Compact 1.9 THz Multi-Pixel Local Oscillator

Imran Mehdi
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

Invited talk for Special Session
New Developments and Technologies for Space Applications

Asia-Pacific Microwave Conference
Kyoto, Japan
November 2018

Outline

- **Multi-pixel Receivers: why do we need them?**
- **Technical Approach**
- **Array Receivers**
  - Mixers
  - LO subsystem
  - Receiver system
- **Summary**

Filamentary Structure and Star Formation

Determining Characteristics of Filaments & Required Probes

KINEMATICS: ^{13}CO

DENSITIES: multiple transitions of ^{13}CO, $C^{18}O$, HCN & others

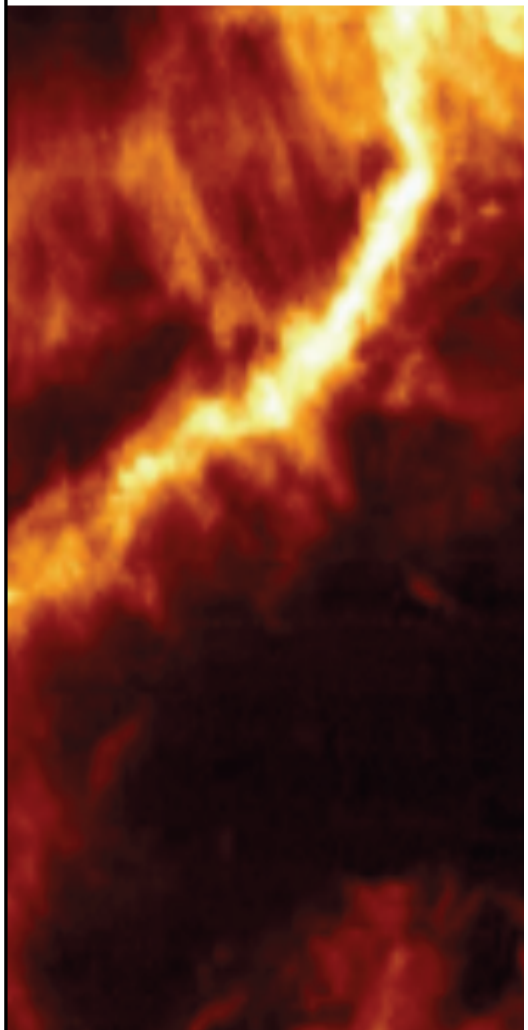
TEMPERATURE: ^{12}CO, NH_3

MAGNETIC FIELD: submm dust polarization (HAWC$^+$)

MASS ACCRETION: C^+
The extinction in regions around filaments is low so that carbon is likely in the form of C^+

Velocity shifts of few tenths of km/s expected

LARGE-SCALE HIGH VELOCITY RESOLUTION IMAGES OF MANY SQ. ARCMIN. REGIONS ARE ESSENTIAL



Central portion of Taurus in ^{13}CO with ang. res. $\Delta\Theta = 50''$

Herschel observations have established the ubiquity of filaments

Stars form in dense condensations within filaments

But what controls formation of filaments and their evolution?

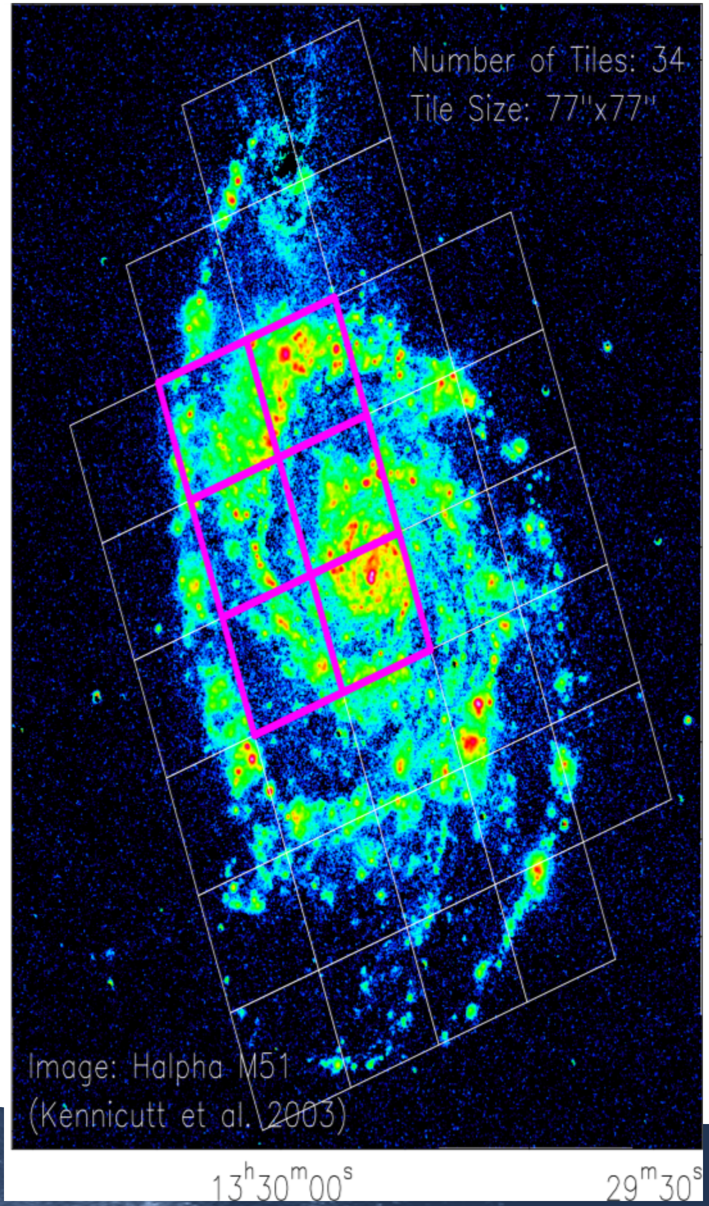
And most importantly, what determines when they get to point of fragmentation into CORES which then form new stars?

Even Nearby Galaxies Require Higher Angular Resolution than 1' Available from Balloons

Spiral Galaxies

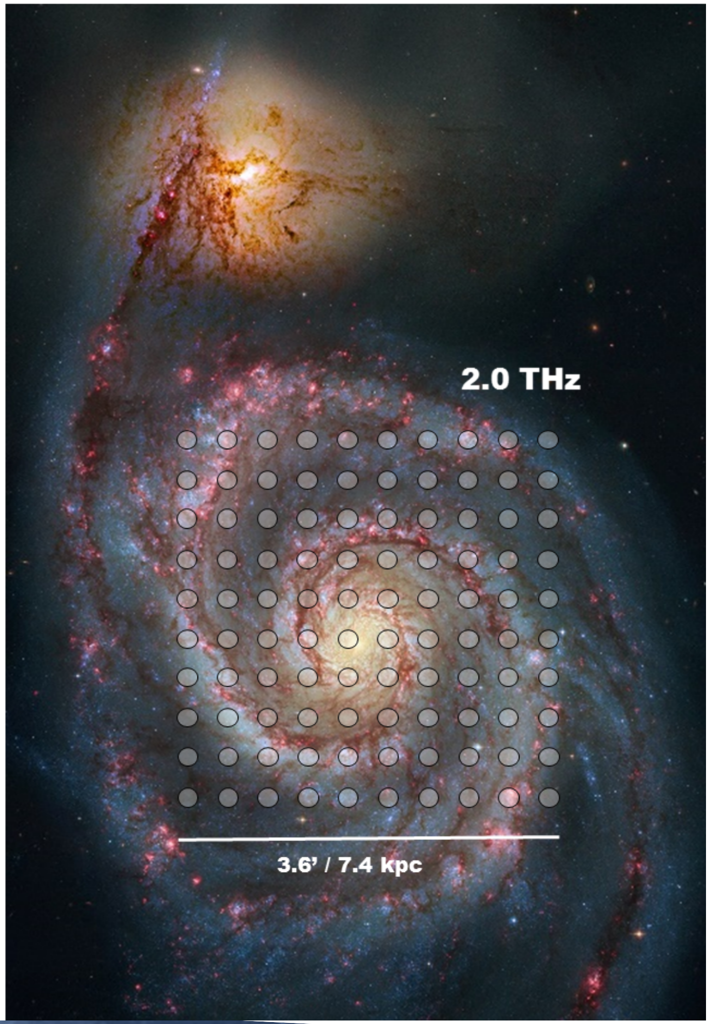
Key questions

- How do spiral arms compress gas and initiate star formation?
- What is the nature of the interstellar medium in the interarm regions – the starting point for next generation of stars?
- How much, and where is the ``CO-Dark Molecular Gas''?
  SOFIA CYCLE 4 ``Impact'' Project
  (J. Pineda, US PI; joint with Germany)
  Map M15 in [CII] 158 µm line with upGREAT and FIFI-LS
  Ang. Res. = 16" = 540 pc (good but not enough to really resolve interstellar clouds)
  60 hr upGREAT+ 15 hr FIFI-LS
  2 yr; 15 flights
- **ARRAY WITH >> 14 PIXELS WOULD ENABLE IMAGING A COLLECTION OF GALAXIES**

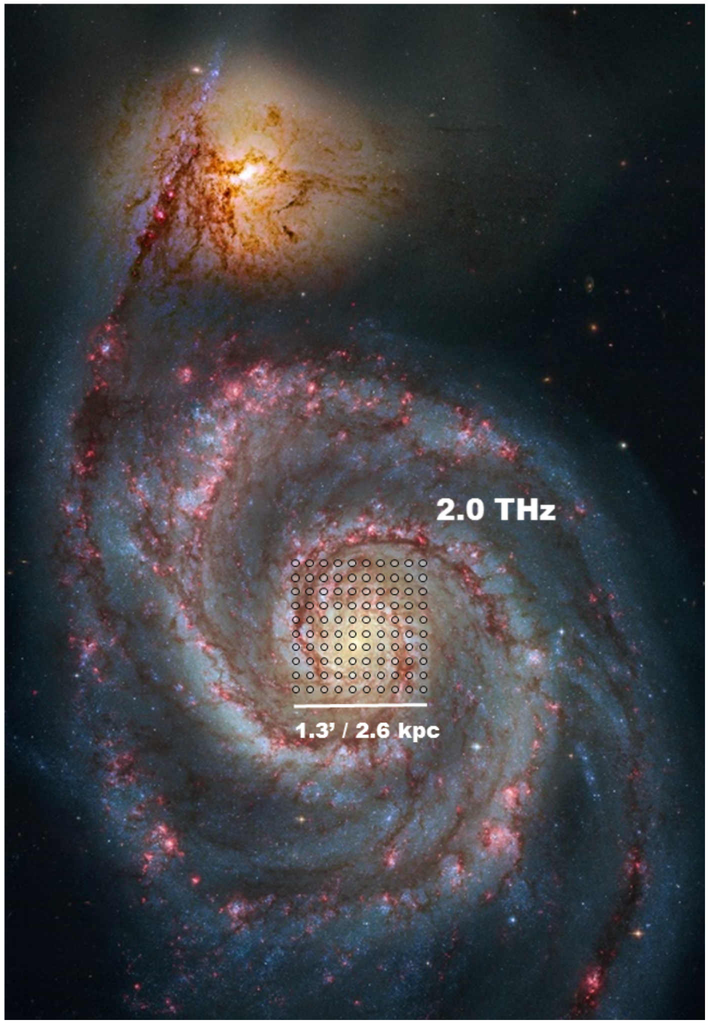


How many pixels to map M51?

Case study #2: Mapping of the star forming regions



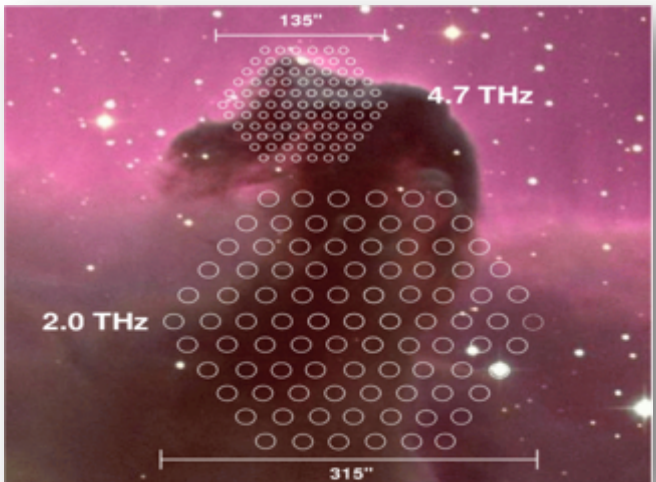
OST 3.5 m dish



OST 10 m dish

Next frontier in THz instruments

Consider imaging a nearby galaxy with the Cerro Chajnantor Atacama Telescope (CCAT):



- **25 m telescope at 5600 m altitude above the Chilean Atacama desert.**
- **The beam size is 6.3" FWHM at 490 GHz.**
- **$^3P_1$–$^3P_0$ fine-structure transition of neutral carbon, [CI], at 492 GHz from a photon dominated region or a nearby galaxy, we must map regions arc-minutes in size.**

This will require > 10^4 independent measurements.

No such mapping was carried out by the HIFI instrument on the Herschel Space Observatory; despite its high sensitivity and absence of any atmosphere.

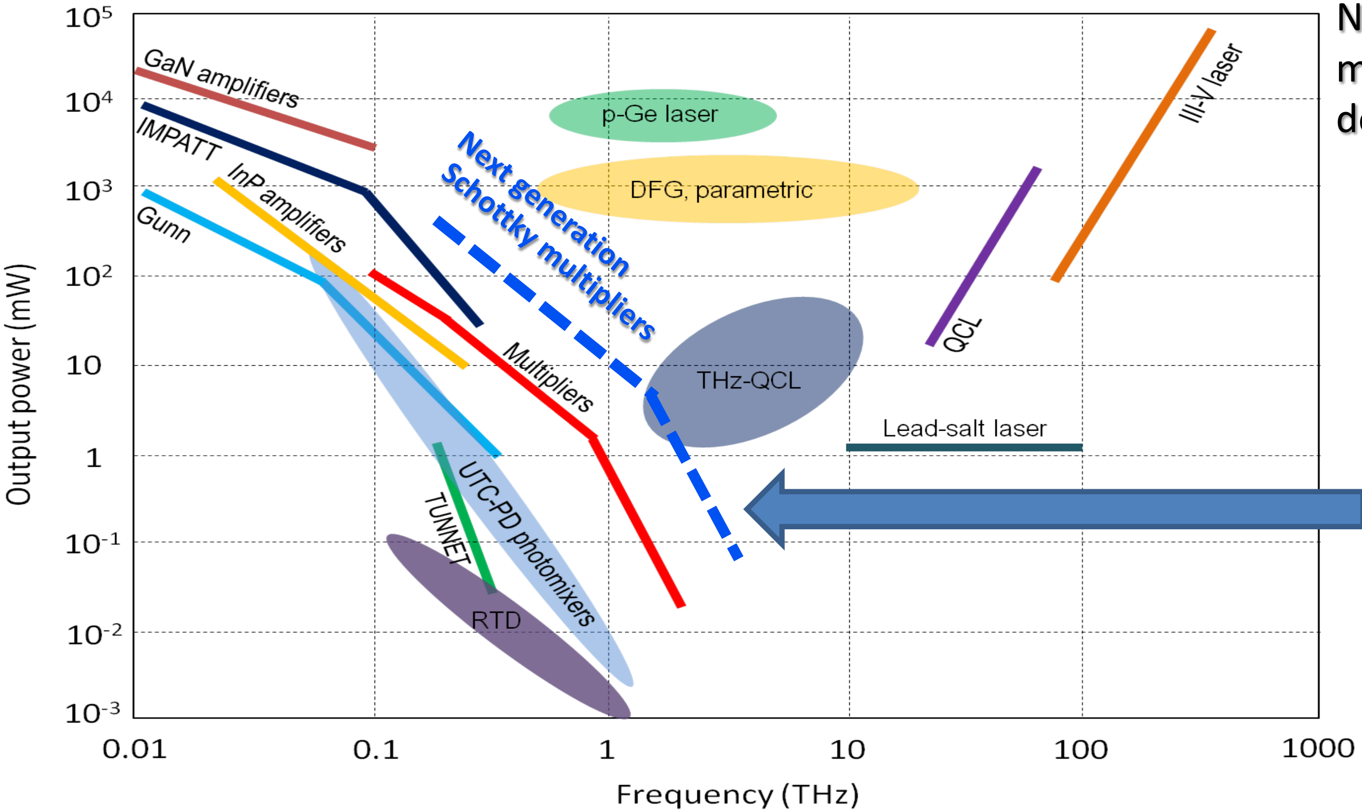
With only a single pixel, mapping times were prohibitively long.

