User Manual

RUBRIComb® Frequency Comb

Revision 02

VESCENT

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Contents

1 Introduction

This manual contains information for operating the Vescent RUBRIComb® Frequency Comb. This manual is applicable to the standard RUBRIComb without additional options.

The RUBRIComb is a fully stabilized frequency comb with a passively mode-locked erbium-doped fiber oscillator. Through precise control of the repetition rate (f_{rep}), the optical beat note frequency (f_{opt}), and the carrier envelope offset frequency (f_{CEO}), the RUBRIComb allows the transfer of the stability of a high-performance laser to far-removed portions of the electromagnetic spectrum.

This section has information for safely operating the RUBRIComb. Please carefully read this section before using the RUBRIComb. Section 2 introduces the user to the instrument and defines all hardware connections. Section 3 discusses the graphical user interface (GUI) for the RUBRIComb. Section 4 helps users immediately get started using the RUBRIComb in their application by showing an example of typical setup and operation. Section 5 contains further detail about the operation of the RUBRIComb. Section 6 covers remote operation of the RUBRIComb. Troubleshooting help can be found in Section 7. For further information, including product specifications, additional resource links, and warranty information, see the appendices.

1.1 Symbol Definitions

The following symbols may be encountered in this manual or on the device.

Symbol	Description
	Caution: Follow instructions to avoid injury or damage to equipment
	Caution: Risk of electric shock
	Caution: Laser beam
	Alternating Current
	Fuse
	Chassis Terminal
	WEEE: Separate collection for waste electric and electronic equipment is required
	Circle Indicator: Indicates relevant item in image
	Pointer Indicator: Points to relevant item in image

1.2 Safety

1. This instrument is intended for use by qualified personnel who recognize shock hazards and laser hazards and are familiar with the safety precautions required to avoid possible injury. Read this instruction manual thoroughly before use to become familiar with the instrument's operations and capabilities.

2. If this instrument is used in a manner not specified by the manufacturer in this manual or other relevant literature, protection provided by the instrument may be impaired.

3. Always operate the RUBRIComb within the temperature and current ranges specified in the unit's final test documentation or Certificate of Conformity (CoC). Improper usage can cause irreparable damage to the laser system.

4. For indoor use only, within a (maximum) Pollution Degree 2, Overvoltage Category II, 35°C ($T_{amb,max}$), with the RUBRIComb installed on a flat, level surface.

5. When rack mounting the RUBRIComb, follow AV Rack Cabinet manufacturer instructions, and use only AV Rack Cabinets with proper approvals.

6. Never look directly into any fiber port! Do not stare into the beam! Never use a fiber scope to view any outputs of the RUBRIComb while the unit is powered.

7. Use of controls or adjustments or performance of procedures other than those specified herein may result in hazardous radiation exposure.

8. The RUBRIComb is not intended for fail-safe operation in hazardous environments or life-threatening situations. The user assumes full responsibility for correct and safe usage of the RUBRIComb in accordance with any applicable laws, codes, regulations, and standards pertaining to their specific application. Vescent is not liable for any consequential damage due to misapplication or failure of the RUBRIComb.

9. To avoid electrical shock hazard, connect the instrument to properly earth-grounded, 3-prong receptacles only. Failure to observe this precaution can result in severe injury or death.

10. This instrument is to be used with the included power cord-set. Do not use a power cord-set with inadequate rating.

11. This equipment is intended to be protected by certified over-current protection of 16/20 A.

12. Before replacing the fuse on the RUBRIComb, turn off the power switch and disconnect the unit from mains power.

13. Except the fuse, there are no field-serviceable parts inside the instrument. Maintenance performed by persons not authorized by Vescent will void the warranty.

14. Do not obstruct the fan exhaust or ventilation holes. Leave clearance around fan for proper ventilation.

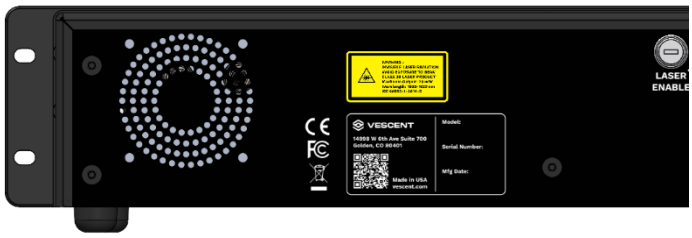
15. Always clean optical fibers before making connections at optical ports. Use the provided optical fiber connector cleaner to clean the optical fiber connector. Cleaning fiber facets *every time* fibers are connected keeps ports free of debris that may damage RUBRIComb bulkhead fibers.

16. Always keep protective caps on optical fiber ports when not in use.

17. To avoid CW breakthrough, keep the oscillator pump diode current within the range specified in the RUBRIComb's final test documentation.

1.3 Affixed Labels

The following labels are affixed to the RUBRIComb housing:

Label	Location
	
Summarizes the maximum output and emitted wavelength of the RUBRIComb.	
	
Alerts user to the output laser aperture ports on the RUBRIComb.	
	
Warns the user about the laser emission hazard at the front of the RUBRIComb.	

2 Hardware

This section discusses the hardware features and connections of the RUBRIComb and the other items that are shipped with the unit.

2.1 Package Contents

The RUBRIComb is shipped in a package designed to provide excellent protection. The shipping box should be saved for future transportation or storage needs.

Carefully remove and inspect the following items that are contained in the shipping box:

- RUBRIComb® Frequency Comb
- Two Operator Keys
- 50 Ω BNC terminator
- Fiber optic connector cleaner, Fujikura One-Click Cleaner Mini-100
- AC Power cord, region-specific
- USB-A to USB-B cable
- Final test documentation

2.2 Controls and Connections

This section introduces all the hardware controls and connection ports on the RUBRIComb.

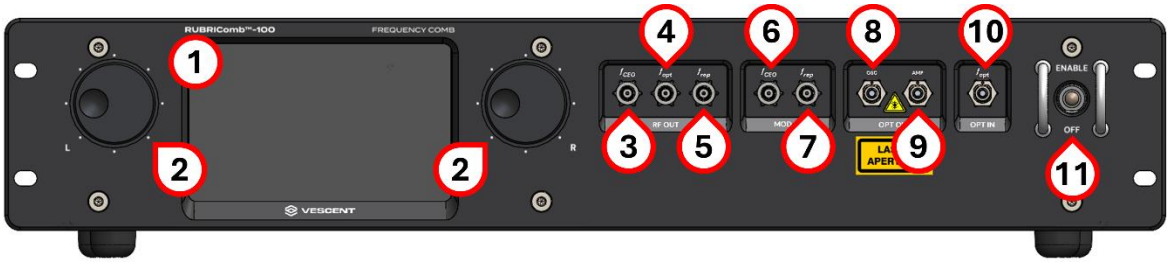
2.2.1 Making Connections at Optical Fiber Ports

To avoid damage to the ports of the RUBRIComb, it is important to take care when mating optical fibers. To keep optical fiber ports free of debris that could damage the RUBRIComb bulkhead fibers, ***always*** clean optical fiber connectors prior to making connections. Even when a fiber is disconnected and immediately reconnected to the same port, it is important to follow proper cleaning procedures.

Refer to this procedure every time a fiber optic cable connection is made at a fiber optic port:

1. Turn off all light sources feeding into the fiber optic cable.
2. Clean the RUBRIComb fiber optic bulkhead with the supplied fiber optic connector cleaner in accordance with the manual for that device.
3. Clean the fiber optic cable connector with the supplied fiber optic connector cleaner in accordance with the manual for that device.
4. Use a fiber optic inspection scope to verify the cleanliness of the fiber optic cable facet.
5. When connecting to a RUBRIComb input port, always check the power level of the incoming light to verify it will not exceed the power limits of the port. Attenuate input signals as necessary.

2.2.2 Front Panel



1. Touchscreen

The primary way to interact with the RUBRIComb is via its front panel touchscreen. General instructions for touchscreen control are discussed in Section 3.

2. Parameter Input Adjustment Knobs

Two rotary knobs allow the user to quickly cycle through parameter list settings and enter numeric inputs. In general, the right knob (R) changes the current selection or the value of a digit, and the left knob (L) changes the digit selection. Additionally, an L or R symbol (see left) on the touchscreen display indicates instances where knob control can be used.

3. Carrier Envelope Offset RF Output (SMA)

RF output port for the comb carrier envelope offset frequency, f_{CEO}.

4. Optical Heterodyne RF Output (SMA)

RF output port for the optical heterodyne signal, f_{opt}. The signal supplied on the Optical Heterodyne Detection port is converted to an electrical RF signal output on this port.

5. Repetition Rate RF Output (SMA)

RF output port for the frequency comb repetition rate, f_{rep}. Several harmonics of the repetition rate are observable. The amplitude of the fundamental tone is typically 0 dBm.

6. Current Modulation Input (SMA)

Modulates the current of the oscillator pump diode for f_{CEO} tuning. Limit input voltage to the range from -5 V to +5 V.

7. PZT Modulation Input (SMA)

Modulates the voltage of the oscillator cavity PZT for f_{rep} fine tuning. Limit input voltage to the range from 0 to 6 V.

The supported f_{rep} tuning range is typically around 60 Hz for the RUBRIComb-100 and 240 Hz for the RUBRIComb-200. For coarse f_{rep} tuning, see the oscillator cavity temperature controls (Section 3.3.3).

8. Oscillator Output Port (FC/APC)

This polarization-maintaining output directly monitors the fiber oscillator output.

Always clean an optical fiber connector before making a connection at this port. Keep protective cap on port when not in use.

9. Amplifier Output Port (FC/APC)

This polarization-maintaining output monitors the fiber amplifier output.

Always clean an optical fiber connector before making a connection at this port. Keep protective cap on port when not in use.

10. Optical Heterodyne Detection Port (FC/APC)

This input port is designed to detect optical heterodyne signal, f_{opt}, and generate an RF signal for optical comb stabilization.

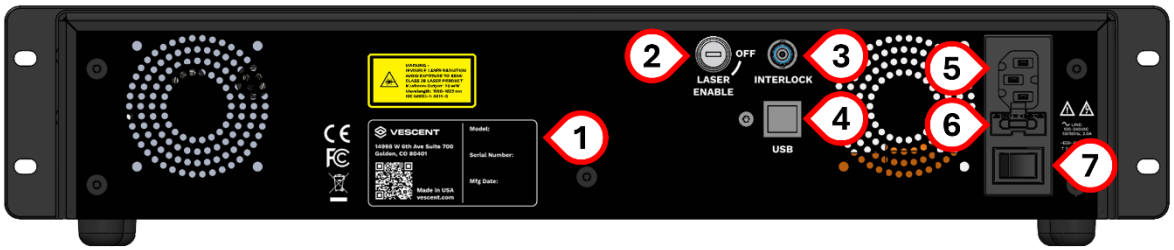
Always clean an optical fiber connector before making a connection at this port. Keep protective cap on port when not in use.

The input limit of this port is 0.6 mW. Exceeding this limit may damage or degrade the RUBRIComb.

11. Laser Enable Switch

This is a manual laser interlock switch. When the toggle switch is pointed at OFF an Interlock error exists. To allow laser emission, flip the toggle switch to point at ENABLE.

2.2.3 Rear Panel



1. Unit Information

Unit information includes the unit model, serial number, and manufacturing date.

2. Access Control Lock

This access control restricts use of the RUBRIComb to authorized operators. The RUBRIComb will only output light if an Operator Key is inserted and oriented vertically ("Laser Enable"). When the key is removed or oriented horizontally ("Off") the RUBRIComb Safety Interlock System (SIS) will trigger.

3. Remote Interlock (BNC)

This port is for disabling the laser output via a remote interlock control. The RUBRIComb will only output light if this port is shorted. When the connection is broken, the RUBRIComb Safety Interlock System (SIS) will trigger.

If not using a remote interlock, leave a 50 Ω BNC terminator on this port.

