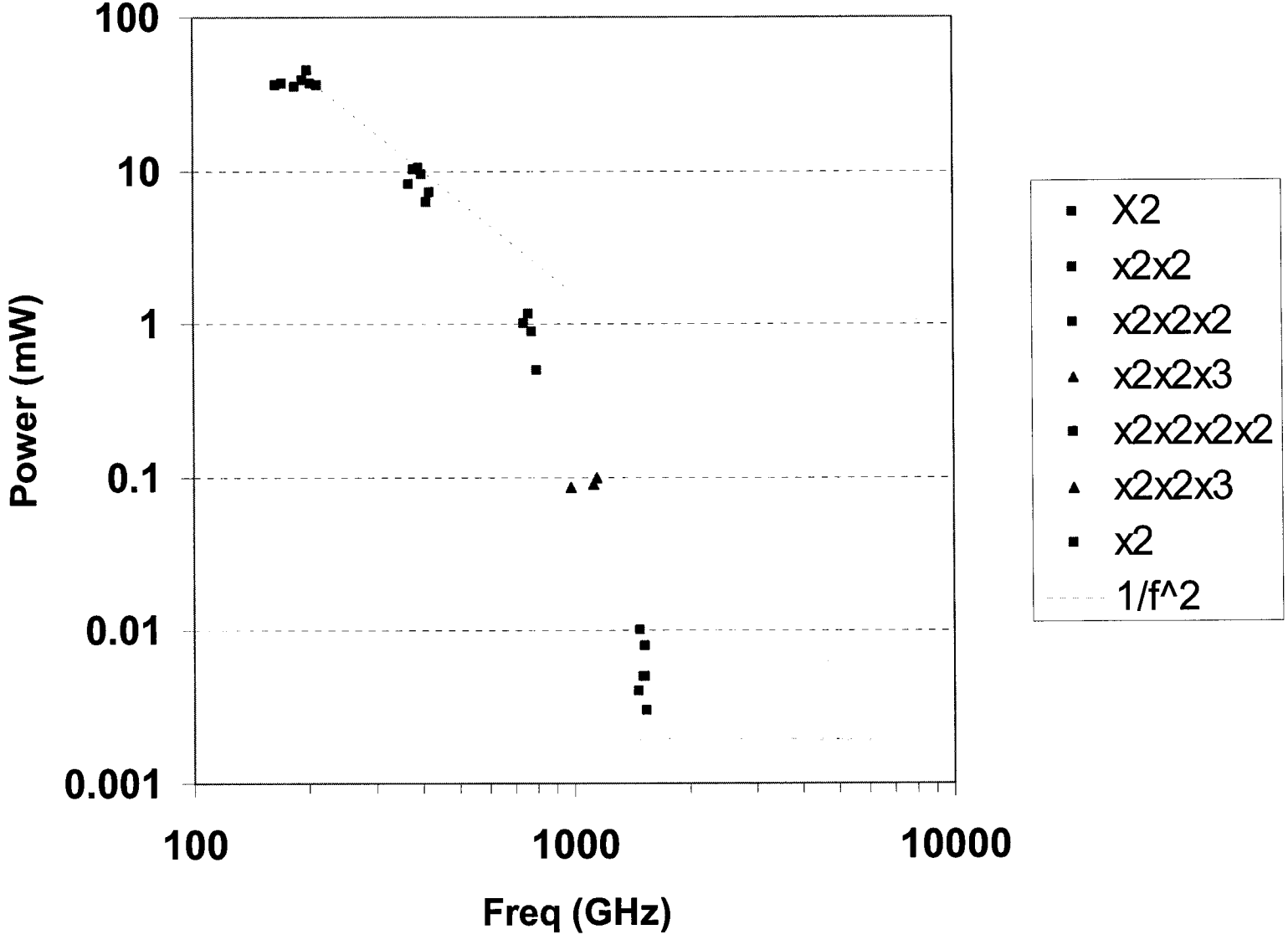
$P_{inc} \approx$ 80 - 100 nW (includes mixer and window losses only)

