The ALMA Approach

B. Shillue

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Overview

- ALMA LO requirements
- ALMA LO Implementation
- ALMA LO Cost (Drivers)
- Recent Work in long-distance synchronization
- SKA Approach, briefly
- Extrapolation to the NGVLA

ALMA Specifications affecting LO and Timing

- Frequency Range 31-950 GHz
- At highest frequency, 1psec ~ lambda
- ALMA site expected Sky delay variations
  - < 500 fsec 50% of the time
  - < 150 fsec 10% of the time
  - < 90 fsec 2.5% of the time
- 1st LO rms integrated phase noise < 53 fsec
- 1st LO phase drift < 18 fsec

ALMA LO Reference Phase Correction
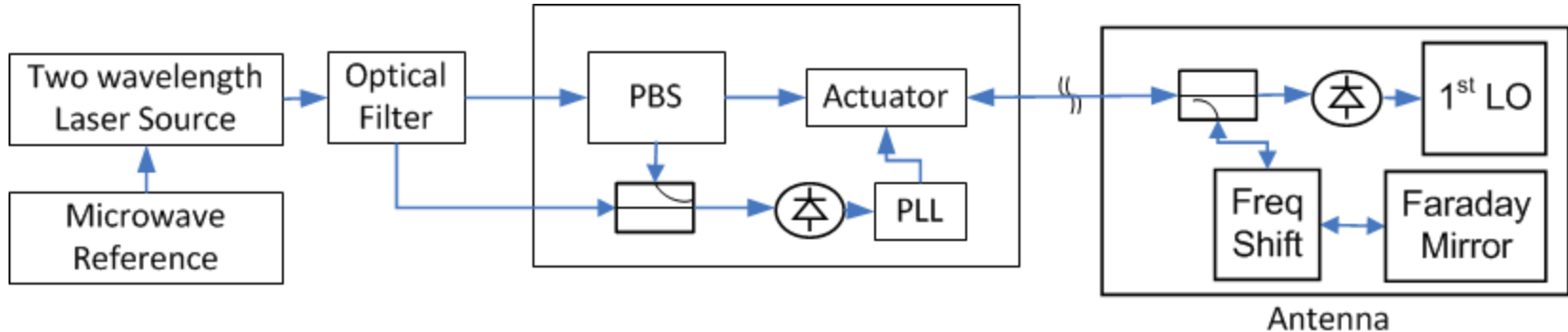
Antenna

- Master and Slave Laser comprise the 1st LO Reference
- Tap off a portion at the antenna
- Frequency Shift, faraday rotate, and return this portion
- Use low frequency photodetection circuit and fiber stretcher to close the round-trip phase loop
- The master laser is an ultra-stable reference

Cost of ALMA Implementation

Item	Cost per Unit	Number Required	Total Cost	
Master Laser	300	1	300	"Yardstick" for round-trip phase
Laser Synthesizer	160	4	800	Provides tunable, switchable 1st LO reference
Line Length Corrector	16	66	1056	Round trip measurement and actuation
LO Photonic Receiver	43	66	2838	EDFA plus frequency shifter
LO Reference Receiver	19	66	1254	Phase lock and distribution
Central Microwave Reference	65	4	260	Main tuning for 1st LO
Photonic Switching and distribution	620	1	620	Subarrays and EDFAs
Fiber Optic Wraps	6.5	132	858	Low polarization rotary joint
Photomixer	8	264	2112	High frequency O/E conversion
1st LO	20	264	5280	YIG, amplifiers, multipliers
2nd LO Synthesizer	9	264	2376	YIG PLL based design
1st LO Synthesizer	2.3	64	147	DDS provides offset, fringe, Walsh functions
Total			17901	

Significant Cost Drivers

- 1st and 2nd LO YIG-based synthesizers are 43% of overall cost, consider central synthesis for NGVLA

- "Special" photonics cost are high: custom lasers, custom high frequency detectors, frequency shifters

- "Ordinary" photonics costs are low: diode lasers, telecom devices, fiber, switches, isolators, ...etc

ALMA Limitations

- Group delay variation vs. temperature. This usually shows up for tau > 1e3 sec, and appears to be repeatable and proportional to stretcher voltage, therefore should be amenable to calibration
- The following are not correctable:
  - Polarization mode noise term
  - Temperature variation on uncorrected fiber
  - Gravitational fiber deformation effect on uncorrected LO Photonic Receiver fiber
  - Polarization to Phase conversion in the photomixer
  - Amplitude to Phase Conversion in the photomixer

ALMA Limitations (2)

