# Advanced CORFM Final Report

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Figure 1. Advanced CORFM - Microwave and Control Module

Figure 2. Advanced CORFM - Optical and Power Module

**The Advanced CORFM is a programmable fiber-optic delay line providing delays from 0 to 166.912 usecs in 1024 nsec steps at X-band. Path switch times are less than 100 nsecs.** Figure 1 shows the module holding all microwave and digital electronics along with three 200 mwatt, 1319 nm diode-pumped Nd-YAG lasers. Figure 2 top shows the module holding optical fiber spools and Figure 2 bottom shows the power module based on Power-One linear power supplies. In order to minimize noise, all power systems are linear and internal clocks for all switching control and bias circuits are deactivated after each optical delay path is switched.

**The maximum input signal level is -5 dBm with output at -5.66 dBm +/- 0.41 dB across all delay paths. The worst-case SFDR is ~ 89 dB with SNR greater than 101 dB.**

This report is divided into the following sections with the brief overview given above:  Section 1 - External and Internal Pictures, Section 2 - Remote PC Control Interface Description, Section 3 - Calibration Procedure, Section 4 - Performance, Section 5 - Design Overview, and Section 6 - Future Improvements.

## Section 1 - External and Internal Pictures

Figures 3 and 4 show the right and left sides of the Microwave and Control Module.  The side panels are designed for quick removal for service and repair work.  Figure 5, with the left side panel removed, shows the microwave electronics for Segments 3 and 4 of the delay line.  Delay line segments will be discussed in Section 5.  Figure 6, with the right side panel removed, shows the microwave electronics for Segments 1 and 2 of the delay line.  Figure 7 shows a closer view of Segments 1 and 2.  Figure 8 shows a back view of the Microwave and Control Module.  A top panel (not shown) may be removed allowing access to the digital control subsystem which interfaces PC commands to segment microwave switches.

Figure 3.  Microwave and Control Module - Right Side View

Figure 4.  Microwave and Control Module - Left Side View

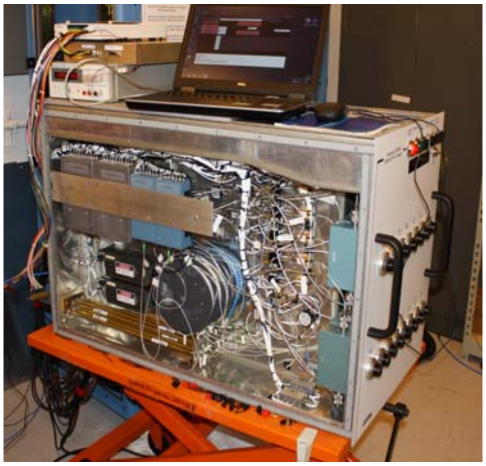
Figure 5. Microwave and Control Module - Left Inside View

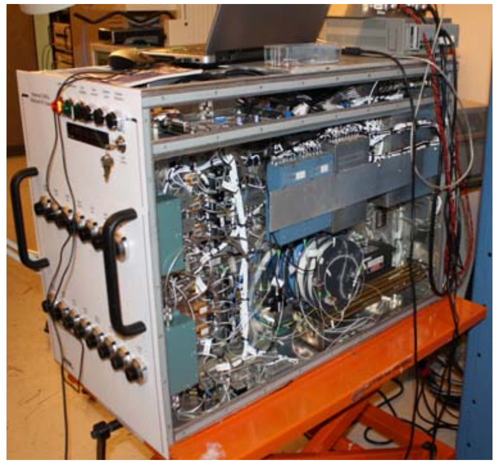
Figure 6. Microwave and Control Module - Right Inside View

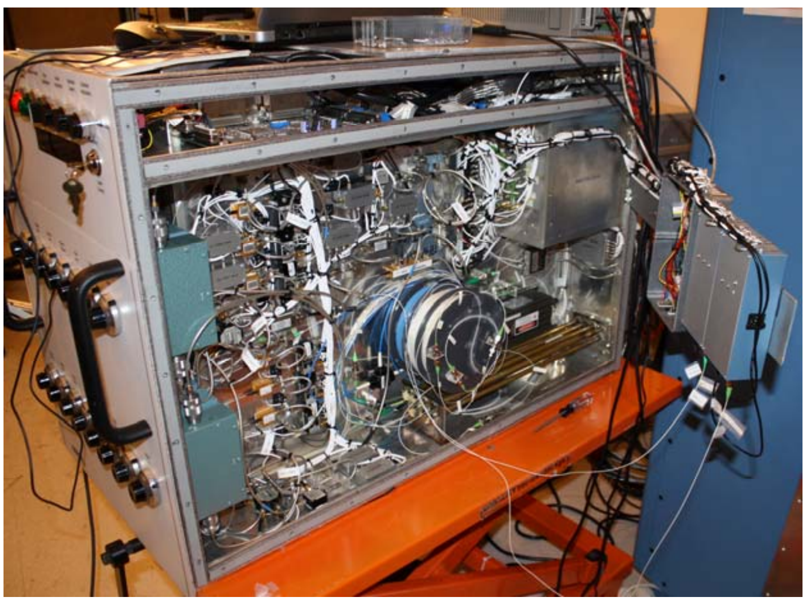
Figure 7. Microwave and Control Module - Closer View of Right Side

Figure 8. Microwave and Control Module - Back View

Figure 9 shows the back side of the Optical Module where fiber connections are made to the Microwave and Control Module. Figure 10 shows the delay line as it is being assembled into an enclosed 19" rack.

Figures 11 and 12 are views of the delay line as it was being constructed.

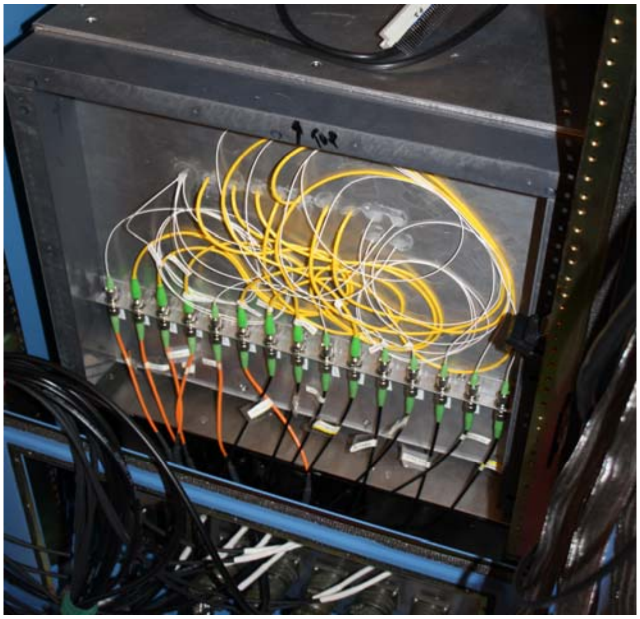

Figure 9. Optical Module - Back View

Figure 10.  Before Assembly into 19" Rack

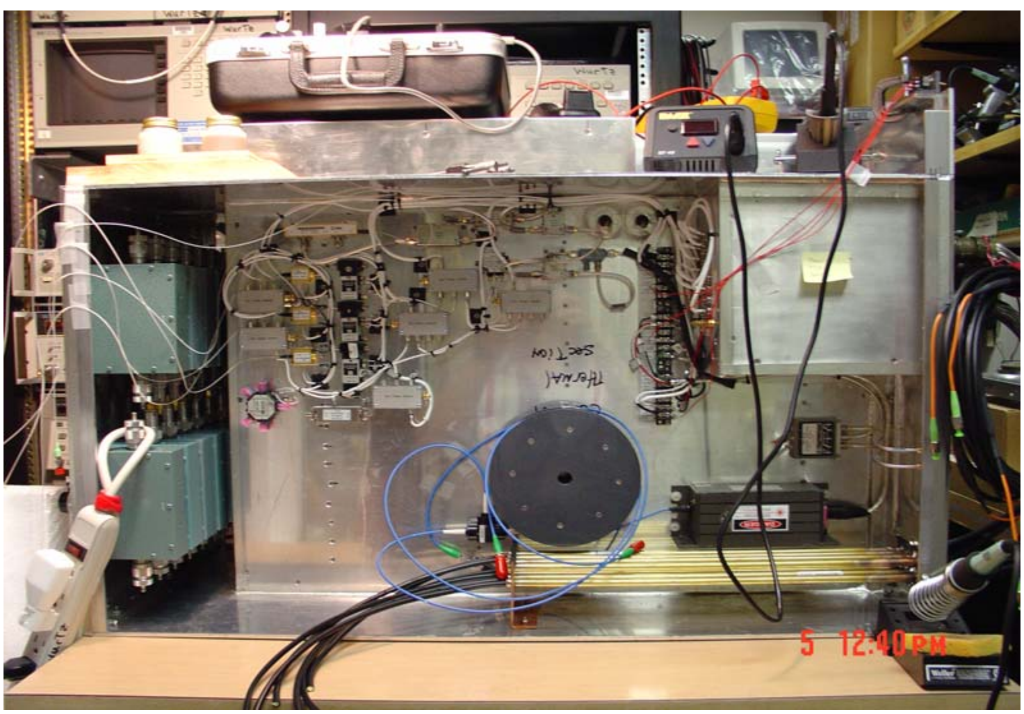

Figure 11.  Microwave and Control Module during Construction

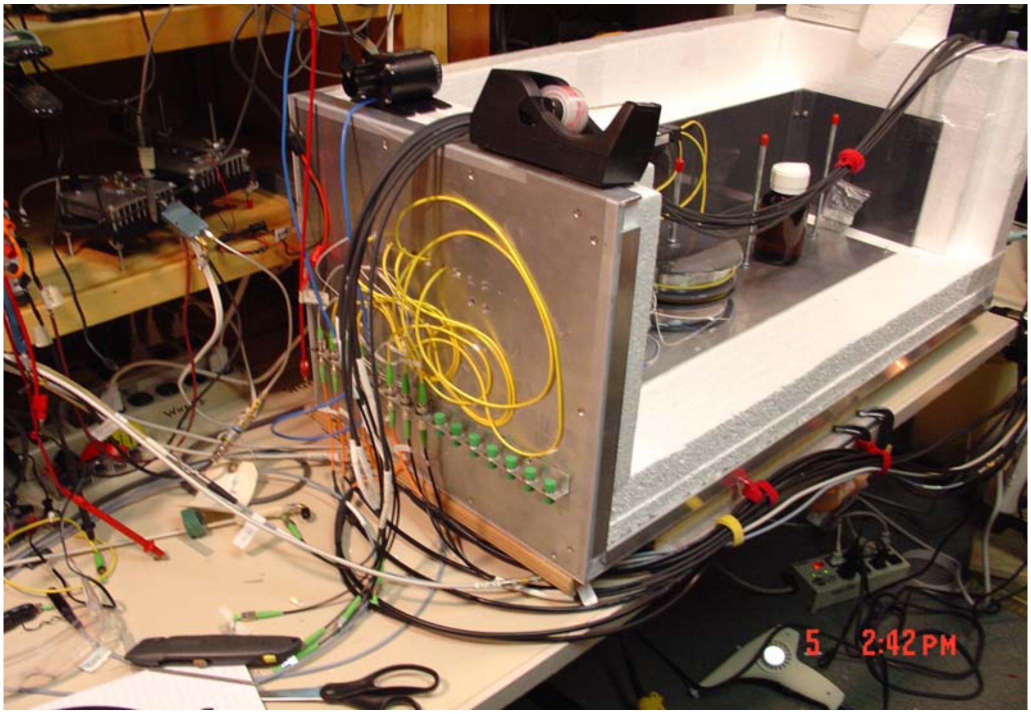

Figure 12. Optical Module during Construction

## Section 2 - Remote PC Control Interface Description

Figure 13 shows the remote PC control electrical interface for the Advanced CORFM with the software interface shown in Figure 14. The Advanced CORFM may be controlled either through its front panel or by a remote interface with connections on the back side of the Microwave and Control Module. To enable the remote PC control interface, insure the "run/calibration" knob on the Microwave and Control Module is turned in the horizontal position. The alternative "calibration" mode will be described in Section 3 below.