I_C = 137 μA

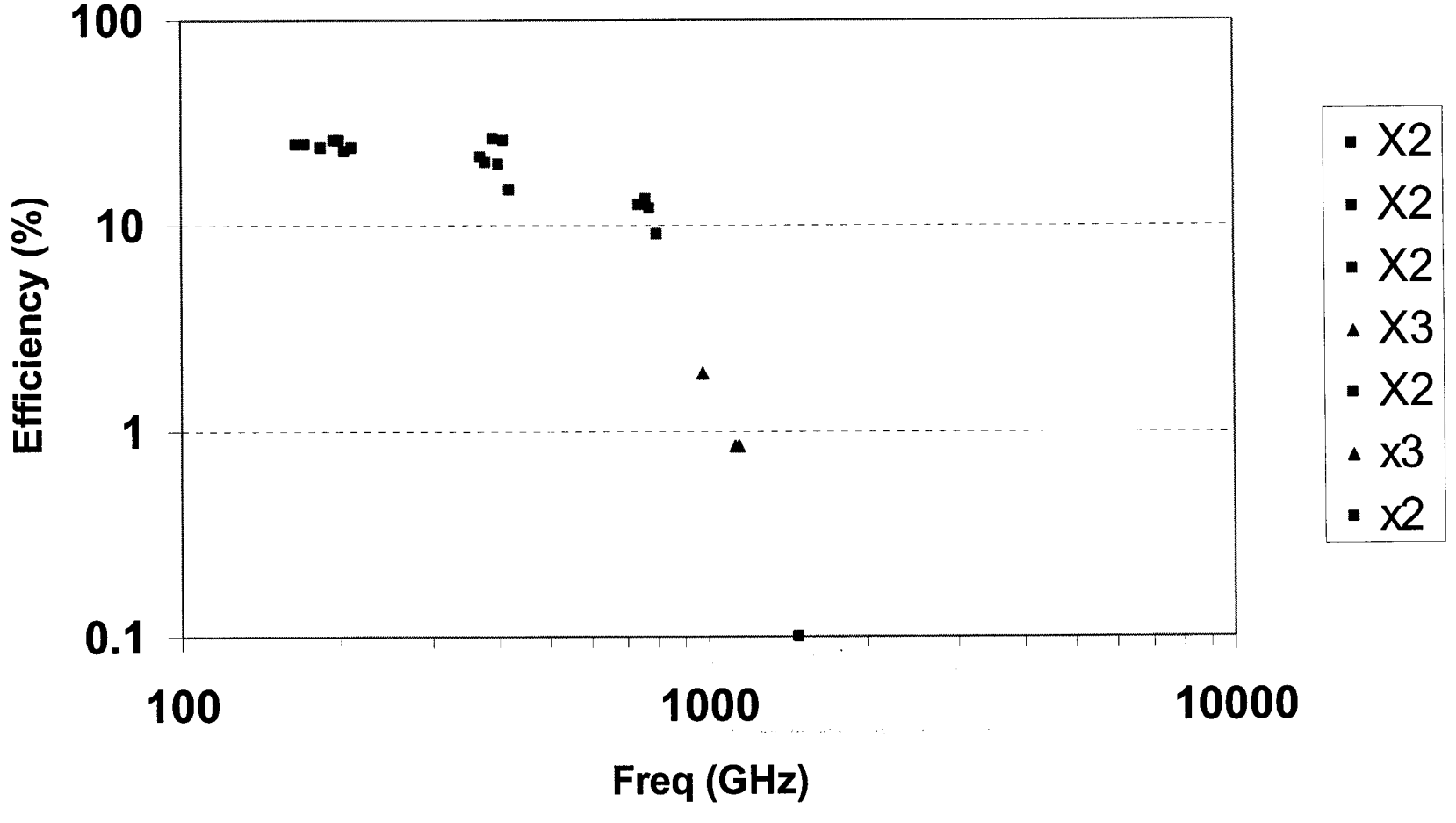
R_N = 34 Ω

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

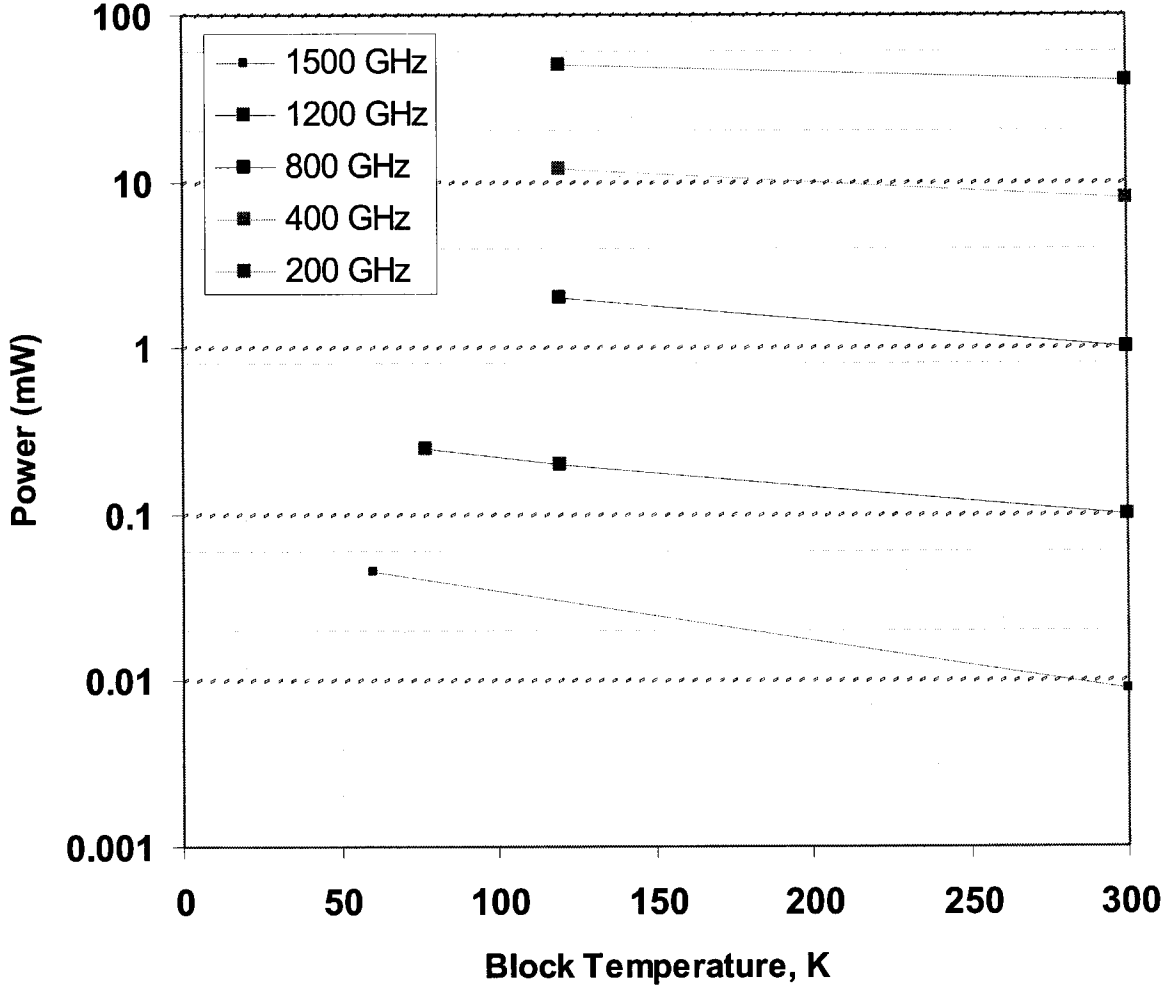
Current status of LO Sources at 300K



