ALMA Memo No. 311

Noise Measurements of YIG-Tuned Oscillator Sources for the ALMA LO

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In this memo, we present measurements of the noise of YIG-tuned oscillators (YTOs) at their fundamental frequency and multiplied to millimeter-wave frequencies. Based on these measurements, we verify that the phase noise goals for this component can be met with a 300-kHz bandwidth phase lock loop (PLL) as long as the fundamental YTO frequency is not above 27 GHz. We also present measurements of phase noise added by multipliers and power amplifiers, with the conclusion that their contribution is insignificant. Preliminary W-band amplitude noise measurements using a SIS mixer are also presented, indicating that specifications can be met with this architecture. Phase and amplitude noise measurements are compared to a millimeter-wave Gunn oscillator.

1. Introduction

This memo describes phase and amplitude noise measurements of a prototype version of the YTO-based driver for the ALMA LO, summarizing the work on the third Technical Development Area (TDA) described in ALMA Memo 207 [1]. The prototype driver chain consists of an 18-30 GHz YTO followed by a FET doubler, Q-band power amplifier, balanced varactor doubler, and W-band power amplifier. Measurements are compared to the proposed specifications and goals for this system (see Appendix).

Phase noise, the short time scale (<1 s) zero-mean fluctuations primarily caused by upconverted low-frequency device noise, is discussed in section 2. Section 2 begins by giving some useful definitions for the characterization of phase noise. The phase noise measurement setup, as well as the phase-locked loop (PLL) itself, is then described. Measurements of the YTO as a function of frequency are presented, giving a clear upper limit on YTO frequency for low phase-noise operation. The results are compared to a Gunn oscillator. This is followed by discussion and measurements of phase noise added by multipliers and power amplifiers. Amplitude noise, the "white" thermal noise at 4-12 GHz from the carrier which is downconverted to the IF band, is discussed in section 3. Section 3 describes preliminary measurements on contributions of YTO driver LO amplitude noise to receiver noise compared to a Gunn oscillator LO.

It is helpful to separate the concept of phase drift, long time-scale (>1 s) fluctuations caused by effects such as temperature change, from phase noise. Phase noise can be specified in a few different ways: fast time fluctuation or distance error (seconds or microns, 1fs = 0.3 μm), which is ideally constant with frequency; rms phase error (radians or degrees), which ideally scales linearly with frequency; and in spectral density versus offset frequency dBc/Hz, which ideally scales as the frequency squared. Phase drift measurements will be described in a future ALMA memo.

Just as with phase, we can define amplitude drift, or stability, as long term fluctuations in power due to the same temperature effects. Measurements of amplitude stability will be presented with the phase drift measurements in a future ALMA memo. Amplitude noise is most conveniently specified on the LO as a noise-to-signal ratio (K/μW). By knowing the power required and noise rejection of the mixer, the contribution of LO noise to receiver noise can be easily calculated (see Section 7.4 in Appendix).

2. Phase Noise

Phase noise on the LO is transferred to the IF, radian for radian, resulting in a decrease in coherence at the correlator output. The expression describing this loss in coherence is

$$C_F = e^{-\frac{\Psi^2}{2}} \qquad (1)$$

where Ψ is the rms phase deviation, in radians, at the interferometer RF frequency for all fluctuation frequencies greater than 1 Hz [2]. It is convenient to characterize the local oscillator by its fast time fluctuation, $\tau_{LO} = \Psi_{LO}/\omega_{LO}$, where Ψ_{LO} is the measured rms phase fluctuation in radians at the LO frequency, ω_{LO}. The phase deviation due to LO instability is then

$$\Psi_{LO} = \omega_{L0}\tau_{LO} \qquad (2)$$

To calculate the fast-time fluctuation, we must integrate the spectral density of phase fluctuations, $S_\varphi(f_{off})$ expressed in units of phase variance per unit bandwidth, over some range of offset frequencies (f_{off}). It is most convenient, however, to measure the single sideband (SSB) phase noise to carrier ratio per Hertz bandwidth, $L(f_{off})$, given in dBc/Hz. $L(f_{off})$ is equal to one-half $S(f_{off})$ if the total phase deviations are much less than one radian. This is known as the small angle approximation. If this is so, $L(f_{off})$ can be integrated over some offset frequency range (typically from 1 Hz to 1 MHz or more) to find the fast time fluctuation,

$$\tau_{LO}^2 = \frac{2}{\omega_{LO}^2}\int_{f_L}^{f_H} L(f_{off})\,df_{off} \qquad (3)$$

A proposed specification and goal for the phase noise of the LO electronics is 63 and 31.4 fs respectively, as shown in Table 4 in the Appendix.

We begin by describing the phase noise measurement setup. This is followed by measurements of the YTO alone, which determines the phase noise performance of the "YTO driver outside" component in Table 4 in the Appendix. Section 2.3 compares this to the phase noise performance of a millimeter-wave Gunn oscillator. Section 2.4 investigates the phase noise introduced by individual multipliers and power amplifiers in the driver chain. Finally, Section 2.5 presents phase noise measurements of a full 80-GHz YTO driver chain LO.

2.1 Phase Lock Loop and Measurement Setup

The HP E5500 Phase Noise Measurement System is used for all the measurements described in this memo. The setup used to take measurements is shown in Fig. 1. The loop can be closed anywhere in the chain following the YTO by placing the directional coupler at that point. The frequency into the coupler is set to N * 600 MHz + 103.65 MHz. We chose 103.65 MHz as the offset because a clean voltage-controlled crystal oscillator (VCXO) was available. The 600-MHz reference is a very clean signal provided by the testset. This passes through a comb generator into a balanced mixer to downconvert the coupled signal to 103.65 MHz. The 103.65 MHz IF is filtered and amplified to drive the phase detector. The phase detector output is passed through an active second-order loop filter, where it is then used as the correction voltage for the YTO. The loop bandwidth is controlled by the component values of the loop filter.

