MMA Memo #267

Photonic Techniques for Use on the Atacama Large Millimeter Array

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Abstract

Progress on a photonic local oscillator that may be suitable for the Atacama Large Millimeter Array (ALMA) is described. The proposed system is based on the coherent heterodyne of 1550 nm infrared signals generated at a central location and then distributed over optical fiber to each antenna. The length of each fiber is held constant by a servo system which uses an optical interferometer to measure the fiber path length. The difference between the two laser frequencies is converted at the receivers to a radio frequency (RF) signal by a high-speed photomixer.

Introduction

NRAO, in a joint project with European Observatories, is in the development stage of building an instrument consisting of about 64 antennas, each 12 meters in diameter, connected together to form an interferometer array for operation in the millimeter/sub-millimeter wavelength range. Each antenna is equipped with at least ten heterodyne receivers covering bands from 30 GHz to 1 THz. These heterodyne receivers consist of superconductor-insulator-superconductor (SIS) mixers cooled to 4 degrees Kelvin, followed by low noise intermediate frequency (IF) amplifiers, and require a high purity, frequency-stable local-oscillator (LO) with several microwatts of power and tunability from 30 GHz-1 THz.

The concept of a photonic local oscillator for the Millimeter Array (later to become the ALMA project) was first described in [1], and here we report progress over the past year. The proposed system generates the LO by mixing two lasers with a difference frequency equal to the desired LO frequency. The laser frequencies are transmitted over single mode fiber from a central location to the various antennas that make up the array. The distances involved vary from a few hundred meters up to 30 km for the most remote antennas, so the use of lasers in the low-loss 1550-nm fiber-window is advantageous. The progress outlined here includes:

1. A demonstration that the difference frequency between the two lasers may be locked to a stable microwave reference frequency with sufficient spectral purity for our application.
2. A demonstration that a closed-loop correction system may be applied to keep the fiber length constant in the face of thermally and mechanically induced perturbations.

System Design

A block diagram of our laboratory prototype is shown in Figure 1. Our measurements to date have been confined to difference frequencies that are obtainable with commercial components, to about 60 GHz. In addition, in this laboratory prototype experiment we used a 1 km spool of fiber.

The setup shown in Figure 1 depicts two lasers separated by the desired LO difference frequency and phase-locked to a microwave reference (in this case, 11.1 GHz) at the source end of a 1 km long fiber. One laser is a fiber-ring laser which exhibits a high degree of spectral purity and stability [2], the second laser is an external-cavity-diode laser. The fiber laser is both the master laser for the optical phase lock and the phase standard for the fiber length measurement.

