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Operators Manual and Technical Reference for the *Z-Beamlet* Phase Modulation Failsafe System: Version 1

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Abstract

The need for pulse energies exceeding 4 kJ and pulse lengths $\geq$ 2 ns in Sandia's *Z-Beamlet* laser (ZBL) requires that the single-frequency spectrum of its fiber-laser master oscillator be converted to a phase modulated spectrum with a modulation index $\geq$ 5. Because accidental injection of single-frequency light into ZBL could result in damage to optical materials from transverse stimulated Brillouin scattering, the presence of phase modulated (PM) light must be monitored by a reliable failsafe system that can stop a laser shot within of a few 10's of ns following a failure of the PM system. This requirement is met by combining optical heterodyne detection with high-speed electronics to indicate the presence or absence of phase modulated light. The transition time for the failsafe signal resulting from a sudden failure using this technique is approximately 35 ns. This is sufficiently short to safely stop a single-frequency laser pulse from leaving ZBL's regenerative amplifier with an approximately 35 ns margin of safety. This manual and technical reference contains detailed instructions for daily use of the PM failsafe system and provides enough additional information for its maintenance and repair.

Acknowledgment

The phase modulation failsafe system described in this report was developed and assembled primarily by Dr. Darrell Armstrong in Org. 1682 during 2012–2014, however conversations with Ian Smith, Verle Bigman, Briggs Atherton, and others, provided useful input during its initial development. Deployment and initial characterization and testing of the PM failsafe system required the efforts of many members of Org. 1682 that have a working knowledge of the operation of the *Z-Beamlett* laser, including Patrick Rambo, Jens Schwarz, Ian Smith, Jonathon Shores, Shane Speas, and John Porter.

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1 Introduction

This manual and technical reference provides instructions for the use of the phase modulation (PM) failsafe system developed at Sandia National Laboratories for the *Z-Beamlett* laser (ZBL). In addition to instructions on its use, the manual also provides enough information to maintain, repair, and if necessary reproduce the entire PM failsafe system. The operating instructions are contained primarily in Secs. 2 and 3, while the remainder of the manual contains technical details about the design and assembly of the PM failsafe system, including why we use phase modulation and optical heterodyne detection to generate the failsafe signal used by ZBL's timing electronics.

Conventions used in this manual: The only conventions we attempt to adhere to are capitalization of manufacturer's names and instrument names, capitalization of front panel labels on various instruments, and anything referred to specifically or explicitly such as "the Regen" or "ZBL's Regen," as compared to "a regen." Some examples: the time constant setting on the Lock-In Amplifier is referred to as "Time Constant" because it's a front-panel input parameter, and "Servo Amp" is a single instrument, whereas "servo loop" is an unspecific, generic term for an amplified and filtered network comprised of detectors, various instruments and other devices.

Because the use of phase modulation is dictated by the risk of damage associated with transverse stimulated Brillouin Scattering (SBS), Sec. 1.1 provides a brief discussion of why transverse SBS can cause damage in high energy laser systems, and how SBS can be suppressed. Safe operating limits for two different modulation indices relevant to this PM failsafe system are discussed in Sec. 1.2.

1.1 *Z-Beamlet* Mission Requirements: Higher Energy Requires Phase Modulation to Suppress Transverse Stimulated Brillouin Scattering

The pulse energy of Sandia National Laboratories' *Z-Beamlet* laser has been ≤ 4 kJ since it was originally brought on line, with the length of any single pulse nominally ≤ 2 ns. To meet future requirements of the *Z*-Accelerator's magnetized liner inertial fusion program (MagLIF), ZBL's energy must be increased to generate second harmonic (2ω) pulses of at least 6 kJ, which requires modifications to ZBL. In its standard configuration ZBL uses a single-frequency CW fiber laser as its master oscillator whose output is acousto- and electro-optically modulated to produce single or multiple pulses with initial shapes and temporal separation for specific applications. These pulses are injected into a regenerative amplifier (regen). The Regen's output is then injected into ZBL's amplification chain, which after full amplification usually results in temporally square pulses with lengths ≥ 1 ns. To extract additional energy requires pulse lengths ≥ 2 ns, where the longer pulse, greater fluence (J/cm^2), and 30 cm beam diameter together provide conditions capable of reaching the threshold for transverse stimulated Brillouin scattering, a nonlinear process that is usually observed only for large diameter beams found in multi-kJ laser systems. Typical of most nonlinear processes, transverse SBS turns on suddenly after exceeding an initial threshold, and once excited it can be amplified to the point where it leads to serious if not catastrophic damage, so it is mandatory that ZBL's operating conditions remain below the SBS threshold.

A complete physical description of transverse SBS is complex and beyond the scope of this manual, however in simple terms the buildup of acoustic energy from SBS can forms grating that scatters light perpendicular, or transverse, to the beam propagation direction and confines it within a thin layer below the surface an optical element. If the scattered light is sufficiently powerful the possibility for serious damage exists for all types of optical materials. The gain process that initiates and amplifies transverse SBS in large diameter optical elements is reasonably well understood and it has been observed experimentally, described theoretically for most relevant operating conditions, and also suppressed using spectral broadening techniques. A partial listing of previous work relevant to transverse SBS in large laser systems can be found in Refs. [1–7].

Although various types of spectral broadening can probably suppress SBS, a conceptually simple spectrum that is effective for this purpose consists of multiple discrete laser lines with non-degenerate frequencies, where the peak power for each individual line remains below the SBS threshold. An arbitrarily composed multi-line spectrum, however, can't be used because beat frequencies between the discrete laser lines can result in deep amplitude modulation (AM), and AM alone can also lead to optical damage in high energy laser systems. For example, consider two pulses with equal energy, one having a smooth temporal envelope and the other being deeply amplitude modulated with a modulation period much shorter than the pulse length. The series of short spikes in the pulse with AM may or may not be capable of initiating and amplifying transverse SBS, but a single spike might possess peak power that exceeds optical damage thresholds for processes other than SBS, so AM must be avoided. This is especially true if the spectral line separation results in a beat frequency period that is much shorter than the duration of the pulse. Fortunately the unique characteristics of a multi-line spectrum derived from phase modulation produce optical power that is constant in time, or for short pulses, temporal envelopes that are smooth and possess no AM. Consequently phase modulation is the only practical way to produce a multi-line spectrum that can be used to suppress transverse SBS.

Although PM provides the appropriate spectral and temporal characteristics, any perturbation of the relative phases and amplitudes of the discrete lines in its spectrum will result in unwanted AM. Given the modulation frequency of 14.8 GHz currently used in ZBL's PM failsafe system, and a modulation index $\beta \approx 5.5$, the resulting PM spectral width approaches 1 nm. This is sufficient for dispersion in optical fibers to induce phase shifts that result in AM for propagation distances greater than a few meters, and it's also sufficient for gain narrowing in ZBL's Regenerative Amplifier, and in subsequent amplifier stages, to produce AM by modifying the spectral amplitudes of the PM sidebands. Because induced AM from these mechanisms is highly undesirable, implementation of PM-based spectral broadening must include thorough testing of the temporal characteristics of the amplified pulses to confirm there is no significant conversion of PM to AM. Previous work with PM light in large laser systems such as the Omega Laser, [4] the National Ignition Facility (NIF), and Laser MegaJoule (LMJ), [8,9] has demonstrated PM to AM conversion, and various techniques for reducing PM to AM conversion have been developed. Similar techniques will be employed on ZBL as necessary during deployment of the PM failsafe system, and they are discussed in Sec. 4.4.

To suppress transverse SBS the spectral line separation must exceed the SBS line width, which for the optical materials used in ZBL is approximately 1 GHz. In practice larger line separations, or equivalently higher PM frequencies, are typically employed, with the ZBL PM failsafe system using 14.8 GHz.[1] In addition traditional sinusoidal modulation is typically used, where the resulting PM sidebands have inhomogeneous spectral densities, however non-sinusoidal modulation has been shown to produce PM sidebands of equal spectral density. [12] Although uniformly distributed optical power in the PM spectrum might offer an additional margin of safety, traditional sinusoidal drive with a sufficiently large modulation index, say $\beta \gtrsim 5$, can easily and safely suppress SBS, so we have not pursued any alternative modulation schemes.

1.2 Safe Operating Limits for ZBL Using Phase Modulated Light

The PM failsafe system uses a modulation index that results in a carrier amplitude of zero, with two examples being $\beta = 5.52$ and $\beta = 8.65$, as shown in Sec. A.2. Using these two β's, and thresholds for transverse SBS that were measured during earlier work on the Nova Laser [2], we can estimate a margin of safety for operation of ZBL at higher energies with longer pulses. To do this we distribute the fluence for a given pulse energy among the relative amplitudes of the PM sidebands and make sure the fluence for any sideband alone is well below the SBS threshold.

In Ref. [2] they measured a threshold condition $H_T \approx 2.3\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ for $\lambda = 350$ nm in fused silica and compared their results to predictions that assume the SBS gain is transient for pulse lengths of a few ns, and obtained good agreement. The transient gain is proportional to $\lambda_{\mathrm{pump}}^{-2}$, so with $\lambda_{\mathrm{pump}}(1\omega) = 1053$ nm throughout ZBL's amplification chain, and $\lambda_{\mathrm{pump}}(2\omega) = 527$ nm in the 2ω generation crystal and subsequent transmissive optics, wavelength-scaling suggests H_T could be as high as $20\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ throughout ZBL's amplifier section, and as high as $9\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ in the 2ω crystal and in subsequent 2ω optics. Although wavelength scaling works to our advantage it has not been rigorously confirmed and there appear to be no reliable measurements of the 1ω transverse SBS threshold, so $H_T \approx 2.3\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ can serve as a lower limit with the understanding that it represents a very conservative limit. In addition to the influence of wavelength scaling the gain time for transverse SBS and the aperture transit time due to the beam diameter also affect H_T, and ZBL's 30 cm square beam profile is smaller than in Ref. [2], but again we'll neglect these differences and retain $H_T \approx 2.3\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ as a useful limit.

Without additional amplification ZBL can probably reach a maximum 1ω energy of 4 kJ for a pulse length ≥ 1 ns, so assuming 1 ns as a starting point results in an operating condition of $\sim 4.44\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$. If we increase the 1ω energy to 10 kJ and assume a more realistic pulse length of 4 ns, this value increases to $\sim 44.4\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$, which should definitely exceed the 1ω transverse SBS threshold for single frequency operation. If we now use a PM spectrum with $\beta = 5.52$ we find the 4th-order sidebands have the largest amplitude of about 0.1568, so we multiply 10 kJ by that factor and divide by 2 to account for the sidebands at $\pm$ frequencies and with all

[1] 14.8 GHz is higher than necessary for the purpose of suppressing transverse SBS, however it's prudent to develop the system to operate at this frequency, and up to 17–18 GHz if needed, because it would ease incorporation of a spatial beam smoothing technique based on spectral dispersion, should that become necessary. See for example Refs. [4, 10, 11].

else equal get $3.48\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$, which exceeds our conservative limit of $2.3\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$ but not by a significant amount. If we repeat this exercise using $\beta = 8.65$ the 7th-order sidebands are the largest with amplitude of about 0.114, and the result is $2.53\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$, which is closer to the conservative limit. Although this simple exercise suggests $\beta = 8.65$ might be the best choice, the additional bandwidth might weakly affect 2ω generation efficiency but more likely also worsen the PM to AM conversion problem, so it may be undesirable. Regardless of the final choice of β, wavelength scaling for transient SBS gain suggests ZBL should be able to operate safely below the SBS threshold for the energies required by the MagLIF program.

As a final extreme example using $\beta = 5.52$ and a pulse length of 6 ns, what is the largest 1ω energy that can be used without exceeding the wavelength-scaled 1ω value of $H_T \approx 20\,\mathrm{J}\cdot\mathrm{nsec}/\mathrm{cm}^2$? The answer is around 38.3 kJ, which is almost certainly unobtainable for ZBL.

2 The Major Subcomponents of the PM Failsafe System

The major subcomponents of the PM failsafe system include three Sandia-built 19 inch rack-mounted boxes that are labeled Laser and Optical Components, RF and Control Electronics, and DC Power Supplies, and a rack-mounted fiber laser amplifier from IPG Photonics. Another Sandia built subcomponent housed in a Thorlabs 19 inch rack-mount box is a grating compressor that is used to compensate for dispersion primarily from the 30 m long polarizing (PZ) fiber that delivers the PM pulses from the master oscillator room (MOR) to the Regen in the ZBL High Bay. The four boxes assembled at Sandia use primarily components-off-the-shelf (COTS), but they also include low-voltage electronics that were custom designed as part the control system. The complete PM failsafe system also includes an SRS SR510 Lock-in Amplifier, a New Focus LB1005 High-Speed Servo Controller, and an external controller for the NP Photonics "Rock Laser" that is housed inside the Laser and Optical Components Box. The NP Photonics Rock Laser is the stabilized single-frequency fiber laser whose output is phase modulated to provide the broadened multi-line spectrum for injection seeding the Regenerative Amplifier in ZBL's front end.

Manuals for the commercial products are available online from their vendors, and in some cases from the binder for the PM Failsafe System in the MO292 Document Depository. Some of these manuals are also available in the directory \\FS01960NT\ZBL_PM_Failsafe on the Documentation Server. The manual and technical information for the four boxes assembled at Sandia, and instructions for operation of the ZBL PM failsafe system in general, are found in this document. Sections. 2.1–2.4 below provide a brief description of the function of each of the rack-mounted Sandia-built boxes, and Table A.1 in Sec. A.1 lists all of the external electrical and optical connections for the system. Detailed descriptions of the contents of each of the Sandia-built boxes, and the principles of their operation, are found in Sec. 4.

2.1 Laser and Optical Components Box

The Laser and Optical Components Box has two outputs: One is a fiber-coupled optical port that accepts an SMPM or PZ patch cord with an FC/APC connector that provides the PM light that is injected into an IPG Photonics Amplifier and then eventually into ZBL's Regen; the other is a 2 GHz heterodyne beat note that is the fundamental electrical signal for the failsafe system. The optical power at the fiber-coupled port at 1053 nm is > 6 mW, the PM frequency is 14.8 GHz, and the modulation index is nominally 5.52, however single-frequency light is also available for specific system settings. The electrical signal is generated by an 8 GHz DC-coupled optical detector that converts an optical heterodyne beat note into an RF electrical signal. The 2 GHz RF signal is filtered and amplified in the RF and Control Electronics Box where it's power is detected to provide the failsafe signal.

Inside the box the optical heterodyne beat note is generated using two PM spectra: One is the "main" PM spectrum at 14.8 GHz that is injected into ZBL's Regen and the other is a 12.8 GHz "reference" spectrum with $\beta = 2.42$. A single first-order sideband of the reference spectrum is selected using a scanning Fabry-Perot étalon as a filter, and this sideband is then mixed with the main spectrum in SMPM fiber to generate the heterodyne beat note. Because the optical detector is DC-coupled the beat note rides on top of a DC level that is later removed by electrical filtering. For the system to be operational, and the failsafe armed, the étalon must be locked to the first-order sideband of the reference PM spectrum as described in Sec. 3.4. The complete contents of the Laser and Optical Components Box, and the functions of all of its internal components, are described in Sec. 4.2.

2.2 RF and Control Electronics Box

The main function of the RF and Control Electronics Box is to convert the 2 GHz RF beat note into a high-speed TTL output that serves as the failsafe signal. The conversion process involves band-pass filtering, amplification, RF power sensing, and a final low-pass filtering step. The resulting "trigger" signal then passes through a two-stage latch-to-ground circuit, and then drives the control input of a 5 GHz solid-state switch that provides high-to-low or low-to-high TTL transitions. The signals from the switch are fanned out through 180 MHz, 250 mA buffers so that if necessary the failsafe signals can continuously drive 50 Ω loads. A toggle switch on the front panel selects the TTL transition, with two equal channels for high-low or low-high. Figure 1 shows the front panel of this box.

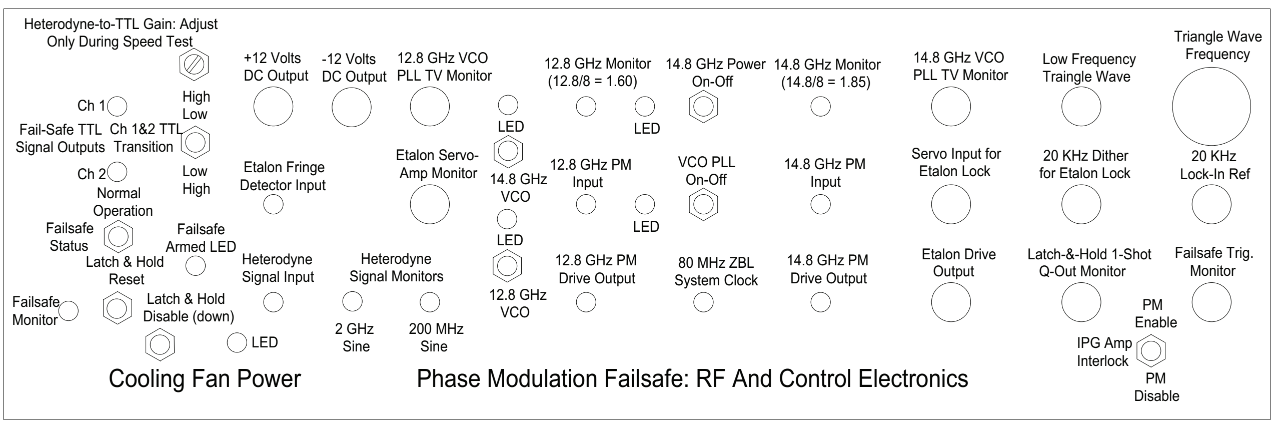

Figure 1: Front panel of the RF and Control Electronics Box. A photo is shown in Sec. A.11.

The RF and Control Electronics Box also provides the RF power for the phase modulators and includes two phase-locked loops (PLL). The PLLs stabilize the 12.8 GHz reference PM frequency and the main 14.8 GHz PM frequency against the 80 MHz ZBL system clock so that they produce a heterodyne frequency of 2 GHz. Because the heterodyne beat note results from optically filtering the reference PM spectrum, which requires locking an étalon to a sideband, this box also provides low-voltage electronics to aid in that task. These electronics include: A 20 KHz sine-wave dither sent to the étalon to generate an error signal; a square-wave reference for the Lock-In Amplifier that demodulates the error signal; a low-frequency triangle wave sent to the Servo Amp and *xy*-oscilloscopes for optimizing demodulation signals and for observing etalon fringes, and also for driving a home-built scanning étalon for monitoring the main PM spectrum; amplification of the 0–10 V Servo Amp output up to 5–45 V for controlling the reference étalon, and an output monitor for the Servo Amplifier's output signal.

The RF and Control Electronics Box also provides the interlock for the IPG Photonics Fiber Amplifier. The interlock becomes active only if two signals are present; the étalon fringe signal from the reference PM, and the trigger signal for the 5 GHz switches in the failsafe system. The interlock can also be activated for single-frequency injection seeding of ZBL's Regenerative Amplifier. In this situation the main PM drive power is off and there is no failsafe trigger, so a front panel toggle switch can deactivate the need for the DC voltage associated with the trigger signal. The deactivation can only be used when the latch-to-ground and hold circuity is also deactivated, as described in Sec. 4.3.8.

The RF and Control Electronics Box is the most complex component of the failsafe system. Complete details of its internal components and how they operate is provided in Sec. 4.3.

2.3 DC Power Supplies Box

The DC Power Supplies Box contains six individually fused open-chassis linear supplies that provide electrical power to the RF and Control Electronics Box. These supplies are intentionally housed in a separate box to reduce coupling of stray 60 Hz signals into the low-voltage and RF electronics. The photograph of its interior in Fig. 2 shows the locations of the linear supplies, labeled by voltage values. Table 1 lists the part numbers for the linear power supplies.

Table 1: Parts list for Fig. 2 – DC power supplies

Voltage	Manufacturer	Part number
±5	Power One	HAA5-1.5/OVP-AG
±12	Power One	HBB15-1.5-AG
±15	Power One	HBB15-1.5-AG†
+15 (3A)	Power One	HC15-3-AG
±24	Power One	HAA24-0.6-AG
+48	Power One	HB48-0.5-AG‡

† Same as ±12 V supply, adjusted to ±15 V. ‡ Adjusted to +50 V

Data sheets for the linear supplies in Fig. 2 are available only on the Documentation Server in the directory \\FS01960NT\ZBL_PM_Failsafe\ICs_and_linear_supplies.

2.4 Rack Mounted Grating Compressor for Dispersion Compensation

The Grating Compressor is housed in a Thorlabs RBX32 slide out rack that contains an aluminum breadboard for mounting optical components. This slide out rack also contains the "Chopper," a free-space-coupled EOM-based amplitude modulator used to transmit relatively long μs length pulses at 250 Hz to reduce the otherwise 100% duty cycle of the CW light from the fiber amplifier. The Chopper, which precedes the compressor, is required because the two-stage fiber-coupled

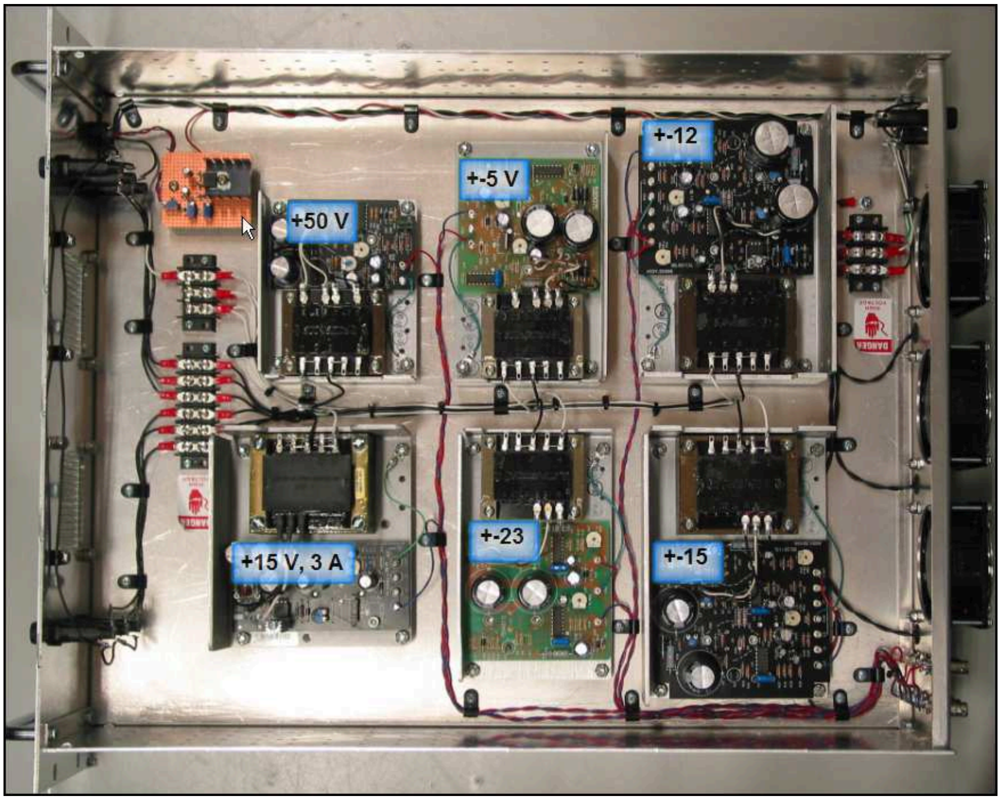

Figure 2: Locations of the linear supplies inside of the DC Power Supplies Box.

Mach-Zehnder amplitude modulator (Shaper) that provides the final high-bandwidth pulse shaping prior to injection into the Regen can't tolerate average optical power at 1053 nm much greater than about 20–25 mW.

The grating compressor is in a Treacy configuration to compensate for the estimated total 2nd-order dispersion $k''z = 1.68 \times 10^6$ fs^2 in the 30 m long PZ fiber that transmits the shaped pulses from the MOR to the Regen. The dispersion was estimated assuming the PZ fiber has a fused silica core, however the estimate neglects a small amount of additional dispersion from propagation in the fibers in various other components, including the fiber in the IPG Photonics Amplifier. The compressor is required because the dispersion from these fibers would convert a fraction of the PM light to amplitude modulated light. Additional details about the compressor, including a photograph of the compressor assembly, are provided in Sec. 4.4.1, and in a SAND report that discusses deployment of the PM failsafe system. [13]

3 Daily Operation of the PM Failsafe System

For day to day operation the PM failsafe system should be maintained in a fully warm condition, where only the seed laser optical power (*not the power for seed laser's control box*) and the fiber amplifier are turned on and off. If the seed laser is off the failsafe system will be in an unarmed state, where the VCOs that power the two phase modulators will be off, even if their switches are in the on position and their red power-on LEDs are illuminated. To arm the failsafe system you must first check the status of two toggle switches and then follow the procedures below:

1. The Latch & Hold Disable toggle switch located in the lower left corner of the RF and Control Electronics Box must be in its up position.

2. The Failsafe Status toggle switch located above the Latch & Hold Disable switch must be down to select the Latch & Hold Reset condition, which ignores the failed condition and allows the VCO power to be on – as long as their power switches are on. *When the system is unarmed and not in use but you want to maintain the RF electronics in a warmed-up condition, the Failsafe Status toggle switch should be left in the down position.*

Only after the étalon for the reference optical spectrum is locked as described in Sec. 3.4 can the system be fully armed by moving the Failsafe Status toggle switch to its up position. Any disruption to the conditions required for the system to remain armed will cause the latch-to-ground and hold circuitry described in Sec. 4.3.8 to deactivate the system, thus requiring reset by an individual trained in its opereration.

3.1 Power On Settings

There are three main power switches on the Sandia-built boxes that must be in their on positions for proper operation of the PM failsafe system:

Front panel rocker switch on DC Power Supplies Box Provides power for all RF components and all other electronics in the RF and Control Electronics Box.

Back panel rocker switch on the RF and Control Electronics Box This switch should remain in the on position at all times. It provides power to a 5 V linear supply that powers all of the cooling fans in this box.

Front panel cooling fan power on RF and Control Electronics Box This toggle switch must be on and its LED illuminated when the rocker switch for the DC power supplies is on. The RF electronics can probably operate without damage with the fans off, but the power output of the voltage controlled oscillators (VCO) and RF amplifiers that drive the phase modulators will be affected without cooling.

There are four additional toggle switches near the center of the front panel of the RF and Control Electronics Box that will be on with their LEDs illuminated during normal operation. The only time any of them will be off is for testing the operation of the PM failsafe system, or for single frequency operation. These switches are:

14.8 GHz VCO Power switch for the 14.8 GHz VCO.

12.8 GHz VCO Power switch for the 12.8 GHz VCO.

14.8 GHz Power On-Off Power switch for the 14.8 GHz RF amplifier. This amplifier is on a separate power supply in the DC Power Supplies Box, and has its own toggle switch, because it can require as many as 3A during startup.