4. Serial Port (USB-B)

Use a standard USB-A to USB-B cable to connect the RUBRIComb to a computer for remote operation and updating firmware. For further information see Section 6.

5. Power Port

Use the provided AC power cord to connect this port to a properly grounded mains receptacle.

6. Fuse

The RUBRIComb has a factory-installed fuse. To replace the fuse, follow the procedure below:

- Flip the RUBRIComb Power switch off.
- Disconnect the RUBRIComb from mains power.
- Remove the fuse cover.
- Replace the blown fuse with a 5mm x 20mm fuse rated to 250 V and 2A.
- Replace the fuse cover.

7. Power Switch

While the Power port is connected to mains power toggle this switch from O to | to turn on the RUBRIComb.

3 Graphical User Interface

This section discusses how the user interacts with the graphical user interface (GUI) and introduces the different types of buttons, windows, and screens a user will see on the touchscreen display.

3.1 Control Bar

On the left edge of the RUBRIComb touchscreen is the Control Bar. The table below briefly explains the functionality of each Control Bar button.

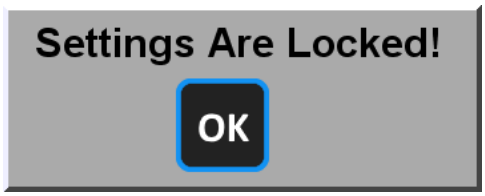
Symbol	Button Name	Function When Tapped
	Home	Returns to Home screen. Home is the screen which appears when the user powers up the unit. See Section 3.3.1.
	Back	Returns to previous screen.
	Parameter Lock	Toggles the Parameter Lock. The Parameter Lock prevents certain fields from being edited. See Section 3.1.1.
	System Settings	Enters the System Settings screen. See Section 3.3.3.

3.1.1 Parameter Lock

The Parameter Lock is a toggle button which helps prevent accidental settings changes.

The symbol to the left indicates the Parameter Lock is in the unlocked state. In the unlocked state, it is possible to interact with any field bordered in blue. Tap the symbol to switch the Parameter Lock to the locked state.

The symbol to the left indicates the Parameter Lock is in the locked state. In the locked state, certain fields will be locked so they cannot be changed until the lock is released. Interacting with a locked button will open the following alert window:



Navigation buttons and many toggle buttons will still be operable in the locked state. Tap the symbol to switch the Parameter Lock to the unlocked state.

3.2 Button Types

The types of GUI buttons and their functionality are discussed here.

Tap a button to interact. It is possible to select the functionality or edit the values of a field bordered in blue. Some buttons have a second parameter edit mode that activates after touching and holding the button for a couple of seconds. Interacting with a button will cause the unit to beep.

3.2.1 Navigation Buttons

Navigation buttons change the screen shown on the display.

Tapping a Navigation button will take the GUI to the corresponding screen. Most Navigation buttons are in the Control bar (see Section 3.1) located on the left of all screens.

3.2.2 Toggle Buttons

Toggle buttons allow the user to switch a parameter between two states.

Tapping a toggle button will switch its state between two options or between a disabled and an enabled state.

For a toggle button which toggles between enabled and disabled states, the button background and text indicate the current state of the button. White text on a black background indicates the toggle is in the disabled state. Black text on a colored background indicates the toggle is in the enabled state.

3.2.3 Dropdown Menus

Dropdown menus allow the user to choose a parameter setting from a list of values.

Tapping a dropdown menu will reveal the list of available choices. The current selection will be bordered in white. Tapping one of the choices selects it and closes the dropdown menu. Tapping outside the dropdown menu closes the dropdown menu and retains the original choice.

3.2.4 Numeric Fields

Numeric fields allow the user to choose a custom numeric value for a given parameter.

Tapping a numeric field will change its border from blue to yellow. Rotary knob editing mode is active while the border is yellow. The underlined digit is the currently active digit. Rotating the L-knob changes the currently active digit. Rotating the R-knob changes the value of the currently active digit. Tap anywhere on the display to disable rotary knob editing mode and change the field border back to blue.

If the rotary knob editing mode is active for 60 consecutive seconds without user input, then the unit will beep and rotary knob editing mode will deactivate. The border of the choice selector will turn red momentarily before returning to blue.

Touching and holding a numeric field launches the numeric keypad. The desired value can be typed into the numeric field by using the keypad. Tapping the Confirm key confirms the value and updates the parameter. When an invalid value is entered into a keypad, the value will be coerced to the nearest valid value. Keypad buttons are described in the table below.

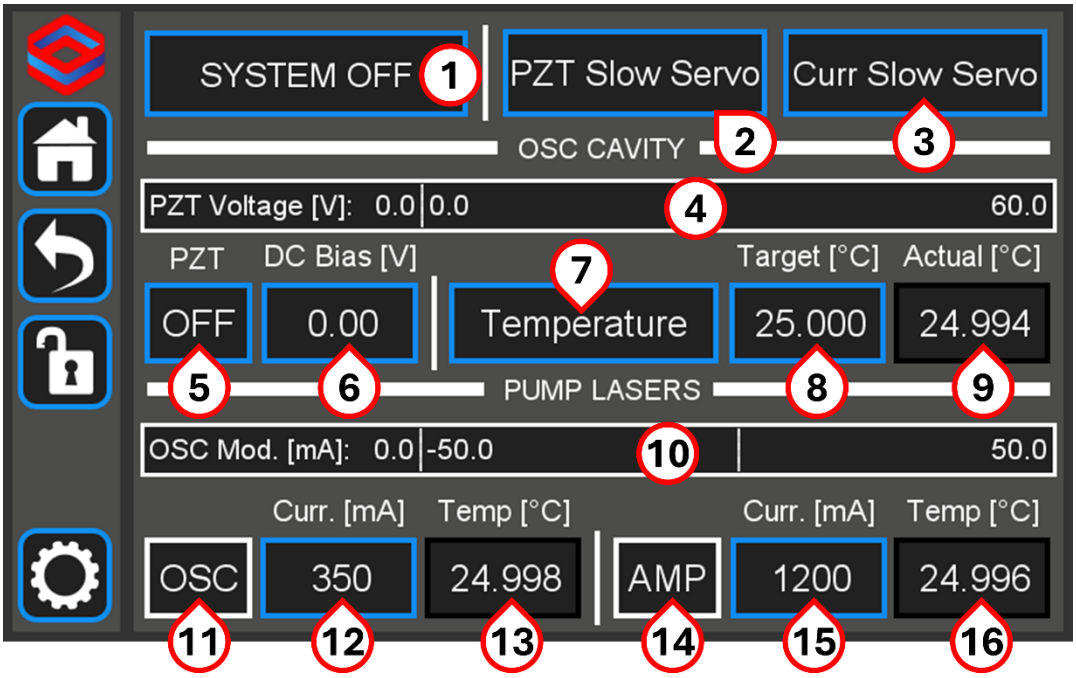
Numeric Keypad Buttons

Symbol	Button Name	Function When Tapped
	Plus/Minus	Changes sign of the value
	Numeric	Inputs tapped number as the next digit
	Decimal Point	Inputs decimal point as the next digit
	Delete	Deletes last digit in the numeric field
	Clear	Clears numeric field
	Back	Exits keypad without accepting changes
	Confirm	Accepts value in numeric field and exits keypad

3.3 Screens

Each of the following sections introduces a screen encountered during operation of the RUBRIComb and describes the function of the contained displays and controls.

3.3.1 Home Screen



After start-up the RUBRIComb will display the Home screen. This view summarizes the current state of the RUBRIComb. The Home screen is divided into three sections. The buttons in the top section activate various modes of comb operation. The middle section is dedicated to controls for the oscillator cavity. The bottom section controls the pump diode current and monitors the diode temperatures.

There are several temperature indicators on the Home screen. The background color of each indicator changes depending on the state of the corresponding temperature plant:

Black - The temperature plant is not under active control.

Red - An error has occurred.

Yellow - The temperature plant is under active control and the measured Temperature Error magnitude is greater than 10 mK.

Green - The temperature plant is under active control and the measured Temperature Error magnitude is less than 10 mK.

1. Operation Mode Selector: Dropdown menu for the RUBRIComb mode setting. The behavior while in each mode is as follows:

SYSTEM OFF - Initial mode when starting up the RUBRIComb. All temperature and current controls are in the off state.

STANDBY - In STANDBY mode, the RUBRIComb will stabilize the temperature of the pump diodes and oscillator cavity.

Upon starting STANDBY mode, the Operation Mode button flashes white, and temperature indicators turn yellow. When the temperature controllers stabilize around their setpoints, their indicators turn green. Once all temperatures stabilize, the Operation Mode selector stops flashing. At this point it is possible to switch to LASER ON mode.

LASER ON - In LASER ON mode, the temperature and current controls are in the on state and the laser is active.

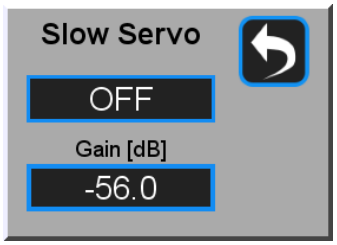
This mode is only available after the temperature of the pump diodes and oscillator cavity have been stabilized. Upon switching to this mode, the Operation Mode selector will flash for 5 seconds. After the conclusion of this safety delay the RUBRIComb will begin supplying current to the pump diodes.

The Oscillator Pump Diode turns on first and the RUBRIComb searches for a mode-locked signal. After the mode-locked signal is verified, the Amplifier Pump Diode turns on.

ERROR - If an error condition is triggered, the RUBRIComb will enter an error state. The Operation Mode selector will flash red and display an error message. No other operation mode can be selected.

To exit the error state, the condition causing the error must first be resolved. Then tap on the error message to return to normal operation. For more information on error states, see Section 5.3.

2. PZT Slow Servo: The PZT Slow Servo controls the temperature of the oscillator cavity to prevent drift of the intracavity PZT voltage over long periods of time. This button turns white when the PZT Slow Servo is active. Tap this button to open the PZT Slow Servo window (below).



The first button toggles the state of the PZT Slow Servo between ON and OFF. To turn on the PZT Slow Servo, the RUBRIComb must be in the LASER ON operational mode and the PZT Modulation must be enabled.

The Gain [dB] field defines the feedback gain for the PZT Slow Servo. This value is set in the factory for optimal response. Consult Vescent technical support before changing the gain.

Turn on the PZT Slow Servo after establishing an f_{opt} lock. Turn off the PZT Slow before removing an f_{opt} lock.

3. Current Slow Servo: The Current Slow Servo controls the oscillator pump diode setpoint current to keep the modulation current centered at 0 mA. This helps maintain an f_{CEO} lock over long periods of time.

Tap this button to toggle the state of the Current Slow Servo. This button turns white when the Current Slow Servo is active.

Turn on the Current Slow Servo after establishing an f_{CEO} lock. Turn off the Current Slow Servo before removing an f_{CEO} lock.

4. PZT Voltage Indicator Bar: Shows the PZT voltage numerically (left) and in bar format (right). The bar indicator has a vertical white line marking the value of the PZT Bias Voltage. A blue bar starting from the left side shows the present PZT voltage. If the blue bar is absent, then the PZT modulation voltage is at its lower voltage limit (0 V) or is disabled. If the blue section fills the bar, then the PZT servo is at its upper voltage limit (60 V).

5. PZT Modulation Enable: The PZT voltage is a length control for the oscillator cavity. PZT modulation is the fast control for the comb repetition rate.

Tap this button to toggle PZT modulation state. When set to OFF, the PZT voltage is not controlled. When set to ×10, the PZT modulation responds to the PZT Bias Voltage and signals on the PZT Modulation Input port. The voltage applied to the PZT is

$$V_{PZT} = PZT\ Bias + (10 \times PZT\ Modulation\ Input)\ .$$

6. PZT Bias Voltage: Sets the bias voltage for the PZT. The recommended PZT bias during typical operation is 0 Volts. Note, changing this voltage limits the dynamic range of the modulation input.