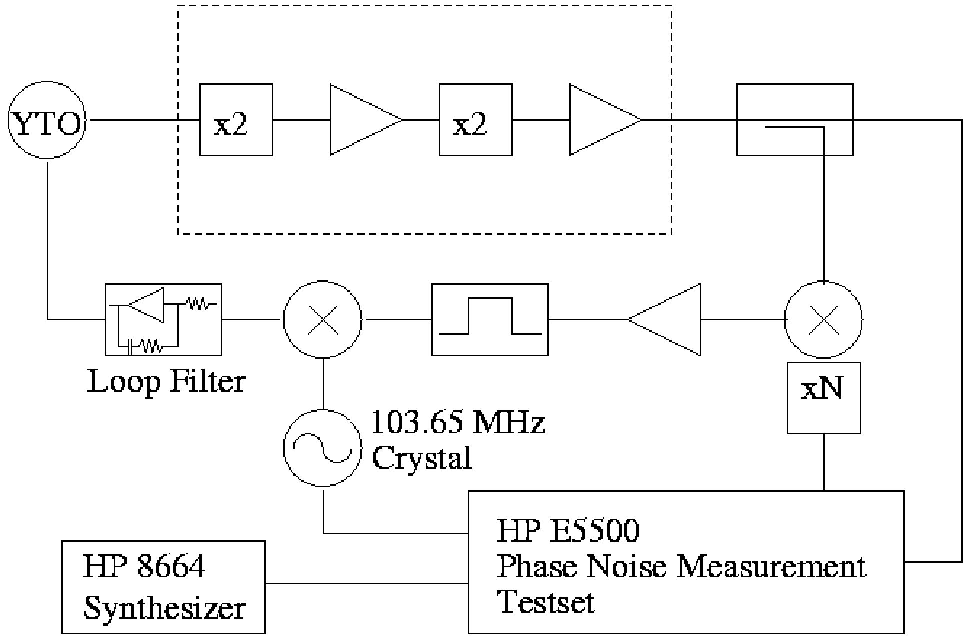

Figure 1 Block diagram of phase noise measurement setup.

The RF output is sent to the test set where it is also downconverted with a harmonic of the ultra-clean 600-MHz signal. The phase reference for the resulting signal is provided by a tunable HP 8664 synthesizer. The output of the internal phase detector is used to close the loop by tuning the 103.65 MHz VCXO and is analyzed by the test set to measure phase noise.

The phase-locked loop essentially acts as a lowpass filter for the reference phase noise and a highpass filter for the YTO phase noise. The reference includes the multiplied 600-MHz signal used for downconversion as well as the VCXO. Therefore, for minimum total phase noise, the optimum cutoff frequency (or loop bandwidth) is the offset frequency for which the reference phase noise is equal to the YTO phase noise. There is also a transition region which consists of both reference and YTO noise components and depends strongly on loop design. For instance, we have been able to reduce the noise in this region by adding an extra pole making the loop filter third-order instead of second.

A sample measurement output is shown in Fig. 2. This shows measured phase noise as a function of offset freqeuncy for the unlocked YTO at 21.0 GHz and the YTO at 20.9635 GHz (N=35) locked. For these measurements, the reference noise spectrum intersects the YTO noise spectrum at approximately 100 kHz, so the loop filter is designed to place the corner frequency there. It appears that the noise spectrum bottoms out above -140 dBc/Hz. This is not the noise floor of the YTO, but rather the noise floor of the HP 8664 synthesizer [3]. The HP E5500 is verified by observing the output on a spectrum analyzer and finding good agreement between the measured spectrum and the plot of $L(f_{off})$. We also examined the voltage output from the phase detector on an oscilloscope and rms voltmeter, noting agreement with the HP E5500 within a few percent.

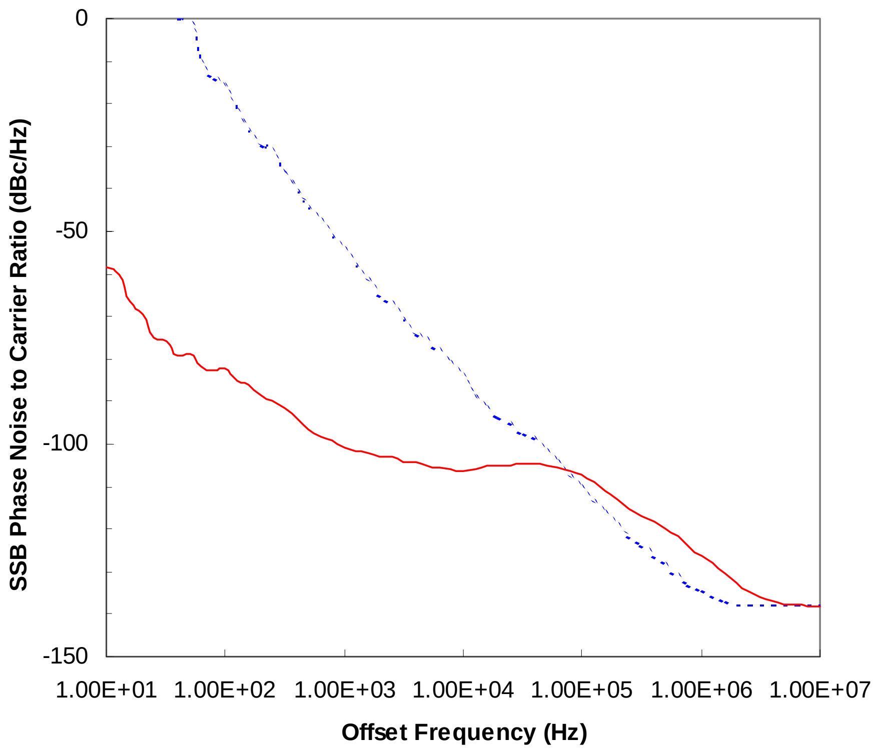

Figure 2 Measured phase noise of the unlocked YTO (dashed line) at 21.0 GHz and the phase-locked YTO (solid line) at 20.9635 GHz.

2.2 Phase Noise of YTOs

The highest frequency YTO commercially available is made by Micro Lambda, Inc. and operates up to 26 GHz. The initial plan required a YTO up to 30 GHz. A 18-30 GHz YTO was purchased as a specialty item from Micro Lambda. This is the YTO used for the measurements described in this memo.

The phase noise spectrum of the 18-30 GHz YTO was measured at several different oscillation frequencies using the setup described earlier. The results are plotted in Fig. 3. This plot shows phase noise at offsets of 10 kHz, 100 kHz, and 1 MHz as a function of oscillation frequency. Above about 27 GHz, the phase noise begins to increase exponentially, much faster than the expected 20 log n multiplication ratio. Discussions with MicroLambda lead to the conclusion that this rapid degradation is primarily due to the FET used as the active element [4].