THz Array receivers

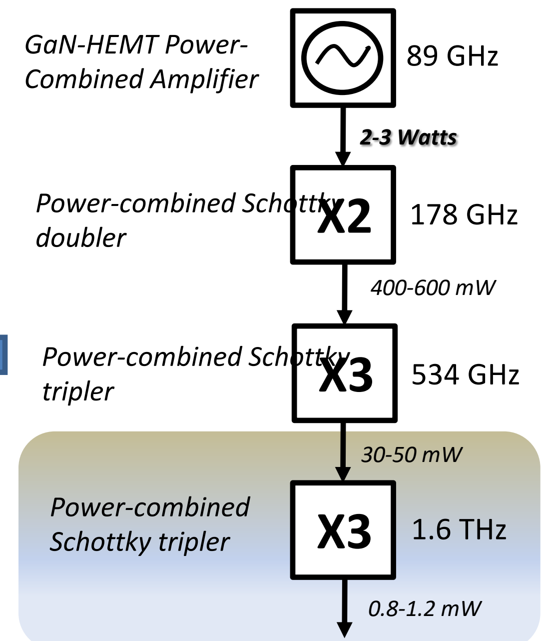
- Must Haves
  - 100's of pixels
  - 10-100 uW of output power
  - Electronic tuning
  - No spurious noise
  - **Reduced DC power**
  - Modularity (building, testing, & calibration)

- Should Haves
  - Robust to thermal variation
  - Simple packaging but consistent with best practices
  - Redundancy and/or lack of single point failure items

THz Sources



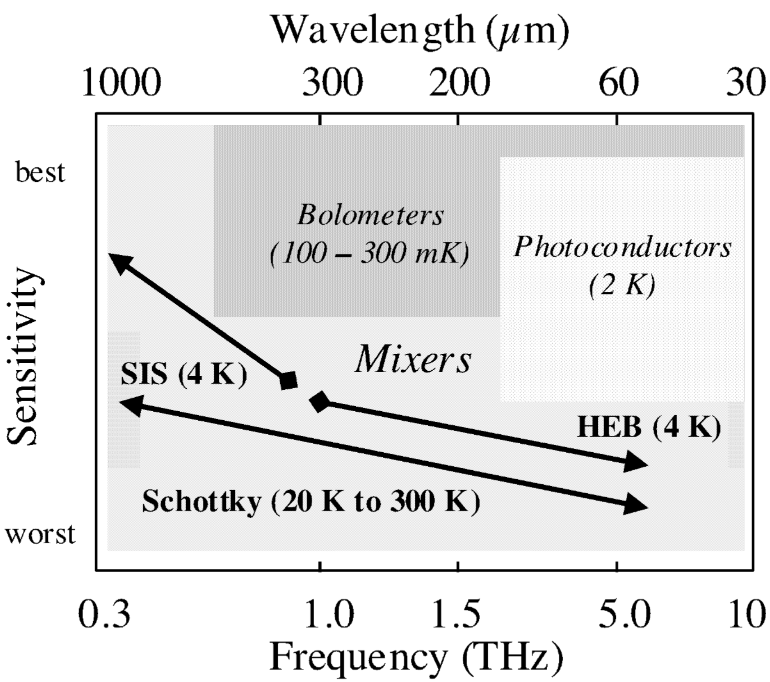
Next generation Schottky multiplied LO sources could deliver:

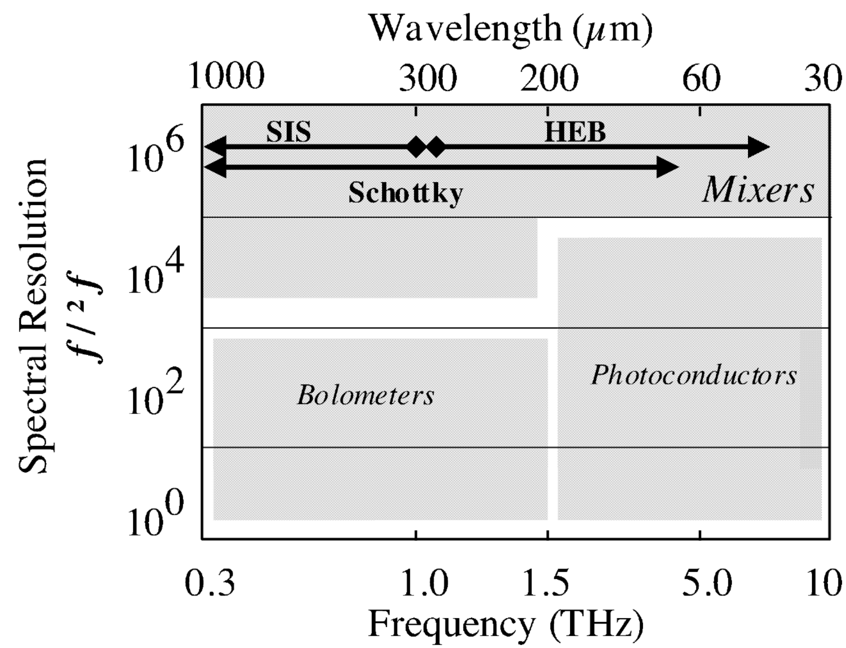


Challenges:

1. Develop multi-pixel LO schemes
2. Improve overall DC-to-RF efficiency
3. Enable sources beyond 2.7 THz

What Detector should be used?

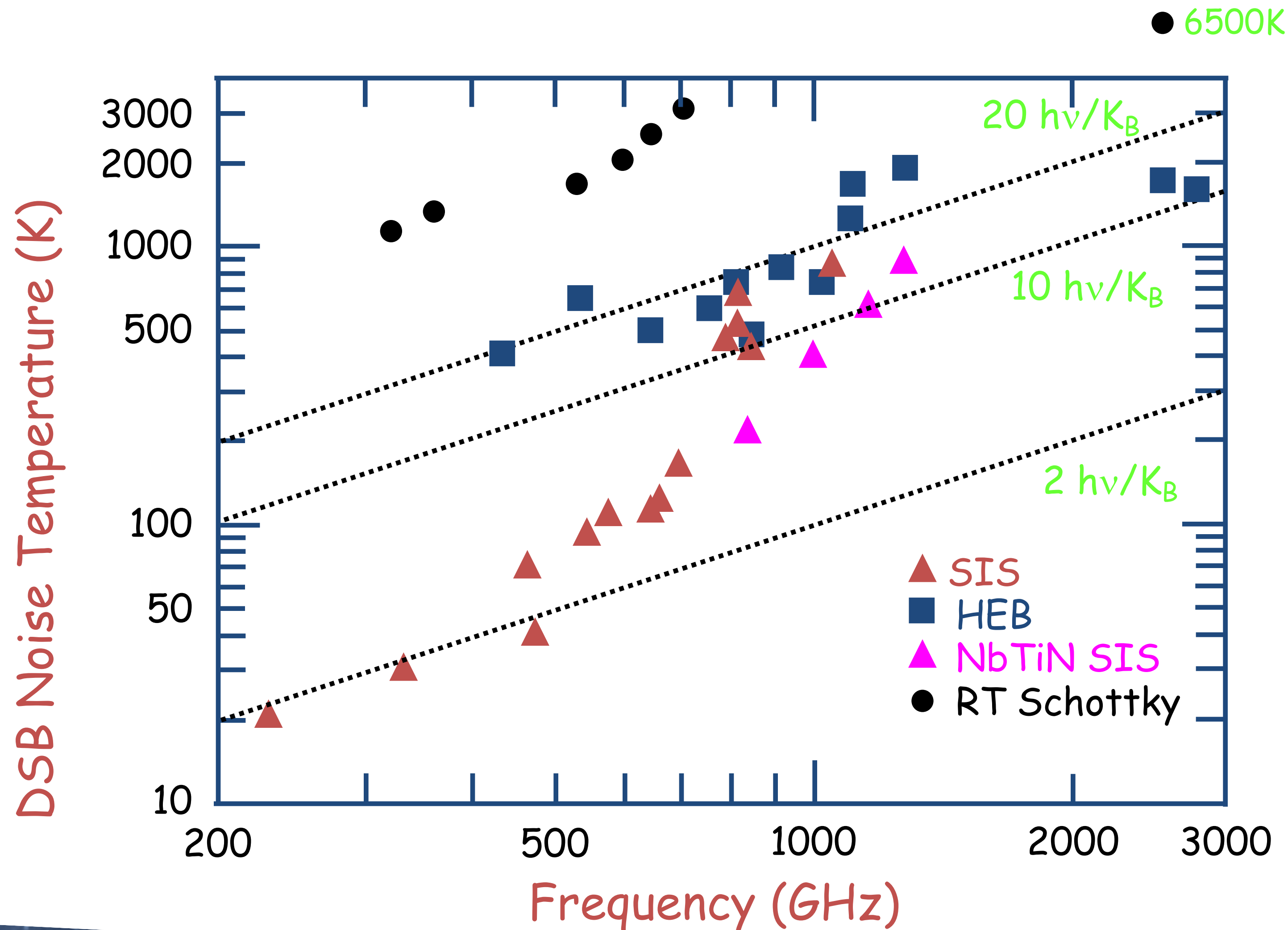




Trade-off

- Sensitivity vs Operating Temperature
- Spectral resolution
- Scientific goals and objectives

Heterodyne Mixers



What are we trying to accomplish

1. Hardware to pump 100's of pixels from 500 GHz to 4.7 THz
2. Large bandwidth a 'should have'
3. Output power to be about 10 microwatt per pixel
4. Control of power per pixel a 'should have'
5. Electronic tuning a 'must have'
6. Phase noise better than or equal to HIFI approach
7. Thermal stability a 'must have'
8. Production consistent with best flight hardware development
9. Scalable in pixel count
10. Redundancy and/or lack of single point failure items

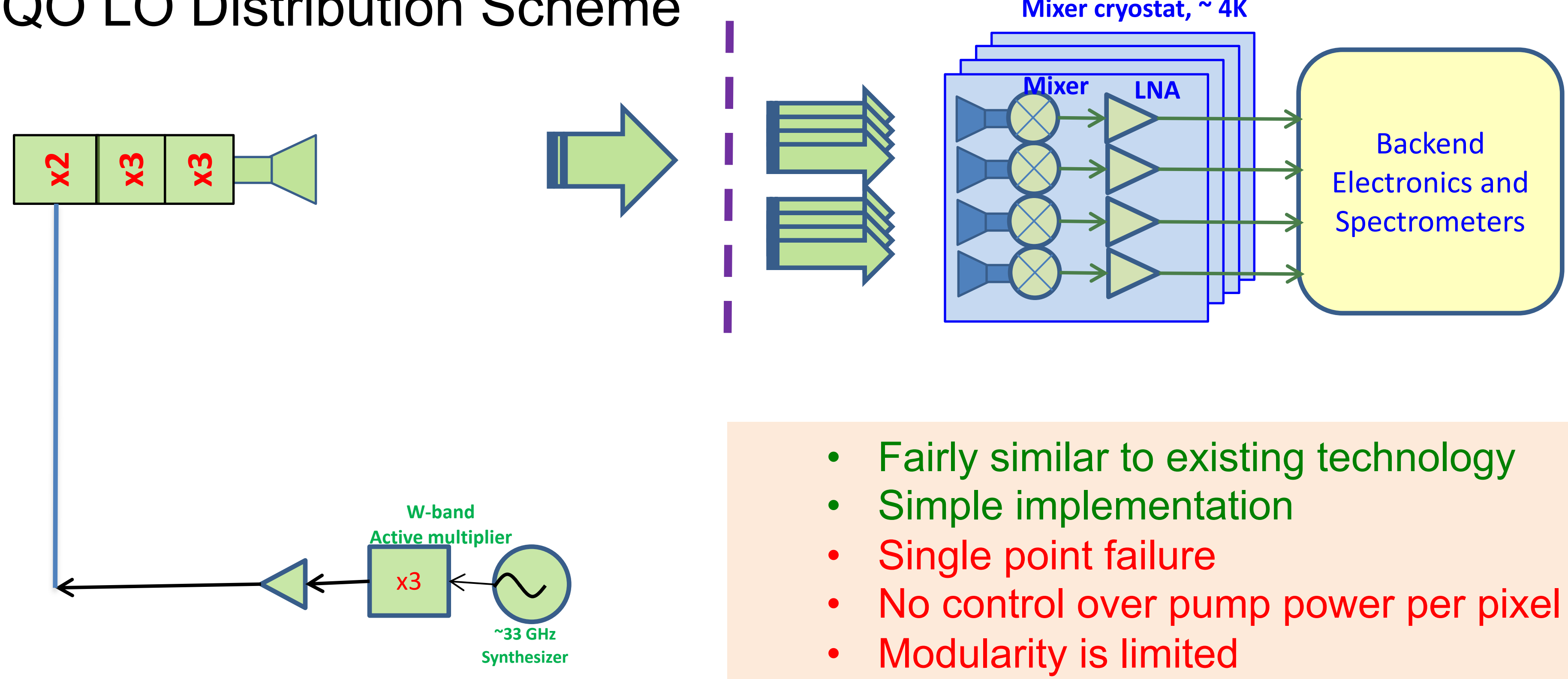
What is the best way to couple LO?

	Via grating	QO (pixel to pixel)	Waveguide
Pros	• Single LO beam	• Per pixel power control	• Better interface
Cons	• Single point failure • No per pixel power control • Coupling loss	• More complicated LO scheme • Larger volume ?	• Insertion loss • Thermal break

Ultimately, will depend on array size and implementation capabilities

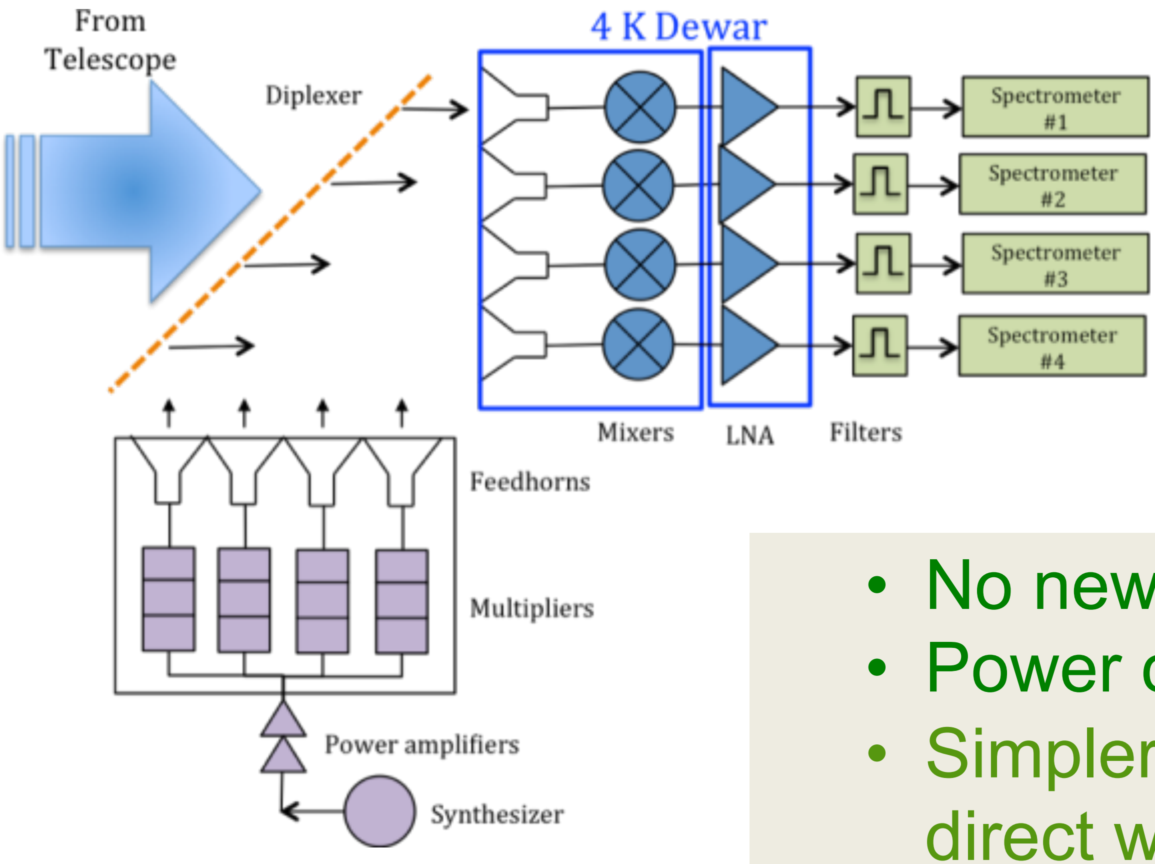
Single source via grating

QO LO Distribution Scheme



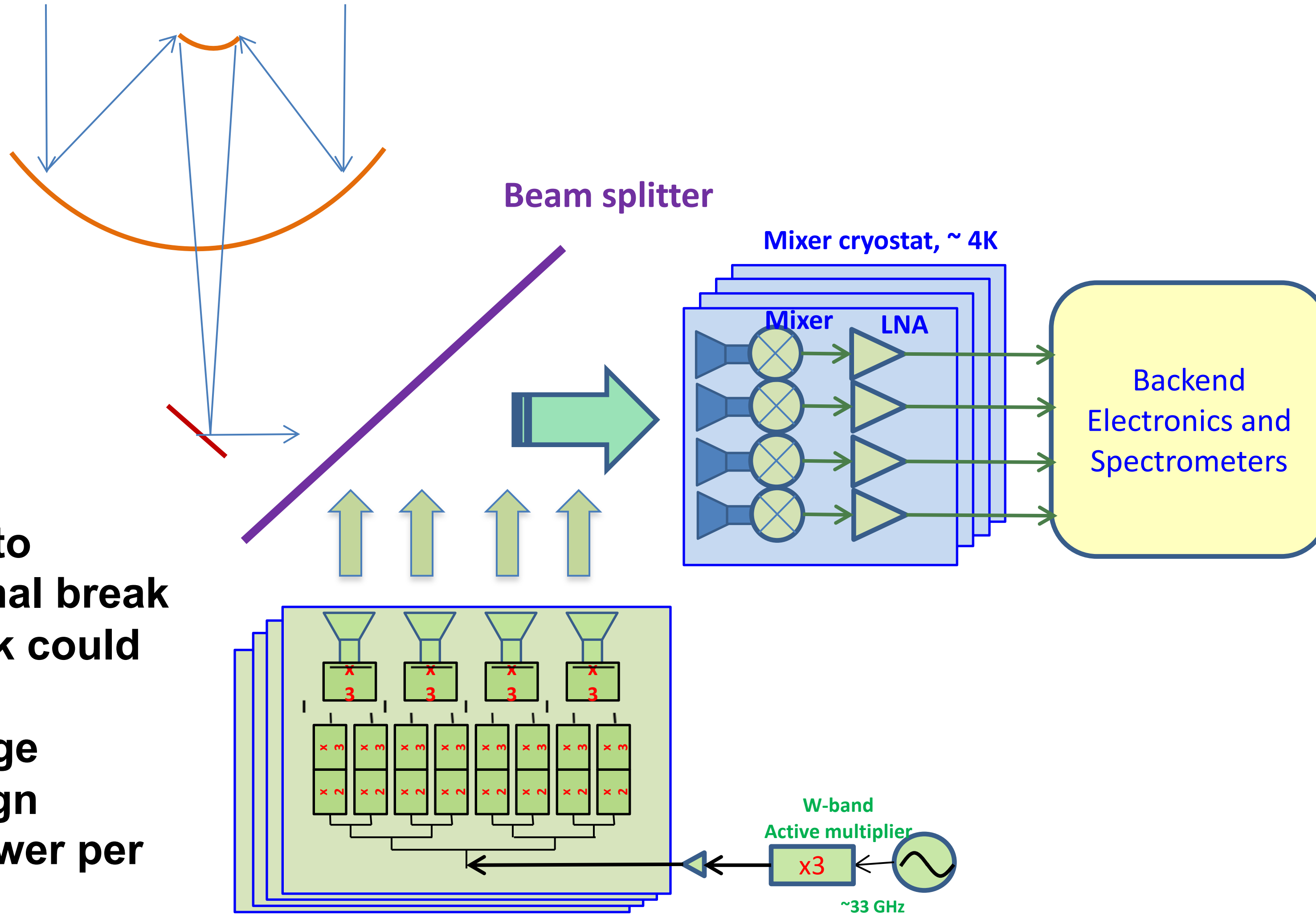
- Fairly similar to existing technology
- Simple implementation
- Single point failure
- No control over pump power per pixel
- Modularity is limited
- Concern about thermal load on initial stages
- Limited bandwidth