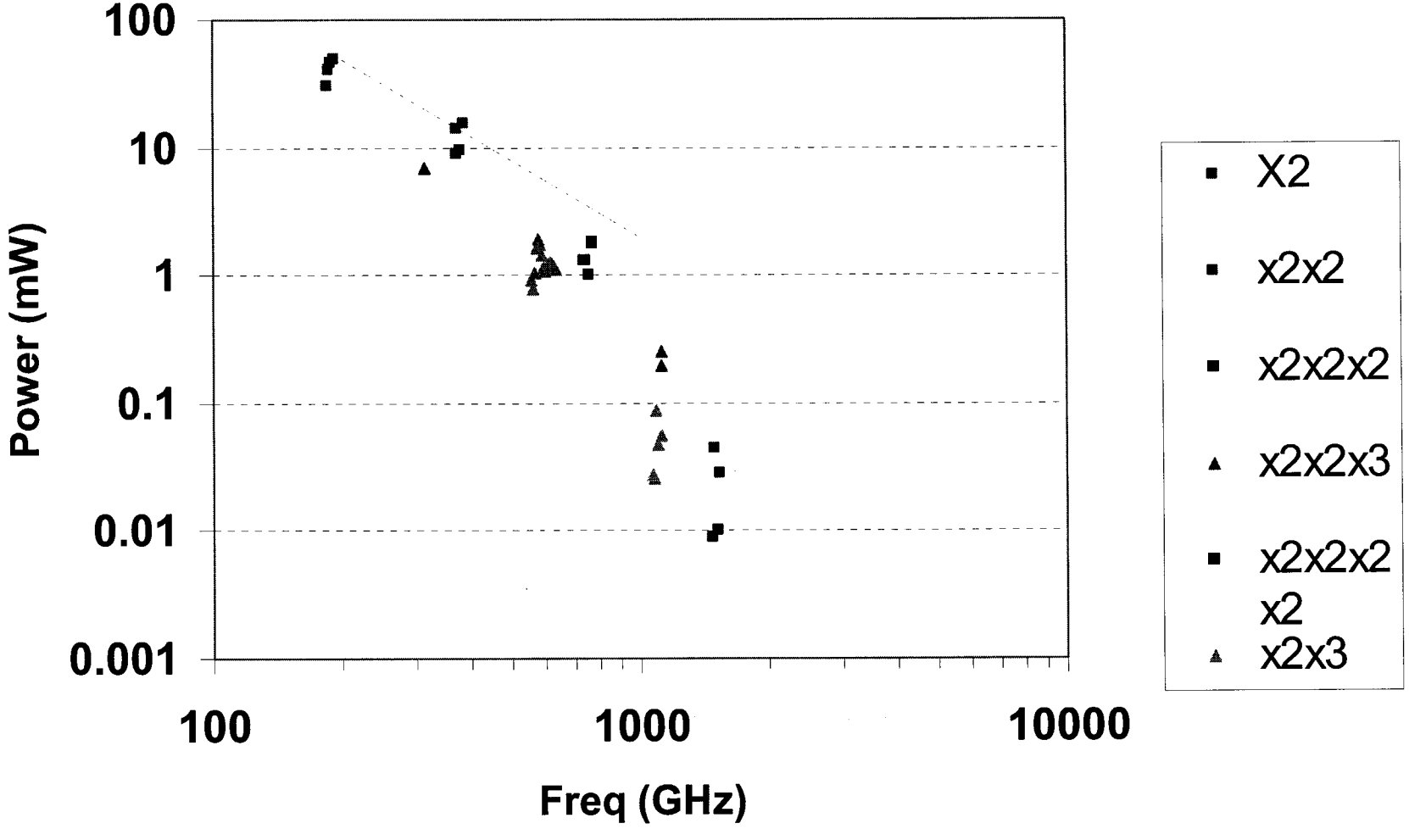
Current status of LO Sources at 300K



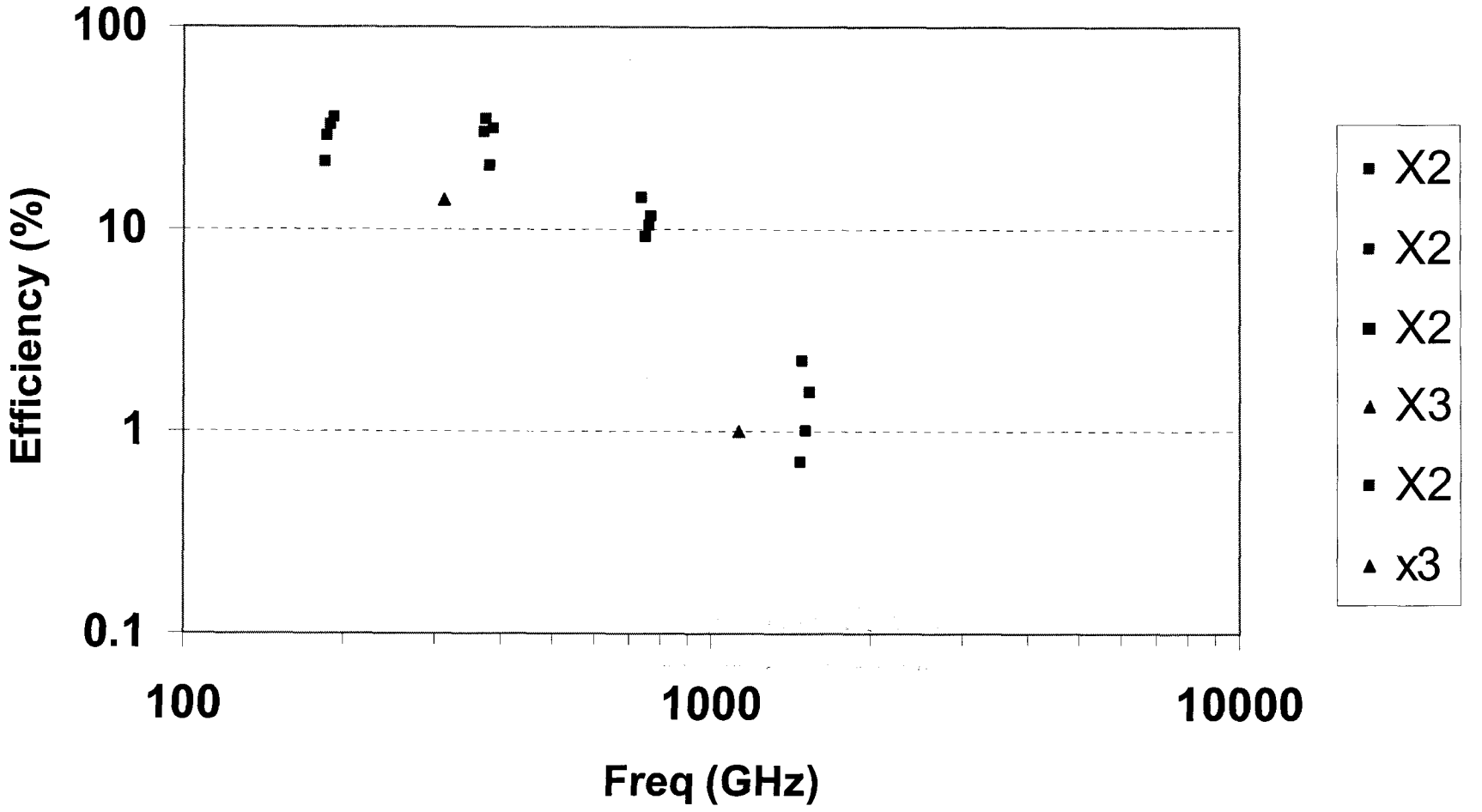
Output Power vs Block Temperature



