MMA Memo 200

Photonic local oscillator for the Millimeter Array

J.M. Payne[a], L. D'Addario[b], D.T. Emerson[a], A.R. Kerr[b], B. Shillue[a]

[a]National Radio Astronomy Observatory, 949 N. Cherry Ave., Tucson, AZ 85721*

[b]National Radio Astronomy Observatory, 2015 Ivy Road, Charlottesville, VA 22903*

ABSTRACT

A photonic local oscillator system for the Millimeter Array is described. The mixing of coherent infrared signals generated at a central location and distributed in the 1.3-1.55 μm wavelength window over optical fiber holds the promise of savings in both cost and manpower over a conventional system. This proposed system, using the many commercially developed components now available also offers advantages in ease of maintenance and reliability.

Keywords: laser, millimeter-wave, submillimeter-wave, photomixer, phase lock, local oscillator, Millimeter Array, radio telescope

1. INTRODUCTION

The National Radio Astronomy Observatory (NRAO) is in the development stage of building the Millimeter Array (MMA), an array of around 40 antennas connected together to form an interferometer array to operate in the millimeter/sub-millimeter wavelength range.

A crucial part of the instrumentation for such an array is the local oscillator system. Most receivers for the array will consist of superconductor-insulator-superconductor (SIS) mixers cooled to 4 K, followed by low noise intermediate frequency (IF) amplifiers. Such a heterodyne receiving system requires a high purity signal to mix with the incoming astronomical signal of interest. This local oscillator (LO) signal must be highly coherent with a power level of several microwatts and locked in phase to a microwave reference source. Recent advances in laser diode technology and optical fiber transmission systems raise the possibility of a local oscillator system for the MMA based on the mixing of two optical signals separated by the required local oscillator frequency. Such a system could be realized using mainly commercially available components resulting in significant savings in both cost and manpower when compared to the conventional approach of a phase locked oscillator followed by passive multipliers.

Several groups have worked on systems similar to this. The phase locking of the beat note between two infrared lasers to an external microwave standard with the spectral purity required of the MMA was first demonstrated many years ago[1] and is now regarded as routine. Beat notes of up to several THz have been demonstrated with a cooled fiber-coupled photomixer at power levels that appear to be adequate for supplying the LO to the SIS receivers on the MMA.[2] New detector fabrication techniques hold the promise of increased power levels in the wavelength range of the MMA.[3]

The potential advantages of such a system may be summarized as follows. A more detailed explanation of these points is given in the main body of the paper.

1) The majority of the components needed for the realization of the proposed scheme are commercially available. The communications industry has a huge investment in optical fiber systems and the system outlined here exploits these fairly recent developments. We can be certain that intense development in this area will continue.

2) All of the frequency synthesis components of the local oscillator system may be situated in a laboratory environment remote from the array. At the antennas, only some leveling electronics and a photomixer are required. In terms of serviceability and reliability this is regarded as a great advantage.

*The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

3) The receiver interface is greatly simplified. Due to bandwidth requirements, the usual Martin-Puplett quasi-optical LO injection scheme will not be appropriate. LO injection using conventional methods with waveguides entering into the cryogenic enclosure (for each receiver band) would involve a relatively high loss and may complicate the thermal design of the receiver. In contrast, all that will be needed in the photonic system is one optical fiber into the receiver dewar resulting in negligible heat load. Vacuum feed-throughs for fiber are fully developed commercially.

4) There is a great reduction in complexity (discussed in Section 3.1 below).

5) The proposed system eliminates the need for the usual microwave harmonic mixers.

6) The real cost promises to be far less than a conventional system.

2. MMA LOCAL OSCILLATOR REQUIREMENTS

The key requirements for the MMA local oscillator system are (1) continuous coverage from about 30 GHz to approximately 900 GHz, and (2) high differential phase stability between receivers in different antennas, both long term and short term. The long term instability is a phase drift, which if slow enough can be corrected by astronomical calibration. The goal is to limit the instrumental phase drift to a few degrees over a few minutes even at the highest frequency; the limiting instrumental factor here is likely to be the local oscillator distribution system, but that is independent of which technology -- for example photonic or conventional -- is chosen for local oscillator signal generation. The limiting phase stability overall is expected to be set by atmospheric effects, primarily from temporal and spatial variations in the atmospheric water vapor. Ideally, all instrumental drifts would be less than these unavoidable atmospheric instabilities. The short term phase instability is equivalent to a loss of coherence between signals, which ultimately corresponds directly to a loss in sensitivity. An rms phase jitter of 0.3 radians at each antenna implies a 5% loss in sensitivity.