The delay line is also equipped with a "laser enable/disable" switch. Be sure the lasers are enabled for remote operation. The delay line also has two large LEDs: green and red. If the delay line is fully functional and in remote PC mode, the green led will turn on. The remote software interface also displays the green led status. If the red led emits, then the delay line either has problems or is in "calibration" mode.

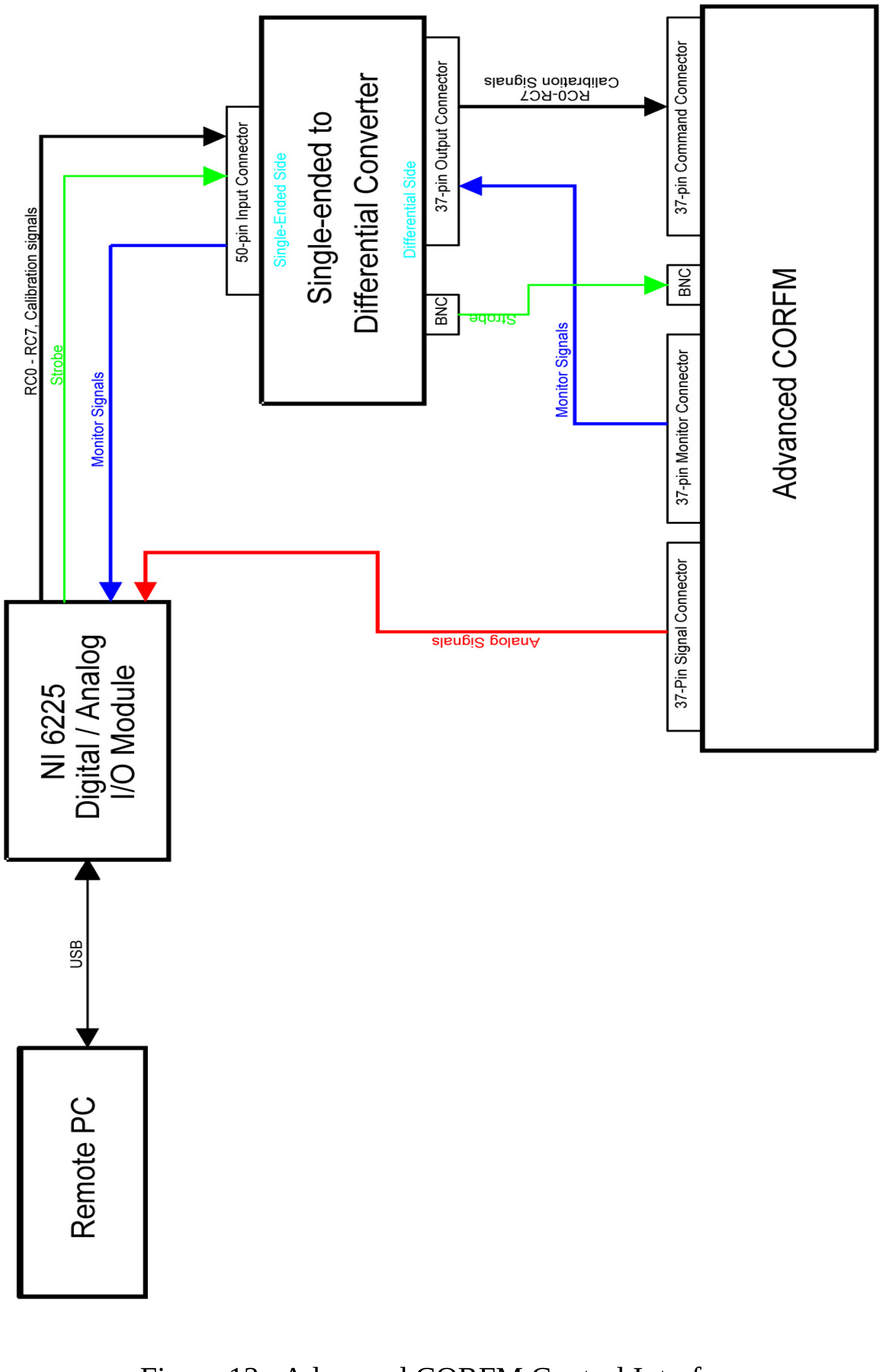


Figure 13. Advanced CORFM Control Interface

Figure 13 and Tables 1 through 4 below show and list the electrical pin assignments for the remote PC interface. For testing, the remote PC controls a National Instruments NI6225 analog/digital I/O device via USB. The NI6225 device generates and records single-ended digital and analog I/O. The single-ended signals are interfaced to the Advanced CORFM through a single-to-differential convertor with exception of analog feedback from the Advanced CORFM's 37-pin Signal Connector. Single-ended analog feedback from the Advanced CORFM interfaces directly with the NI6225 analog input ports.

Table 1 lists the 8-bit delay range, strobe, external modulator calibration, and laser power calibration single-ended signal assignments from the NI6225, through the differential convertor, to the 37-pin Command connector on the Advanced CORFM. The differential convertor generates a separate Strobe BNC interface to the Advanced CORFM as listed in Table 2.

| NI6225 USB to Digital/Analog I/O Device | Single-Ended to Differential Converter 50-pin Input Connector | Single-Ended to Differential Converter 37-pin Output Command Connector | Advanced CORFM 37-pin Command Connector |
|---|---|---|---|
| P0.0 (RC0) | Pin23 (RC0) | Pin13 (RC0+) | Pin1 (RC0+) |
| | | Pin32 (RC0-) | Pin20 (RC0-) |
| P0.1 (RC1) | Pin25 (RC1) | Pin12 (RC1+) | Pin2 (RC1+) |
| | | Pin31 (RC1-) | Pin21 (RC1-) |
| P0.2 (RC2) | Pin27 (RC2) | Pin11 (RC2+) | Pin3 (RC2+) |
| | | Pin30 (RC2-) | Pin22 (RC2-) |
| P0.3 (RC3) | Pin29 (RC3) | Pin10 (RC3+) | Pin4 (RC3+) |
| | | Pin29 (RC3-) | Pin23 (RC3-) |
| P0.4 (RC4) | Pin31 (RC4) | Pin9 (RC4+) | Pin5 (RC4+) |
| | | Pin28 (RC4-) | Pin24 (RC4-) |
| P0.5 (RC5) | Pin33 (RC5) | Pin8 (RC5+) | Pin6 (RC5+) |
| | | Pin27 (RC5-) | Pin25 (RC5-) |
| P0.6 (RC6) | Pin35 (RC6) | Pin7 (RC6+) | Pin7 (RC6+) |
| | | Pin26 (RC6-) | Pin26 (RC6-) |
| P0.7 (RC7) | Pin37 (RC7) | Pin6 (RC7+) | Pin8 (RC7+) |
| | | Pin25 (RC7-) | Pin27 (RC7-) |
| P1.1 (Ext Mod Bias cal) | Pin21 (Ext Mod Bias cal) | Pin14 (Ext Mod Bias Cal+) | Pin14 (Ext Mod Bias Cal+) - Start Cal on Rising Edge |
| | | Pin33 (Ext Mod Bias Cal-) | Pin33 (Ext Mod Bias Cal-) |
| P1.2 (Laser Optical Power Cal) | Pin19 (Laser Optical Power Cal) | Pin15 (Laser Optical Power Cal+) | Pin15 (Laser Optical Power Cal+) - Start Cal on Rising Edge |
| | | Pin34 (Laser Optical Power Cal-) | Pin34 (Laser Optical Power Cal-) |

Table 1. Interface to Advanced CORFM 37-Pin Command Connector

| NI6225 USB to Digital/Analog I/O Device | Single-Ended to Differential Converter 50-pin Input Connector | Single-Ended to Differential Converter Output BNC Connector | Advanced CORFM Strobe BNC Connector |
|---|---|---|---|
| P1.0 (Strobe) | Pin17 (Strobe) | BNC+ (Strobe+) - Inside Pin | BNC+ (Strobe+) - Inside Pin |
| | | BNC- (Strobe-) - Outside Shell | BNC- (Strobe-) - Outside Shell |

Table 2. Interface to Advanced CORFM BNC Strobe Connector

Table 3 lists the differential digital monitor signals from the Advanced CORFM's 37-pin Monitor connector back through the differential convertor to the NI6225 single-ended input. The 8-bit monitor range bus called for in the specification did not make it to the 37-pin Monitor Connector and was left unconnected. Connection will be made after initial Advanced CORFM testing.