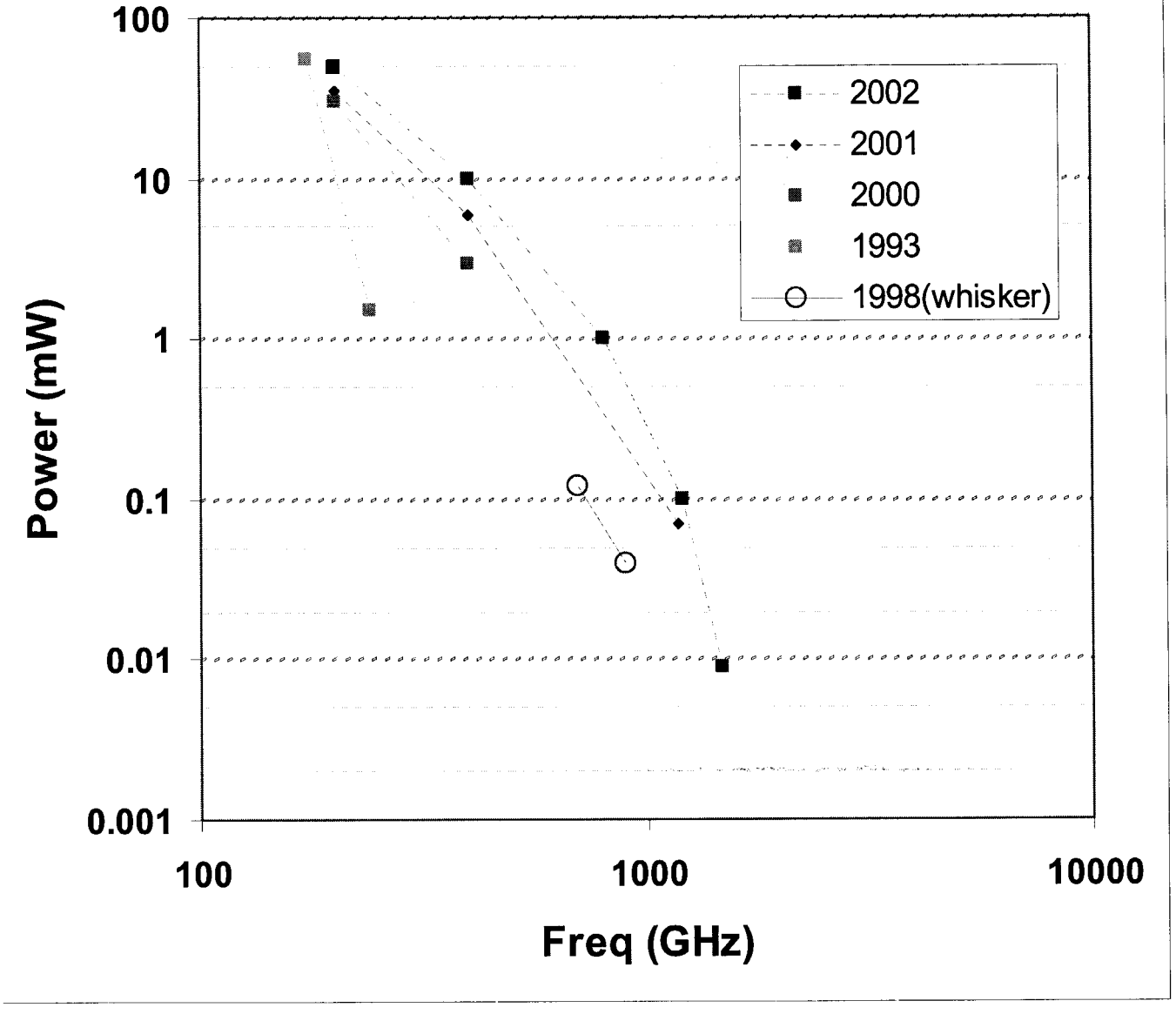
Current status of LO Sources at 60-120K



Current status of LO Sources at 60-120K

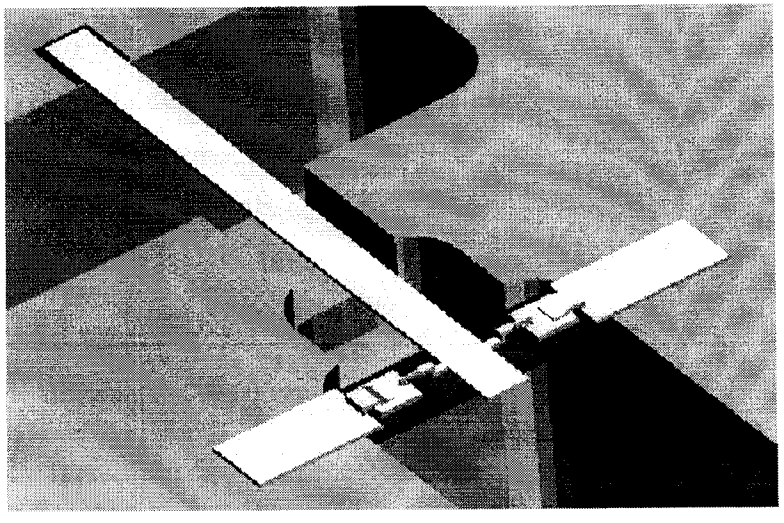


How far have we come?



