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First LO Reference Synthesizer Test Module

A proposal by

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1 SCOPE

This proposal is in response to a statement of work (SOW) issued by Dr. Bill Shillue of NRAO on January 19, 2005, entitled: "1st LO Reference Synthesizer Test Module Specifications – Bend–56.02.00.00.0006-A-SPE". The objective of this SOW reads as: "A test set is required to provide a coherent 1st LO Reference for use in testing the Front End. The test set is used to provide an input to the ALMA 1st LO cartridge-mounted photomixer as a means of phase-locking the first LO.

What is envisaged is either:

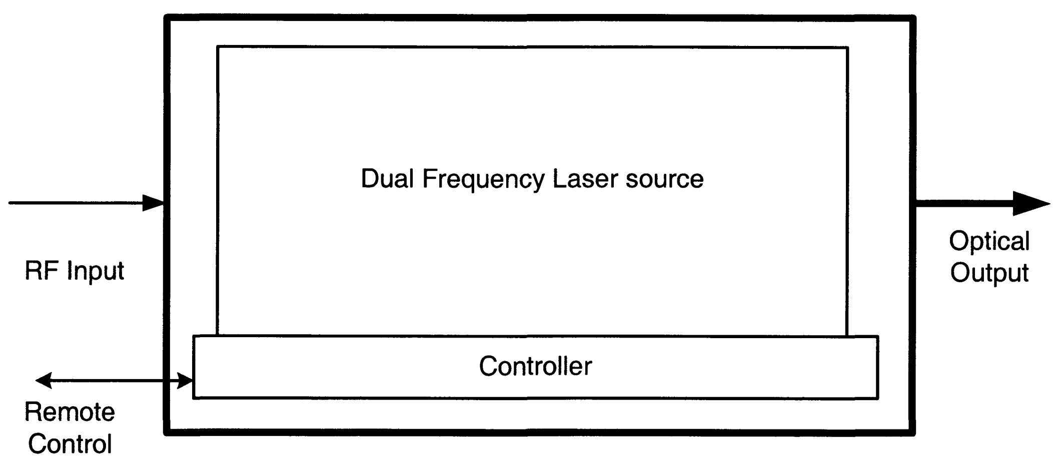
1. A single wavelength laser source modulated with sufficiently high index to create phase coherent sidebands above 100 GHz or...
2. A two-laser phase or injection-locked system with very low residual phase noise."

DiCOS believes that it is important to take this opportunity to supply a module that will move further the development of the system-ready ALMA Laser Synthesizer. It is for this reason that we first recall the situation of the actual Laser Synthesizer design and we discuss on possible improvements. At the end, DiCOS proposes a thorough evaluation of different solutions, some preliminary tests on the most promising ones and the delivery of two modules that will fulfill the requirements of the SOW while being close to meet the full blown ALMA system requirements.

2 BRIEF DESCRIPTION OF THE ENVISIONED TEST SET

The test set has to provide two mutually coherent light signals on a single mode optical fiber with their polarization highly parallel. The optical source can be seen as a dual frequency laser source for which one component of the optical signal is considered as a Master Laser Signal and the other one a Slave Laser Signal. The frequency offset between the two optical signals must be tunable in the millimeter range, the precise value being set by an external low phase noise RF input. An embedded controller allows the setting of all parameters, the start up and calibration procedure and the communications with an external controller.

A functional representation of the test set system can be illustrated as follow



3 STATED PRELIMINARY REQUIREMENTS

From the SOW requirements for the test module, DiCOS has constructed the following table.

