Photonics and the Atacama Large Millimeter Array Project

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What is “photonics”?

- **Photonics** is the science and technology of generating and controlling photons (i.e. light).

- Photonics typically operates at frequencies on the order of (hundreds of) Terahertz. (one million times your basic FM radio).

- The science of photonics includes the emission, transmission, amplification, detection, modulation, and switching of light. Photonic devices include lasers, light emitting diodes (LEDs), fiber optics, and photonic crystals.
Where can I find photonics?

- CD/DVD/Blu Ray players
- High Speed communications/internet
- Long distance phone
- Lasik eye surgery/dermatology
- Spectroscopy/Spectrometry/Medical Analysis
- Welding/Cutting/Machining
- Scanners/Barcodes
- LiDAR/Sensors/Smart Structures
- Precision manufacturing
- Numerous scientific disciplines

... Just about anywhere really.
For example:

Using a very high power, very focused laser to create a simulated star then using it to measure (and then subtract) the atmospheric disturbance.
Photonics can simplify things

- Each telescope (antenna) generates 120 Gbits of data every second.
- If we were to use coaxial cables (your home internet, @ 100 Mbit/s) we would need 1,200 cables, per antenna!
- ONE optical fiber could carry all the data, from 100 antennas if needed.
Photonics can simplify things

- Very low loss optical fiber is a widely available, mature technology (< 0.2 dB/km @ 1550 nm) = less power required, meaning better efficiency at lower cost.
- Telecom industry offers a huge variety of all optical technologies, including amplification (EDFA), splitting, detection, switching and polarization control = large pool of available technical solutions
- Access to this wide range of technology is now affordable.
Function of Photonics in ALMA

In order to work, an interferometer must:

Preserve the correct phase relationships between the individual antennas in order to act as a singly aperture

Combine the signals from each antenna (preserving amplitude and phase)
Function of Photonics in ALMA

- To provide a *continuously tunable* (27-122 GHz) *fast-switching* reference, and the 20.833 Hz (48ms TE), 25 MHz, 125 MHz, 2 GHz … references.

- Up to six independently tunable Subarrays

- Combine and distribute the References (optically @1556-1557 nm & 1532 nm) to Antenna Receivers by optical fiber and stabilize them to within 12 fsec over $10^2$—$10^3$ seconds, meaning:

  10 miles of fiber actively stabilized to within 1/10,000th of an inch over 20 minutes at a time, for all 66 antennas, simultaneously!
Photonic LO system: on paper

Master Laser

Photonic Distribution

Elevation wrap

Azimuth wrap

Buried Fiber Optic Cable, L<15 km

Laser Synthesizers

4 sets of 66 Fibers

Subarray Switch Modules

Line Length Corrector Modules

1 Set of 66 Fibers

Frequency References

Laser Synthesizers

4 sets of 66 Fibers

Subarray Switch Modules

Line Length Corrector Modules

1 Set of 66 Fibers

LO Photonic Receiver

Band 1

Band 2

Band 9

Band 10

To other Antennas

Master Laser (1556 nm)

Master + Slave (1556 + 1557 nm)

Electronic Signal

Band 1

Band 2

LO Photonic Receiver

Band 9

Band 10

Electronic Signal

Newer REU Program Network
- High Coherence length and stability
- Narrow linewidth DFB fiber laser frequency-locked to a Rb two-photon transition
- Fully portable, rack mount, high reliability
- Qualified for high altitude (5000m, ½ atm) operation
- Automated locking and remote operation
Master Laser Stability and Coherence

> 50% Coherence at 30 km

< 2e-11 ASD Frequency
Stability required
Result < 10^-12
Laser Synthesizer

- PLL corrects phase noise to ~0.010 rad, < 27 fsec
- High Polarization Extinction Ratio 20 dB
- Frequency Switching < 500 msec
- Extremely accurate PLL double loop technique for high phase coherence between the master and slave laser
- Overall 1st LO phase noise was measured with millimeter-wave antenna-based LO locked to the Laser Synthesizer: < 53 fsec for 65-122 GHz
**Photonic Reference Distribution**

1. **Rb-Standard 5 MHz**
2. **Master Laser**
3. **ML Photonic Distribution**
4. **Central Reference Distributor**
5. **1st LO Microwave Synthesizer**
6. **Laser Synthesizer**
7. **EDFA + 1:5 splitter**
8. **EDFA + 1:5 splitter**
9. **EDFA + 1:5 splitter**
10. **EDFA + 1:5 splitter**
11. **EDFA + 1:5 splitter**
12. **1:16 splitter module**
13. **1:16 splitter module**
14. **1:16 splitter module**
15. **1:16 splitter module**

Only first output shown, goes to Antennas 1–16

Only first output shown, goes to Subarray Switch #1

Subarray Switch #1
Challenge: building it at 16,400 ft

Correctly route and connect almost 600 fiber cables, each having a different length and function.