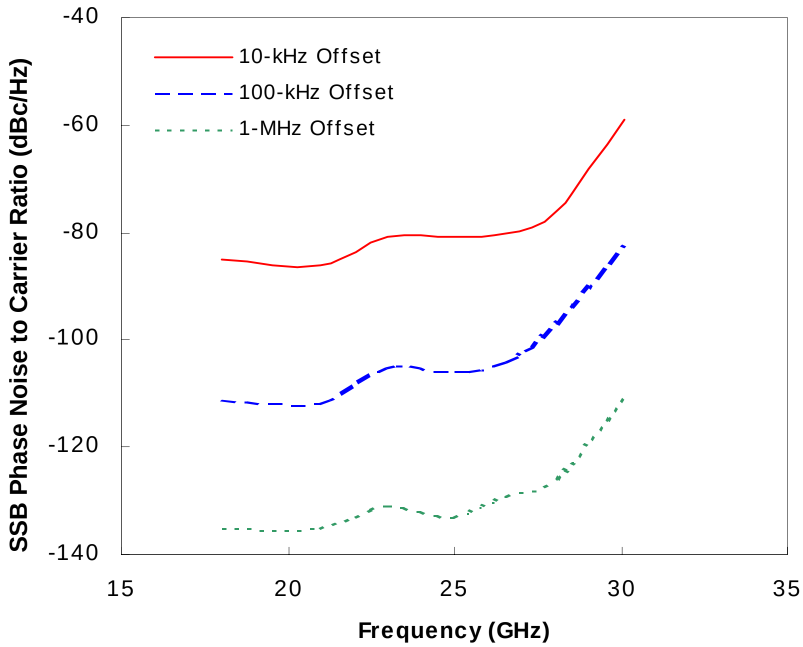

Figure 3 Measured phase noise of the YTO at 10-kHz, 100-kHz, and 1-MHz offsets as a function of oscillation frequencies.

To see the effect this rapid degradation in phase noise performance of the YTO has in terms of the goals and specifications for LO phase noise, we need to look at the expected integrated phase noise for the YTO as a function of frequency. If a $1/f^2$ spectrum from the cutoff frequency to infinity is assumed, the rms time error outside the loop can be calculated as

$$\tau_{LO,outsideloop} = \frac{1}{\omega_{LO}}\sqrt{2 f_c L(f_c)} \qquad (4)$$

where f_c is the cutoff frequency (loop bandwidth). It can also be shown that Eq. (4) is the rms time error inside the loop assuming a constant noise level with offset frequency. Using this equation and the measurements shown in Fig. 3, the expected rms error outside the loop can be calculated as a function of YTO frequency for several different loop bandwidths. Fig. 4 shows the integrated phase noise outside the loop for 100-kHz, 300-kHz, and 1-MHz loop bandwidths. The proposed goal and specification for this component of phase noise are 10 and 15 fs respectively, as shown in Table 3 of the Appendix. The goal is easily met with a 300-kHz loop bandwidth for YTO frequencies below 27 GHz. YTO frequencies above 27 GHz are a concern only for bands 8-10 (see Fig. 8 in Appendix). For these drivers, we will use a x6, rather than x4, architecture referring to the multipliers inside the dashed box in Fig. 1. This reduces the maximum YTO frequency for these bands from 30.5 to 20.4 GHz.

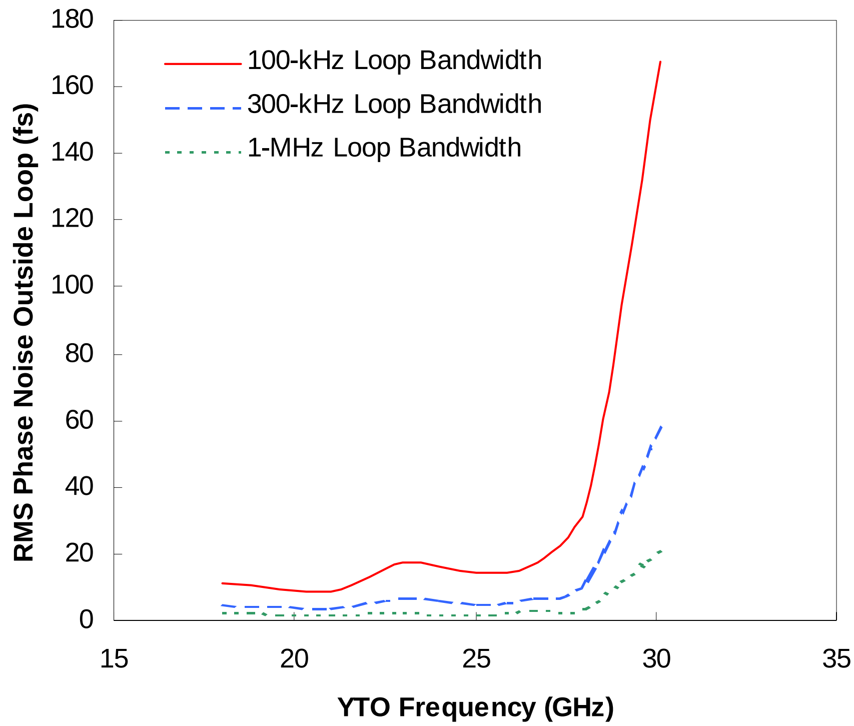

Figure 4 Calculated rms phase noise integrated from loop cutoff to infinity for 100-kHz, 300-kHz, and 1-MHz loop bandwidths.

2.3 Comparison to Gunn Oscillator

As a comparison, we measured the spectrum of a second-harmonic InP Gunn oscillator manufactured by Carlstrom of the type commonly used for radio astronomy. This oscillator is mechanically tunable from 67-97 GHz and puts out over 75 mW from 68-85 GHz. It also can be phase locked. We measured -100 dBc/Hz at a 1-MHz offset. So with a 1-MHz loop bandwidth, noise contributed by the Gunn outside the loop would be approximately 26.5 fs at 85 GHz. To meet the 10 fs goal, a 2-MHz loop bandwidth is required (where the phase noise spectral density is approximately -112 dBc/Hz, resulting in a rms error outside the loop of 9.4 fs.