Individual LO per pixel (QO)



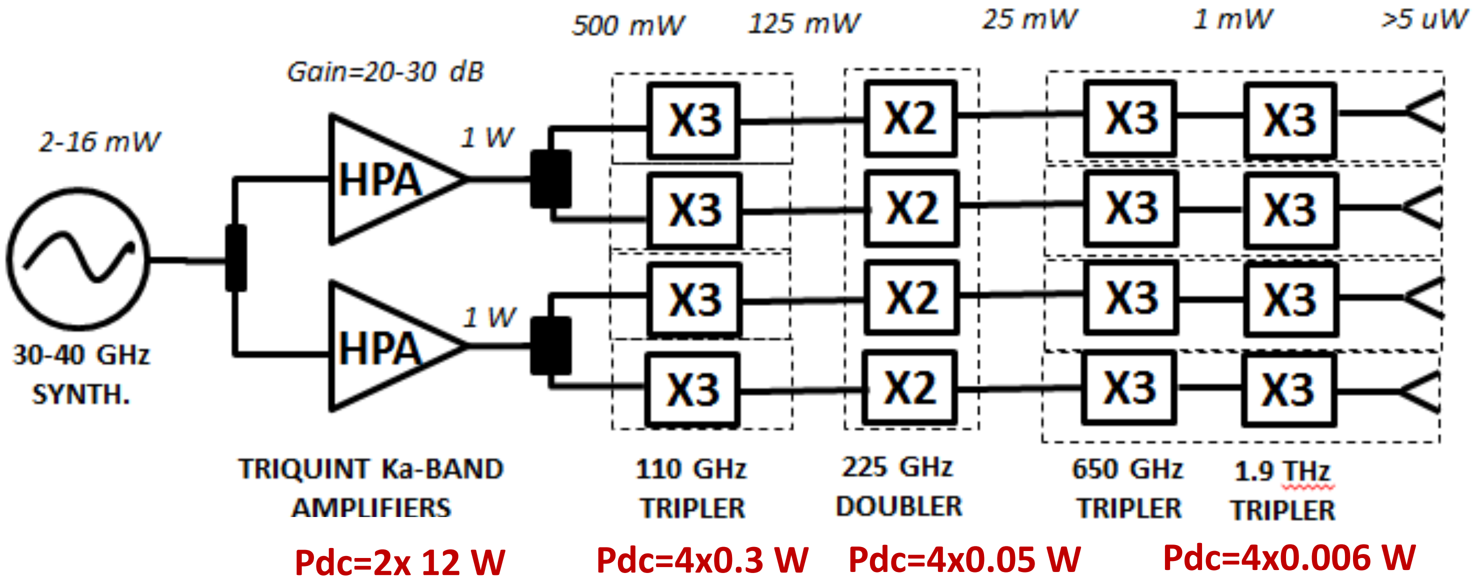
- No new technology
- Power control per pixel
- Simpler imaging optics or direct waveguide interface
- High DC power requirement
- Large H/W part count

Modular approach

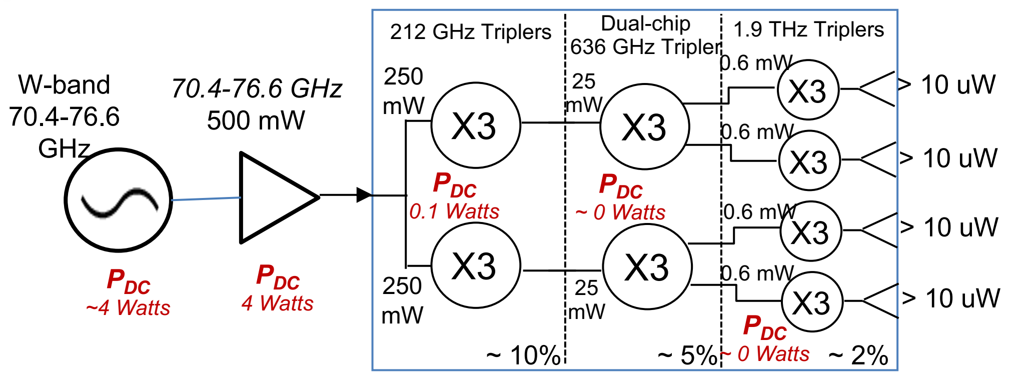


- ✓ QO coupling to provide thermal break
- ✓ Thermal break could be at the first multiplier stage
- ✓ Modular design
- ✓ Control of power per pixel

DEVELOPMENT of MULTI-PIXEL LO AT 1.9 THz



POWER BUDGET
6.35 W/pixel



POWER BUDGET
~2 W/pixel

Power combined dual-chip265-340 Tripler

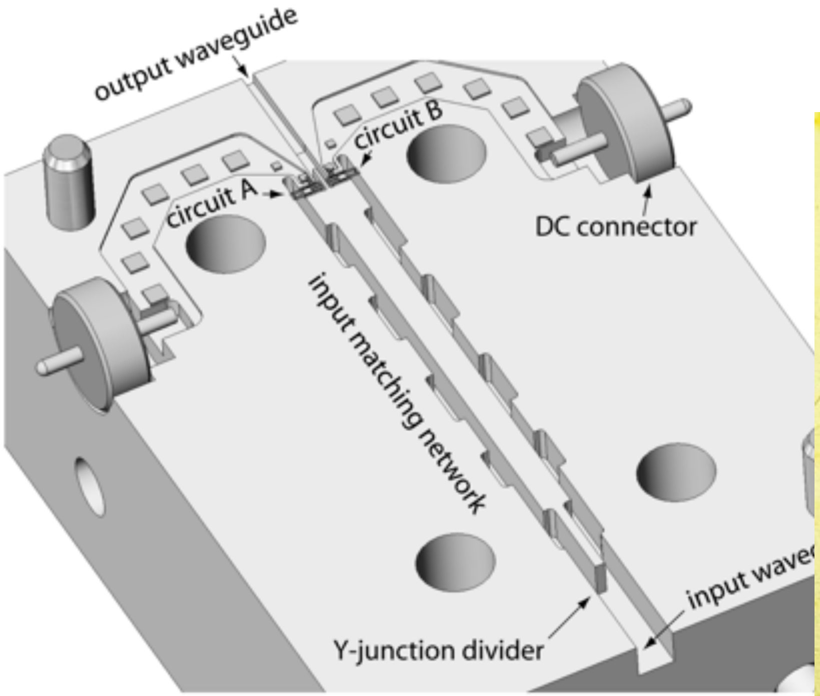
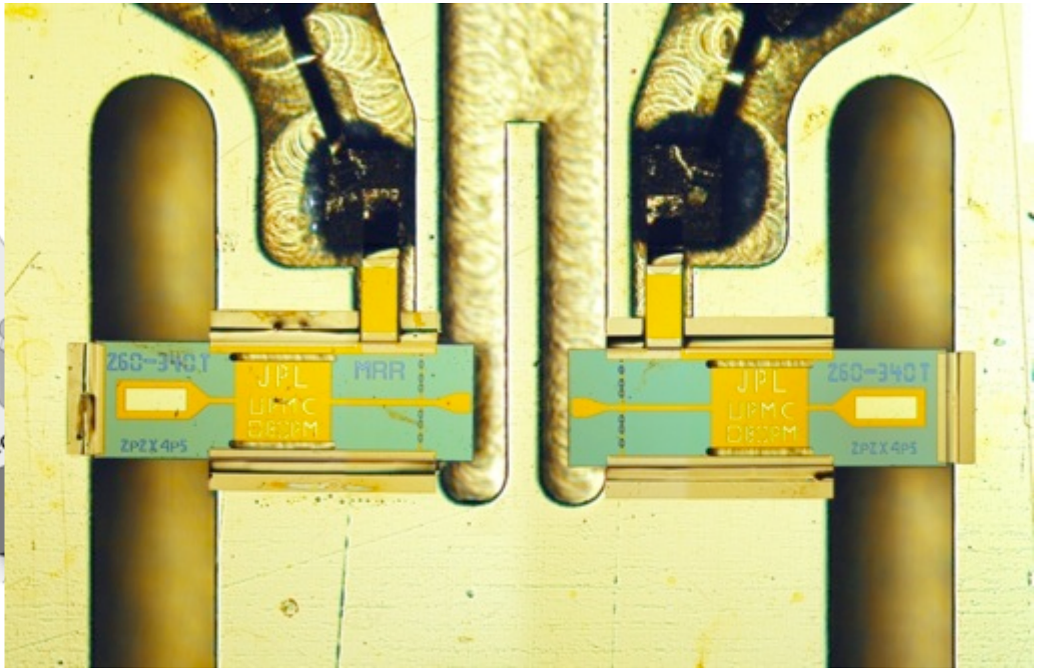
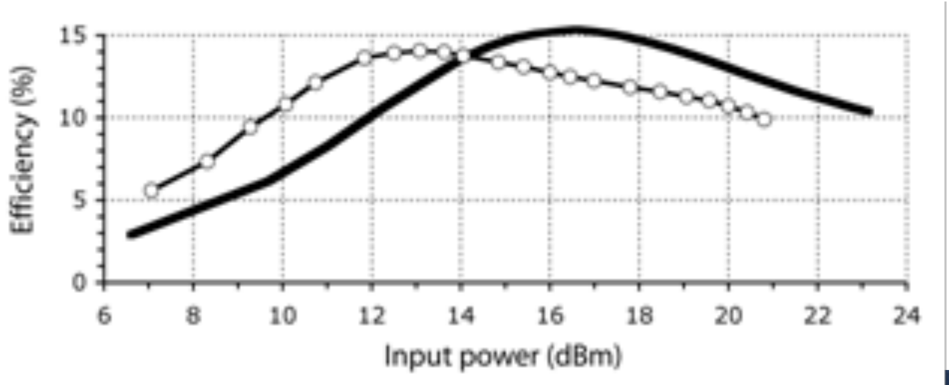


Fig. 1. 3D schematic view of the bottom half of the power-combined 260-340 GHz frequency tripler based on two mirror-image integrated circuits

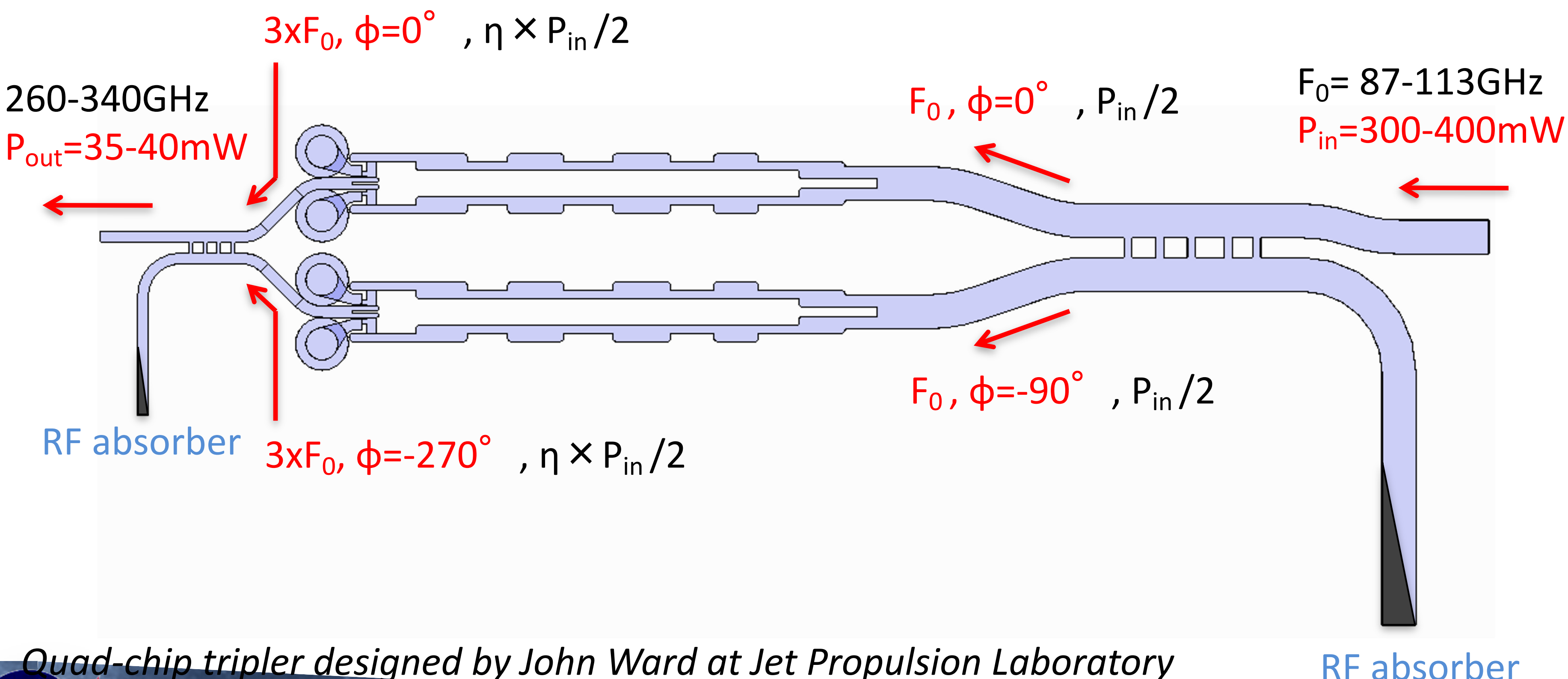




>30 mW at 320 GHz

Quad-chip 260-340GHz Balanced Tripler

- Two dual-chip triplers combined with 90° hybrid couplers.
- 24 Schottky anodes
- 4 independent bias lines

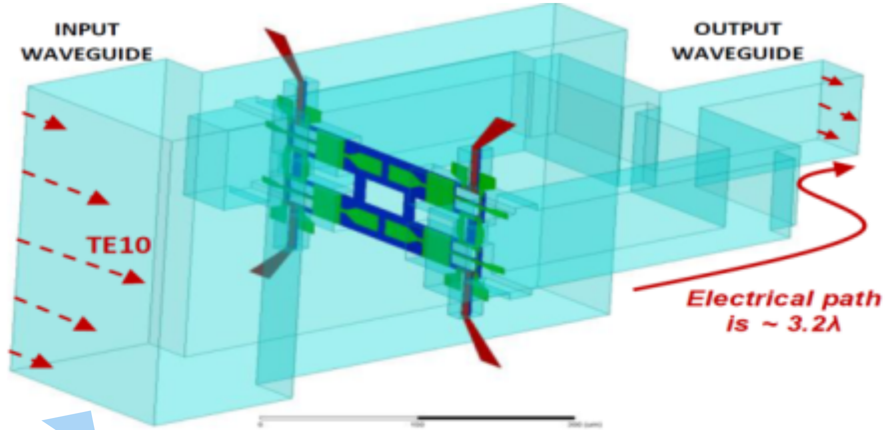


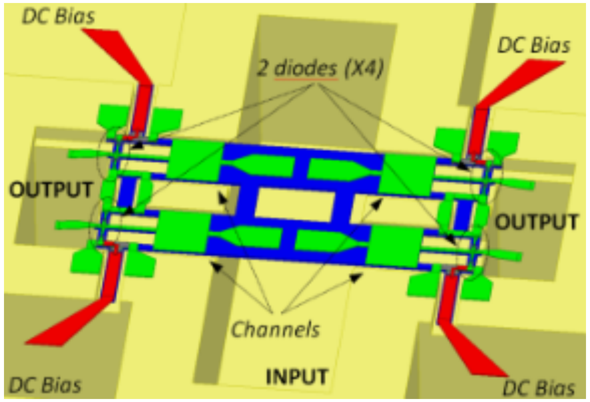
Quad-chip tripler designed by John Ward at Jet Propulsion Laboratory

Chip designed by Alain Maestrini, Observatory of Paris

ON-CHIP POWER COMBINED FREQUENCY MULTIPLIERS

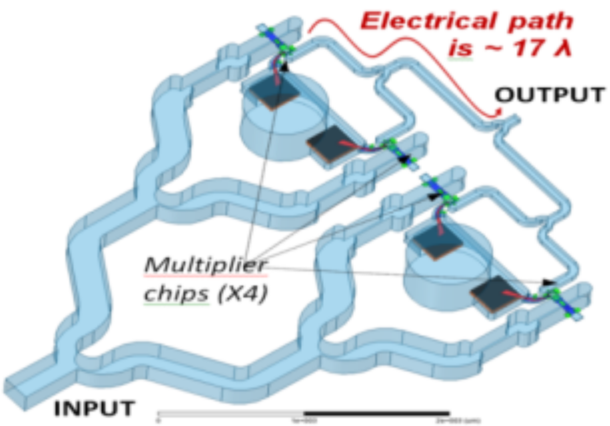
- Power x4
- Size /10
- Losses /5
- Lithographic accuracy x10



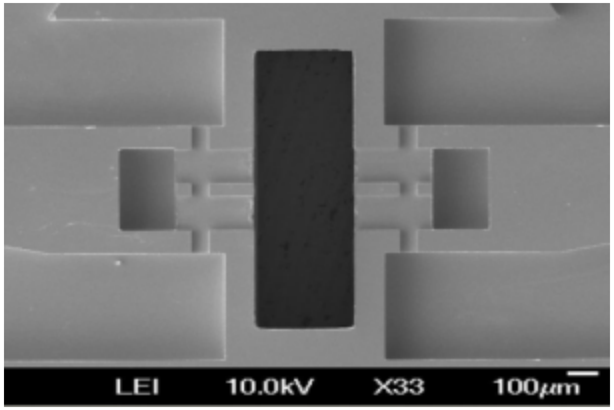


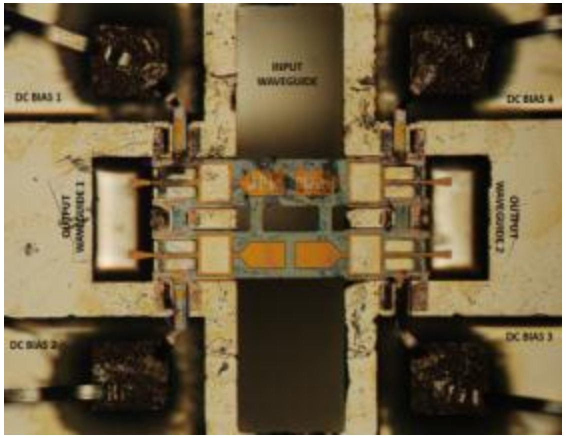
- Lithographic precision for allignment and machining
- No need for waveguide power-dividing

U.S patent (CIT 5953-P), Jet Propulsion Laboratory, California Institute of Technology.



