Subject:	Date:	From:
Future Potential for the MZM Laser Synthesizer Development	October 27, 2011 DK007_2011	Derek Kubo
To:	**cc:**	**Location/Phone:**
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References: ALMA_sub_project_status_and_new_initiatives.doc MZM_LS_development 2011feb11a.ppt

1. Introduction

ASIAA's involvement with the MZM Laser Synthesizer began from a collaboration[1] effort with NAOJ in 2008. Hitoshi Kiuchi of NAOJ had developed a prototype MZM Laser Synthesizer along with an associated Line Length Corrector. This prototype system was successfully demonstrated at the ALMA-NA facility in Charlottesville and was shown to provide significantly better phase noise performance over the baseline unit manufactured by TeraXion, Inc. During this time, the baseline unit was encountering technical difficulties meeting phase noise requirements, and as a result the ALMA management made the decision to pursue an Alternate Laser Synthesizer (ALS) based on the MZM approach to reduce the program risk.

ASIAA's initial role in the collaboration during the 2008 timeframe was to identify a suitable manufacture in Taiwan to engineer and manufacture the MZM Laser Synthesizer for potential insertion into the ALMA Central LO system. ASIAA approached a number of manufactures in Taiwan without success. The actual task was oriented toward design and development and was deemed out-of-scope for most manufacturing facilities. In January 2009, Ming-Tang and myself met with Hitoshi Kiuchi at NAOJ to discuss the technical details of the development and resulted in the ASIAA Hawaii office subsequently taking on this task. Figures 1 – 3 describe the physical end product as of August 2010.

***Figure 1 Oblique view of completed MZM Laser Synthesizer, July 2010**. Chassis is rack mountable, 19 x 22 x 8.75 inches, fully EMI compliant, total weight of 42 pounds (19 kg) with covers installed.*

[1] Nagayoshi Ohashi of ASIAA instigated the initial collaboration with NAOJ.

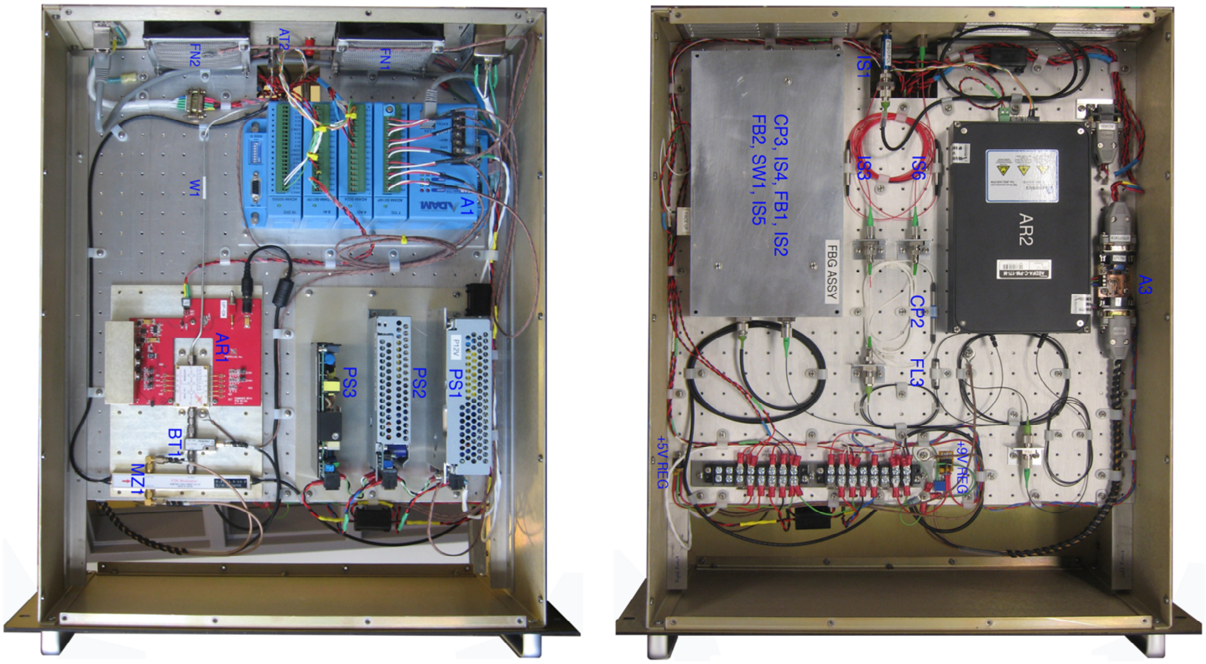

Figure 2 Bottom and top chassis views. *Left – bottom view with DC power supplies, Centellax RF power amplifier (AR1), Sumitomo MZM device (MZ1), and ADAM controller (A1). Note intake fans at rear (FN1, FN2). Right – top view with FBG assembly, EDFA (AR2), optical band-pass filter (FL3), and DC power bus.*