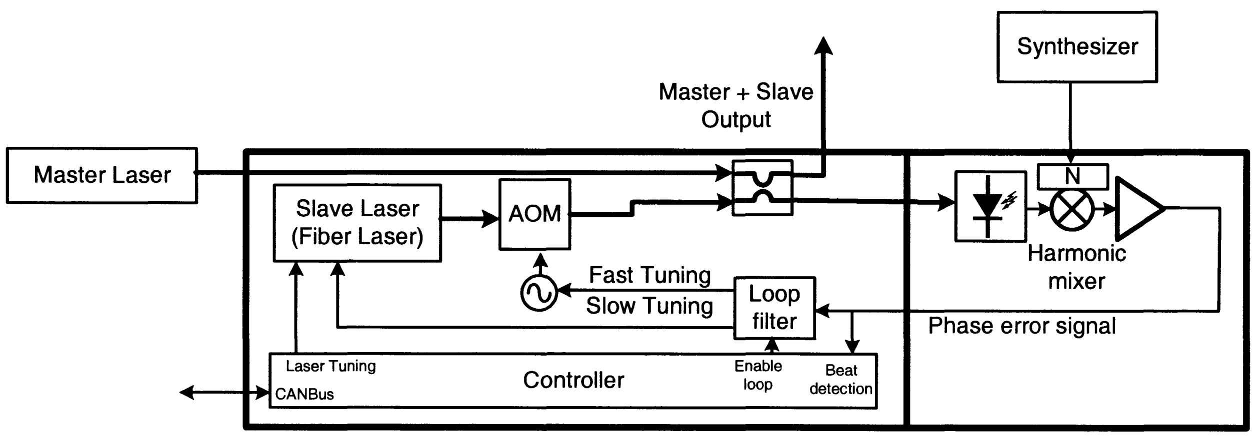
	Preliminary requirements	Comments
Optical output		
Dual Wavelengths mutually coherent	In the range 1545 to 1570 nm. If fixed wavelength at 1556.2 nm then tunable wavelength between 1556.4 and 1557.4 nm	ALMA Master laser prototype at 1556 nm
Phase noise variance for each wavelengths of interest	TBD	To meet phase noise requirement on beat note
Frequency stability	TBD	To meet frequency stability requirement on beat note
Dual optical output power product	P1 > 1 mW and P2 > 1 mW P1xP2 > 1 mW^2	This is the corresponding intensity of the scalar product of electric field amplitude with aligned polarization)
Ratio of polarization	Not specified	To meet the dual optical output power product
Optical output connector	E2000/APC	
Optical output fiber type	Single Mode	Polarization maintaining SMF preferred
Optical frequency difference (Optical beat note)		
Frequency ranges	27.3 GHz to 121.7 GHz	Current ALMA prototype Laser Synthesizer uses 4 bands (27.3 GHz to 141.6 GHz)
Tuning frequency increments	TBD	Can be 10 GHz or less
Phase noise variance	< 0.0045 rad at 27.3 GHz	Will depend on optical signals spectral phase noise and photoreceiver noise (photomixer + amplifier)
Phase noise bandwidth	1 kHz to 10 MHz	There might be bandwidth limitations imposed by other system elements
RF input reference		
Source	Single frequency, low phase noise, CW	
Frequency range	8 to 12 GHz	
Power	+13 dBm	
Computer interface		
Protocol	Ethernet, GPIB, RS-232 or CANbus	CANbus preferred
Physical		
Size	standard rack mount width	Cooling fans discourage
Electrical		
Power supply	AC linear type	
Environmental		
Operating conditions	Not specified	Typical laboratory conditions

Note: If necessary for the construction of a prototype version of this Test Set System, NRAO will be able to provide a W-Band Harmonic Mixer, a Photomixer, and an optical switch.

4 CURRENT ARCHITECTURE FOR THE ALMA LASER SYNTHESIZER

The NRAO has developed a Laser Synthesizer based on the offset phase-locking of a Calibrated Tunable Narrow Linewidth Laser (CTNLL) to a Master Laser Prototype. The phase locking is done electrically by tuning the CTNLL frequency with an external frequency shifter for high speed tuning and by adjusting the laser PZT for the slower tuning. In the current design, the optical phase-lock loop (OPLL) is based on the comparison of the phase of the beat signal between the Master and Slave to the phase of a low noise microwave synthesizer. The beat signal is taken after the final coupler that combines the two laser signals, ensuring that all possible phase drifts caused by the optical components are compensated. Such a feature should be maintained in any future development.