It should be noted that in the literature, fundamental mode InP Gunn oscillators have been reported up to 151 GHz with 58mW output power and -100 dBc/Hz phase noise at 500-kHz offset [5], but only over a narrow mechanically-tuned bandwidth.

We also note that there is an engineering tradeoff between loop bandwidth and required phase noise spectral density of the reference. For instance, as mentioned in the previous section a 300-kHz loop bandwidth for the YTO would be more than adequate. The required phase noise spectral density for the reference at 120 GHz is then -97.3 dBc/ Hz to meet the 14 fs goal for phase noise contributed by the reference. For the Gunn oscillator, with a 2 MHz required loop bandwidth, the phase noise spectral density of the reference at 85 GHz needs to be -108.5 dBc/Hz to meet the goal.

2.4 Additive Phase Noise of Power Amplifiers and Multipliers

A solid-state power amplifier can impart phase noise onto a signal as it is being amplified via three mechanisms. Fluctuations in insertion phase can modulate the signal as it passes through the amplifier (intrinsic phase noise of amplifier). Thermal amplitude noise can be converted to phase noise during amplification when the amplifier is operating in a nonlinear regime (saturated) due to insertion phase no longer being constant with input power. AM-PM conversion can also result from noise on the bias lines. This last mechanism can be eliminated from concern by suitable bias voltage regulation.

Halford, et al [6] and Moore and Kopp [7] have experimentally found for amplifiers measured from 1 MHz to 10 GHz that the intrinsic phase noise spectral density, due to fluctuations in insertion phase, is independent of input frequency and approximately equal to

$$\frac{-115\frac{dBc}{Hz}}{f_0} \qquad (5)$$

where f_0 is the offset frequency. Halford [6] noted that this is also true of multipliers and independent of multiplication factor for the multipliers that he tested. This is significantly less than the phase noise of either the YTO or a very good millimeter-wave reference and therefore should not be a concern.

AM-PM conversion resulting from nonlinear operation of the amplifier is caused by the dependence of insertion phase on input amplitude when the amplifier is near or is being saturated. The equations describing this process are presented for multipliers in [8] and apply to amplifiers as well. For typical levels of phase variation versus input power and input amplitude noise at least an order of magnitude less than input phase noise, AM-PM conversion does not noticeably affect the phase noise of the output signal. For the power levels and phase noise in the YTO chains described in this memo, no AM-PM conversion should be noticeable unless there is thermal noise well in excess of 10^6 K, which should not occur unless there is a parasitic oscillation at some point.

To measure phase noise contributions from individual components, the loop was locked after the YTO at 19.90365 GHz before any additional components. This enables accurate measurements of additive phase noise of components by not including variations in loop parameters by locking at different frequencies. Fig. 5 shows the integrated phase noise from 1-100 kHz in nanometers at each point in the chain. Integration was stopped at 100 kHz because above this point, the measurements were already below the noise floor of the W-band harmonic mixer. However, since any additive phase noise would decrease with offset frequency, below 100 kHz is the most crucial range. These contributions will of course be corrected by the loop when the loop is closed after the last power amplifier, but these measurements suggest what to expect from the high-frequency multipliers outside the loop. The chain consists of the YTO, a FET doubler using the HP HMMC5040 MMIC, a Q-band power amplifier made with the same device, a balanced diode doubler [9], and a 71-84 GHz power amplifier on loan from JPL. It should be noted that both amplifiers were heavily saturated. Ten independently calibrated measurements were made at each point in the chain. The uncertainty range shown is three standards of deviation.

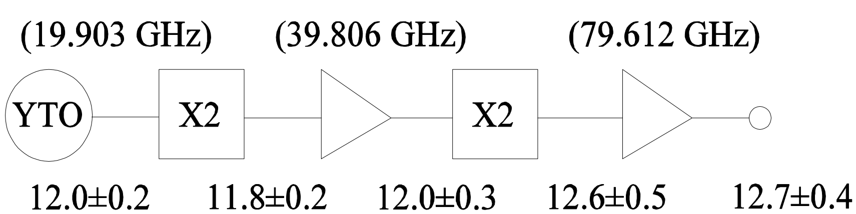

Figure 5 Measured phase noise in femtoseconds integrated from 1-100 kHz at each point in the YTO driver chain. The uncertainty range is three standards of deviation.

As shown, the individual contributions are small. However, looking from one end of the chain to the other and keeping in mind that the phase noise contributions add in quadrature, there does appear to be a very real increase, which can be worked out to be a 4 +/- 1 fs contribution from the combination of all four additional components. The balanced doubler is the same design used for many of the out-of-loop high-frequency doublers. Even making the worst case argument that all of the measured additive phase noise is from the balanced doubler, the result is much less than the 10 fs budgeted for each of these multipliers (see Table 4).

The most precise measurements in this chain were made before and after the W-band power amplifier. Based on these measurements, we determine that the additive phase noise of that amplifier is 1.3 +/- 0.7 fs (mean plus or minus standard deviation of mean). The additive phase noise from power amplifiers or multipliers inside the loop is not significant enough to influence loop design.