VCO PLL On-Off This switch interrupts the power for the PLL that forces the 14.8 GHz VCO to phase-lock to the 80 MHz ZBL system clock.[2] When this switch is off the system will enter a PM failure state. Note that you shouldn't test the response time of the failsafe system using this switch, or any other toggle switch, because they are slow mechanical switches and are not debounced. The procedure for carrying out a speed test and setting a threshold for failsafe response is described in Sec. A.7.

3.2 Warmup Time

Electrical systems The electronic warmup time for the system is about 20 minutes however it's best to leave the DC power supplies, the RF electronics, and the cooling fans for the RF electronics, on at all times. The electronics can be operated immediately after a fully cold startup but doing so is not recommended.

Laser system The warmup time for the NP Photonics fiber laser may be as long as 20 minutes. Before the temperature stabilizes oscillation alternates between single- and multi-mode so the heterodyne beat note will also be unstable. Due to the long warmup time the NP Photonics Control Module should be left on at all times. The laser itself does not have to left be on, just the laser's heater, and it's on when the Control Module is on. Even when warm, turning on the laser changes its temperature due to heating from pump light, so the green Temp LED will probably go off for a minute or so. Wait until the green LED is illuminated again before locking the étalon to a PM sideband.

Optical system There might also be warmup time due to absorptive heating in the étalon's mirrors when it's locked to a PM sideband. This effect is probably real but hasn't been rigorously confirmed. Heating and thermal expansion are inferred by locking the étalon and observing the Servo Amp's output using the Étalon Servo Amp Monitor on the front panel on the RF and Control Electronics Box. Heating is enhanced when the étalon is locked on resonance because almost all incident optical power is coupled into the cavity. After warmup, unlocking

[2]This switch is an artifact from a VCO control scheme no longer in use, where the previous 15 GHz and 17 GHz frequencies were offset-locked using their difference frequency, relative to stable reference oscillators.

the étalon to reset the Servo Amp's integrator is optional as the voltage drift for 24 hour time periods is probably less than 15% of the Servo Amp's output range.

3.3 Observation of the Heterodyne Beat Note

The PM failsafe system was designed so that users can observe a heterodyne beat note only when the étalon that filters the reference PM spectrum transmits a first-order sideband. This restriction ensures the system will operate correctly and is imposed by inserting a 1.7–2.3 GHz bandpass filter after the optical detector. Without filtering a user could potentially select a different sideband and the system would probably not function correctly. For example, the étalon could be locked to a second-order sideband of the reference PM spectrum and produce a 4 GHz beat note by interfering with a second-order sideband from the main PM spectrum. This 4 GHz signal could in principle be processed by the electronics described in Sec. 4.3.1 and shown in Fig. 12, but if its amplitude is either too small or too large, the system could behave unpredictably. To aid users in selecting the correct sideband the RF and Control Electronics Box offers two different front panel monitors for observing the beat note.

One monitor directly samples the 2 GHz sine wave so its use requires an oscilloscope with sufficiently high bandwidth. This is the actual electronic beat note sampled by a directional coupler so its amplitude changes as the étalon is scanned across the laser line. The other monitor's output comes form a $\div 10$ prescaler that produces a 200 MHz sine wave of fixed amplitude, so it can be observed with almost any newer digital oscilloscope. The prescaler's input bandwidth is 0.1–12 GHz and it's minimum detectable power is about -15 dBm (~ 0.03 mW), so if random noise with sufficient amplitude is present at its input it will divide its frequency by 10. To reduce the influence of noise the input signal is filtered with another 1.7–2.3 GHz bandpass filter, and the output is filtered with a 225 MHz low-pass filter, as shown in Fig. 12. When the étalon is far enough off resonance the frequency and amplitude of the 200 MHz sine wave will fluctuate randomly, but when a stable 2 GHz beat note is present at the prescaler's input, the output of the $\div 10$ monitor will stabilize and appear as a 200 MHz sine wave of foxed amplitude.

3.4 Locking the Étalon to a First-Order Sideband of the Reference Phase Modulator's Optical Spectrum

The PM failsafe system can generate a failsafe event only when the étalon that filters a first-order sideband from the reference PM spectrum is actively locked to one of these two sidebands.[3] To obtain and maintain lock requires user interaction with two commercial instruments; the SRS SR510 Lock-in Amplifier and the New Focus LB1005 Servo Controller, which we usually refer to as the Servo Amp. The front panels for these instruments are shown in Figs. 3 and 4. Active lock also

[3] When the system temperature is stable the étalon might "sit" near the top a fringe for a long time without active lock. The heterodyne beat note's amplitude might be sufficient for normal operation, but operating in this manner is tantamount to living dangerously, so don't do it. If the system won't maintain active lock then it can't be relied on to work properly, so any problem should be diagnosed and corrected.

requires electronics inside the RF and Control Electronics Box, but they're not user accessible and shouldn't require adjustment.

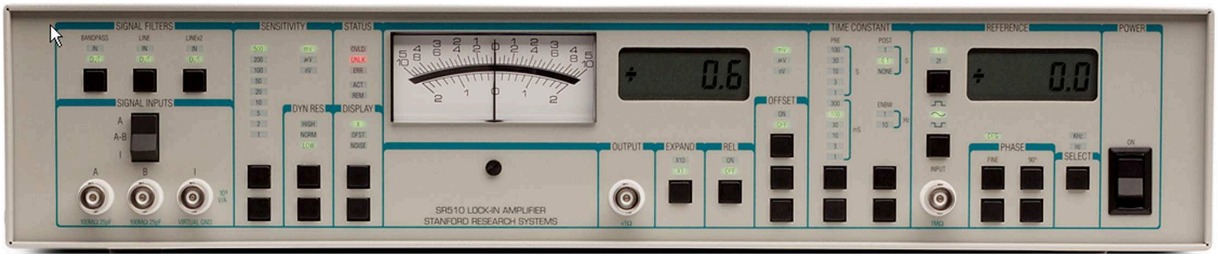

Figure 3: The front panel of the SRS SR510 Lock-in Amplifier. The settings a user might occasionally adjust are the Sensitivity, the Time Constant (Pre, not Post), the Reference Phase, and the Offset. After initial adjustments these settings will probably remain unchanged.

Figure 4: The front panel of the New Focus LB1005 Servo Controller (Servo Amp). The only setting a user might occasionally adjust is the Gain. The P-I Corner and Low Frequency Gain Limit (LFGL) will remain unchanged unless the PM failsafe system is modified. The Input Offset is not required so it was disabled by a back panel switch. To obtain lock the user will adjust the Sweep Center knob, which controls the étalon's cavity mirror separation and therefore selects a specific PM sideband, and if necessary the Sweep Span knob to observe fringes on an *xy*-oscilloscope. The Lock Off – LFGL – Lock On toggle switch opens and closes the servo loop.

Settings for the Lock-In Amp and Servo Amp should be stable unless the PM failsafe system is modified in some way, e.g., by changing the lengths of cables between the RF and Control Electronics Box, the Lock-In Amp and the Servo Amp, or perhaps by changing the RF drive power to the main phase modulator to operate at a different modulation index. In the event of these modifications the Phase of the Lock-In Amp's Reference signal might have to be reset, and also perhaps the Lock-In Amp's Sensitivity. For the Servo Amp, the Gain and the P-I Corner might also require adjustment. Procedures for making these four adjustments are given in Secs. 3.4.4–3.4.7. In the absence of modifications the settings shown in Table 2 reflect the correct settings for the Lock-In Amp and Servo Amp after the PM failsafe system was installed and tested.

3.4.1 Locking the Étalon: The Simple Case

If the PM failsafe system is warm, the laser temperature was previously stable and the laser itself has been on long enough so its green Temp LED is illuminated, and the Sweep Center knob on

Table 2: Settings for the Lock-in Amp and Servo Amp

Setting	Value
Lock-in Amp	
Signal Filters	All set to In
Signal Inputs	Switch and Input on A
Sensitivity	1 mV
Dynamic Reserve	Normal
Display	X
Expand	$\times 1$
Rel	Off
Offset	On
Time Constant (Pre)	30 ms[a]
Time Constant (Post)	None
Reference (frequency)	f
Reference Phase (degrees)	54
Waveform	Sine
Servo Amp	
Input	A (-B with ground cap)
Output	Set to 0 – 10 V
Input Offset	500 (zero volts)[b]
PI Corner	100 Hz
LF Gain Limit	Prop.[c]
Gain	$\sim$ 290 (variable)

(a) The Lock-In Amp's Time Constant will occasionally be adjusted to obtain lock and diagnose system performance.
(b) The input offset is disabled but the knob is set to its default dial position of 500, or zero volts.
(c) The LF Gain Limit is set to proportional. For any other value (dB) the LFGL is disabled when the Servo Amp's toggle switch is in the Lock On position.

the Servo Amp is set so the étalon transmission is close to a peak of a first-order sideband, then locking the étalon requires little more than putting the Lock Off – LFGL – Lock On toggle switch in the Lock On position to close the servo loop. In practice it usually works best to use a two-step process: Move the toggle switch to the LFGL position first, wait a few seconds, then try moving it the Lock On position. If the servo hops out of lock just try again until you achieve lock to the top of the fringe.[4] When closed the Servo Amp's output continuously adjusts the étalon's cavity length so it remains locked to the peak of the fringe. If an oscilloscope is monitoring the 2 GHz heterodyne beat note it should be observable at a reduced amplitude before the étalon is locked, and at full amplitude afterwards. If the 200 MHz beat note is monitored instead, as shown in Fig. 5, its fixed amplitude will change from random noise to a stable sine wave. To monitor the voltage

[4]The difficulty "grabbing the fringe" is due to the Lock-In Amp's 30 ms Time Constant. The long Time Constant makes sense for an étalon with low thermal drift and a narrow bandwidth laser with very good long-term frequency stability, but it does require setting the Sweep Center knob for maximum transmission through the étalon. To best way to succeed is to allow the system to thermalize by repeatedly adjusting the Sweep Center knob until the étalon transmission sits still at the top of a fringe. This might take more than a minute so don't be impatient.

for transmission of a fringe before and after lock, the box-mounted toggle switch on Channel 2 of the 35 MHz analog scope must be in "Fringe Detector" position, as shown in Fig. 5. When stable lock is obtained the Failsafe Status toggle switch described in Sec. 3 can be moved to the Normal Operation position and the IPG Photonics Fiber Amp can be turned on to inject light in ZBL's Regen.[5]

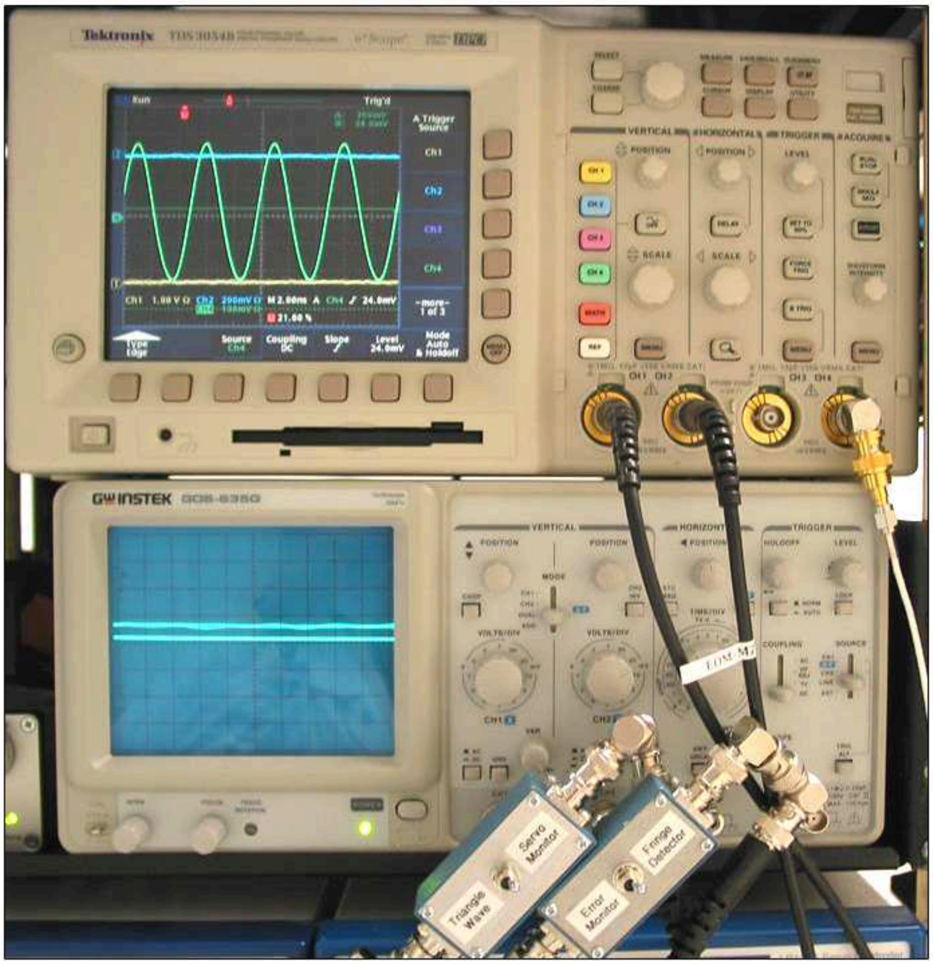

Figure 5: These two oscilloscopes are used with the PM failsafe system. The upper digital scope monitors the pulses used to drive the "Shaper," a Mach-Zehnder amplitude modulator that controls the pulse shapes injected into the Regen, and it also displays the 200 MHz heterodyne beat note from the $\div$10 prescalar. The lower analog scope operates in *xy* or *yt*-mode and displays three signals selected with the box-mounted toggle switches: Servo Monitor (Ch1), the output of the Servo Amp that is amplified to drive the PZT in the reference étalon; Error Monitor (Ch2), the error output from the Servo Amp; Fringe Detector (Ch2), the output from the fringe detector for the reference étalon. For *xy*-mode the toggle switch on Ch1 is moved to Triangle Wave. In this photograph the the étalon is locked to the peak of the fringe, which produces a DC signal of about 90 mV. The Servo Monitor signal is about 4 V, which is near the mid-range of the servo output.

[5] See italicized text in Sec. 3.5 if the IPG Photonics Amp disrupts the étalon lock.

3.4.2 Locking the Étalon: Finding a First-Order PM Sideband

If there is no heterodyne beat note, or no transmission through the étalon, then locating a fringe for a first-order sideband might require a few more steps.[6] To explain the process we'll turn off the 12.8 GHz VCO and begin with single frequency operation. This might not always be necessary, but a single frequency reference spectrum reduces ambiguity and provides a good starting point. The instructions below, and the fringe patterns and other signals in Fig. 6 will guide you through the process of locating, and locking to, the correct étalon fringe.

1. Turn the 12.8 GHz VCO power off using the toggle switch on the front panel of the RF and Control Electronics Box.

2. Put the analog scope in *xy*-mode with the box-mounted toggle switch connected to Channel 2 in the Fringe Detector position, and put the box-mounted toggle switch connected to Channel 1 in the Triangle Wave position. The knob labeled Triangle Wave Frequency on the front panel of the RF and Control Electronics Box controls the *xy* sweep rate of 1–130 Hz. Set the sweep rate near its lowest frequency.

3. Rotate the Sweep Span knob on the Servo Amp clockwise to begin sweeping the étalon cavity length. The knob clicks in and out of its off position. Increase the Span until you see more than one fringe, as shown in Fig. 6(a). Adjust the Servo Amp's Sweep Center knob so the fringes are at roughly equal distance from the center of the sweep, as shown in the figure.

4. Now turn on the 12.8 GHz VCO power and you should see the fringe pattern in Fig. 6(b). To reproduce the fringe height as shown you'll have to change the gain on the scope. You might also need to adjust the Sweep Span. Note that the modulation frequency exceeds the étalon's 10 GHz free spectral range (FSR) so you'll see overlapping PM sidebands.

5. Now rotate the Sweep Center knob so that the fringes on the left side of Fig. 6(b) are in the center of the scope's screen, and then reduce the Sweep Span until you reproduce the fringe pattern in Fig. 6(c), where the gain has been reduced compared to (b). If for some reason you accidentally zeroed in on the fringes contained in the dashed yellow boxes in Fig. 6(d), these are the wrong fringes. (The fringes on the right of Fig. 6(b) also work but the pattern in Fig. 6(c) will be reversed.)

6. Rotate the Sweep Span knob until it clicks into its off position. Put the scope back into *yt*-mode, trigger on line with time base around 1 ms, and move the toggle switch on Channel 1 to Servo Monitor. Now rotate the Sweep Center knob until the voltage you see in the scope is close to the height of the taller fringe in Fig. 6(c). The voltage will drift some but should stay within about half of the peak height of the fringe. To make sure you've selected the correct fringe observe the 200 MHz heterodyne beat note on the digital scope to see if it stabilizes (the 14.8 GHz VCO and amp must be on). Now make sure the Servo Monitor voltage is near the center of the servo range, about 4–6 V, however slightly higher or lower servo voltage is OK.

[6] Misalignment of the reference beam to the étalon is unlikely, so there is no discussion of the alignment procedure.

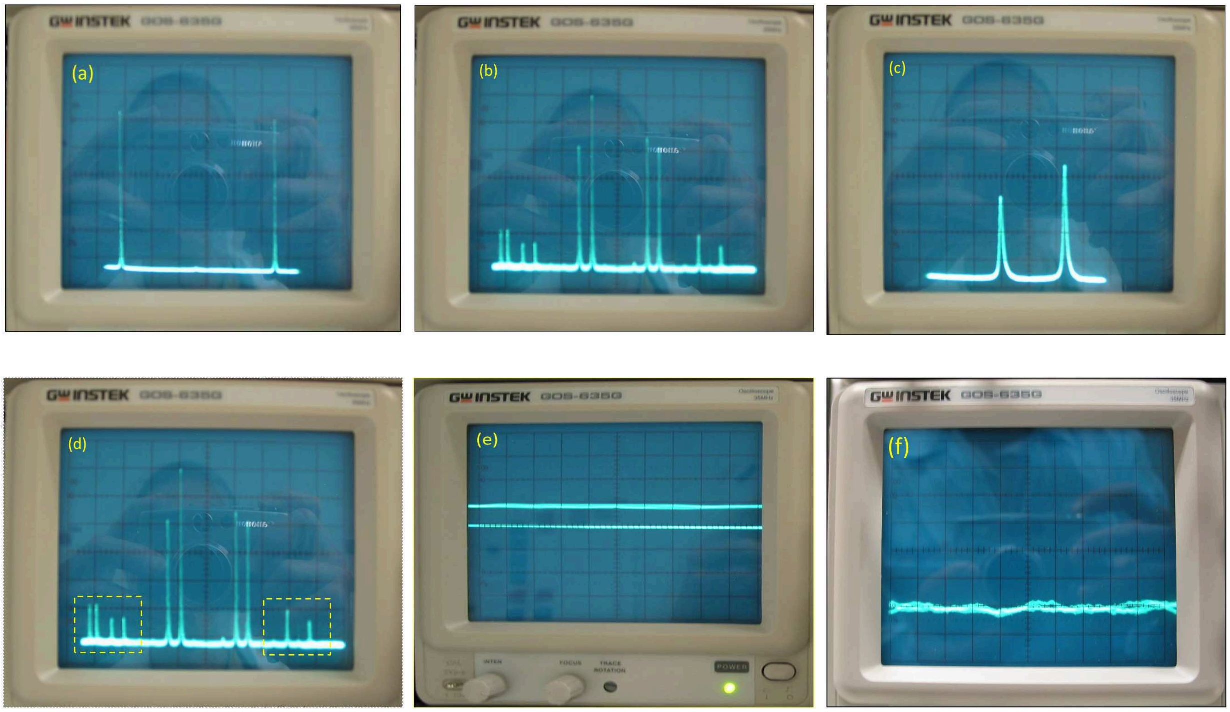

Figure 6: (a) Étalon fringes for single frequency operation. Power is off for the 12.8 GHz VCO that drives the reference phase modulator. (b) Fringes with the power on for the 12.8 GHz phase modulator. The modulation index is 2.4 and and the étalon's FSR is only 10 GHz so higher-order PM sidebands overlap. (c) The two fringes on the left in (b), with a change in the gain and offset. The taller fringe is the first-order sideband used to generate the heterodyne beat note. The ratio of the heights of these two fringes depends on the modulation index so it may be different than shown here. (d) Any of the fringes in the yellow dashed boxes are the wrong fringes and won't produce a heterodyne beat note. (e) The signal from the Fringe Detector when the étalon is locked to the peak of the fringe (upper trace at $\sim$ 90 mV in this example) and signal from the Servo Monitor, about 4 v. (f) The error signal from the Servo Amp's Error Monitor.

7. Push the Lock Off – LFGL – Lock On toggle switch on the Servo Amp to the LFGL position. If the scope trace "snaps" to the top of the fringe, then push this switch to the Lock On position. If the étalon drifted outside of the "capture range" and didn't lock to the peak of the fringe, repeat steps 6 and 7 as necessary. The Sweep Center knob requires a light touch so be patient. Also, you'll achieve lock more reliably if you continue to adjust the Sweep Center knob for a minute of so until the system stabilizes to the point where the étalon transmission sits still near the peak of the fringe.

8. Finally, you might need to check the gain on the Servo Amp. Put the box-mounted toggle switch on Channel 2 in the Error Monitor position to view the Servo Amp's error signal shown in Fig. 6(f). Nominally the error signal's baseline should be in the range of 10–40 mV (*that's the value for this system and its unique settings – it could be different for some other servo application*). If the error signal is larger increase the gain slightly. Now put the toggle switch in the Fringe Detector position and make sure the fringe signal isn't oscillating. If it oscillates the gain is too high and the servo loop might become unstable. Note that the amplitude of the oscillation depends on the Lock-In Amp's Time Constant, so set the gain

using the nominal value of 30 ms. Two examples of oscillation in the fringe signal are shown in Fig. 8.

3.4.3 The Étalon Won't Lock: How to Check Settings for the Lock-In Amp and Servo Amp

If the procedure in Sec. 3.4.2 failed then settings for the Lock-In Amp or the Servo Amp are probably incorrect, or there is a component failure in the system. Neglecting the last possibility, you'll need to confirm the Lock-In Amp and Servo Amp are set up correctly. Sections 3.4.4–3.4.7 describe how to check and adjust important settings for these two instruments. Adjustment of one setting can affect another so there's repetition and redundancy among the following procedures, but four shorter procedures are probably easier to digest than a single long one. After checking the settings and making any needed adjustments, repeat the procedure in Sec. 3.4.2. If the system still won't function correctly, and the étalon can't be locked, then refer to Secs. 4.2–4.3 for additional technical details, or obtain help from qualified personnel.[7]

3.4.4 How to Adjust the Lock-In Amplifier's Reference Phase

Background: The method we use to lock the étalon to a PM sideband is referred to as dither locking, or sometimes first-derivative dither locking. We use this method to lock to a peak rather than a simple "side lock" because it achieves maximum transmission through the étalon and therefore maximizes the amplitude of the heterodyne beat note. Application of this method is limited by various considerations, but those are left to a brief discussion of dither-locking in Sec. A.3. For now it's sufficient to say our system is well suited to this technique. To achieve lock we dither the étalon cavity length at 20 kHz and use the same 20 kHz as the reference to a Lock-In Amp to demodulate the time-varying voltage $V(t) = V(\omega(t))$, that is generated by the étalon's fringe detector. The resulting error signal is proportional to $dV/d\omega$, where ω is the angular frequency and ω_0 locates the peak of an étalon resonance. Dither locking requires a specific phase relationship between the Lock-In Amp's reference and $V(t)$ so it must be set correctly, which is the subject of this section. The procedure below describes how to tell if the phase is correct, and how to adjust it if necessary.

1. This procedure is simpler using a single frequency spectrum so put the toggle switch for the 12.8 GHz VCO on the front panel of the RF and Control Electronics Box in the off position.

2. Place the Lock Off – LFGL – Lock On toggle switch on the Servo Amp in the Lock Off position. Set the oscilloscope to *xy*-mode and put the toggle switch on the scope's Channel 2 in the Fringe Detector position. Rotate the Sweep Scan knob on the Servo Amp so the étalon cavity length is swept at low frequency. Use the Sweep Center knob on the Servo Amp to place an étalon fringe in the center of the sweep then reduce the Sweep Scan so the fringe width is about $1/5$ of the sweep range.

[7] If the author is available he's the best person to contact. Otherwise, this manual and its technical reference sections should contain enough information for a good experimenter to sort things out.

3. The lock-In Amp's Pre Time Constant was probably set at 30 ms but it must be set to 1 or 3 ms to accurately observe the characteristics of the demodulated signal (the error signal), so change it if necessary.

4. Now put the toggle switch on Channel 2 in the Error Monitor position and you should see a signal that is similar to the signals in Fig. 7. The error signal will likely be much larger than the fringe signal so set the scope's gain accordingly. Also, ground Channel 2 and set zero volts to the vertical center of the scope, then observe the signal again.

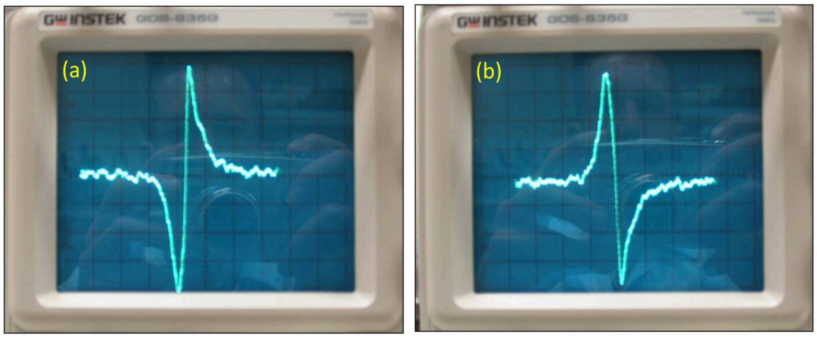

Figure 7: (a) The demodulated étalon fringe signal from the Lock-In Amp as seen through the Servo Amp's error monitor. To reproduce this signal the Lock-In Amp's Time Constant needs to be set on 1 or 3 ms. (b) The same signal as in (a) with the Lock-In Amp Reference Phase shifted by 180°. Only one of these two signals has the correct phase to lock to the peak of a fringe.

5. If the error signal looks very similar to either of the signals in Fig. 7 then the Lock-In Amp's Reference Phase is probably OK, but we'll test that as we work through the rest of these steps.