| Advanced CORFM 37-pin Monitor Connector | Single-Ended to Differential Converter 37-pin Output Monitor Connector | Single-Ended to Differential Converter 50-pin Input Connector | NI6225 USB to Digital/Analog I/O Device |
|---|---|---|---|
| Pin11 (Monitor Cal Run Mode+) | Pin8 (Monitor Cal Run Mode+) | Pin1 (Monitor Cal Run Mode) | P2.0 (Monitor Cal Run Mode) - 1 for run mode, 0 for cal mode |
| Pin30 (Monitor Cal Run Mode-) | Pin27 (Monitor Cal Run Mode-) | | |
| Pin14 (Monitor Ext Mod Cal+) | Pin7 (Monitor Ext Mod Cal+) | Pin3 (Monitor Ext Mod Cal) | P2.1 (Monitor Ext Mod Cal) - 0 for calibration, 1 for complete |
| Pin33 (Monitor Ext Mod Cal-) | Pin26 (Monitor Ext Mod Cal-) | | |
| Pin15 (Monitor Laser Power Cal+) | Pin6 (Monitor Laser Power Cal+) | Pin5 (Monitor Laser Power Cal) | P2.2 (Monitor Laser Power Cal - 0 for calibration, 1 for complete |
| Pin34 (Monitor Laser Power Cal-) | Pin25 (Monitor Laser Power Cal-) | | |
| Pin13 (Monitor Laser Standby+) | Pin5 (Monitor Laser Standby+) | Pin7 (Monitor Laser Standby) | P2.3 (Monitor Laser Standby) - 1 for laser active, 0 for standby |
| Pin32 (Monitor Laser Standby-) | Pin24 (Monitor Laser Standby-) | | |
| Pin12 (Monitor Operational Status+) | Pin4 (Monitor Operational Status+) | Pin9 (Monitor Operational Status) | P2.4 (Monitor Operational Status) - 1 for system ready (green light)<br>0 for system not ready (red light) |
| Pin31 (Monitor Operational Status-) | Pin23 (Monitor Operational Status-) | | |
| | | Pin50 (Digital Gnd) | Pin114 (Digital Gnd) |

Table 3. Interface to Advanced CORFM 37-Pin Monitor Connector

Table 4 lists the internal signals being monitored and interfaced through the 37-pin Signal connector, namely the four external modulator dc biases and three laser power control voltages.  Additional feedback will be added in the future.  These single-ended analog signals connect directly with the NI6225 single-ended analog inputs from the 37-pin Signal Connector.

| Advanced CORFM 37-pin Signal Connector | NI6225 USB to Digital/Analog I/O Device |
|---|---|
| Pin20 (Ext Mod Bias 1, -10V to +10V) | AI57 (Ext Mod Bias 1) |
| Pin21 (Ext Mod Bias 2, -10V to +10V) | AI58 (Ext Mod Bias 2) |
| Pin22 (Ext Mod Bias 3, -10V to +10V) | AI59 (Ext Mod Bias 3) |
| Pin23 (Ext Mod Bias 4, -10V to +10V) | AI60 (Ext Mod Bias 4) |
| Pin24 (Laser 1 Control Voltage, -10V to +2V) | AI61 (Laser 1 Control Voltage) |
| Pin25 (Laser 2 Control Voltage, -10V to +2V) | AI62 (Laser 2 Control Voltage) |
| Pin26 (Laser 3 Control Voltage, -10V to +2V) | AI63 (Laser 3 Control Voltage) |
| Pin37 (Analog Gnd) | Pin88 (AI Gnd) |

Table 4. Interface to the Advanced CORFM 37-Pin Signal Connector

Figure 14 shows a C# program that was written to test the Advanced CORFM remote interface.  All monitor data is captured in an output log file with Matlab format for post processing. An example is shown in Table 5. The program controls and displays increasing or decreasing delays from 0 to 166.912 usecs, and system status (red or green), external modulator bias status and enabling, laser power calibration status and enabling, and a strip chart display of monitored signals.

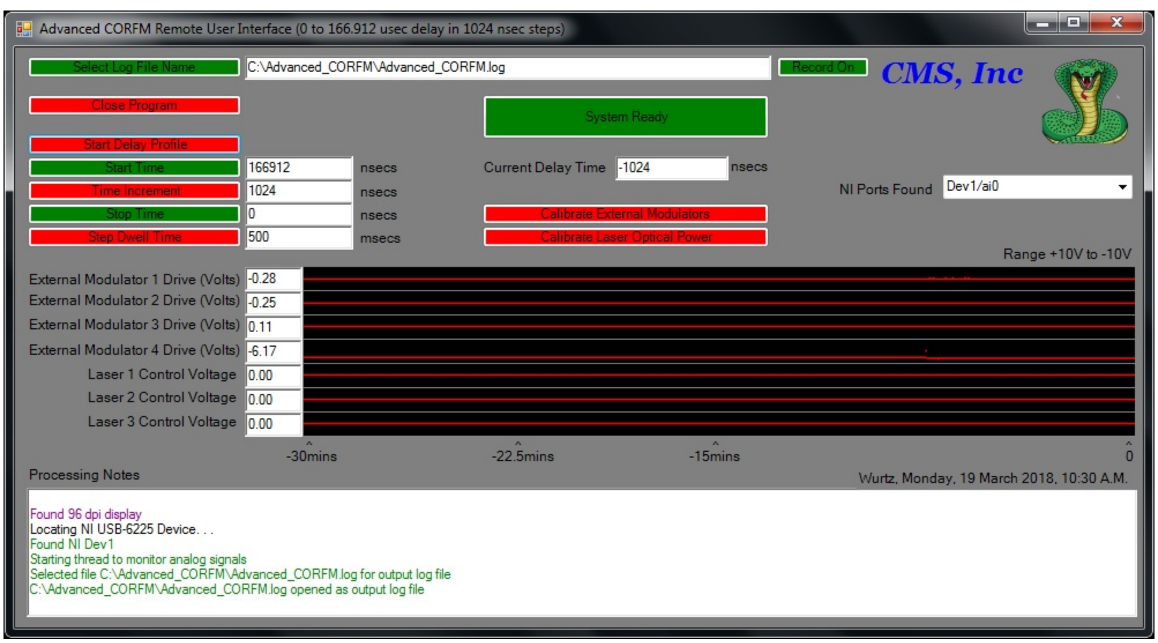

Figure 14.  Advanced CORFM Remote Software Interface

```
%DateTime   ExtMod1DCBiasVoltage   ExtMod2DCBiasVoltage
ExtMod3DCBiasVoltage   ExtMod4DCBiasVoltage   Laser1ControlVoltage
Laser2ControlVoltage   Laser3ControlVoltage
4/24/2018 4:05:16 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:17 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:18 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:19 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:20 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:21 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:22 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:23 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:24 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:25 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:26 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:27 PM -0.28 -0.25 0.11 -6.17 0.00 0.00 0.00
4/24/2018 4:05:28 PM -0.29 -0.26 0.11 0.00 0.00 0.00 0.00
4/24/2018 4:05:29 PM -0.29 -0.25 0.11 -4.48 0.00 0.00 0.00
4/24/2018 4:05:30 PM -0.28 -0.22 0.11 -6.09 0.00 0.00 0.00
4/24/2018 4:05:31 PM -0.29 -0.25 0.11 -6.22 0.00 0.00 0.00
```

Table 5.  Example Content of the "Advanced_CORFM.log" File

## Section 3 - Calibration Procedure

Calibration tunes the Advanced CORFM so that each delay path provides the same S21 or gain metric.  Calibration is driven by the segmented architecture of the Advanced CORFM, which is further described in Section 5.  Briefly, programmable delays are provided by four delay segments connected in sequence.  Delay Segment 1 provides for 0, 1024, 2048, and 3072 nsecs delay.  Delay Segment 2 provides for 0, 4096, 8192, and 12288 nsecs delay.  Delay Segment 3 provides for 0, 16384, 32768, and 49152 nsecs delay.  Delay Segment 4 provides for 0, 65536, and 102400 nsecs delay.

First, put the Advanced CORFM in "calibration mode" by setting the "run/calibration" knob vertical.  Before calibrating, press the "calibrate modulators" button to calibrate the external modulators for quadrature operation. After the external modulator bias operation is complete, press the "calibration laser" button to calibrate the laser optical power levels. When completed, rotate all gain potentiometers counterclockwise for least gain attenuation for each delay path.

With a signal source set to 10.25 GHz and -22.75 dBm power level, in this case, and spectrum analyzer attached to the output test SMA connector on the back of Microwave and Control Module, measure the power level of each delay path in Segment 1. The input signal level was kept low to prevent possible saturation before all delay paths are calibrated. Press and hold the "delay increment" button for 1 second to step through Segment 1 delays. Table 6 shows the uncalibrated gain of each delay path. Be sure to correct for input and output interface cable loss. In this case, the interface cable loss was 1.8 dB per 3 ft at 10.25 GHz.

The 2048 nsec delay path has the lowest gain compared to other delay paths in Segment 1. Accordingly, adjust the gain for each delay path in Segment 1 to match that of the 2048 nsec path. The final calibrated gain of each delay path in Segment 1 is listed in the right-most column of Table 6. Continue the procedure for Delay Segments 2, 3, and 4. Tables 7, 8, and 9 show the uncalibrated and calibrated gains of each delay path in Segments 2, 3, and 4, respectively.

| Segment 1 Delay Path | Uncalibrated Output Power (dBm) | Calibrated Output Power (dBm) |
|---|---|---|
| 0 nsecs (Stage 1 bypass) | +6.46 dBm | -1.70 dBm |
| 1024 nsec delay | -1.12 dBm | -1.70 dBm |
| 2048 nsec delay | -1.70 dBm | -1.70 dBm |
| 3048 nsec delay | +0.19 dBm | -1.70 dBm |

Table 6. Uncalibrated and Calibrated Gain of Delay Segment 1

| Segment 2 Delay Path | Uncalibrated Output Power (dBm) | Calibrated Output Power (dBm) |
|---|---|---|
| 0 nsecs (Stage 2 bypass) | -1.70 dBm | -8.58 dBm |
| 4096 nsec delay | -8.58 dBm | -8.58 dBm |
| 8192 nsec delay | -7.24 dBm | -8.58 dBm |
| 12288 nsec delay | -7.51 dBm | -8.58 dBm |

Table 7. Uncalibrated and Calibrated Gain of Delay Segment 2

| Segment 3 Delay Path | Uncalibrated Output Power (dBm) | Calibrated Output Power (dBm) |
|---|---|---|
| 0 nsecs (Stage 3 bypass) | -8.58 dBm | -9.65 dBm |
| 16384 nsec delay | -6.91 dBm | -9.65 dBm |
| 32768 nsec delay | -7.62 dBm | -9.65 dBm |
| 49152 nsec delay | -9.65 dBm | -9.65 dBm |

Table 8. Uncalibrated and Calibrated Gain of Delay Segment 3

| Segment 4 Delay Path | Uncalibrated Output Power (dBm) | Calibrated Output Power (dBm) |
|---|---|---|
| 0 nsecs (Stage 4 bypass) | -9.65 dBm | -23.41 dBm |
| 65536 nsec delay | -23.41 dBm | -23.41 dBm |
| 102400 nsec delay | -22.54 dBm | -23.41 dBm |

Table 9. Uncalibrated and Calibrated Gain of Delay Segment 4

As a final gain check for each delay path, set the 10.25 GHz test signal at the maximum input level of -5.0 dBm . Table 10 lists the calibrated gain of each delay path.

| Delay Path (nsecs) | System Gain (dB) |
|---|---|
| 0 | -5.41 |
| 1024 | -5.53 |
| 2048 | -5.57 |
| 3072 | -5.46 |
| 4096 | -6.02 |
| 8192 | -6.07 |
| 12288 | -6.00 |
| 16384 | -5.58 |
| 32768 | -5.25 |
| 49152 | -5.43 |
| 65536 | -5.81 |
| 102400 | -5.32 |

Table 10. Calibrated Gain of each Delay Path

## Section 4 - Performance

Figure 15 shows the Advanced CORFM output for the longest delay path of each segment engaged for a total delay of 166.912 usecs. The input was a 10.25 GHz CW signal at approximately -2.0 dBm. Sideband noise at ~ 31 MHz each side of the input was recorded showing a SFDR of ~89 dB. The overall SNR is ~101.5 dBc. Figure 16 shows the same delay path with each external modulator calibration circuit active. Figures 17 through 20 show S-parameter performance and insertion delay over a range from 9.5 GHz to 10.5 GHz. For the longest delay path, the S21 parameter is ~1.3 dB +/- 1.9 dB. Insertion delay for the Advanced CORFM is ~ 65.5 nsecs.

