ALMA MEMO #440: PHOTONIC TECHNIQUES FOR LOCAL OSCILLATOR GENERATION AND DISTRIBUTION IN MILLIMETER-WAVE RADIO ASTRONOMY

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Abstract

A number of photonics techniques are being used for Local Oscillator (LO) generation and distribution for millimeter-wavelength radio astronomy. Many of these are being implemented or considered for use on the Atacama Large Millimeter Array (ALMA) project.

Introduction

The ALMA project is a large radio astronomy project consisting of an array of 64 antennas each outfitted with low-noise heterodyne receivers spanning 27-938 GHz in ten discrete bands. Generating the LOs for these receivers is a significant challenge, and this paper discusses the photonic techniques that are being used for this.

The motivation for using photonic LO generation is to take advantage of low fiber loss and high-performance telecommunications devices to create a remote LO capability. This would eliminate costly LO components that would otherwise be located at each antenna. Because sufficient output power from photomixers is not yet available at the highest ALMA frequencies, the current plan is to distribute a phase-stable reference signal over fiber of up to 142 GHz, and then use that signal to phase-lock electronic oscillators and frequency multipliers at each antenna. It is hoped that future progress will allow an evolution to a system in which the LO is provided directly from the output of a photomixer.

The simplest photonic implementation of a millimeter or submillimeter wave-source consists of a laser heterodyne source and a photomixer (photodetector operated as a mixing element) with a very wide output bandwidth [1]. Tuneable and phase-locked laser heterodyne sources have now been built with low phase noise and wide tuning capability [2,3]. Photomixers have been developed with measurable output power up to at least 800 GHz for 1.5 μm devices and well above 1 THz for 0.8 μm devices. [4,5]

For the ALMA baseline, a photonic reference approach has been adopted, in which a dual laser heterodyne in the frequency range of 27-142 GHz is distributed from a central location to each of the 64 antennas. Every receiver will incorporate a photomixer that converts the two laser wavelengths to an RF signal. This RF signal is then used as a reference to phase-lock a conventional microwave oscillator/multiplier chain, as shown in Figure 1. A further option of a photonic LO directly pumping the SIS receiver is an option if photomixers and other technologies can be proven viable for all bands. The direct photonic LO approach is shown in Figure 2.

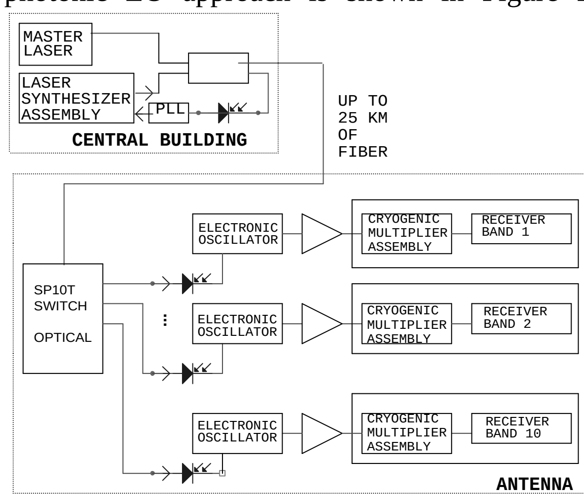

Figure 1 -ALMA Photonic LO Reference System. Frequency Range is 27-142 GHz.

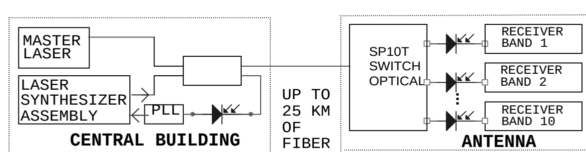

Figure 2 – Direct Photonic LO System. Frequency Range is 27-938 GHz.

High-Frequency Photomixers

Commercial photodetectors have been developed to work with output response as high as DC to 60 GHz. Several effects such as the transit-time of the photo-generated carrier, the RC-delay of the device, and the carrier lifetime limit the operation bandwidth of these devices. Recently, several new techniques have been developed to extend the range to THz output frequencies. These include: PIN photodetectors with a special doping profile to enhance carrier velocity [6], traveling-wave photodetectors [7], and short-lifetime photodetectors [8]. A similar type of PIN device is available from a commercial vendor in a chip package [9]. Our measurements of that chip yielded a highly efficient output power of -14 dBm at 109 GHz with an input optical power of 6 mW from each laser and a DC photocurrent of 3 mA. Subsequently, a packaged version of this device was designed and fabricated by the Millimetre and Sub-millimetre Group at Rutherford Appleton Laboratory in Great Britain [10]. This device, shown in Fig. 3, consists of a fiber pigtailed input, a coaxial bias voltage input, and a WR-10 waveguide output. The measured output power is greater than 100 µW from 75-100 GHz. Further measurements yielded measurable output power to above 600 GHz [11], and preliminary results of current work indicate photomixer output power above 10 µW from 160-230 GHz [12].