6. If the baseline of the error signal deviates much from ground then use the Lock-In Amp's Offset adjustment to return the signal's baseline to ground. If the signal appears clipped, and the LEDs for the Lock-In Amp's Sensitivity are blinking red, then set the Sensitivity to a higher value. Additional details on setting the Lock-In Amps' Sensitivity are given in Sec. 3.4.5.

7. The lock point in the error signal is at ground along the steep slope, so if the signal is asymmetric the system probably won't lock very well, or if it's symmetric but out of phase by 180° it won't lock at all. Observe this signal and compare it to the signals in Fig. 7.

8. To optimize the Reference Phase use the Lock-In Amp's Reference Phase buttons (Fine, not 90°) to make the demodulated signal as large as possible and symmetric about ground. The maximum in the signal may not be immediately obvious so optimization might require a few iterations. You might find the error signal is already optimized, and if it is you should be able to lock the étalon to the fringe without any further phase adjustments.

9. To achieve lock, turn off the sweep, put the Channel 2 toggle switch in the Fringe Detector position, set the Lock-In Amp's Time Constant to 10 or 30 ms and use the Sweep Center knob to locate the peak of the fringe. Put the Servo Amp's toggle switch in the LFGL

position and the system should appear to lock. Note that the single-frequency fringe is much larger than a first-order PM sideband so the servo gain might be to high and the signal from the fringe detector might oscillate. Turn down the gain if necessary to further optimize the lock.

10. If the fringe detector voltage moves away from the peak and approaches zero, the reference phase is likely off by 180°. Deviation from the peak is usually not subtle and could be described as being "blown out of lock," but how quickly this happens depends on various Lock-In Amp settings. If you observe this behavior after several attempts to lock then try using the Lock-In Amp's Reference Phase 90° buttons to shift the phase by 180°. The demodulated signal should switch phase as shown in Fig. 7.

11. If you do obtain a satisfactory lock then set the Servo Amp's toggle switch to Lock Off and turn on the 12.8 GHz VCO. Use the procedure in Sec. 3.4.2 to locate the correct fringe for the first-order sideband and re-establish lock. You'll need to set the Lock-In Amp's Pre Time Constant back to 30 ms, perhaps reset the Lock-In Amp's Sensitivity, and also reset the servo gain to get a "tight" long-term lock. Note that the response to the Sweep Center knob will be slower for the 30 ms Time Constant.

12. Finally, if you're new to stabilization techniques such as dither locking, be patient and realize it may require several iterations to get things right.

3.4.5 How to Adjust the Lock-In Amplifier's Sensitivity

To correctly set the Lock-In Amp's Sensitivity for long-term operational lock (i.e., with the 12.8 GHz reference PM drive on, not off, as in Sec. 3.4.4) make sure the 12.8 GHz VCO is on and follow the instructions in Sec. 3.4.2 to locate an étalon fringe that corresponds to a first-order PM sideband. Also, you must have the Lock-In Reference Phase set correctly as described in Sec. 3.4.4.

1. Begin by repeating steps 2–4 in Sec. 3.4.4.

2. Use the Triangle Wave Frequency knob on the RF and Control Electronics Box to set the sweep frequency to its lowest value of about 1 Hz.

3. While sweeping the étalon's cavity length select a sensitivity value where there is noticeable deflection of the Lock-In Amp's needle with the Display on X. If the LED for that setting is flashing red the sensitivity is too low, so set it to a higher value. Many times the correct value will be about two settings below where the LED flashed red, e.g., reducing the sensitivity from 200 μV to 1 mV.

4. Ideally we want close to full deflection of the needle while sweeping through the steep-sloped portion of the demodulated signals shown in Fig. 7. To actually see this much deflection you'll probably have to put the Sweep Span knob in its off position and manually sweep using the Sweep Center knob. If it's difficult to manually maintain the zero-volt lock point on the steep slope then you might need to set the sensitivity to the next lower setting.

5. At this point the sensitivity should be close to optimum but if you later find it's difficult to obtain lock using the Sweep Center knob on the Servo Amp it's OK to further reduce the sensitivity.

3.4.6 How to Adjust the Gain for the Servo Amplifier

To optimize the adjustments in this section you must be able to lock the étalon. If that is not the case then see Secs. 3.4.1, 3.4.2, 3.4.4, or 3.4.5. The procedures here are also used in Sec. 3.4.7.

1. After you have determined appropriate settings for the Lock-In's Sensitivity and Time Constant (currently 30 ms), lock the étalon to a first-order PM sideband and observe the étalon fringe signal with the analog scope's hannel 2 toggle switch set to Fringe Detector, and with the scope triggered on line. Adjust the scope's time base as necessary, usually about 1 ms.

2. Adjust the gain knob on the Servo Amp until the fringe signal appears like the one shown in Fig. 8(a), where there are very small excursions from the average value. If the gain is too low the fringe signal might drift away from the peak of the fringe. If the gain is a little too high the signal will exhibit small oscillations as shown in Fig. 8(b), and if the gain is so high that the servo loop begins to oscillate, the fringe signal might appear as shown in Fig. 8(c), however a lower Time Constant of 10 ms might be required to observe the oscillations.

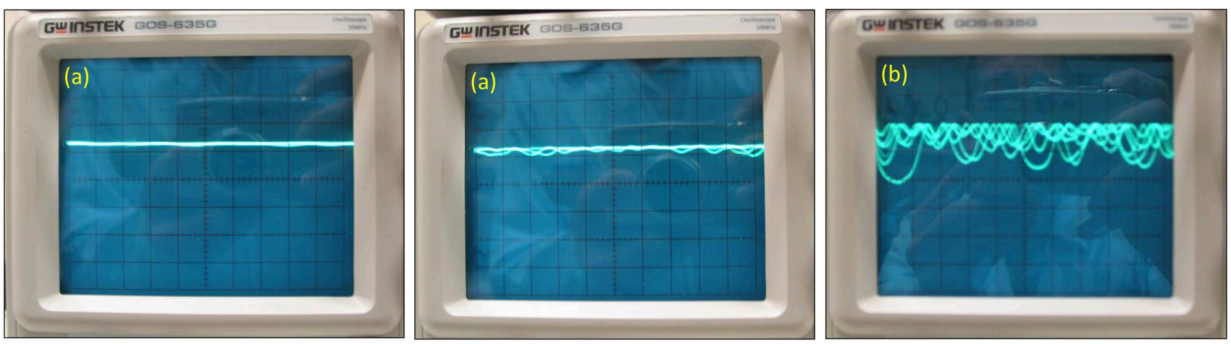

Figure 8: (a) The étalon fringe signal when the gain is set correctly. There will usually be some very small excursions in the fringe signal. (b) Étalon fringe signal showing a small amount of oscillation when the Servo Amp's Gain is slightly too high. This amount of oscillation is undesirable so the gain should be reduced until the fringe signal appears approximately the same as in (a). Note that the amplitude of oscillation depends on the Lock-In Amp's Time Constant, so use the setting for long-term lock to make these adjustments, currently 30 ms. (c) Étalon fringe signal with gain set intentionally too high to induce oscillation. This is done for estimating the P-I Corner frequency for the Servo Amp as described in Sec. 3.4.7.

3. For additional guidance for setting the gain, set the Channel 2 toggle switch to Error Monitor and observe the error signal. For the settings in Table 2 the baseline for the error signal should be in the range of 10–40 mV. Note that this value of the error signal applies to this system in particular and not to some other servo application.

4. Adjust the gain knob to observe the behavior of the error signal. If the gain is low enough that the fringe signal might drift away from the peak of the fringe, the error signal will increase. If the gain is too high so that oscillation begins to set in, the error signal will also indicate oscillation. We don't want the servo system working too hard so observing the error signal, in addition to the étalon fringe signal, provides good guidance for finding a stable operating point.

3.4.7 Selecting the P-I Corner for the Servo Amplifier

The P-I corner frequency is the 3 dB break frequency after which the servo loop's proportional gain dominates over integral gain. The P-I corner must be determined for each servo system and this is easy to do using a simple rule. As before in Sec. 3.4.6 setting the P-I corner frequency requires the abilit to lock the étalon, at least for a short period of time. If you can't obtain lock see Secs. 3.4.1, 3.4.2, 3.4.4, 3.4.5, or 3.4.6 as necessary.

1. Begin by repeating steps 1 and 2 in Sec. 3.4.6 and then set the Servo Amp Gain until you reproduce the fringe signal oscillations shown in Fig. 8(c). The oscillation might not be identical in appearance to the signal shown in Fig. 8(c) and it might not have a well-defined easy to determine oscillation frequency. It's OK to reduce the Lock-In Amp's Time Constant from the nominal setting of 30 ms to enhance the oscillations, but don't reduce it below 10 ms.

2. Approximate the oscillation frequency from the fringe signal on the analog scope. This is easy for some dither-locked systems because oscillation appears as a stable sine wave. If that's the case trigger on the signal and read its frequency. If the oscillation signal appears to contain multiple frequencies as in Fig. 8(c) then determine a "best estimate" frequency.

3. After estimating the oscillation frequency, f_{osc}, use this simple rule to determine the P-I corner frequency, $f_{\mathrm{P-I}}$:

$$f_{\mathrm{P-I}} = \frac{f_{\mathrm{osc}}}{2\pi} \quad (\mathrm{Hz}) \tag{1}$$

4. $f_{\mathrm{P-I}}$ in Eq. 1 probably won't coincide with one of the values available from the Servo Amp's P-I Corner knob, so select the nearest frequency.

5. Lock the system and test the suitability of the P-I corner frequency (if you reduced the Lock-In Amp's Time Constant then reset it to 0 ms). If the lock is unstable against small changes in gain or environmental perturbations (yelling or whistling for acoustically coupled systems, pounding on the optical table) then try the next closest P-I corner frequency. There should be one P-I corner that results in the most stable lock.

3.5 Activating the Latch-to-Ground and Hold Circuit to Arm the Failsafe

The PM failsafe system includes a latch-and-hold circuit described in Sec. 4.3.8 that grounds the inputs to the fast switches shown in Fig. 12 for any failure in the PM failsafe system. When a failure occurs the fast stage of this circuit responds in about 30 ns and temporarily holds the switch inputs at ground for about 2.5 ms. During this time period the interlock for the IPG Amp will trip and a relay interrupts the power for both VCOs, effectively shutting down the system. The shutdown process occurs approximately 2 ms after the initial 30 ns fast response. After shutdown the PM failsafe system can be reactivated only by an individual trained in its operation.

As described at the beginning of Sec. 3, the Latch & Hold Disable toggle switch must be in its up position, and the Failsafe Status toggle switch must be in the down position to select the Latch & Hold Reset condition to turn on the VCOs so the étalon that filters the reference PM spectrum can be locked. After the étalon is locked the Latch & Hold circuit can be activated by moving the Failsafe Status toggle switch up for Normal Operation. When the green LED is illuminated the Failsafe system is armed and the IPG Photonics Fiber Amplifier can be turned on to inject light into ZBL's Regen. Any subsequent failure of any part of the system will ground the inputs to the fast switches, turn off the IPG Amp, and turn off the VCOs that power the phase modulators.

Note: Rotating the key on the front panel of the IPG Photonics Amplifier to its on position sometimes generates a high-speed free-space RF field that has sufficient strength to affect various components in the PM failsafe system. A typical result from this disturbance is the étalon might come unlocked, which results in the system shutting down as if there were an actual failsafe event. There appears to be no practical way to eliminate this ”feature” of the IPG Amp, so if it continues to disrupt the system, try this alternate sequence of events: (1) Adjust Sweep Center for maximum étalon transmission; (2) Turn on the IPG Amp; (3) Quickly put the Servo Amp toggle switch in the lock position; (4) Quickly put the Failsafe Status toggle in the up position. Steps 3 and 4 must be completed well before the IPG Amp completes its turn-on sequence or else the interlock signal from the control electronics will shut it down.

3.5.1 The Special Case of Single Frequency Operation

Single frequency operation is a special operating mode for the PM failsafe system that is used solely for diagnostic purposes. Configuring the system for single frequency operation circumvents normal operation of the latch-to-ground and hold circuit so the IPG Amp can be activated, but the interlock for the IPG Amp will otherwise function normally. If the system electronics are redesigned at a later date single frequency operation can become a standard operating mode but for now it can only accessed using the following procedure.

1. Turn off the power for the 14.8 GHz VCO using the toggle switch on the front of the RF and Control Electronics Box. If the failsafe system was previously armed this will trip the interlock for the IPG Amp.

2. Put the IPG Amp Interlock toggle switch in the down position that is labeled PM Disable.

This replaces the failsafe TTL trigger with 5V DC in the IPG Amp interlock circuit and bypasses a solid state relay on the latch-to-ground and hold circuit board that would normally open the shorted circuit that activates the interlock. Operation of the IPG Amp interlock is described below in Sec. 3.6.

3. Put the Failsafe Status toggle switch in the down position labeled Latch & Hold Reset so the 12.8 GHz VCO will remain operational.

4. The position of the Latch & Hold Disable toggle switch doesn't matter so leave it in the up position (enabled).

5. If the étalon is not locked to a 12.8 GHz PM sideband then choose one of the two sidebands where the peak of the fringe is near the nominal voltage observed on the oscilloscope. There will be no heterodyne beat note that normally indicates the correct PM sideband but it doesn't matter for single frequency operatoin. This step is required to provide a short circuit for the IPG Amp interlock.

6. Turn the key for the IPG Amp to its On position and configure the power output accordingly. For PM output this is nominally 0.8 W.

7. Do not accidentally move the Failsafe Status toggle switch to its up position for Normal Operation because doing so will trip the interlock for the IPG Amp.

3.6 Operation of the Interlock for the IPG Photonics Amplifier

There are two operational states for the interlock that controls the IPG Photonics Fiber Amplifier. The default state is for injection of phase modulated light into ZBL's Regenerative Amplifier, while the other allows injection of single frequency light. Either state requires the presence of two TTL signals to provide a short circuit the interlock: One is derived from the first-order PM sideband that is transmitted through the étalon; the second is derived from the failsafe trigger signal, or for single-frequency light, from 5V DC supplied by the low-voltage circuit board. The intentional redundancy of requiring two signals adds a margin of safety for the use of PM light because the system must be fully operational or the IPG Amp will shut down. For single frequency light the requirement that the étalon be locked ensures that light is injected into the amplifier before it can be activated, otherwise it can suffer serious damage. The interlock circuit consists of pre-amps and Schmitt triggers for each signal followed by an AND gate that drives a solid state relay that forms the short to deactivate the IPG Amp's interlock. The interlock circuit is shown in Sec. 4.3.4. The latch-to-ground and hold circuit board described in Sec. 4.3.8 contains a secondary solid state relay that interrupts the short and trips the interlock in the event of a system failure, and single frequency operation bypasses this secondary relay, but it doesn't otherwise affect the operation of the interlock.

The interlock states are selected by a toggle switch in the lower right corner of the front panel of the RF and Control Electronics Box that is labeled IPG AMP Interlock. The toggle has positions for "PM Enable" and "PM Disable," where the disabled position replaces the failsafe's trigger signal with 5V DC. In the PM Enable state the étalon must be locked to a first-order sideband of the 12.8 GHz reference PM spectrum so that the resulting optical heterodyne beat note can be detected and converted to the failsafe trigger voltage, which is TTL high. For the PM Disable state the 14.8 GHz drive will be turned off, but the 12.8 GHz PM drive should remain on at all times and the étalon should remain locked to a first-order PM reference sideband.[8]

3.7 The High-Low and Low-High Failsafe Transitions

On the left side of the front panel of the RF and Control Electronics Box there are two SMA bulkhead connectors labeled "Failsafe TTL Signal Outputs" for Ch1 and Ch2, and one toggle switch labeled High-Low and Low-High.

When driving a $50\,\Omega$ load on a high speed oscilloscope the high–to–low transition occurs from about 2.8 V to ground, and the low–to–high transition from ground to ≤ 2 V initially, then up to ~ 2.8 V after a delay of approximately 25μs. After the heterodyne beat note disappears, the transition time to a level of 1 V, up or down, can be adjusted from approximately 28–40 ns. A typical 30 ns negative-going transition is shown in Fig. A.9 in Sec. A.7 where instructions are given for carrying out a failsafe speed test.

The delay of 25μs that follows the initial positive-going fast transition into $50\,\Omega$ is undesirable but it would be difficult to entirely eliminate it. Fortunately it probably doesn't matter because the low–to–high trigger-inhibit inputs on the SRS DG645 pulse generators that are used throughout ZBL respond near 1 V for a positive going edge, and their input impedance is typically closer to 1 MΩ. The charge-up time into $50\,\Omega$ observed for a high speed measurement will likely be reduced when driving 1 MΩ loads. The SRS DG 535 pulse generators that were ordered with custom trigger inhibit inputs are active for TTL high and inhibited by a falling edge at about 1 V, so the high–to–low transition works well with these instruments. *Note that a high–to–low transition terminated into* $50\,\Omega$ *is preferred from a safety standpoint because loss of the high failsafe signal for any reason inhibits triggering, whereas using low–to–high to inhibit the trigger could allow triggering during a system failure.*

[8]For the PM Disable state the interlock can probably operate with the 12.8 GHz reference PM drive off and the étalon locked to a fringe from the single-frequency spectrum, but if you've read Secs. 3.4.1–3.4.7 you know it's not worth the hassle of changing the Lock-In Amp and Servo Amp settings, so don't do it. An additional AND gate that would require the reference PM drive be on could eliminate the ability to lock to a single-frequency fringe, but there's no reason to operate the system that way so it was not included in the design of the circuit board. Also, you might figure out that about 90 mV could be applied to the Étalon Fringe Detector Input on the front of the RF and Control Electronics Box to duplicate the voltage for normal operating conditions when the étalon is locked to a first-order sideband. *This should never be done under any circumstances because it completely decouples operation of the amplifier from the presence of seed light. Absence of seed light can result in serious damage to the amplifier.*

3.8 Periodic Test of the PM Failsafe System

The PM Failsafe System should be tested periodically to ensure it will function as expected. The test is simple and consists of generating a failsafe event by turning off the power to the main PM VCO using its front panel toggle switch on the RF and Control Electronics Box. A digital oscilloscope with bandwidth of 500 MHz is adequate for observing the failsafe signal during the test. The required steps are listed below.

1. The PM Failsafe System must be armed as described in Sec. 3.5 to carry out this test.

2. Attach an unused Failsafe TTL Signal Output on the RF and Control Electronics Box to a digital oscilloscope with bandwidth of 500 MHz and set the Transition toggle switch for High-Low. Set the vertical scale to 500 mV with 50 Ω termination and set the time base to 20 ns. A lower bandwidth oscilloscope can be used if there is nothing else available.

3. Set the scope's trigger for auto roll mode and you should observe the failsafe signal's DC voltage level of about 2.5 V.

4. Now set the trigger to detect a falling edge the with the trigger point one time division or so from the left edge of the display and set the trigger level to about 1.5 V. Set the scope for a single sequence acquisition.

5. Turn off the power for the main PM VCO using its toggle switch on the front of the RF and Control Electronics Box and acquire a waveform. If this is the first test and the scope will be dedicated for this test you might want to save this waveform as one of the scope's reference waveforms so it can be displayed again as a good example for subsequent tests. An example of reference and secondary failsafe signal waveforms for this test are shown in Fig. 9.

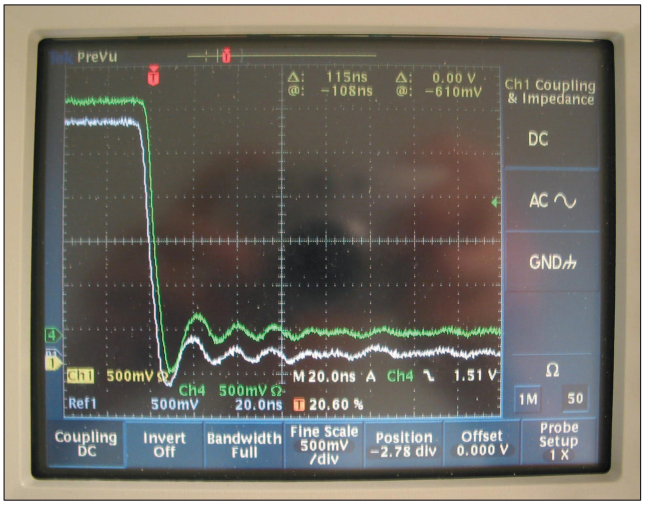

Figure 9: Example high-low failsafe signal waveforms for a periodic test of the PM Failsafe System.

6. If the waveform you observe oscillates wildly or doesn't fall to ground and stay at ground then don't rely on the PM Failsafe System. If you set the Transition toggle switch to Low-High then replace "ground" in the previous sentence with "TTL high." Either way, if the system failed the test the problem must be diagnosed and corrected.

7. In the event of a failure or poor behavior of the failsafe system, there are two other signals that can be observed, they are: Latch–&–Hold 1-Shot Q-Out Monitor; and Failsafe Trigger Monitor. These signals are available from two BNC bulkhead connectors in the lower right corner on the front panel of the RF and Control Electronics Box. For a normal system test the 1-Shot Q-Out Monitor should go high to about 1.5 V then drop to a little below 1 V so that it remains above ground for a total of > 2 ms, while the Failsafe Trigger Monitor should make a high–to–low transition to ground and stay there. The edges of these signals should display transitions as fast as the failsafe signal and precede the failsafe signal by approximately 10 ns. If the behavior of these signals is other than described here, the cause must be determined and the problem corrected.

8. If all is well, re-arm the system as described in Sec. 3.5.

4 Principles of Operation of the PM Failsafe System

Sections 4.1–4.3 describe the principles of operation of the PM failsafe system and provide details about two of the three Sandia-built rack-mounted boxes that comprise most of the system. We begin with a short discussion of how optical heterodyne techniques are used to detect phase modulated light.

4.1 Use of Optical Heterodyne Techniques to Detect PM

Detection of phase modulated light using heterodyne techniques is based on generating an optical beat note that is converted to an RF electrical signal using a high speed detector. Although optical heterodyne techniques can achieve extremely high sensitivity [14], in free-space their usefulness can be diminished by aberrations in lenses, beam tilts, poor beam overlap, refractive turbulence, and speckle. On the other hand a system consisting of mostly SMPM fiber like the one shown in Sec. 4.2 is largely immune to these effects because the interacting waves are confined to a waveguide with the dimensions of the lowest-order spatial mode. The only challenge posed by the fiber based system in Sec. 4.2 is that some form of phase stabilization might be required because it forms an amplitude-splitting Mach-Zehnder interferometer with a phase modulator in each leg, where two waves derived from the same source are individually modulated at different frequencies and later recombined to generate the beat note. We refer to these waves as the "reference" and the "main," where the main PM spectrum is characterized by a higher modulation frequency and higher modulation index β. The number of PM sidebands, their amplitudes, and the carrier amplitude, are determined by β, and if the two β's result in nonzero carrier amplitudes then the carriers interfere to generate a slowly varying baseline, i.e., they form an étalon fringe analogous to the fringes observed with single frequency light.[9] The degree to which the resulting slow baseline drift can influence the amplitude and stability of the high frequency heterodyne beat note depends on each β and how much the system is exposed to environmental perturbations such as acoustical coupling and temperature variations. Fortunately these low frequency perturbations can be largely eliminated by selecting β's that result in zero carrier amplitude so that the heterodyne beat note maintains a stable amplitude. For this reason the ZBL PM failsafe system uses β's with zero carrier amplitude.[10] Although loss of the carrier reduces the number of discrete lines in a PM spectrum by one, modern fiber-coupled $LiNbO_3$ phase modulators easily compensate for the loss because large β's with more than enough additional sidebands can be produced using modest RF drive power.

Figure 10 shows two simulated PM spectra used in the ZBL phase modulation failsafe system, where the solid red sideband indicates the portion of the reference PM spectrum that is filtered by an étalon and mixed with the main PM spectrum to produce an optical beat note. The amplitudes

[9] See Sec. A.2 if you are unfamiliar with phase modulation and the effect of the modulation index β.

[10] During initial development the PM failsafe system used $\beta_{\text{main}} \approx 4.8$ and a temperature tuned solid étalon with a free spectral range > 100 GHz, but its finesse was too low to uniquely isolate a single first-order PM sideband as desired, so it suffered from carrier interference. Use of the high-finesse 10 GHz tunable étalon as a filter eliminates interference, but we retained the zero-carrier β's because we anticipate employing the slow-drift β monitoring technique described in Sec. A.5 in a future version of the PM failsafe sytem.

of the sidebands are correct for PM waves with $\beta = 2.42$ and $\beta = 5.52$ that have equal total power, but the actual amplitudes of the interfering sidebands in the failsafe system are different. In addition, the system currently uses a main PM frequency of 14.8 GHz and reference PM frequency of 12.8 GHz. The plot is intentionally truncated at the ±5th-order sidebands for clarity. As shown in Fig. 10 the beat note frequency for interference of the +1-order sidebands is 2 GHz, while higher interference frequencies from non-equal sideband orders, e.g., +1-order reference interfering with +2-order main at 19 GHz, are integrated by the optical detector due to its 8 GHz bandwidth so the power for the higher frequencies contributes to a DC offset in the detector's output. A 1.7–2.3 GHz bandpass filter eliminates the DC offset and other remaining frequencies outside of its pass-band before the detector's output is processed to generate a failsafe signal.

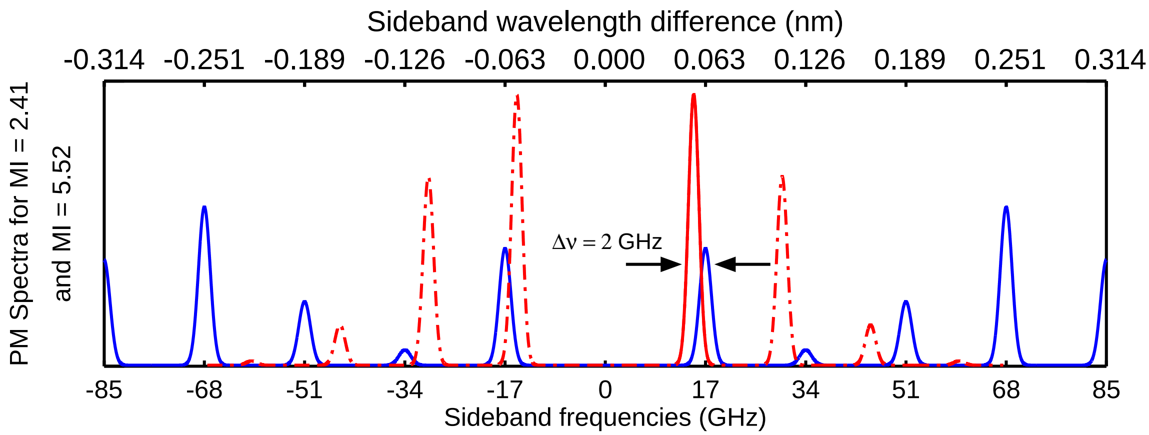

Figure 10: Plot of PM spectra for MI = 2.42 (red) and MI = 5.52 (blue) showing how first-order sideband interference generates the 2 GHz heterodyne beat note used for the PM failsafe system. In this example the main modulation frequency is 17 GHz and the reference frequency is 15 GHz, and the solid red sideband represents the first-order sideband transmitted by the étalon. The main and reference frequencies in the current system are 14.8 GHz and 12.8 GHz, respectively. See text for additional details.