3. THE PROPOSED SYSTEM FOR THE MMA

3.1 Overall block diagram

A block diagram of the proposed system is shown in Fig 1. An optical wavelength in the range of 1.3-1.55 μm is chosen for the system, since components have been developed for the fiber communication industry in this range. Also, the fiber wavelength window 1.3-1.55 μm has low loss and low dispersion. Fiber loss is lowest at 1.55 μm, about 0.2 dB per km, but dispersion is higher at 1.55 μm than at 1.3 μm, where the standard single-mode fiber dispersion becomes zero. Virtually all of the components familiar to microwave engineers are available at these wavelengths in fiber. In any case, the low fiber loss enables the LO components to be situated remotely from the antennas in a laboratory environment, perhaps in the same building that houses the correlator.

In Fig. 1, a fixed frequency master laser generates an optical frequency F1 (~200 THz). A second, tunable, laser generates an optical frequency F2 differing from F1 by the desired LO frequency (30-900 GHz). A portion of the output of the master laser is coupled into an optical comb generator driven by a microwave signal at a frequency F3 (around 10 GHz). One of the teeth of the comb spectrum is selected by an internal filter in the comb generator and fed, with a portion of the power from the second laser, into a photomixer to produce a beat frequency F4 (~100 MHz). This is compared in phase with the reference oscillator, also at F4, and the difference used to control the second laser, thus closing the phase-lock loop.

The individual slight frequency differences required for fringe rotation are supplied in the phase locked loops for each antenna by adjusting F4. The local oscillator signal for each antenna is then transmitted from the central location, on a single optical fiber per antenna, as two optical signals separated in frequency by the required local oscillator frequency. The scheme showed in Fig. 1 has a single master laser and 40 lasers that are tuned to the individual wavelength required by each antenna. Thus forty fibers, each carrying two optical signals, are required. At the antenna the scheme is very simple; see Fig. 2. Commercially available switches route the fiber to the appropriate photomixer that will be situated within the vacuum space of the receiver dewar. The required leveling of the LO signal may be achieved by commercially available optical attenuators outside the dewar and in series with the fiber.