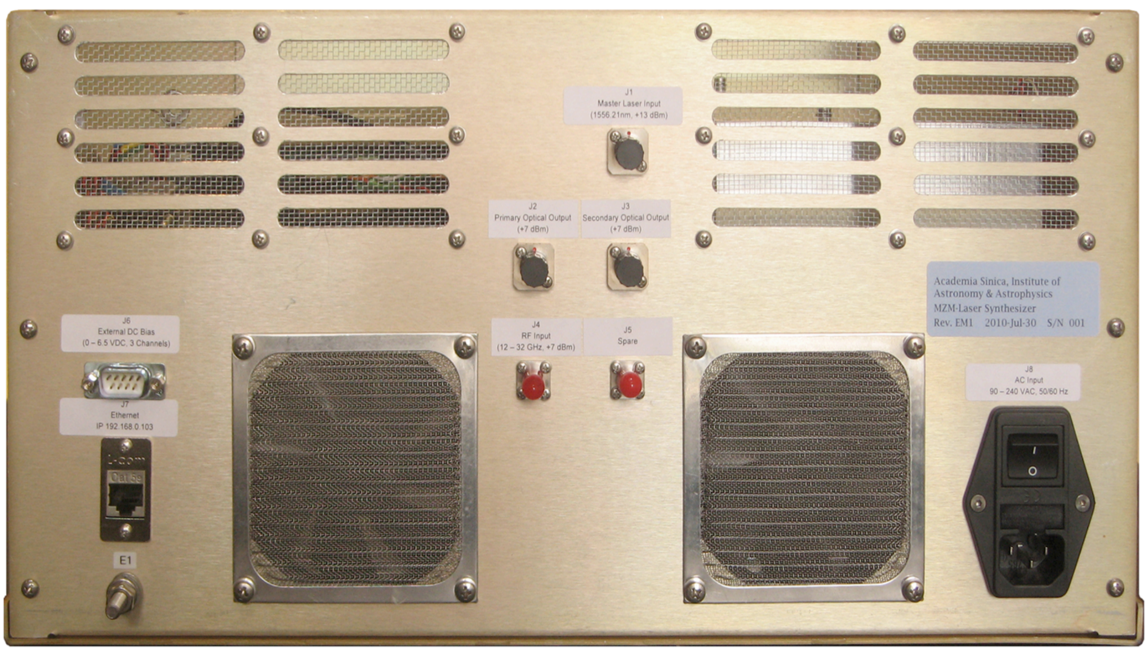

Figure 3 Rear panel. *All inputs and outputs are via the rear panel. Note the intake air is drawn though the 2 fans located below the fixed deck and exhausts through vents on the upper deck.*

2. Technical Description and Performance

A simplified block diagram of the unit is provided in *Figure 4*. A pure optical tone at 1556.21 nm is provided to the unit input via J1, which is modulated by the MZM device to generate a pair of optical tones spaced apart by either $2xRF_{in}$ (null bias mode) or $4xRF_{in}$ (full bias mode), where RF_{in} is the J5 RF reference input. Null bias mode is used to support bands 1 and 5 where the reference frequencies to the Warm Cartridge Assemblies (WCA) range from 27 to 34 GHz. The term "null bias" is used to describe cancelling or nulling of the optical carrier within the MZM device. Full bias mode is used for the remaining bands to cover 65 to 122 GHz, however, in this case the carrier is not suppressed within the MZM and requires removal with the use of Fiber Bragg Grating (FBG) filters. Applying an appropriate set of DC biases to the MZM ports from the ADAM controller determines the mode. Because the entire process is lossy an EDFA is used to boost the optical signal back to useable levels. An optical band-pass filter is used to remove out-of-band optical noise generated by the EDFA.

Figure 5 describes the typical output spectral performance at 100 GHz. The center and right plots were taken at the output of an NTT photomixer which represents an aggregate performance of 1.1 degrees RMS (3 kHz – 3 MHz)[2] and includes contributions from the RF input reference and MZM Laser Synthesizer. The residual contribution from the MZM Laser Synthesizer was calculated to be 0.4 degrees, or 11 fsec at 100 GHz, well under the unit specification limit of 27 fsec (1 kHz to 1 MHz). It is informative to note that though the NAOJ prototype and ASIAA engineering model utilized different components (Sumitomo MZM stayed the same) along with a slightly different architecture, the end result in terms of phase noise was nearly identical.