2.5 Phase Noise of Full Driver

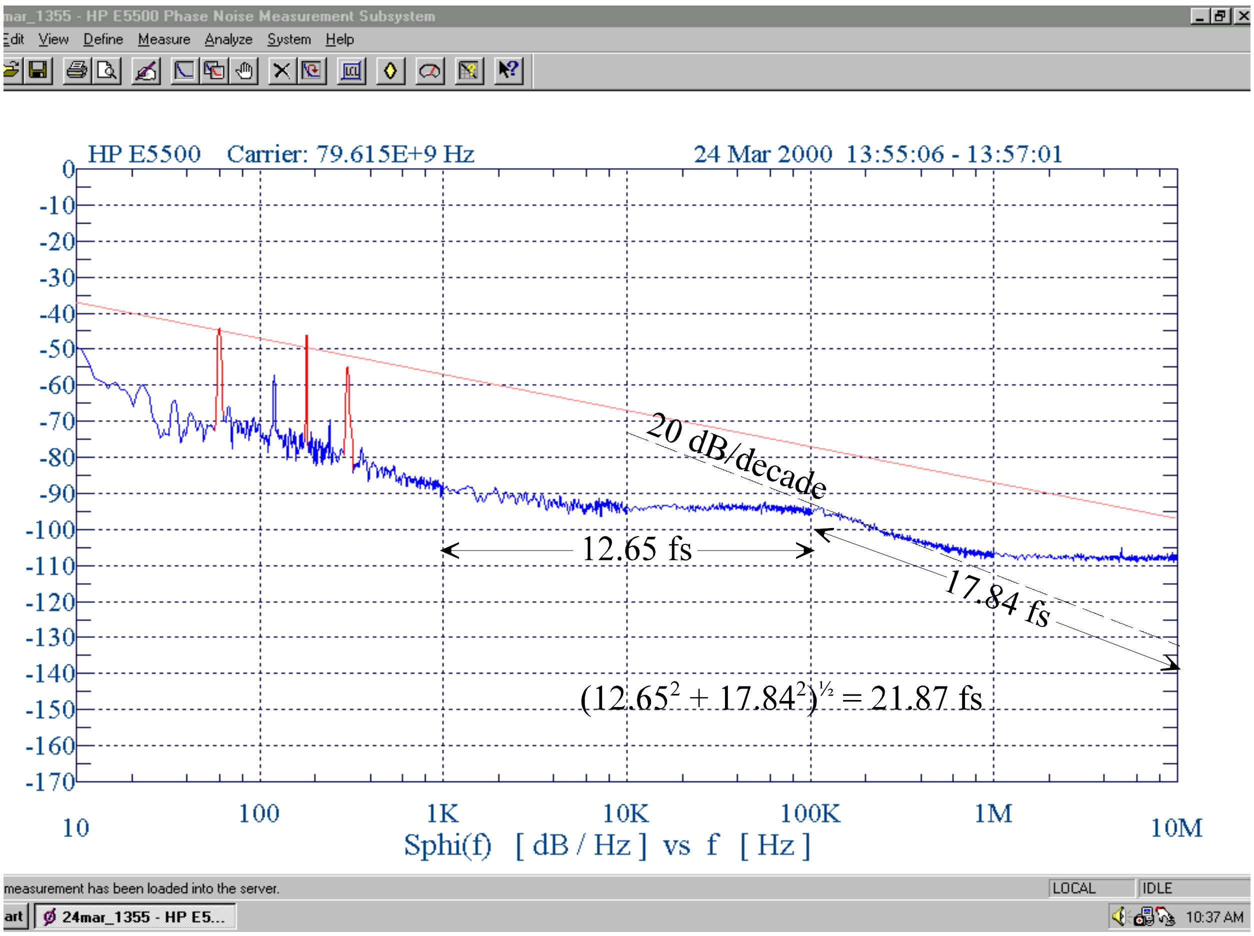

Figure 6 HP E5500 phase noise measurement of 79.615 GHz YTO driver LO chain.

Fig. 6 shows the phase noise measurement of the full YTO driver LO chain consisting of the components described in the previous section. The PLL is closed at the YTO frequency, 19.903 GHz. This is the same setup used for the additive phase noise measurements described earlier. We have made measurements with the PLL locked at 79.615 GHz. The results, in terms of phase noise, are basically identical since the doublers and amplifiers add little if any phase noise. The primary advantage in locking at the higher frequency is in terms of phase *drift*.

Labeled on the plot is the integrated phase noise from 1-100 kHz, 12.65 fs, and the calculated phase noise from 100 kHz to infinity, 17.84 fs, based on Eq. (4). The calculated phase noise assumes a 20 dB/decade drop in phase noise outside the phase lock loop as represented by the dashed line superimposed on the plot. As mentioned earlier in Section 2.1, the flattening of the phase noise spectrum near 500 kHz is not due to the noise floor of the YTO, but rather due to measurement equipment. Note that the noise inside the loop meets the goal as shown in Table 4 while the noise outside the loop does not quite meet the specification. The total noise in these two regions is 21.87 fs, which is less than the total of the specification for these two ranges, 29.15 fs. As mentioned earlier, the loop bandwidth should be close to 300 kHz with a better reference, rather than the 100-kHz bandwidth used here.

3. Amplitude Noise

The proposed goal and specification for the amplitude noise contributed by the LO is 3 and 10 K/μW respectively. Noise at the IF (4-12 GHz away from the carrier of the LO) will be downconverted into the IF passband and add to the total system noise temperature at a level equal to the noise temperature of the LO power. For a balanced mixer, this added noise would be less by a factor equal to the LO isolation provided by the mixer (typically 10-20 dB).

To measure the noise-to-signal ratio (N/S) of a YTO chain LO, a W-band SIS mixer with 1.4 GHz IF was used. This is shown in Fig. 6. The LO supplied was switched between a Gunn oscillator and a YTO driver LO identical to the chain used for the phase noise measurements described in the previous section. The frequency of the Gunn and YTO driver LO were both unlocked and tuned to 78.0 GHz.

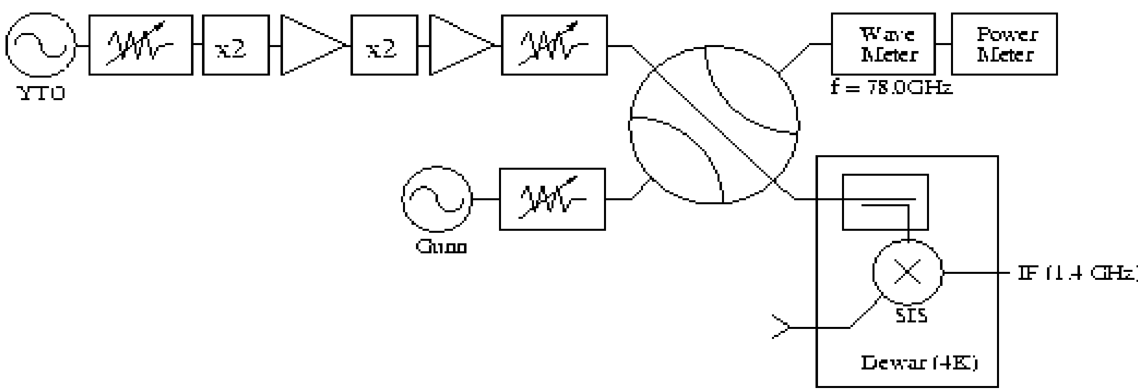

Figure 7 Measurement setup for amplitude noise comparison of Gunn oscillator LO versus YTO driver LO.