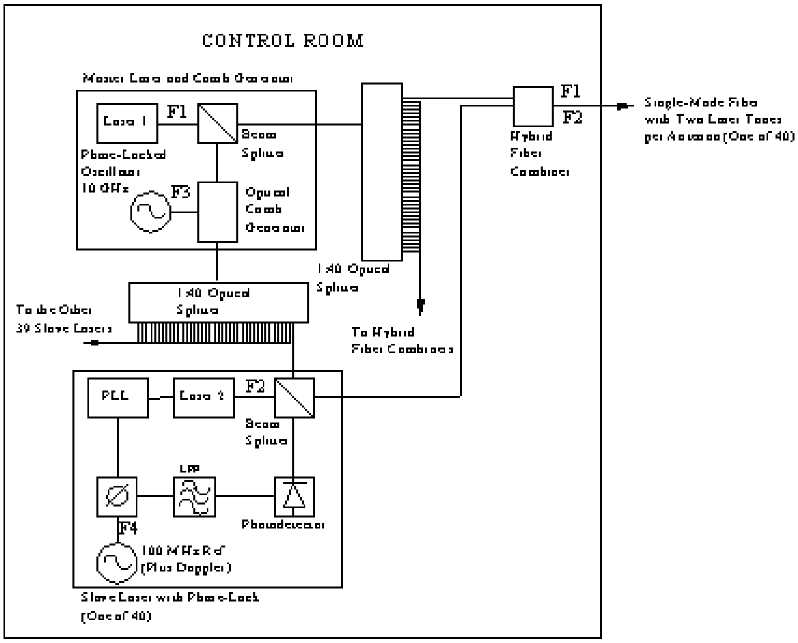

Figure 1 - Laser heterodyne system with optical phase locked loop

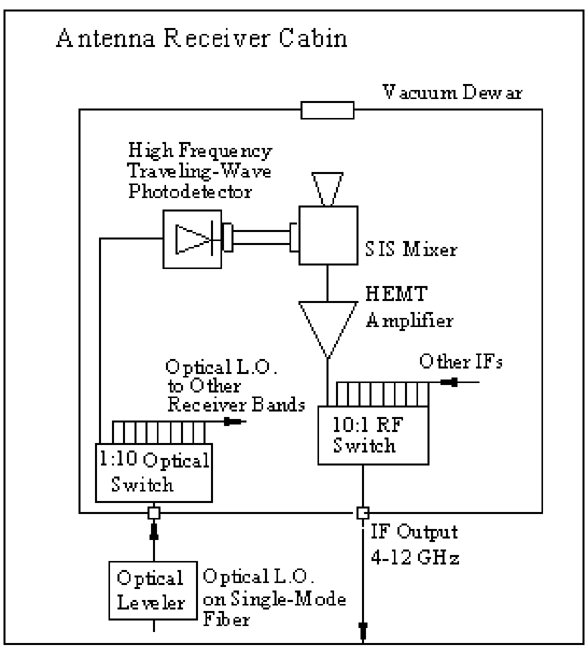

Figure 2 - Photonic LO detection scheme, at receiver

3.2 Theory

Two important parameters to consider are the amount of millimeter-wavelength power that can be generated by the photomixer and its expected broadband noise. We would like to know whether there is any fundamental reason that the method cannot meet our goals and we investigate that here by means of simple theoretical models.

Let the photomixer be modeled as an ideal photoconductor with a quantum efficiency nu that generates a carrier of charge *e* in response to incident photons. Because of an applied DC electric field, the generated carriers cause a current in the external circuit, and this current flows through the load resistor, R_L. We take the source impedance of the photomixer to be much greater than R_L at all frequencies of interest, so that it can be treated as a current source. Under these conditions, it can be shown that the responsivity, *r* (current per unit optical power absorbed) is given by:

$$r = \frac{\eta e}{h\upsilon} \quad \textbf{(1)}$$

at optical frequency *v*. (Here and subsequently, *e*, *h*, and *k* are the usual physical constants). If two optical carriers of equal power are incident at slightly different frequencies then the power delivered to R_L at the difference frequency is:

$$P_{RF} = \frac{1}{2}(rP_{opt})^2 R_L \quad \textit{Signal Power} \quad \textbf{(2)}$$

where P_{opt} is the total absorbed optical power.

The desired RF signal is accompanied by broadband noise with several causes. We have investigated photomixer shot-noise, laser relative intensity noise, and quantum zero-point fluctuation noise. In the simple theory, all of these produce white noise throughout the photomixer output bandwidth; the resulting expressions are given below as noise temperatures:

$$T_{SHOT} = \frac{2e}{k} r P_{OPT} R_L \quad \textit{Shot Noise} \quad \textbf{(3)}$$

$$T_{ZP} = \frac{2\ e}{k} \eta\ r\ P_{opt} R_L \quad \textit{Zero-Point Fluctuation Noise} \quad \textbf{(4)}$$

$$T_{RIN} = \frac{r^2}{k} P_{opt}^2 R_L N_{RI} \quad \textit{Relative Intensity Noise} \quad \textbf{(5)}$$

where $N_{RI} = (\Delta P/P)^2$ is the usual RIN specification of each laser, with ΔP^2 being its power fluctuation spectrum (per unit bandwidth) and *P* being its average power. Note that the desired signal power P_{RF} is proportional to the laser power squared, and the first two noise power terms are simply proportional to the laser power. If these sources of noise dominate, then we can improve the signal-to-noise by increasing the laser power. The third noise term, T_{RIN}, is proportional to the square of the laser power and thus increases as fast as P_{RF}, which puts a limit on the advantage that can be gained by increasing the laser power.

We have evaluated the above expressions for the two cases shown in Table 1. These are for total incident optical powers of 1 mW and 10 mW, respectively, and with realistic values for all other parameters (η=0.5, N_{RI}=-165 dBc/Hz, λ=1.55µm). The noise temperatures are also shown after P_{RF} has been attenuated to 1 µW, which is roughly the level needed to pump an SIS mixer.