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



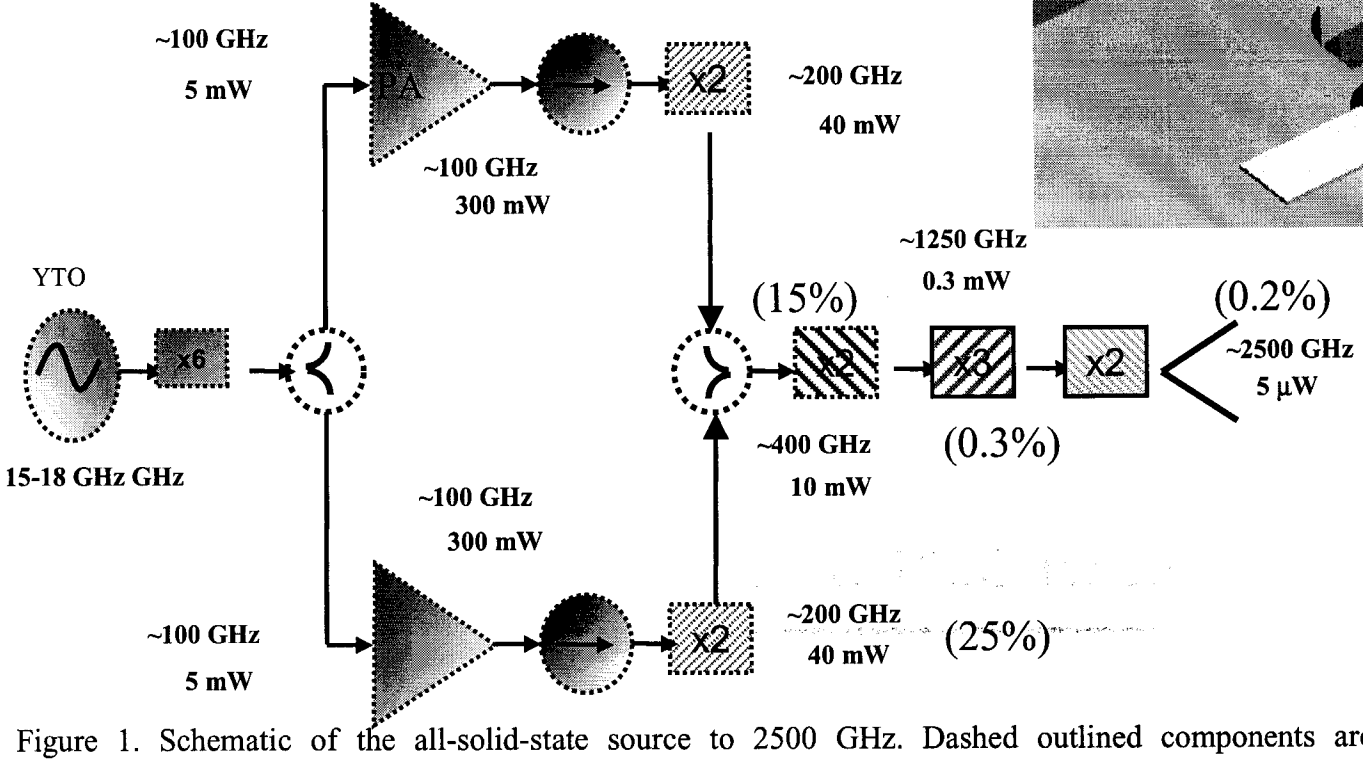
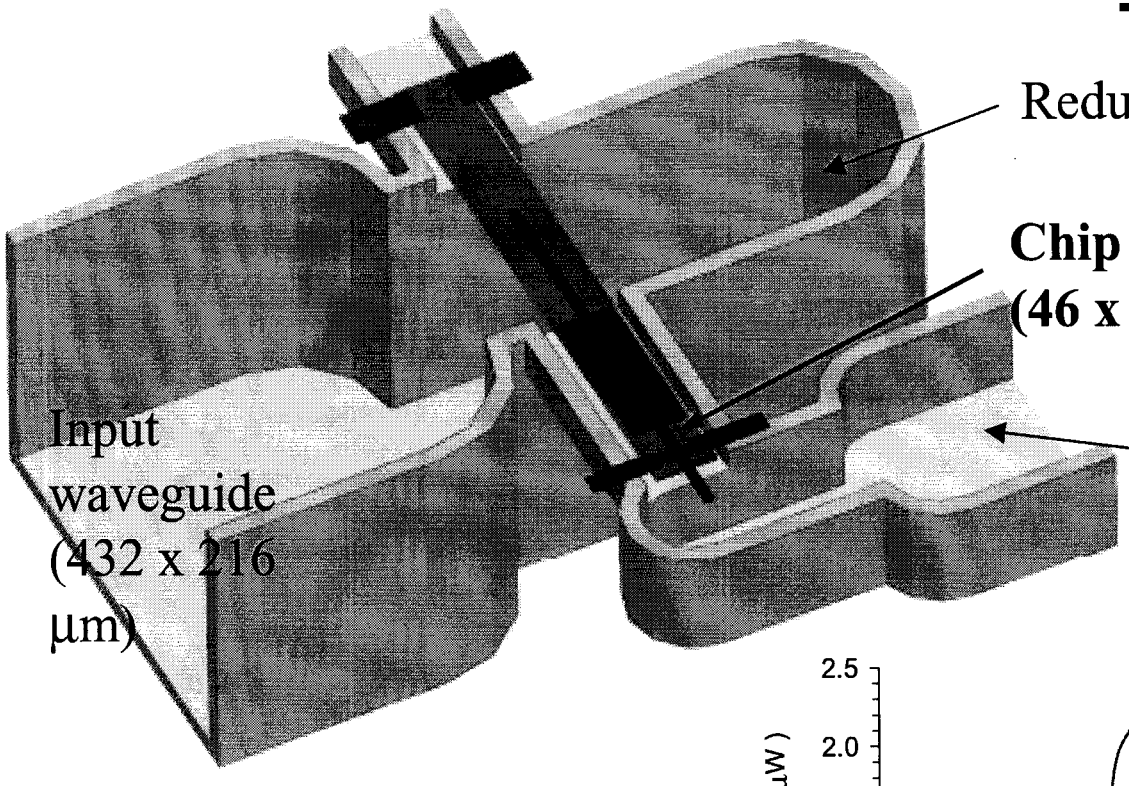
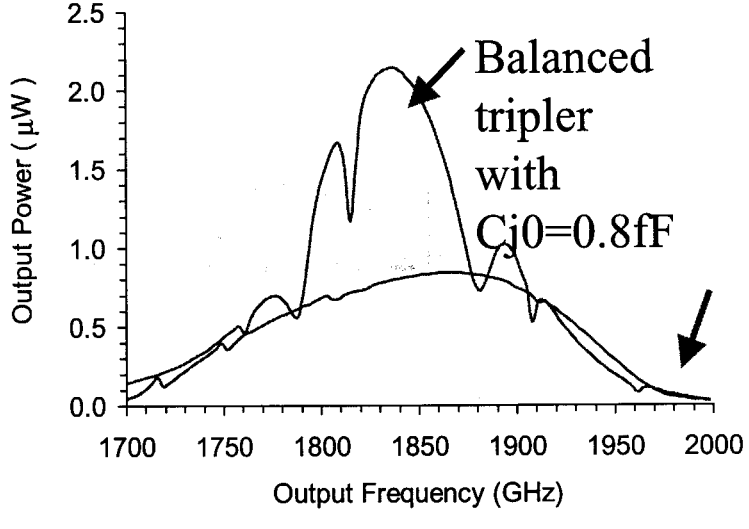