7. Oscillator Cavity Temperature Settings: Navigates to the Oscillator Cavity Temperature Detail screen (see Section 3.3.3).

8. Oscillator Cavity Temperature Setpoint: Temperature setpoint for the oscillator cavity. The oscillator cavity temperature is a length control for the oscillator cavity. Coarsely tune the repetition rate of the comb by changing the temperature of the oscillator cavity.

9. Oscillator Cavity Temperature Indicator: Measured temperature of the oscillator cavity.

10. Oscillator Modulation Current Indicator Bar: Shows the oscillator modulation current numerically (left) and in bar format (right). The bar indicator has a vertical line marking the middle of the modulation range. The blue bar extends from that line to represent the present current. If the blue bar fills the left (right) side of the bar, then the oscillator modulation is at its lower (upper) current limit.

11. Oscillator Pump Diode State Indicator: The background color is black when the Oscillator Pump Diode is off and white when the Oscillator Pump Diode is on.

12. Oscillator Pump Diode Current Setpoint: Current setpoint for the oscillator cavity pump diode. The oscillator pump diode current controls f_{CEO}.

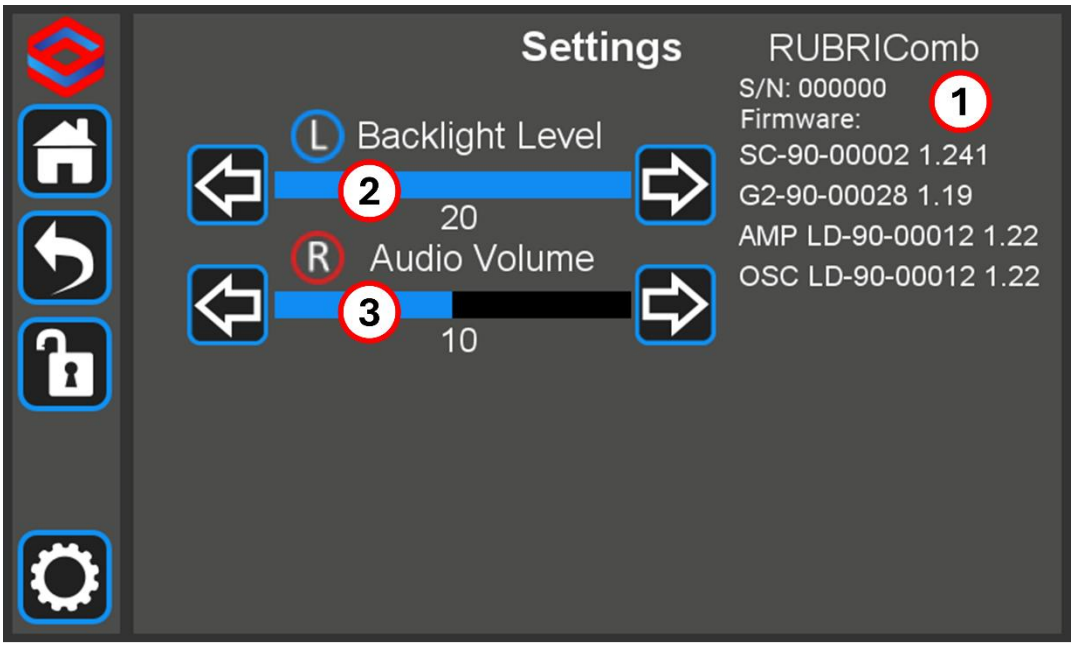
13. Oscillator Pump Diode Temperature Indicator: Measured temperature of the oscillator cavity pump diode.

14. Amplifier Pump Diode State Indicator: The background color is black when the Amplifier Pump Diode is off and white when the Amplifier Pump Diode is on.

15. Amplifier Pump Diode Current Setpoint: Current setpoint for the amplification fiber pump diode.

16. Amplifier Pump Diode Temperature Indicator: Measured temperature of the amplifier fiber pump diode.

3.3.2 *System Settings Screen*



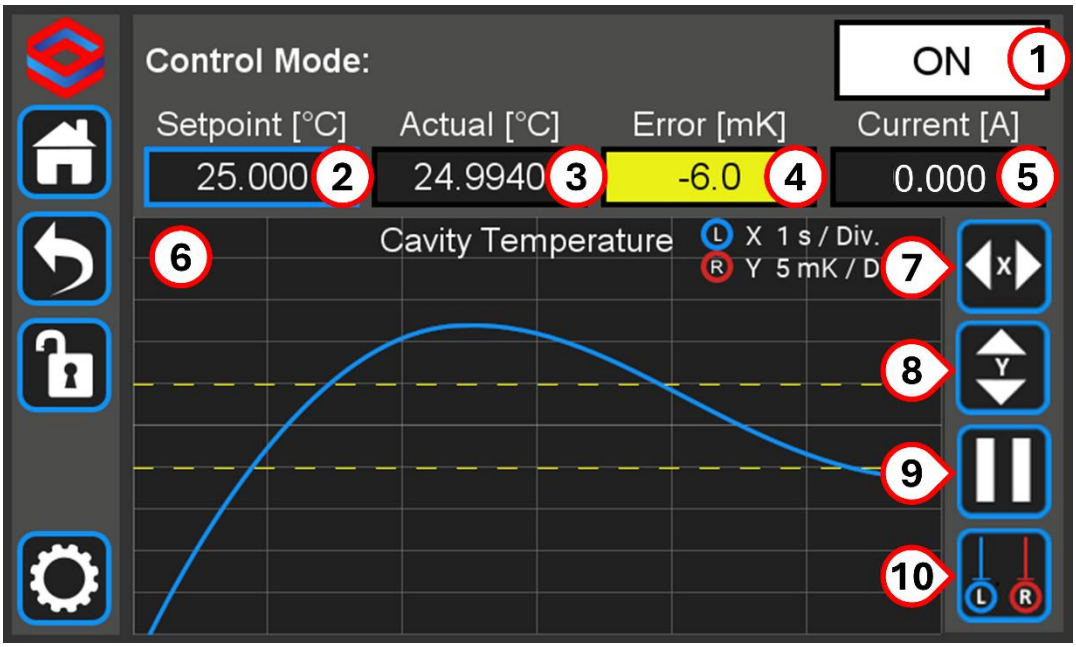
The System Settings (gear) icon navigates the user to the System Settings screen. This screen displays information specific to the unit and has controls for general settings.

1. Unit Information: Includes the Serial Number (S/N) of the unit, and the system controller (SC), frequency comb (Gen2), and laser driver (LD) firmware versions.

2. Backlight Level: The arrows adjust the backlight level of the touchscreen display. The Left knob also adjusts the backlight level.

3. Audio Volume: The arrows adjust the volume of the feedback beeps. The Right knob also adjusts the volume. To completely mute the unit, turn the volume down all the way.

3.3.3 *Oscillator Cavity Temperature Detail Screen*



The RUBRIComb regulates the temperature of its oscillator pump diode, amplifier pump diode, and oscillator cavity. The temperature servos for the pump diodes are optimized in the factory and are activated exclusively via the Operation Mode selector. The oscillator cavity has additional controls that are available on the Oscillator Cavity Temperature Detail screen, shown above.

1. Cavity Temperature Controller State indicator: Tap to toggle the state of the cavity temperature controller.

2. Setpoint Temperature: Temperature setpoint for the oscillator cavity. The oscillator cavity temperature is a length control for the oscillator cavity. Coarsely tune the repetition rate of the comb by changing the temperature of the oscillator cavity.

3. Actual Temperature indicator: Measured temperature of the oscillator cavity. If the actual temperature exceeds the temperature limits, the background of this indicator will turn red.

4. Temperature Error indicator: Temperature difference between the temperature setpoint and actual temperature. The background color of this box changes depending on the current state of the oscillator cavity temperature plant:

Black - The temperature plant is off.

Red - An error has occurred.

Yellow - The temperature plant is under active servo control and the present Temperature Error magnitude is greater than 10 mK.

Green - The temperature plant is under active servo control and the present Temperature Error magnitude is less than 10 mK.

5. Output Indicator: Tap to cycle through displaying the current through, voltage across, and power delivered to the transducer.

6. Temperature Error Graph: Displays a rolling update plot of the Temperature Error as a blue line. The solid white horizontal line at center represents no temperature difference between the Setpoint Temperature and Actual Temperature.

Up to four horizonal dotted lines may be visible on the display. The yellow dotted lines show the 10 mK lock range (see Temperature Error indicator above). The red dotted lines (not visible) show the factory-defined cavity temperature limits.

The X- and Y-axis scaling are shown in the top right corner of the plot.

7. Adjust X Scale: Tap to see additional scaling options for the X-axis of the Temperature Error Graph.

8. Adjust Y Scale: Tap to see additional scaling options for the Y-axis of the Temperature Error Graph.

9. Pause/Restart: Tap to pause updates to the Temperature Error Graph. Tap again to resume updates.

10. Cursor Display: While active (white background), two cursors are displayed on the Temperature Error Graph. Turn the Parameter Adjustment Knobs to change the position of the cursors.

4 Getting Started

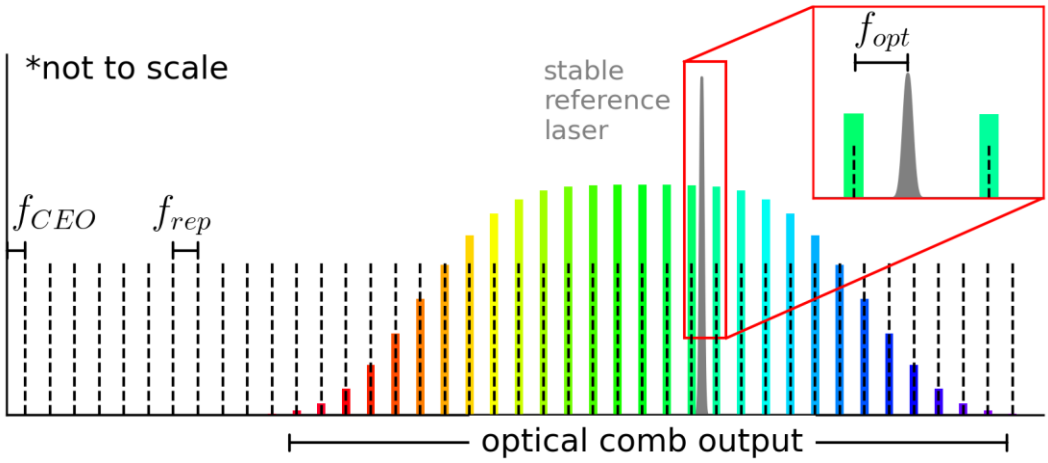
This section explains typical use of the RUBRIComb for new users. A brief theory of operation is followed by an example of typical setup and instructions for stabilizing the comb. Keep in mind that the following are general guidelines for operating the RUBRIComb. Exact settings will vary for your application and hardware.

4.1 Theory of Operation

A frequency comb emits a spectrum of evenly spaced laser modes with frequencies defined by the comb equation,

$$f_n = f_{CEO} + n * f_{rep},$$

where f_n is the frequency of mode n, f_{rep} is the repetition rate that defines the spacing between each comb mode, and f_{CEO} is the carrier envelope frequency that defines the zero-frequency offset. A sketch of an optical comb output is shown below.



The nominal f_{rep} of the RUBRIComb is either 100 MHz (RUBRIComb-100) or 200 MHz (RUBRIComb-200) and the f_{CEO} tuning range is greater than f_{rep}. The output of the RUBRIComb is centered around 1560 nm. As with any free-running frequency comb, the frequencies of the individual comb modes will fluctuate substantially.

