

Wavelength Control and Locking with Sub-MHz Precision

A PZT actuator on one of the resonator mirrors enables the Verdi™ output wavelength to be rapidly tuned over a range of several GHz or tightly locked to an external frequency reference. Servo control provides an even narrower spectral linewidth for applications such as atom trapping and cooling.

Introduction and Overview

Coherent Verdi lasers are unique among commercial CW DPSS (diode-pumped solid-state) near-IR (1.064 μm) and green (532 nm) lasers in providing high-power, mode-hop-free, single-longitudinal-mode output with low intensity noise and a narrow spectral linewidth. The specified linewidth of a few MHz is orders of magnitude narrower than that of alternative multi-mode lasers, making Verdi an excellent choice for trapping and cooling applications, where wavelength (frequency) jitter limits the lowest achievable temperature of the trapped atoms. Verdi's narrow linewidth also provides very high coherence as a critical benefit for interferometric applications and coherence-based metrology. A new feature – a PZT actuator on one of the resonator mirrors – enables the time-averaged linewidth to be significantly reduced by locking the laser output wavelength to an external reference such as a temperature-stabilized interferometer or an atomic/molecular absorption line. A simple servo control loop can lower the linewidth by an order of magnitude and stabilize the absolute laser output wavelength with similar precision. The PZT actuator also enables rapid tuning over several GHz for applications that require wavelength agility. This feature is now standard on all Verdi-IR lasers and optional on all Verdi-green lasers (excluding the new Verdi G-Series), where it is also offered as a factory retrofit upgrade.

Intrinsic vs. Time-Averaged Spectral Linewidth

Verdi DPSS is a high performance CW laser with a $\text{Nd}^{3+}:\text{YVO}_4$ (vanadate) gain crystal in a stable unidirectional ring resonator. Near IR output is extracted through an output-coupling mirror and green output is generated by frequency doubling in an intra-cavity LBO crystal. This type of resonator can support many longitudinal cavity modes with wavelengths λ given by

$$\lambda = \frac{L}{N}$$

where N is an integer and L is the cavity length. N is (order-of-magnitude) 500,000 at the fundamental wavelength of 1.06 μm . The separation of these modes is called the free spectral range (FSR) and is given by

$$\text{FSR} = \frac{c}{nL}$$

where n is the refractive index and c is the speed of light. A detailed calculation would take into account the refractive index of every intra-cavity optic. The FSR is (order-of-magnitude) 500 MHz at the fundamental wavelength. The spectral linewidth of a single-longitudinal-mode laser is the spectral bandwidth of the lasing cavity mode.

Like a passive Fabry-Perot cavity, the linewidth of a DPSS laser decreases with cavity finesse and increases with any intra-cavity losses, while the gain narrows the linewidth. In steady-state operation the gain of a laser is equal to the sum of all losses. This condition is also the limit where the linewidth becomes zero and the output would be truly monochromatic. However, spontaneous emission generates weak ephemeral beams, incoherent with the lasing cavity mode. This emission causes amplitude noise and determines the intrinsic linewidth of a DPSS laser. The intrinsic linewidth of a vanadate laser is just a fraction of a Hz.

The time-averaged spectral linewidth is broadened by wavelength jitter. There are various mechanisms with different time domains that modulate the wavelength, so the measured linewidth depends on the environment the laser is operating in and the time domain of the measurement. Pump-amplitude noise broadens the linewidth to a few kHz over a 100 μs measurement window. Acoustic noise stimulates mechanical resonances in the resonator,

which modulate the resonator length and therefore the wavelength. Acoustic noise, from sources like laboratory equipment or even people, is the dominant contributor to the time-averaged linewidth. The linewidth of a Verdi is specified as <5 MHz in the green and <2.5 MHz in the near-IR over a 50 ms measurement window.

Spectral Linewidth Reduction and Wavelength Stabilization

Analysis by Coherent engineers determined that most of the Verdi wavelength jitter is caused by mechanical resonances that modulate the resonator length between a few hundred Hz and a few kHz. This jitter can be cancelled by rapidly moving a resonator mirror to maintain a constant cavity length over this time domain. This is analogous to the operation of noise cancelling headphones, which generate additional sound waves to mimic the unwanted ambient noise, but with a phase difference of 180° . The ear therefore experiences only the melodic sound waves the listener wants to hear.