Figure 1. Schematic of the all-solid-state source to 2500 GHz. Dashed outlined components are either commercially available or have already been demonstrated in our laboratory. Solid outlined components are to be developed under this proposal.

1.9 THz Balanced Tripler



Input power = 2.5 mW



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

Challenges

- Improve bandwidth—better designs, re-configurable circuits
- Simplify chain construction—micro-machined blocks, increased integration
- Arrays—quasi optical techniques, leverage MEMs knowledge
- Flight qualification—tolerarnt designs, proven technology
- Implementation—diversified skill mix, better machining, better testing procedures
- Planar devices—increase yield, increase throughput and uniformity, reduce time to completion

Finally…

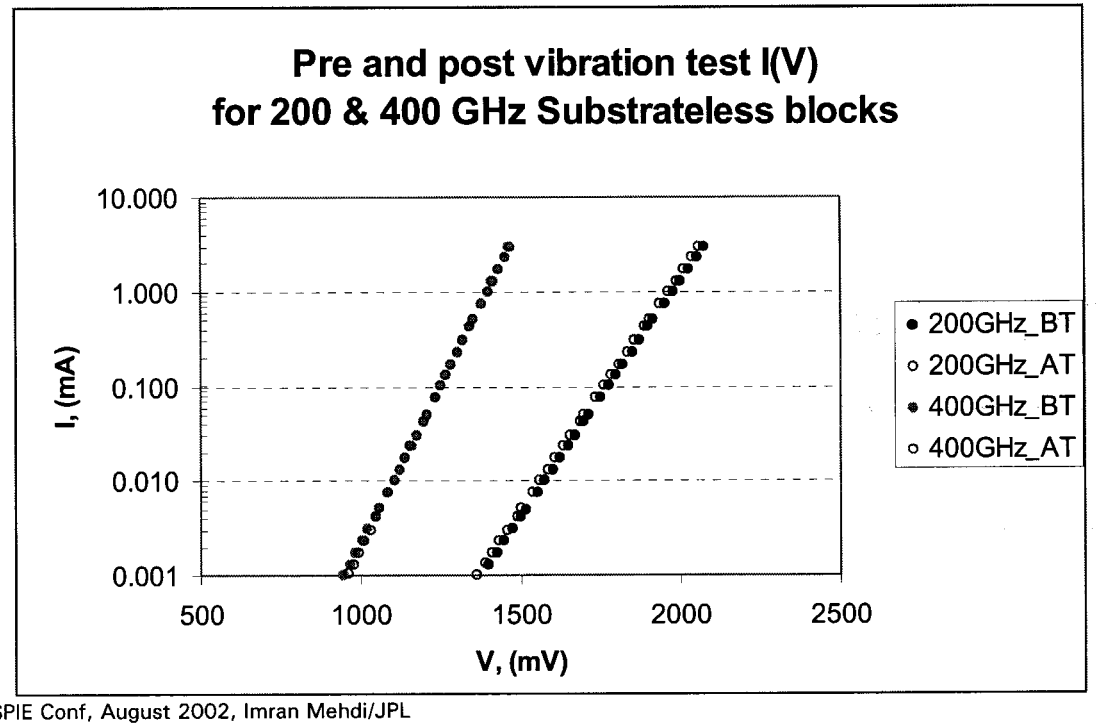
NASA led concerted effort of the last three years has now made it possible to realistically baseline solid state LO sources well into the THz range. However, it continues to be a niche technology highly dependent on NASA sponsorship. After Herschel further technology development will be directly proportional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