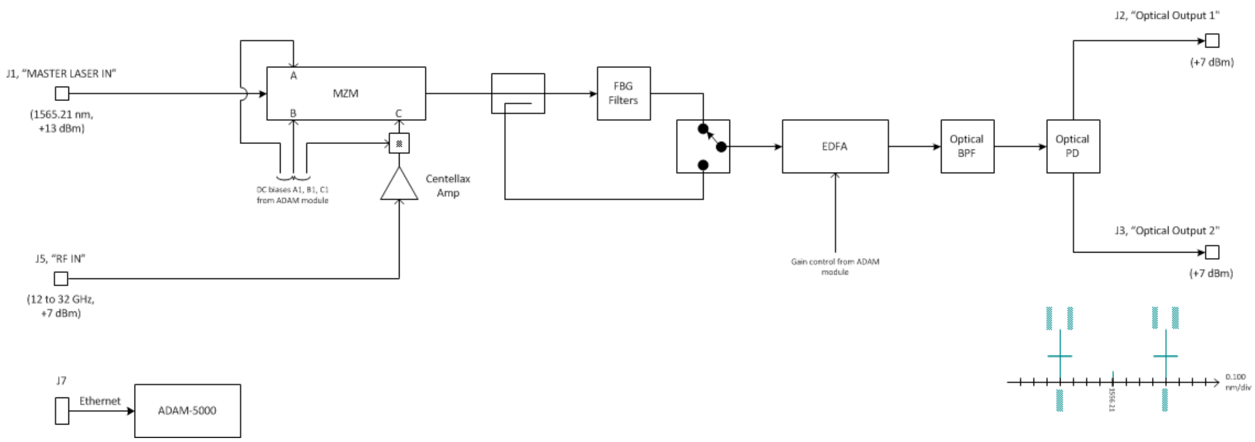

Figure 4 Simplified block diagram MZM Laser Synthesizer. *The key custom devices are the Sumitomo Mach-Zehnder Modulator (MZM), Centellax RF power amplifier, Avensys Fiber Bragg Grating (FBG) filters, and Ebrium Doped Fiber Amplifier (EDFA).*

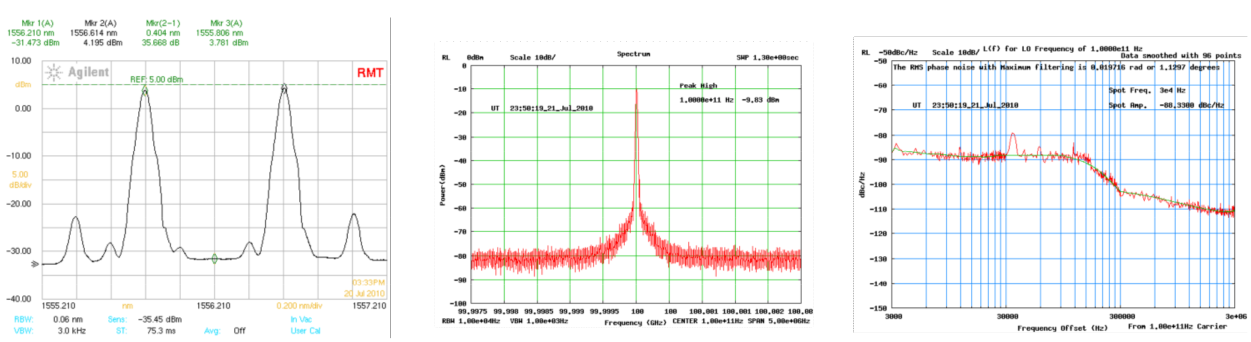

Figure 5 Output spectrum at 100 GHz. *Left – optical output spectrum. Center – 100 GHz RF spectrum as seen at a photomixer output. Right – phase noise plot of 100 GHz RF output spectrum, 1.1 degrees RMS (3 kHz – 3 MHz).*

[2] Integration bandwidth of test equipment was limited from 3 kHz to 3 MHz (could not do 1 kHz to 1 MHz).

3. Personnel

The MZM Laser Synthesizer development consisted of the following individuals:

Hitoshi Kiuchi, hardware engineer, NAOJ. Developed the original MZM Laser Synthesizer prototype and associated dual differencing Line Length Corrector. Kiuchi-san served as a technical consultant to ASIAA during the development, test and delivery phases of the project.

Ranjani Srinivasan, software developer, ASIAA Hawaii. Developed the software associated to the MZM Laser Synthesizer, which includes the monitor/control software, calibration software, and a large suite of custom test software. She also performed a large fraction of the hardware tests.

Johnson Han, hardware engineer, ASIAA Hawaii. Lead engineer for MZM-LORTM (described in Section 9).

John Pascual, technician, ASIAA Hawaii. Assisted with metal fabrication for the chassis.

Derek Kubo, hardware engineer, ASIAA Hawaii. Lead engineer for MZM Laser Synthesizer. Developed the electrical, optical, mechanical, and thermal design for the unit. Performed unit assembly and test.

Ming-Tang Chen, deputy director, ASIAA Hawaii. Project manager for MZM Laser Synthesizer.