- Polarization mode noise
  - **Shen et al,"The Temporal Drift Due to Polarization Noise in a Photonic Phase Reference Distribution System", IEEE JLT, Aug 2008**
  - **Minimized by low State-of-Polarization-Change (SOPC) Fiber Stretcher**
  - **Minimized by custom low-SOPC Fiber Optic Wrap**
  - **Low PMD fiber installation**
  - **Photomixer has significant DGD**

- Temperature effect of uncorrected fiber
  - Design for minimum DL*DT (thermal design, fiber length matching)

- Photomixer Effects
  - Can be significant : Design for stable amplitude and polarization

- Tilt: Effect of gravity
  - Matched length and semi-rigid fiber cables in Front End(< 0.3 fsec delay change per degree of antenna tilt

Alternate ALMA LO Reference
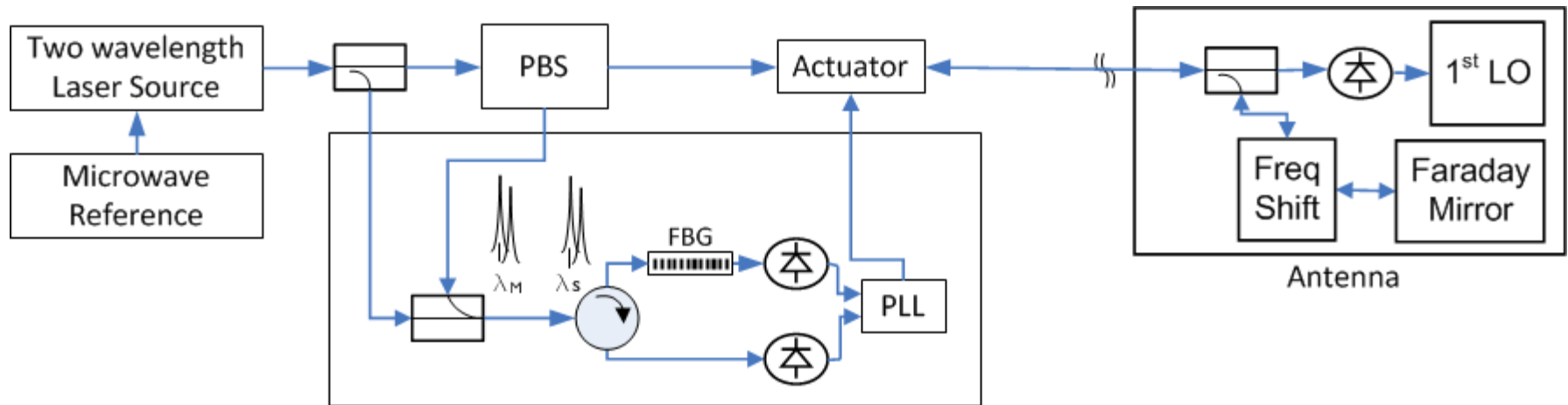
- Dual-Difference Detector *eliminates Group Delay error term*
- Does not require coherent or stable Master Laser
- Actual LO reference frequency phase is zeroed
- *Kiuchi*, "Highly stable millimeter-wave signal distribution with an optical round-trip phase stabilizer." *MTT-S Trans* (2008)

Synchronization over Optical Fiber Recent Work

- High-precision optical-frequency dissemination on branching optical-fiber networks ," Schediwy et al, Optics Letters, Vol. 38,Issue 15,pp. 2893-2896(2013)doi: 10.1364/OL.38.002893

- "Simultaneous remote transfer of accurate timing and optical frequency over a public network," Lopez et al, Appl Phys B, (2013)

- "Optical Frequency Transfer over a Single-Span 1840 km Fiber Link," Droste et al, PRL, 11,110801 (2013)

- Wang, Bo, et al. "Fiber-based ultra-stable frequency synchronization using client-side, 1f-2f active compensation method." *arXiv preprint arXiv:1409.3342* (2014).

- Raupach, S. M. F., A. Koczwara, and G. Grosche. "Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier." *Optics express* 22.22 (2014): 26537-26547.

- Lopez, Olivier, et al. "Cascaded optical link on a telecommunication fiber network for ultra-stable frequency dissemination." *SPIE OPTO*. International Society for Optics and Photonics, 2015.