4.2 Details of the Laser and Optical Components Box

The Laser and Optical Components Box houses the stabilized fiber laser and all fiber-optical components required to generate the optical heterodyne beat note. This box also contains a gain-adjustable transimpedance amplified detector for the étalon fringe signal and a fiber-coupled 8 GHz detector for the heterodyne signal. A functional diagram of the contents of this box is shown in Fig. 11, and Table 3 contains a list of its major components, except for the mechanical parts in a cage assembly that houses the étalon and its coupling optics. Specifications for some of these components are included in the PM Failsafe Binder that is located in the MO292 Document Depository, and they are also available from the Documentation Server in directory \\FS01960NT\ZBL_PM_Failsafe.

Because fiber optics are susceptible to perturbation from acoustical coupling, the top panel and three of the side panels are lined with vibration-absorbing sorbothane sheets held in place by plexiglass. The numerous switches and bulkhead connectors in the front panel make it difficult to attach the same sound-deadening liner to its interior surface, so this panel can transmit sound, but the contents of the box are reasonably well decoupled from the surrounding environment. The front panel connections are listed in Table A.1.

On the bottom of the box the laser and all optical components, including a cage system that holds the étalon assembly, are mounted to an aluminum breadboard that rests on five Sorbothane feet. Because Sorbothane is somewhat sticky the feet are not mounted to the bottom panel on the box, so this box must remain horizontal and upright at all times. It must never be tilted, shaken, dropped from any height, or be subject to any form of rough handling.

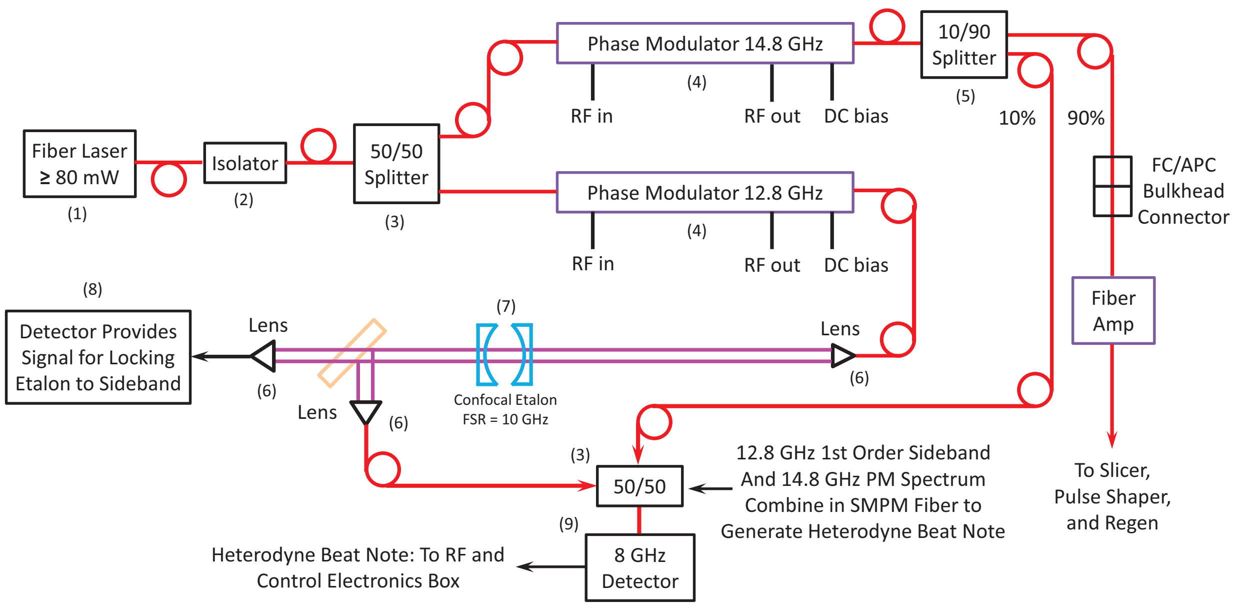

Figure 11: Functional diagram for the contents of the Laser and Optical Components Box. The mode matching lenses for the confocal scanning étalon, and its output collimating lens, are not shown in the figure but appear in order in Table 3, numbers 10–13, along with all other numbered parts. The fiber amplifier is in a separate rack mounted box. See text for additional details.

Anyone experienced with lasers, fiber optics, and electro-optics, should find the the operating principles of the Laser and Optical Components Box to be second nature. Figure 11, along with the discussion in Sec. 4.1, should be sufficient to understand how the fiber-optic components in this box work together to provide phase modulated light to seed ZBL's Regen, and how they generate the heterodyne beat note. In general this is a"hands off" box because nothing inside should ever require adjustment unless a major component must be replaced. In that case there are only two important considerations:

Laser replacement If the laser fails and can't be repaired it must be replaced with a laser that has specifications for long-term frequency stability and line width that are similar to those for the NP Photonics Rock Laser. The laser power should not exceed 80–85 mW at 1053 NM because higher power could damage the fiber-coupled $LiNbO_3$ waveguide modulators. Although these modulators accommodate optical power in the range of 1W for telecom wavelengths, the combination of photo-refractive effects and smaller mode diameter at 1053 nm

Table 3: Part list for Fig. 11 – Laser and Optical Components Box

No.	Description	Manufacturer	Part number
1	Fiber laser	NP Photonics	RFLSA-2000-1-1053-PM-SS0†
2	Optical Isolator	Thorlabs	IO-J-1064APC
3	50/50 fiber splitter	Thorlabs	PMC1060-50B-APC
4	Phase modulator	EOSpace	PM-0K3-20-PFA-PFA-106-DC-UL‡
5	10/90 fiber splitter	Thorlabs	PMC1060-90B-APC
6	Fiber collimation lens	Thorlabs	TC12APC-1064
7	Scanning étalon	Thorlabs	SA210-8B
8	Fringe detector	Thorlabs	PDA36A§
9	Fast detector	Thorlabs	PDA8GS
10	Étalon input lens	Thorlabs	C280TME-1064♮
11	Étalon input lens	Thorlabs	C110TME-1064♮
12	Étalon input lens	Thorlabs	LA1509-C
13	Étalon output lens	Thorlabs	LA1708-C

† The NP Photonics fiber laser and IPG Photonics Fiber Amplifier were sold together by NP Photonics using a single part number.
‡ The two EOSpace phase modulators are identical with serial numbers 121623 and 121626.
§ The gain setting for the finge detector is 20 dB with a bandwidth of 1 MHz.
♮ The C280TME and C110TME lenses form a down-collimating Keplerian telescope.

restrict the maximum continuous optical power for each modulator to about 30 mW.

Étalon realignment In the unlikely event the étalon becomes damaged, a replacement must be essentially the same otherwise the mode matching optics will have to be replaced as well.[11] Replacement requires realignment and it must be done carefully otherwise the coupling efficiency into the fiber for the 50/50 combiner will be poor. The confocal étalon alignment is correct when its transmitted beam, on resonance, forms a single spot in the far field. It's possible to achieve what appears to be good coupling and high finesse with a less than ideal far field beam pattern.

4.3 Details of the RF and Control Electronics Box

This section provides brief descriptions of the functions of the various subsystems housed inside the RF and Control Electronics Box, including figures with circuit diagrams for each subsystem. Part numbers for the individual components are in tables below the figures. Complete specifications for these components are included in the PM Failsafe Binder that is located in the MO292 Document Depository, and they are also available from the Documentation Server in directory \\FS01960NT\ZBL_PM_Failsafe.

The descriptions of the subcomponents are not complete in every detail, but an engineer or

[11] Department 1682 (it's designation when this manual was written) owns a replacement étalon.

experimenter with some knowledge of RF electronics, some background with simple analog circuits that use standard IC's, and some patience, should be able to understand the failsafe system's electronics. To aid in that task some explanation of how various components work together will be provided, and if it becomes necessary to trouble-shoot the circuit board, the locations of the IC's are shown in Fig. A.11 in Sec. A.9. The locations of the IC's on the latch-to-ground and hold circuit board do not identically match the diagram in Fig. 20 but they are easily identified otherwise.

4.3.1 The Electronics for Converting the Heterodyne Beat Note to TTL

Figure 12 shows the RF components that convert a 2 GHz electrical beat note into a high-bandwidth TTL failsafe signal. The conversion process uses pre- and post-amplification, power detection, and low-pass filtering, but does not use phase-sensitive demodulation as required, for example, by the techniques shown in Figs. A.3 and A.4. Instead, optical heterodyne detection effectively plays the role of demodulation by down-shifting the 14.8 GHz modulation frequency to a 2 GHz optical beat note. Although 2 GHz falls in the microwave band it's a low enough frequency that suitable optical detectors and RF power detectors are inexpensive and readily available. Use of power detection is particularly convenient and reliable because unlike electrical demodulation techniques it requires no local oscillator.

Although RF power detectors are simple to employ, their output signals might require filtering before they are used in high bandwidth applications such as the ZBL PM failsafe system.[12] When the power detector's output is observed with sufficient bandwidth it is seen to consist of a DC baseline plus occasional residual high frequency spikes. To eliminate any possibility of spurious triggering of the 5 GHz switches in Fig.12, the spikes must be removed by a low-pass filter. Prior to filtering, the power detector's output can be amplified as necessary using high-bandwidth DC-coupled amplifiers until the baseline reaches a level that exceeds the TTL threshold for the switches. After filtering, the remaining DC provides what we call the failsafe trigger for the system. The trigger controls the inputs to the pair of switches that have their RF inputs biased at 5 V, and the switches are followed by 180 MHz fast buffers. The buffers are included to ensure that the failsafe system can continuously source enough current for devices that have input impedance of 50 Ω. As discussed in Sec. 3.7 the 5 GHz switches have outputs for high–to–low and low–to–high transitions.

Immediately following the 2 GHz band pass filter in Fig. 12 the beat note amplitude is typically a few 10's of mV so it must be amplified for its detected power to result in an adequate DC voltage. To provide enough gain prior to power detection the system employs several stages of amplification, so it's possible to unintentionally saturate the input of a subsequent amplifier. At the onset of saturation the temporal response of the system will increase to 100's of ns from a nominal value of about 25–40 ns. To prevent this from occurring the variable attenuator that follows the directional coupler can be adjusted to control the overall gain. This adjustment can done correctly

[12]There are active and passive RF power detectors. The Crystek detectors used in this system are passive and are observed to sometimes transmit residual high frequencies so their output must be filtered. This might not be true for active RF power detectors.

only while monitoring the system's response time using the speed test described in Sec. A.7. If the amplitude of the heterodyne beat note following the 2 GHz band pass filter in Fig. 12 changes for any reason, a speed test should be carried out immediately to reset the variable attenuator.

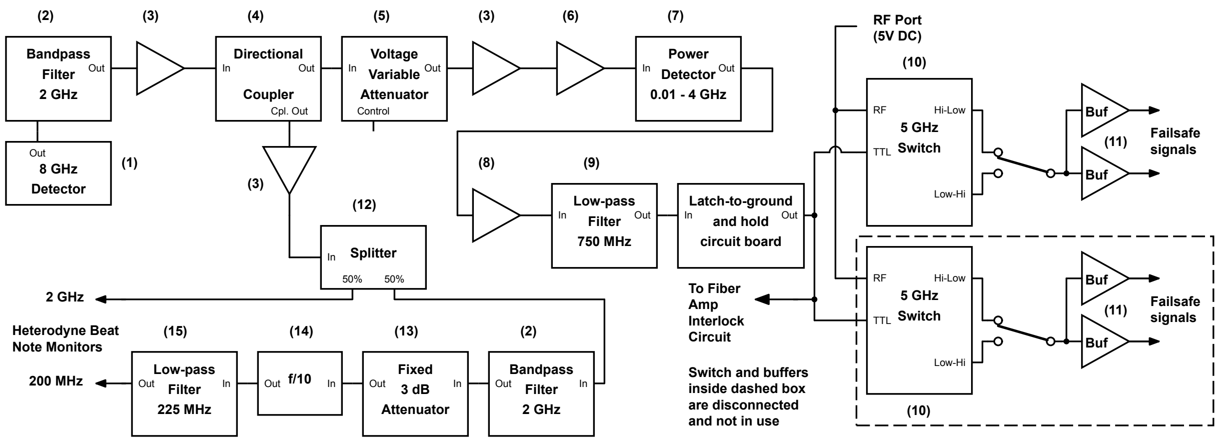

Figure 12: The subsystem that converts the 2 GHz beat note into a TTL level signal is located on the left side of the RF and Control Electronics Box as shown in Fig. A.13. The 5 GHz switches (10) are mounted on the left-side panel of the box, and the four buffers (11) are mounted on a separate circuit board on the same panel near the front of the box. The 8 GHz optical detector (1) is located in the Laser and Optical Components Box. The switch and buffers within the dashed box were disconnected so their front panel connections could be converted for use by the latch-and-hold to ground circuit. See Table 4 for parts list.

Table 4: Part list for Fig. 12 – Heterodyne electronics

No.	Description	Manufacturer	Part number
1	Detector	Thorlabs	PDA8GS
2	Bandpass filter	Mini-Circuits	VBFZ-2000+
3	Wideband amp	Mini-Circuits	ZX60-V63+
4	Bi-directional coupler	Mini-Circuits	ZX30-20-20BD+
5	Variable attenuator	Mini-Circuits	ZX73-2500+
6	DC coupled amp	Mini-Circuits	ERA-5+-TB-431-5+
7	Power detector	Crystek	CPDETLS-4000
8	DC coupled amp	RF Bay	DCA-50-14
9	Low pass filter	Mini-Circuits	SLP-750+
10	High isolation switch	Mini-Circuits	ZASWA-2-50DR+
11	High speed buffer	Burr-Brown	BUF634
12	Power splitter	Mini-Circuits	ZFRSC-123-S+
13	Attenuator	Mini-Circuits	BW-S3W2+
14	÷10 Prescalar	RF Bay	FPS-10-12
15	Low pass filter	Mini-Circuits	VLFX-225

4.3.2 The 14.8 GHz PM Drive and Phase-Locked Loop

The 14.8 GHz PM drive provides power for the main phase modulator. Its frequency is controlled by the PLL in Fig. 13, which locks it to ZBL's 80 MHz system clock. The reference frequency of 12.8 GHz is also locked to the 80 MHz clock, as shown in Fig. 14, and the relative phase stability of the two drive frequencies is more than sufficient for generating the 2 GHz heterodyne beat note and the failsafe signal. Unfortunately the phase stability of 14.8 GHz drive relative to the optical pulses injected into ZBL, which are timed relative to the 80 MHz clock, is not sufficient for the time-averaged or time-interleaved measurements one might make using a sampling oscilloscope.

The RF signal for the phase detector in the PLL is generated from the external termination port on the main phase modulator in the Laser and Optical Components Box. This signal returns to the RF and Control Electronics Box and passes through a 50/50 power splitter as shown in Fig. 13. Half of the split power is sent to a ÷8 prescalar to generate 14.8/8 GHz monitor signal, while the other half passes through ÷5 and ÷37 prescalars and into the RF port of the phase detector in the PLL.

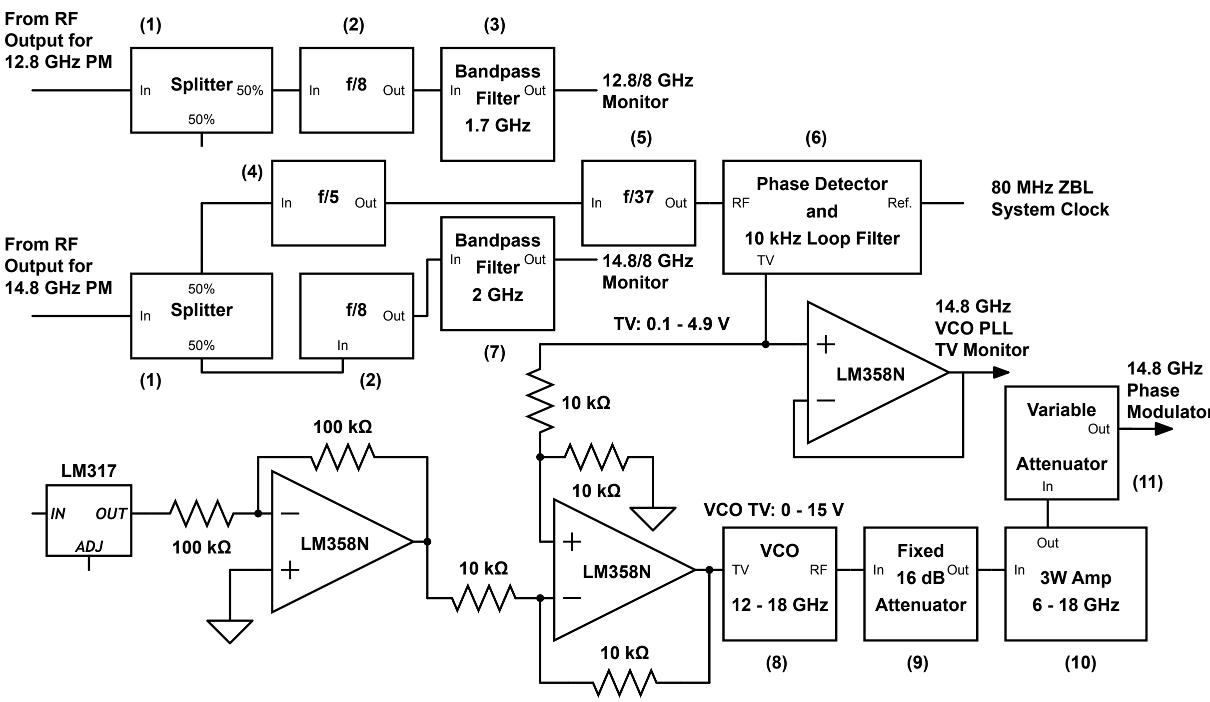

Figure 13: For the subsystem that provides the 14.8 GHz drive for the main phase modulator, the PLL that phase-locks to the ZBL 80 MHz system clock is located on the right side of the RF and Control Electronics Box, while the 3W RF amp and VCO are located near the center, as shown in Fig. A.13. The LM317 adjustable regulator and the LM358N op amps are located on the low voltage circuit board. There is a 10 dB attenuator before the 50/50 splitter for the 14.8 GHz input that is not shown in the figure. The divider and filter for the 12.8 GHz monitor are located near the 14.8 GHz components so they are included in this figure. See Table 5 for parts list.

The tuning voltage (TV) from the phase detector has a range of 0.1–4.9 V, typical of RF components intended for use in PLL's. Unfortunately the high frequency VCO's that drive the phase

Table 5: Part list for Fig. 13 – 14.8 GHz drive and PLL

No.	Description	Manufacturer	Part number
1	Power splitter	Mini-Circuits	ZX10-2-183+
2	÷8 Prescalar	RF Bay	FPS-8-20
3	Bandpass filter	Mini-Circuits	VBFZ-1690+
4	÷5 Prescalar	RF Bay	FPS-5-15
5	÷37 Prescalar	RF Bay	FBS-37-7
6	Phase detector	RF Bay	PDF-100
7	Bandpass filter	Mini-Circuits	VBFZ-2000+
8	VCO	Herley	V6120A
9	Attenuator	Mini-Circuits	BW-S15W2+ and BW-S1W2+
10	3W RF amp	Mini-Circuits	ZVE-3W-183+
11	Variable attenuator	Narda	4791

modulators require TV's up to 15 V so the complete PLL apparatus includes a summing amplifier that adds a DC offset to the phase detector's TV. The summing amp is actually an inverting amp followed by a differential amp, a configuration that circumvents impedance matching issues arising from the 50 Ω outputs of instruments such as high speed servo amplifiers.[13] The summing amp with its adjustable DC input, the VCO and subsequent amplifier, and a variable attenuator, are shown in the lower half of Fig. 13. The variable attenuator provides control of the drive power for the main phase modulator to allow selection of more than one PM spectrum, such as those with $\beta = 5.520$ or $\beta = 8.654$, as shown in Fig. A.1.

The variable attenuator is located inside the Laser and Optical Components Box and this box is closed during normal operation, so it's difficult to access its output port to measure the RF power. We can however measure the residual RF power at the front panel of this box because it's returned to the PLL in Fig. 13, along with the residual RF power from the 12.8 GHz reference modulator. Knowing that about 620 mW enters the attenuator and its insertion loss is about 1 db, and for minimum attenuation the residual power is about 48 mW, the maximum power dissipation is around 450 mW and results in $\beta \geq 8.6$. The modulators use external termination to eliminate heating from an internal resistance of 50 Ω, and evidently little power is lost to any other form of material heating. The low dissipative loss was confirmed by monitoring the modulator's temperature, which increases by only a few °C at maximum power. The power dissipation is therefore primarily due to the capacitance of the modulator, which for 14.8 GHz and 450 mW works out to be a few pF. For the other two modulation indices with zero carrier amplitude, $\beta = 5.52$ and $\beta = 2.4$, the residual power is 23 mw and 10 mW, respectively, but the additional reduction in RF drive power due to increased attenuation is unknown.

[13]The two stage summing amp is convenient but is a holdover from an earlier configuration of the PM failsafe system that required locking a PM sideband to a temperature stabilized étalon. In that system the 50 Ω output of the Servo Amp had to be summed with a DC offset to reach the appropriate voltage for the VCO's TV. Unfortunately the Servo Amp's low Z_{out} sank all the current in a conventional summing circuit based on a single op amp, so it didn't work very well. So in that case two amps – one acting a lot like a buffer – was better than one

4.3.3 The 12.8 GHz PM Drive and Phase-Locked Loop

The 12.8 GHz PM drive provides power for the reference phase modulator. Its frequency is controlled by the PLL in Fig. 14, which locks it to ZBL's 80 MHz system clock. As before with the 14.8 GHz drive, incompatibility between the phase detector's TV and the VCO's TV require using the same summing amplifier arrangement shown in Fig. 13. Otherwise the only significant difference from the 14.8 GHz drive is the absence of a variable attenuator, so the RF power is controlled with fixed attenuators in increments of 1 dB, which is fine enough to obtain $\beta \approx 2.405$, as required.

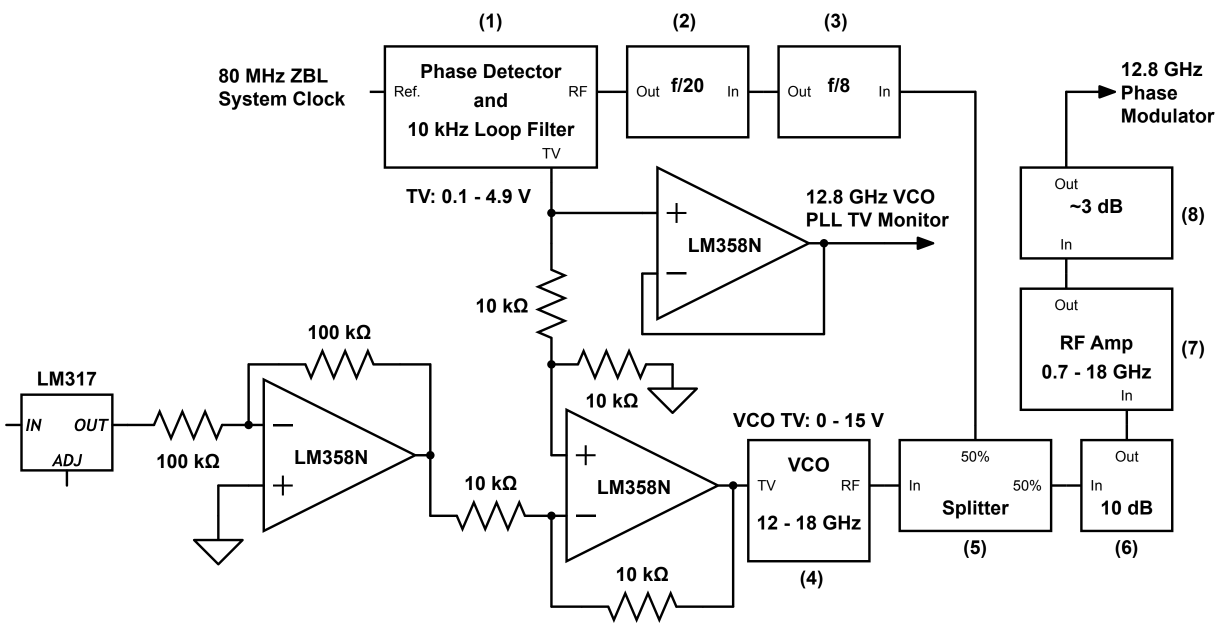

Figure 14: The VCO and RF amp that provide the 12.8 GHz drive to the reference phase modulator, along with the PLL that phase-locks to the ZBL 80 MHz system clock, are located on the left side of the RF and Control Electronics Box in Fig. A.13 below the latch-to-ground and hold circuit board. The LM317 adjustable regulator and the LM358N op amps are located on the low voltage circuit board. See Table 6 for parts list.

Table 6: Part list for Fig. 14 – 12.8 GHz drive and PLL

No.	Description	Manufacturer	Part number
1	Phase detector	RF Bay	DPF-100
2	÷20 Prescalar	RF Bay	FPS-20-13
3	÷8 Prescalar	RF Bay	FPS-8-18
4	VCO	Herley	V6120A
5	Power splitter	Mini-Circuits	ZX10-2-183+
6	Attenuator	Mini-Circuits	BW-S10W2+
7	RF amp	Mini-Circuits	ZVA-183+
8	Attenuator	Mini-Circuits	BW-S3W2+

4.3.4 The Interlock for the IPG Photonics Fiber Amplifier

Operation of the IPG Photonics Fiber Amplifier's interlock circuit was previously discussed in Sec. 3.6. As seen in Fig. 15 it requires two input signals to defeat the interlock; one being the TTL level trigger sent to the 5 GHz switches, and the other the étalon fringe signal when the étalon is locked to a first order PM sideband. Both signals must be amplified to ~ 5 V DC, which is accomplished using non-inverting amplifiers. The amplified signals are sent to non-inverting Schmitt triggers, and then to an AND gate that controls an optically isolated solid state relay that short-circuits the IPG Amplifier's interlock. The inputs to the AND gate see ground through 100 kΩ resistors to eliminate leakage current generating a false safe condition for the amplifier. The output of the Schmitt trigger for the PM failsafe TTL signal can be replaced by 5 V DC to allow operation with single frequency light, if necessary. Note that the front panel PM Enable/Disable switch for the interlock also bypasses the relay labeled "Latch and hold reset" on the latch-to-ground and hold circuit board in Fig. 20 when the switch is set to PM Disable.