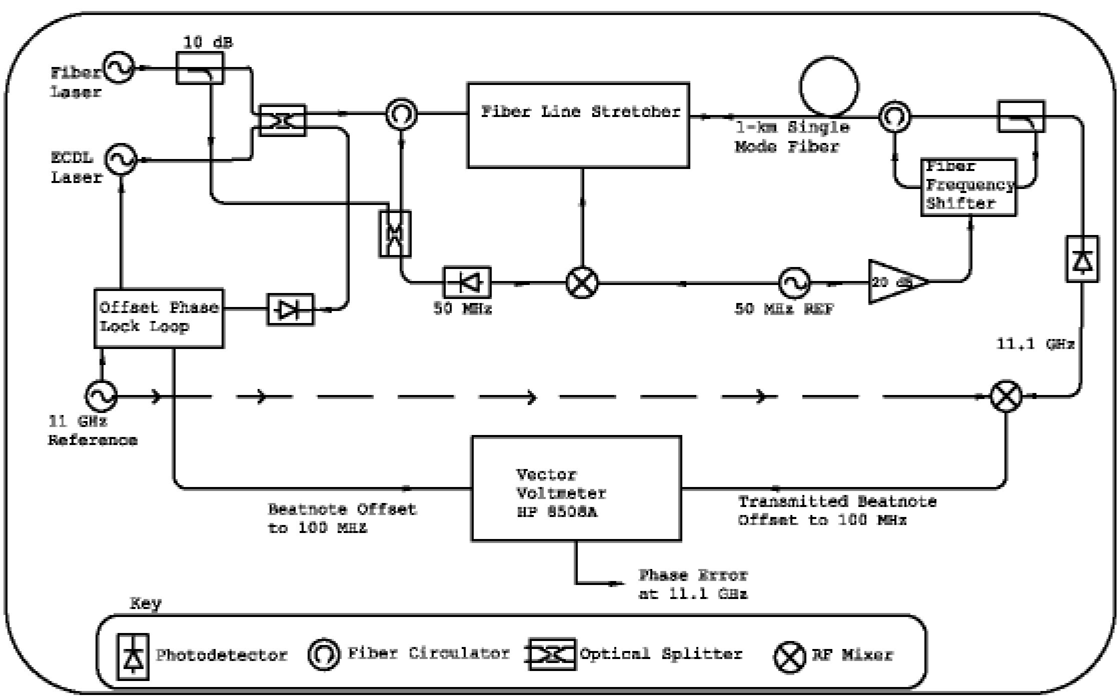

Figure 1: Simultaneous demonstration of round-trip phase correction and transmission of photonic LO.

At the far end of the fiber, a portion of the light is coupled off, frequency shifted by 50 MHz, and returned over the 1-km fiber. The returning light is combined with the fiber laser at the source end, creating a fiber interferometer. The phase difference is measured, and a correction is applied to the fiber line stretcher.

Phase Lock

To the left of Figure 1 is the phase lock schematic. A portion of the output from the two lasers is combined and detected by a high-speed photodetector. In this instance the photodetector had a 3dB bandwidth of 25 GHz. A DC-20 GHz frequency synthesizer provides a reference (this is shown as an 11 GHz reference in the figure which pertains to a particular experiment described later). The output from the photodiode is mixed with the synthesizer and the output is locked to a 100 MHz reference in a conventional electronic digital phase detector. The phase detector output is filtered and applied as a correction to the slave ECDL laser's current modulation port. A typical result from the phase lock system is shown in Figure 2. This plot shows the near-in phase noise at 100 MHz after downconversion from the lock frequency. The spectrum of the lock signal is clean, with the linewidth being far less than the 1 Hz resolution bandwidth of the spectrum analyzer. The phase-lock has remained stable and in-lock for a one week period, after which it was turned off.

With this rather simple phase lock loop and a commercial detector, we have seen no difference in the spectral purity of the phase

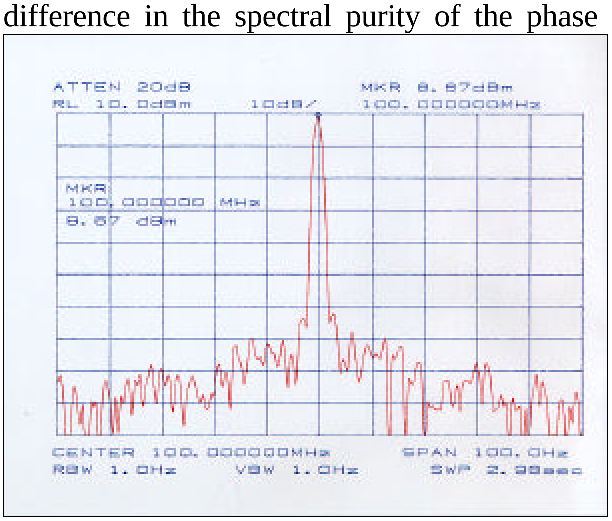

Figure 2: 100 MHz beatnote derived from offset in the phase lock loop

locked beatnote from 100MHz-20 GHz. We therefore conclude that there is no mechanism intrinsic to the lasers or detector that would degrade the spectral purity for difference frequencies as high as 1-THz. The total measured phase noise satisfies the ALMA specification for total instrumental phase noise of less than 10 degrees. [3] Phase-locking at higher frequencies in the 100 GHz--1THz range is more difficult, and the conventional technique uses harmonic microwave mixers. We are currently working on techniques of optical comb generation [1] which will allow us to lock onto sidebands of the master laser, a technique which has been proven recently to work well for locking of THz difference frequencies [4,5]. This technique appears to be simpler than conventional microwave harmonic phase locking and may result in less overall noise from the multiplied microwave reference.