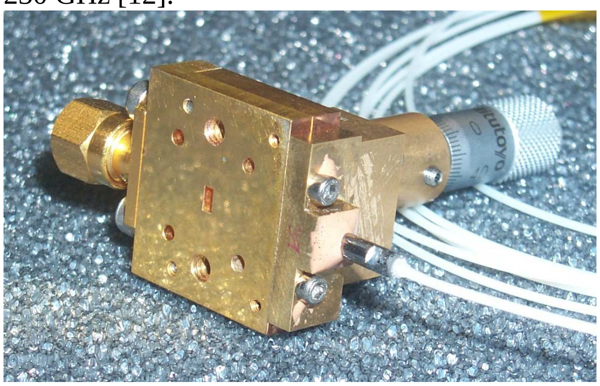

Figure 3 – W-band photomixer in 75-110 GHz frequency band.

Millimeter-Wave Phase-Locking

Phase locking of a dual laser heterodyne source requires a fixed reference laser with a second laser locked to the first one electronically at a particular offset. In principle, the technique is no different from phase locking of a microwave source. However, because of the frequency translation involved in photomixing, the laser beatnote generally has wider linewidth, and higher phase noise, frequency jitter and drift than microwave oscillators. Nevertheless, phase-locking of lasers is commonplace, and there are many results in which the total integrated RMS phase error is much less than 0.1 radians [2,3,13]. We have done similar experiments phase locking lasers above 100 GHz using a microwave harmonic mixer in an optical phase-lock-loop, for example using the setup shown in Fig 4. A typical spectrum of the phase-locked output is as shown in Fig. 5. This is a spectrum of an external-cavity diode laser locked to a fiber laser.

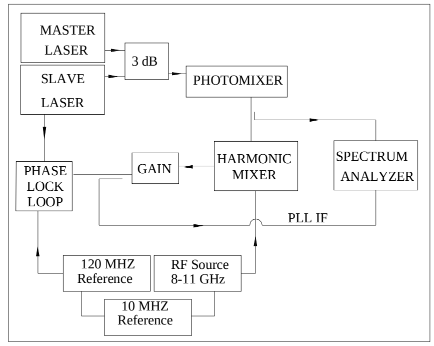

Figure 4 – Experimental setup for millimeter-wave phase locking of lasers using a microwave harmonic mixer approach.

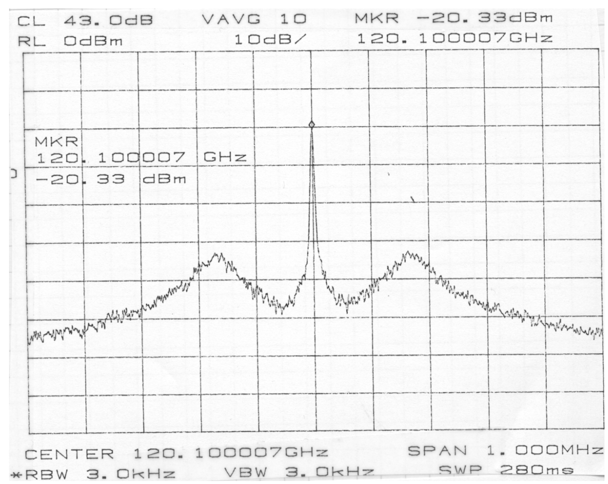

Figure 5 – Spectrum of phase lock at 120 GHz using harmonic mixer approach

To extend the phase-locking technique to higher frequencies it is possible to use the technique with a millimetre-wave harmonic mixer [14], but it becomes cumbersome and expensive, as the harmonic mixer must be tailored to the frequency band of interest. A more promising technique is to use an optical comb generator to develop coherent sidebands of the master laser at multiples of the microwave reference frequency [15]. Phase locking of the slave laser to one of the sidebands requires no high-frequency microwave components but yields the desired millimetre-wave beatnote. We have used this technique in collaboration with the photonics group at University of Kent, UK, using the setup depicted in Fig. 5. The resulting spectrum of the phase-lock at 123 GHz is shown in Fig. 6.

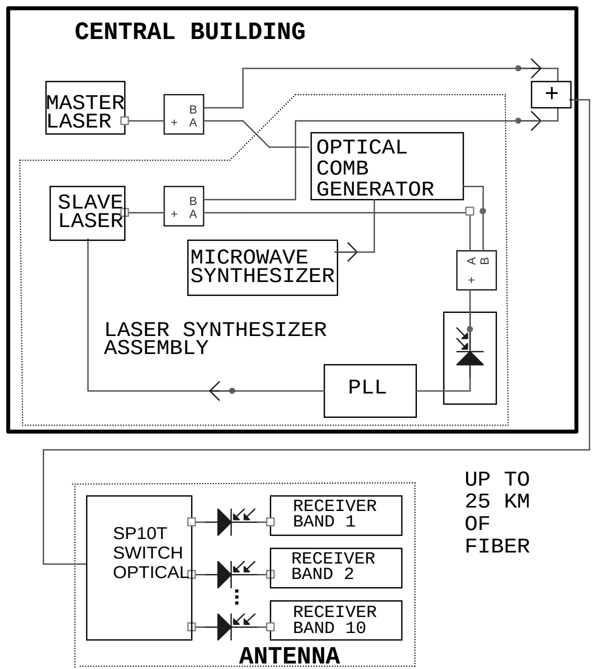

Figure 5 - ALMA Direct Photonic Approach using Optical Comb Generator to Achieve High Frequency Phase-Locking