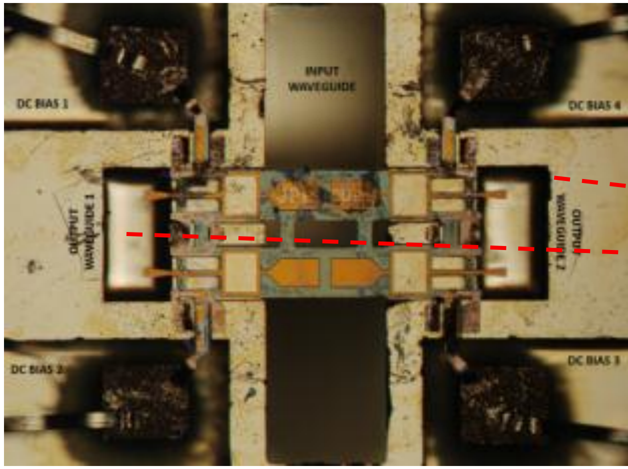
Metal split-block (20mmx20mmx8mm)

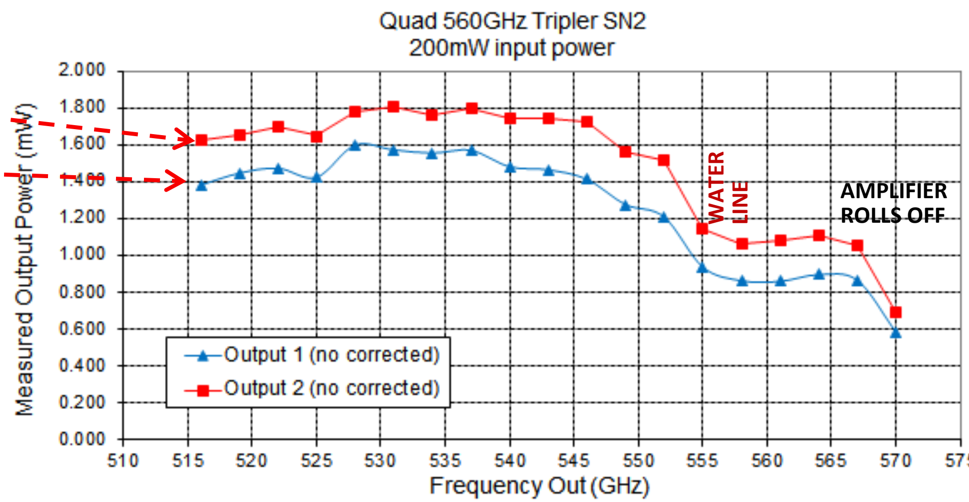


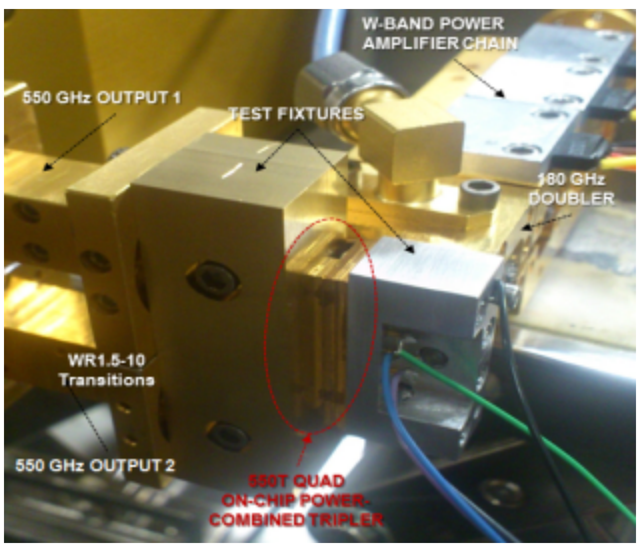


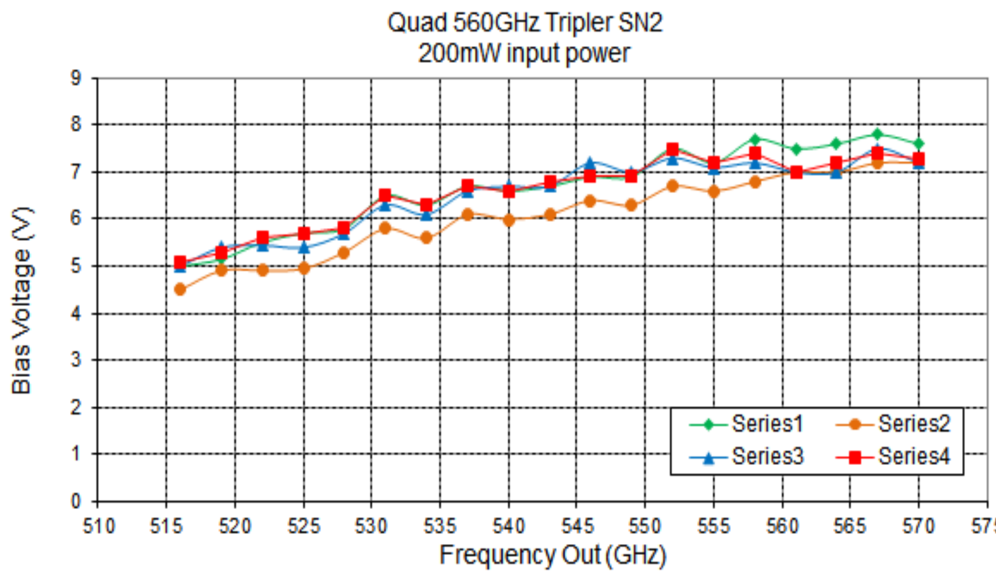
Quad Chip Performance

510-570 GHz On-Chip Power-Combined Tripler





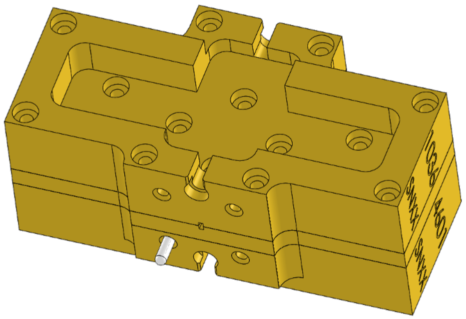




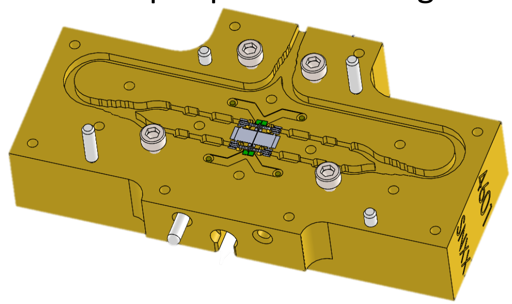
Power Combined Quad Chip

(176 GHz DOUBLER)

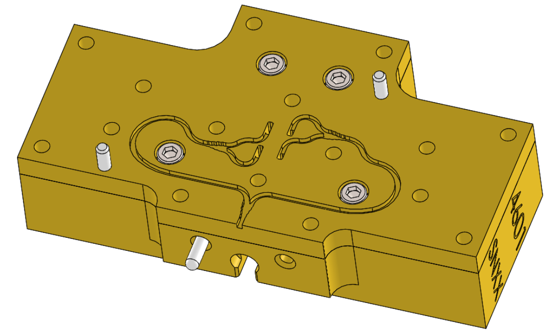
quad-doubler block

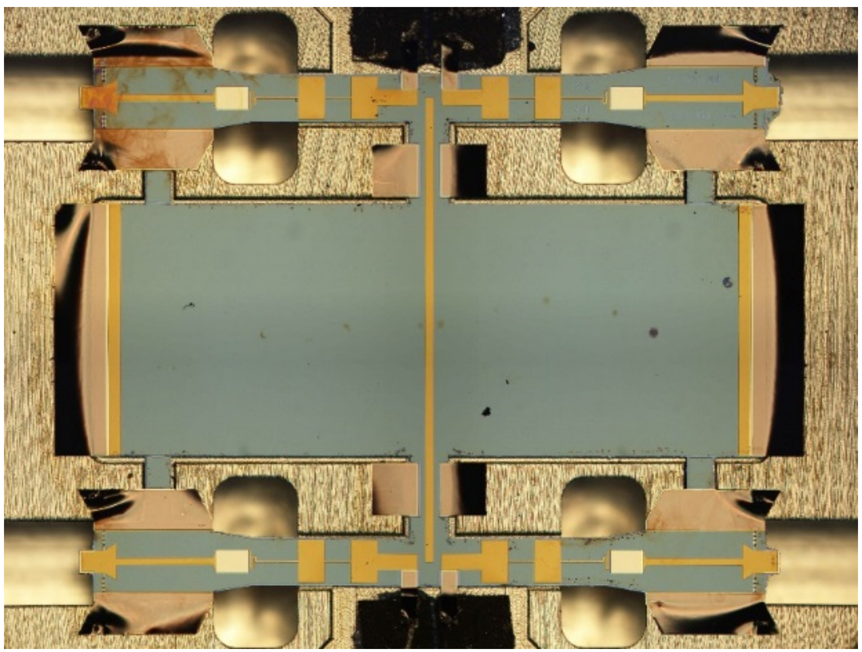


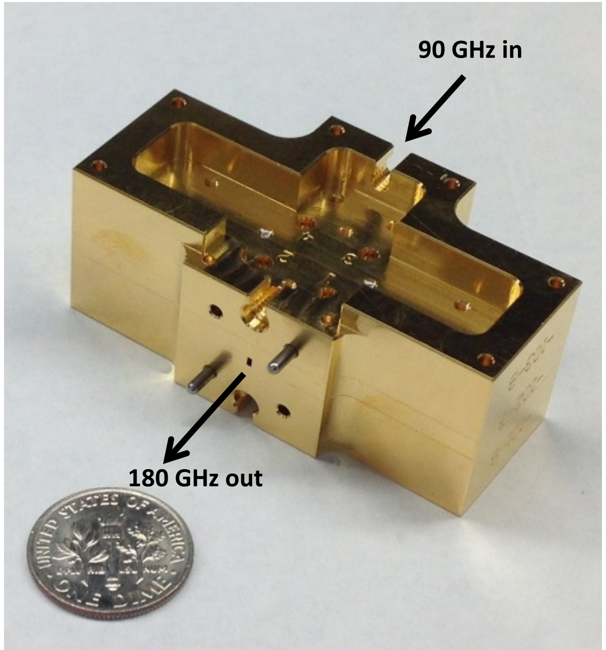
input power dividing



output power combining



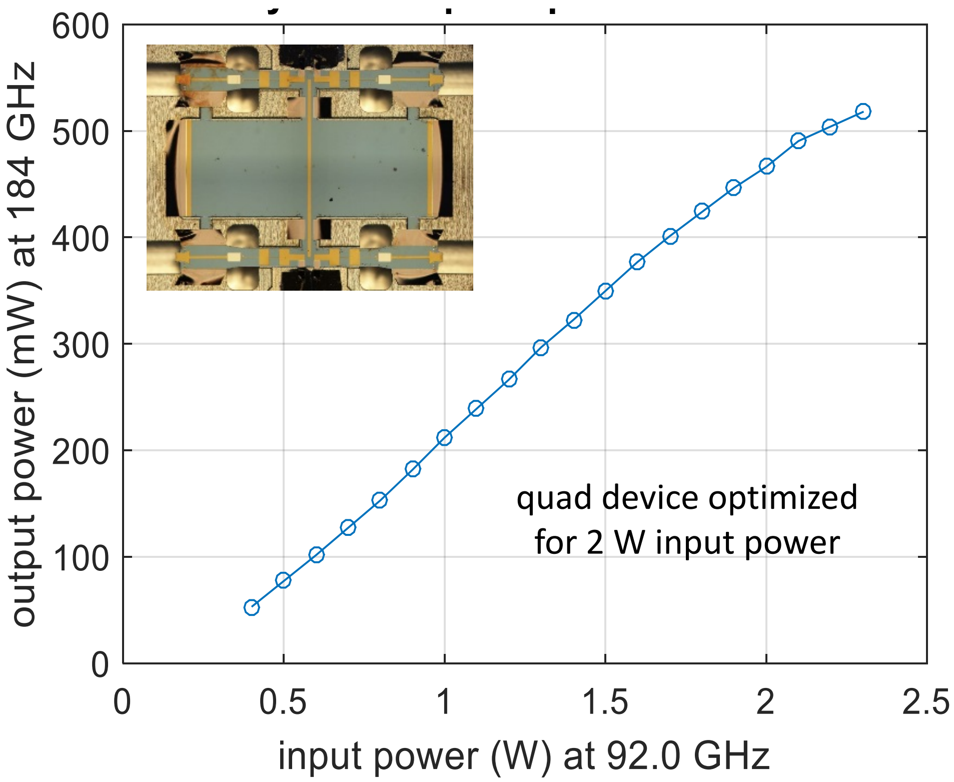


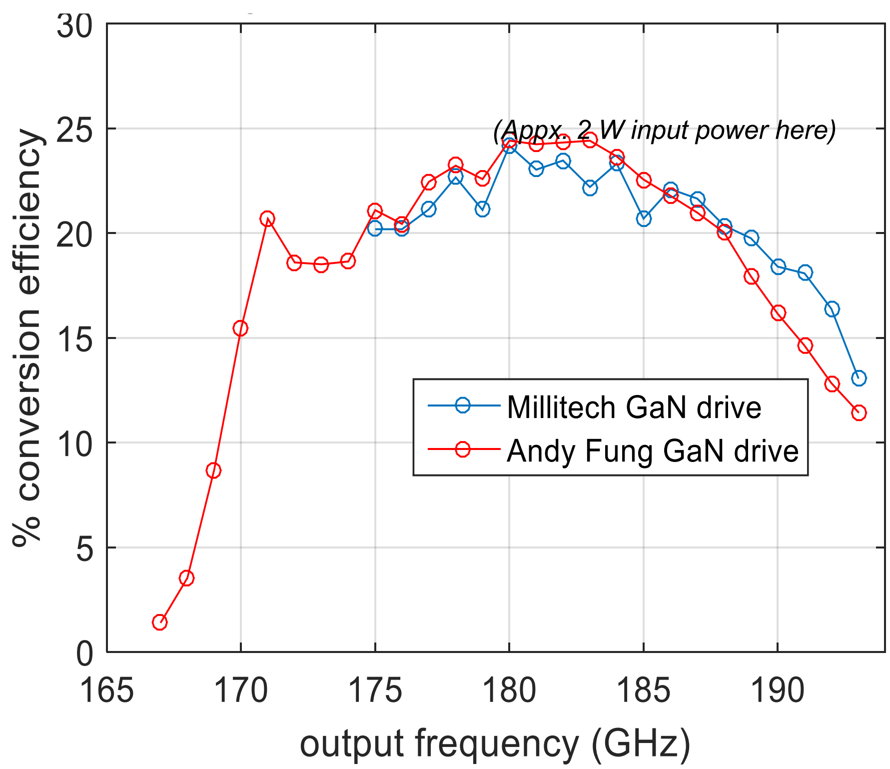


Quad on-chip power-combined GaAs 180 GHz doubler design together with compact housing able to handle more than 2 Watts and produce around 500 mW output

Power Combined Quad Chip
(176 GHz DOUBLER)

- **World-record output power achieved at 189 GHz (94.5 GHz input): >500 mW output!**
- **Fairly flat response with ~23% conversion efficiency (2 W input) over >10 GHz bandwidth.**





x10 state of the art. Herchel/HIFI devices delivered 50 mW with max input power of 200 mW. Requirement fr this Project was 400 mW.