The following figure shows a schematic view of the actual ALMA Laser Synthesizer incorporating a CTNLL based DFB fiber laser, a single controller and a beat note-based tuning and locking control loop.



This design meets the noise requirements of the project and the technical risks seems to be relatively low. There are however some practical concerns concerning the reliability and availability of the DFB fiber laser source that need to be addressed to ensure that the current solution can lead to system-ready units meeting the full ALMA system requirements.

We recall that the target RMS phase noise on the beat note for ALMA project is equivalent to a time delay fluctuations of 35 fs, which at a beat note frequency of 42 GHz (worst case) corresponds to 0.008 rad RMS. The Master Laser and Slave Laser frequency noise power spectral densities or, consequently, their lineshapes are key elements in determining the residual differential phase noise that can be obtained by phase-locking the two lasers. The linewidth alone is not a sufficient parameter to specify the required lasers. In the case of the current OPLL design of the Laser Synthesizer, it is a good thing that the lasers have a dominant flicker frequency noise instead of the usually encountered white frequency noise, since this allows a proper functioning with a reasonable locking bandwidth. If semiconductor lasers were to be used, other phase-locking mechanisms would have to be considered.

5 OTHER POSSIBLE ARCHITECTURES FOR THE ALMA LASER SYNTHESIZER

DiCOS has already begun an analysis on various ways to address the requirements of the ALMA Laser Synthesizer and has supplied NRAO with a document entitled "Laser synthesizer improvements analysis" dated October 29, 2004. In the following, we recall the main considerations reported in this document.

5.1 Improving the fiber laser based CTNLL

A straightforward approach to improve the actual Laser Synthesizer design is to keep the current architecture and try to improve the DFB fiber laser performances in order to compensate the drawbacks found with the CTNLL. It might be possible to do so by implanting in a new design the modifications applied by DiCOS during the realization of the CTNLL. However, the main difficulty will remain to find a laser manufacturer that will guaranty a laser offering a narrow linewidth (2 kHz), a broad and stable tuning range, a high bandwidth tuning mechanism, a wide operation temperature and a high reliability. In any case, extensive testing of the laser to determine its actual frequency noise and reliability would have to be performed before a final design of the CTNLL can be committed.

5.2 Using an external cavity laser

An external cavity laser (ECL) could be used to replace the DFB fiber laser in the current design. External cavity lasers offer relatively narrow linewidth, on the order of a few hundreds of kHz and wide tuning range, typically over 30 nm. Many manufacturers offer such lasers in the form of telecommunication-grade integrated modules with Telcordia qualification but for specific wavelength (ITU-Grid). They are also available from T&M instrumentation where continuous tuning without mode hops still remains an issue. The linewidth specified by the manufacturers tend to be somewhat optimistic. The external cavity lasers often are very sensitive to mechanical vibrations and acoustical noise. Some manufacturer remove from their linewidth specification the effect of the mechanical instability of the tuning system, which is the major contribution to their linewidth. A very careful study of the true frequency noise power spectral density has to be done before selecting such a laser for the Laser Synthesizer since the performance of the OPLL depends strongly on this aspect.