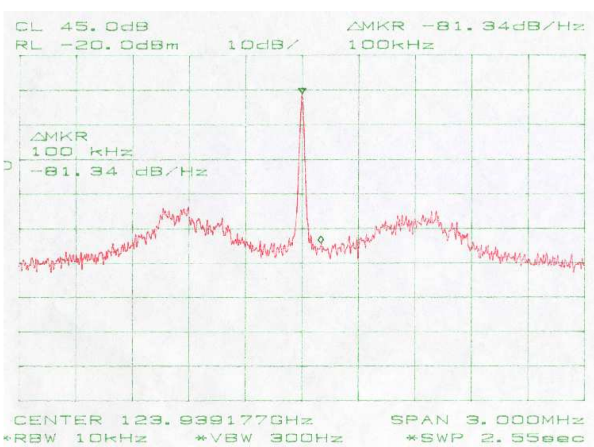

Figure 6 - Spectrum of Phase Locked Lasers at 123 GHz Using Optical Comb Generator Approach.

The overall phase noise is very similar to that obtained with the harmonic mixer technique, but in this case we were able to achieve phase lock up to 258 GHz, and expect to be able to go to much higher frequencies in further work. In both spectrums shown here the limiting factor in the phase noise is noise contribution from the cavity laser that is not adequately suppressed in the phase-lock-loop. This is also being addressed in further work in which wider loop bandwidth is expected to achieve much lower overall phase noise. More detail of the comb generator work appears in another paper at this conference [16].

Radio Astronomy Receiver Noise

In radio astronomy applications, the LO must be widely tuneable, coherent, and have a high signal-to-noise ratio (S/N). In the 100-1000 GHz regime, SIS mixers have been used primarily in the lowest-noise cooled heterodyne receivers. The required power level for a photonic LO for SIS receivers depends on a number of parameters: receiving band frequency, the number of junctions in the SIS-device, and the way the LO is coupled into the SIS mixer. ALMA has adopted a specification of 100 μW of available power required for all bands. If the coupling level to the SIS device is 20 dB then that will leave 1 μW available to the mixer, which is generally more than sufficient. We have calculated the theoretical noise level injected into the SIS receiver by a photonic LO, and normalized the noise to 1 μW of RF power. In Fig. 8 this is plotted with the laser relative-intensity-noise (RIN) as a parameter.

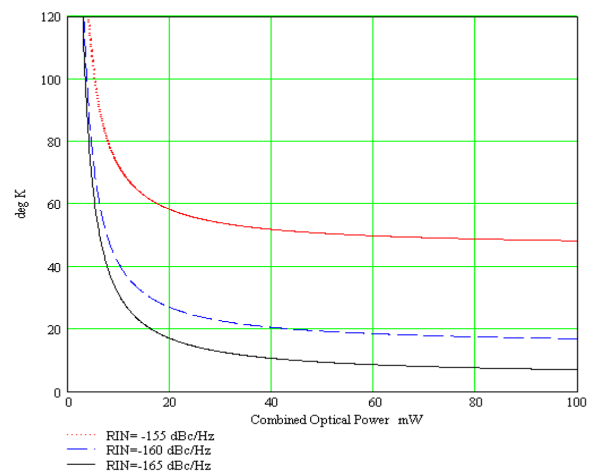

Figure 6 – Calculated Receiver LO Noise as a function of Laser RIN. Assumes photomixer responsivity of 0.25 mA/mW.

Notice that the LO noise decreases with increasing optical input level up to a point after which it levels off. This is because the photomixer shot noise dominates for low input levels and is proportional to the photomixer current level, whereas the generated RF signal is proportional to the square of the photomixer current. At higher input levels the RIN noise begins to dominate and as this is proportional to the square of the photomixer current, further increases in the input optical power yield no further increase in the S/N

From this plot it is clear that in order to minimize the LO noise introduced by a photonic LO one must select a laser with very low RIN.

Recently, in collaborative tests with Nobeyama Radio Observatory, we demonstrated a direct photonic LO with low-RIN lasers in the frequency range of 95-110 GHz. In this test, a UTC photomixer with high saturation level (input optical power 180mW, device current 20 mA) was used. The receiver noise in this range was not significantly higher (less than 3 deg K) using the photonic LO as compared to using a low-noise Gunn oscillator RF source [17].

Conclusion

We have summarized ongoing work and recent advances in photonics that will be useful for generation of LO signals for millimeter wave radio astronomy. In particular, photomixers are now available capable of generating adequate power to serve directly as the LO for 3 mm band SIS receivers. It is expected that these will soon be available for 1 mm bands and perhaps at even higher frequencies. Moreover the new generation of devices works in the 1.55 μm optical window, thus offering the potential of remote LO generation with distribution by fiber optic cables. Preliminary receiver tests using a photonic LO indicate that the LO source can be made to have low AM noise in addition to being widely tuneable.

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