CLOSING THE "TERAHERTZ GAP" WITH ROOM-TEMPERATURE ALL-SOLID-STATE LO SOURCES

Total dc power consumption is only ~ 20 W

No cooling needed, works at 300 K

Large bandwidth, Gaussian beam, temperature stable, frequency stable, no need

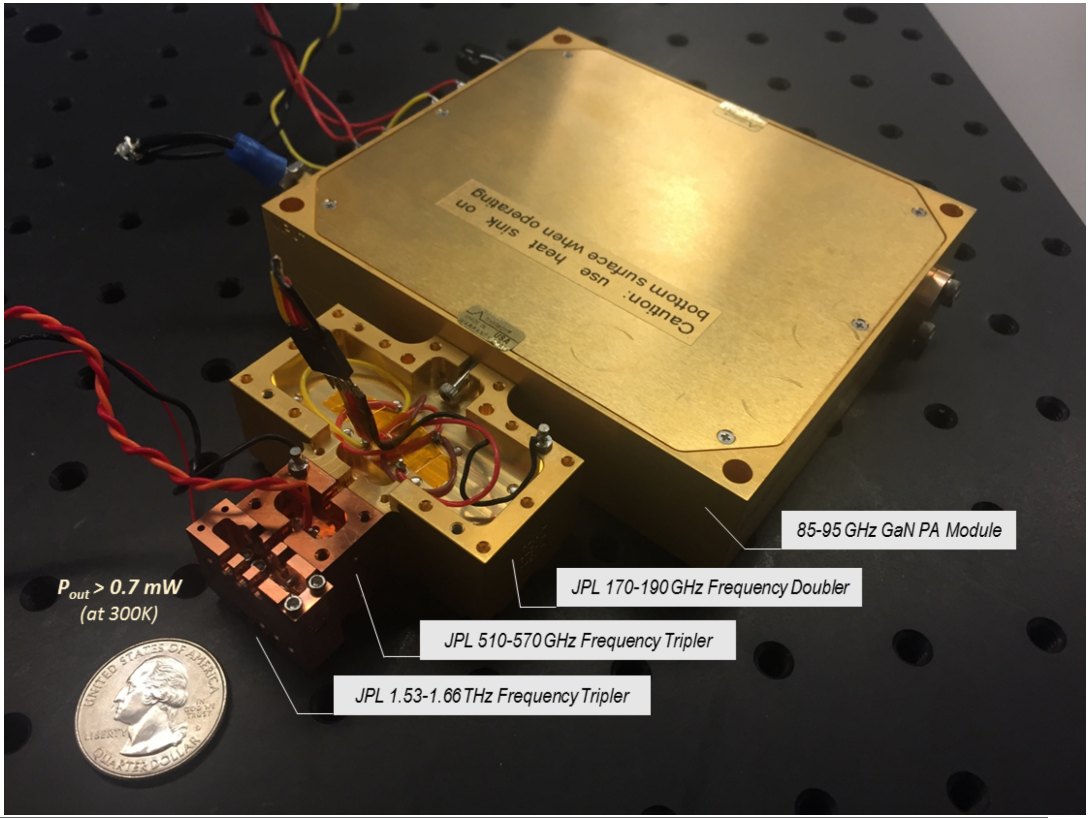
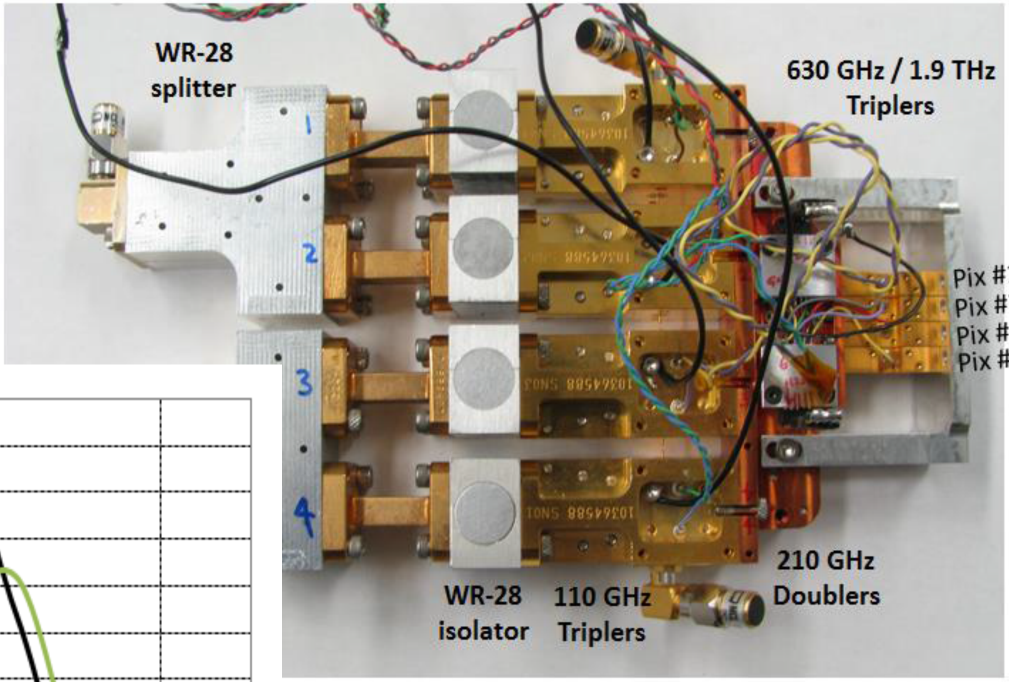
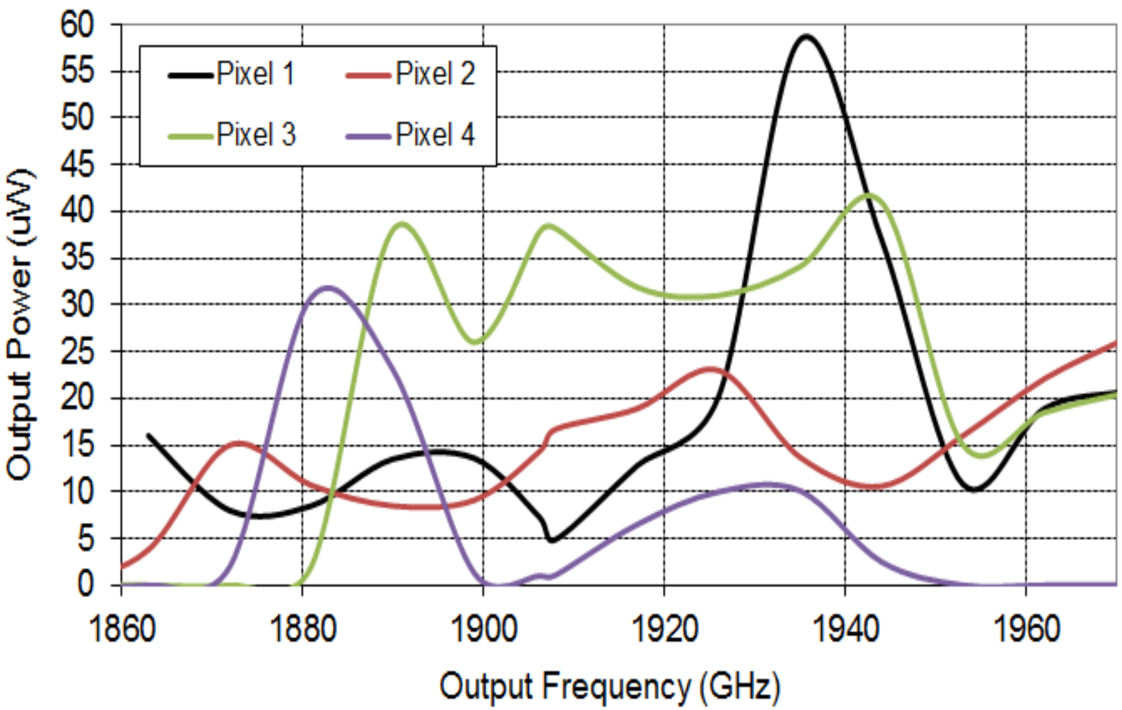


Fig: High-power 1.6 THz frequency multiplied LO source recently demonstrated at JPL, exhibiting a world record output power of 0.7 mW at room-temperature operation. 10+ times improvement over the previous state-of-the-art.

	PREVIOUS STATE-OF-THE-ART			THIS WORK		
	Max. Input	Max. Output	Peak Efficiency	Max. Input	Max. Output	Peak Efficiency
110 GHz Frequency Tripler	-	-	-	**900 mW**	**200 mW**	**30%**
180 GHz Frequency Doubler	250 mW	50 mW	25%	**2.5 Watts**	**550 mW**	**25 %**
230 GHz Frequency Tripler	240 mW	22 mW	14%	**700 mW**	**130 mW**	**21 %**
340 GHz Frequency Tripler	150 mW	10 mW	10%	**> 300 mW**	**40 mW**	**15 %**
527 GHz Frequency Tripler	50 mW	2.5 mW	7%	**> 500 mW***	**> 30 mW***	**7 %***
1.6 THz Frequency Tripler	3 mW	50 uW	2 %	**> 40 mW***	**> 1 mW***	**3 %***

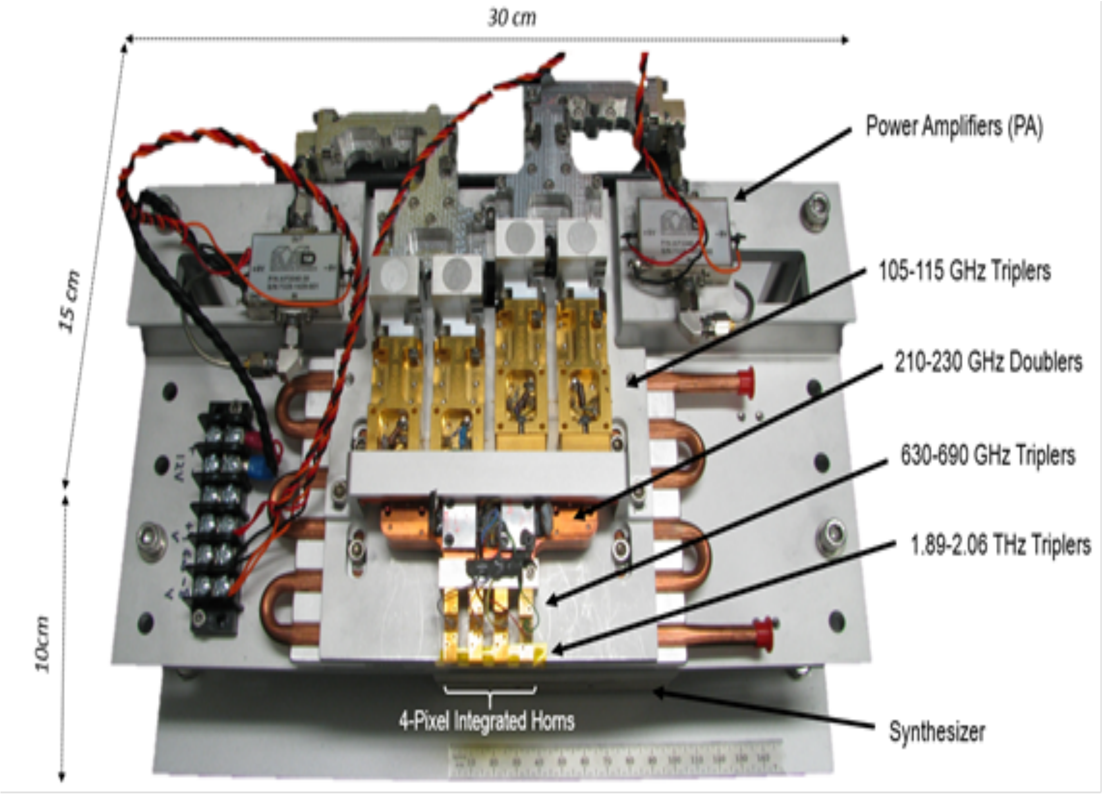
DEVELOPMENT of MULTI-PIXEL LO AT 1.9 THz: BIASLESS 1.9 THz TRIPLERS





4-pixel Chain

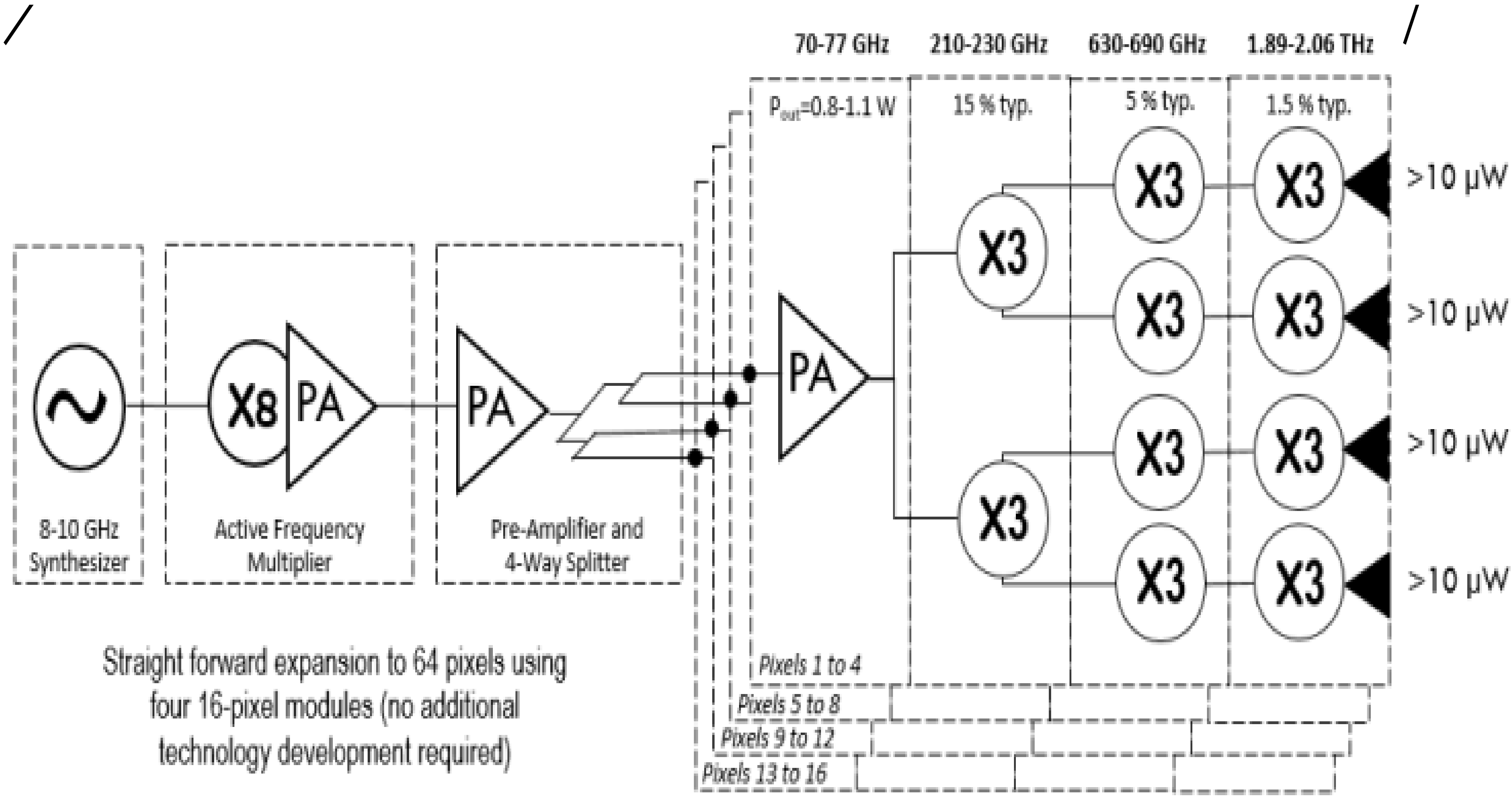
X3X2X3X3 architecture



1.9 THz 4-Pixel Frequency Multiplied Chain delivered by JPL for NASA's Stratospheric Terahertz Observatory, STO-2 (Dec. 2016).