Even to sustain the current capability NASA support will be required

Vibration Test on the Substrateless MMCs

- 200 and 400 GHz blocks, block length parallel to x-axis, 1st order random test

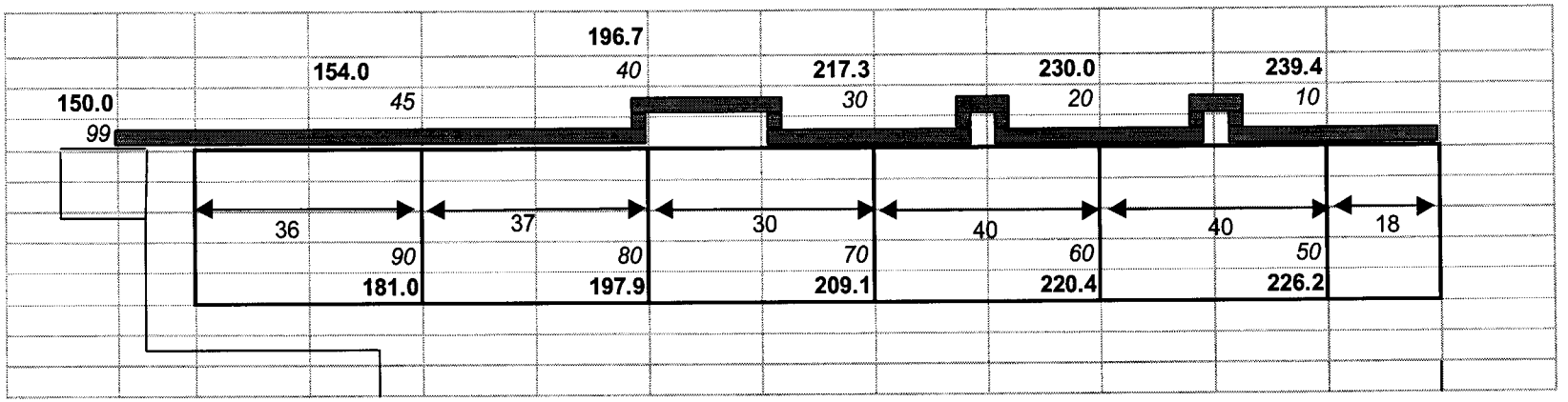
Test I specifications	Test II specifications
20 Hz--0.001 g^2/Hz	20 Hz--0.001 g^2/Hz
20-100 Hz--+6dB/oct	20-100 Hz--+6dB/oct
100-500 Hz--0.1, 0.2,0.4,0.6,0.8,1.0,1.2 g^2/Hz	100-1000 Hz--0.8 g^2/Hz
500-2000 Hz-- -6dB/oct	1000-2000 Hz-- -6dB/oct
Overall: 7.9,10.9,15,18,21,23,28 GRMS	Overall: 28.7 GRMS
Duration: 60 seconds	Duration: 440 seconds

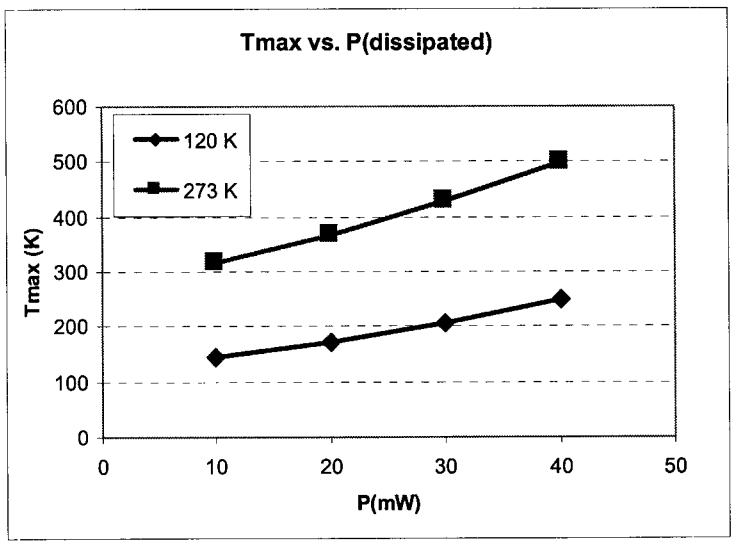


- **no change in I(V)**
- **no change in RF**

(only 200 GHz measured)

Chip thermal design



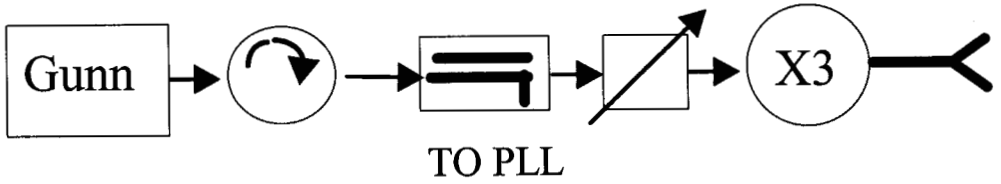


Chip thermal model--conduction only

- Thicker metalization (1.6 um)
- wider beam leads (60 um)
- shorter beam leads (10 um)

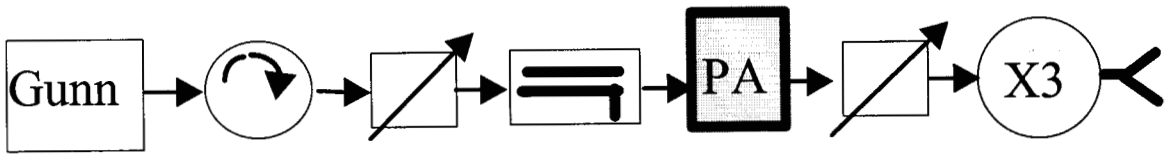
Noise considerations for power amplifiers

Test with a SIS 278 GHz receiver
at CSO on Mauna Kea, Hawaii



(a)