A primary method for stabilizing a frequency comb is the optical beat frequency lock approach. In this method, the output of the comb is combined with the light from a stable continuous-wave (CW) reference laser to generate a heterodyne beat signal. The fundamental beat frequency, f_{opt}, originates from the frequency difference between the CW reference laser and the nearest comb mode. The nearest comb mode is stabilized by locking f_{opt} to an RF source. At the same time, f_{CEO} is locked to a second RF source. Locking these two frequencies effectively anchors the comb spectrum at two distant frequencies and thus stabilizes the comb.

4.2 Typical Setup: Optical Beat Frequency Lock

This section discusses how to perform an optical beat frequency lock with the RUBRIComb.

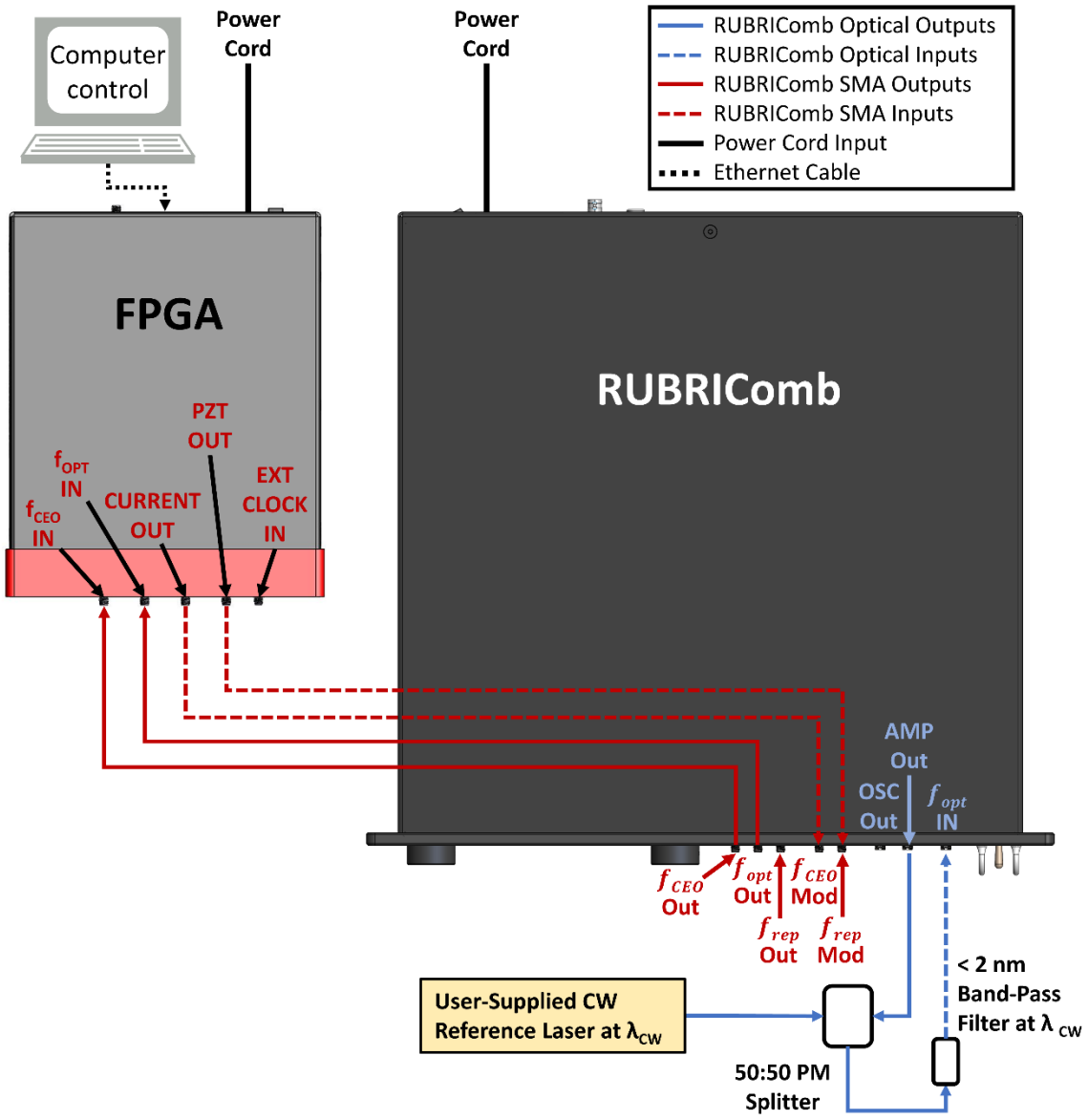
4.2.1 Required Equipment

This is a list of equipment required for the optical beat frequency lock. Be aware that the CW reference laser frequency instability is passed to the comb spectrum (see Section 5.2), so it is important to choose a CW reference laser that is sufficiently stable for the desired application.

The set-up requires the following hardware:

- RUBRIComb
- CW reference laser with wavelength between 1520 nm and 1580 nm.
- Vescent SLICE-FPGA-II
- Computer
- Ethernet cable
- C-band 50:50 polarization-maintaining (PM) coupler
- <2 nm band-pass filter at same wavelength as the CW reference laser
- PM1550 FC/APC fiber optic cables
- SMA-SMA cables
- Power meter
- Optional, but recommended: RF Spectrum Analyzer

4.2.2 *Hardware Setup Procedure*



A hardware connection diagram for the optical beat frequency lock is shown above. The following instructions detail the full procedure for setting up the hardware.

1. Use the provided AC power cord to connect the RUBRIComb to mains power.

2. Use the Remote Interlock port to implement any required safety interlocks.

    a. If interlocks are not required to comply with local safety requirements, place a 50 Ω BNC terminator on the RUBRIComb Remote Interlock port.

3. Insert the Operator key into the Access Control Lock and turn to Laser Enable.

4. Flip the Laser Enable switch to ENABLE.
5. Flip the RUBRIComb Power switch on.
6. Set the RUBRIComb Operation Mode to STANDBY. Continue with the following steps while the temperature servos stabilize.
7. Prepare to connect the 50:50 PM coupler to the RUBRIComb AMP OPT OUT port.

   a. Clean the AMP OPT OUT bulkhead with the fiber optic cleaner.
   b. Clean one input of the 50:50 PM coupler with the fiber optic cleaner.
   c. Insert the 50:50 PM coupler input into the AMP OPT OUT port.

8. Connect the CW reference laser to the other input of the 50:50 PM coupler.
9. Connect the output of the 50:50 PM coupler to a band-pass filter with <2 nm bandwidth at the same wavelength as the CW reference laser.
10. Start CW reference laser emission.
11. Measure the optical power at the output of the band-pass filter with a power meter.
12. Attenuate the CW reference laser power until it is approximately 0.4 mW.
13. Set the RUBRIComb Operation Mode to LASER ON and wait for laser emission to start.

14. The combined power output of the CW reference laser and comb will depend on the wavelength and bandwidth of the band-pass filter.
   a. Ensure the combined measured power at the band-pass filter output does not exceed 0.6 mW. Attenuate the CW reference laser power further as necessary.
   b. If the combined power is less than 0.1 mW, increase the power of the CW reference laser.
15. Record the CW reference laser settings.
16. Turn off the CW reference laser and return the RUBRIComb Operation Mode to STANDBY.
17. Prepare to connect the band-pass filter output to the RUBRIComb f_{opt} OPT IN port.

a. Clean the f_{opt} OPT IN bulkhead with the fiber optic cleaner.

b. Clean the band-pass filter output with the fiber optic cleaner.

c. Insert the band-pass filter output into the f_{opt} OPT IN port.

18. The RUBRIComb converts the optical beat note between the CW reference laser and the comb output into an electrical signal on the f_{opt} RF OUT port. Use an SMA cable to connect this port to the f_{opt} IN port on the FPGA.

19. Refer to the connection diagram to make the remaining SMA port connections between the RUBRIComb and the FPGA.

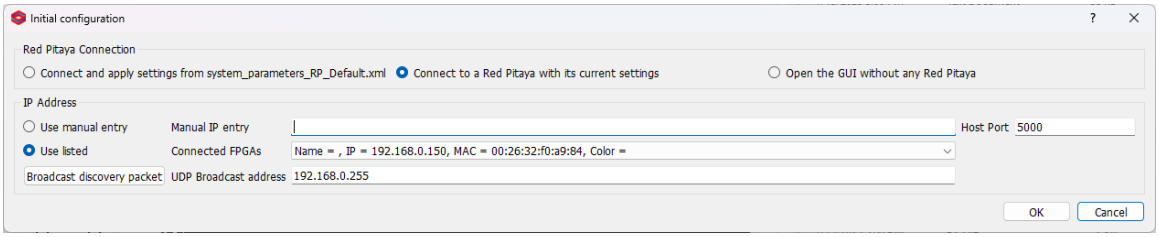
20. Set the RUBRIComb Operation Mode to LASER ON. Wait for laser emission to start.

21. Start CW reference laser emission with the recorded laser settings.

22. Optional: Disconnect the cable at the FPGA-SLICE-II f_{opt} IN port and connect it to an RF spectrum analyzer to view the beat note. This step is helpful when trying to troubleshoot issues with the f_{opt} signal.

4.2.3 FPGA Software Setup Procedure

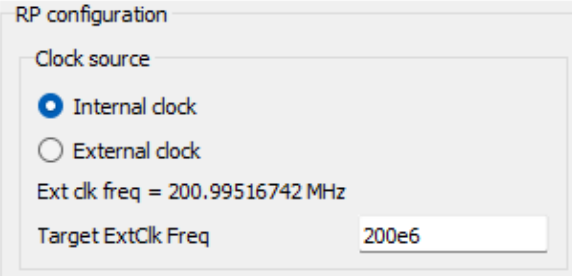
1. Connect the SLICE-FPGA-II to the control computer with an ethernet cable.
2. Turn on the SLICE-FPGA-II.
3. Connect the USB memory stick provided with the SLICE-FPGA-II to the control computer.
4. Copy the compressed SLICE-FPGA-II software package files to a permanent local directory on the control computer.
5. Extract the Digital Servo Python GUI folder.
6. Refer to the README to install WinPython.
7. Open the folder created by the WinPython installer.
8. Double-click "WinPython Command Prompt"
9. In the command prompt window, use the "cd" command to navigate to the "digital_servo_python_gui_SLICE-FPGA-II" directory.
10. Enter "python XEM_GUI3.py" into the console and hit enter. This will launch the Initial Configuration window (below).



11. Select "Connect to Red Pitaya with its current settings".
12. Under IP Address, check that the SLICE-FPGA-II is recognized.
    a. If the device is recognized, the device name and IP address will appear in the "Connected FPGAs" line.
    b. If the device is not initially found, click "Broadcast delivery packet" to search for the device.
    c. If you continue to have trouble connecting to the SLICE-FPGA-II, check the firewall settings on the control computer.
13. Click 'OK'.