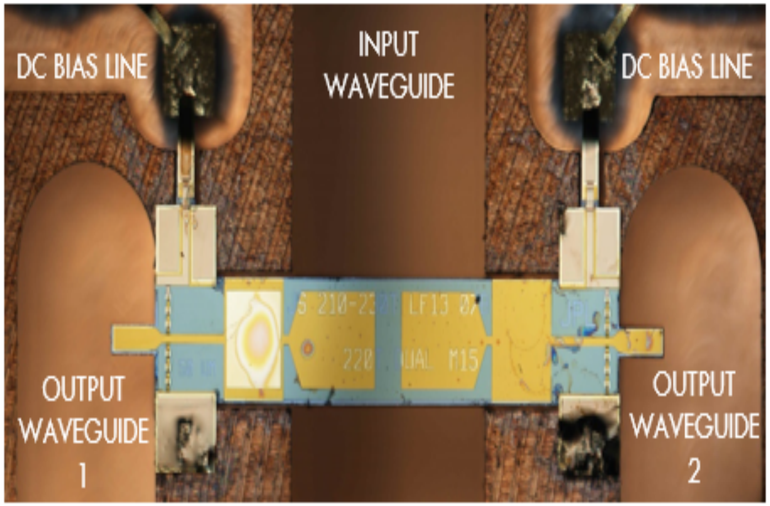
Power Consumption= 28 Watts/pixel

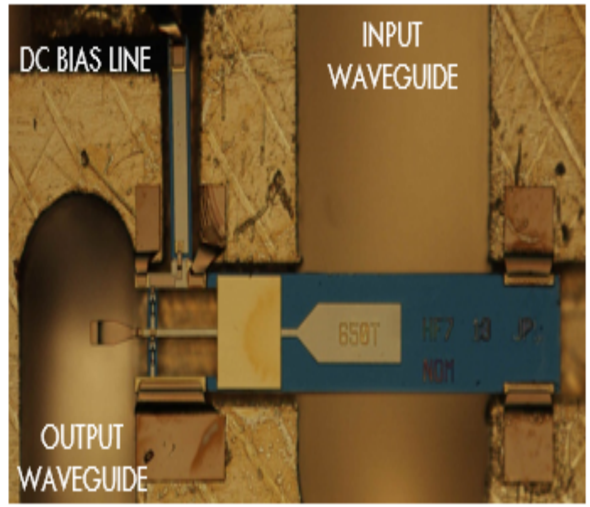
16-Pixel 1.9-2.06 THz LO subsystem

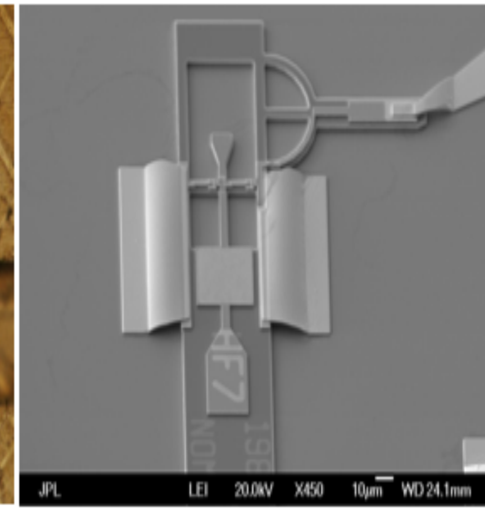


Power Consumption= 2.3 Watts/pixel

Optimized Device Designs for Power and Efficiency







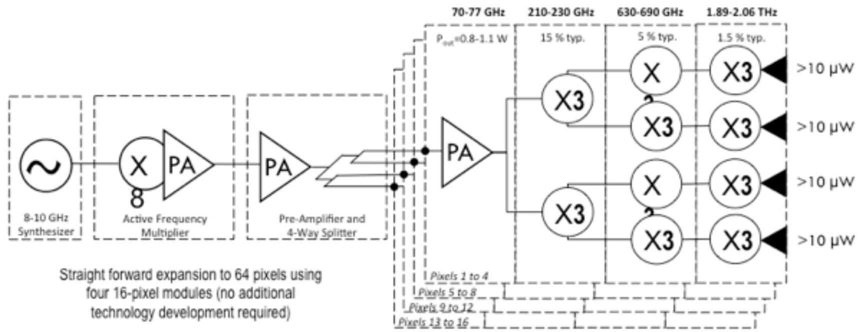
1st STAGE: On-chip Power Combined 210-240 GHz Tripler (JPL/Caltech patented technology)

2nd STAGE: High-Power 600-700 GHz Tripler (State-of-the-art)

3rd STAGE: Biasable 1.9-2.06 THz Tripler (First biasable tripler demonstrated beyond 1.5 THz)

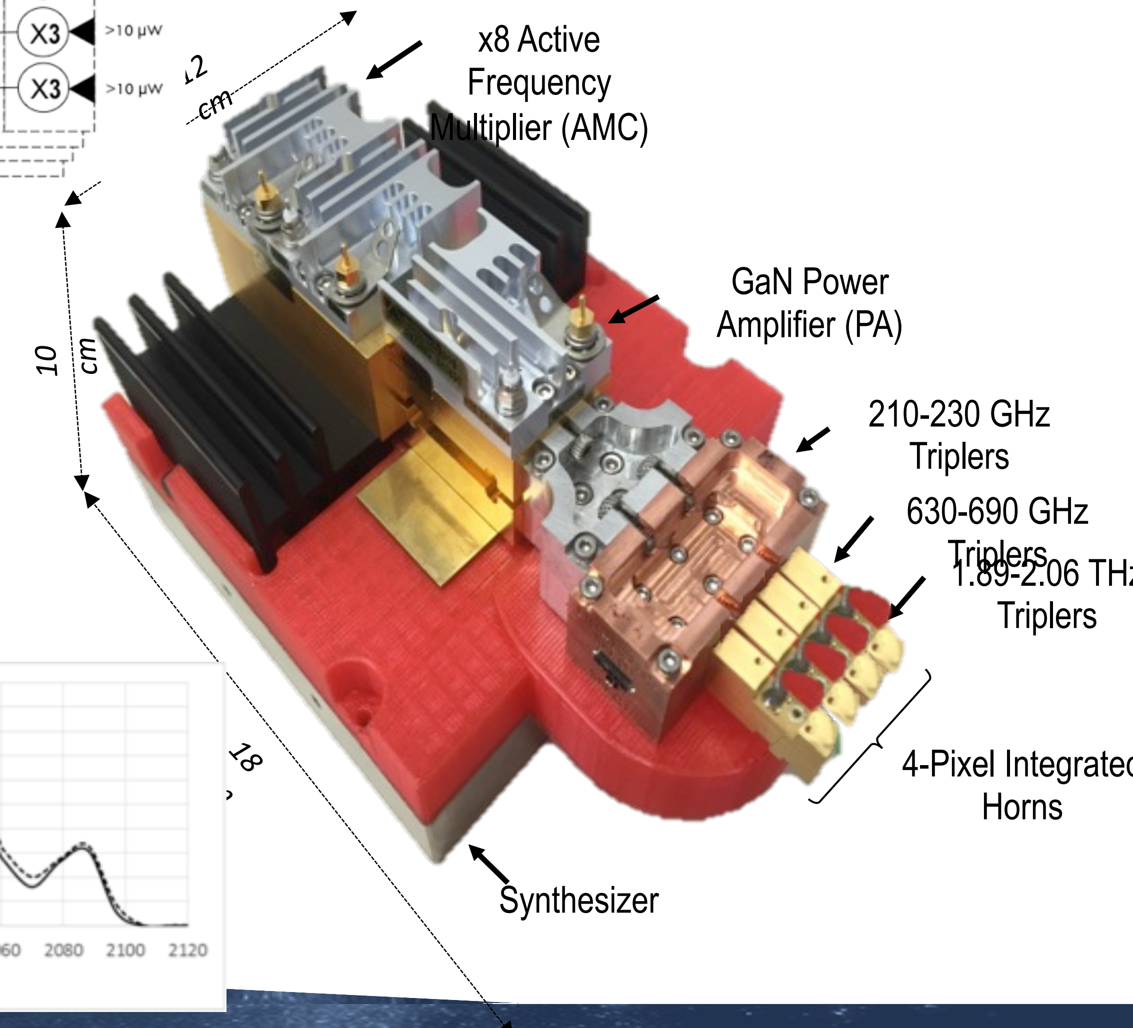
All required multipliers (x3x3x3) needed for the 16-pixel LO source have been designed, fabricated and tested.