The amount of signal power, P_{RF}, as seen in Table 1, is 9.6 µW for a 1 mW optical input and 960 µW for a 10 mW optical input. The LO power requirement will depend on several factors: the number of junctions in the SIS mixer; whether the mixer is single-ended, balanced, or sideband separating and balanced; and whether one or two polarizations are required. The results in the table do show that sufficient LO power on the µW level will be available using reasonable optical input power levels.

Note that for single-ended SIS mixers, any noise accompanying the desired LO signal at a frequency offset equal to the IF of the mixer is equivalent to noise at the mixer's input, so that it adds directly to the receiver temperature. From Table 1, the theoretical noise level for a combined optical power of 1 mW is about 120 K per 1 µW signal power. This is too large for all but perhaps the highest frequency bands intended for the MMA, so we would have to rely on the additional noise rejection that balanced SIS mixers are expected to provide.4 Even then the system could be marginal in the most sensitive bands. With 10 mW of optical power, the total noise contribution is only 16 K, but if the balanced SIS mixer provides at least 10 dB of LO to IF isolation, then the LO noise contribution to receiver noise will be negligible.

	Noise Temp (K)	Normalized to 1 µW
Case One P_{RF} = 9.6 mW P_{OPT}=1 mW	T_{SHOT}=718 K	75 (K/µW)
	T_{ZP}=359 K	37 (K/µW)
	T_{RIN}=44 K	4.6 (K/µW)
Case Two P_{RF} = 960 mW P_{OPT}=10 mW	T_{SHOT}=7180 K	7.5 (K/µW)
	T_{ZP}=3590 K	3.7 (K/µW)
	T_{RIN}=4400 K	4.6 (K/µW)

Table 1 – Signal and Noise Power Budget for Laser LO

For both cases, η=0.5, λ=1.55 µm and N_{RI}=-165 dBc/Hz

3.3 Details of critical components

3.3.1 Lasers

It is felt that advantage must be taken of the 1.3-1.55 µm band for the reasons mentioned earlier. Nd:YAG lasers have both high spectral purity and high output power and have been used for much of the early work in this field. However, they have a very restricted tuning range resulting in a maximum beat note frequency of only 100 GHz. There appear to be only two laser options in this band that give the high spectral purity, tunability, and phase locking ability that our application requires; these are erbium-doped fiber lasers and external cavity semiconductor lasers. The fiber lasers have greater spectral purity and higher output powers but we are unable to find evidence that they are easily phase locked to an external microwave reference. The external cavity laser has less spectral purity (but adequate, we believe) and less output power, but has been phase locked easily, by ourselves and others. So our choice is to use the external cavity diode laser.

3.3.2 Photomixers

At the present time there are 3 types of photomixer designed for high frequency and high RF power output.

1) A low-temperature-grown GaAs planar photomixer, with the optical beam at normal incidence to the surface.2 This type of photomixer has demonstrated output to around 5 THz, but is inherently inefficient. Nevertheless, a cooled fiber-coupled photomixer of this type has recently been shown to have sufficient power output over the frequency range required for the MMA. However, we have decided not to pursue this method because the inefficient conversion means that the photomixer must be operated near its burnout level to get sufficient power.

2) The traveling wave photodiode, which is essentially a long Schottky junction above an optical waveguide. Photons from the waveguide are absorbed along the length of the diode, which has a short transit time for photogenerated carriers. The frequency response, however, is limited by the differential phase shift between the optical waveguide and the RF Schottky transmission line; higher frequency response can be obtained by shortening the diode, but this reduces the photon coupling efficiency. Nevertheless, a 3-dB bandwidth of 520 GHz with a DC quantum efficiency of 8% has been recently demonstrated.[5]

3) A third photomixer design, the velocity matched distributed photodetector (VMDP)3 developed at UCLA largely overcomes these shortcomings, and should be capable of high conversion efficiency over broad frequency bands. Like the traveling wave photodetector, the VMDP uses an optical waveguide, but the photons are absorbed by an array of photo-Schottky diodes along the length of the waveguide. The diodes are connected to a metal transmission line (two-wire, or coplanar waveguide) running parallel to the optical waveguide. By appropriate design, the propagation velocity on the RF transmission line can be made to match that of the optical waveguide. This is illustrated in Figure 3. To date, the VMDP has only been demonstrated to 60 GHz, but it appears possible to extend its operation to much higher frequencies.