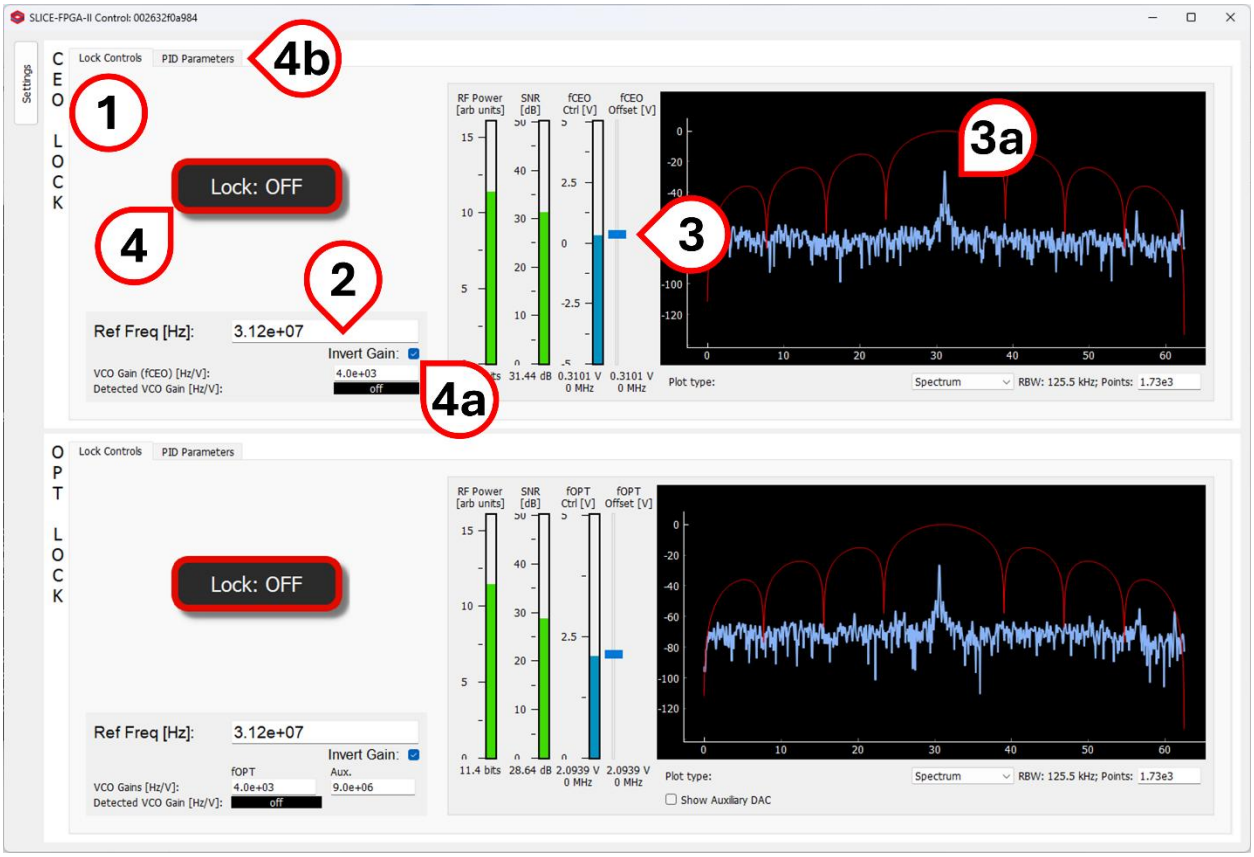
14. Click the Settings button at the upper left of the new window.

15. In the "Clock source" box, choose "Internal clock"

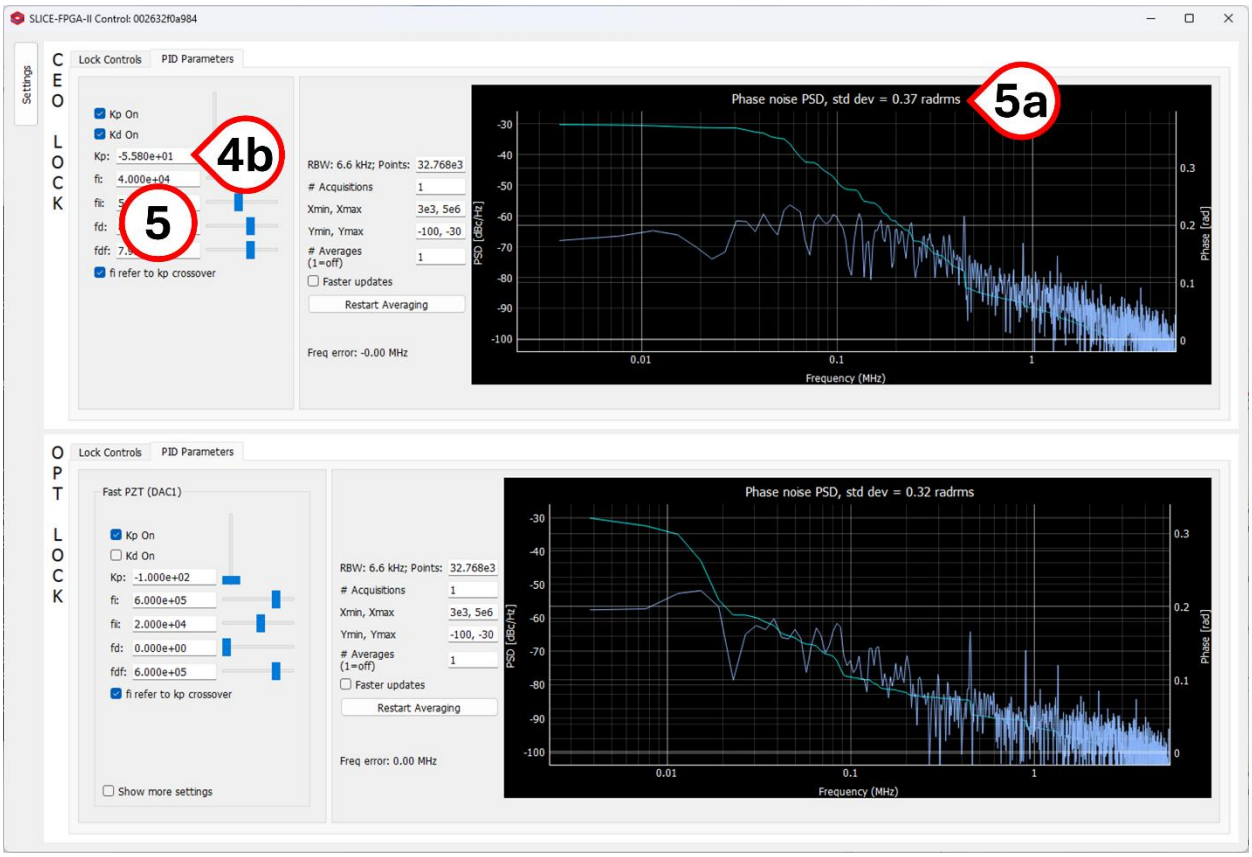


16. Close the Settings window.

4.2.4 Locking f_{CEO}



1. Look for the CEO LOCK controls that occupy the top half of the SLICE-FPGA-II GUI.
2. Set the desired f_{CEO} frequency in the Ref Freq [Hz] input. Note, this frequency should be less than $f_{rep}/2$.
3. Click and drag the fCEO Offset [V] slider.
    a. Center the beat note peak in the red filter trace.
4. Click the CEO Lock toggle button to initiate the f_{CEO} lock.
    a. If the system does not lock the beat note peak to the center of the plot, toggle the CEO Lock to OFF. Toggle the Invert Gain setting and try locking again.
    b. If the system still does not lock, try lowering the loop filter gain value (K_p) in the PID Parameters tab.



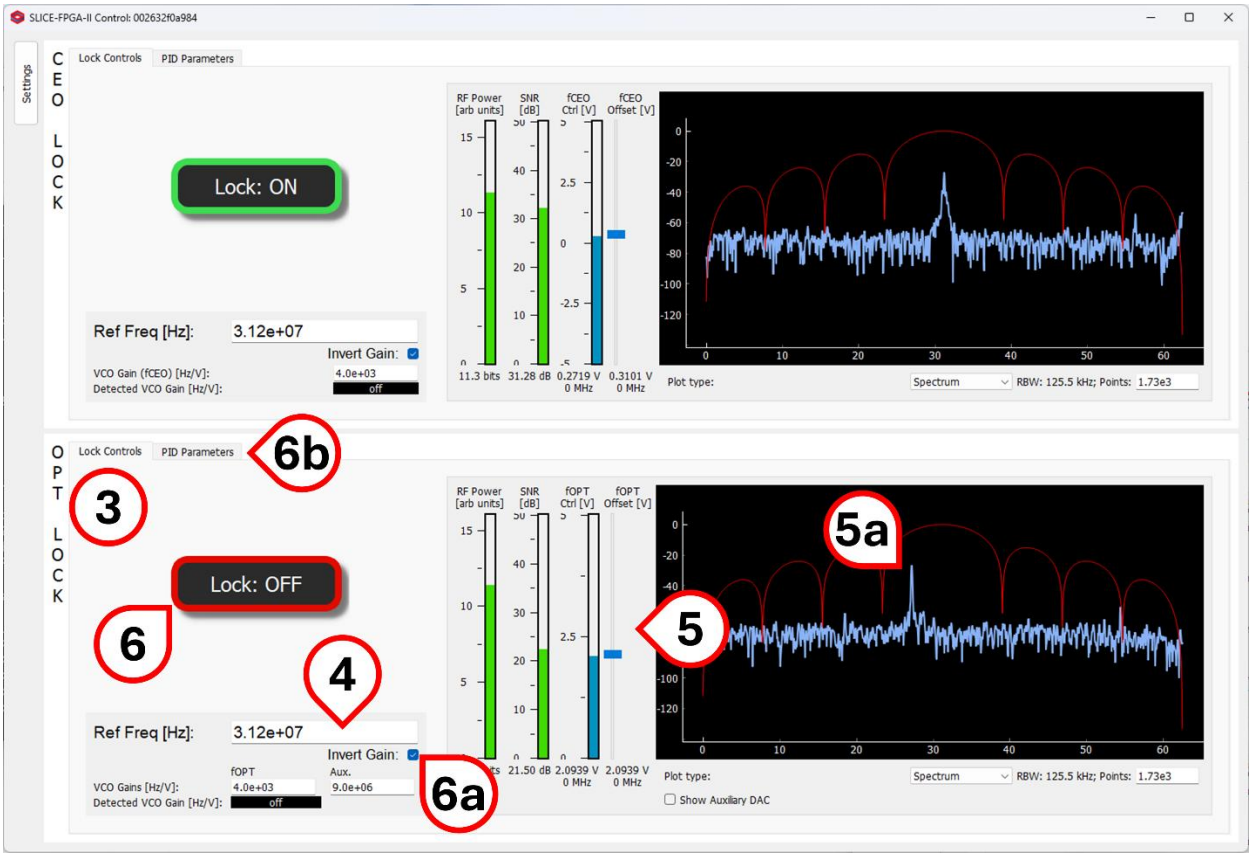
5. The loop filter parameters are factory-set for optimal performance.

    a. If the phase noise power spectral density (PSD) is greater than 0.4 radians when locked, try tuning the loop filter gain value (K_p).

6. Go to the RUBRIComb GUI and turn on the Current Slow Servo.

    a. During shutdown, turn off the Current Slow Servo before removing the f_{CEO} lock.

4.2.5 Locking f_{opt}



1. Ensure the CW reference laser and Amplifier Output port light are properly mixed and input on the Optical Heterodyne Detection port.