Verdi lasers can be stabilized in this way when one of the resonator mirrors is mounted on a piezo-electric (PZT) actuator. The resonator mirror with the least alignment sensitivity was selected for this role. In order to correct for both acoustic noise (linewidth narrowing) and thermal drift (long-term wavelength stabilization), the PZT mirror assembly is a sandwich containing two stacks of PZT material. A short stack is optimal for smaller displacements with a very fast response and a tall stack enables larger cavity length changes with a slower response. These stacks can be driven independently with 0-100V inputs through two BNC connectors located on the back of the laser head. The output wavelength of the Verdi can be compared to an external reference and drive signal(s) generated to cancel any wavelength jitter or drift.

Because of the small displacements required to cancel acoustic noise and the low inertia of the mirror assembly, the short stack enables cavity length adjustment at frequencies up to 20 kHz. The total displacement of the tall stack from 0V to 100V tunes the laser output by at least 6.4 GHz in the green and at least 3.2 GHz in the near-IR. Typical thermal drifts without wavelength stabilization are a few hundred MHz/hour under steady-state conditions in an air-conditioned laboratory.

Spectral Linewidth Reduction Demonstration

To verify the performance of the PZT feature, a 532 nm Verdi DPSS laser was purposely built in an assembly with a well-defined mechanical resonance. The output beam was aligned into two identical Azure™ resonators as shown below. The Azure is a Coherent product which uses a resonance-enhanced doubling cavity to generate 266 nm CW light. For this test the doubling crystal was removed. The concept is simple; lock the Verdi to the “reference” cavity and use the “analyzer” cavity to monitor any residual changes in the Verdi wavelength.

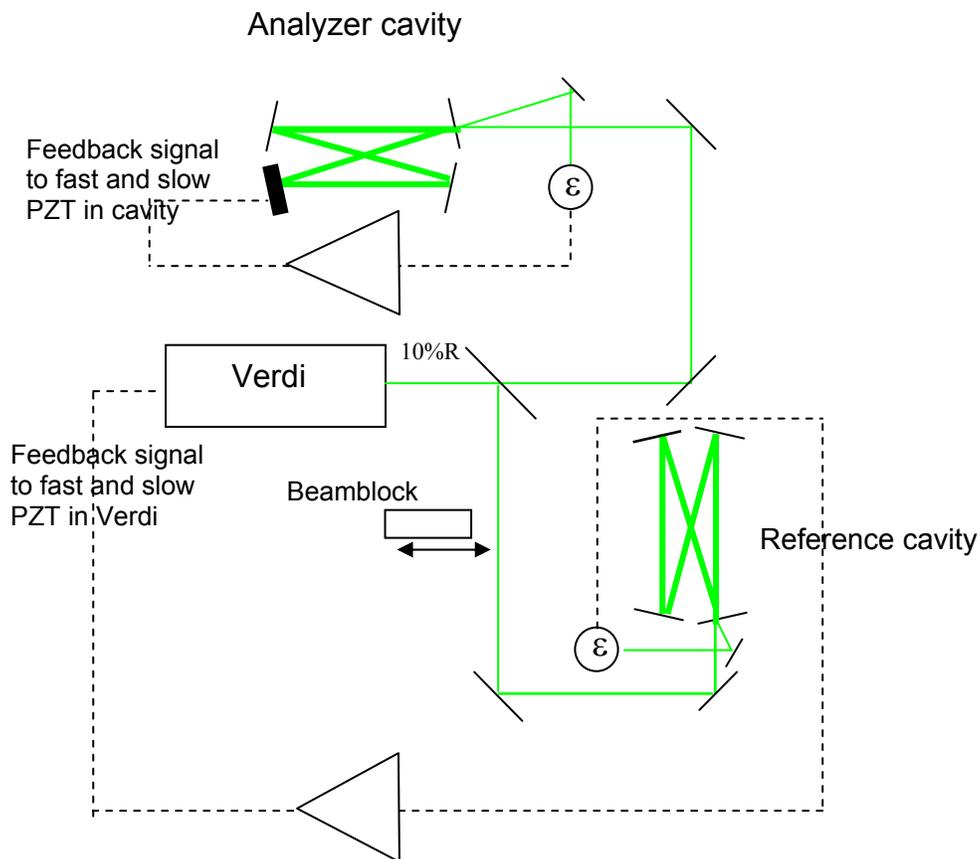


Figure 1. The wavelength of a Verdi with a PZT-actuated mirror was locked to the reference cavity. Stabilization of the Verdi wavelength was verified using the analyzer cavity.

Approximately 10% of the Verdi power was mode-matched into the reference cavity. The light reflected back from this cavity contained information about the relative difference between the Verdi wavelength and the wavelength of the reference cavity. A Haensch-Couillaud scheme was used to lock the Verdi wavelength to the fixed wavelength of the reference cavity. The reflected light was directed into an error signal unit and after suitable filtering and amplification the inverted error signal was fed to the fast and slow inputs of the Verdi PZT mirror.