- Newbury, N. R., P. A. Williams, and W. C. Swann. "Coherent transfer of an optical carrier over 251 km." *Optics letters* 32.21 (2007): 3056-3058.
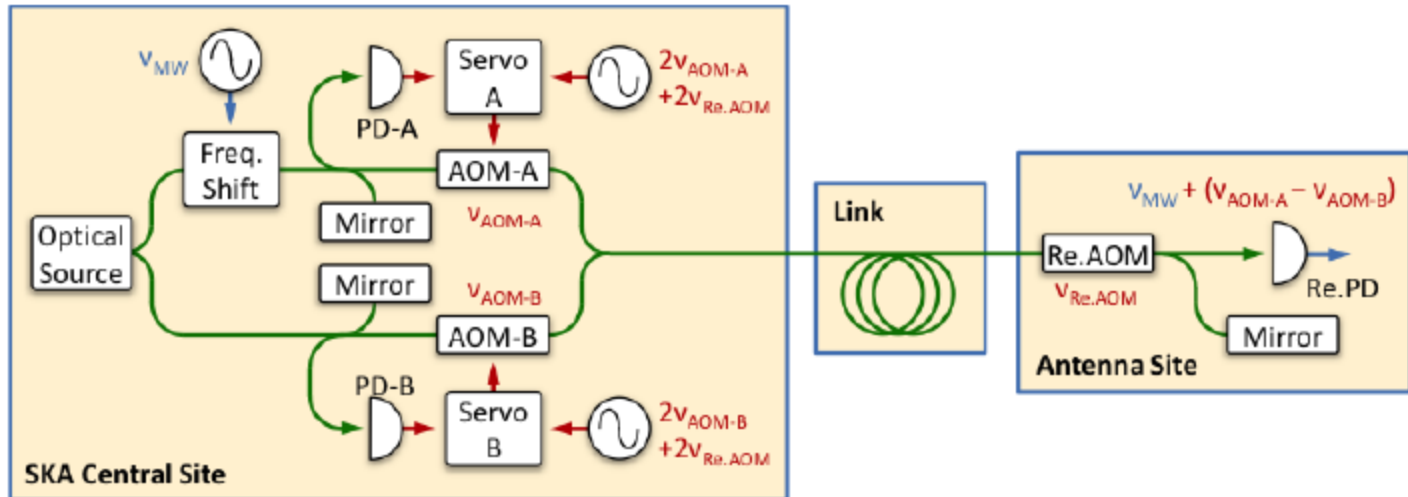
SKA Approach #1:
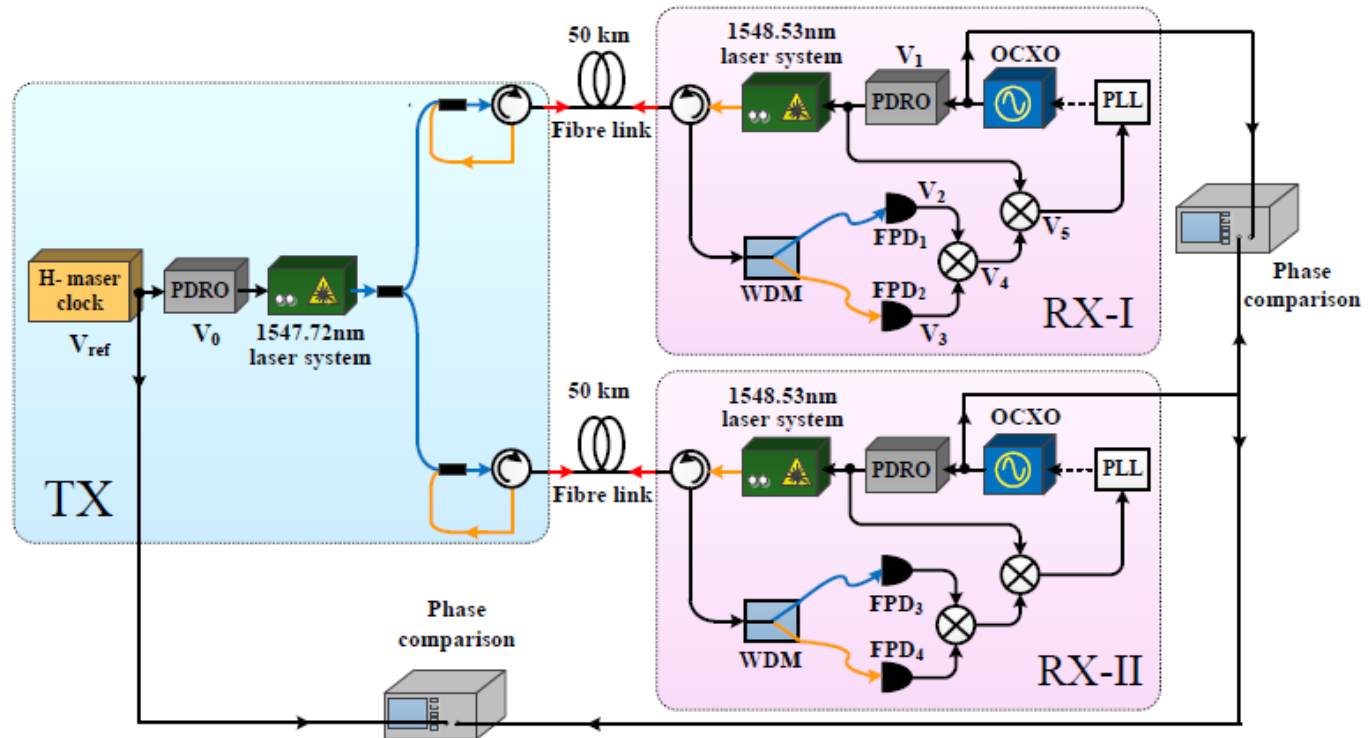
Active RF Phase Compensation 1f:2f system
- 1 GHz and 2 GHz oscillators used
- Higher frequencies synthesized at the telescope
- tested successfully at ~ 75 km
- tested at long distance ~150 km (using two-way EDFAs)
- Demonstrated over fiber routed on poles