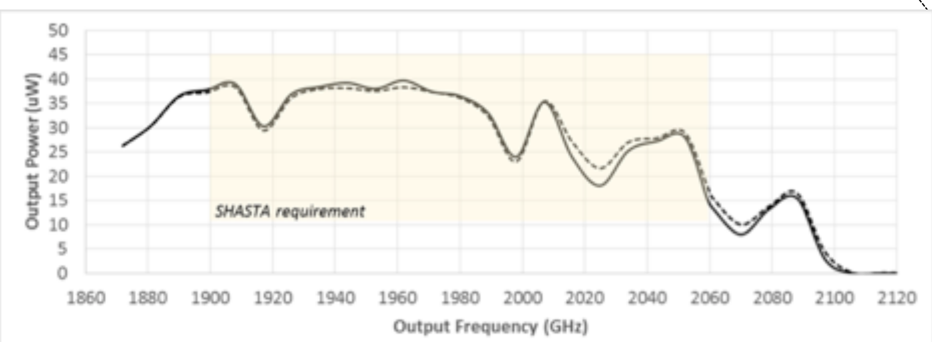
Multi-pixel LO source for 1.9-2.06 THz



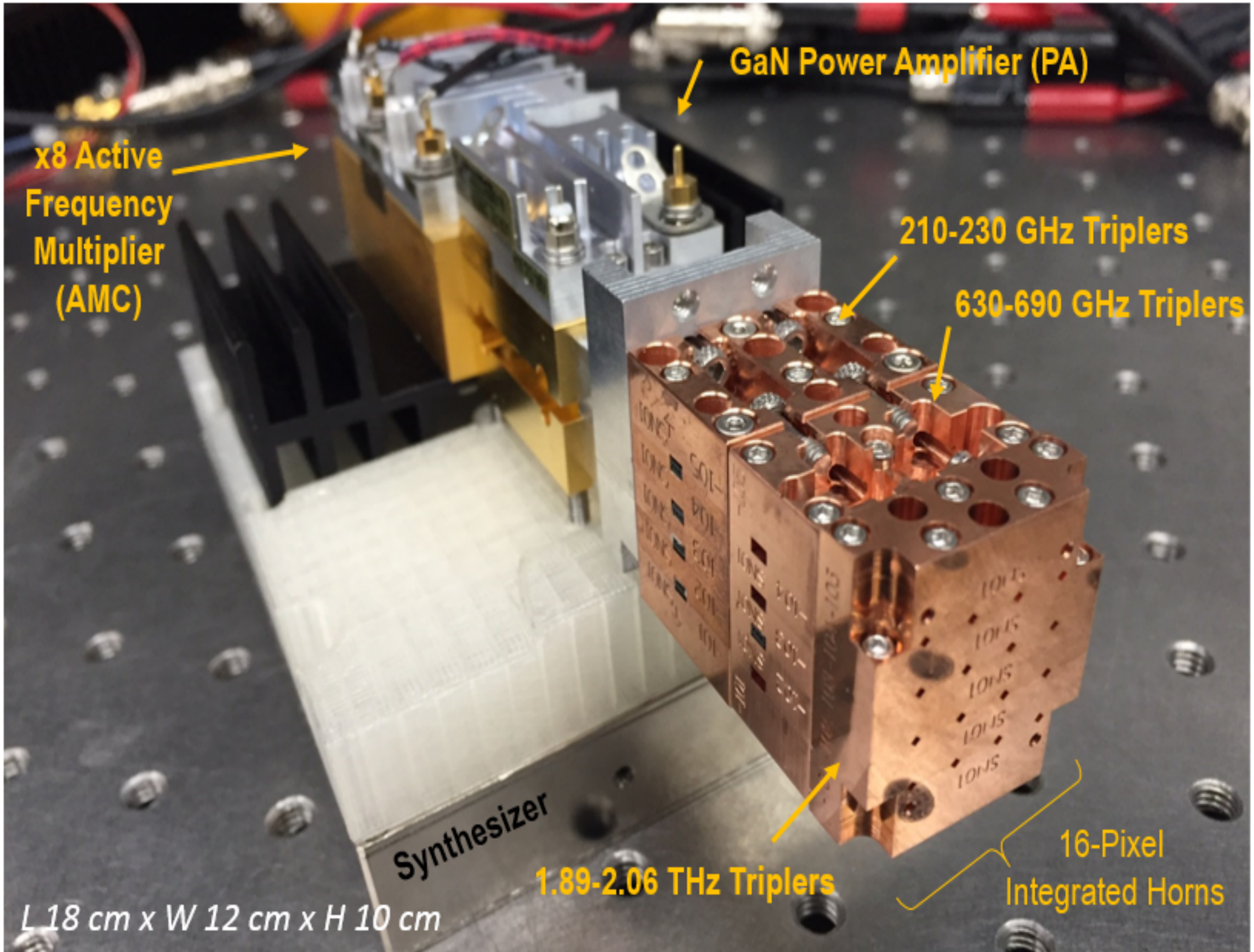
4-Pixel, 15 μW/pixel at 1.9 THz

dc power consumption: ~ 5.9 W/pixel



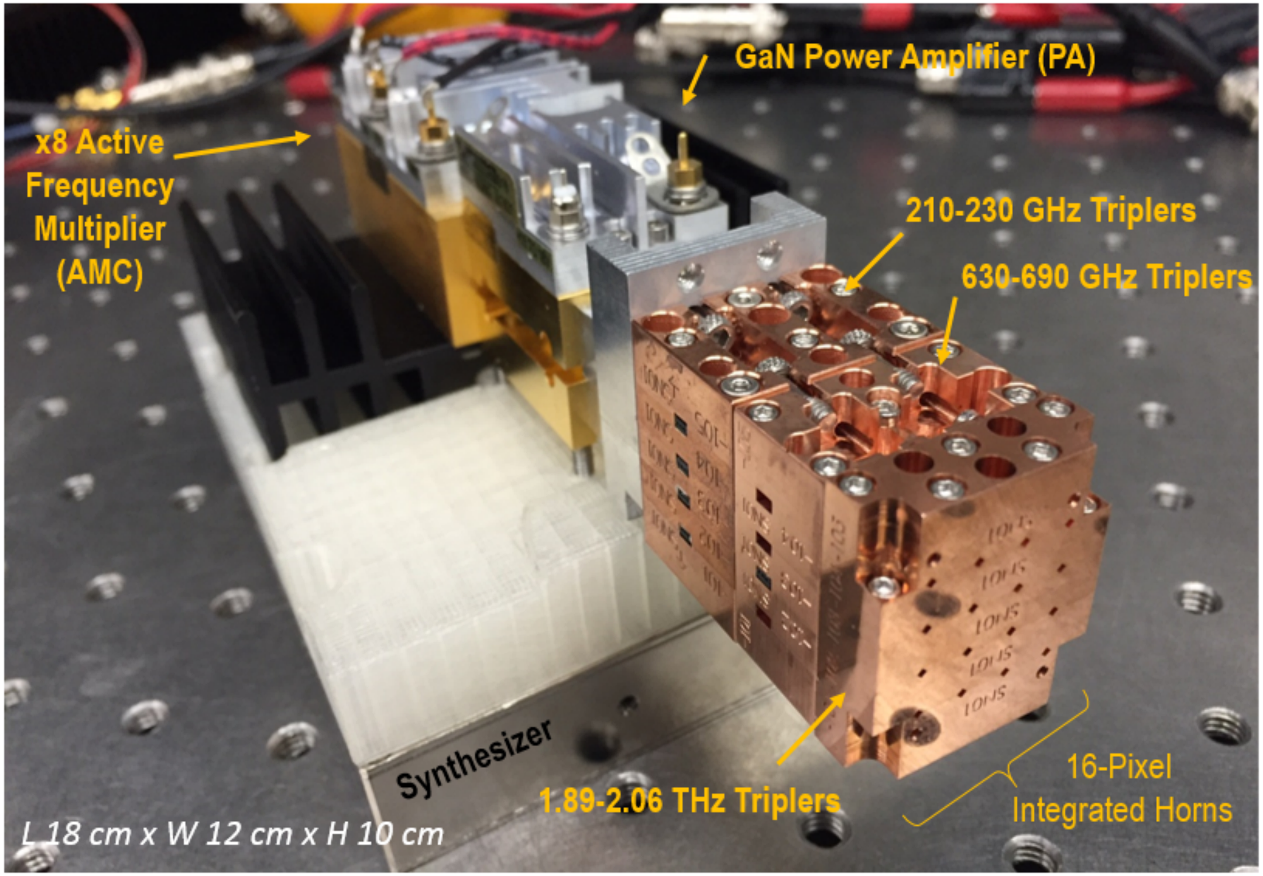


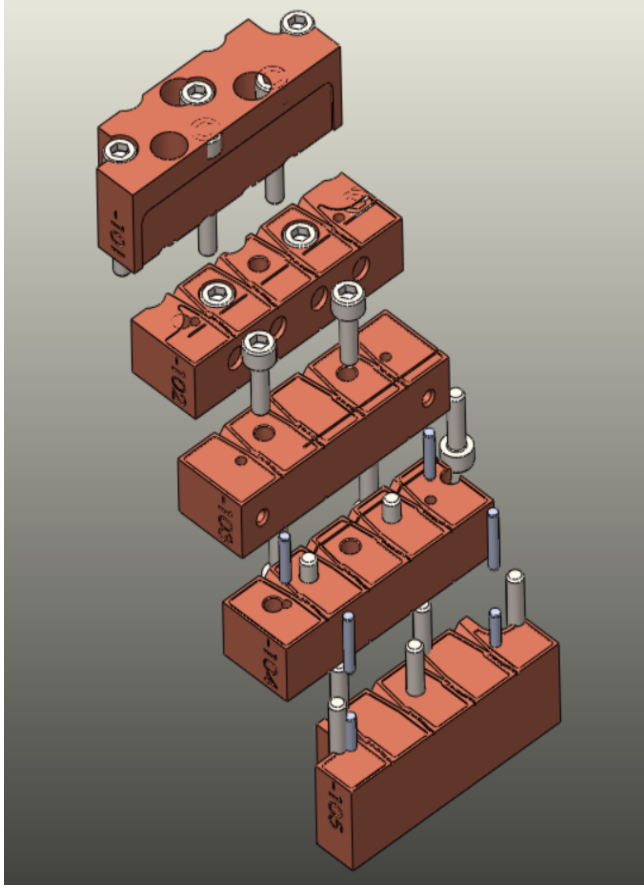
16-Pixel 1.9-2.06 THz LO subsystem



Power Consumption= 2.3 Watts/pixel

16-pixel 1.9 THz LO system: STACKING





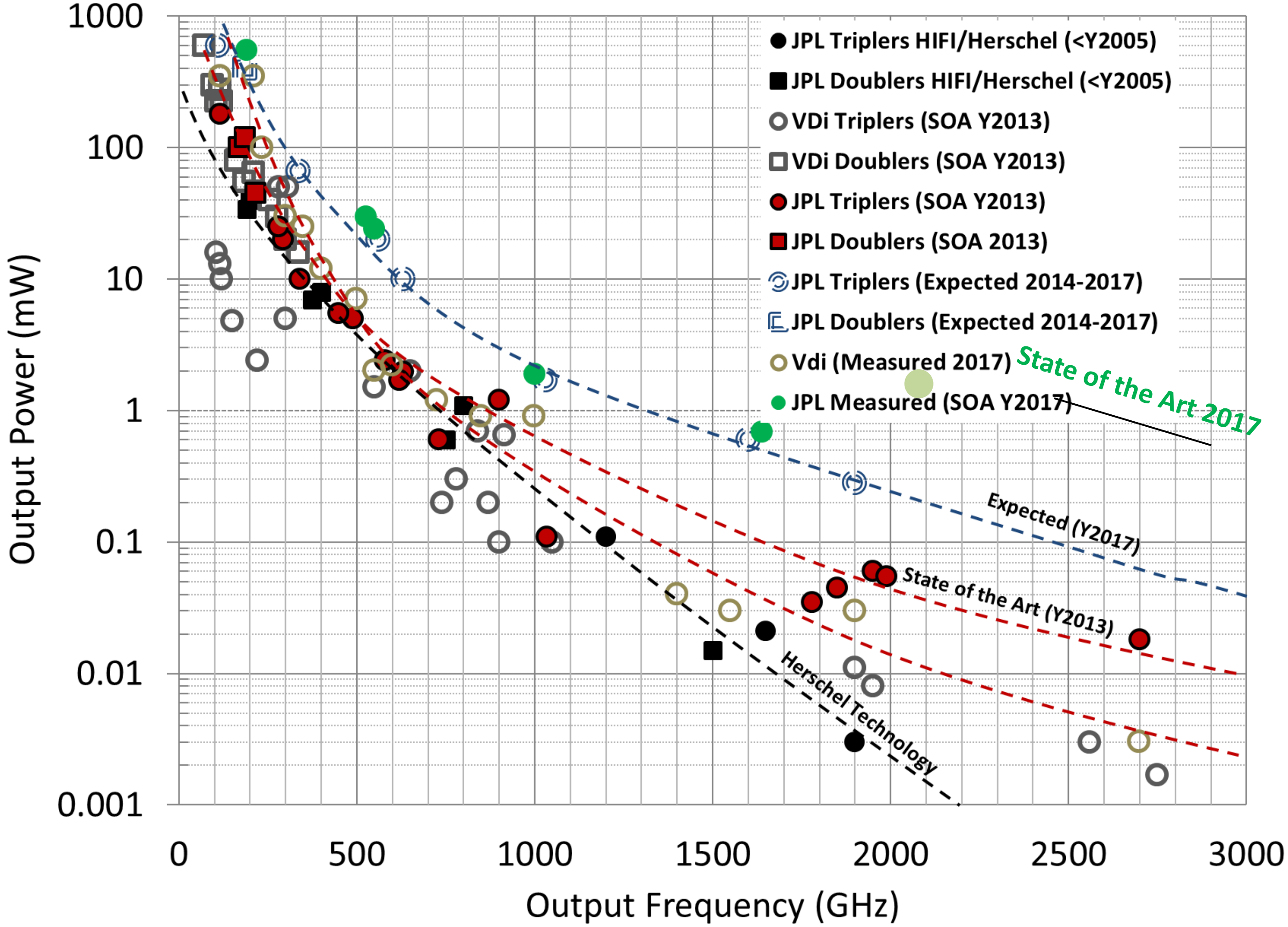
The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

Power Consumption= 2.3 Watts/pixel or 1.25 Watts/pixel using W-band CMOS synthesizers

X3X3X3 Architecture

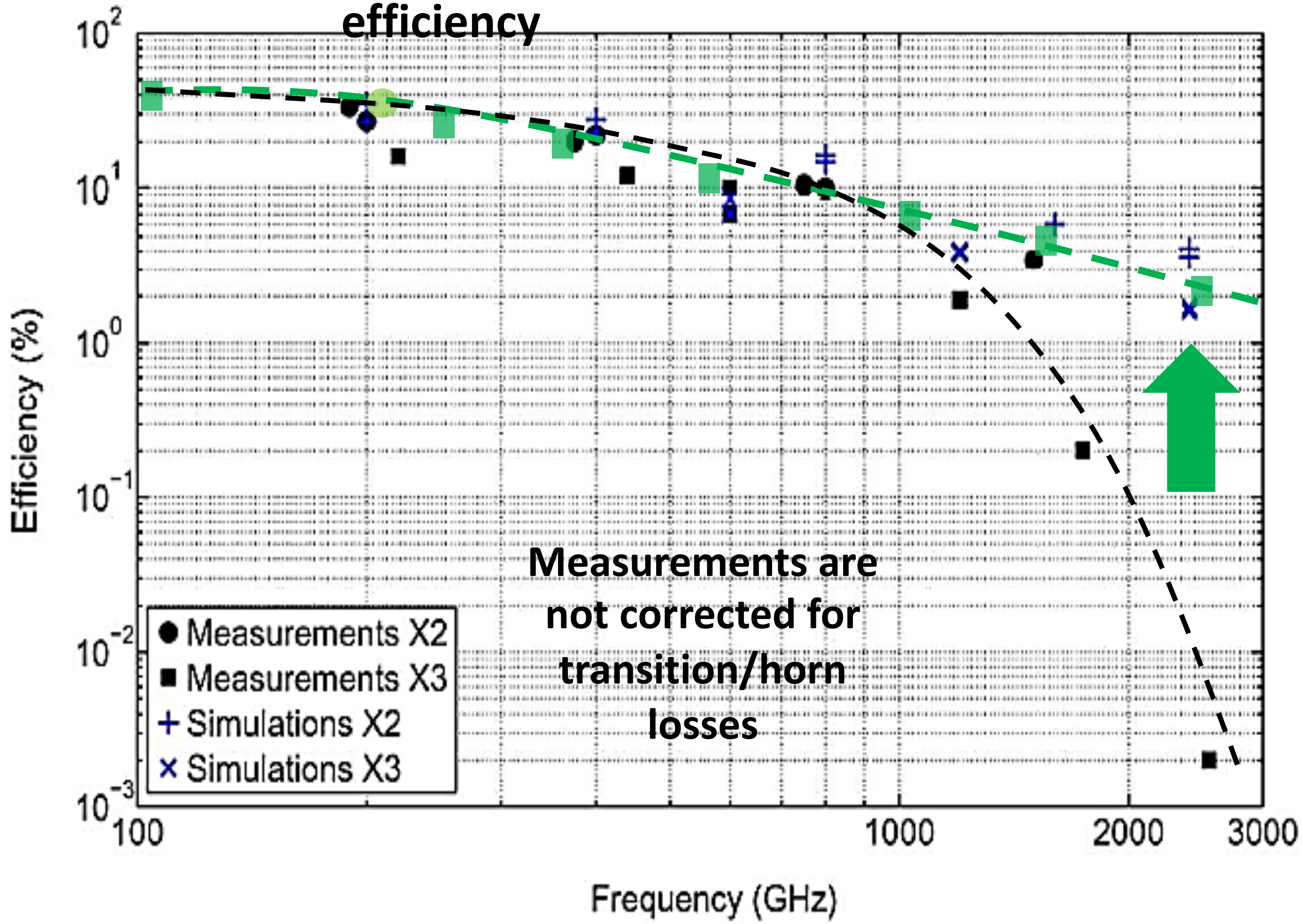
Room Temperature THz Sources--SOA

Multi-pixel heterodyne are now possible in the THz range



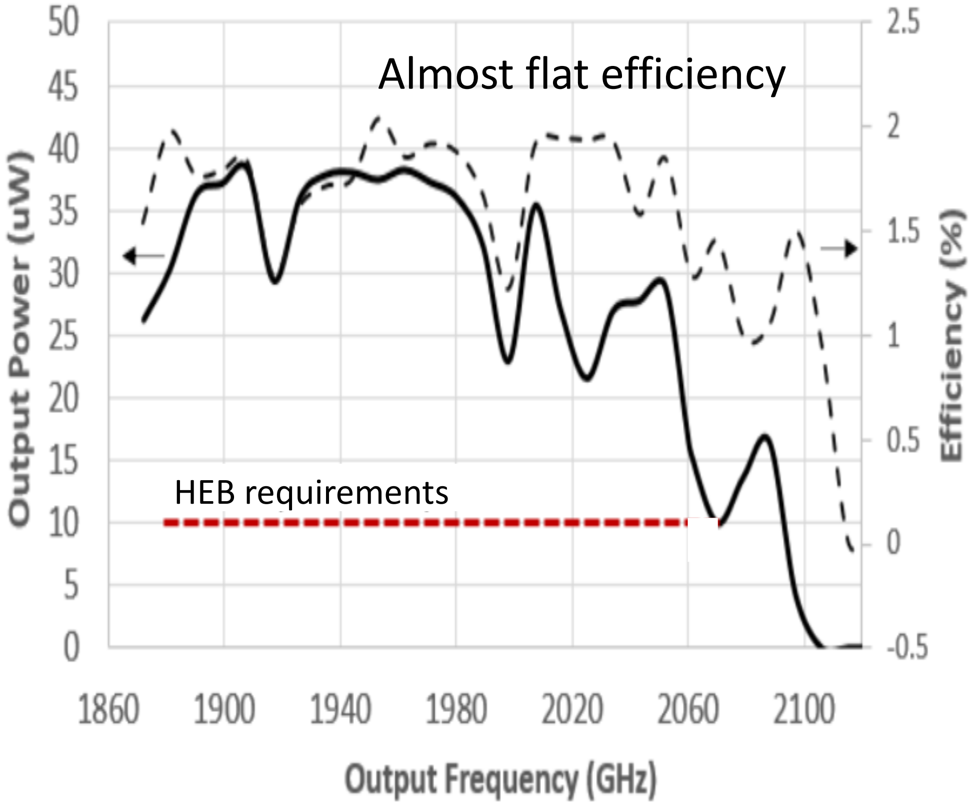
Room Temperature THz Sources--SOA

Optimized designs and precise manufacturing leads to improvement in efficiency

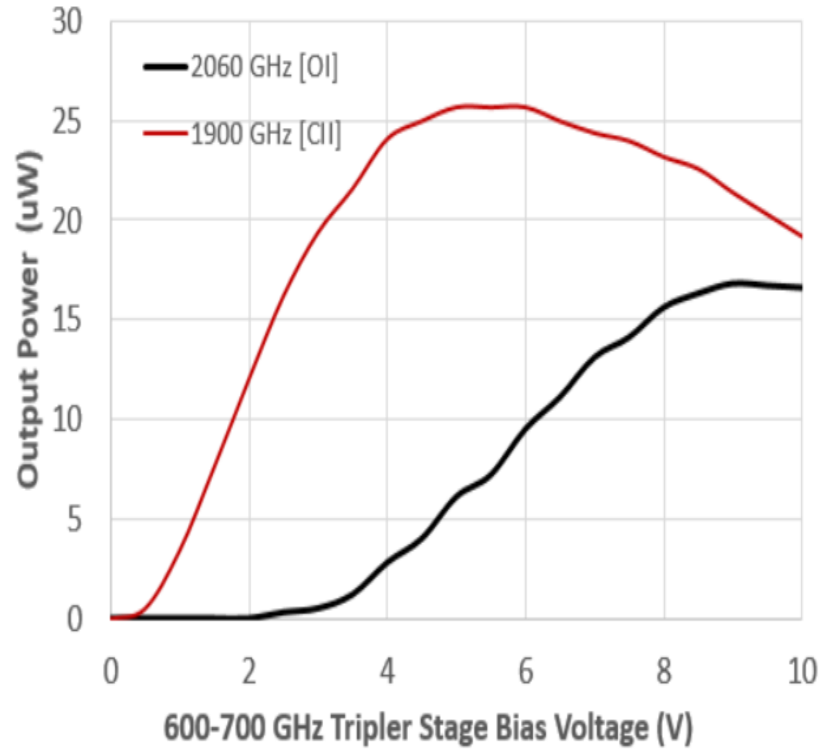


LO Chain Typical Performance

High power/large bandwidth source with no cooling required

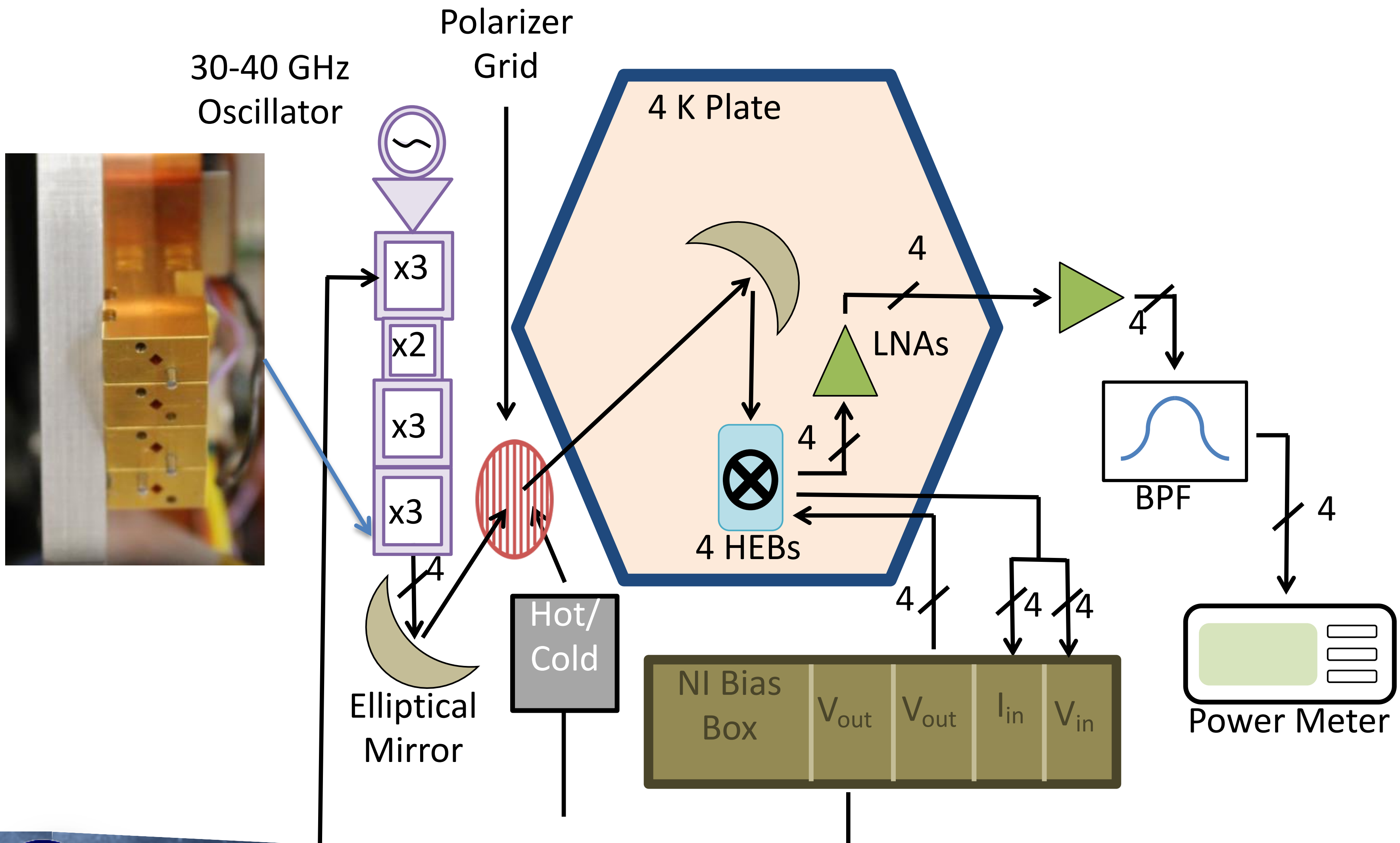


Individual output power per pixel adjustment

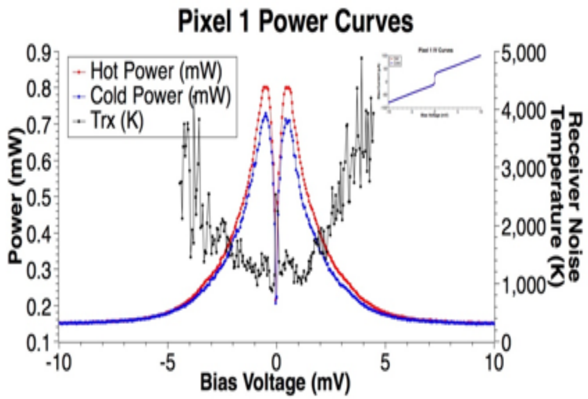


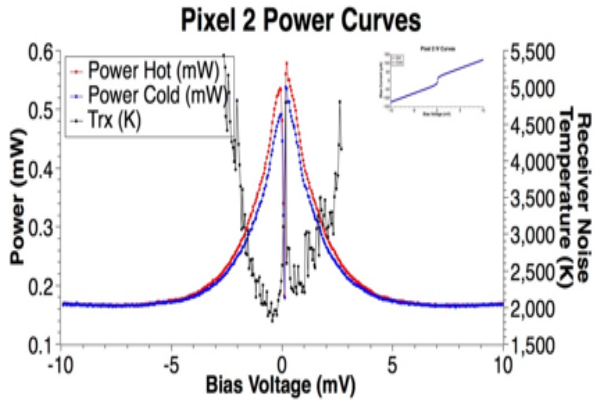
- *Substantial power margin, i.e., reduces critical alignment tolerances*
- *Improves system level stability*
- *Reduces LO noise contribution*
- *Output power control via bias (adjust power per pixel)*