The total receiver noise with the Gunn oscillator LO was 185.2 +/- 1.0 K with the SIS mixer being operated below its optimum tuning range of 90-116 GHz. The additional receiver noise measured using the YTO driver chain LO was 5.1 +/- 1.2 K (mean plus or minus standard deviation of the mean). Based on the knowledge that the N/S of the Gunn is approximately 1 K/μW [10] and the loss of the LO coupling into the dewar, the N/S of the YTO chain was calculated to be 3.7 +/- 0.9 K/μW. This figure is expected to be less for higher IF frequencies. A 240-GHz wideband varactor tripler is currently being developed at the CDL for use on the ALMA test interferometer. Future work includes making the same amplitude noise measurements at 240 GHz at the ALMA IF (4-12 GHz) over the full frequency range of the band.

A similar measurement was performed by Mehdi et al on the Caltech Submillimeter-wave Observatory (CSO) [11]. A slight *decrease* in receiver noise temperature was measured when inserting a MMIC power amplifier into their LO chain after a Gunn oscillator.

4. Conclusions

We have presented measured data of phase noise from the YTO, both inside and outside the PLL. These measurements show that with a loop bandwidth of only a few hundred kHz, we can easily meet the specifications for phase noise. The additive phase noise of amplifiers and multipliers was measured and found to be negligible. Preliminary amplitude noise measurements were presented with encouraging results, meeting specifications and very close to the goal. Future work in this area includes extending the bandwidth of the driver chain and verifying that the noise specifications can be met over the full bandwidth.

5. Acknowledgments

These measurements would not be possible without the technical support of Dan Boyd and Mike Stogoski. We would also like to thank Todd Boyd for amplifier assembly, "Matt" Dillon for machining of amplifier housings, Kirk Crady for dewar setup, and S. K. Pan for SIS mixer setup and helpful discussions. We would also like to thank Charles Reichert for use of the PLL design program and helpful discussions as well as John Webber for helpful comments on this document.

6. References

[1] R. Bradley, "Wide bandwidth, YIG-based sources and modern frequency multipliers for the MMA local oscillator system," ALMA Memo No. 207, April 1998.

[2] S. Weinreb, "Short-term phase stability requirements for interferometer coherence," May 1983. Internal Report.

[3] Agilent Test and Measurement Catalog 2000, pp. 201.

[4] R. Leier, Micro Lambda, Inc., private communication.

[5] H. Eisele and G. I. Haddad, "High-performance InP Gunn devices for fundamental-mode operation in D-band (110-170 GHz)," *IEEE Microwave and Guided Wave Lett*., vol. 5, pp. 385-387, Nov. 1995.

[6] D. Halford, A. E. Wainright, and J. A. Barnes, "Flicker noise of phase in rf amplifiers and frequency multipliers: charcterization, cause, and cure," in *Proc. 22nd Annu. Symp. Frequency Contr*., (Atlantic City, NJ), pp. 340-341, Apr. 1968.

[7] C. Moore and B. Kopp, "Phase and amplitude noise due to analog control components," *Microwave J*., pp. 64-72, Dec. 1998.

[8] E. Bava, G. P. Bava, A. D. Marchi, and A. Godone, "Measurement of static AM-PM conversion in frequency multipliers," *IEEE Trans. Instrum. Meas*., vol. IM-26, pp. 33-38, Mar. 1977.

[9] D. W. Porterfield, T. W. Crowe, R. F. Bradley, and N. R. Erickson, "A high-power fixed-tuned millimeter-wave balanced frequency doubler," *IEEE Trans. Microwave Theory Tech*., vol. 47, pp. 419-425, Apr. 1999.

[10] S. K. Pan, private communication.

[11] I. Mehdi, T. Gaier, J. Kooi, B. Fujiwara, and R. Lai, "A W-band HEMT based power amplifier module for millimeter-wave LO multipliers," *9th Int. Symp. On Space Terahertz Tech*., (Pasadena, CA), pp. 573-578, Mar 1998.

[12] J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," Rev. of Modern Phys., vol. 4, pp. 1055-1113, 1985.

[13] A. R. Kerr and S-K. Pan, private communication.

[14] L. D' Addario, private communication.

[15] L. D'Addario, "ALMA Phase Stability Specification–Notes," Mar. 16, 2000 .http://www.tuc.nrao.edu/~ldaddari/phaseSpecs.txt

7. Appendix

This appendix contains background information that may be useful to the reader in analyzing the results presented in this memo. This information includes tables of proposed specification and goals, frequency requirements, power requirements, and phase noise budget for the LO system. Explanation is provided where necessary. The information contained here represents our proposed plan for how the first LO system should be organized and specified based on our study and measurements. It is provided as a context aid for the reader and does not necessarily represent the current baseline LO design.

7.1 LO System Specifications and Goals

Table 1 Summary of proposed specifications and goals for the LO system.

Item	**Specification**	**Goal**
Frequency Range	Up to 950 GHz in 10 bands (see Table 1)	Same as specification
Output Power	Depends on band (see Table 2)	100 μW
Amplitude Noise	10 K/μW	3 K/μW
Amplitude Stability	.03% <1s, 3% between levelings	.01% <1s, 1% between levelings
Phase Noise (>1 Hz)	63 fs (18.9 μm)	31.4 fs (9.4 μm)
Phase Drift (<1 Hz)	29.2 fs (8.8 μm)	6.9 fs (2.1 μm)

7.2 LO Frequency Requirements

Table 2 Summary of the first LO frequency specification. *An IF of 4-12 GHz is assumed.*

Priority	Band #	Rcvr Band GHz	LO Band GHz	27-33 GHz	68-76 GHz	71-94 GHz	87-108 GHz	99-122 GHz
2	1a 1b	31-44	27-33 53-59	X1 X2				
2 *	2a 2b	67-90	90-104 79-94			 X1	X1 	
1	3a 3b	89-116 *	71-94 * 97-108 *			X1 	 X1	
2	4	125-163	137-151		X2			
3	5	163-211	175-199				X2	
1	6	211-275	223-263			X3		
1	7	275-370	287-358			X4		
3	8	385-500	397-488					X4
1	9	602-720	614-708					X6
3	10	787-950	799-938					X8

***** to be extended to 85-116 GHz if feasible, in which case Band 2 priority drops to 3, and LO Band 3b becomes 93-108 GHz.