Courtesy K. Grainge, SKA SDT Lead, U. Manchester

SKA Approach #2

Active Optical Phase Compensation

Two wavelengths transmitted, each is phase corrected independently

- Higher frequencies can be synthesized centrally
- tested successfully at ~ 75 km
- tested at long distance ~150 km (using two-way EDFAs)
- Demonstrated over fiber routed on poles

Courtesy K. Grainge, SKA SDT Lead, U. Manchester

NgVLA Parameters affecting LO and Timing

- LO and LO Reference distribution typically one of the last things specified, … after receivers, bands, bandwidths, digitizers…etc
- Nevertheless can assume broadly tunable, low phase noise LO with frequency switching and fine tuning requirements

NGVLA Phase stability requirement
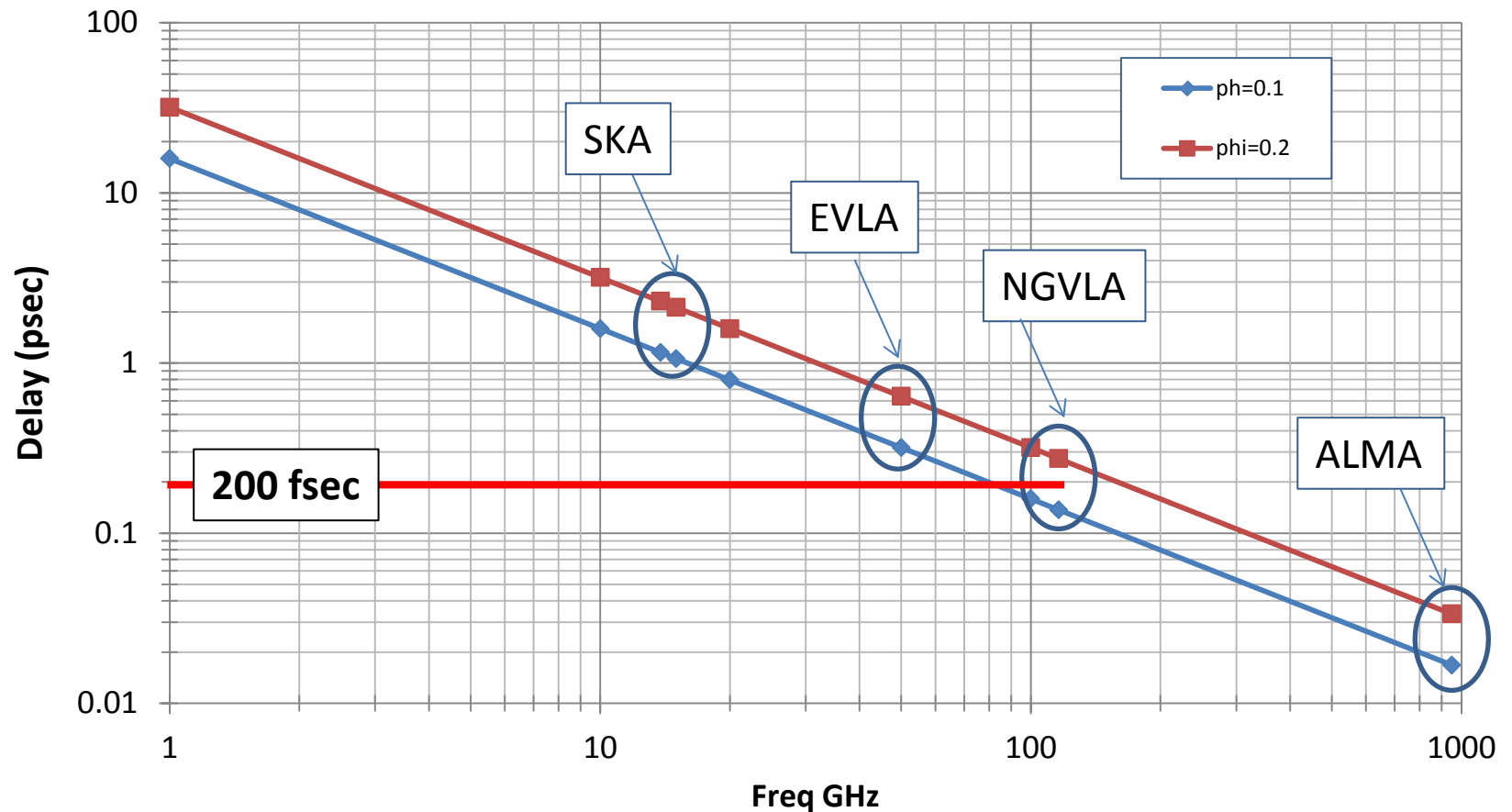
Possible NGVLA Approach
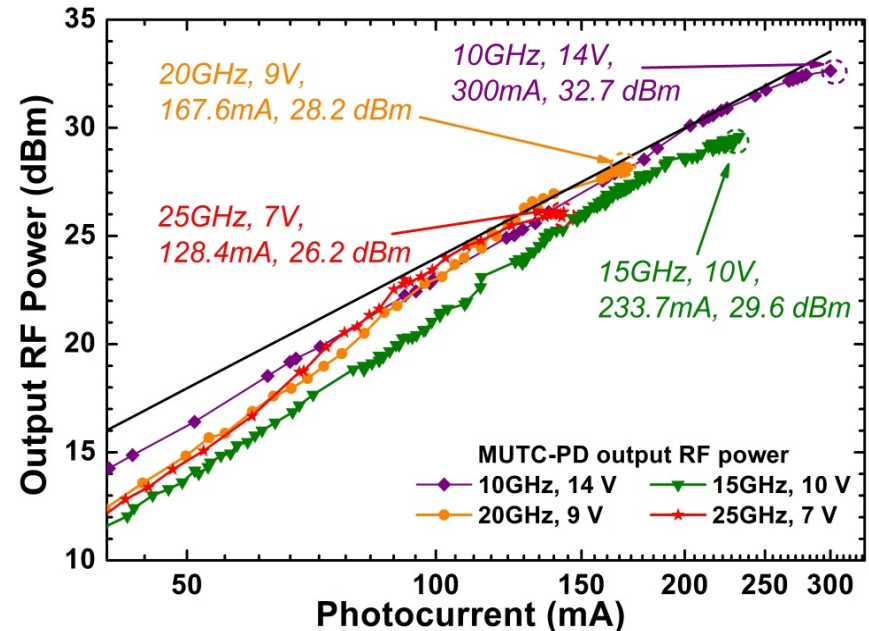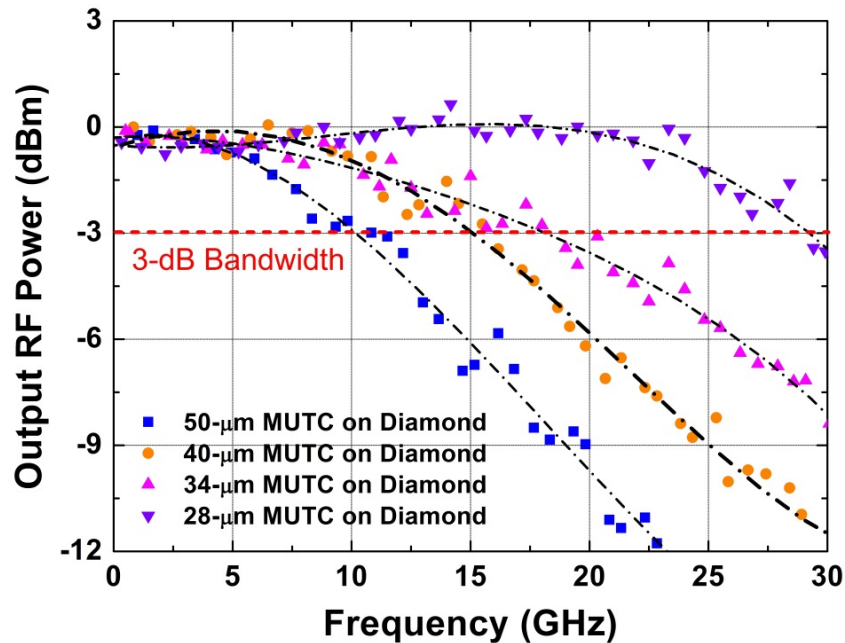