Transmission of phase stable LO

Figure 1 depicts a technique for continuous correction of the fiber length by means of an optical interferometer which keeps the overall path length error much less than one optical wavelength (1.55 microns). The ALMA specification requires that uncorrected changes in path length of each fiber, due to temperature changes or mechanical stress, be within 17 microns.

As mentioned previously, the frequency offset optical signal from the round trip is mixed with the source laser and the phase of the resulting difference frequency is used to adjust the length of the fiber within a closed servo loop. This fiber line stretcher consists of:

- A piezoelectric line stretcher to adjust for the fastest variation (few kHz of bandwidth) in the phase of the signal. This inexpensive commercial product has a range of 50 microns.
- An air-gap stretcher driven by a linear motor to account for slow changes in fiber path length. and has a range of several mm. The bandwidth of this device is 2 Hz and it has a travel range of several mm. The assembly consists of an air-gap between two lensed-fibers, through which a collimated beam passes with low loss.

The fiber line stretcher is shown in Figure 3.

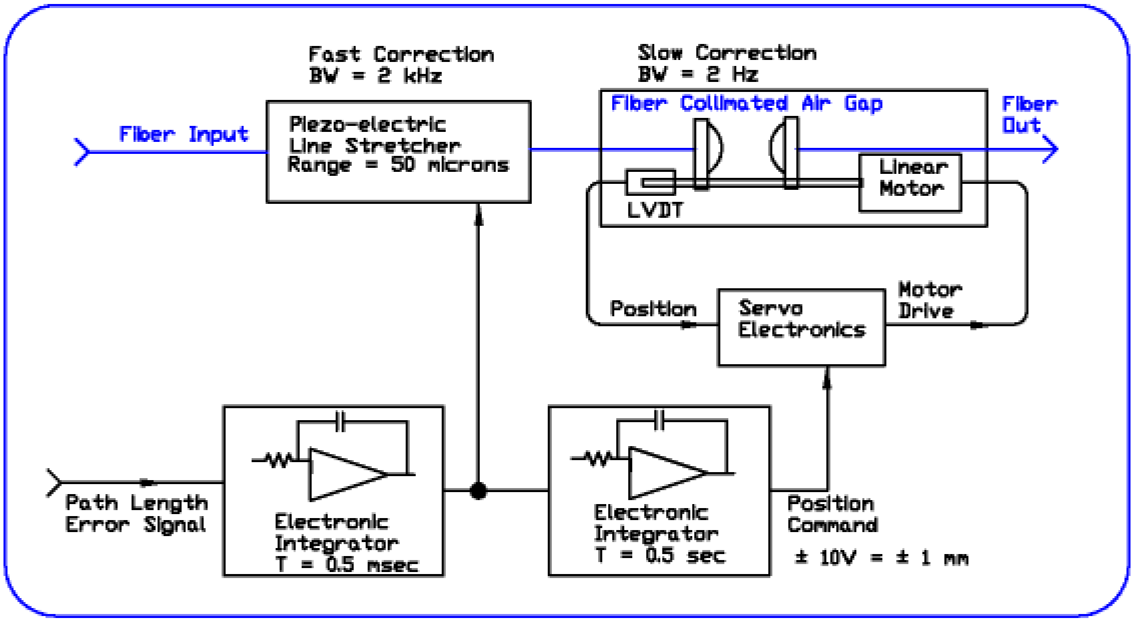

Figure 3: Fiber Line Stretcher

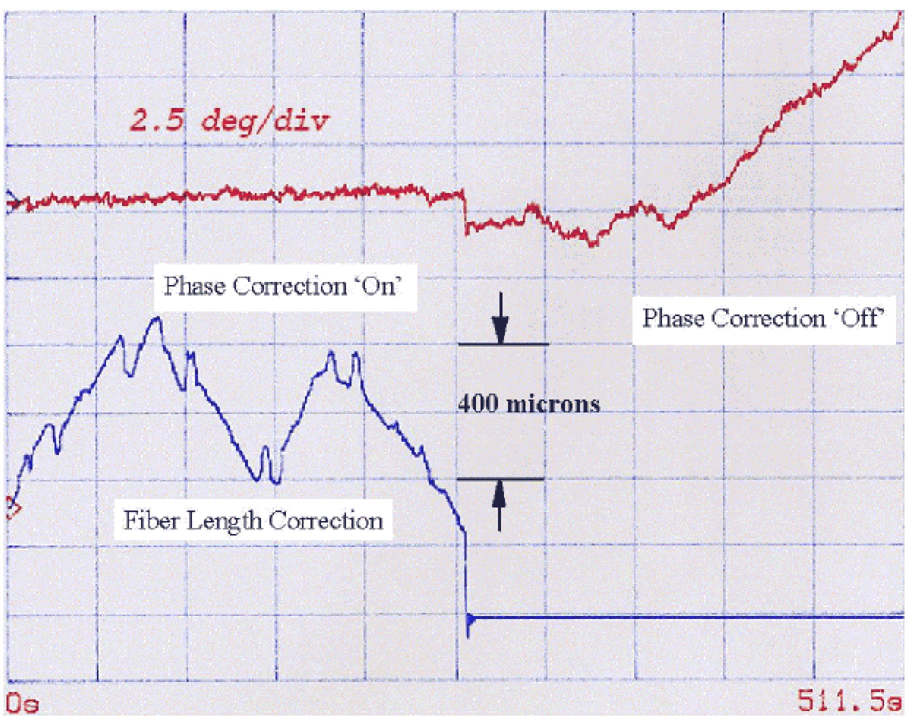

Figure 4: Comparison of Phase Difference between 11.1 GHz phase-locked beatnote before and after being transmitted through a 1-km single mode fiber: with correction 'on' and 'off'. Bottom trace is the movement of the slow fiber length corrector

In the experiment shown in Figure 1, an 11.1 GHz difference frequency was phase-locked and transmitted over 1 km of fiber. The phase of the detected difference frequency before and after transmission through the fiber was compared. Figure 4 shows the result of this phase comparison with the phase correction turned on and then off over an 8-minute period. The corrected portion is very flat, with an RMS of about 0.06-degrees. The uncorrected portion shows the phase drifting at a rate of several degrees per minute. It is important to note that this is phase at 11.1 GHz due to path length changes, thus uncorrected phase errors would be much greater at higher frequencies. The corrected phase, however, should be frequency independent. Our plan is to repeat this test at a 100 GHz LO frequency for a 20-km fiber.