... And doing it at 5000 meters of altitude, where the atmospheric pressure is half that at sea level.
Challenge: getting the signal there

Because each antenna can be moved ...
Almost 200 antenna pads (foundations)

Challenge: getting the signal there
Challenge: Round Trip Phase Correction

Round-trip phase correction path in red
Additional Measures for Phase Stability

- The specification 18 fsec (3.6 microns) is very tight for a 15 km fiber!
- The Master Laser/round trip phase correction removes drifts on the two-way path, but there are several places where uncorrected fiber is unavoidable.
- An uncorrected length of fiber 1 meter long, changing temperature by 0.5 degrees will push the system out-of-spec!
- Thus all uncorrected fiber is insulated, length matched, and put in a temperature controlled environment
Experimental setup used in Line Length Correction Tests - Aug 2003
Polarization to phase conversion

Resulting residual phase error as a function of antenna azimuth angle

Residual phase error as a function of antenna azimuth angle – no circulators

Fiber stretcher polarization change interacting with fiber PMD and component DGD. Shen, IEEE MWP2005)

\[ \Delta \tau_{\text{max}} = 0.55 \cdot DGD_R \cdot \sin(SOPC) \]
Replaced the Circulators with a Polarization Beam Splitter (PBS) + Faraday Rotator Mirror (FRM) combination and used the Martinelli Effect to redirect the light.

- Three polarization controllers (PC) and a polarimeter were included in the design.
- Used only components with the lowest dependence on polarization (DGD and PDL).
  - The fiber path to each antenna is phase corrected by a piezo-Fiber Stretcher Assembly
  - Polarization calibration suppresses undesired polarization variation on the LLC output
Line Length Corrector and Subarray Switch

- Each Line Length Corrector Module is paired with a Subarray Switch (SAS) module, one per antenna
- 66 Total Pairs
- Subarray Switch selects one of six sources, and is the start and end of the round trip phase correction

Line Length Corrector:
- Fiber path has a polarization controller, Fiber Stretcher Assembly, and polarimeter
- The fiber path to each antenna is phase corrected by a piezo-Fiber Stretcher Assembly
- Polarization calibration suppresses undesired polarization variation on the LLC output
Polarization problem fixed -2

To eliminate polarization-to-phase conversion resulting from antenna motion, a low SOP change fiber wrap has been developed. Fiber motion is bend-only (no twist), with constant bend radius, and no elevation change. (patented)

Less than 0.4 radians SOP change for 540-degree antenna rotation. SOP change plotted against input polarization.
Polarization problem fixed -2

Azimuth angle from ~170° to 170° in 134 s

+170° → -170° 60s  -170° → -90° 90° → +90°  +90° → +1° → -1° → +1° → -1°...
Other challenges: burying the fiber

Laying the cable down deep
(0.8~1 meter depth)
Photomixer

• Design and production by Rutherford-Appleton Lab, UK

<table>
<thead>
<tr>
<th>TYPE</th>
<th>FREQ (GHZ)</th>
<th>W-GUIDE</th>
<th>BAND</th>
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<td>WR-12 Band 4, 8, 9</td>
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Photomixer with assembly for mechanical stability, and output fiber connector

Photomixer for Band 9, with co-located Faraday Mirror device for round-trip phase correction
The ALMA Photonic System

Master Slave

27-122 GHz

Atacama Large Millimeter/submillimeter Array

28 GHz

27-122 GHz
ALMA Photonics: unique, cutting edge stuff ...

On Axis Fiber Optic Wrap

Highly customized, ultra stable laser developed for this project

Unique high speed optical to RF conversion using photomixers (RAL)

Custom piezo driven fiber stretcher + polarimeter + polarization controller

One of a kind optical modules and armored cables designed by NRAO
What it looks like today
A Test of installed system at the ALMA High Site: 14 km of fiber

The equivalent plot in Allen Standard Deviation of frequency variation at 84 GHz showing < 1e-16 at 100 sec

Black = fiber stretcher voltage for 14km antenna path
Red = Reference path (about 10m fiber)
Blue = Measured phase difference between two 1st LO assemblies at 84 GHz
Does it work?
Earthquake response

March 4 2010 earthquake in northern region
Earthquake response

- Stretcher Voltages over the 3.5 hours centered on the earthquake
- Long term trend is due to outdoor temperature changes
- Fast ripples on half hour timescales are due to indoor temperature changes.
- The system's earthquake response is the spike at center
Using ALMA as part of a VLBI network of antennas with 100-1000 km separation could lead to breakthrough Science

Thank you.

Questions?