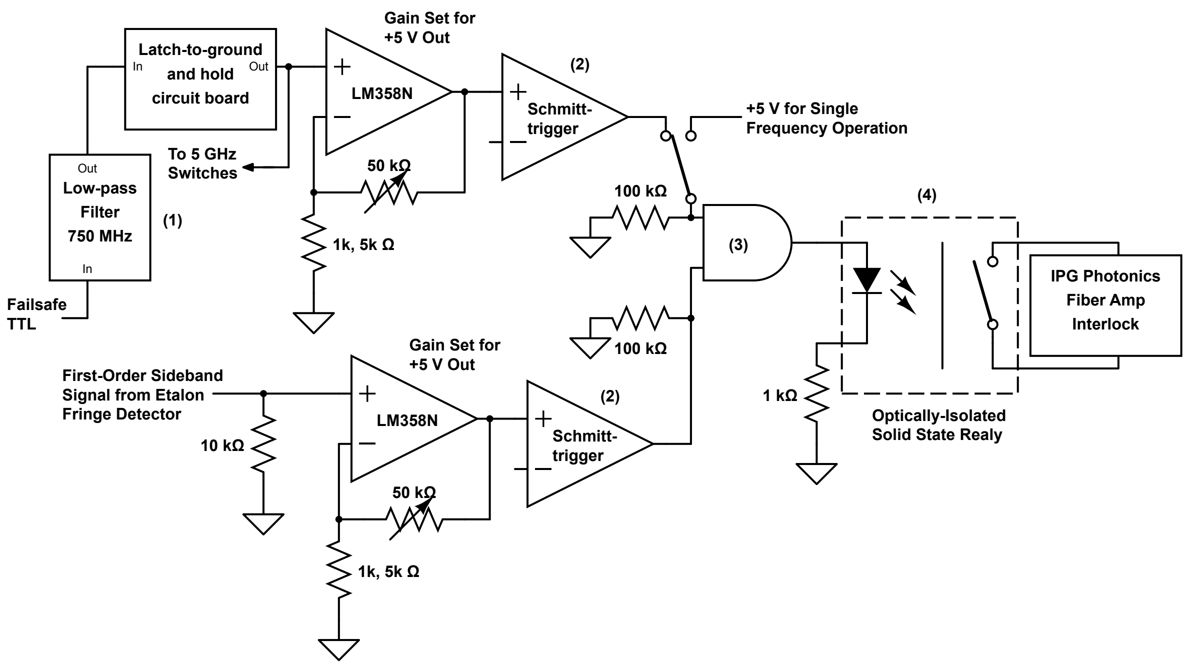

Figure 15: Circuit diagram for the IPG Photonics Amp interlock on the low voltage circuit board. The low-pass filter (1) is part of the heterodyne-to-TTL subsystem shown in Fig. 12, and the Latch-to-ground and hold circuit board is separate from the low-voltage circuit board. See Table 7 for parts list.

Table 7: Part list for Fig. 15 – Interlock circuit

No.	Description	Manufacturer	Part number
1	Low pass filter	Mini-Circuits	SLP-750+
2	Schmitt trigger	Phillips	74HC7014
3	AND gate	Texas Instruments	SN74HCT08N
4	Solid state relay	Avago	ASSR-1411-001E

4.3.5 The Op Amp Circuit for the Étalon

The maximum voltage that can be applied to the étalon's PZT is 150 V. The Servo Amp's nominal output range is -10 to $+10$ V however PZT's can't be exposed to negative voltages so the servo range is set to 0 – 10 V. At 633 nm the voltage per FSR (10 GHz) is about 5 V so the servo range alone is insufficient for sweeping and locking the étalon, so we amplify the Servo Amp's Output. The circuit in Fig. 16 does so with voltage gain ≈ 4 and output range of 5 – 45 V using an Apex high voltage op amp. The Apex op amp's maximum supply voltage difference is 300 V, but our comparatively low output range permits using supply voltages of only -12 V and $+50$ V.

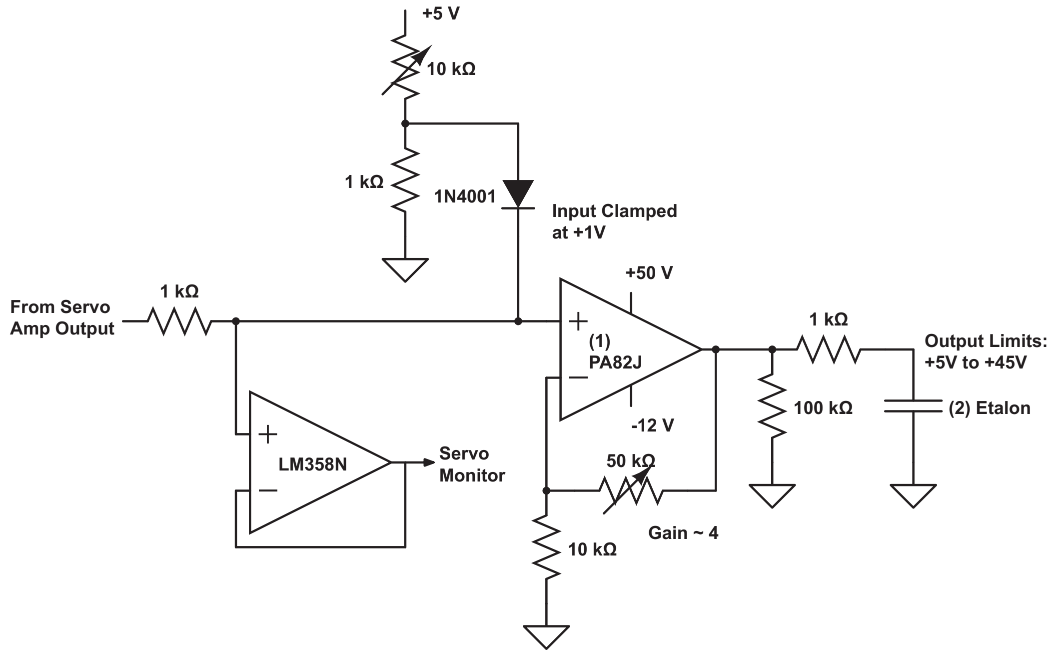

Figure 16: Circuit diagram for the op amp on the low voltage circuit board that drives the étalon. The étalon is housed in the Laser and Optical Components Box. See Table 8 for parts list.

Table 8: Part list for Fig. 16 – Étalon op amp

No.	Description	Manufacturer	Part number
1	HV op amp	Apex	PA82J
2	Étalon	Thorlabs	SA210-8B

The op amp circuit is simple and includes a monitor buffer for observing the servo output, however it also includes two additional features worth pointing out. Although the servo output is limited to 0 – 10 V the op amp's input is clamped at ~ 1 V to make certain its output can't swing below zero and damage the étalon's PZT.[14] In addition, because the étalon behaves like a pure capacitive load, oscillation can occur at resonant frequencies when it is coupled to an amplifier. In

[14]Yes, the output can be clamped as well but with positive-only input from the Servo Amp there was little reason to do so. The clamp is there mostly to keep the étalon from being driven all the way to zero volts.

fact this system suffered from small amplitude oscillations at a resonant frequency much higher than the 20 kHz dither frequency used to generate the error signal for locking the étalon. To eliminate the oscillation the output to the étalon is dampened by the 1 kΩ and 100 kΩ resistors. There are ways to rigorously analyze systems such as this one but unfortunately important parameters for the Apex op amp are not well known.[15] In this case the values for the damping resistors used here are experimenter's best guesses, but they work well so that oscillation is no longer observed.

4.3.6 The Waveform Generators on the Circuit Board

There are three waveform generator IC's on the low voltage circuit board; two are used to generate sine-wave dither signals and corresponding square wave reference signals at 4 kHz and 20 kHz, and the other is used to generate the 1–130 Hz triangle wave for the Servo Amp Sweep In and for the X-channel on oscilloscopes. The circuit diagram for all three is shown in Fig. 17 and the resistor and capacitor values are given in Table 9. The resistors labeled R_A and R_B control the symmetry and duty cycle of the waveforms, while R_F affects only the frequency. The voltage dividers for the sine- and square-waves in Fig. 17 are required to reduce the amplitude of these signals as necessary.

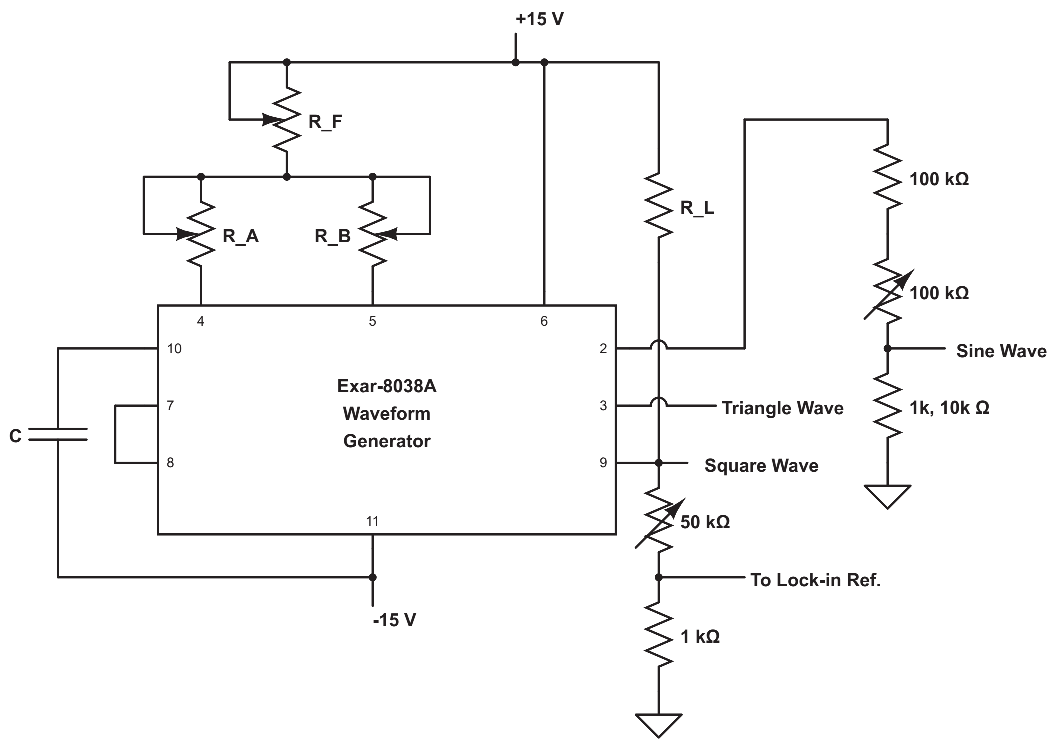

Figure 17: Circuit diagram for the three Exar-8038A waveform generator IC's on the low voltage circuit board. See Table 9 for resistor and capacitor values.

[15] For example see the analysis of op amps coupled to capacitive loads, and various possible solutions, on Analog Devices' website, www.analog.com/library/analogdialogue/archives/31-2/appleng.html.

Table 9: Resistor and capacitor values for Fig. 17 – Waveform generators

Frequency	R_F	R_A	R_B	R_L	C
4 kHz	1 k	1 k	1 k	10 k	$2 \times 0.047\mu$F
20 kHz	11 k	1 k	1 k	10 k	2×1nF
1–130 Hz	500 k	10 k	10 k	1 M	0.66μF

4.3.7 The Voltage Regulators on the Circuit Board

The voltage regulators on the circuit board are all TO-220 packages with passive heat sinking. Supply voltage is $\pm$ 23 V depending on the sign of the output. Diagrams for the four different types of regulators are shown in Fig. 18. One of four LM317 adjustable regulators supplies +18 V for the LM358 op-amps used in the summing circuits for the VCO TV's in Figs. 13 and 14, another two supply DC offset voltages for the VCO TV's, and one is unused. All other fixed-voltage regulators provide supply voltages for components on and off the circuit board, excluding any of the RF components with SMA connectors, which are powered by the linear supplies in the DC Power Supplies Box. The off-board components powered by the regulators and their respective voltages can be determined from Table A.2.

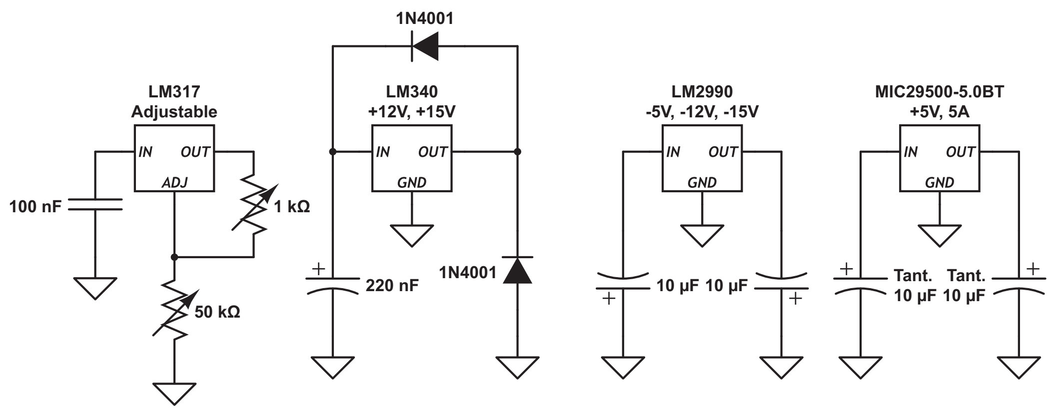

Figure 18: Voltage regulators on the low voltage circuit board in the RF and Control Electronics Box. See Table 10 for parts list.

4.3.8 The Latch-to-Ground and Hold Circuit Board

The RF power detector in Fig. 12 generates a DC voltage, referred to as the failsafe trigger, that is a nonlinear function of the power in the heterodyne signal. If the trigger falls below the threshold for the 5 GHz switches in Fig. 12 then the failsafe output makes a high-to-low or low-to-high transition, depending on the position of front panel TTL Transition switch. The transition time following disappearance of the heterodyne signal is 30–40 ns, depending on the overall gain in the amplification chain, and should the heterodyne signal suddenly recover, the reverse transition is essentially identical. Figure 19 shows an example of multiple transitions, where the power for the main PM VCO was shut off using its mechanical toggle switch, resulting in high-speed transitions

Table 10: Part list for Fig. 18 – Voltage regulators

Voltage	Manufacturer	Part number
Adjustable	Texas Instruments	LM317
+5 (5A)	Micrel	MIC29501-5.0BT
−5	National Semiconductor	LM2990T-5.0
+12	National Semiconductor	LM340T-12
−12	National Semiconductor	LM2990T-12
+15	National Semiconductor	LM340T-15
−15	National Semiconductor	LM2990T-15

that appear random in time due to mechanical switch bounce. To eliminate the possibility of multiple high-speed transitions during an actual failure the TTL trigger must stay low after a falling edge, thus holding the inputs to the 5 GHz switches near ground until an operator resets the system. This type of well behaved response to changes in the heterodyne signal can be obtained from a latch-to-ground and hold circuit connected to the inputs to the fast switches.

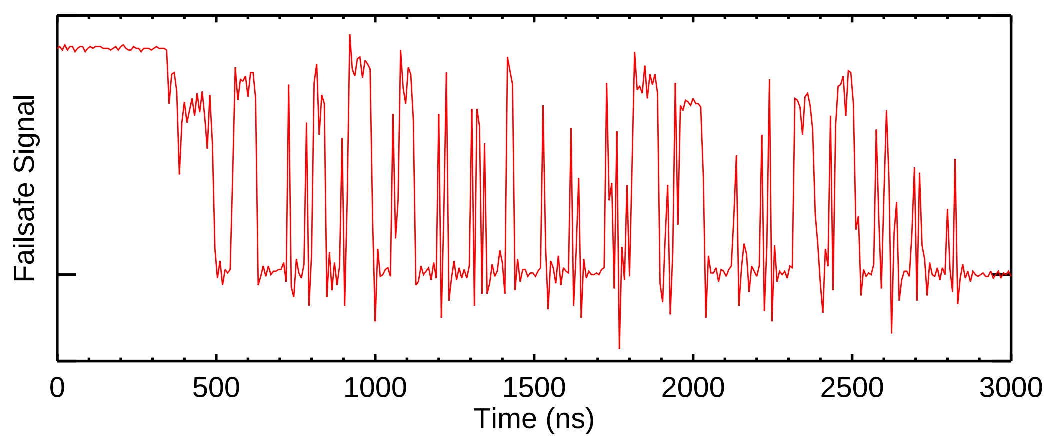

Figure 19: An example of the failsafe output when the main PM drive is shut off using the toggle switch for its VCO. To observe these random state changes due to switch bounce the Latch and Hold Disable toggle switch on the front panel of the RF and Control Electronics Box must be in the Disable position.

It would be convenient to use a commercial latch-and-hold IC to obtain the desired response to the heterodyne signal, however most IC's of this type are designed for data multiplexing on μs time scales and therefore respond too slowly. Consequently a two-stage latch-to-ground and hold circuit was developed where the fast stage pulls the TTL trigger near ground in about 30 ns and holds it there while a slower second stage shuts off the VCO power ~ 2 ms later to disable the system and safely latch the failsafe until the system is reset by a human operator. This circuit is shown in Fig. 20.

The fast stage of the circuit uses a high speed buffer with gain of 2 to sample the TTL trigger. The buffer output controls a retriggerable one-shot whose Q output drives the bases of two bipolar NPN transistors in parallel so that when Q goes high and saturates the bases, the collectors – which are attached to the inputs of the fast switches – quickly approach ground. For high current applications the use of bipolar transistors in parallel constitutes bad design practice but the currents in this circuit are only a few 10's of mA, and a faster transition is obtained using parallel transistors. Approximately 30 ns after failure of the heterodyne signal the outputs of the 5 GHz switches change state, while the RC time constant of the one-shot maintains its Q output in the high state for ~ 2.5 ms.

The slow stage is built from a quad op-amp with one inverting summing amp and one non-inverting summing amp, where each amp samples the failsafe TTL trigger. The two remaining amps provide DC offset control to the inputs of the summing amps so their outputs maintain approximate $\pm$ symmetry about ground. The two summing amps are connected across the coils of a mechanical relay with the polarity set so its contacts remain closed when the trigger is TTL high, but if the trigger falls to TTL low the output of each summing amp changes sign to reverse polarity across the relay's coils. The mechanical relay then interrupts the power for each VCO so that after the failsafe trigger reaches TTL low there is no possibility of generating the heterodyne signal required for the failsafe trigger to return to TTL high.[16]

The slow stage circuitry also provides a reset condition through the front panel toggle switch labeled Failsafe Status that temporarily restores power to the VCO's and simultaneously opens the circuit for the interlock to the IPG Photonics Fiber Amp, thus disabling the amp. After an operator resets the system – which requires re-locking the étalon to the reference PM sideband – the Failsafe Status switch can be put in its Normal Operation position so that the two summing amps see the failsafe trigger at TTL high, thus closing the relay's contacts. On the circuit board in Fig. 20 the reset condition is controlled by various ASSR-1411 solid state relays, and by the EDE2008 Pushbutton Debouncer, whose buffered output temporarily forces the outputs of the summing amps to maintain the polarity required for the relay to close its contacts. A second quad op-amp, followed by a Schmitt trigger, samples the failsafe TTL trigger to illuminate a green LED on the front panel, and set the front-panel Failsafe Monitor to TTL high, whenever the failsafe trigger is in its high state. The Failsafe Monitor has slower response than the Failsafe TTL Signal Outputs and is intended for use with control systems that could interrupt ZBL or Z countdowns.

4.4 Techniques for Reducing Conversion of PM to AM

Section 1.1 discussed conversion of PM to AM and indicated that steps must be taken to compensate for unwanted AM to maintain the safe operating limits afforded by the use of PM light. Sections 4.4.1 and 4.4.2 below describe implementations of dispersion compensation using a grating compressor and spectral amplitude modification using a birefringent filter that are required to reduce AM to acceptable levels.

[16] When the electronics are redesigned during development of a subsequent version II of the PM Failsafe System the mechanical relay will be replaced by a suitable solid state relay or a switching transistor.

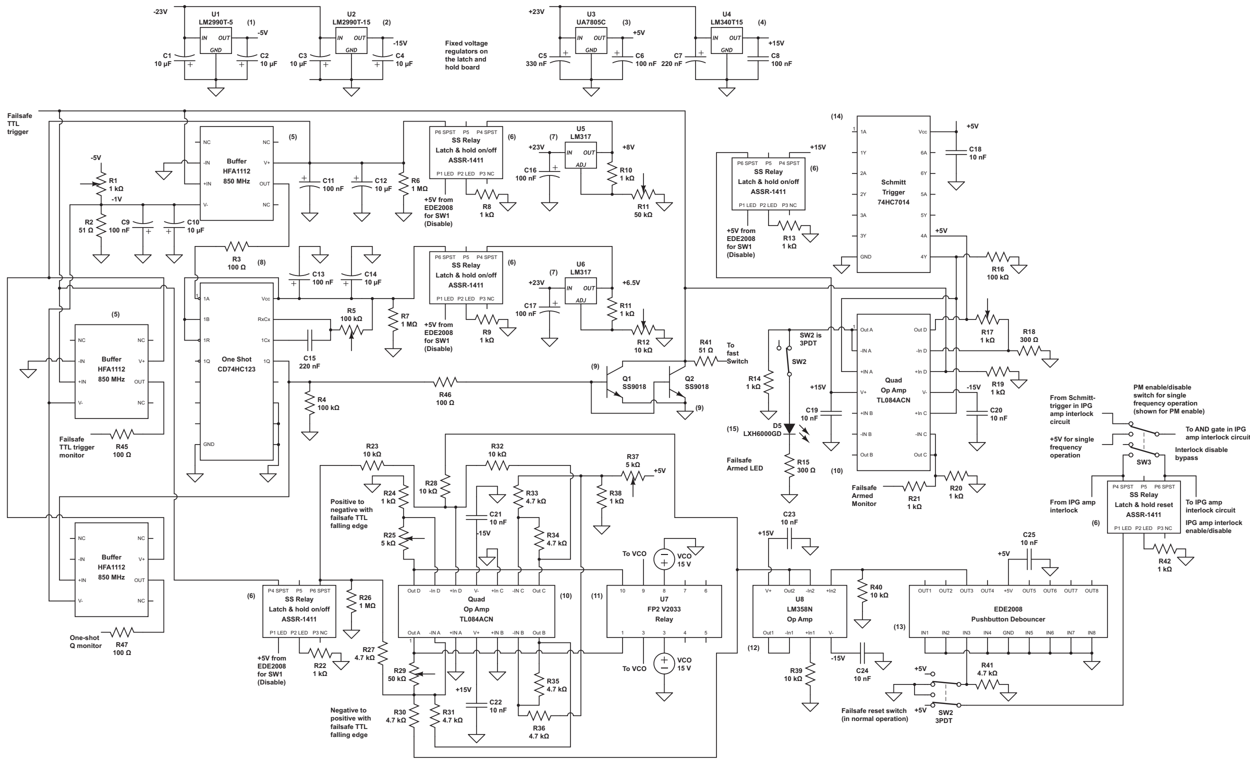

Figure 20: Latch-to-ground and hold circuit board in the RF and Control Electronics Box. See text for description and Table 11 for parts list.

4.4.1 Use of a Grating Compressor for Dispersion Compensation

The PM failsafe system was originally deployed in the 986 High Bay close to ZBL's Regenerative Amplifier, thus reducing the propagation distance of PM light in fiber to at most a few meters. Originally SMPM fiber (Panda) was used to deliver PM light from the output of the pulse-shaping Mach-Zehnder amplitude modulator to the Regen, which was a reasonable choice given the fiber's short length.[17] Unfortunately coupling of the electromagnetic pulse (EMP) from sources such as cable bundles carrying current to the main amplifier flashlamps for ZBL and Z-PetaWatt (ZPW) can completely disrupt the failsafe signal. Each bundle contains approximately 100 cables and each cable carries about 10 kA at 18 kV, and coupling to the RF electronics induced a failsafe event with a signal similar in appearance to the switch-bounce transitions shown in Fig. 19.[18] During initial deployment the latch-to-ground and hold circuitry described in Sec. 4.3.8 was not yet installed, but had it been in place the system would have entered its shut-down state or suffered other spurious

[17]SMPM Panda fiber is generally a poor choice for PM light because the initial orientation of the linear polarization relative to the slow and fast axes can change over long propagation distances, i.e., it doesn't actually act like a polarizer, so the difference in slow/fast-axis dispersion can enhance conversion of PM to AM. Reduced PM to AM conversion is achieved by using polarizing (PZ) fiber, where stress birefringence is imposed using a bow-tie configuration.

[18]Evidently the EMP was strongly coupled to the high-bandwidth RF components, but perhaps less so to lower frequency components such as the Lock-in Amp, the Servo Amp, and associated circuitry because the étalon maintained lock to the reference PM sideband during many of the early tests when ZPW or ZBL were fired. No attempt was made to identify those components most strongly coupled to the EMP disturbance.

Table 11: Part list for Fig. 20 – Latch-to-ground and hold circuit board

No.	Description	Manufacturer	Part number
1	−5V Regulator	Texas Instruments	LM2990T-5
2	−15V Regulator	Texas Instruments	LM2990T-15
3	+5V Regulator	Texas Instruments	UA7805C
4	+15V Regulator	Texas Instruments	LM340T15
5	Buffer amp	Intersil	HFA1112
6	Solid state relay	Avago	ASSR-1411
7	Adj. regulator	Texas Instruments	LM317
8	One-shot	Texas Instruments	CD74HC123
9	NPN transistor	Fairchild	SS9018
10	Quad op amp	Texas Instruments	TL084ACN
11	Signal relay	Axicom	FP2 Relay
12	Op amp	ST Microelectronics	LM358N
13	Debouncer	Digital Engineering	EDE2008
14	Schmitt trigger	Philips	74HC7014
15	Green LED	Lumex	SSI-LXH600DG-150

failures. Because adequately shielding sensitive electronics can be difficult and costly, the PM failsafe system was moved a safe distance away to the MOR, which is accessed from the ZBL control room. Relocating the system required a fiber run to the Regen of 30 m using polarizing (PZ) fiber, which increased the total material dispersion sufficiently that AM of at least 10% of peak height was observed on the pulses propagating through the fiber. Figure 21(a) shows a 1 ns pulse after propagation through the fiber without PM while Fig. 21(b) shows the same pulse with the PM on and an increase in AM of about 10%. Injecting this amount of AM into the Regen is considered unacceptable so dispersion compensation must be used to reduce it an acceptable level.