High Speed Photodetector
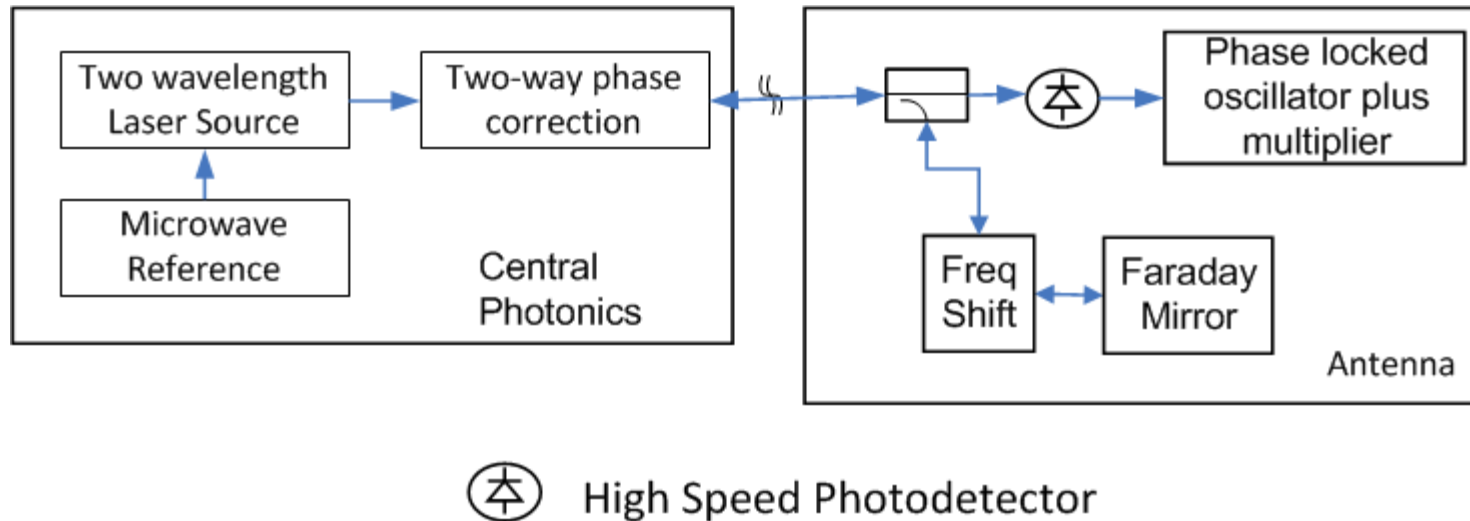
- Phase correction could use AOMs for infinite correction range
- Central Photonics needs to be engineered for PMD-mitigation
- Fringe tracking, Walsh functions applied centrally?
- Even simpler: LO output directly from photodetector
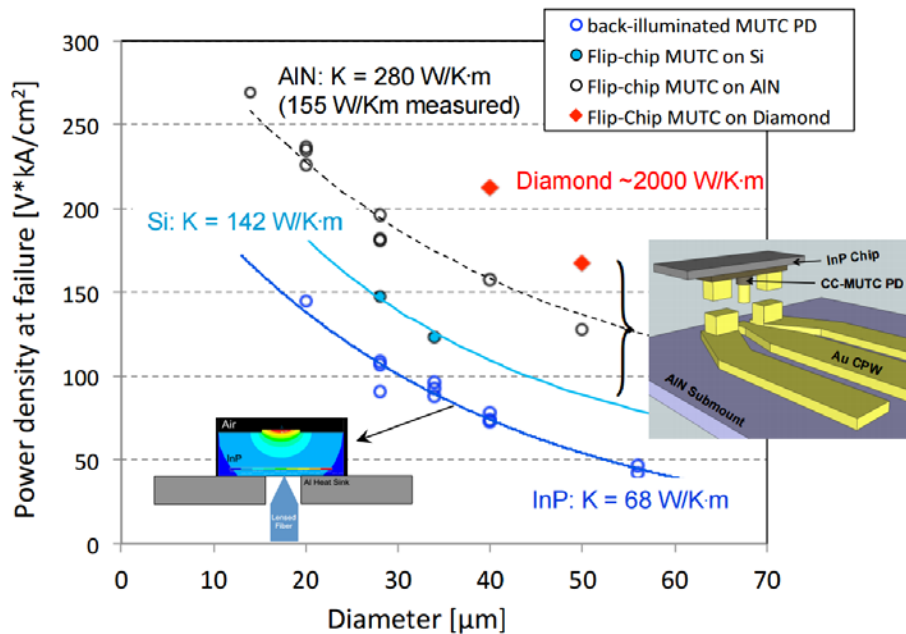
Bandwidth and output power