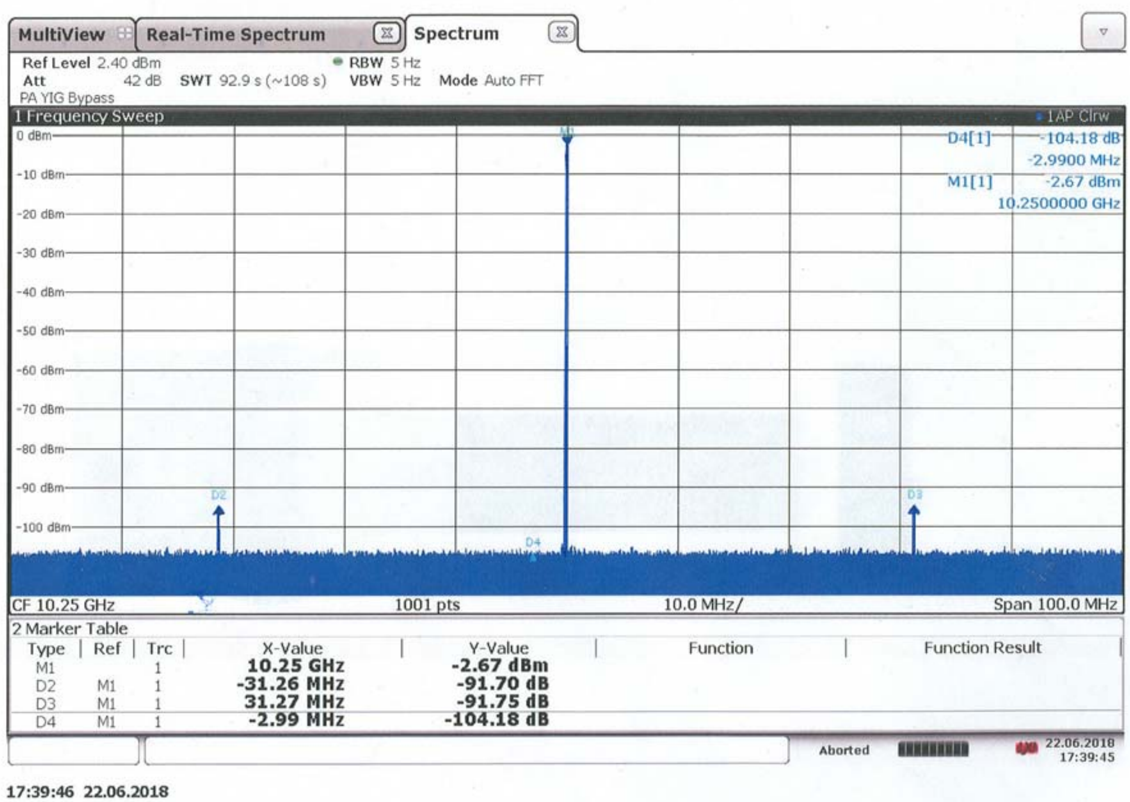


Figure 15. Longest Delay Path with External Modulator Calibration Off

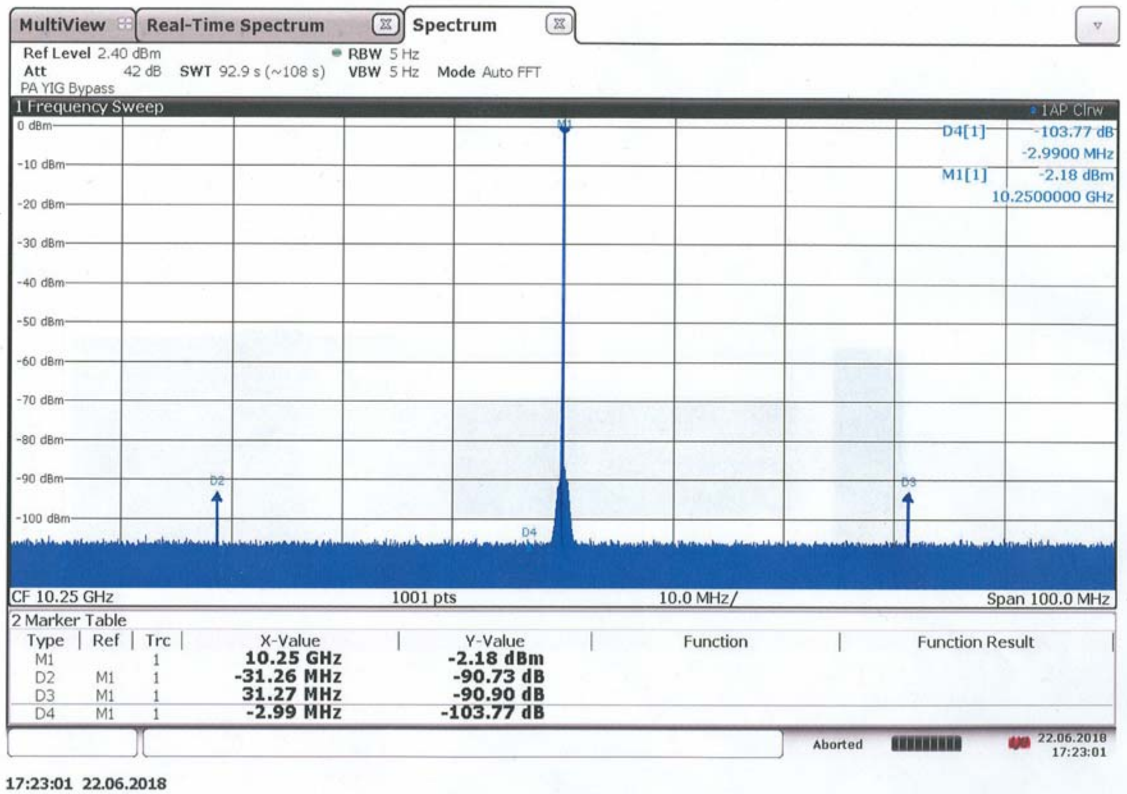


Figure 16. Longest Delay Path with External Modulator Calibration On

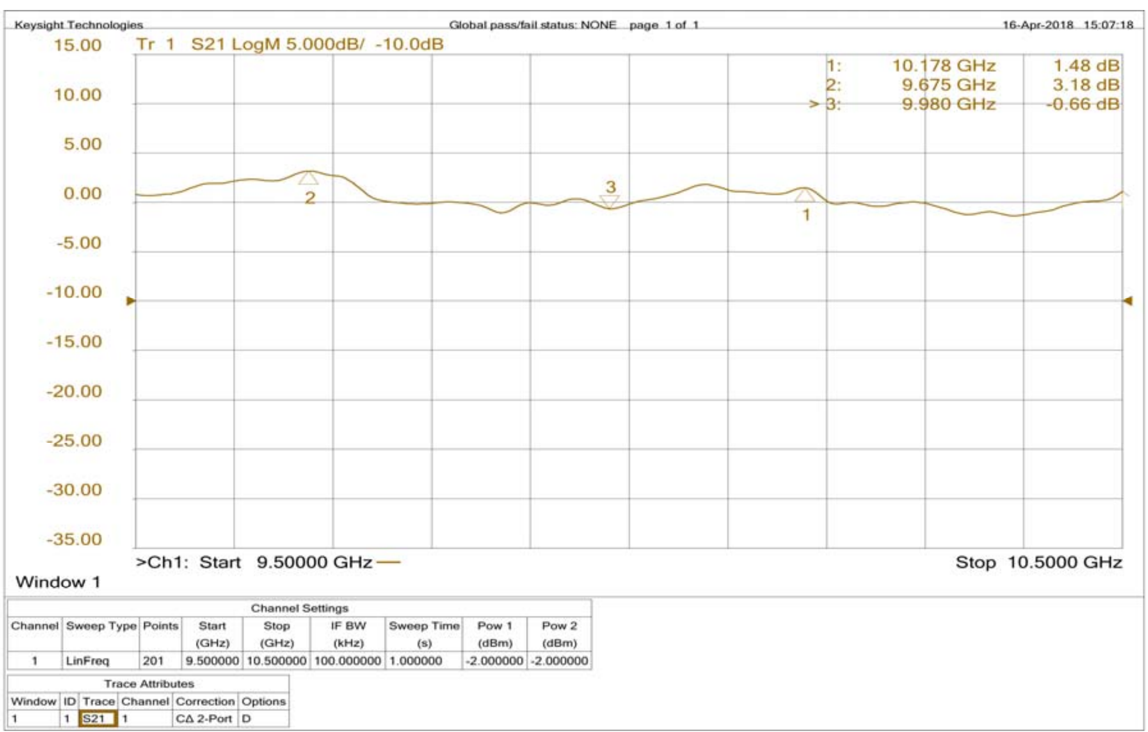


Figure 17. S21 Parameter of Longest Delay Path over Span of 1 GHz

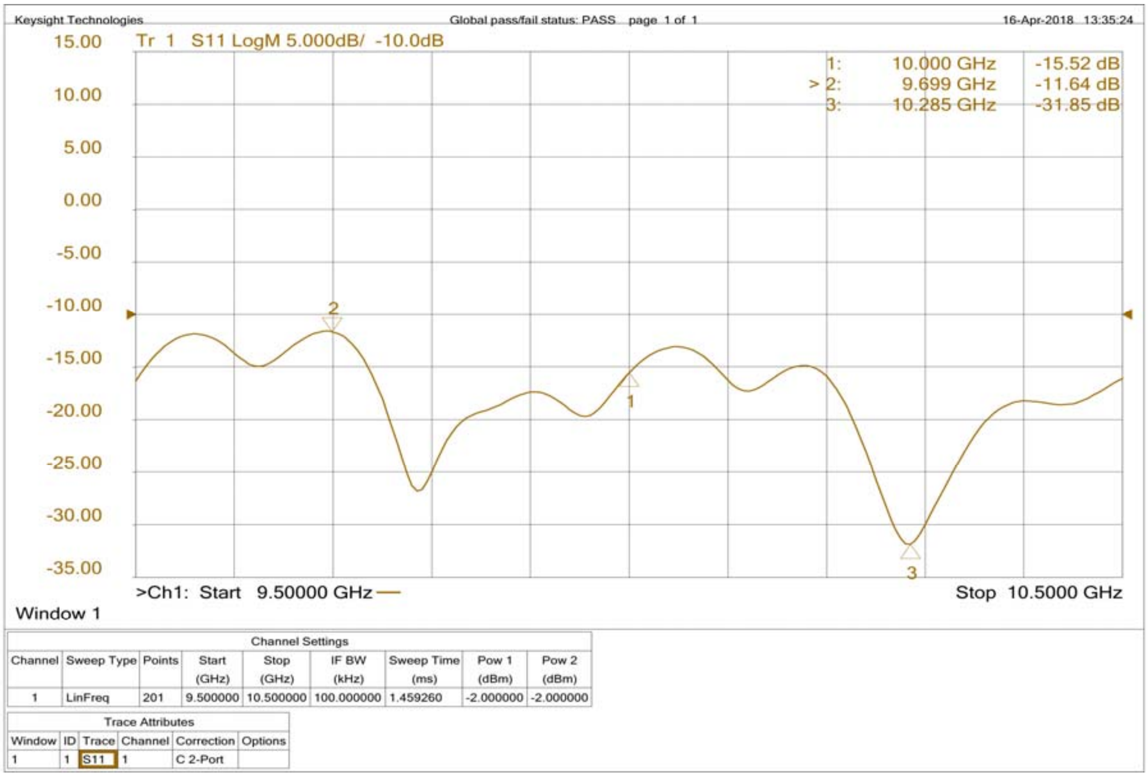


Figure 18. S11 Parameter over Span of 1 GHz

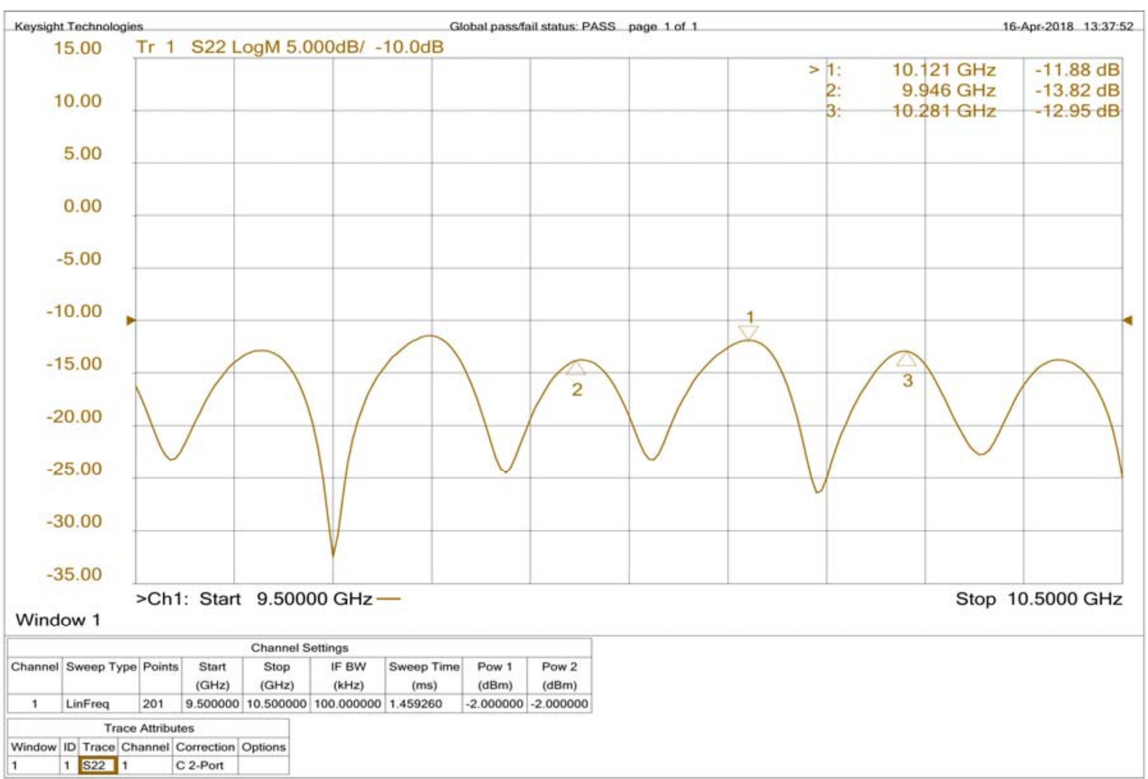


Figure 19. S22 Parameter over Span of 1 GHz

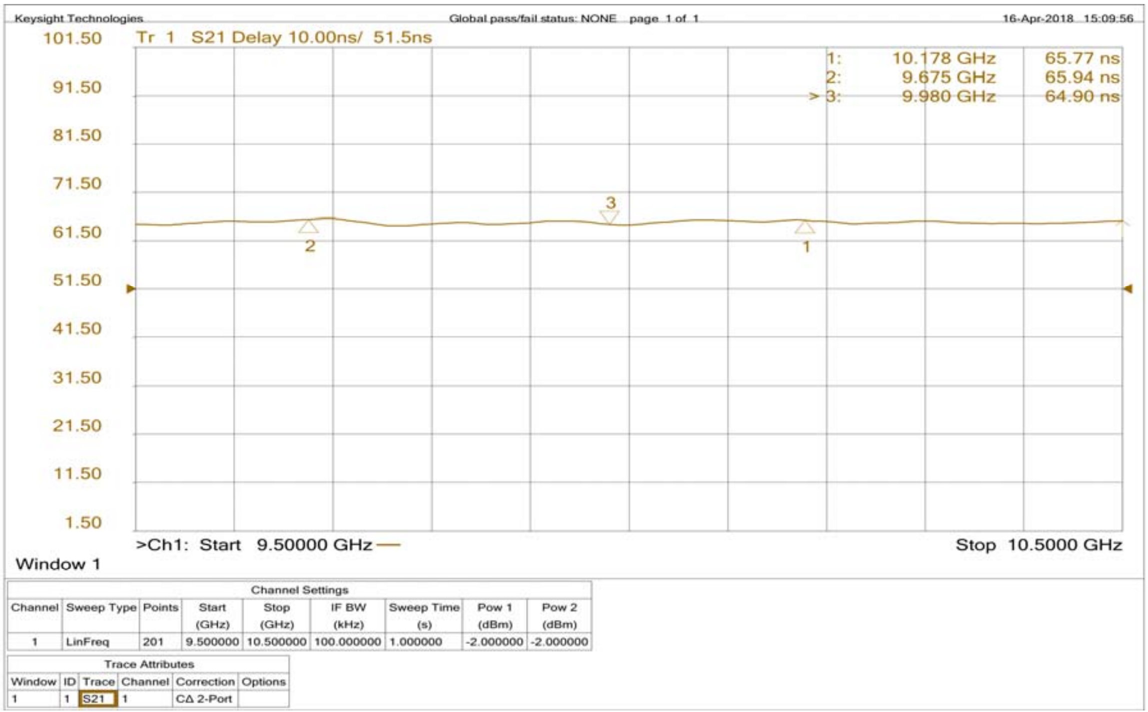


Figure 20. Insertion Delay

## Section 5 - Design Overview

The Advanced CORFM is built from four basic building blocks or segments placed together in sequence. Connection between each segment is in the RF/microwave domain via SMA semi-flex cables. Within each segment, RF is modulated onto a light carrier at 1319 nms by using a lithium niobate external modulator. The modulated light is then delayed through different lengths of optical fiber with approximately 1.4 nsecs of delay per foot of fiber length. At the end of each fiber length or fiber spool, light to RF conversion is achieved by Agere high power photodiodes. By switching between different lengths of optical fiber spools, the total delay from 0 to 166.912 usecs in 1024 nsec steps is achieved.

Figure 21 below shows the block diagram of RF components in Segment 1, which provides for delays of 0, 1024, 2048, and 3072 nsecs. Figure 25 shows the block diagram of optical components for Segment 1. The overlap between the two diagrams is at the external modulator and photodiode components. Part numbers are shown in red and serve to correlate the block diagram to the physical components in the Microwave and Control Module, shown in Figure 1. Displayed in magenta are the actual RF power levels and optical power levels taken as the delay line was constructed.