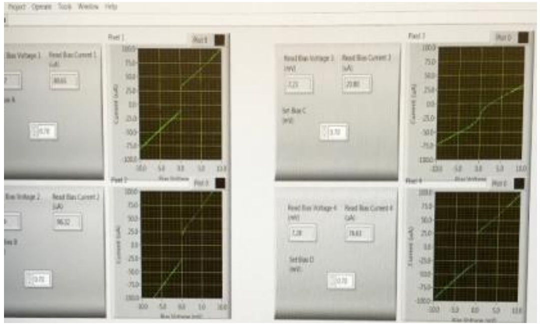
Receiver Setup



Multi-pixel Receiver measurements

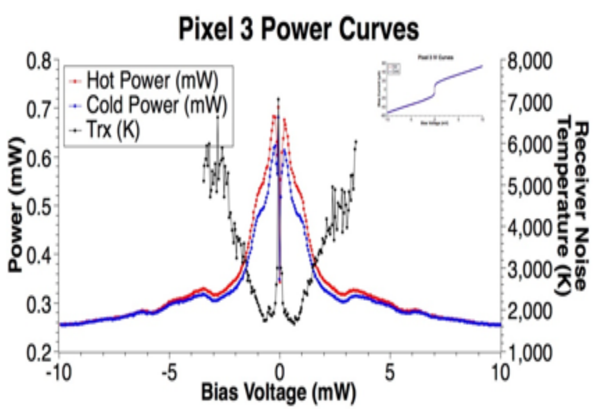


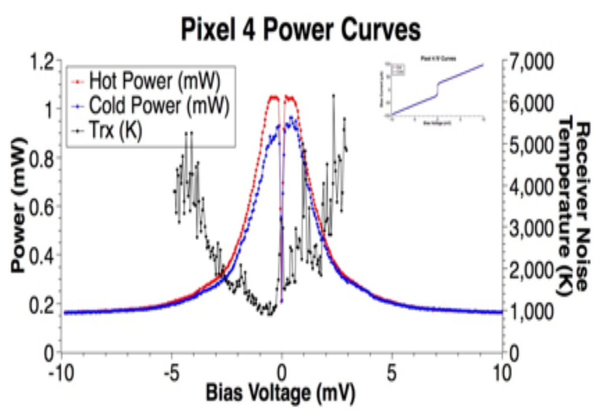


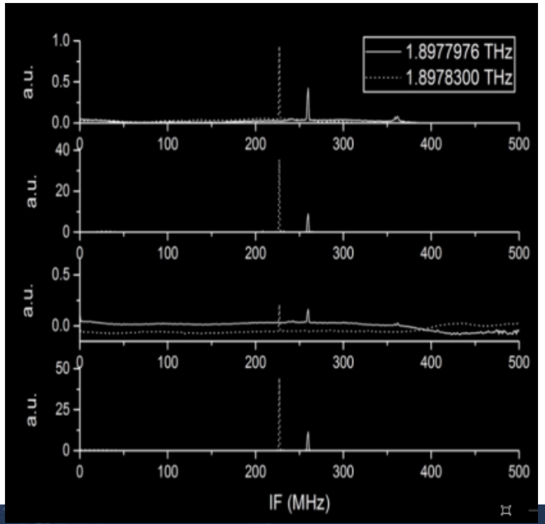


Best Y-Factor: 1.21, T_{rx} = 900 K

Best Y-Factor: 1.11, T_{rx} = 1800 K



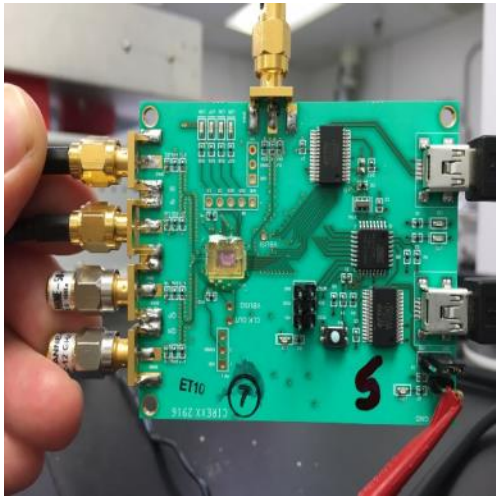




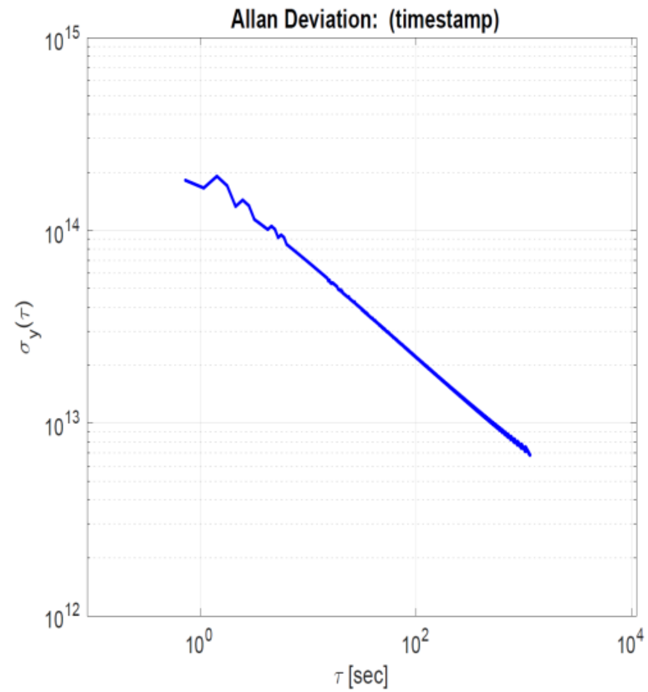
Best Y-Factor: 1.12, T_{rx} = 1700 K

Best Y-Factor: 1.21, T_{rx} = 900 K

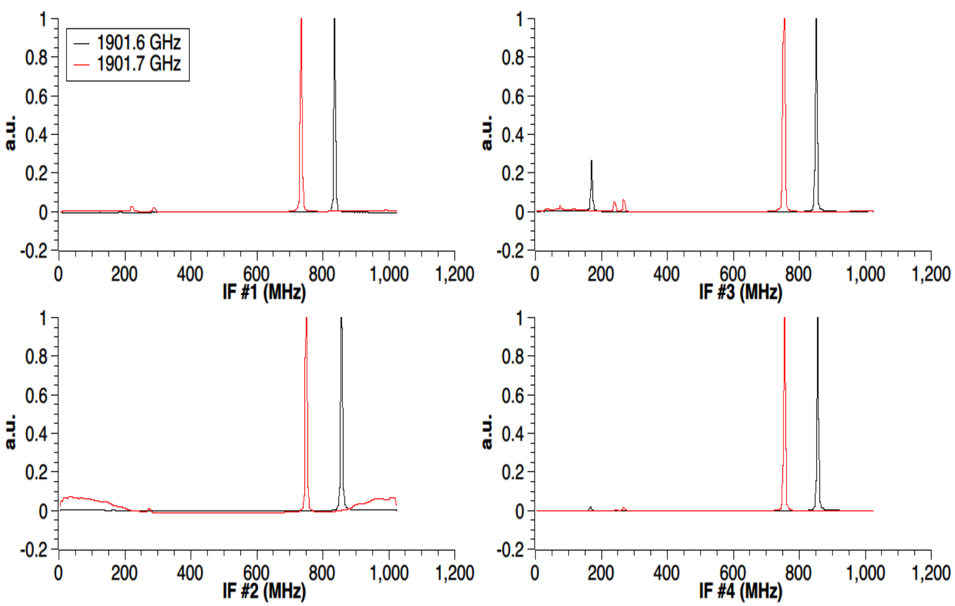
End-to-End Demonstration



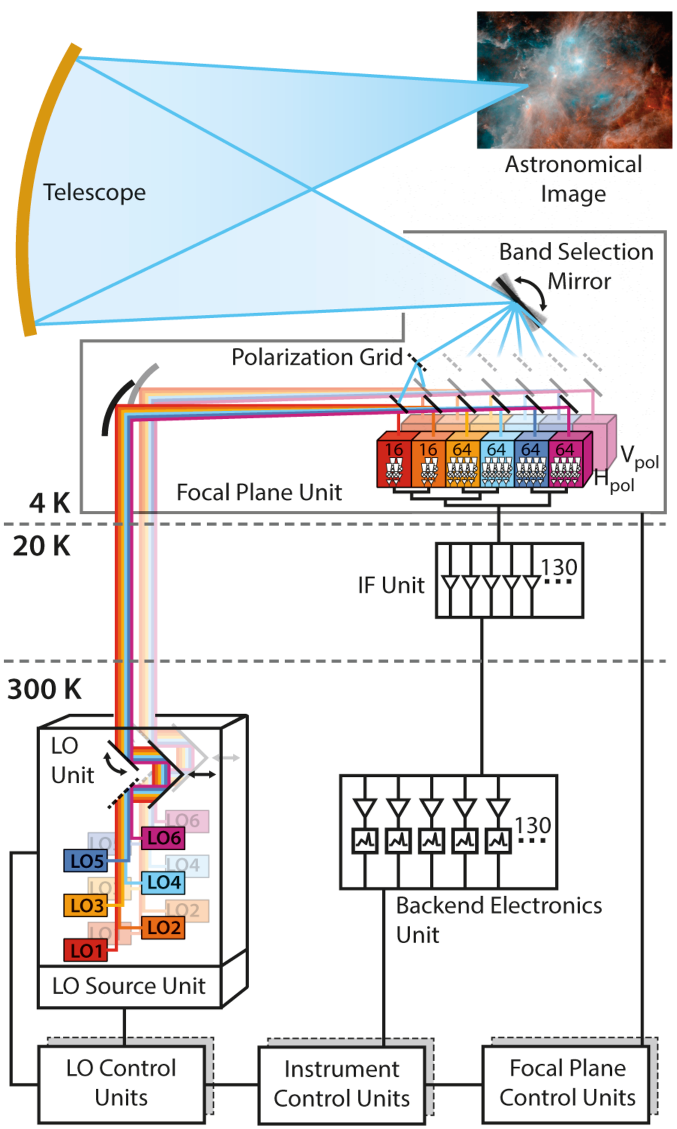
Prototype 1-GHz 256-channel spectrometer



Preliminary stability measurements indicate that the noise integrates down as expected



HEtrodyne Receivers on the Origins Space Telescope (HERO)



- NASA sanctioned next large (>2B$) mission concept study
- In competition with 3 other mission concepts
- Community discussion underway to decide on optimal path forward.
  - OST is single dish, 9-meter diameter, cooled to 4K
  - Discussions are open to science community
  - Currently 5 instruments are being studied
    - Far-IR Imaging Polarimeter
    - Heterodyne Instrument
    - High-Res Far-IR Spectrometer
    - Medium-Res Survey Spectrometer
    - Mid-IR Spectrometer-Coronagraph

HERO (Heterodyne Instrument for OST)

- Availability of 4K, 20K, and 300K platforms
- At 4K only 100 mW of dissipation is allocated
- At 20K only 250 mW of dissipation is allocated

Col.	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Band	ν(min)	ν(min)	λ(max)	λ(min)	Max Δλ/λ	IF BW2	Mixer	# pixels	# pixels	Trx	Beam s	T_{rms} (mK)	Line Flux	Line flux per time
	(GHz)	(GHz)	(μm)	(μm)		(km/s)	Type	Fall-back	Goal	K (DSB)	arc sec	in 1h at λ/Δλ =10^6	W/m^2 at 5σ, 10^6 res 9m tel. 1h	W m^-2 s^0.5, 9m, 5σ
1	484	648	610	429	10^7	4240	SIS	2x4	2x16	40	14.3	1.77	2.62E-21	1.63E-19
2	648	864	429	300	10^7	3175	SIS	2x4	2x16	80	10.0	3.07	5.31E-21	3.77E-19
3	864	1134	300	250	10^7	2402	SIS	2x4	2x16	110	7.6	3.67	8.34E-21	5.96E-19
4	1134	1512	250	188	10^7	1814	HEB	2x4	2x16	180	6.0	5.22	1.75E-20	1.12E-18
5	1512	1998	188	136	10^7	1368	HEB	2x4	2x64	250	4.5	6.29	2.69E-20	1.80E-18
6	1998	2700	136	111	10^7	1022	HEB	2x4	2x16	300	3.4	6.52	3.89E-20	2.49E-18
7	4536	4752	66	63	10^7	517	HEB	2x4	2x64	500	1.8	7.73	9.72E-20	5.84E-18

Table caption:

Col. 6 Max Δλ/λ max. resolution achievable, technically higher resolution can be reached easily if desired

Col. 7 Instantaneous bandwidth in km/s (it is assumed that we have 8 GHz IF bandwidth at all bands)

Col. 9, 10 The pixels will be arranged in 2 x NxN arrays, e.g. for 32 pixels there are 2 x 4x4 arrays. The two NxN arrays are overlaid at two different linear polarization.

Col 11 Relatively conservative receiver sensitivity estimate

Col 12 Diffraction limited beam size for 9m telescope

Col 13 Line sensitivity at 1 sigma, a factor of 2 has been taken into account to convert from DSB to SSB, however no factor for on/off has been taken into account.

Col 14 Assumed is 9m dish with 0.8 aperture efficiency, resolution λ/Δλ =10^6, and 5σ for 1h

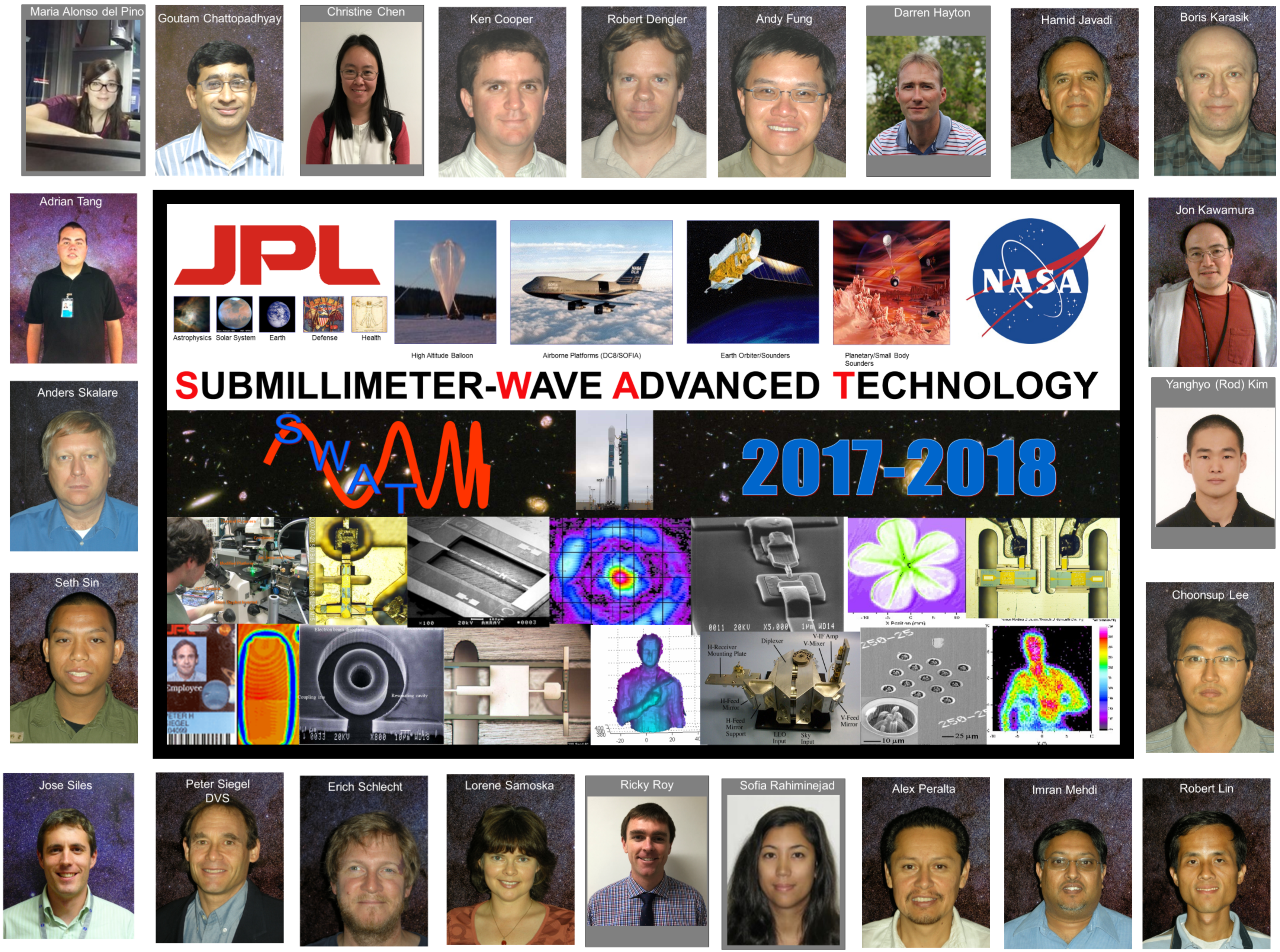
Col 15 Assumed is 9m dish with 0.8 aperture efficiency, resolution λ/Δλ =10^6, and 5σ per unit time

(Table courtesy of M. Wiedner, LERMA)

Summary

- 16-pixel LO subsystem has been assembled
  - Record output power
  - Output power from each pixel is controllable
  - Compact low DC-power/pixel approach
  - Modular, room temperature operation
- Receiver system demonstrated with a 4-pixel Hot Electron Bolometer
- Future work will explore further integration and approaches to making the chain more compact and low power with increased bandwidth

Acknowledgement: Wish to acknowledge past and present members of my group at JPL that have made the presented work possible. This work was carried out at JPL, California Institute of Technology, under a contract with NASA.


Maria Alonso del Pino
Goutam Chattopadhyay
Christine Chen
Ken Cooper
Robert Dengler
Andy Fung
Darren Hayton
Hamid Javadi
Boris Karasik
Adrian Tang
Jon Kawamura
Anders Skalare
Yanghyo (Rod) Kim
Seth Sin
Choonsup Lee
JPL
Astrophysics
Solar System
Earth
Defense
Health
High Altitude Balloon
Airborne Platforms (DC8/SOFIA)
Earth Orbiter/Sounders
Planetary/Small Body Sounders
NASA
SUBMILLIMETER-WAVE ADVANCED TECHNOLOGY
SWAT
2017-2018
Jose Siles
Peter Siegel DVS
Erich Schlecht
Lorene Samoska
Ricky Roy
Sofia Rahiminejad
Alex Peralta
Imran Mehdi
Robert Lin