4. Position in International Field

Though it is difficult to say for certain, it is my belief that there are not many competitors in this field of optical LO generation. The original photonics approach for generating a millimeter or sub-millimeter wave LO was to beat a pair of phase locked lasers against each other to produce a desired difference frequency. This is the approach taken by NRAO-NA and eventually culminated in the baseline Laser Synthesizer manufactured by TeraXion, Inc, of Montreal, Quebec.

A second approach involved the development of the Lithium Niobate Mach-Zehnder Modulator. Increasing data transmission rates for the long haul fiber communications industry drove this technology. The first publicized instance that I'm aware of utilizing this MZM technology for LO generation was by SAO of Cambridge, Massachusetts, in March 2002[3]. SAO has since developed some rudimentary hardware and has even performed some interferometric observations utilizing the SMA telescope in Hawaii.

The following is my list of organizations in terms of MZM Laser Synthesizer expertise in descending order: NAOJ, ASIAA, SAO, and DAS Photonics[4]. At present, we are dependent on NAOJ to act as a go between for the custom MZM device manufactured by Sumitomo Osaka Cement. The technology contained within the MZM device is considered very proprietary. It should be mentioned that the original approach taken on by TeraXion was extremely ambitious and required a non-trivial amount of NRE resources. TeraXion specializes in the development of optical systems from the ground up and would be very competitive should they desire to enter this market[5]. TeraXion manufactured a number of custom components used within the MZM LORTM.

5. Readiness for ALMA Implementation

The primary goal for the MZM Laser Synthesizer engineering model was to produce a unit that could be used to demonstrate its performance and compatibility with the existing Central LO system. In terms of this goal, we were successful in that we discovered a glaring incompatibility with the baseline Line Length Corrector in fast frequency switching mode. Fast frequency switching is a mode where the observing band and LO reference frequency are changed back and forth in intervals as often as 10 seconds for calibration purposes. Calibration is typically performed using band 3 on an astronomical calibrator. *Figure 6* exemplifies the difference between the output spectrums of the baseline TeraXion vs. the MZM Laser Synthesizers. The baseline Line Length Corrector operates by measuring the phase difference between the transmitted and reflected master laser round trip phase to and from the antenna. An FBG filter is used to remove the slave laser prior to phase comparison. A mechanical fiber line stretcher is used to keep the phase difference at a fixed minimal value. For the baseline Laser Synthesizer, the master laser reference is always present at a fixed wavelength of 1556.21 nm. For the MZM Laser Synthesizer the LSB is used for phase comparison (same FBG filter is used to remove the USB), however, each time an LO frequency change is elicited the LSB wavelength changes. Since the round trip phase through the fiber is a function

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[3] Thirteenth International Symposium on Space Terahertz Technology, Harvard University, March 2002.
[4] DAS Photonics located in Valencia, Spain, provided EU-FEIC with their version of the MZM-LORTM.
[5] TeraXion was approached by NAOJ and NRAO to develop the MZM Laser Synthesizer prior to ASIAA's involvement in 2008. They are aware that we have taken on this effort.

of wavelength, each time the frequency changes there is a step function change in the round trip phase. This abrupt phase change causes the Line Length Corrector fringe counter to lose lock.

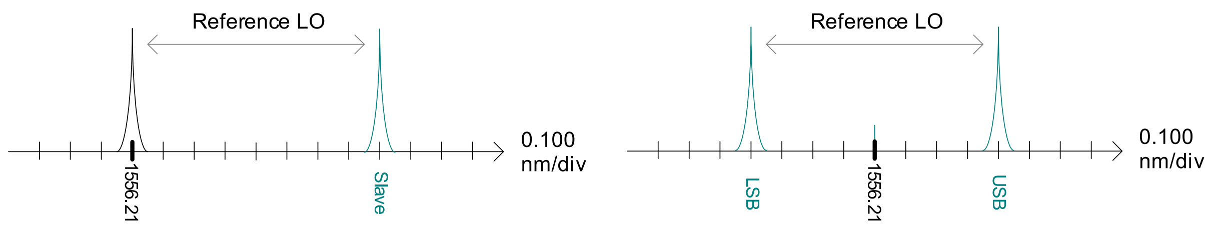

***Figure 6 Comparison of Baseline vs MZM Spectrums**. Left – optical output spectrum of TeraXion, left master laser tone is fixed, right slave laser varies in wavelength. Right – optical output spectrum of MZM Laser Synthesizer, both LSB and USB tones move.*

Two possible solutions have been suggested by NRAO-NA:

a) Re-inject the 1556.21 nm master laser into the signal stream after the MZM Laser Synthesizer resulting in 3 optical tones being sent to the antennas. All 3 tones will be reflected back to the source from the antenna (via Faraday rotator mirror). A new set of extremely tightly specified FBG filters will be required within each Line Length Corrector to remove the 2 undesired LSB and USB tones. Preliminary tests conducted on a limited set of WCAs have indicated that the introduction of the third tone does not affect lock reliability or phase noise.

b) Offset the reference laser to the MZM Laser Synthesizer by several 10's of nanometers such that the LSB and USB are located relatively far away from 1556.21 nm (will require re-specifying filters within the MZM unit). Re-inject the 1556.21 nm master laser into the signal stream after the MZM unit. Install a set of FBG filters within the antennas to prevent the 1556.21 nm tone from reaching the WCAs. Allow all 3 tones to be reflected back to the source from the antenna. A set of loosely specified FBG filters will be required within each Line Length Corrector to remove the 2 undesired LSB and USB tones.