Figures 22 and 26 show block diagrams for Segment 2 providing delays of 0, 4096, 8192, and 12288 nsecs. Figure 23 and 27 show block diagrams for Segment 3 providing delays of 0, 16384, 32768, and 49152 nsecs. Figures 24 and 28 show the block diagrams for Segment 4 providing delays of 65536 and 102400 nsecs.

Analysis of the block diagrams shows a little variation in RF power levels from one segment to another. This is due to the fact that the delay line was not built in a single day, which the sponsor can verify. Between construction and tuning "sittings", test equipment was turned on and off and moved about, along with interface cabling, while other projects were being supported in the lab.

Not shown in the Figures below, there is a custom Altera-based FPGA control system that interfaces to all RF/Microwave switches and various control points to select optical fiber spools and control various calibration circuits. The custom control system provides an RS422 interface to a controlling PC.

Each external modulator is held at optimum quadrature operation by a custom FPGA based control system. The quadrature control system is activated periodically at the discretion of the remote PC to update the quadrature point. Because the external modulator quadrature control system injects KTB noise in the optical network to perform its operation, it is turned off while taking delay measures through the delay line.

Each laser, of which there are three, also has a custom optical power controller to maintain constant optical power levels as the lasers heat and cool with time. All clock oscillators on the various controllers deactivate while not in operation to reduce the spurious noise within the delay line.