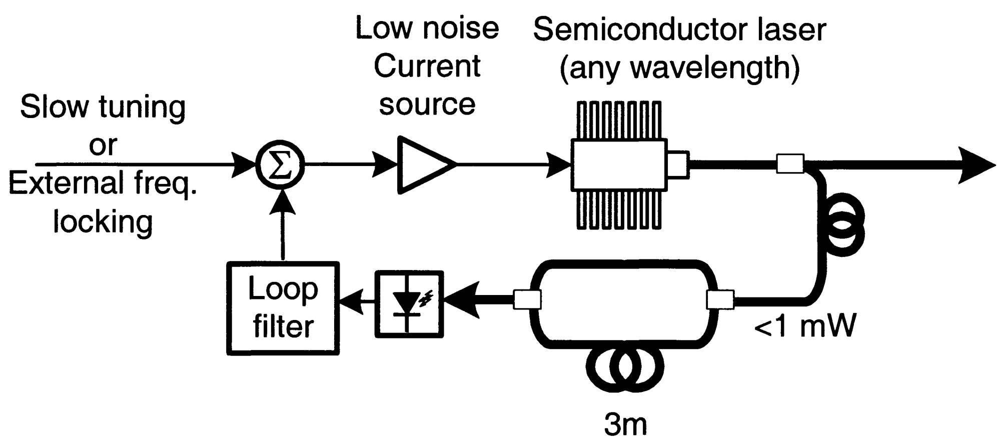
5.3 Using a semiconductor laser

A semiconductor laser can also be considered as the slave laser in the base plan OPLL design. It can be a relatively narrow linewidth (400 kHz) telecommunication-grade semiconductor laser. Fast feedback control can be applied directly to the injection current of the laser to perform frequency tuning and phase locking. The laser can easily be tuned over more than 125 GHz (1 nm) by changing the injection current and more than 250 GHz (2 nm) through thermal tuning. This approach offers the advantage of replacing the fiber laser with a Telcordia-qualified component. The locking loop design becomes very simple where the external optical frequency shifter can be removed as long as the laser frequency modulation bandwidth is sufficiently wide.

The drawback of this approach is the high tuning bandwidth required to realize a phase-lock that offers a sufficiently low residual phase noise. Since semiconductor lasers may have frequency noise that extend over a larger frequency range (white frequency noise), they require very high locking bandwidth to achieve a lock with the desired beat note purity.. In theory, a locking bandwidth of 12.5 GHz would probably be required!

5.4 Using a semiconductor laser with an external linewidth narrowing system.

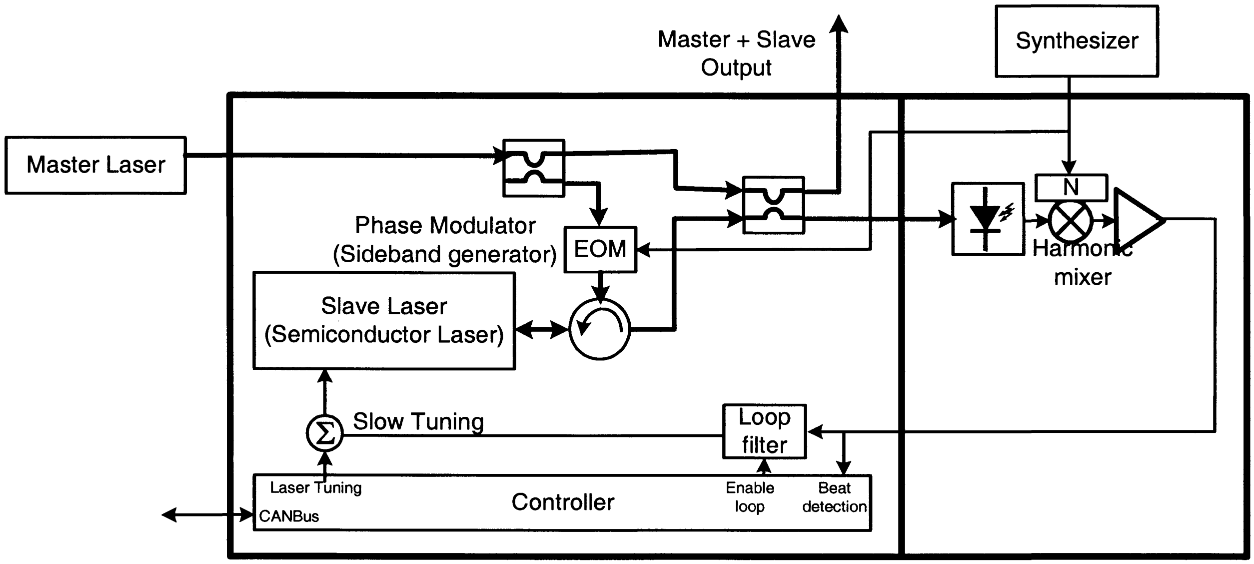
DiCOS is pursuing the development of a frequency noise reduction technology for semiconductor lasers, which allows for a dramatic reduction of their linewidth and a greater coherence length. This technique uses a few meters of optical fiber as a delay line to evaluate the frequency fluctuations on a short-term basis. An electrical signal is then returned to the laser to correct them. No optical cavity is formed, which eliminates the optical alignments, mechanical stability and mode-hopping problems. This is an all-fiber design. The linewidth reduction system is very simple and does not require more than an optical coupler, a photodetector and some simple control electronics, in addition to the polarization-maintaining fiber. This system is illustrated in the following figure:



DiCOS has made some simulations that show the effect of frequency noise reduction on the laser coherence. It is easy to see that the frequency noise reduction system brings the total phase noise of the laser down enough to cause the coherence to stay above 50%, no matter which propagation length! Without this noise reduction technique, the coherence would be almost zero after a 1 km propagation delay (~3 μs). In practice, the slow frequency fluctuations of the optical delay line will create low frequency noise that will cause the coherence of the laser to disappear over very long distances (thousands of km), unless additional absolute frequency stabilization is added to the laser. Note that a 50% coherence corresponds to a total phase noise of 1.4 rad^2.

5.5 Using an optical injection locked semiconductor laser as Slave Laser

Another simple way to achieve a high laser frequency-locking bandwidth is to injection-lock the slave laser to a sideband of an optical spectrum generated by phase-modulating the Master Laser. The frequency offset between the Master and Slave laser can be tuned by changing the modulation frequency and by selecting which sideband the Slave Laser is lock to. The following figure gives a schematic view of the system.

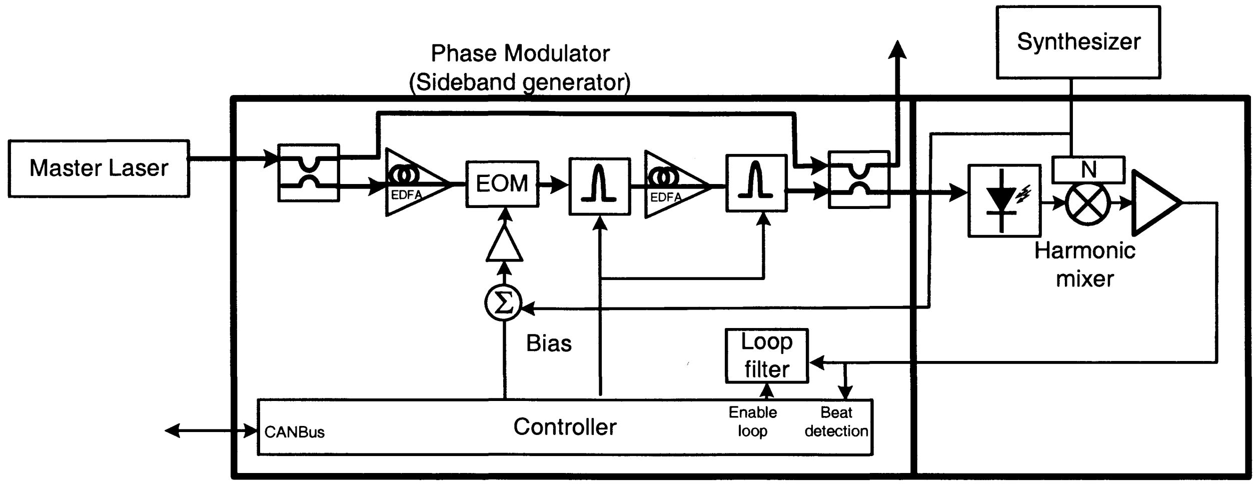


Injection locking still leaves a phase ambiguity caused by the natural frequency drift of the Slave Laser relative to the Master laser. An electrical phase locked loop is still necessary to perform slow correction on the Slave Laser nominal frequency in order to eliminate that drift. This correction is made relatively fast through the injection current. As for the actual design, the external locking loop operates from the beat note of the signal taken after the final coupling of the Master and Slave signals.