2. Enable PZT modulation from the RUBRIComb GUI (see Section 3.3.1).

3. Look for the OPT LOCK controls that occupy the bottom half of the SLICE-FPGA-II GUI.

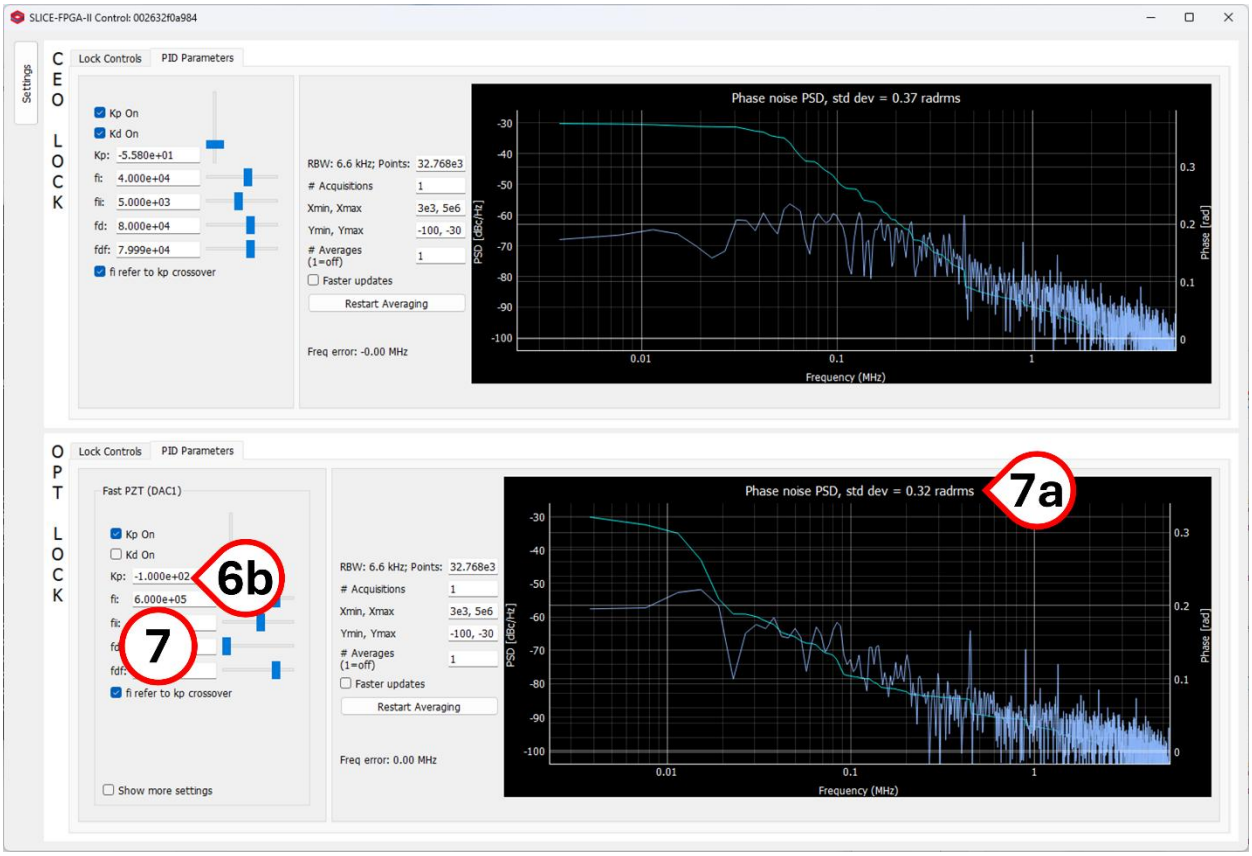
4. Set the desired f_{opt} frequency in the Ref Freq [Hz] input. Note, this frequency should be less than $f_{rep}/2$.

5. Click and drag the fOPT Offset [V] slider.

    a. Center the beat note peak in the red filter trace.

6. Click the OPT Lock toggle button to initiate the f_{opt} lock.

    a. If the system does not lock the beat note peak to the center of the plot, toggle the OPT Lock to OFF. Toggle the Invert Gain setting and try locking again.



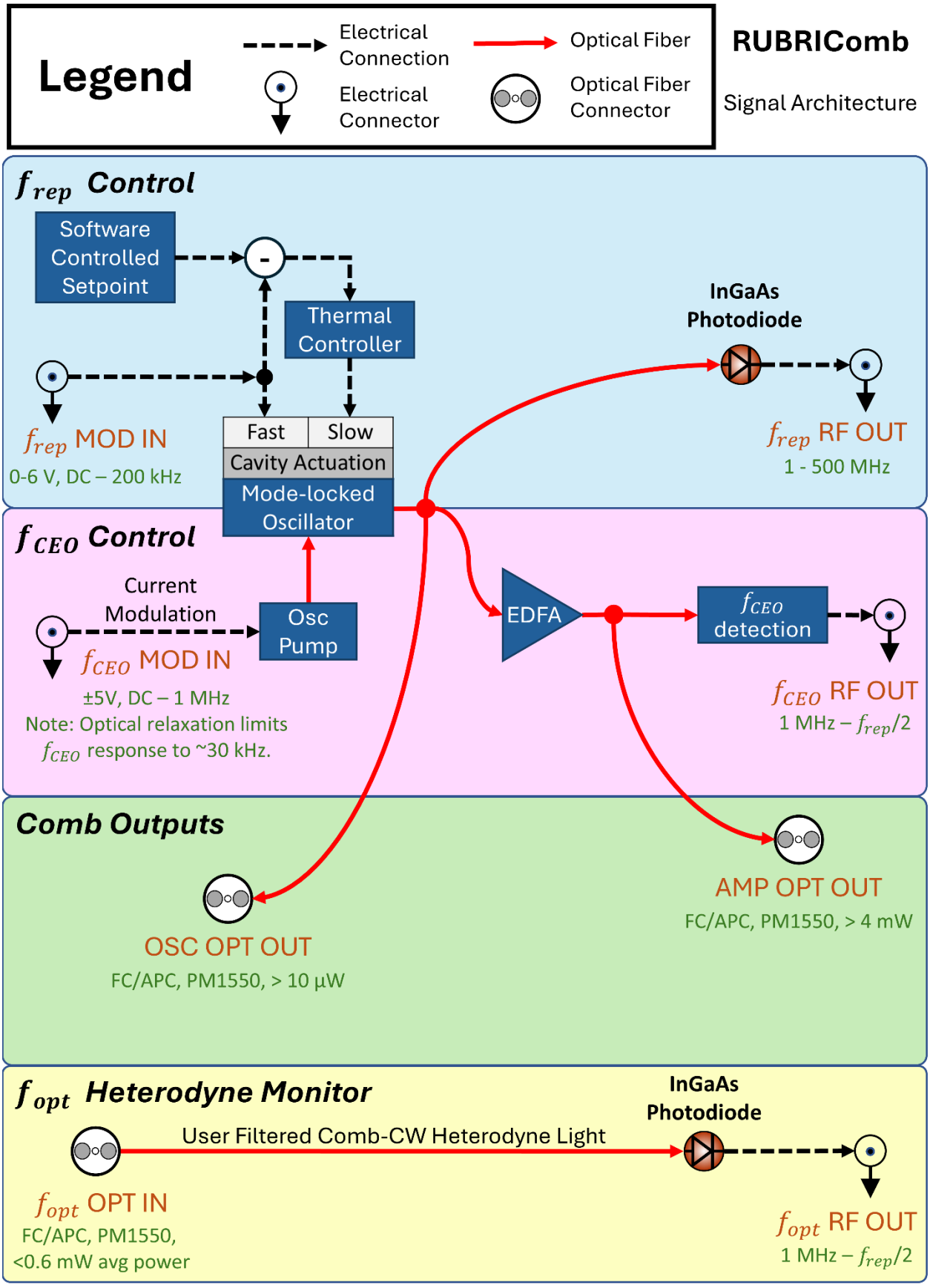
b. If the system still does not lock, try lowering the loop filter gain value (K_p) in the PID Parameters tab.

7. The loop filter parameters are factory-set for optimal performance.

   a. If the phase noise power spectral density (PSD) is greater than 0.4 radians when locked, try tuning the loop filter gain value (K_p).

8. Go to the RUBRIComb GUI and turn on the PZT Slow Servo.

   a. During shutdown, turn off the PZT Slow Servo before removing the f_{opt} lock.


Legend
Electrical Connection
Optical Fiber
Electrical Connector
Optical Fiber Connector
RUBRIComb
Signal Architecture
f_{rep} Control
Software Controlled Setpoint
Thermal Controller
InGaAs Photodiode
f_{rep} MOD IN
0-6 V, DC – 200 kHz
Fast
Slow
Cavity Actuation
Mode-locked Oscillator
f_{rep} RF OUT
1 - 500 MHz
f_{CEO} Control
Current Modulation
Osc Pump
EDFA
f_{CEO} detection
f_{CEO} MOD IN
±5V, DC – 1 MHz
Note: Optical relaxation limits f_{CEO} response to ~30 kHz.
f_{CEO} RF OUT
1 MHz – f_{rep}/2
Comb Outputs
AMP OPT OUT
FC/APC, PM1550, > 4 mW
OSC OPT OUT
FC/APC, PM1550, > 10 µW
f_{opt} Heterodyne Monitor
InGaAs Photodiode
User Filtered Comb-CW Heterodyne Light
f_{opt} OPT IN
FC/APC, PM1550,
<0.6 mW avg power
f_{opt} RF OUT
1 MHz – f_{rep}/2

5 Detailed Operations

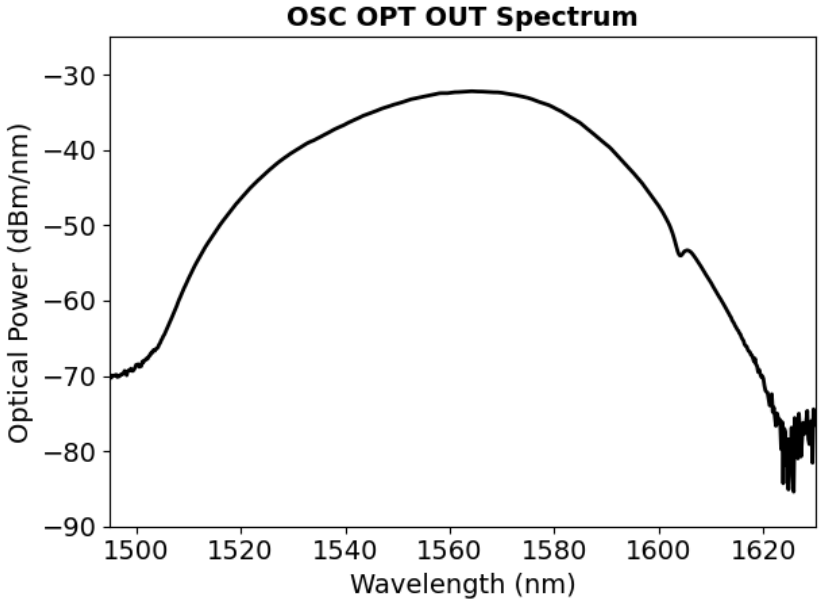
This section provides additional details about the operation of the RUBRIComb. All plots shown in this section are derived from measurements taken with a RUBRIComb-100.

5.1 Comb Signal Architecture

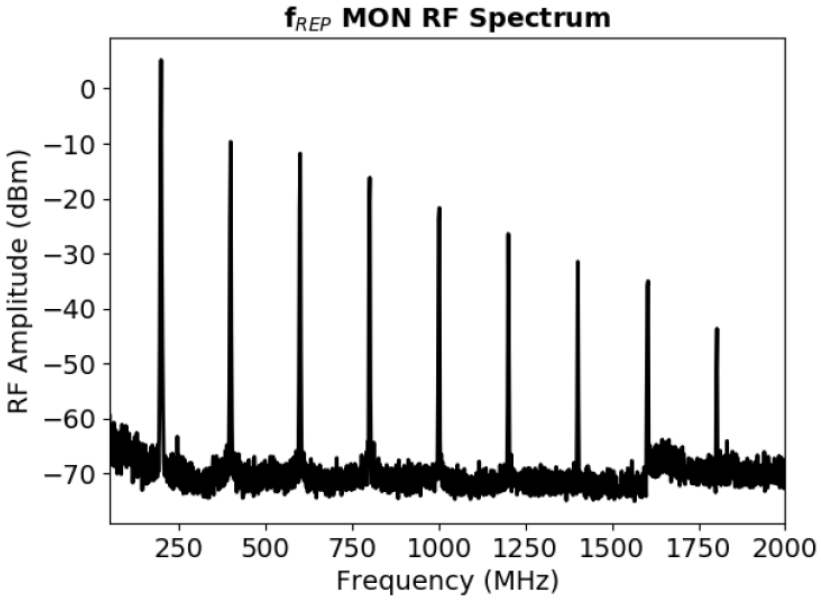
The block diagram schematic on the previous page shows the general signal architecture of the RUBRIComb. The RUBRIComb is a fiber frequency comb with a mode-locked fiber oscillator cavity at its core. The oscillator pump diode current controls f_{CEO} and cavity length determines f_{rep}.