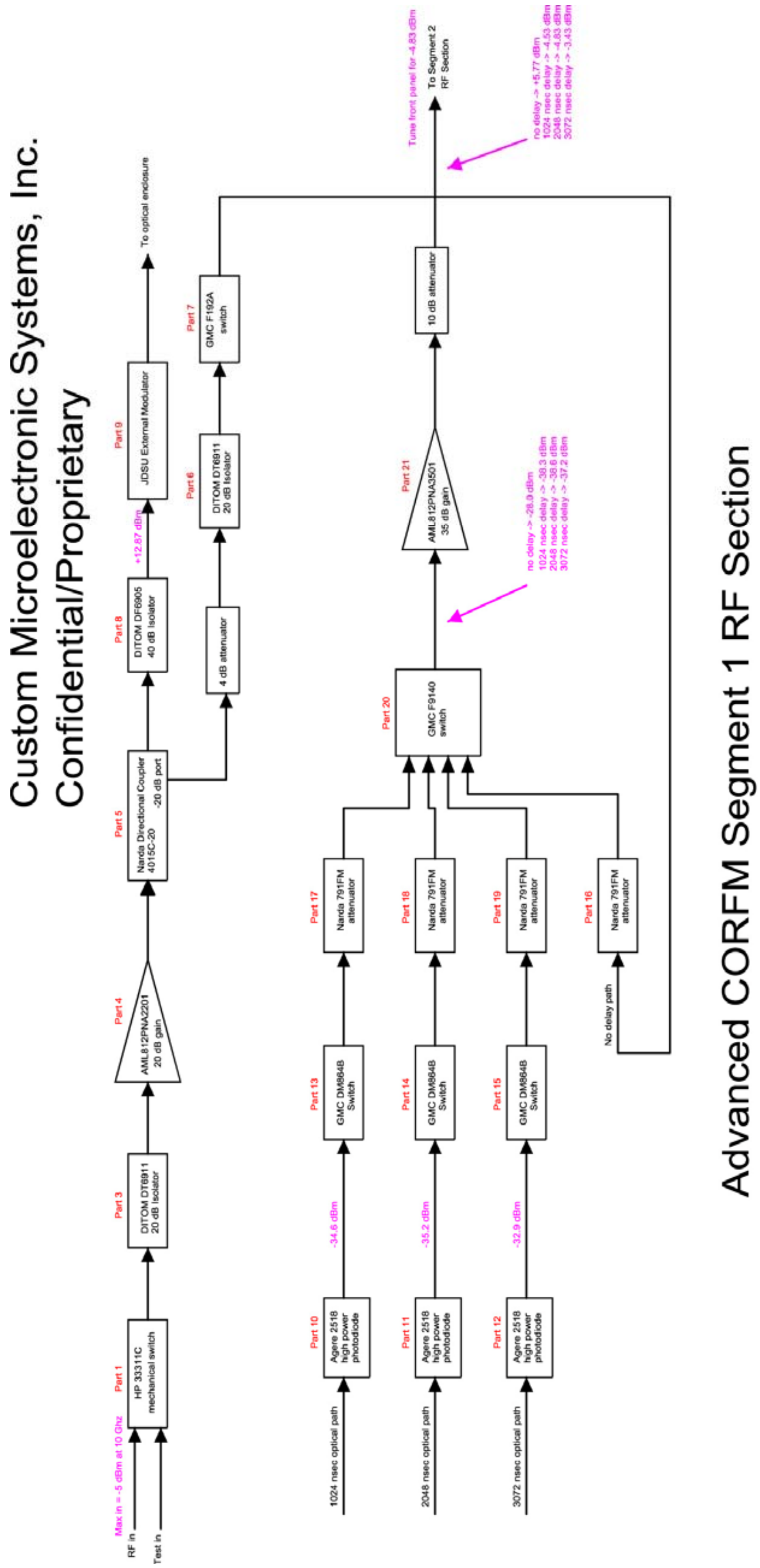


Figure 21. Advanced CORFM Segment 1 RF Diagram

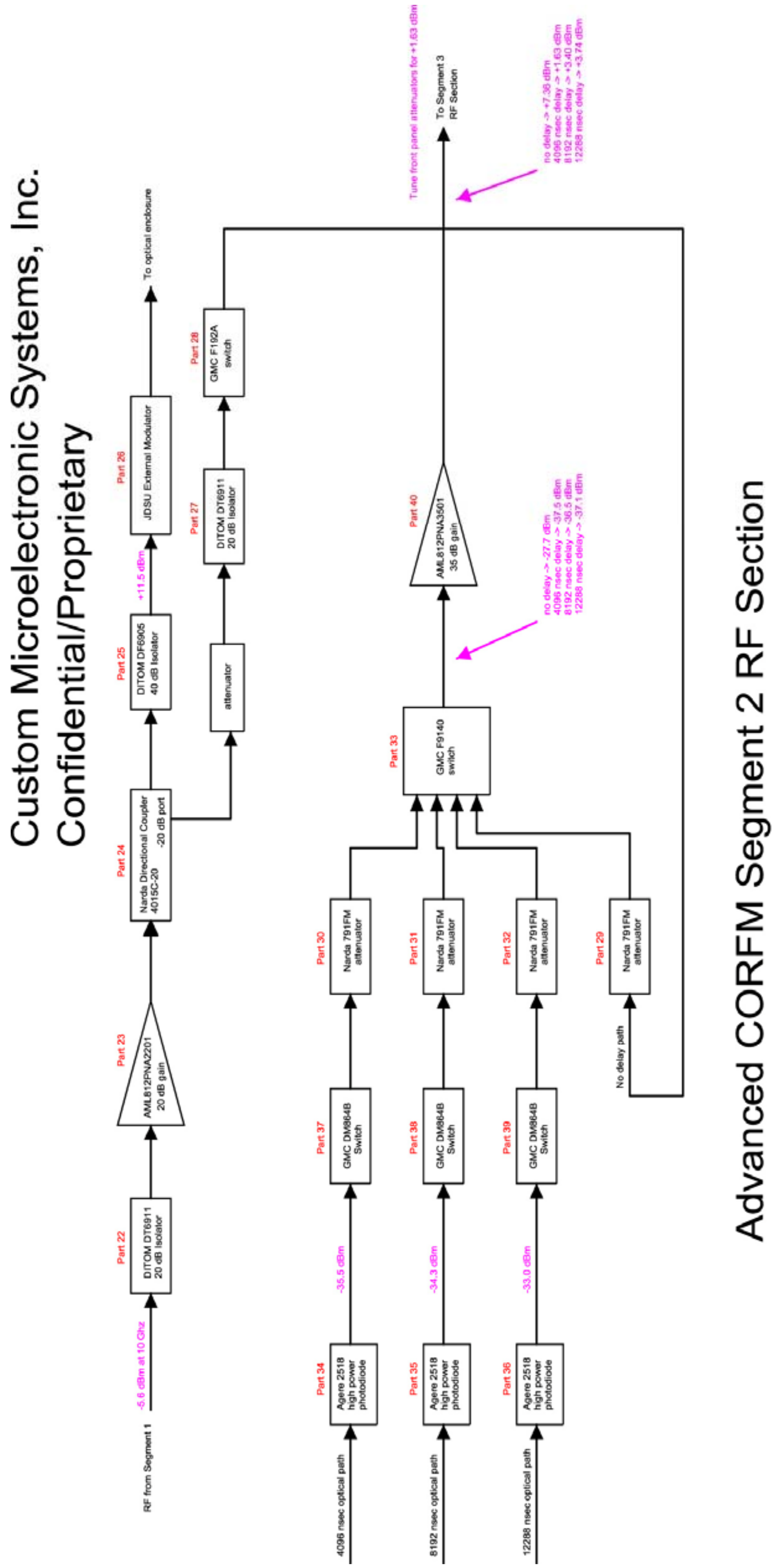


Figure 22. Advanced CORFM Segment 2 RF Diagram

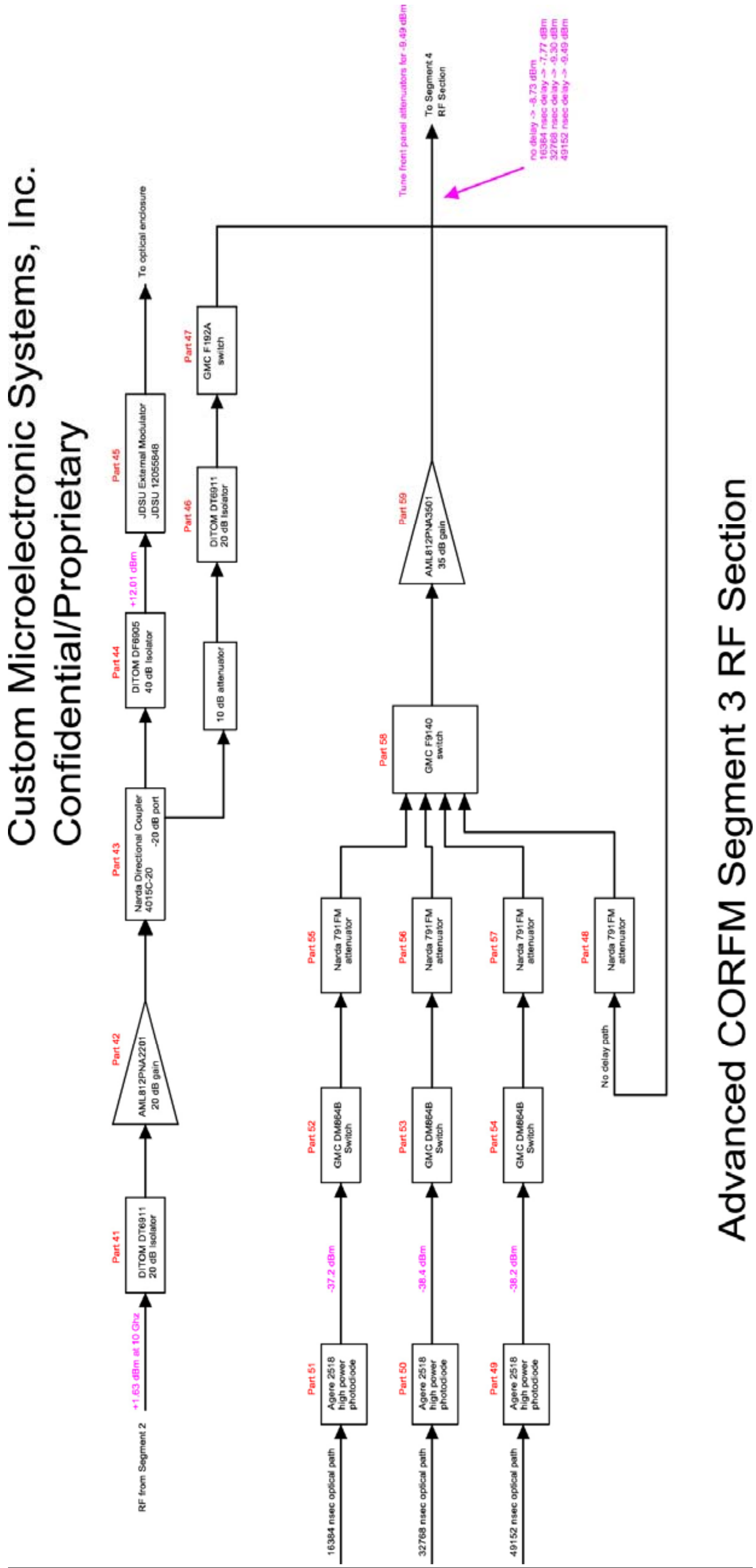


Figure 23. Advanced CORFM Segment 3 RF Diagram

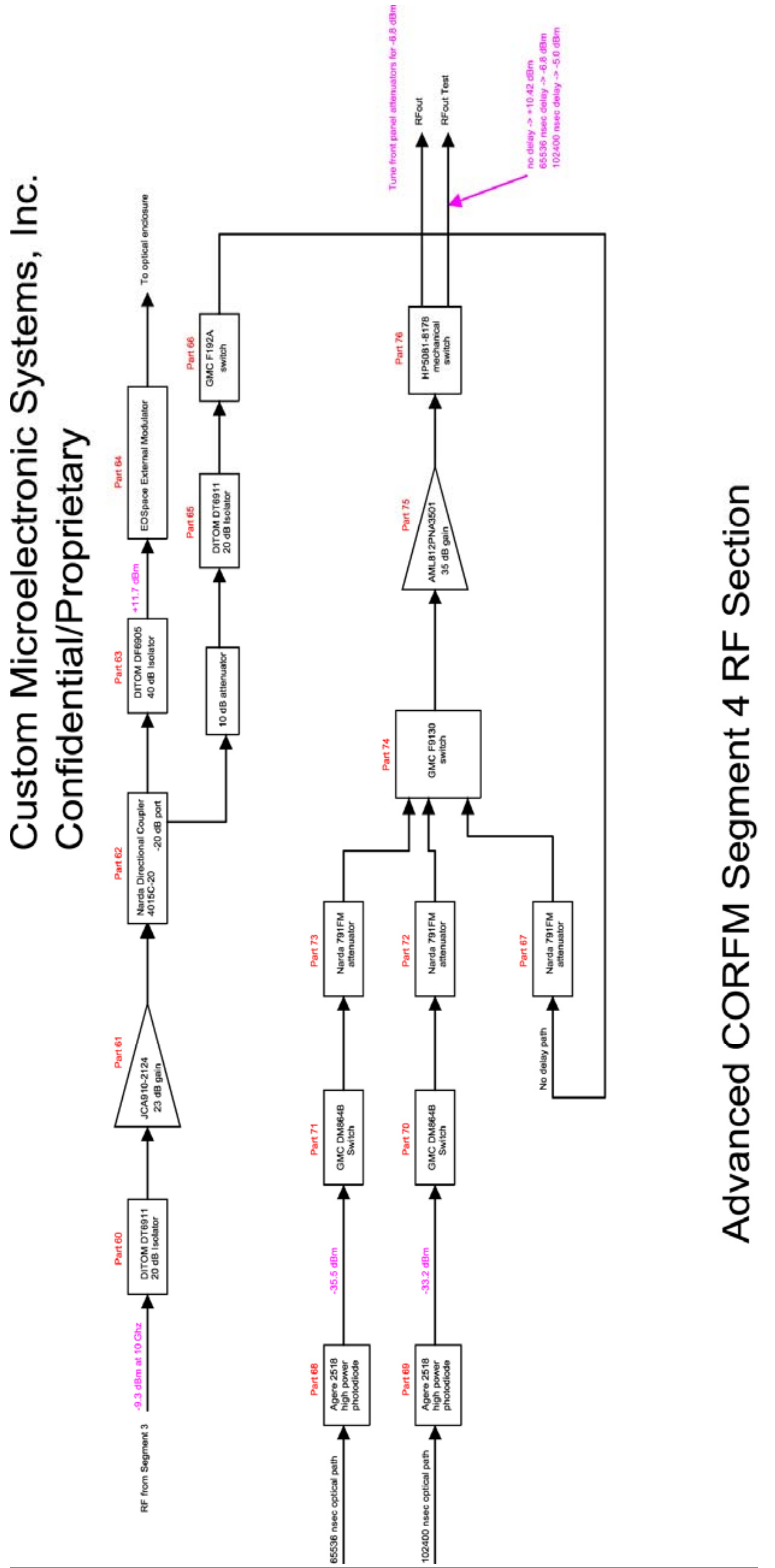


Figure 24. Advanced CORFM Segment 4 RF Diagram

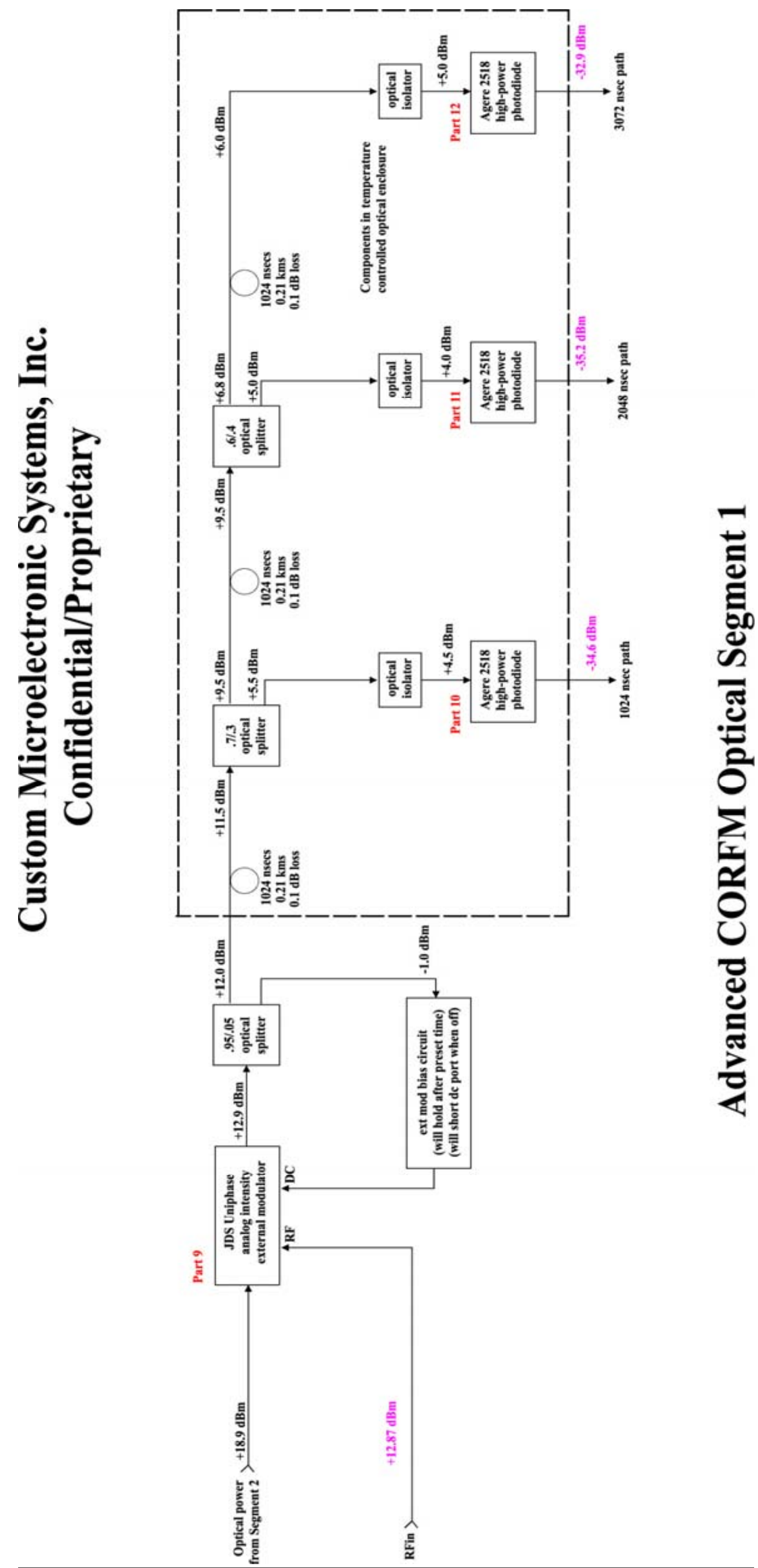


Figure 25. Advanced CORFM Segment 1 Optical Diagram

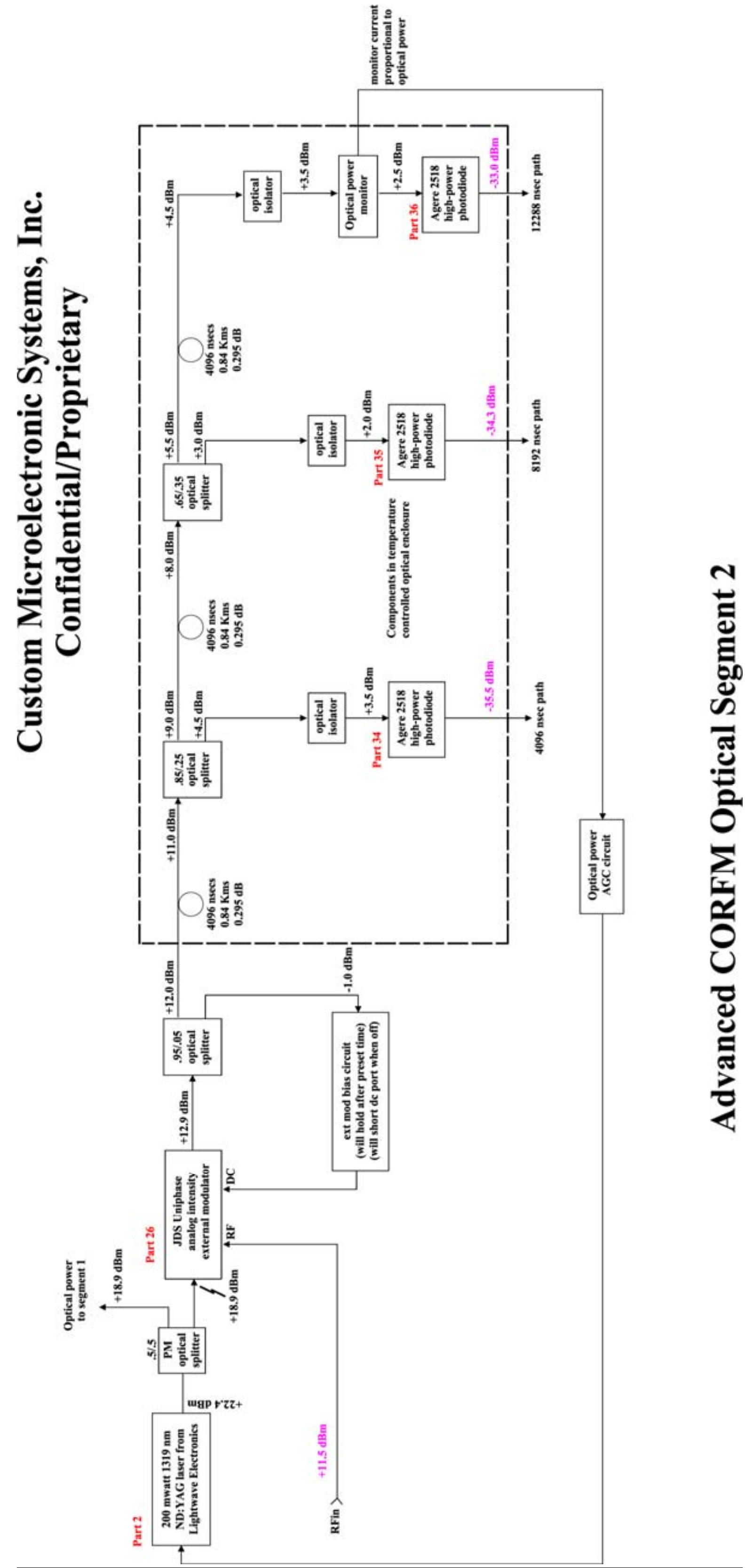


Figure 26. Advanced CORFM Segment 2 Optical Diagram

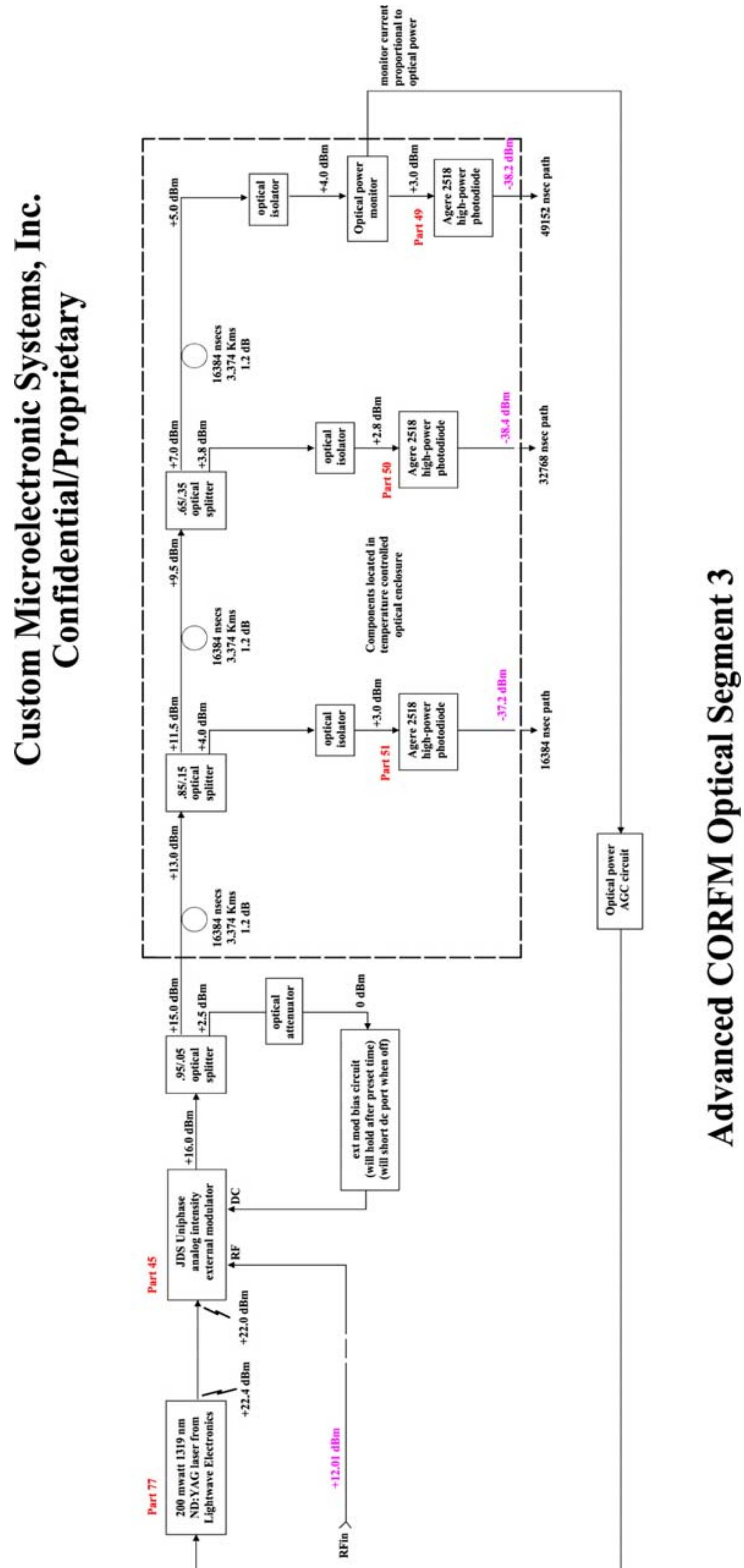


Figure 27.  Advanced CORFM Segment 3 Optical Diagram

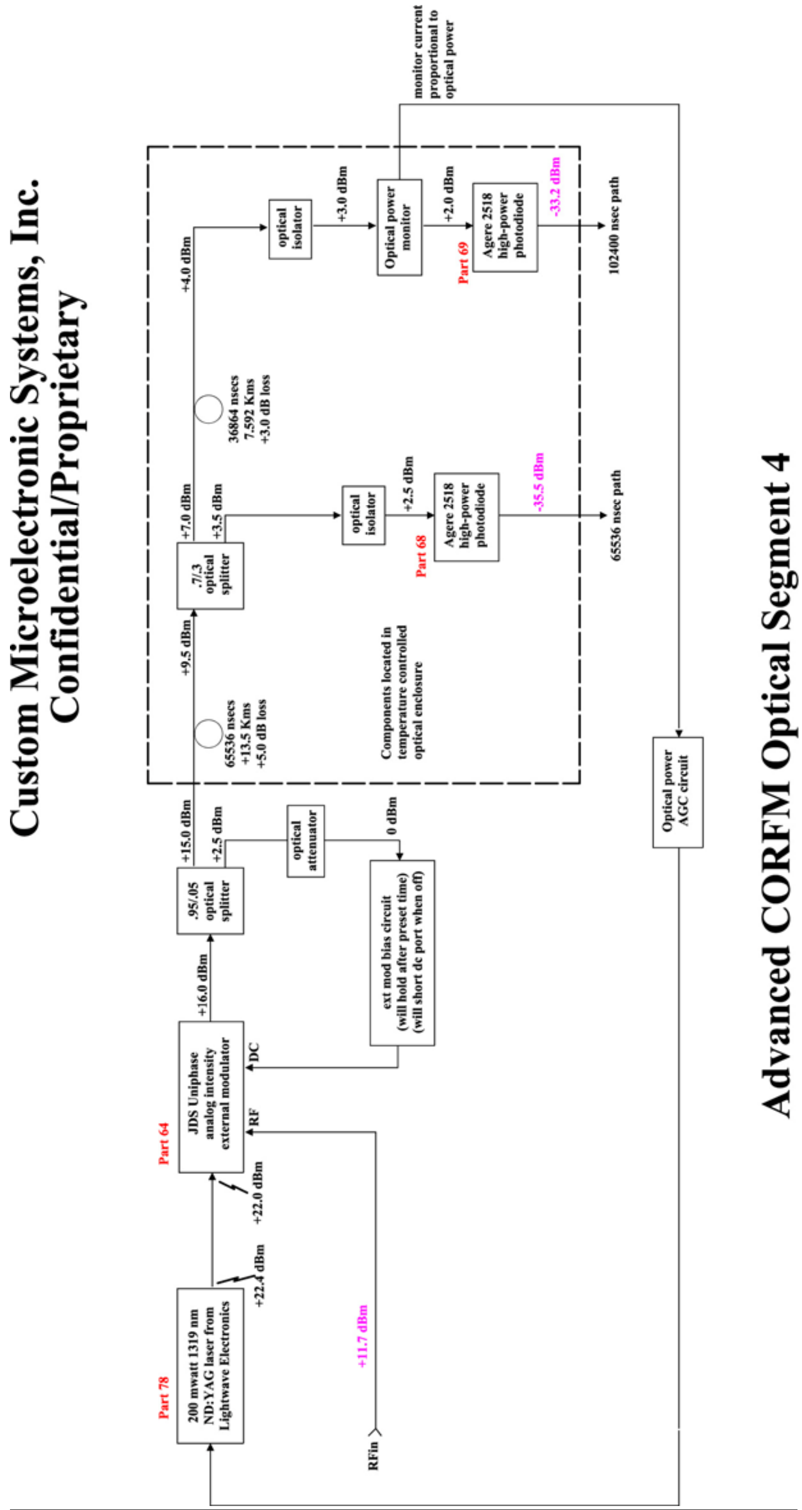


Figure 28.  Advanced CORFM Segment 4 Optical Diagram

## Section 6 - Future Improvements

1. The Advanced CORFM provides monitoring of several test points from power system voltages, to external modulator bias points, to optical power levels. Currently, these test points are not isolated. Recently, an 8-channel isolation PCB was completed. The isolation PCBs should be added to the delay line.