In addition to the issue with the Line Length corrector above, there are two other known items that need to be addressed prior to insertion into the Central LO system. The first of these two is associated to remote control and status of the unit. The MZM Laser Synthesizer is currently controlled via Ethernet, however, the default communication protocol for ALMA is CAN-bus. We would need to change the communication protocol to CAN-bus. Furthermore, the MZM Laser Synthesizer internal functions (MZM DC biases, EDFA gain, mode switch position) are currently controlled from a Linux PC located outside of the unit. The ALMA Central LO system desires to send only simple frequency commands over CAN-bus to the MZM Laser Synthesizer. As a result we would need to add a microcontroller within the unit to allow it to operate standalone without an external Linux PC. The second item is in regards to the MZM Laser Synthesizer mechanical package. Though the outer dimensions of the baseline TeraXion and the MZM Laser Synthesizers are identical, the MZM does not provide a vertical path for air to flow through the chassis. If the MZM Laser Synthesizer ever gets implemented into the Central LO system, ALMA may request that we repackage to comply with this flow through chassis design.

What are the chances that the MZM Laser Synthesizer will be implemented into the Central LO system? It has been shown that the phase noise performance of the MZM Laser Synthesizer is approximately a factor of two better than the baseline TeraXion unit which is operating just under the specification margin. However, due to the contributions of other phase noise sources, preliminary calculations have shown that the overall coherence improvement will be only 7% at 950 GHz, and less at all other frequencies. In my opinion, it would be prudent to stay with the current system for the next 2 or 3 years until all of the hardware has stabilized and been well characterized. In the meantime we could propose to take the MZM Laser Synthesizer to Chile to characterize the actual coherence improvement over the baseline system (comparison will have to be performed without fast frequency switching). Is the coherence improvement better or worse than calculated? If it is significantly better than calculated then one could make an argument that the cost and effort to upgrade the system would pay for itself in increased observing efficiency.

6. Future Potential

Outside of possibly performing a test in Chile, we have no definitive plans for continuing the MZM Laser Synthesizer project as of this writing.

7. New Initiatives

We have had some discussions of possibly applying the MZM Laser Synthesizer technology to the SMA and VLBI projects. The SMA uses a conventional RF derived system to generate LOs for its 200, 300, 400, and 600 GHz receiver bands. It was eventually determined that phase noise of the existing system was sufficiently low for its primary observing bands of 200 and 300 GHz and does not warrant any improvement. One area that the SMA could benefit from is a Line Length Corrector that could compensate for the non-deterministic LO phase movements associated to azimuth movements of the antenna. However, it is believed that a Line Length Corrector could be developed for the existing SMA system without the use of the MZM Laser Synthesizer.

ASIAA is currently working on a 12 meter VLBI telescope that may be fielded in Greenland. The MZM Laser Synthesizer fits in well for this application because it will allow use of existing ALMA LO hardware.

Finally, in addition to the MZM Laser Synthesizer, we have also developed an MZM LORTM that is currently in use at EA-FEIC to test ALMA front-ends. The MZM LORTM generates a pair of phase coherent LO tones at different frequencies that could be used for single dish holography. One tone would go to the holography LO emitter (e.g., 106 GHz) and the other to the receiver LO (e.g., 100 GHz), both via arbitrary lengths of optical fibers. A difference of 6 GHz would exit the receiver and would be phase coherent with the original 3 GHz reference fed to the MZM LORTM.

8. Publications

We are currently working on an IEEE paper for the MZM Laser Synthesizer and plan to submit it toward the end of 2011. Thereafter we plan to generate a companion IEEE paper describing the MZM LORTM.

9. Related Work on MZM LORTM

The MZM-LORTM instrument was developed to support the 2nd test line at EA-FEIC. The goal for this instrument was to replicate the performance of the existing baseline LORTM developed by TeraXion. Though the required absolute phase noise requirement for this unit was not as stringent as the MZM Laser Synthesizer, the complexity for this unit was nearly a factor of two over the MZM Laser Synthesizer. *Figures 7 – 9* describe the physical end product as delivered to EA-FEIC in July of 2011. The MZM LORTM unit functions to generate 3 optical tones denoted as LSB1, LSB2, and USB (LSB = Lower Side Band, USB = Upper Side Band). A simplified functional block diagram is described in *Figure 10*. Refer to the spectral plot shown in the upper right of *Figure 10*, and actual measured spectral plots shown in *Figure 11*.