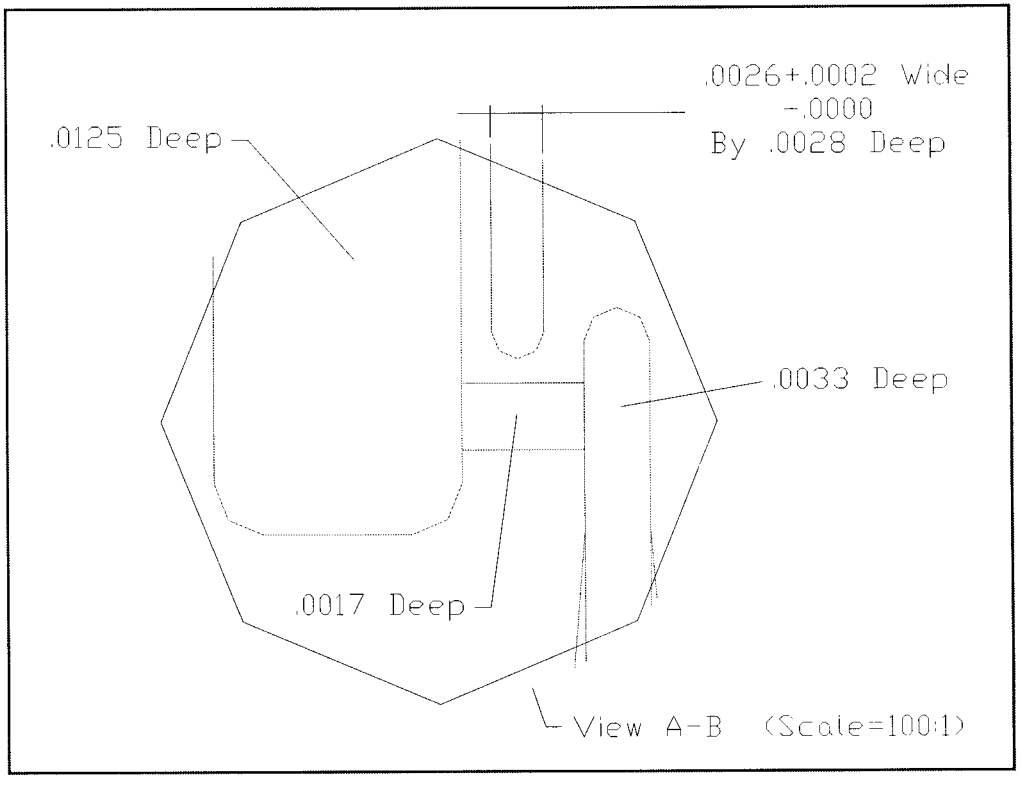
T_{rec} = 22.5 K

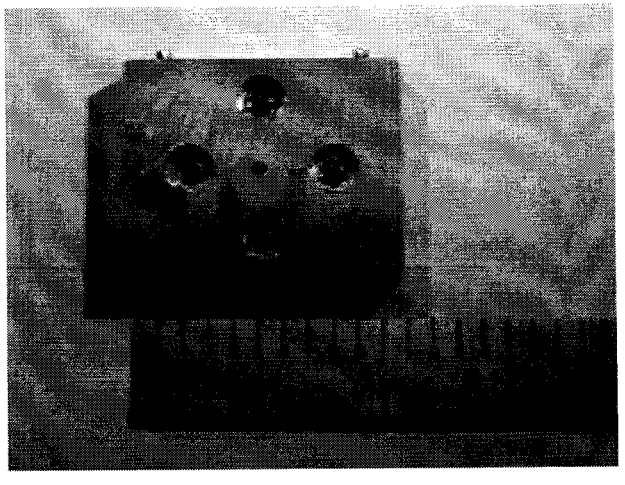


(b)

T_{rec} = 21.3 K

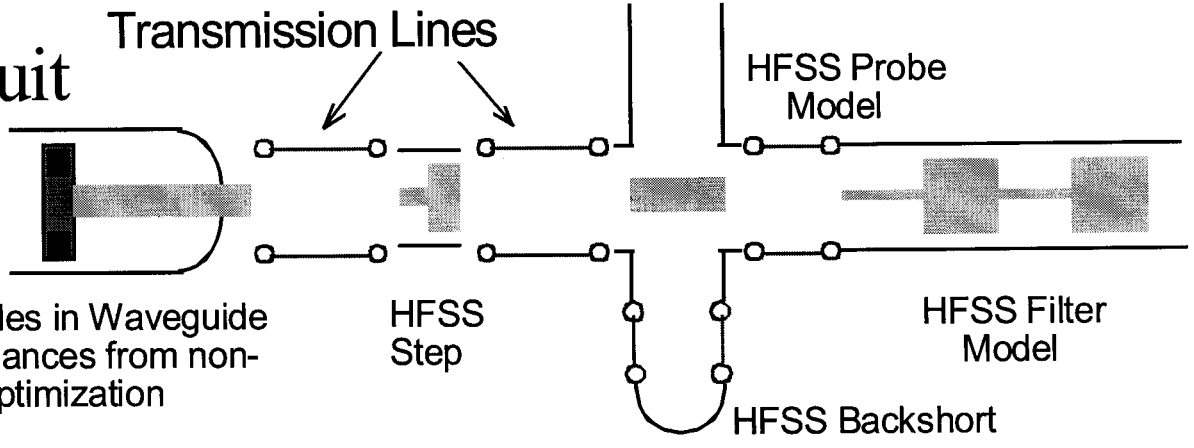
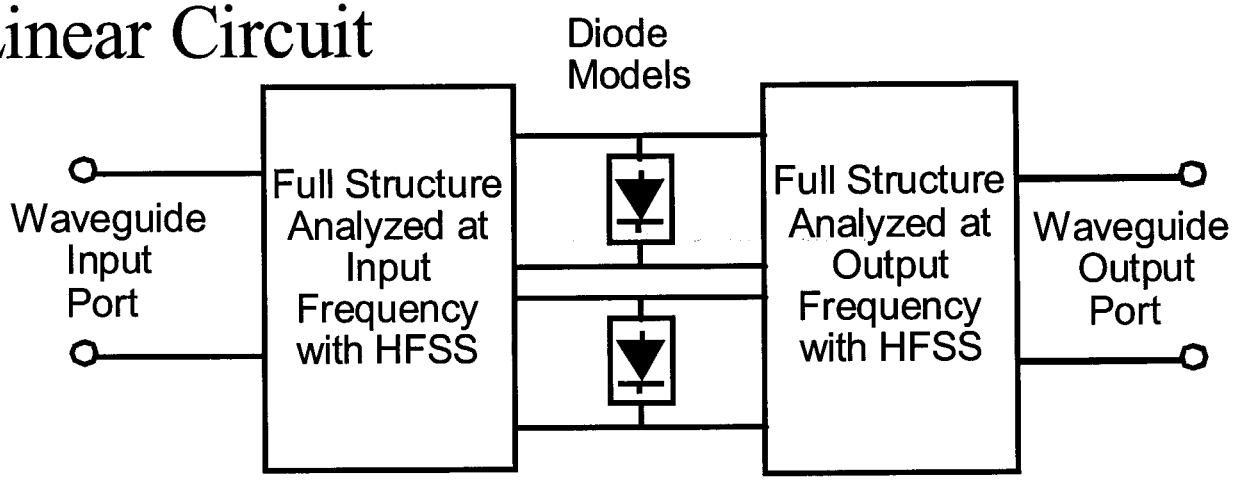
Waveguide block for 1200 GHz tripler





Multiplier Design Strategy

Linear Circuit



Non-Linear Circuit