2. The overall system controller interfacing the remote PC to the Advanced CORFM is a legacy custom Altera-based FPGA design. The sponsor is Xilinx based with its other development efforts. The custom controller should be upgraded to a Xilinx COTS solution to provide for readily available replacement units and greater interface flexibility.

3. The external modulator quadrature control circuits are a custom legacy Altera-based FPGA/analog design that required some white wire modifications to support the Advanced CORFM. These circuits should be re-fabricated using recent Xilinx FPGA technology and built in quantities to support the life of the Advanced CORFM.

4. The laser optical power control system attached to each laser is actually deactivated in the Advanced CORFM. An issue of feedback stability while delaying RF signals through the delay line materialized late in the design of the system. A solution has been found; but, will require a redesign of the optical power controller PCB. Along with the original circuit being based on legacy Altera FPGA technology, the circuit should be re-fabricated using recent Xilinx FPGAs and in quantities to support the life of the delay line.

5. The original concept of the Advanced CORFM was to support quick serviceability. However, after having time to observe the setting and application of the Advanced CORFM, some enhancements need to be made to reduce down time in the event of malfunction during critical tests.

6. The SNR of the Advanced CORFM can be improved by driving the external modulators harder at their RF inputs. Each external modulator by specification can handle signal levels up to +24 dBm. Currently, input RF drive is set to a conservative +10 dBm to reduce 2nd order harmonic effects. If a reduced SFDR can be tolerated, the SNR can be improved.

7.  Optical link loss can be reduced which would improve the SNR by implementing a custom high power transimpedance photodiode at the end of each optical fiber spool.  The current design uses standard high-power photodiodes for EO conversion.