As with the MZM Laser Synthesizer unit, the assembly for the MZM LORTM unit was performed in the ASIAA office facility in Hilo. The assembly of the LORTM was an iterative process of trying out a physical configuration then measuring the resultant phase stability between the reference signal and test signal. The unit was shipped to the Taichung EA-FEIC facility in July of 2011 where a battery of acceptance tests was performed over a 3-week period. A phase stability plot between 100 and 106 GHz tones over a period of 100 minutes is shown in *Figure 12*. Note the 0.5 degree peak-to-peak phase stability and corresponding Allan deviation performances.

Figure 7 Oblique view of completed MZM LORTM, July 2011*. The physical dimensions of this unit, including the front panel rack mounting holes, are identical to the baseline TeraXion LORTM unit. Note the air exhaust vents located toward the bottom of the front panel.*

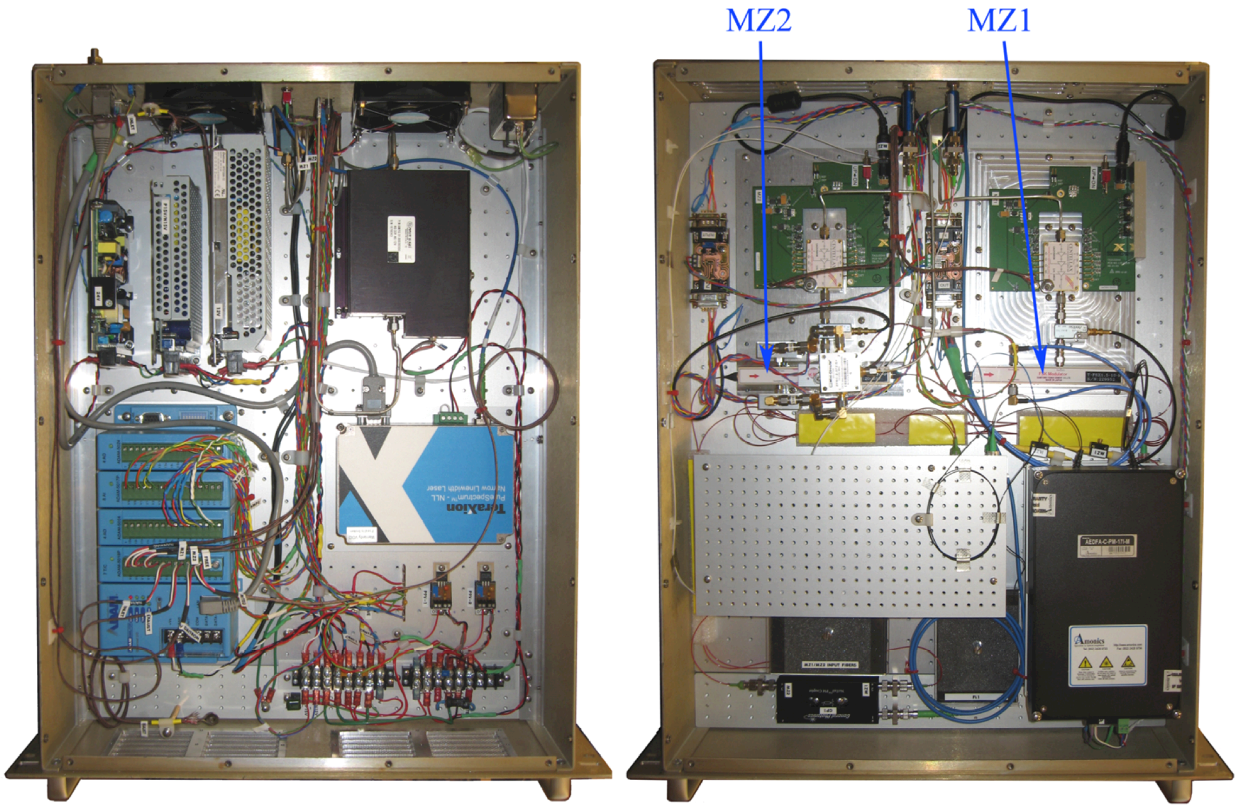

Figure 8 Bottom and top chassis views. *Left – bottom view of the lower deck with DC power supplies, Miteq IF power amplifier (black box upper right), TeraXion laser, ADAM controller, DC power bus, and 2 intake fans on the rear panel. Right – top view of upper deck containing all of the optical components (minus the laser). Note the higher packaging density of this unit as compared to the MZM Laser Synthesizer.*