The very high effective locking bandwidth achieved by optical injection may yield beat note phase noise levels better than the targeted value, therefore leaving more margin for other phase drift effects coming from other parts of the Photonic LO system.

5.6 Using generation of sidebands and spectral selection

The optical injection-locked laser uses essentially the laser as an amplifier. Starting from this concept, it might be possible to generate the offset carrier by directly selecting and amplifying one optical sideband issued from the phase modulator. The following figure illustrated the system.



This approach has the advantage that there is no fast locking loop. The phase noise of the sideband is determined only by the phase noise of the driving oscillator. A slow locking loop might still be necessary to compensate the slow delay variation in the optical components and in fibers. The technical challenge of this approach is to generate a sideband with sufficient power using standard, off-the-shelf telecommunication components.

5.7 Using a dual frequency laser

It is possible to generate two highly correlated laser signals using the same gain medium. In that case, the optical feedback structure has to be resonant for at least two modes and the gain has to be sufficient to reach the oscillation condition for each mode. If more than two modes are to reach oscillation, a filter must be added to bring their gain down, below oscillation threshold. The stimulated emission and the feedback structure being the same for the two modes, their phase noises are highly correlated. So when a beat note is generated, the RF spectrum is of very high purity.

The mode selection can be accomplished a Fabry-Perot type structure. The issues are essentially the independent control of the nominal frequency and the offset frequency.

6 DiCOS Proposal

Preliminary results show that the actual Laser Synthesizer design yields to the required residual phase noise system requirements but needs some improvements mostly in terms of reliability. Since most of the concerns with this design are associated with the DFB fiber laser used in the Calibrated Tunable Narrow Linewidth Laser (CTNLL), solutions are considered to improve or replace this laser. The previous sections have enumerated other laser solutions worthy of a serious analysis.

DiCOS also believes that the approach using a frequency-modulated Master Laser with some means to filter out one sideband mode and generating the millimeter wave signal by beating this selected mode with the Master Laser signal is worthy of a thorough analysis. The side mode selection can be done by injecting a semiconductor laser or by a direct selection with a narrow filter and amplification. Each method offers a simplified architecture using only Telcordia qualified optical components and a broad optical phase-locking loop bandwidth. Since both system architectures are very much similar, their relative merits could then be compared very easily without having to change much of the system.

DiCOS proposes:
To supply NRAO with a First LO Reference Test Module that will fulfill the requirements of the SOW dated 2005-01-19, numbered BEND-56.02.00.00.006-A-SPE, and will also be a prototype for the ALMA system ready Laser Synthesizer. To do so, DiCOS proposes to accomplish the following work:

Phase 1: To complete the analysis study already undertaken and summarized herein, taking into account the availability of Telcordia qualified components and the requirements of the overall ALMA system;
Phase 2: To run experimental tests on selected solutions in order to better evaluate their potential and to select, in collaboration with NRAO, the most promising design solution;
Phase 3: To build, characterize and deliver to NRAO two (2) First LO Reference Synthesizer Test Modules .

7 DELIVERABLES

The deliverables within this proposal are:
Phase 1: A report on the analysis study of possible solutions for the improvement of the ALMA Laser Synthesizer design.
Phase 2: A presentation to NRAO on the results obtained form experimental tests on selected solutions
Phase 3: Delivery of two (2) First LO Reference Synthesizer Test Modules with a report on the characterization of their performances.

8 SCHEDULE

Phase 1, Analysis study: Month #1
Phase 2, Tests on selected solutions: Month #2, #3 and #4
Phase 3, Realization and characterization of two (2) First LO reference Test Set units: Month #5, #6, #7 and #8.

9 BUDGET

To be discussed

The equipment needed to characterize some performances of the millimeter wave signal generated might be very expensive. A special arrangement will have to be negotiated with NRAO to reduce the cost for this part of the project to a minimum.