Although any of the above 3 options would be good candidates for development, we are concentrating our development efforts on the VMDP. We feel that this technique will yield the best power conversion efficiency, which is critical to our application. No matter which device is finally selected, however, another important issue is the RF output coupling at millimeter wavelengths. Below 300 GHz we intend to couple the output into fundamental mode waveguide, and above this frequency a quasi-optical approach will probably be used.

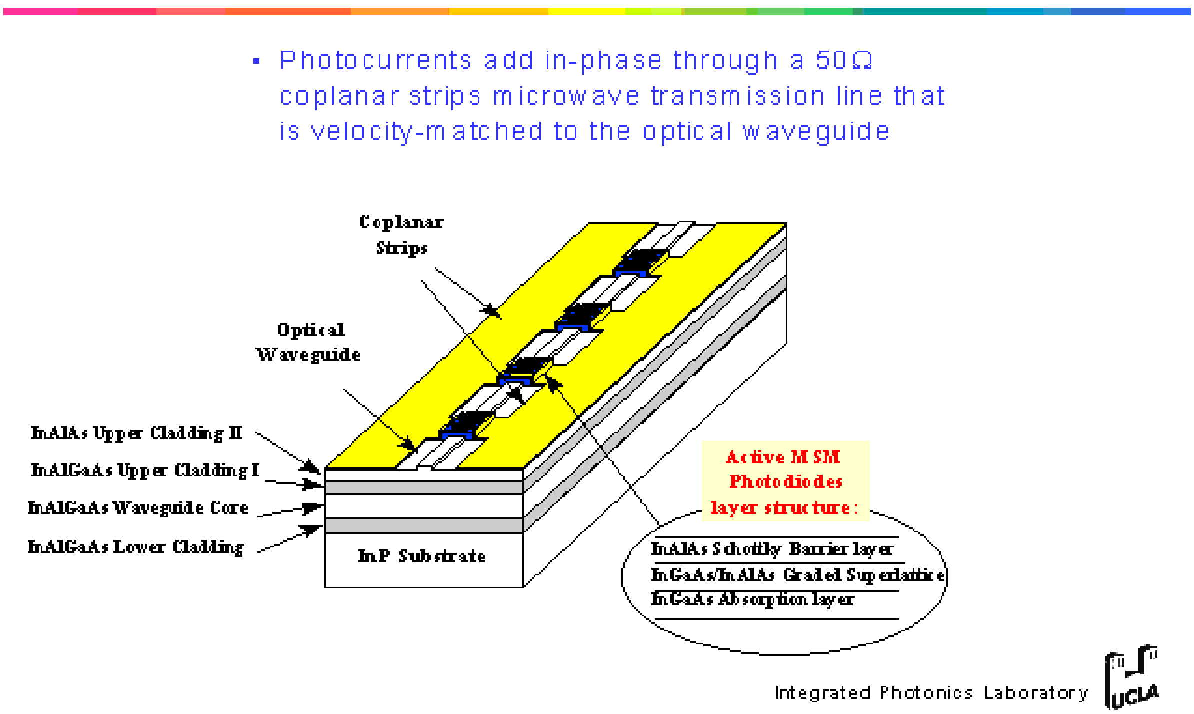

Figure 3 - Schematic of Long Wavelength Velocity-Matched Distributed Photodetector (VMDP)
(Provided courtesy of the Integrated Photonics Laboratory at UCLA)

3.3.3 Optical comb generator

Optical comb generation is a technique that is being developed for optical frequency synthesis and appears to be an ideal method for translating our optically generated LO to an IF suitable for phase locking. In this method, a stabilized microwave source is used to phase modulate a laser in such a way that the optical carrier develops sidebands containing a comb of spectral lines at offset frequencies that are multiples of the microwave source frequency. Recent research has demonstrated that the comb can be made to extend to offsets as high as 4 THz from the carrier. If one of our lasers is modulated in this way, we can simply phase lock the other laser using whichever comb frequency falls conveniently close to it, i.e., with a difference frequency in the low frequency microwave region (< 10 GHz). The microwave difference frequency required for phase locking is obtained by combining the two optical signals in a photomixer. The conventional phase locked local oscillator in a mm-wave receiver also starts with a stabilized microwave oscillator, but this is applied at a high level to a diode harmonic mixer. The resulting diode conductance waveform contains high order harmonics, one of which beats with a sample of the LO to produce the desired microwave IF for phase locking. One difficulty with this approach is that each receiver waveguide band requires a separate harmonic mixer because the diode circuit must be matched to the waveguide being used. By comparison, the proposed scheme requires only a single photomixer operating in a relatively narrow range of optical frequencies to cover the desired LO frequencies (30-900 GHz).