Using an estimate of the group velocity dispersion (GVD) for fused silica of $k'' = 559$ fs^2/cm at 1054 nm and fiber length of 30 m gives total dispersion of $k''z = 1.68 \times 10^6$ fs^2. To compensate for second-order dispersion at this level a compressor in the Treacy configuration was designed that consists of grating pairs in a double-pass configuration. [15] The compressor, which is shown in Fig. 22, uses 1500 groove/mm gratings with an input angle of 65°, diffracted angle of 42.42°, angular separation of 22.57°, and grating separation of 9–10 cm. The entire assembly, which also contains a free-space coupled EOM-based amplitude modulator called the "Chopper," along with the compressor, is housed in a slide-out rack assembly.[19] Although the estimate of $k''z$ neglected other fiber components in the system that propagate PM light, such as the IPG Photonics Amp, the compressor was designed to offer enough adjustment to accommodate for these additional sources of dispersion.

Following installation and optimization of the grating compressor, additional measurements

[19]The Chopper protects the fiber-coupled Mach-Zehnder amplitude modulator responsible for final pulse shaping by reducing average power to ≤ 25 mW. The MZ modulator material is $LiNbO_3$ with dimensions similar to single-mode fiber for $\lambda \approx 1$ μm and is therefore susceptible to photo-refractive damage. The EOM-based Chopper delivers ~ 1 μs pulses at 250 Hz to reduce the average optical power to a safe level.

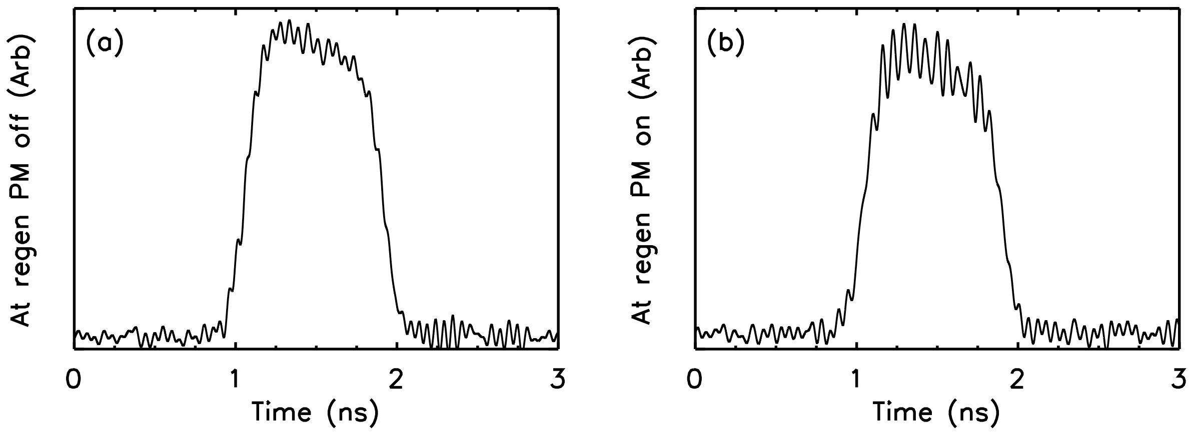

Figure 21: (a) 1 ns pulse at the Regen without PM where the pulse height variations are approximately 7% of peak height. (b) The same pulse with PM where the pulse height variations are now approximately 17%. Although PZ fiber maintains polarization and eliminates the problems associated with SMPM fiber, the total dispersion still converts PM to AM for sufficient propagation distances, thus requiring use of dispersion compensation techniques. These pulses were recorded using a fiber-coupled detector with bandwidth as high 50 GHz connected directly to a 20 GHz oscilloscope.

using 8 ns pulses show a negligible increase in AM with the PM on. In Fig. 23(a) the PM is off,

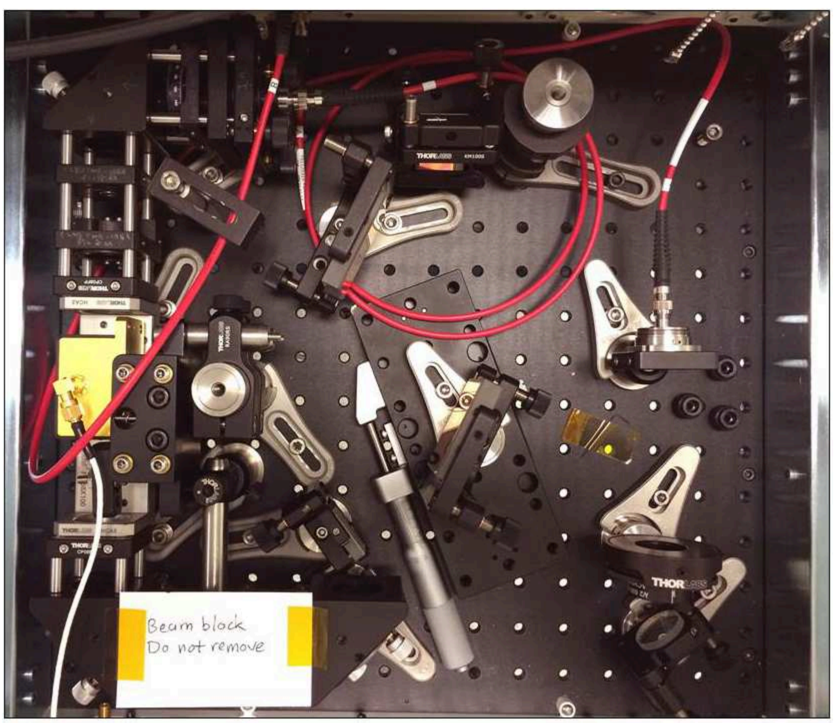

Figure 22: Grating compressor and EOM-based amplitude modulator referred to as the Chopper. The red jacket on the fiber patch-chords denotes PZ fiber. The 30 m PZ fiber from the Shaper to the Regen has a metal reinforced jacket that is silver in appearance.

and in Fig. 23(b) the PM is on but the increase in AM is only $\sim 2.7\%$. This reduction in AM due to dispersion compensation is more than adequate for injecting PM pulses into ZBL's Regenerative Amplifier.

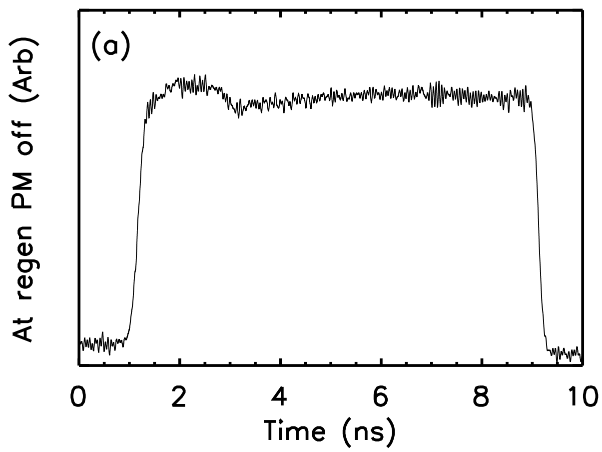

Figure 23: (a) 8 ns pulse at the Regen without PM that displays characteristic noise from a 50 GHz detector and a 20 GHz oscilloscope after propagating through a 30 m PZ fiber. The grating compressor in Fig. 22 was installed when these data were recorded. (b) The same pulse with PM on that displays an increase in AM of only 2.7% due to dispersion compensation from the grating compressor shown in Fig. 22.

4.4.2 Use of a Birefringent Tuner for Spectral Amplitude Modification

Dispersion compensation is effective for reducing PM to AM conversion in long waveguides such as the 30 m PZ fiber, however it can't compensate for another source of AM, namely gain narrowing in ZBL's Regenerative Amplifier. Any modification to the spectral amplitudes of the PM sidebands, even if it is symmetric about the carrier frequency, will induce AM, and subtle changes associated with multi-pass gain-narrowing can lead to significant PM to AM conversion. Fortunately a birefringent filter (BRF) can induce spectral amplitude modification that can at least partially compensate for this effect. Birefringent filters are commonly used as intra-cavity tuning elements in single-frequency CW lasers, usually in a multi-plate configuration that achieves high transmission over a broad tuning range while simultaneously inducing sufficient cavity losses to select a single mode. [16, 17] For use in a regenerative amplifier the design is much simpler and consists of a single BRF plate as a spectral filter that has a transmission bandwidth much broader than the gain-bandwidth of the lasing medium. For use in ZBL's Regen a plate thickness of 6 mm was sufficient to largely eliminate AM induced by gain narrowing.

As shown in Fig. 24 the BRF is placed inside the Regen at normal incidence just after the thin-film polarizer that is used as an output coupler. The BRF is rotated until a minimum in the AM is observed. Figure 25 shows the output of the four-pass Rod Amp – the next amplification stage following the Regen – for a dual-pulse format with approximately 1.3 J total energy with and without PM, where any difference in AM is negligible. This is an expected result because the gain, and resulting gain narrowing in the Rod Amp, is much smaller than in the Regen.

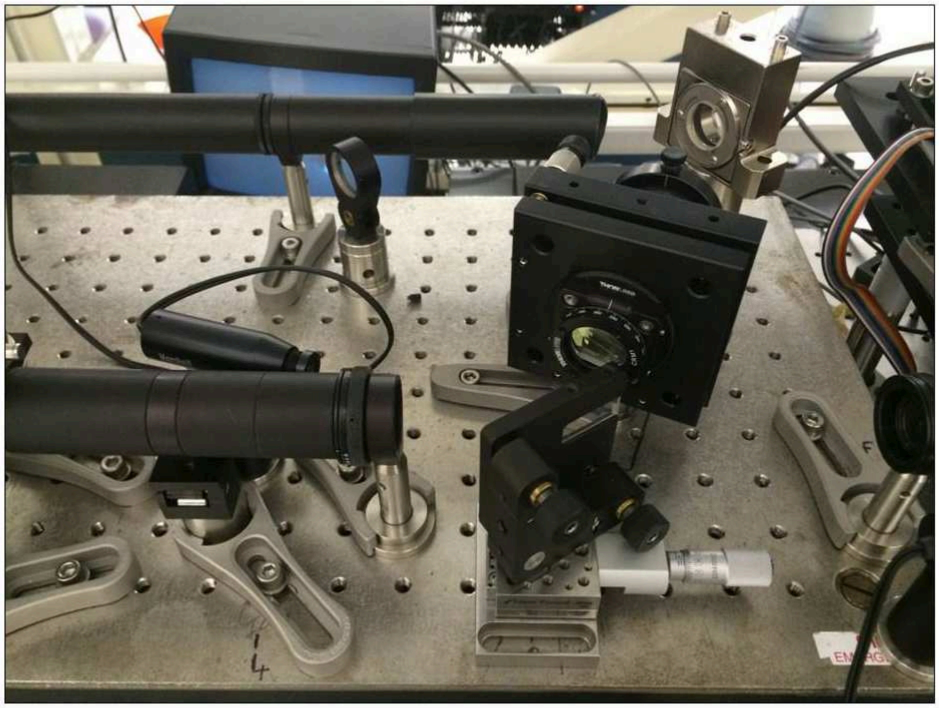

Figure 24: Location of the birefringent filter in a rotation mount inside of ZBL's Regenerative Amplifier.

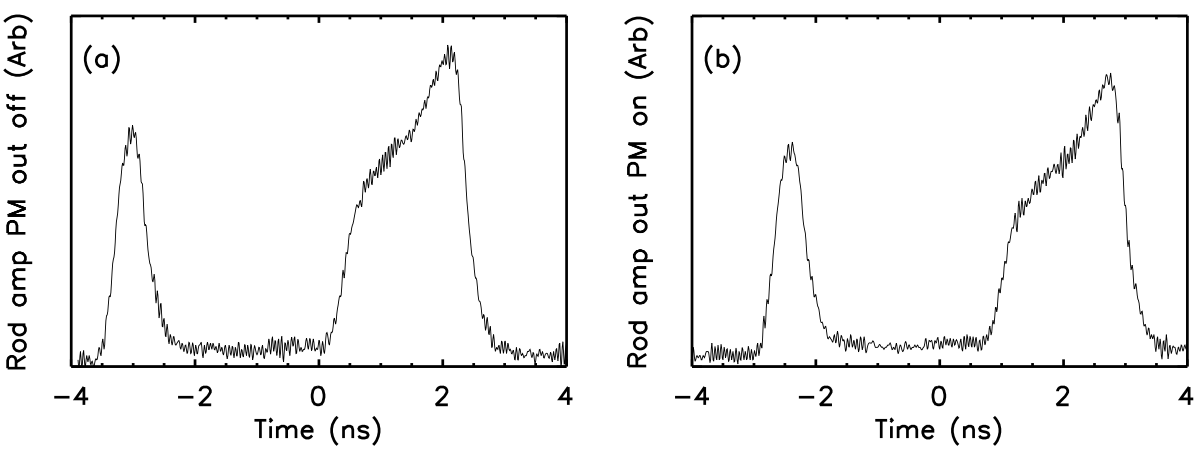

Figure 25: (a) Dual pulse output from the ZBL Rod Amp with no PM and total energy approximately 1.3 J with the birefringent filter in the Regenerative Amplifier. (b) The same pulse with PM on that displays essentially no increase in AM. This result is expected because the gain, and gain narrowing, in the Rod Amp is comparatively small compared to gain in the Regen.

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Appendix

A.1 External Connections for the PM Failsafe System

Table A.1: External electrical and optical connections for the PM failsafe system. *Abbreviations*: Laser and Optical Components Box (LOC Box); RF and Control Electrical Components Box (RFEC Box); DC Power Supplies Box (DCPS Box). *Numbers for cables*: RG58 or RG223 with BNC connector (1); 18 GHz with SMA connector, Mini-Circuits, blue color (2); Other cables, e.g., RG174, with SMA connector (3); SMPM FC/APC fiber patch cord (4).

From	To	Cable
Front Panel Connections		
RFEC Box: +12 Volts DC Output	LOC Box: +12 Volts DC Input	1
RFEC Box: −12 Volts DC Output	LOC Box: −12 Volts DC Input	1
RFEC Box: 12.8 GHz PM Drive Output	LOC Box: 12.8 GHz PM Drive Input	2
RFEC Box: 14.8 GHz PM Drive Output	LOC Box: 14.8 GHz PM Drive Input	2
RFEC Box: Etalon Drive Output	LOC Box: Etalon Drive Input	1
RFEC Box: 20 KHz Dither for Etalon Lock	Servo Amp: Mod 1 Input (back panel)	1
RFEC Box: 20 KHz Lock-in Ref	Lock-In Amp: Reference Input	1
RFEC Box: Low Frequency Triangle Wave	Servo Amps: Sweep In; Oscilloscopes X (Switch Box: Triangle Wave)	1
RFEC Box: Failsafe TTL Signal Outputs	SRS DG535 for Regen Slicer PC	3
RFEC Box: Failsafe Monitor	To Interrupt ZBL and Z Countdowns (not in use)	3
RFEC Box: Etalon Servo Amp Monitor	Oscilloscope X (Switch Box: Servo Monitor)	1
RFEC Box: Heterodyne Signal Monitors	Oscilloscope (200 MHz always connected)	3
RFEC Box: 12.8 GHz Monitor (12.8/8 = 1.60)	Oscilloscope (if connected)	3
RFEC Box: 14.8 GHz Monitor (14.8/8 = 1.85)	Oscilloscope (if connected)	3
RFEC Box: 80 MHz ZBL System Clock	80 MHz clock available in MOR	1
LOC Box: 12.8 GHz PM Output	RFEC Box: 12.8 GHz PM Input	2
LOC Box: 14.8 GHz PM Output	RFEC Box: 14.8 GHz PM Input	2
LOC Box: Heterodyne Signal Output	RFEC Box: Heterodyne Signal Input	2
LOC Box: Heterodyne Fringe Detector Output	RFEC Box: Heterodyne Fringe Detector Input	3
LOC Box: Heterodyne Fringe Detector Output	Lock-In Amp: Signal Input A (T'd from LOC Box)	1
LOC Box: PM Light Output	IPG Fiber Amplifier Input	4
Lock-In Amp: Signal Input A	Oscilloscope Y (T'd to Switch Box: Fringe Detector)	1
Lock-In Amp: Output	Servo Amp: Input A	1
Servo Amp: Output	RFEC Box: Servo Input for Etalon Lock	1
Servo Amp: Error Monitor	Oscilloscope Y (Switch Box: Error Monitor)	1
Rear Panel Connections		
DCPS Box: +5V	RFEC Box: +5V	1
DCPS Box: −5V	RFEC Box: −5V	1
DCPS Box: +12V	RFEC Box: +12V	1
DCPS Box: −12V	RFEC Box: −12V	1
DCPS Box: +15V	RFEC Box: +15V	1
DCPS Box: −15V	RFEC Box: −15V	1
DCPS Box: +23V	RFEC Box: +23V	1
DCPS Box: −23V	RFEC Box: −23V	1
DCPS Box: +15V 3A	RFEC Box: +15V 3A	1
DCPS Box: +50V	RFEC Box: +50V	1
RFEC Box: To Interlock for IPG Photonics Amp	IPG Photonics Amp: Interlock	1

A.2 Phase Modulation Spectra

The PM failsafe system uses phase modulated waves with two different modulation indices. One is the reference wave with $\beta \approx 2.42$ and the other is the PM wave injected into ZBL, which can have $\beta \approx 5.52$ or $\beta \approx 8.65$. All β's used in this system result in PM spectra that have zero carrier amplitude. To help understand the operation of this system it's useful to simulate PM spectra and this can be done using a well known Bessel function expansion, which is presented below, along with example plots of PM spectra for various β's.

For sine wave modulation the instantaneous phase is given by

$$\Theta(t) = 2\pi f_{\mathrm{c}} t + \frac{\Delta f}{f_{\mathrm{m}}} \sin(2\pi f_{\mathrm{m}} t)$$

where f_{c} is the carrier frequency, f_{m} the modulation frequency, Δf the deviation in frequency either side of f_{c}, and $\beta = \Delta f / f_{\mathrm{m}}$ is the modulation index. A phase modulated signal can then be written as

$$S(t) = A\cos\{2\pi f_{\mathrm{c}} t + \beta \sin(2\pi f_{\mathrm{m}} t)\}.$$

Using identities for the Bessel functions, $S(t)$ can be rewritten in a form that is convenient for understanding PM spectra,

$$\begin{aligned} S(t) &= AJ_0(\beta)\cos(2\pi f_{\mathrm{c}} t) \\ &+ A\sum_{k=1}^{\infty} J_{2k}\{\beta\}[\sin\{2\pi(f_{\mathrm{c}} + 2k f_{\mathrm{m}})t\} + \sin\{2\pi(f_{\mathrm{c}} - 2k f_{\mathrm{m}})t\}] \\ &+ A\sum_{k=0}^{\infty} J_{2k+1}\{\beta\}[\cos\{2\pi(f_{\mathrm{c}} + (2k+1) f_{\mathrm{m}})t\} + \cos\{2\pi(f_{\mathrm{c}} - (2k+1) f_{\mathrm{m}})t\}], \end{aligned}$$

which tells us the amplitudes of the sine and cosine terms at integer multiples of the modulation frequency are given by Bessel functions of the first kind of the corresponding order, evaluated at the modulation index. The power spectrum that results from this signal consists of a carrier at $f_{\mathrm{m}} = 0$ and a series of sidebands located at $\pm$ integer multiples of f_{m} with magnitudes equal to the squares of the Bessel functions. Given the complex appearance of $S(t)$ this simple result for PM power spectra makes their simulation on a computer quite easy. All that's required is to initially generate a narrow "triangle spectrum" consisting of peak values given by $J_k\{\beta\}$ for each sideband at $k \cdot f_{\mathrm{m}}$, with half-peak values on each side, evaluated up to a sufficiently high order for a given β. The triangle spectrum is then convolved with a Gaussian kernel. The PM spectra shown in fig. A.1 were generated using this approach, where $\beta = 1.0$, 2.405, 5.520, 8.654, and are plotted on a linear scale against the sideband order.

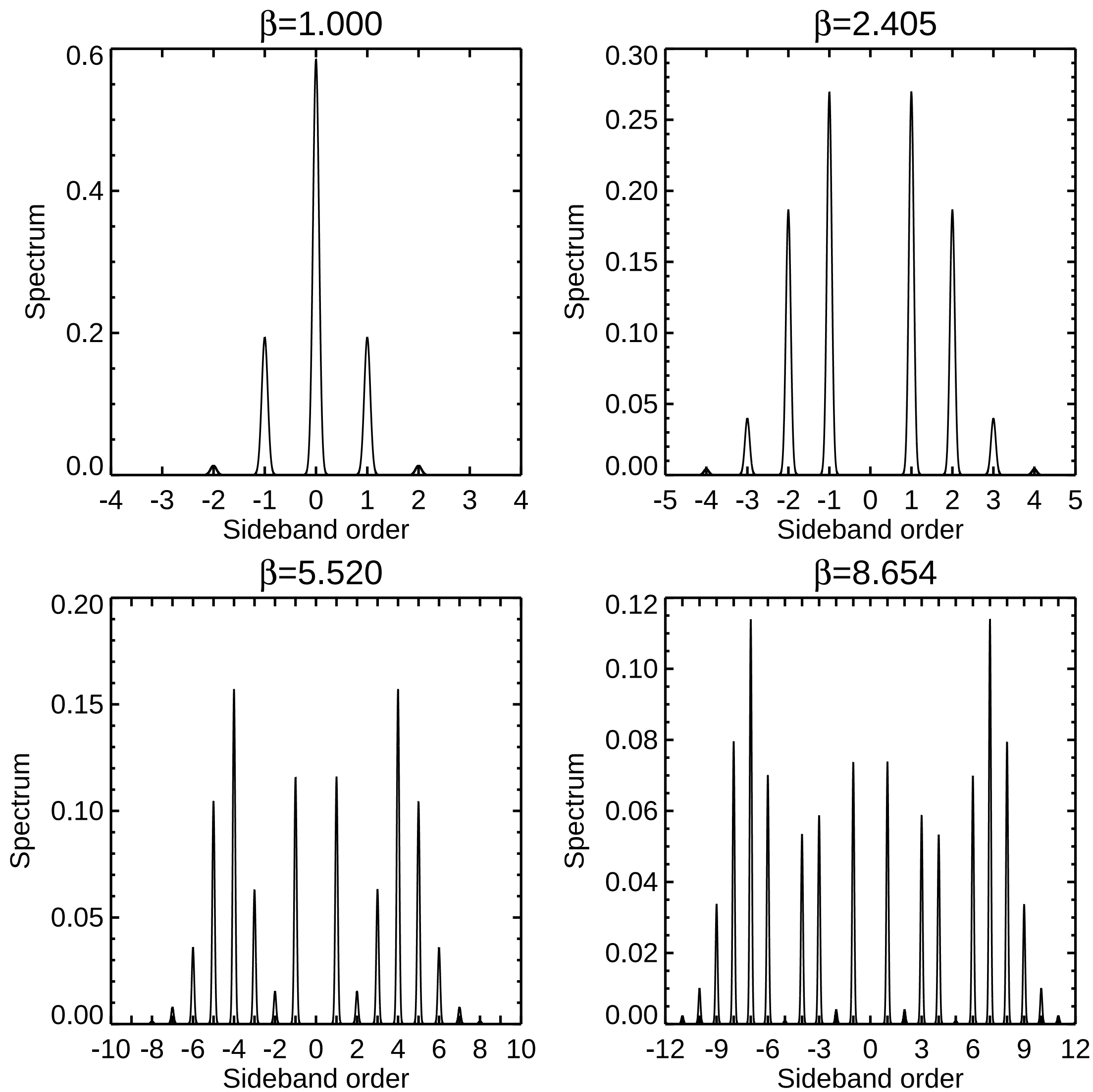

Figure A.1: Four examples of PM spectra for various values of the modulation index, with $\beta \leq 1$ generally considered a small index. The PM reference spectrum always has $\beta \approx 2.42$ and the main PM spectrum nominally uses $\beta \approx 5.52$ but can be increased to $\beta \approx 8.65$ if necessary. The absence of the carriers is intentional to eliminate low frequency homodyne drift in the Mach-Zehnder interferometer formed by the optical heterodyne apparatus, as described in Sec. 4.2.

A.3 A Brief discussion of Dither Locking

Dither locking is a frequency stabilization technique that seeks out and locks to a peak or a valley in some signal.[20] Example applications where dither locking is used include locking a laser to an étalon, or vice versa, and locking a laser to an atomic or molecular line due to absorption of resonant light. Dither locking is a low frequency technique limited by the servo loop bandwidth

[20] The discussion of dither locking presented here was derived from notes on this topic from the Cal Tech Advanced Physics Lab, www.its.caltech.edu/∼ph76a/pdh.pdf

and therefore stabilizes the average frequency, which means it cannot be used to make fast phase corrections that would be required, for example, to narrow the line width of a laser.

The idea behind dither locking is to sinusoidally modulate, or dither, the laser frequency at some frequency Ω, producing a voltage signal $V(t) = V(\omega(t)) \simeq V[\omega_{\text{center}} + \Delta\omega\cos(\Omega t)]$.[21] If $\beta = \Delta\omega/\Omega \gg 1$, then the voltage signal behaves as if the laser frequency were slowly oscillating back and forth.

A lock-in amplifier with reference frequency Ω can then produce an error signal $\varepsilon(\omega)$ that is the Fourier component of $V(t)$ at frequency Ω. Expanding $V(\omega) \approx V_0 - A(\omega - \omega_0)^2$ for ω near the peak frequency ω_0, we have

$$\begin{aligned} V(t) &= V[\omega_{\text{center}} + \Delta\omega\cos(\Omega t)] \\ &\simeq V(\omega_{\text{center}}) + \frac{dV}{d\omega}(\omega_{\text{center}}) \cdot \Delta\omega\cos(\Omega t) + \ldots \end{aligned}$$

and so the Fourier component is

$$\begin{aligned} \varepsilon &\sim \frac{dV}{d\omega}(\omega) \cdot \Delta\omega \\ &\sim 2A\Delta\omega(\omega - \omega_0). \end{aligned}$$

This error signal has the desired properties that $\varepsilon(\omega_0) = 0$ and $d\varepsilon/d\omega(\omega_0) \neq 0$; thus it can be used in a feedback loop to lock the laser frequency at ω_0. (If this isn't clear, draw a picture of $V(\omega)$ near ω_0 and think about it. No matter what the form of $V(\omega)$, selecting the Fourier component of a dithered signal produces an error signal proportional to $dV/d\omega$.)