7.3 LO Power Requirements

The local oscillator must provide adequate mixer pump power for both HFET and SIS based receivers. A conventional balanced mixer used in a millimeter-wave HFET front-end requires approximately 5 mW of LO power. However, 20 mW may be required if a sideband-separating mixer follows the low noise HFET amplifier.

The LO power required for SIS mixers will depend upon several factors. Based on the theory of Tucker and Feldman [12] the required LO power is given by

$$P_{LO} = \frac{\left[\dfrac{N_j h f \alpha}{e}\right]^2}{2R_n}$$

where N_j is the number of junctions, h is Planck's constant, f is the operating frequency, α is a parameter that characterizes the normalized level of LO amplitude across the SIS junction and is usually set to unity, e is the electron charge, and R_n is the normal state resistance taken here to be approximately 20 ohms [13]. These requirements are given in Table 3.

In the worst-case scenario where only single-ended, two-port SIS mixers are used, a waveguide or quasi-optical LO coupler, having a coupling factor of -20 dB, will be required to combine the LO and RF signals appropriately. The LO power required at the input of the coupler is also given in Table 7.2.4. However, if a balanced mixer can be utilized, the LO power is supplied via a separate LO port on the mixer thus rendering the coupler unnecessary. Column #7 in Table 7.2.4 lists the power requirements for a balanced mixer configuration that is both image separating and balanced. The last column is a suggested *specification* per RF band based upon a 50 percent overhead for the worst-case conditions. The LO power *goal* will be 100 µW per band to ensure adequate power to overcome losses within the mixer block.

Table 3 Summary of local oscillator power requirements and specifications.

ALMA Receiver Band	LO Tuning Range [GHz]	Type of Receiver Front-End	Number of SIS Junctions	Minimum Required Mixer Power	Required Power at Input of -20 dBLO Coupler of SIS Mixer	Required Power at LO port of an Image - Reject & Balanced SIS Mixer	LO Power Specification of 50%Over Worst-Case
1a 1b	27-33 53-59	HFET	---	5 mW	---	---	5 mW
2a 2b	90-104 79-94	HFET	---	5 mW	---	---	5 mW
3a 3b	71-94 93-108	HFET SIS	— 4	5 mW 0.10 µW	— 10 µW	— 0.40 µW	5 mW 15 µW
4	137-151	SIS	4	0.15 µW	15 µW	0.60 µW	23 µW
5	175-199	SIS	4	0.26 µW	26 µW	1.06 µW	39 µW
6	223-263	SIS	4	0.46 µW	46 µW	1.84 µW	69 µW
7	287-358	SIS	2	0.21 µW	21 µW	0.84 µW	32 µW
8	397-488	SIS	2	0.40 µW	40 µW	---	60 µW
9	614-708	SIS	1	0.21 µW	21 µW	---	32 µW
10	799-938	SIS	1	0.37µW	36 µW	0.73 µW	54 µW

7.4 Amplitude Noise Specification

The following specification for receiver noise was proposed: "*SSB noise temperature of the receiver at its input beam shall not exceed 10 hf/k, where h and k are the usual physical constants. This applies to any frequency f within the tuning range of the receiver; considerably better performance is expected near the center of the tuning range*." [14]. It is reasonable to expect this number to be close to 5 photons near the center of the band, for most bands [13].

Calculating the LO contribution to receiver noise as a fraction of photon noise gives:

$$\frac{P_{LO}\left[\frac{N}{S}\right]_{LO}}{T_{ph}} = \frac{10^6 \cdot N_j^2 h\, k\, f\alpha^2}{2e^2 R_N}\left[\frac{N}{S}\right]_{LO}$$

where k is Boltzmann's constant, $(N/S)_{LO}$ is the noise-to-signal power ratio of the LO in K/μW and T_{ph} is hf / k. α is assumed to be unity. To obtain an upper limit, we assume four junctions ($N_j = 4$) through 275 GHz, two junctions from 275-500 GHz, and one junction in the two upper bands. We assume a resistance of 20 ohms ($R_n = 20\ \Omega$). This result is plotted in Fig. 7 as a function of frequency for $(N/S)_{LO}$ of 3 and 10 K/μW.

The amplitude noise from the LO should not add appreciably to the intrinsic mixer noise temperature at any given RF band. We assume here that mixers operating up to 275 GHz will be of the balanced type so at least 10 dB of LO amplitude noise rejection will be obtained. Therefore, the ALMA receiver band with the greatest LO noise is near 500 GHz. Assuming that the receiver noise at 500 GHz can be as low as 5 photons, this implies that a $(N/S)_{LO}$ of 10 K/μW will add less than 4 % to receiver noise in this band. Therefore, 10 K/μW will be adopted as the *specification*. As a *goal* we would like the LO noise to add less than 1% to the mixer noise; this corresponds to an LO amplitude noise of 3 K/μW.

7.5 Phase Noise Specifications

The phase noise budget supporting the goal given in [15] assigns 31 fs to the electronics. This *goal* appears reasonable based upon our recent measurements of the phase noise contributions from key source components. However, as a *specification*, we recommend that twice this value, or 63 fs, be adopted for the electronics. This gives 85% coherence at 950 GHz when the atmosphere and antenna phase noise contributions are as given in [14]. Our phase noise allocation for the LO electronics based upon this goal and specification is given in Table 4.