Thus, we can use a single comb generator for all bands in a single receiver, or potentially for all the receivers in the entire array. In addition, whereas the comb is actually at optical frequencies, none of the generated comb lines can appear in the receiver IF as interference.

Several researchers have used optical comb generators to generate THz difference frequencies.6,7,8 In each case a microwave signal is used to drive a lithium-niobate phase-modulator to generate a comb of span greater than 1 THz. Moreover, in each case, one of the comb outputs was phase locked to a low-frequency radio reference using the same frequency differencing scheme that we are proposing. The phase lock frequencies were, respectively, 1.5 THz, 487 GHz, and 665 GHz.

Fig. 4 shows some details of the proposed method, taken from the work of Jun Ye et al.6 The master laser goes through a beam splitter and then a series of optical elements preceding the first cavity. The quarter-wave polarizer ensures that whatever signal is reflected from the first cavity is redirected to a photodiode detector. This enables locking of the cavity to the laser frequency. The optical comb generator consists of a phase modulator embedded in a resonant optical cavity made up of mirrors M1 and M2. The modulation is a stabilized microwave signal of high spectral purity. The resonant modulator is made in such a way that the optical signal propagating through the device has a velocity matched to that of the modulating signal. The optical cavity, which is external to the modulator, is made to resonate at multiples of the modulating frequency, thereby enhancing the comb-generator effect. The output thus consists of the carrier and a comb series of sidebands separated by the modulation frequency. A second cavity, made up of mirrors M2 and M3, is tuned to a single picket of the optical comb; this filters out all of the other comb pickets and the optical carrier, thereby enhancing the signal-to-noise of the phase locked loop.

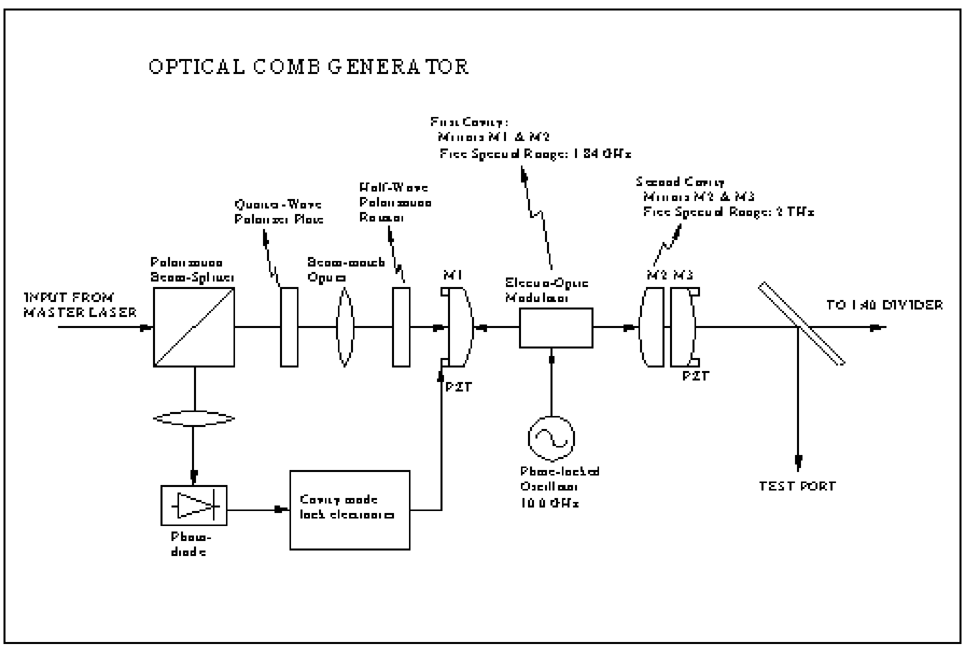

Figure 4 - Optical Comb Generator - Detailed View
(Adapted from Reference 6)

The second laser is split and its output is combined with the output of the optical comb generator. This laser is set to a frequency offset, for example, of 500 GHz from the first laser. With judicious choice of modulation frequency, it will be separated from one of the comb outputs by an amount less than ~5 GHz which can then be easily phase locked by the standard RF methods.