The cavity length is controlled in two ways. Fast cavity actuation is performed by modulating the voltage on the intracavity piezoelectric transducer (PZT). Slow cavity actuation is performed by changing the cavity temperature. A thermal controller ensures the cavity temperature remains stable. When the PZT Slow Servo is enabled, both actuation methods work together to keep f_{rep} stable over long periods of time.

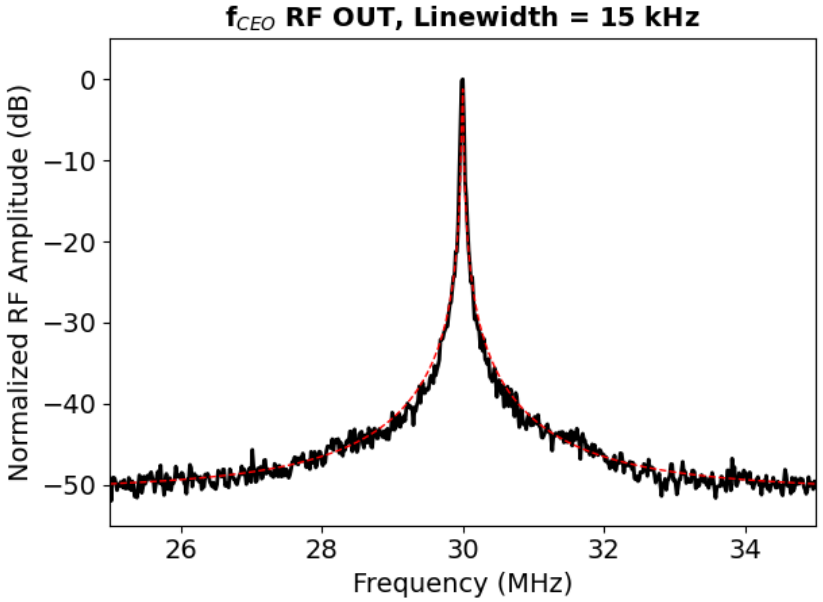
The oscillator cavity outputs a comb signal that is centered around 1560 nm. The OSC OPT OUT port directly monitors this signal. An example of the OSC OPT OUT output is seen below.



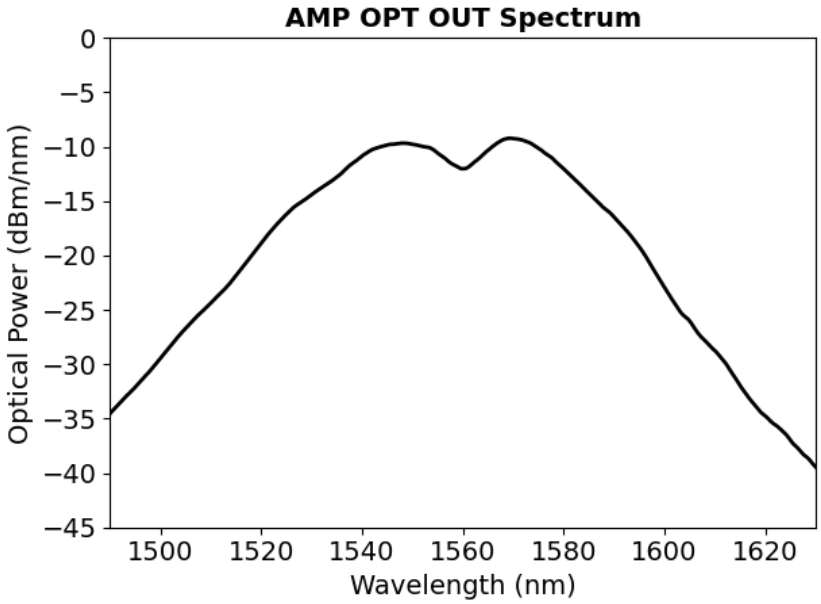
A second monitor collects the oscillator output on a photodiode. The output contains the fundamental frequency mode and harmonics of f_{rep}. An example of the f_{rep} RF OUT spectrum is seen below.



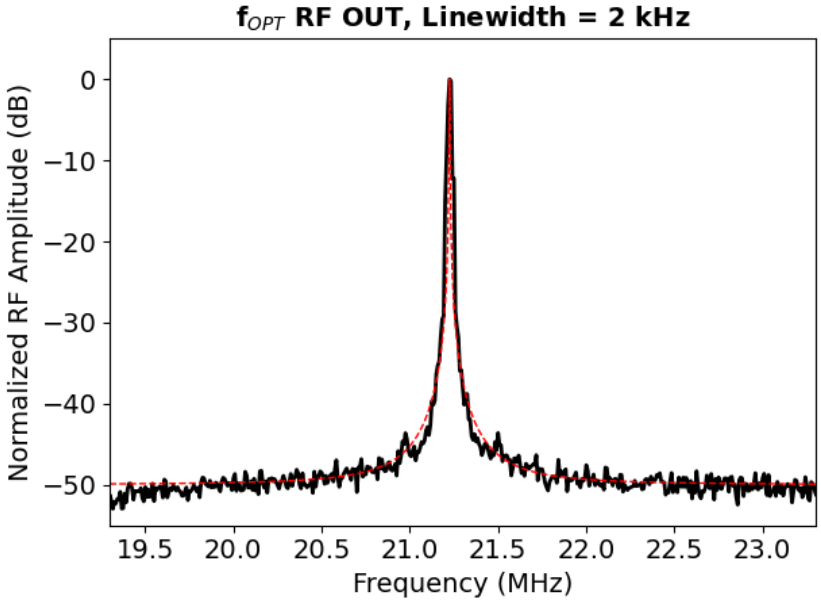
The remaining oscillator light is amplified in an erbium-doped fiber amplifier (EDFA). The EDFA has a dedicated amplifier pump diode (not shown) that controls the amplifier output. The amplifier output is used for two purposes. First, some light is used for f_{CEO} detection. An example of the f_{CEO} RF OUT spectrum is seen below.



The remaining amplifier light is output on the AMP OPT OUT port. This light is intended to be used for generating a heterodyne beat signal, f_{opt}, when performing an optical beat frequency lock. An example of the AMP OPT OUT spectrum is seen below.



To generate the signal for an optical lock, the AMP OPT OUT signal is combined with the light from a stable CW reference laser. The RUBRIComb has a dedicated optical input for detecting this optical heterodyne signal and converting it to RF. Below is an example of the captured f_{opt} RF OUT signal. In this example, a RIO Planex 1550 nm laser acts as the CW reference laser.



5.2 Stability of the Frequency Comb

In an optical beat frequency lock, the stability of the comb modes is primarily defined by the CW reference laser.

The beat note f_{opt} is the beat note originating from the CW reference laser frequency f_{CW} and the nearest comb mode f_n, i.e.,

$$f_{opt} = |f_n - f_{CW}| \, .$$

When this frequency is locked to an RF oscillator and f_{CEO} is also locked to its own RF signal, the repetition rate of the laser is robustly fixed to

$$f_{rep} = \frac{f_{CW} \pm f_{opt} \pm f_{CEO}}{n} \, .$$

This correlates to a frequency stability given by the equation

$$\partial f_{rep} = \frac{\left(\partial |f_{CW}|^2 \pm \partial |f_{opt}|^2 \pm \partial |f_{CEO}|^2\right)^{1/2}}{n} \, .$$

This illustrates how the repetition rate stability, and thus the stability of each comb mode, is dependent on the stability of the CW reference laser. Keep this in mind when choosing a reference laser for an optical beat note frequency lock.

5.3 Errors

When an error is triggered, the Operation Mode selector flashes red and warning text appears on the button. Use the warning text to identify the error from the section titles below.

Many of the errors initiate the Safety Shutdown Protocol. During this process the RUBRIComb shuts off its pump diodes, temperature controllers, and PZT modulator, much as it would to return to SYSTEM OFF mode. The Safety Shutdown Protocol is enacted to minimize the risk of harm to the operator and damage to the RUBRIComb.

5.3.1 Interlock Error and the Safety Interlock System

The Safety Interlock System (SIS) is designed to limit laser hazards and reduce risk of injury to human operators and damage to connected equipment. The SIS is designed to satisfy typical laser interlock requirements.

The first element of the SIS is the Access Control lock that restricts use of the RUBRIComb to authorized operators. The provided Operator keys should only be given to operators who have read this manual and have a working knowledge of laser safety. If a key is removed at any point during operation, the SIS system will be engaged.

The second element of the SIS is the Remote Interlock port that allows the user to install a remote interlock system. If a remote interlock system is not required, install the provided 50 Ω BNC terminator on the port. To operate the RUBRIComb, the inner and outer conductors of the port must be electrically connected. If this connection is broken, the SIS will be engaged. Proper use of the Remote Interlock requires that the circuit does *not* connect to ground as this may also engage the SIS.

The final element of the SIS is the Laser Enable Switch. When this toggle switch is flipped into the OFF position, the SIS is engaged.

When the SIS is engaged, the RUBRIComb first returns to STANDBY mode. Then the Operation Mode selector flashes red, and the text changes to "INTERLOCK" to indicate that the RUBRIComb has entered Interlock mode.

To exit Interlock mode, the cause of the interlock must first be resolved. Then the operator can tap on the Operation Mode selector to return to normal operation.

5.3.2 Cav Temp Out of Range

When the temperature of the oscillator cavity is outside the allowed range, a Cav Temp Out of Range error is triggered.

During a Cav Temp Out of Range error, the RUBRIComb initiates the Safety Shutdown Protocol. Then the Operation Mode selector flashes red, and the text changes to "Cav Temp Out of Range".

If applicable, remove the RUBRIComb from an extreme temperature environment. Check that the RUBRIComb is properly ventilated, and the fans are blowing air.

To exit Cav Temp Out of Range mode, wait for the temperature of the oscillator cavity to decrease and then tap the flashing Operation Mode button to return to SYSTEM OFF mode.

5.3.3 Osc Temp Out of Range

When the temperature of the oscillator pump diode is outside the allowed range, an Osc Temp Out of Range error is triggered.

During an Osc Temp Out of Range error, the RUBRIComb initiates the Safety Shutdown Protocol. Then the Operation Mode selector flashes red, and the text changes to "Osc Temp Out of Range".

If applicable, remove the RUBRIComb from an extreme temperature environment. Check that the RUBRIComb is properly ventilated, and the fans are blowing air.

To exit Osc Temp Out of Range mode, wait for the temperature of the oscillator pump diode to decrease and then tap the flashing Operation Mode button to return to SYSTEM OFF mode.

5.3.4 Amp Temp Out of Range

When the temperature of the amplifier pump diode is outside the allowed range, an Amp Temp Out of Range error is triggered.

During an Amp Temp Out of Range error, the RUBRIComb initiates the Safety Shutdown Protocol. Then the Operation Mode selector flashes red, and the text changes to "Amp Temp Out of Range".

If applicable, remove the RUBRIComb from an extreme temperature environment. Check that the RUBRIComb is properly ventilated, and the fans are blowing air.

To exit Amp Temp Out of Range mode, wait for the temperature of the amplifier pump diode to decrease and then tap the flashing Operation Mode button to return to SYSTEM OFF mode.

5.3.5 Mode Lock Timeout

When the oscillator fails to achieve mode lock within the allowed start-up time, the amplifier cannot be turned on. As a result, the RUBRIComb initiates the Safety Shutdown Protocol. Then the Operation Mode selector flashes red, and the text changes to "MODE LOCK TIMEOUT".

To exit Mode Lock Timeout mode, tap the flashing Operation Mode button to return to SYSTEM OFF mode.

Try starting the laser again. If the issue persists, contact Vescent support.

5.3.6 Open Circuit/Over Voltage

The output voltage required to drive one of the pump diodes exceeded its limit.

If the Operation Mode selector is flashing red and the text changes to "Open Circuit / Over Voltage", do not attempt to restart the laser. Please contact Vescent support before continuing.