One problem with the dither-locking method is that the servo bandwidth (how fast the servo can control the system) is limited to a frequency much less than the dither frequency Ω, which in turn must be much less than the frequency scan $\Delta\omega$, and thus much less than the line width of the resonance feature on which one wishes to lock, e.g., the étalon. For a very narrow resonance feature, dither locking may not work well. In general, if we want to control something well, we need to control it quickly – in the language of control theory, we need a servo with a large bandwidth.

Given these limitations is it reasonable to expect that we can obtain a good dither lock for the étalon on our PM failsafe system? The following simple exercise will answer that question. The étalon used in the PM failsafe system has finesse ≈ 150 when perfectly mode matched and the FSR is 10 GHz so its transmission line width is about 66 MHz. Looking directly at the output of the fringe detector, the first order side-band peak measures ~ 85 mV. With the servo loop open the sinusoidal variation in the fringe signal $V(\omega)$ due to the 20 kHz dither, measured at about mid-height on the fringe, is ≤ 2 mV_{pp}. If we assume $V(\omega)$ and $\Delta\omega$ have a one-to-one relationship, then

[21] In the PM failsafe system the laser frequency is not dithered, but instead the length of the étalon's cavity is dithered to produce the error signal. There is no fundamental reason why the laser frequency couldn't be dithered instead.

$\Delta\omega$ is $< 1/40$ of $1/2$ of the 66 MHz line width, or roughly 800 kHz, but it's probably about half that, say 400 – 500 kHz due to the line shape of the fringe. So the resonance width of 66 MHz is greater than $\Delta\omega$ by at least a factor of 50, and it is greater the the dither frequency $\Omega = 20$ kHz or the loop bandwidth, so yes, we should expect to obtain a good dither lock.

A.4 Survey of Failsafe Methods

The PM failsafe system described in this manual is based on optical heterodyne detection. Heterodyne can offer greater safety than some simpler failsafe methods because it has built-in redundancy that reduces the possibility of a false positive condition. Because heterodyne is complex and perhaps more expensive than other competing methods, this section briefly describes several of those other methods and points out shortcomings that prevented their use. Finally, because failsafe methods based on continuous monitoring can have faster response to a failure than methods based on discrete sampling in time at a fixed rate, all such methods such as demodulation of AM on regen pulses were excluded from the survey.

Detecting a PM sideband using an étalon as a filter This method detects the presence of PM light by using a temperature-tuned solid étalon to transmit a specific PM sideband, as shown in Fig. A.2. Although simple it suffers from two flaws: Sufficient frequency discrimination can be difficult with this type of étalon, and the modulation frequency of 14.8 GHz is less than the 50 GHz thermal tuning range of the fiber seed laser, making possible a false positive condition by transmitting the unmodulated carrier. The likelihood of a false positive is low but the existence of this risk prevented selection of this technique.

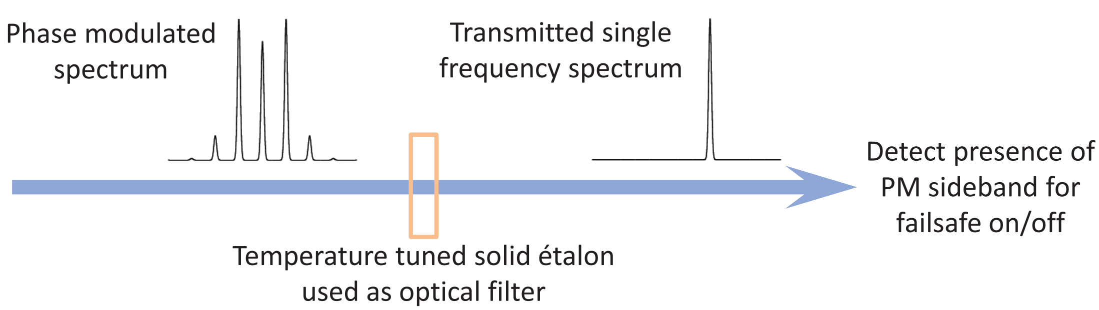

Figure A.2: Detection of PM light using an étalon to transmit a single sideband.

Demodulation of AM by reflection of PM light from an étalon This method uses demodulation to detect AM on a PM spectrum following reflection from an étalon. AM is present because the étalon is tuned to transmit one or more PM sidebands, as shown in Fig. A.3.

Demodulation eliminates a false positive from detection of an unmodulated frequency-shifted carrier, but demodulation requires good relative phase stability between the local oscillator (LO) and radio frequency (RF) signal, otherwise the amplitude of the low-pass filtered intermediate frequency (IF) signal can vary considerably. Any instability is undesirable in a failsafe system so this technique was not selected.

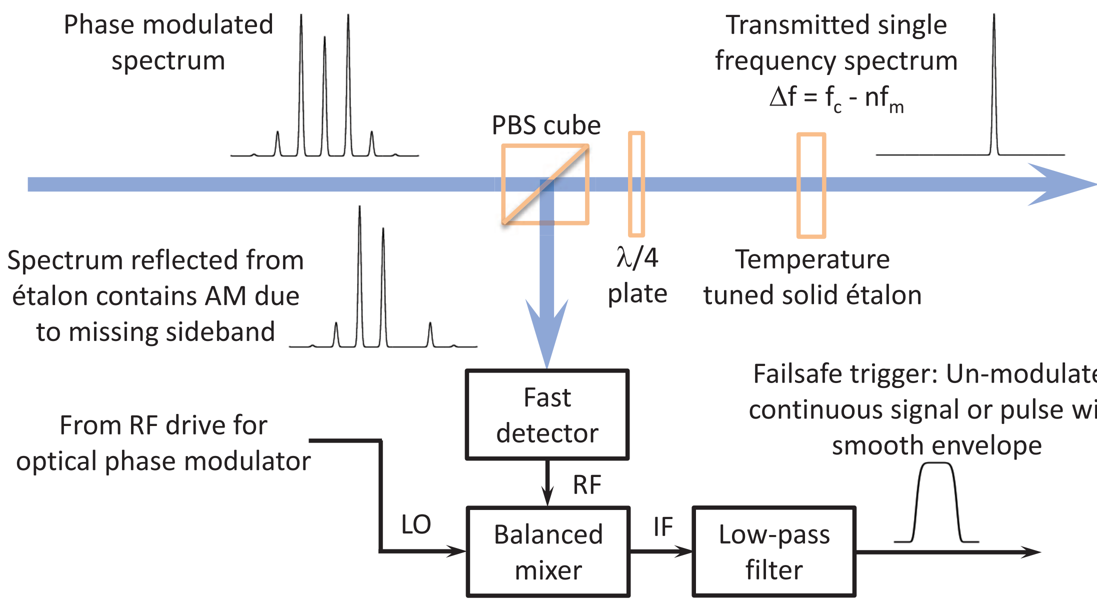

Figure A.3: Detection of PM light using an étalon to transmit a single sideband and reflect an amplitude modulated spectrum, followed by demodulation using a balanced mixer.

Demodulation of AM by transmission of PM through a fiber Bragg grating This method uses demodulation of AM on a PM spectrum that is perturbed by transmission through a fiber Bragg grating, as shown in Fig. A.4.

Reflected AM light could also be detected by modifying this system. This method is initially attractive because it's almost entirely fiber based and therefore requires almost no free-space coupling or alignment [18], but it suffers the same stability issues as reflection from an étalon while introducing the additional issue of environmental perturbation of the fiber structure. Instability is undesirable in a failsafe system, and additional instability is even less desirable, so this method was not selected.

Detection of PM using heterodyne detection Heterodyne detection also requires filtering using an étalon, but in the implementation presented here it uses two distinct phase modulated spectra that are generated independently as shown in Fig. A.5. Failure of of either phase modulator results in a no-go situation. In addition to this fundamental redundancy, the lower frequency of the optical heterodyne beat note – 2 GHz compared to 12–18 GHz for methods that directly generate AM from PM – simplifies conversion to a TTL failsafe trigger without phase-sensitive demodulation using a high-frequency balanced mixer. The failsafe signal is generated using an RF power detector with a frequency limit of 4 GHz. Heterodyne was selected over the other methods discussed in this section because it offers a higher level of safety. Additional details on heterodyne detection are given in Secs. 4.2 and 4.3.

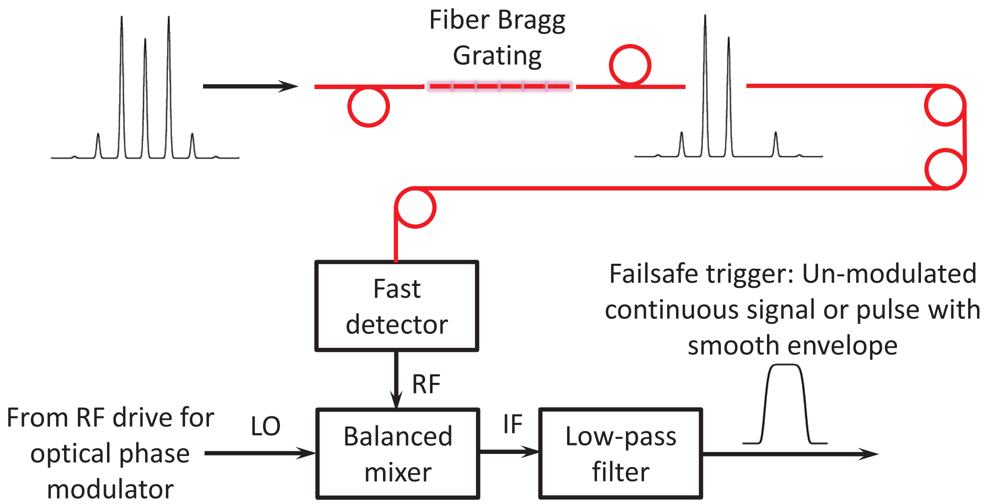

Figure A.4: Detection of PM light using a fiber Bragg grating to generate AM followed by demodulation using a balanced mixer.

A.5 Failsafe Response to Slowly Varying Operating Conditions

The PM Failsafe System provides a good margin of safety against unintended injection of single frequency light as long as just prior to failure the RF drive for each phase modulator provides the correct power and frequency, and the modulators are operating normally. Under these conditions sudden failure of any component results in the Failsafe System safely stopping a pulse from exiting ZBL's Regen with a 35 ns margin of safety, but how would the system respond to slow variations in its operating conditions? This question is unfortunately somewhat difficult to answer. For

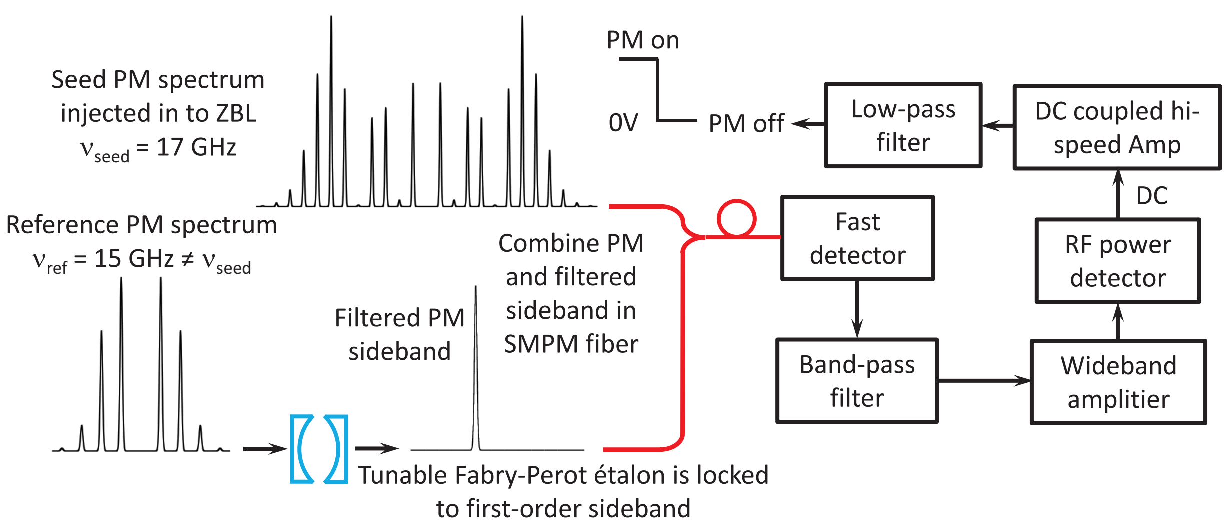

Figure A.5: Detection of PM light using heterodyne detection. A Fabry-Perot étalon with FSR = 10 GHz and finesse of 150 transmits one sideband from a reference PM spectrum and it is combined with the actual seed spectrum to produce an optical heterodyne beat note. The beat note is detected, filtered, amplified, and converted to DC to provide the failsafe trigger.

example, if the main PM modulation index β_{main} changed slowly by a small amount such that the heterodyne power never dropped below the threshold to trigger a failure event, the system would remain armed. If the slow change continued until $\beta_{\text{main}} \approx 2.4$, where the heterodyne signal will be strong but the PM spectrum contains only four strong lines, the system would remain armed even though the small β_{main} wouldn't provide sufficient bandwidth to eliminate transverse SBS during a high energy ZBL shot. Although the conditions for these scenarios to occur aren't known and haven't been encountered, and ZBL's operators would be negligent in not noticing changes in β_{main},[22] the possibility of their occurrence can't be ruled out. What's particularly worrisome is changes of this type occurring in ≤ 0.5 seconds immediately before a shot. ZBL's operators might not notice, and if the failsafe didn't respond, there wouldn't be much they could do anyway. Because none of these hypothetical scenarios can be ruled out entirely, the Failsafe System should be modified to respond to slowly varying changes, and fortunately this is straight forward to do.

Because $\beta_{\text{main}} = 5.52$ produces a PM spectrum with zero carrier amplitude, a simple method for detecting essentially any change in operating conditions would involve detecting the presence of the carrier. These conditions include the RF drive power or it's frequency, and any change in performance of the phase modulator due to aging or damage. A small deviation from $\beta_{\text{main}} = 5.52$, or $\beta_{\text{main}} = 8.65$ – should use of that modulation index become necessary – would result in nonzero carrier amplitude and that would indicate a problem. Detection can be accomplished by applying a low-frequency phase-dither to the main phase modulator through its high-Z input, and mixing a small fraction of its light with a weak un-dithered carrier wave. By using a low-bandwidth optical detector, bandpass or low-pass filtering, and perhaps even simple rectification, conversion of the low frequency fringe signal into a DC voltage could provide a secondary failsafe signal and protection against slowly varying small changes in β_{main}. Of course a real detection circuit would also include adjustable gain and a Schmitt trigger to set an appropriate threshold for detecting a change in β, and replacing rectification with phase-sensitive detection using a lock-in amp would enhance sensitivity. This method can be implemented using additional fiber-optic splitter/combiners alone without optical filtering using an étalon, so it is fundamentally simple and worthy of consideration. Implementing this approach does require additional electronics and probably a higher power seed laser, so it would be practical only during an upgrade to the existing system. A block diagram of the additional optical components is shown in Fig. A.6, while additional electronics would require adding a second buffer, one-shot, and pull-to-ground transistor pair to the diagram of the latch-to-ground and hold circuit board in Fig. 20.

A.6 Scanning Étalon for the PM Failsafe System

The modulation index β must be measured accurately for the main and reference PM spectra. A grating-based optical spectrum analyzer might be capable of making these measurements, but a better choice is a scanning Fabry-Perot étalon with an adjustable free spectral range. Because the PM failsafe system uses a modulation frequency of 14.8 GHz and $\beta = 5.52$ or 8.65, where the highest observable sideband orders are ± 12, the total bandwidth can exceed 400 GHz. A typical

[22] β_{main} is continuously monitored by a scanning étalon and displayed on an *xy*-oscilloscope in the ZBL Control Room.

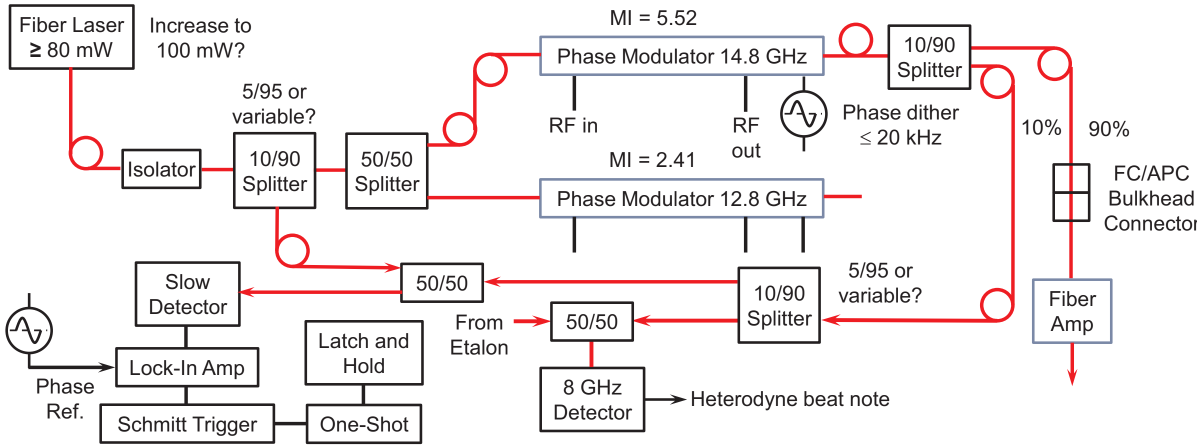

Figure A.6: Block diagram of the additional optical components required for detection of nonzero carrier amplitude for the main PM spectrum. Because each additional fiber component and associated connections consume laser power, a more powerful seed laser would likely be required to add this capability to the existing system. Modifications to the electronics would require adding a secondary buffer, one-shot, and pull-to-ground transistor pair to the latch-to-ground and hold circuit board. See Figs. 11 and 20 for comparison.

large FSR for an off-the-shelf scanning confocal étalon is about 10 GHz, but it's almost impossible to identify the various sidebands when the spectral width for large β exceeds the étalon's FSR. The cost of a custom confocal étalon is prohibitive, especially one with 400 GHz FSR where the dimensions are almost microscopic, so we built a simple flat-flat étalon using off-the-shelf components.

This étalon is shown in Fig. A.7. The mirror separation is set by a linear stage with a differential micrometer (Thorlabs NFL5DP20) that includes a built-in PZT stack with 20μm displacement for scanning. The PZT is driven by a single-axis controller (Thorlabs MDT694A) controlled by a function generator (SRS DS345). Stiff mirror mounts and custom mirrors with $R = 0.98$ (CVI PR1-1053-98-IF-1037-UV) form an étalon with sufficient finesse, however the inherent massiveness and unavoidable flexibility of this design limit scan speeds to a few Hz. The étalon fringes in Fig. 6 were recorded using this device. The scanning étalon can be upgraded to increase its stiffness and allow better control over the parallelism of its two mirrors by replacing the Polaris mount on the stage with a PZT actuated mount (POLARIS-K1PZ). The improved alignment and short-range scanning are obtained by three built-in PZT stacks. In this form the PZT's in the mirror mount would be used for scanning, thus reducing the total mass in motion compared to scanning using the PZT in the linear stage. A three-axis PZT controller that includes master scanning of all three mirror PZT's (Thorlabs MDT693B) would be required to operate this version of étalon.[23]

[23]The scanning étalon has already been upgraded as described, however a further upgrade is underway that replaces the triple PZT Polaris mount with a single tubular PZT stack from Physik Instrumente that will substantially reduce the mass in motion and hopefully allow scanning frequencies of approximately 30 Hz. If all works out well this new system will also include blanking of the *xy*-oscilloscope output in one direction to eliminate the secondary spectrum that appears due to hysteresis effects in PZT scanned étalons.

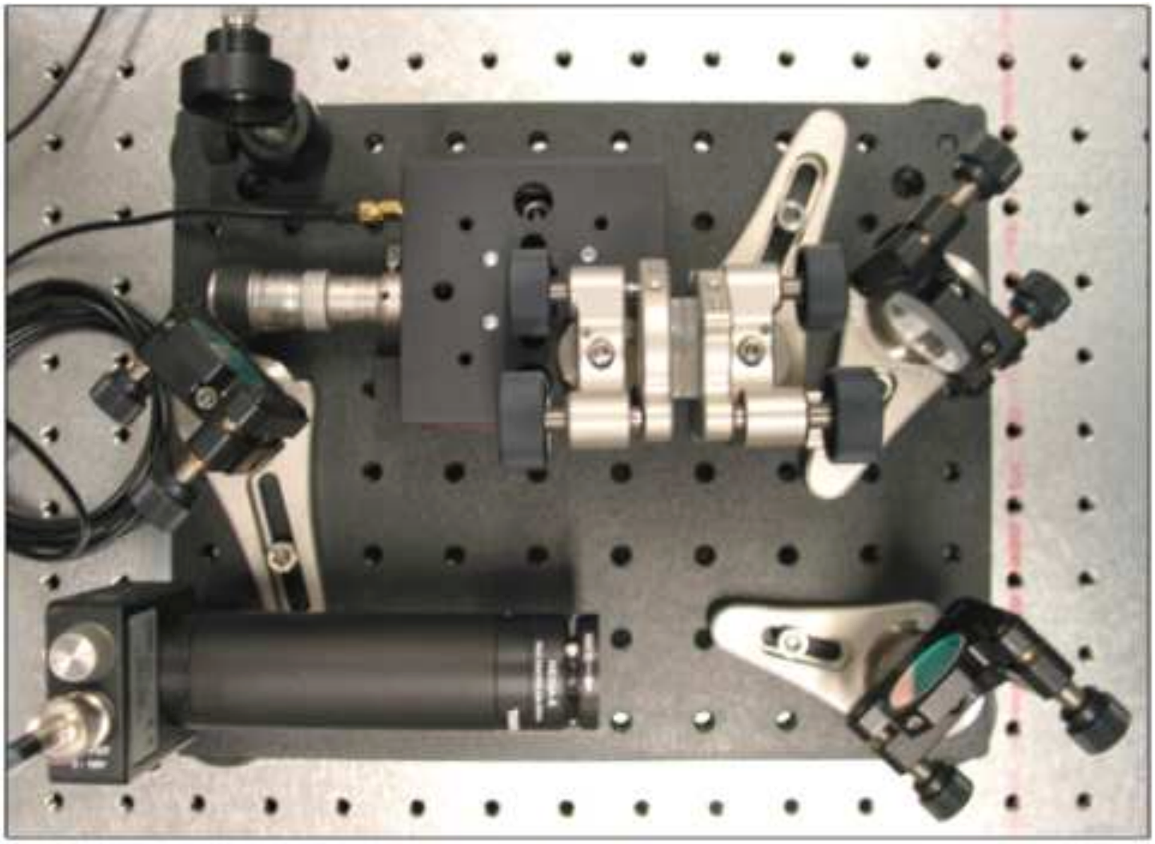

Figure A.7: Scanning Fabry-Perot étalon with adjustable FSR > 300 GHz and finesse of about 100.

A.7 Procedure for Failsafe Speed Tests

The fundamental limit for the response time of the PM failsafe system is imposed by propagation delays in the RF electronics, however additional limits arise due to the overall gain in the heterodyne to TTL conversion chain. If the gain is too low the failsafe trigger signal may fall below the transition threshold of the 5 GHz switches and the failsafe signal can become unstable, and if the gain is too high saturation effects in the amplification stages shown in Fig. 12 can increase the response time by a factor of ten, and perhaps even more. To set the gain to an appropriate level therefore requires measuring the response time of the failsafe system.[24]

The only practical way to accurately measure the response time is to interrupt the heterodyne signal using a very fast electronic switch. As shown in Fig. A.8 this is done by inserting a spare 5 GHz switch (Mini-Circuits ZASWA-2-50DR+) in the path between the 8 GHz detector and the Heterodyne Signal Input on the front panel of the RF and Control Electronics Box. The switch requires ± 5 V power and a TTL trigger supplied by a function generator or pulse generator, and it's a good idea to remove the 8 GHz detector's DC offset by adding a DC block to the switch's RF input. A setup with these components has been dedicated to the PM failsafe system.
The following procedure is used to measure the response time:

[24]"Speed" in this section refers to the response time of the PM failsafe electronics in the MOR.

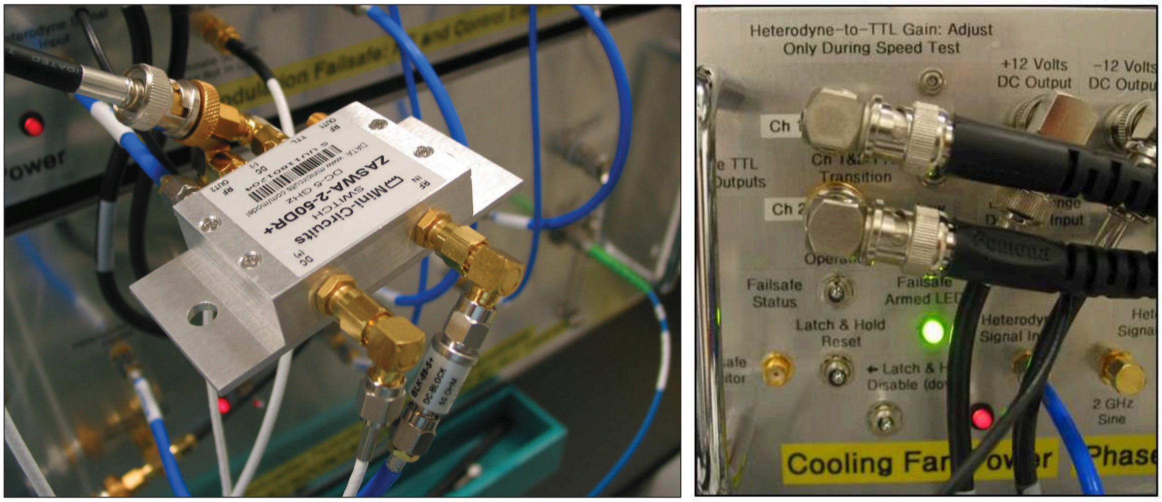

Figure A.8: High speed switch (left) and potentiometer on the upper-left front panel of the RF and Control Electronics Box (right) that are used to measure and adjust the PM failsafe system's response time.