Previous researchers have had success in locking to harmonics as high as 100th order, and have identified some of the critical elements. The laser driving the comb generator should have as high a power as possible, and the microwave reference driving the modulator should be of high power and good spectral purity. The Fabry-Perot cavity should have high finesse, that is, the mirror reflectivity must be very high at the optical frequency. Also, the beams should be well-matched to a high efficiency photodetector. With some attention paid to these critical elements, it is certainly possible to build a phase locked loop with enough signal-to-noise to lock the optical carrier to the microwave reference; this should easily work up to one THz.

4. CONCLUSIONS

We are proposing to generate the local oscillator signals for the NRAO MMA telescopes by phase locking the difference frequency of two lasers. Compared to more conventional schemes involving, for example, Gunn diodes with multiplier chains, this potentially offers enormous savings in cost, much greater simplicity and, hence, higher reliability. The logical choice of technology for distribution of LO signals is over optical fiber, and the optical generation of the LO is ideally married to this, leading to great simplification at the system level. Millimeter-wave generation schemes beating lasers together have already been demonstrated to provide sufficient LO power at frequencies well into the THz region, beyond the highest operating frequency of the MMA.2 Sufficient short term phase stability has already been demonstrated,[1] and the long term phase drifts should be at least no worse than with a conventional system. This area of technology is seeing explosive growth at present, driven by the telecommunications industry. Although we are not aware of any existing system simultaneously combining all the needed attributes of power, stability and broad frequency coverage, all these features have already been individually reported in the literature. We are confident that there are no fundamental obstacles to building a practical, cost-effective laser LO system that meets or exceeds the MMA specifications.

5. REFERENCES

1. K.J. Williams et al., "6-34 GHz offset phase-locking of Nd:YAG 1319 nm nonplanar ring lasers," Electronic Letters, Vol. 25, No. 18, pp. 1242-1243, Aug. 31 1989.

2. S. Verghese, K.A. McIntosh and E.R. Brown, "Highly Tunable Fiber-Coupled Photomixers with Coherent Terahertz Output Power," IEEE Transactions on Microwave Theory and Techniques, Vol. 45, No. 8, pp. 1301 - 1309, Aug. 1997.

3. L.Y. Lin, M.C. Wu, T. Itoh, T.A. Vang, R.E. Muller, D.L. Sivco and A.Y. Cho. "High-Power High-Speed Photodetectors -- Design, Analysis, --> -- and Experimental Demonstration," IEEE Transactions on Microwave --> -- Theory and Techniques, Vol. 45, No. 8, pp. 1320-1331, Aug. 1997.

4. A.R. Kerr and S.-K. Pan, "Design of planar image-separating and balanced SIS mixers," Proceedings of the Seventh International Symposium on Space Terahertz Technology, pp. 207 - 219, 1996.

5. Yi-Jen Chiu, Siegfried B. Fleischer, and John E. Bowers, "Subpicosecond (570 fs) response of p-i-n traveling wave photodetector using low-temperature-grown GaAs," Post-Deadline Papers

Technical Digest of the International Topical Meeting on Microwave Photonics, pp.1-3, Duisburg/Essen, Germany, 1997.

6. Jun Ye, Long-Sheng Ma, Timothy Day, and John L. Hall, "Highly Selective Terahertz Optical Frequency Comb Generator," Optics Letters, Vol. 22, No. 5, pp. 301-303, Mar. 1, 1997.

7. M. Kourogi, K. Nakagawa, and M. Ohtsu, "Wide-Span Optical Frequency Comb Generator for Accurate Optical Frequency Difference Measurement," IEEE Journal of Quantum Electronics, Vol. 29, No. 10, pp. 2693-2701, Oct. 1993.

8. L.R. Brothers, D. Lee, and N.C. Wong, "Terahertz Optical Frequency Comb Generation and Phase-Locking of Optical Parametric Oscillator at 665 GHz," Optics Letters, Vol. 19, No. 4, pp. 245-247, Feb. 15, 1994.