Conclusion

We have demonstrated that it is possible to generate a photonic local oscillator using a two laser heterodyne configuration, and to phase lock the resulting beatnote to a microwave reference. The output from this configuration is a widely tunable local oscillator with frequency independent total phase noise of less than 0.15 radians. Our future work will be to extend this technique to 1-THz.

Moreover, using the same two lasers which are used to generate the LO, we have demonstrated that it is possible to transmit two lasers phase locked to a difference frequency over 1 km of fiber with minimal additional phase error. This is accomplished by using a highly coherent laser to continuously correct the round trip fiber path length. Our future work will include extension of this technique to a 20-km fiber length, and measurement of the transmitted phase at millimeter-wave frequencies.

References

[1] J.M. Payne, L.D. D'Addario, D.T. Emerson, A.R. Kerr, B. Shillue, "Photonic Local Oscillator for the Millimeter Array," Proc. SPIE Conf. On Advanced Tech. MMW, Radio, and Terahertz Telescopes, March, 1998

[2] Zhang, C.Y. Yue, G. W. Schinn, W.R.L. Clements, and J.W.Y. Lit, "Stable Single-Mode Compound Ring Erbium-Doped Fiber Laser,"IEEE Journal of Lightwave Technology, vol. 14, No. 1, Jan. 1996, pp. 104-109.

[3] MMA Project Book, Chapter 2, Science Requirements,http://www.tuc.nrao.edu/~demerson/project_book

[4] Brothers, L.R., D. Lee, and N.C. Wong, "Terahertz Optical Frequency Comb Generator and Phase-Locking of Optical Parametric Oscillator at 665 GHz", *Optics Letters*, Vol. 19, No. 4, pp. 245-7, Feb. 15, 1994.

[5] B. Widiyatmok, M. Kourogi, and M. Ohtsu, "Linking Two Optical Frequency Combs by Heterodyne Optical Phase Locking Between Diode Lasers at 2.6 THz Frequency-Difference," IEEE Photonics Tech Letters, Vol. 11, No. 4, April, 1999, pp. 460-462.