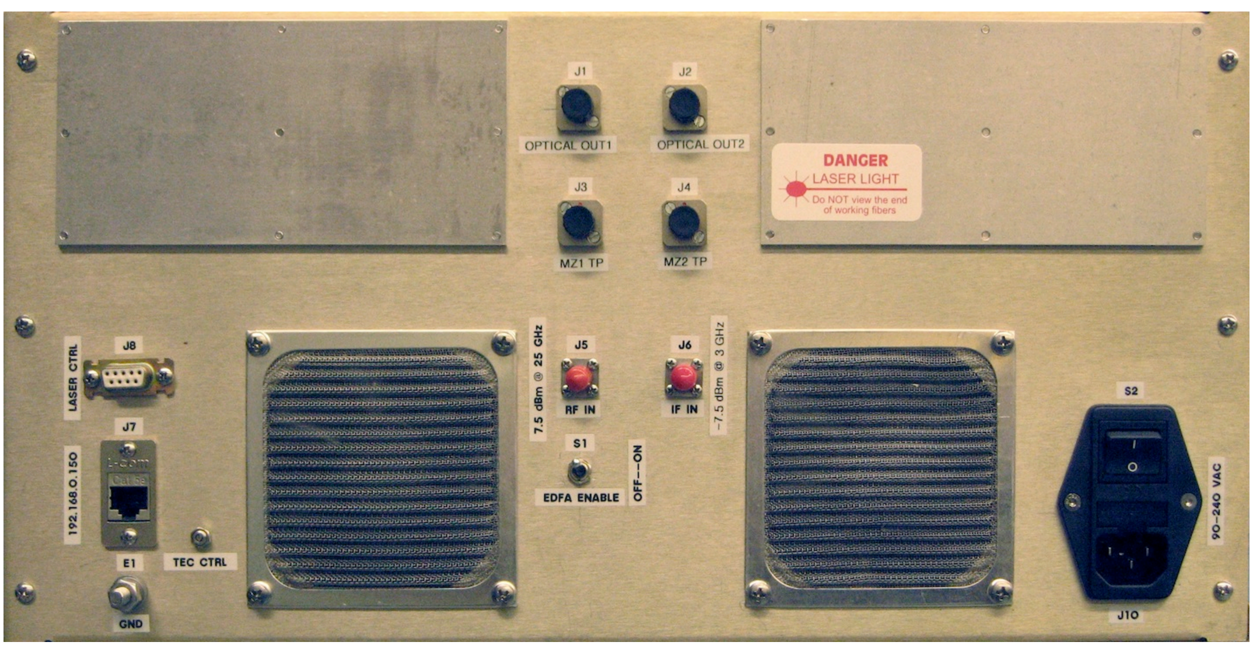

Figure 9 Rear panel. *All inputs and outputs are via the rear panel. Note the blocked exhaust air vents at the top to keep the upper deck isolated from the ambient air temperature variations. Only the lower deck is convection cooled and critical elements from the upper deck are conduction cooled through the aluminum deck plate.*