Diameter (μm)	Frequency (GHz)	RF Power (W) On AlN	RF Power (W) On Diamond	RF Power Improvement
50	10	1.02	1.86	83 %
40	15	0.75	0.92	23 %
34	20	0.37	0.66	78 %
28	25	0.31	0.42	36 %

From J. Campbell, UVA

X. Xie, et al, "Improved power conversion efficiency in high-performance photodiodes by flip-chip bonding on diamond," *Optica*, 2014
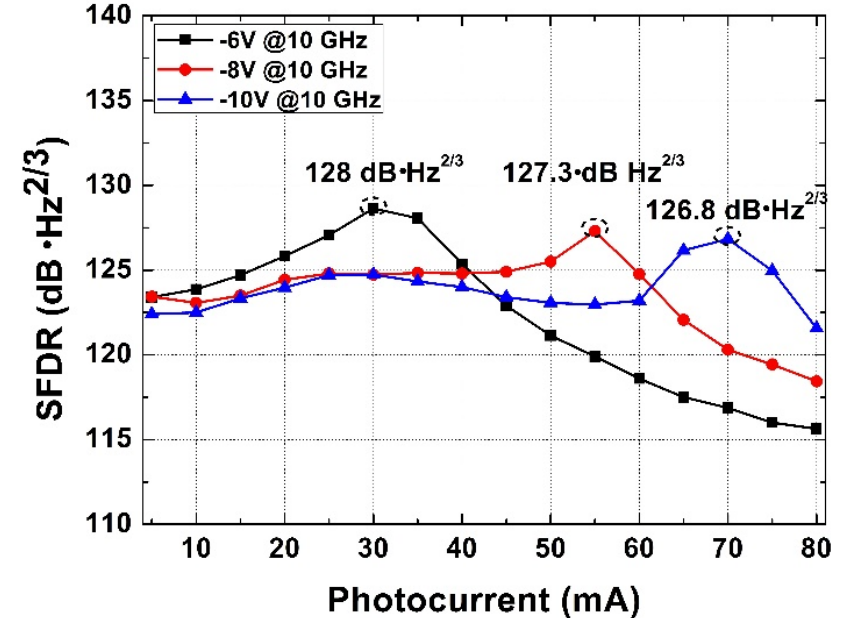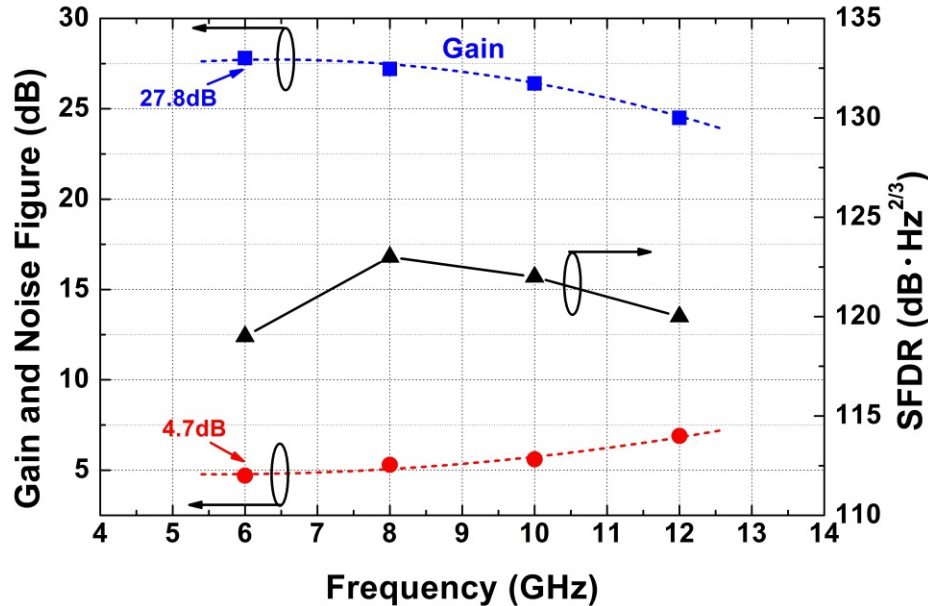
Power summary
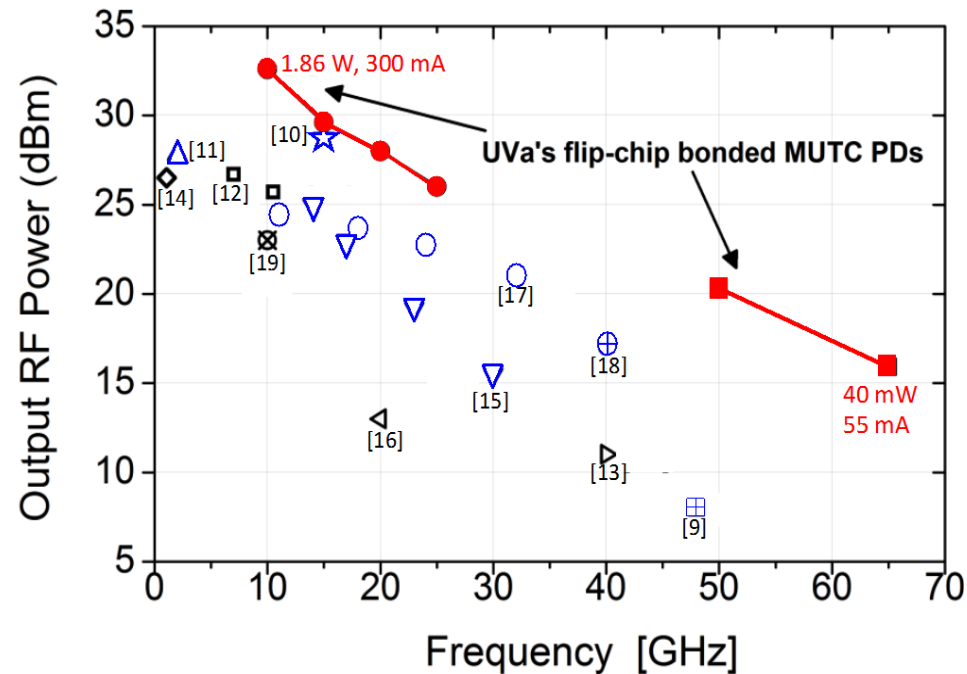
➢ Power density at failure is improved by applying higher thermal conductivity submount .