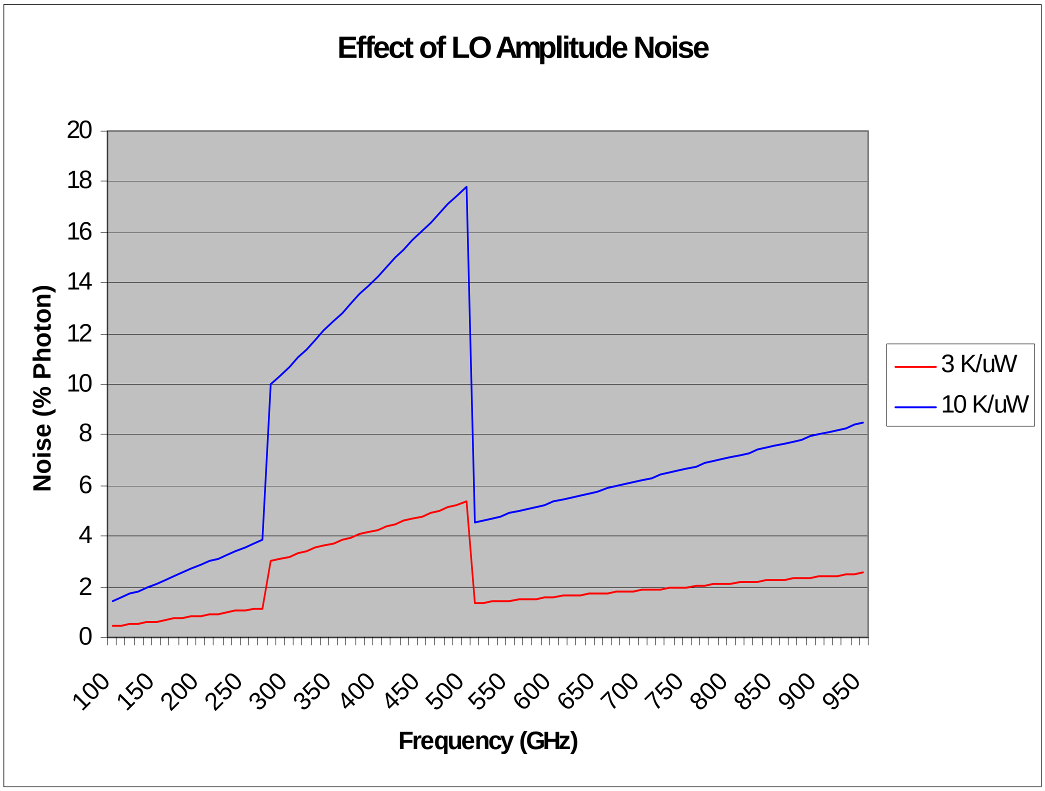

Figure 7 The contribution of LO amplitude noise to receiver noise as a function of frequency. LO amplitude noise is given as percentage of a single photon for LO noise-to-signal (N/S)LO values of 3 and 10 K/μW. Balanced mixers with 10 dB LO noise rejection are assumed below 275 GHz.

In each of the components listed in Table 4, the noise contribution is ascertained by integrating the phase noise power spectral density over an appropriate bandwidth determined by the component's location within the LO system. The bandwidth of the reference source and fiber distribution sub-system is bounded by the array coherence time at the lower end and by the PLL corner frequency at the upper end. "YTO driver inside" refers to the noise of the YTO driver integrated from the array coherence time to the *effective* PLL cutoff frequency (noise attenuated by the loop plus noise of the locking circuitry). This upper bound includes the non-negligible noise contribution from within the transition region between the passband and the stopband of the loop filter. "YTO driver outside" refers to the noise of the YTO driver integrated from the *effective* PLL cutoff frequency to infinity (noise of the oscillator, multipliers, and amplifiers not attenuated by the loop). The phase noise power spectral density for the multipliers outside the loop is integrated over all frequencies.

Table 4 Proposed phase noise allocation for LO Electronics.

Component	**Goal [fs]**	**Specification [fs]**
Reference Source	14	35
Fiber Distribution Subsystem (laser, round-trip fiber corrector, fiber, photomixer)	14	35
YTO Driver Inside	14	25
YTO Driver Outside	10	15
Multiplier #1	10	15
Multiplier #2	10	15
Multiplier #3	10	15
Total	31.4	63

7.6 Proposed LO Distribution Plan

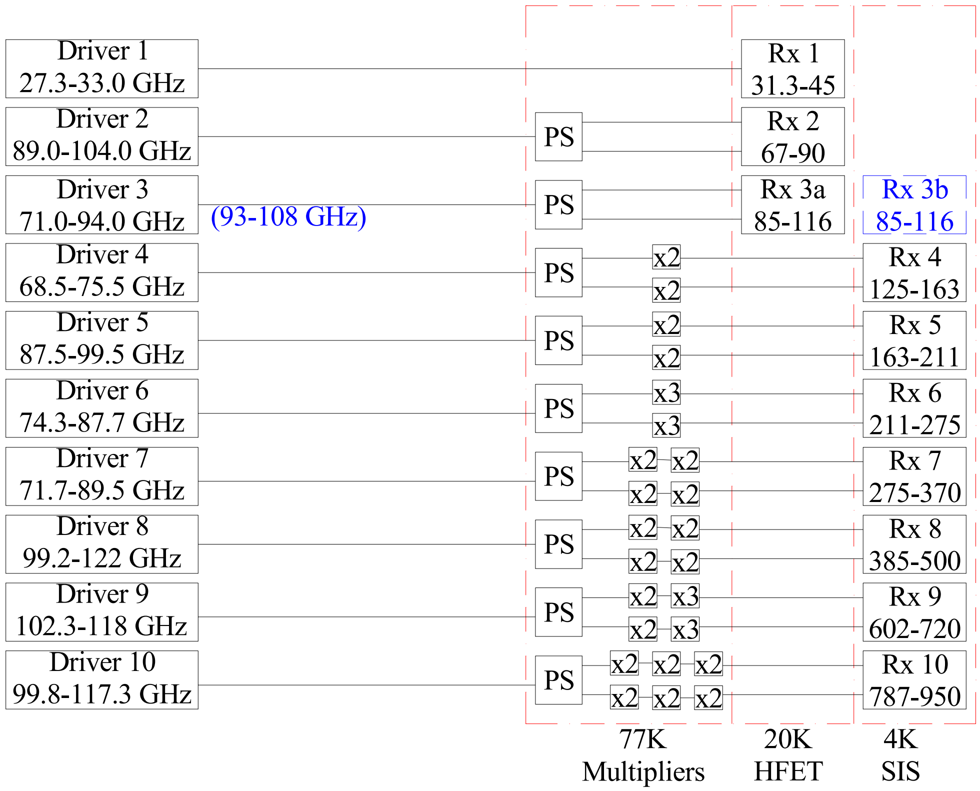

Figure 8 Block diagram of proposed LO distribution plan.