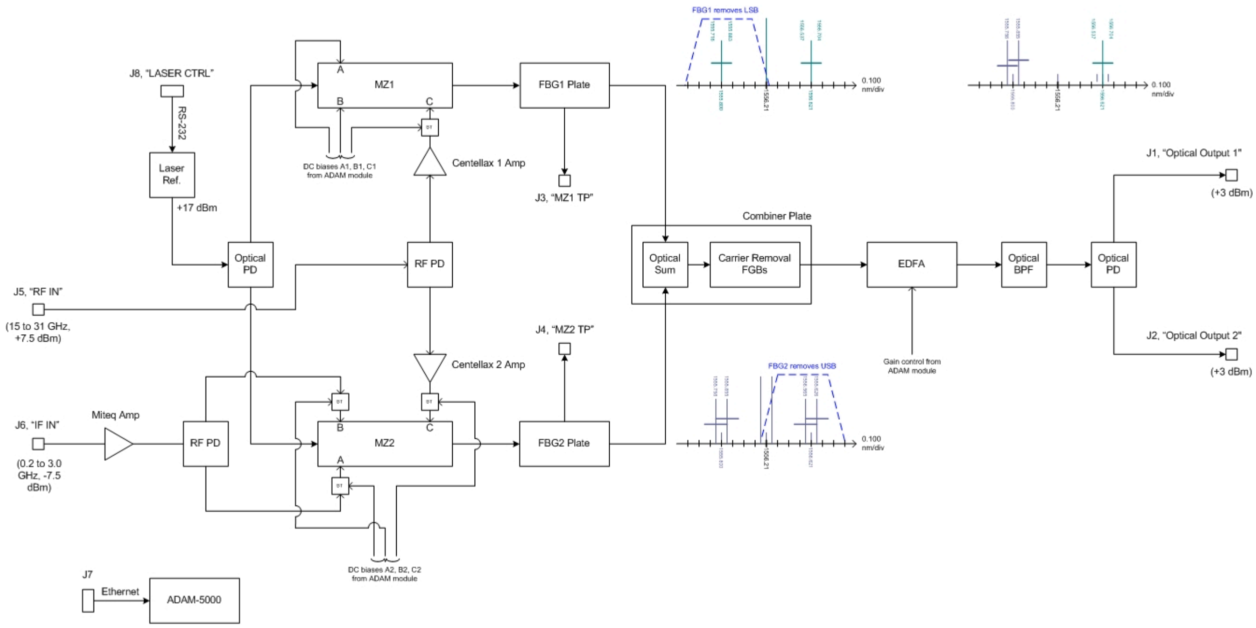

Figure 10 Simplified block diagram of MZM LORTM*.* *This design employs two MZM devices to separately produce two LSB and one USB optical tones. Note the significant increase in complexity over the MZM Laser Synthesizer unit. As we discovered later, mechanical package to maintain constant thermal temperatures of the optical components was very critical to the phase stability performance of the unit. Hence the partitioning and isolation of the optical components from the ambient air.*

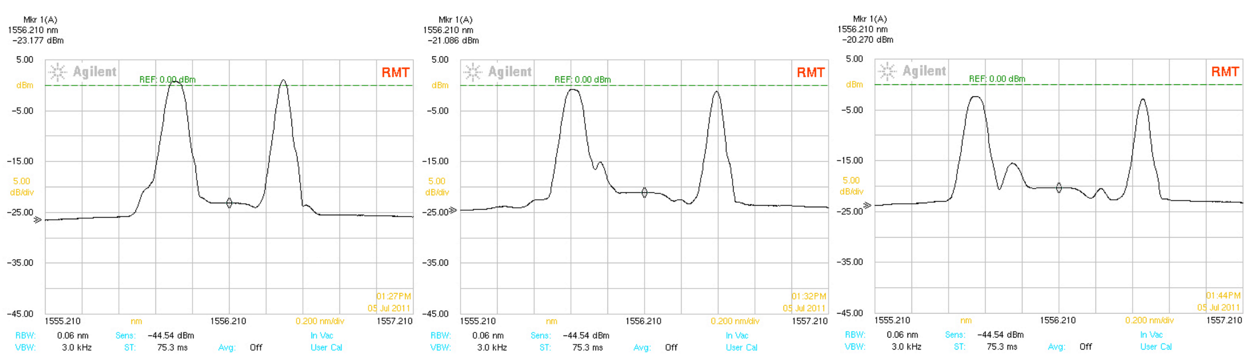

Figure 11 Typical optical output spectrum from MZM LORTM*.* *Left Reference 1 = 18 GHz (69/75 GHz photomixer output), center Reference 1 = 24 GHz (93/99 GHz), right Reference 1 = 30 GHz (117/123 GHz). Note the LSB on the OSA actually consists of 2 tones (LSB1 & LSB2) but is not visible due to limited resolution bandwidth. For all examples above Reference 2 = 3.0 GHz.*

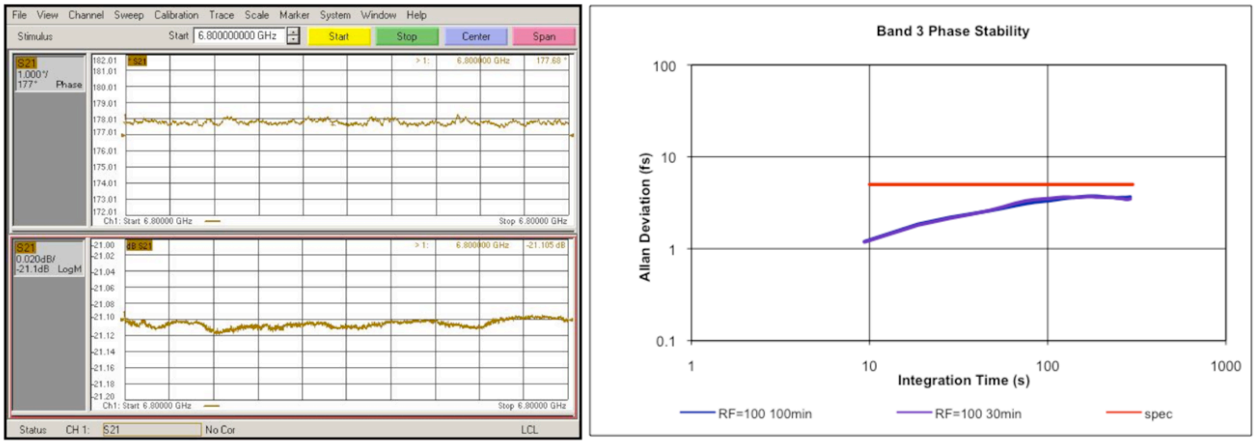

Figure 12 Phase stability with band 3/7 BeaSTS test plate. *100/106 GHz, 0 degree tilt table angle. Left plot – note the small 0.5 degree peak-to-peak phase fluctuation over the 100 minute test run. Right plot – Allan deviation performance exhibiting 1.5 and 3.1 fsec for 10 and 300 seconds, respectively.*