➢ Record-high power level with 1.8 W at 10 GHz is achieved.

From J. Campbell, UVA

In this work, Dr. Zhou designed the mask and finished fabrication and I am responsible for bonding and characterizing devices performance.

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Link performance

- High link gain reaches up to 26 dB at 10 GHz.
- Low noise figure goes down to 6 dB at 10 GHz.
- High SFDR: >120 dB Hz$^{2/3}$.

From J. Campbell, UVA

X. Xie, et al, "High-Gain, Low-Noise-Figure and High-Linearity Analog Photonic Link," *Journal of Lightwave Technology*, 2014

The PMD Issue

- PMD for good (newer) fiber may be ~50 fsec per root km

- Thus 1 psec at 400km

- Over observing timescales ~1hr, the phase drift effect from PMD can be well below this, say 100 fsec

- But, only if good polarization/engineering practice is used, and…

- The variation will be faster if the fiber is not well insulated

The Distance Issue

- Very long phase transfer > 1000 km with high accuracy has been demonstrated

- Bidirectional EDFAs (or Brillouin amplifiers) are used approx every 75 km (at ~$25K) (or every 20 dB loss)

- Must be able to demonstrate unconditional stability in the link (no lasing)

- Repeaters (O/E to E/O) may be needed at longer intervals if S/N is not high enough

- Slightly trickier if the fiber is shared or the trunk is shared

- Good area to investigate: simple experiment with long link, bidi-EDFAs, characterize signal-to-noise

Conclusions

- High frequency and long-distance fiber precision phase transfer is common, but not both at the same time.

- NGVLA fiber length is 30x ALMA

- Extrapolation of prior work appears to indicate that the engineering is feasible

- The equipment may be the easy part, less cost than the infrastructure?