- The entire system must be fully warmed up to carry out this adjustment.
- Before you begin make sure the reference and main PM spectra each have the correct modulation index β. You should not have to adjust either one, but if they are somehow set incorrectly it will affect the size of the heterodyne beat note, and the results of the speed test. See the example reference and main spectra for $\beta = 2.405$ and $\beta = 5.520$, respectively, in Sec. A.2.
- Put the Failsafe Status switch and the Latch and Hold Disable switch in their down positions.
- Obtain a stable heterodyne beat note (see Sec. 3.4 for assistance, if necessary), remove the blue Mini-Circuits cable from the Heterodyne Signal Input bulkhead connector and attach the loose end to the DC block that's connected to the RF IN port on the switch.
- Connect the short high speed cable on the switch's RF OUT 2 port to the Heterodyne Signal Input bulkhead connector.
- Set up a function generator or delay generator to produce a train of TTL pulses at a rate of 10 Hz and 50% duty cycle and attach a cable to the TTL port on the switch. Use a Tee or an additional output to send this TTL signal to an oscilloscope that has a bandwidth of at least 2 GHz and trigger the scope on the falling edge from this signal.
- Connect ± 5 V power to the $\pm$ DC ports on the switch and apply power to the switch.
- Connect either of the Failsafe TTL Signal Outputs on the front panel of the RF and Control Electronics box to another channel on the scope, and set the toggle switch for a High-Low transition.
- If the system is working properly you should see signals on the scope like those in Fig. A.9,

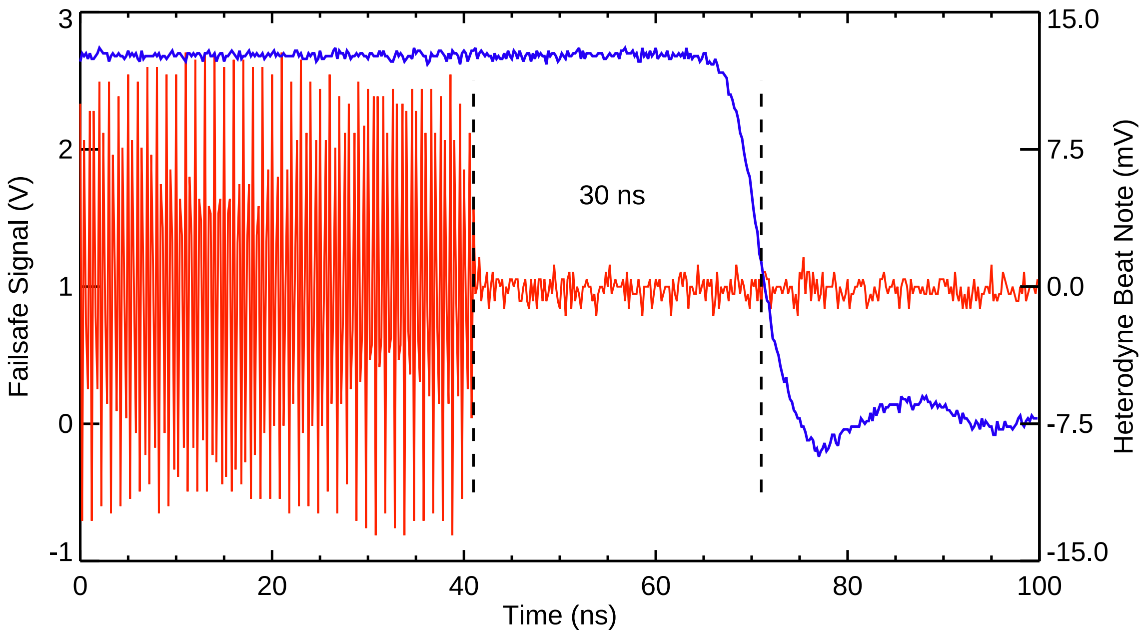

Figure A.9: An example of a 30 ns high to low transition time for the PM failsafe system. The 2 GHz heterodyne beat note is shown in red, and the output from one of the 180 MHz buffers into 50 Ω on a 12 GHz oscilloscope is shown in blue. The transition time to a level of 1 V is adjustable from about 22–40 ns, although the range depends on V_{pp} of the heterodyne beat note. A delay of 35 ns is probably optimum as it results in the threshold for a failsafe event at 40–50% of V_{pp} of the heterodyne beat note.

however the response time will probably be different. Set the baseline for the heterodyne signal so it crosses the falling edge of the failsafe signal at 1 V, as shown in Fig. A.9. This is approximately the transition voltage for the SRS DG535 and DG645 trigger-inhibit inputs.

- If you find the response time is substantially longer than about 40 ns, say several hundred ns, then the gain is too high or something else may be wrong. Otherwise, determine the "good" operating range for the gain by turning the pot on the upper-left front panel on the RF and Control Electronics Box labeled "Heterodyne-to-TTL Gain" as shown in Fig. A.8. With the gain too low the switch won't make a transition, or the failsafe signal might become unstable, and if the gain is too high the transition time will exceed it's nominal maximum of $\leq$ 40 ns. Set the gain so the response time is somewhere between the two extremes, say about 35 ns.

- Set the toggle switch for a Low-High transition to make sure the system response time is similar. As described in Sec. 3.7, when the Failsafe TTL Signal Outputs are terminated into 50 Ω the 0–1 V Low-High transition time will be about the same, but the charge-up time to reach the full output voltage will be around 25 μs.

Now that the response time, or speed, of the failsafe system has been set, it may be a good idea to test the threshold of the failsafe system to make sure everything is working correctly. This is an optional test but the threshold should be checked occasionally to make sure the system is working correctly. The following procedure describes how to measure the threshold for a failsafe transition:

- To carry out this test you'll need to observe the following signals: The étalon transmission for a first-order sideband for the 12.8 GHz reference PM spectrum (toggle switch in the "Fringe Detector" position on the analog scope in the MOR), the failsafe output, and the 2 Ghz heterodyne beat note using its monitor output. The fixed-amplitude 200 MHz beat note cannot be used for this test.

- Because you'll need to continuously monitor the 2 GHz heterodyne beat note, remove the fast switch and reconnect the blue Mini-Circuits cable to the Heterodyne Signal Input bulkhead connector.

- Leave the Failsafe Status switch and the Latch and Hold Disable switch in their down positions.

- Put the toggle switch on the Servo Amp in the Lock Off position and use the Sweep Center knob on the Servo Amp to locate a first order reference sideband on the analog oscilloscope (see Sec. 3.4 for assistance, if necessary). If you've located the correct sideband the 2 GHz heterodyne beat note will also be observed on a fast scope. After locating the first order sideband manually sweep across the sideband using the Sweep Center knob on the Servo Amp. Observe the change in amplitude of the 2 GHz heterodyne beat note on the fast scope. If the failsafe speed was set to about 35 ns you should observe a failsafe transition when the beat note amplitude is about 40–50% of it's maximum V_{pp}. These measurements confirm the system is operating correctly and establish the threshold for a failsafe transition relative to the beat note's amplitude.

- If necessary the failsafe threshold can be set so that a transition occurs at a higher value of the beat note's maximum V_{pp}, say $\sim$ 80 % for higher sensitivity to fluctuations in the beat note amplitude, however this could result in a failsafe speed, or transition time, that could be well below 30 ns, and at this point the system may become unstable and oscillate in and out of the failure state.

- If you observe oscillations then set the threshold to a smaller value of the beat note's V_{pp}. Stable operation should be obtained for failsafe speeds of 30–40 ns. If you can't obtain stable operation then something is wrong with the system. Refer to Sec. 4.3 for assistance.

A.8 The Margin of Safety to Stop a ZBL Shot

The PM Failsafe System is one part of an overall system that controls various timing signals for firing ZBL. In the event of a PM failure the PM Failsafe System inhibits the trigger for an SRS DG535 that controls the Regen's post-cavity "Slicer" Pockels Cell driver. The Slicer ensures that only one pulse from the Regen enters ZBL's amplification chain, and it provides the last readily accessible line of defense to stop an unmodulated shot should the phase modulation fail. Because the ability to safely stop a single-frequency pulse is so important, the margin of safety, measured in time, is a system parameter that must be well known. As of May 2014, that margin of safety is approximately 35 ns, which means the PM Failsafe System can safely stop a shot 35 ns after light from the Mach-Zehnder amplitude modulator, or Shaper, in the MOR enters the PZ fiber on its way to the Regen. This margin of safety means the system can also stop a modulated pulse within that 35 ns window, but given the consequences of amplifying single frequency light when operating conditions might lead to transverse SBS, it's better to be safe than sorry.

The margin of safety is measured relative to the monitor signal from the arbitrary waveform generator (AWG) in the MOR that drives the Shaper. Light enters the PZ fiber 17 ns after the monitor signal, and by comparing this reference time to the complete optical propagation time – which includes transit time for the PZ fiber, and time spent in the Regen cavity – to the overall electrical signal propagation time, we can determine the 35 ns margin. The measurement is carried out by repeating a failsafe speed test, however the duty cycle for the 5 GHz switch is much lower because it's triggered from the 0.2 Hz "heartbeat" so that it can be synched with various other signals that indicate when a pulse leaving the PZ fiber would enter the Regen to be amplified. The simulated failure time is only $\sim$ 40 ns so that the effects of the falling and rising edges of the failsafe signal can be observed while it's swept in time beyond the reference signal from the AWG's monitor. Figure A.10 shows the signals that are used to measure the failsafe margin of safety.

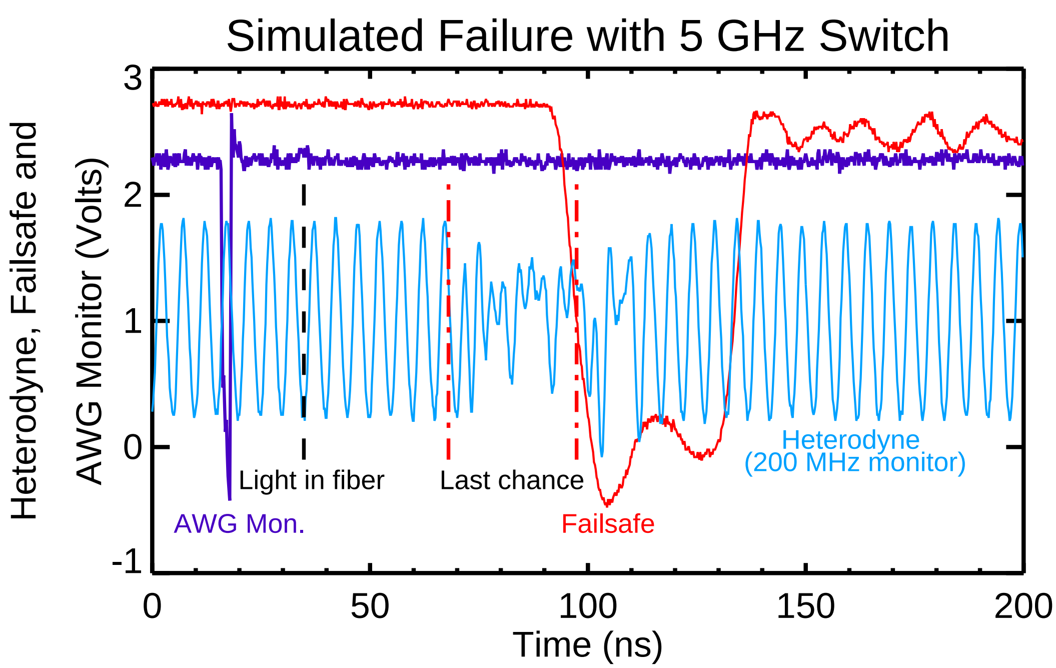

Figure A.10: Signals used to determine the PM Failsafe System's margin of safety to stop an unmodulated pulse from leaving the Regen and entering ZBL's amplifiers. The AWG monitor is shown in dark blue and serves as the reference time for all measurements. The 200 MHz heterodyne beat note monitor is shown in light blue and the failsafe signal is shown in read. The dashed vertical black line indicates when light enters the PZ fiber on its way to the Regen, and the two dashed vertical red lines indicate the last chance to stop a shot, with one measured where the heterodyne beat note fails, and the second at the 1 V point on the failsafe signal's falling edge. The time from "Light in fiber" to the earliest "Last chance" where the heterodyne beat note fails determines the 35 ns margin of safety. See text for additional details.

Although the current margin of safety is adequate and there are no plans to increase its length, it could be increased in two ways. One is to increase the length of the PZ fiber, which also requires adjusting or also perhaps modifying the Grating Compressor. A second way is to reduce the electrical propagation time, in particular the long propagation delays due to the SRS DG535's and DG645's that are used to control the Regen's Pockels Cells. This could be done during a redesign of the PM Failsafe System electronics by using its latch-to-ground and hold capabilities to pull the output of one or more DG's to ground in the event of a failure. In other words the trigger from one of the DG's in the MOR would pass through its own 5 GHz switch so that it would be interrupted before it could reach the DG's in the ZBL High Bay. To maximize the increase in the margin of safety might require relocating various DG's, and any effort would also require additional measurements.

A.9 Locations of IC’s on the Circuit Board

Figure A.11 shows the locations of the IC’s on the low voltage circuit board. The circuit board uses older style mini-DIP packages and sockets and ideally it should be replaced with one constructed from surface mount components. An upgraded circuit board of this type could also include some of the RF and microwave components because many of them are now available in surface mount packages.

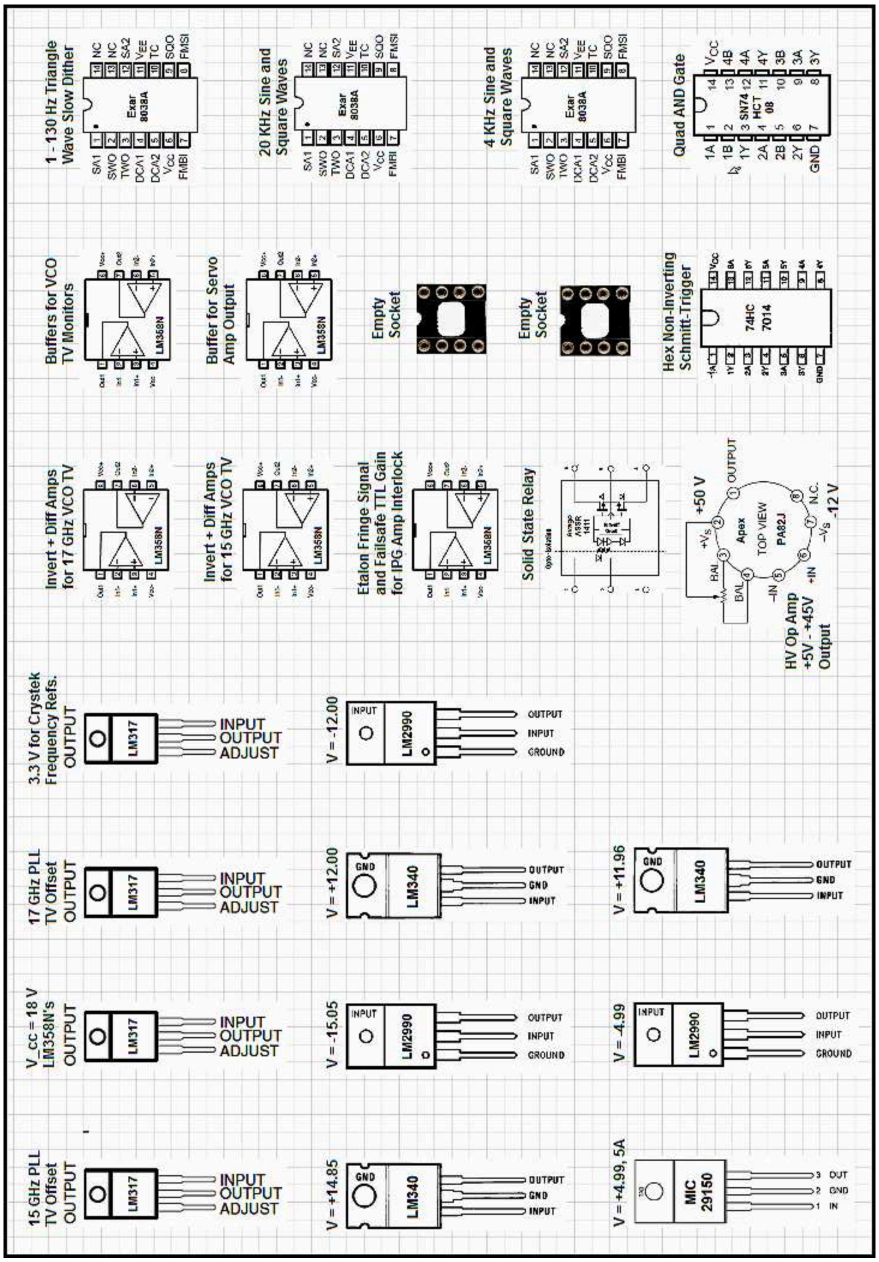

Figure A.11: Locations of the IC’s on the low voltage circuit board in the RF and Control Electronics Box.

A.10 The 37 pin D-Connector

Table A.2: Connections for the 37 pin D-connector inside of the RF and Control Electronics Box. This is the interface between the low-voltage electronics board, front-panel connections, and other connections inside the box.

Pin	Description
1	Ground bar
2	IPG Amp interlock (through Avago solid state relay)
3	IPG Amp interlock (through Avago solid state relay)
4	DC in from heterodyne (for IPG Amp interlock)
5	No connection
6	+5V out for IPG Amp interlock PM enable/disable switch
7	+5V return for IPG Amp interlock switch to Schmitt trigger
8	IPG Amp interlock switch to op amp to amplify heterodyne DC to TTL level
9	No connection
10	PLL TV from phase detector to Σ amp for 12.8 GHz VCO
11	14.8 GHz VCO TV from Σ amp
12	12.8 GHz VCO TV from Σ amp
13	+5V DC for front panel LEDs
14	Return to ground through 600Ω resistor for LEDs
15	No connection
16	−12V DC out for étalon detector in Laser and Optical Components Box
17	PLL TV from phase detector to Σ amp for 14.8 GHz VCO
18	No connection
19	Ground bar
20	Ground bar
21	4 kHz square wave reference for Lock-In Amp
22	Potentiometer for low-frequency triangle-wave frequency adjust (out)
23	Servo Amp input for étalon lock (to Apex PA82J op amp)
24	20 kHz sine wave dither output
25	4 kHz sine wave dither output
26	Potentiometer for low-frequency triangle-wave frequency adjust (return)
27	Amplified servo Amp output for étalon lock (from Apex PA82J op amp)
28	Low Frequency triangle wave output
29	+12V DC out for étalon and fast detectors in Laser and Optical Components Box
30	20 kHz square wave reference for Lock-In Amp
31	14.8 GHz VCO PLL TV monitor on front panel
32	12.8 GHz VCO PLL TV monitor on front panel
33	Servo Amp output monitor on front panel for étalon lock
34	No connection
35	No connection
36	No connection
37	Ground bar

A.11 Photos of the Sandia-Built Boxes

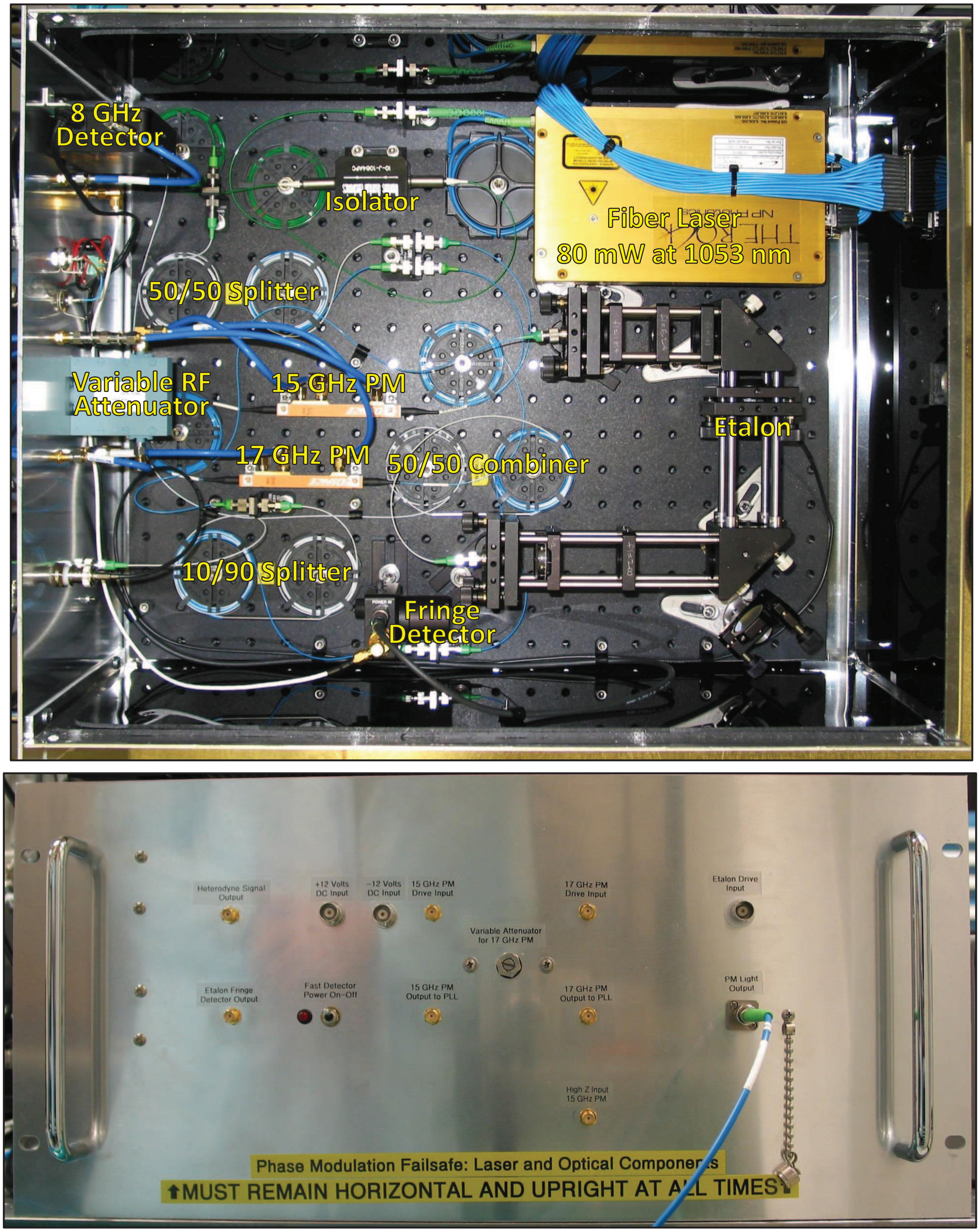

Figure A.12: Photos of the Laser and Optical Components Box with labels for the major components.

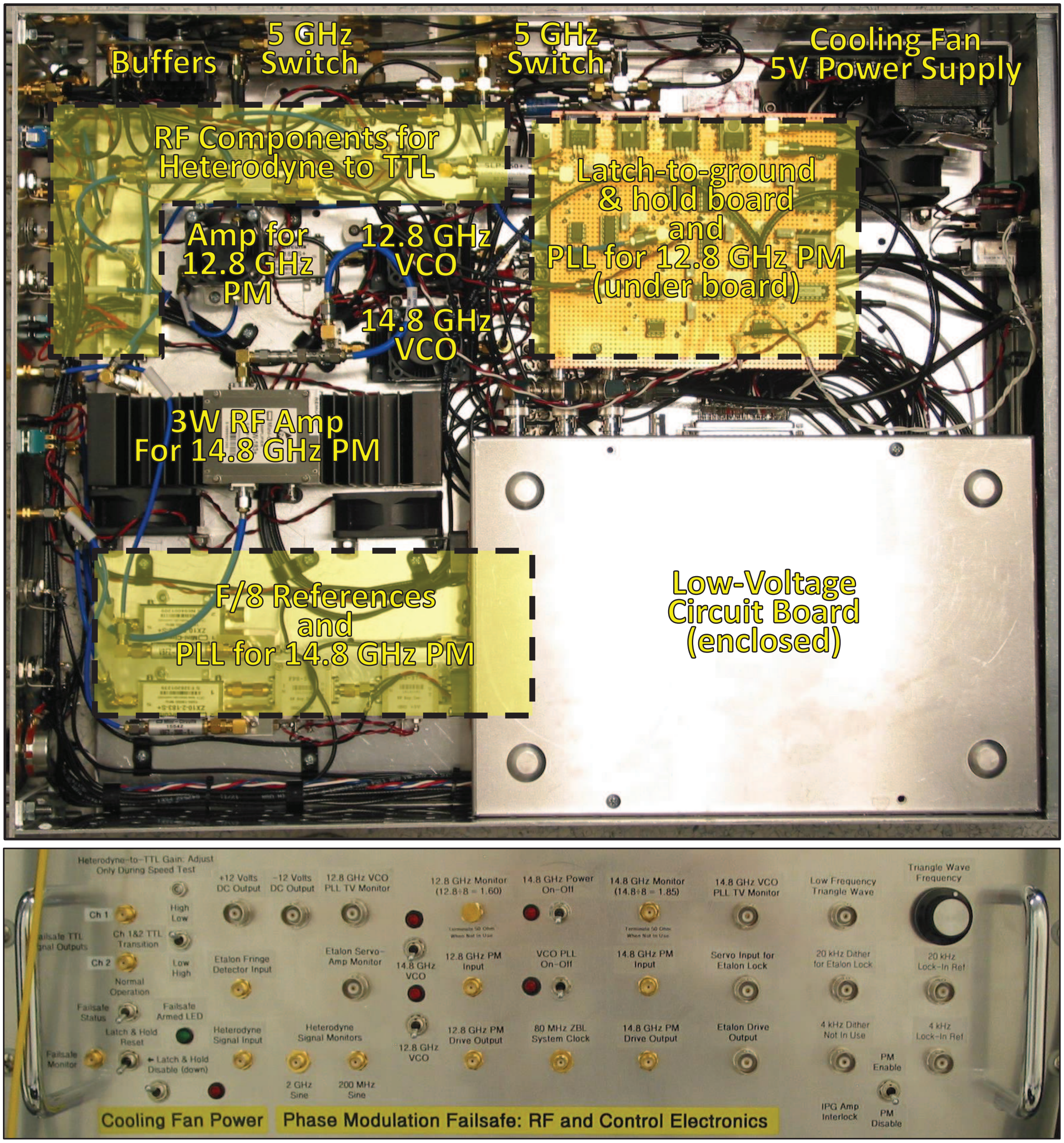

Figure A.13: Photos of the RF and Control Electronics Box with labels for the major components. The transparent yellow regions with dashed black outlines enclose groups of components comprising subsystems, such as the RF electronics for converting the heterodyne beat note to TTL. Note that labels for the two lower right BNC connectors on the front panel now read "Latch–&–Hold 1-Shot Q-Out Monitor" and "Failsafe Trigger Monitor." The use of these outputs is discussed in Sec. 3.8.

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