The remaining 90% of the Verdi power was mode-matched into the analyzer cavity. An identical locking scheme was used, but the inverted error signal from the analyzer cavity was fed back to a PZT-actuated mirror in the analyzer cavity itself. The length of the analyzer cavity therefore followed wavelength changes of the Verdi to maintain lock. The error signal from the analyzer cavity was a direct measure of the Verdi output wavelength.

The analyzer error signal is shown in Figure 2. If the time averaged linewidth is taken as the overall peak-to-peak frequency change over 20 msec, then this Verdi had a linewidth of 5 MHz before stabilization. Cancelling the dominant ≈ 400 Hz jitter reduced the linewidth to <1 MHz. Beta testing at a customer's laboratory demonstrated similar performance. A spectral linewidth less than 1 MHz was achieved by locking a Verdi to an atomic line reference. In principle, with careful engineering, this technique can be used to reduce the spectral linewidth close to the limit imposed by non-acoustic sources.

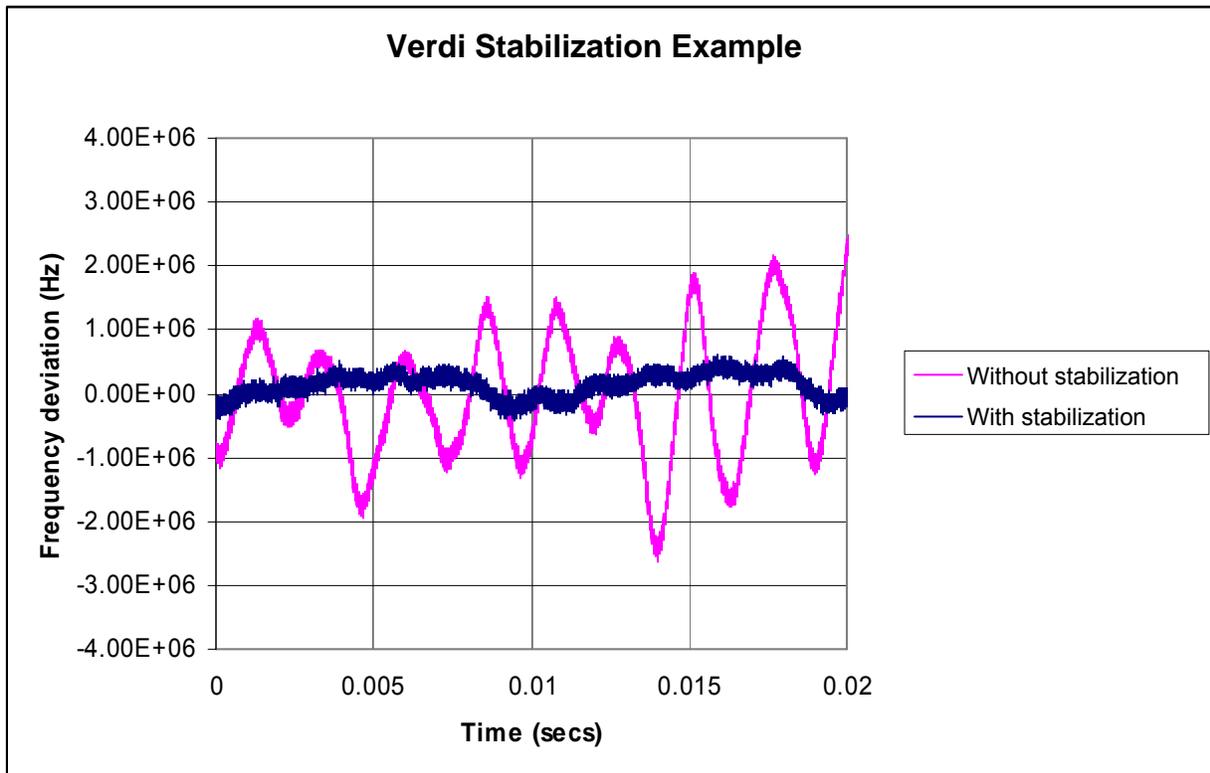


Figure 2. The dramatic effects of Verdi stabilization can be seen in this plot of the analyzer error voltage.

Conclusion

Verdi delivers a narrow spectral linewidth and the lowest intensity noise of any commercial multi-watt CW laser in the near-IR and green thanks to its unique single-longitudinal-mode operation. The new PZT-actuated resonator mirror extends its capabilities, enabling rapid wavelengths tuning and tight locking in to an absolute frequency reference. Sub-MHz wavelength control and sub-MHz spectral linewidth have been demonstrated with relatively simple setups.