5.3.7 Hardware Over Temp

If the temperature of the RUBRIComb exceeds suitable limits, then a Hardware Temperature warning is triggered. The Safety Shutdown Protocol is initiated. The Operation Mode selector flashes red and the text changes to "Hardware Over Temp".

Safely and quickly shut off the RUBRIComb. If applicable, remove the RUBRIComb from an extreme temperature environment. Check that the RUBRIComb is properly ventilated.

5.3.8 15 V Error

The Oscillator Cavity control board has reported an error.

If the Operation Mode selector is flashing red and the text changes to "15 V Error", do not attempt to restart the laser. Turn off the RUBRIComb and contact Vescent support.

6 Remote Operation

This section describes how to set up a remote connection for the RUBRIComb.

6.1 Setting up a Remote Connection

Start by connecting the RUBRIComb to a computer with a USB-A to USB-B cable. Plug the USB-B connector into the USB port on the RUBRIComb and the USB-A connector to a free port on the computer.

In Windows systems, the RUBRIComb will appear as a COM Port. In UNIX-like systems (Linux, MacOS), it will appear as a serial port in the /dev/ folder.

Using a serial terminal application such as Tera Term or Putty, connect to the RUBRIComb with the following parameters:

- Speed: 115200
- Data Length: 8-bit
- Parity: None
- Stop Bits: 1
- New Line Receive: AUTO
- New Line Transmit: CR

Test your connection by sending a command, such as "***IDN?"**

You should see a response like:

Vescent,RUBRIComb,000004,S-V1.241,LD-V1.22,LD-V1.22,GEN2-V1.19

You are now ready to control the RUBRIComb via serial API commands. For a complete list of commands, see the RUBRIComb Serial API Guide.

7 Troubleshooting

The following table describes typical issues that may be encountered while using the RUBRIComb and recommended solutions.

Problem	Recommended Actions
Numeric field does not increase when right rotary knob is turned clockwise -or- Numeric field does not decrease when right rotary knob is turned counterclockwise.	Value likely exceeds a software or user-defined limit. For user-defined limits, adjust the limit to increase the parameter range.
Unable to exit Interlock Error mode.	1. Check the Remote Interlock circuit continuity, the Access Control Lock state, and the Laser Enable Switch state. 2. Ensure the Remote Interlock does not have a path to ground. 3. An Operator Key inserted into the Access Control Lock is grounded. Ensure the key does not conduct to the Remote Interlock port.
Optical output power does not match the values documented in the CoC.	Turn off the comb and check the cleanliness of the optical fibers. If necessary, clean the fibers with the provided fiber optic cleaner.
f_{opt} signal disappears or shows significantly reduced signal-to-noise (SNR).	Check f_{opt} OPT IN power is <0.6 mW. Turn off the comb and check the cleanliness of the optical fibers. If necessary, clean the fibers with the provided fiber optic cleaner.
f_{opt} signal linewidth significantly broadened.	Check CW reference laser performance. Ensure f_{opt} is still locked and PZT is not railed to its maximum or minimum voltage.
f_{opt} signal peak does not respond to modulation on f_{rep} MOD IN.	Check that the PZT is on. Try replacing the cable connected to PZD MOD IN.

f_{CEO} SNR <35 dB	Ensure amplifier current is set to the value in the comb COC. If performance does not match the CoC, increase the amplifier diode current slightly. Do not increase more than 100 mA above operating value. If issue persists, contact Vescent support.
Additional pair of peaks visible adjacent to primary f_{CEO} peak.	If peaks are not present in the CoC RF spectra, contact Vescent support to discuss how oscillator current can be safely reduced.
Cavity temperature changes rapidly after unlocking f_{opt}.	Ensure PZT Slow Servo is off.
Oscillator current rails to its maximum or minimum value after unlocking f_{CEO}.	Ensure Current Slow Servo is off.
Sharp 1550 nm peak is observed on OSC OPT OUT port.	This is a sign of CW Breakthrough. Return to SYSTEM OFF mode and turn off the comb. Contact Vescent support before resuming operation.

A Specifications

A.1 General

Parameter	Value	Units
Center Wavelength	1560	nm
Repetition Rate	100 (for -100) 200 (for -200)	MHz

A.2 Optical Outputs

All optical connectors are PM FC/APC.

Parameter	Min.	Typical	Max.	Units	Comments
Oscillator Average Output Power	0.01			mW	
Oscillator Optical Bandwidth	18	35 (for -100) 25 (for -200)		nm	FWHM
Amplifier Average Output Power	4			mW	
Amplifier Optical Bandwidth	40	70		nm	-10 dB full width

A.3 RF Outputs

All RF connectors are SMA.

Parameter	Minimum	Typical	Maximum	Units	Comments
f_{CEO} Signal-to-Noise Ratio	35			dB	100 kHz RBW
f_{CEO} Integrated Phase Noise		400	1000	mrad	10 Hz-1 MHz
f_{CEO} Frequency Stability[1]			5×10^{-17}		At 1 s, In-loop Modified Allan Deviation
f_{opt} Optical Input Power	0.1		0.6	mW	
f_{opt} Signal-to-Noise Ratio[2]		40		dB	100 kHz RBW
f_{opt} Integrated Phase Noise[2]		200		mrad	10 Hz-1 MHz
f_{opt} Frequency Stability[1,2]			5×10^{-17}		At 1 s, In-loop Modified Allan Deviation
f_{rep} Output Power Level	-10	0	5	dBm	

[1] Allan Deviation from zero-dead-time lambda counter with 1 s gate time.

[2] Depends on user-supplied optical reference. Data given for 1kHz 1560 nm reference laser with >0.1 mW input power when phase locked with a SLICE-FPGA.

A.4 Frequency Transducers

Parameter	Min.	Typical	Max.	Units	Comments
f_{CEO} Tuning Range	100 (for -100) 200 (for -200)			MHz	Pump Current Tuning
f_{CEO} Input Voltage Tuning Range	-5		5	V	SMA Input
f_{rep} PZT Tuning Range	30	60 (for -100) 240 (for -200)		Hz	Depends on Repetition Rate. Temperature tuning spec allows for larger changes in f_{REP}
f_{rep} Input Voltage Tuning Range	0		6	V	SMA Input
f_{rep} Temperature Tuning Range		25 (for -100) 50 (for -200)		kHz	Cavity temperature between 20 and 45 °C
f_{rep} Temperature Tuning Sensitivity		1 (for -100) 2 (for -200)		kHz/°C	Depends on Repetition Rate

A.5 Size, Weight, and Power

Parameter	Value	Units	Comments
Input Line Voltage	100 - 240	VAC	50/60 Hz
Overvoltage Category	II		
Power Consumption	40	W	Maximum
Weight	7.3	kg	
Chassis Volume	17	L	Not including rackmount ears and feet
Dimensions	19 W x 19 D x 3.875 H	in	2U 19" rack mount
	48.3 W x 48.3 D x 9.8 H	cm	

A.6 Environmental

Parameter	Min.	Max.	Units	Comments
Indoor or Outdoor Use	Indoor Use Only			Dry Location Only
Pollution Degree of Environment		2		
Operating Altitude		2000 (6561)	m (ft)	
Operating Temperature	15	35	°C	
Operating Relative Humidity		93	%	Non-condensing
Storage Temperature	-10	70	°C	

A.7 Model Designation

RUBRIComb-(REP)	
REP	Repetition rate of the comb in MHz

B Additional Resources

QR Code	Details
	Vescent Home https://vescent.com/ Additional resources are available at vescent.com

C Service & Maintenance

The RUBRIComb is designed to be maintenance free. No user-serviceable parts are inside the unit. No further calibrations are necessary for the RUBRIComb to meet its accuracy specifications over the lifetime of the product. Opening the instrument case voids the warranty and exposes the user to hazardous voltages that are present inside the instrument case.

Cleaning instructions: Do *not* clean outside surfaces of any Vescent products with solvents such as acetone. Front panels on electronics modules may be cleaned with a mild soap and water solution.

For service or repairs:

1. Contact Vescent customer service via telephone at (+1) 303-296-6766, online at www.vescent.com/support, or via email at info@vescent.com. Customer service will determine if the equipment requires service, repair, calibration, or replacement. Factory office hours are 9:00 am - 5:00 pm MST.

2. If the unit must be returned to Vescent, ask for a Return Merchandise Authorization (RMA) from customer service. **Never send any unit back to Vescent without a completed Return Merchandise Authorization (RMA).**

3. Pack the unit in its original shipping material (if possible) with at least 1 inch of compressible packing material on all sides. Be sure to include an ownership tag and enter a description on the RMA form fully detailing the defect and the conditions under which it was observed.

4. Return the unit, postage prepaid, to Vescent. Do not forget to return a hard copy of the completed RMA form with the unit and write the RMA number on the shipping label. Vescent will refuse and return any package that does not bear an RMA.

5. After repair, the equipment will be returned with a repair report. If the equipment is out of warranty but operates within specifications, a test set-up fee will be charged to the customer. If the equipment is not under warranty, the customer will be invoiced for the cost appearing on the repair report.

6. Vescent is responsible for shipping the unit back to the customer if the unit is under warranty. **Shipping damage is not covered by this warranty,** and shipping insurance, which Vescent recommends, is at the customer's expense.

D Warranty

Vescent hereby warrants to Buyer, that during the applicable Warranty Period (as defined below) the Products will conform to Vescent's published specifications and will be free of defects in materials or workmanship when used, installed and maintained in accordance with Vescent's published specifications. Vescent's sole liability and Buyer's sole and exclusive remedy for breach of warranty shall be limited to, at Vescent's option, either repairing or replacing the defective components of the Product or crediting Buyer for the amount Buyer has paid to Vescent for the applicable Product. Vescent's liability shall apply only to Products which are returned to the factory or authorized repair point, with shipping charges prepaid by Buyer, and which are, after examination, determined to Vescent's satisfaction to be defective due to defects in materials or workmanship. Vescent will only accept returns authorized by a Vescent customer service representative and with a valid RMA number. This warranty does not apply to Products which are designated by Vescent as "Pre-Production Products", e.g. Alpha, Beta or Prototypes or are Products which have been repaired or modified without Vescent's written approval, or subjected to unusual physical, thermal, optical or electrical stress, improper installation or cleaning, misuse, abuse, accident or negligence in use, storage, transportation or handling. The "Warranty Period" during which this warranty applies varies with Product type as follows:

a. For standard Vescent lasers in which a counter is incorporated (i.e. lasers with counters for which Vescent has published a datasheet and which have not been obsoleted by the time of order placement): one (1) year after the date of original shipment or 3,000 hours of use, whichever occurs first;

b. For standard Vescent products other than lasers with counters, (i.e. products for which Vescent has published a datasheet and which have not been obsoleted by the time of order placement): one (1) year after the original shipment;

c. For any other Product including, without limitation, all product types as set forth in sections a. and b. of this clause 5 which are in any way customized, build-to-order, otherwise non-standard and/or are subject of a blanket purchase order: one (1) year after the date of original shipment unless otherwise agreed to in writing on a case by case basis. If, in relation to any Product Vescent offers as an additional purchase option, a warranty period over and above that which is set out in sections b. and c. of this clause 5 ("Extended Warranty") and Buyer exercises such option then the Warranty Period shall be the duration as specified on such Extended Warranty commencing on the date of original shipment. Any Extended Warranty option is only available at the time of and on the same order as the original Product purchase.

d. For any non-warranty Product that has been repaired, Vescent will extend the applicable Warranty Period by sixty (60) calendar days for the specific characteristic of the Product that is repaired by Vescent. Other characteristics of the non-warranty Product will remain uncovered by any warranty.

e. For Products that are discontinued, Vescent's liability shall terminate at the end of the applicable Warranty Period or one (1) year from the date of discontinuity, whichever occurs first.

f. Except for the warranty stated herein and to the extent permitted by applicable law Vescent specifically disclaims any and all warranties, express or implied, including, but not limited to, any warranties of merchantability, fitness for a particular purpose, or noninfringement.