Designing and Manufacturing Femtoseconds Ultra-broadband Lasers: Proven, Hands-free Reliability

This whitepaper reviews how design choices, manufacturing steps and testing protocols substantially increase the reliability of ultra-broadband, flexible femtosecond oscillators for demanding applications such as THz generation, amplifier seeding, broadband spectroscopy and imaging applications. Extensive vibration and temperature stress test results are provided as examples of the protocols developed at Coherent.

Background – The Need for a New Approach to Ultrafast Reliability

Until very recently, in the world of extreme ultrafast lasers (i.e. < 25 fs), scheduled and unscheduled downtime was an accepted annoyance – requiring hours of labor for a skilled laser user. Conversely, in today's research, the ultrafast oscillator is often just a component (albeit a critical one) of a much larger and more complex chain leading to the final experimental result. Operational simplicity and dependable reliability are necessary so that scientists and engineers can focus their attention solely on the application. As an example, ultrafast lasers are often used for seeding or providing probe pulses for particle accelerators and free-electron lasers, where users are allocated fixed and rigorous windows of time to conduct their experiments. If the ultrafast laser is not working optimally during those windows of time, the loss in productivity may cost as much as $30,000/hour for the accelerator facility.

Ti:S ultrafast laser oscillators have been characterized by an implicit trade-off between performance and reliability. For example, there are commercial one-box and highly reliable products able to provide "standard" 100-150 fs pulses with broad tunability and there are other, more maintenance intensive products able to produce very short pulses (< 10 fs) at a single operating point in bandwidth and wavelength. While some of these ultra-short pulse lasers are represented as "hands-free", one-box systems, they still require periodic maintenance to correct for performance degradation, sometimes on a weekly or even daily basis. Finally there are fully open-architecture models that provide a large number of options and system flexibility (like CEP stabilization, optical frequency synchronization or dual pico-/femtosecond operation) that also demand periodic maintenance.

A Completely New Approach to Ultrafast Reliability

To better address today's ultrafast applications and growing demand for high performance as well as day-to-day and long-term reliability, Coherent designed the Vitara series of one-box lasers. Instead of modifying existing designs, the Vitara platform was designed from the ground up to set new standards in both ***performance, flexibility and reliability***, drawing on decades of experience building both ultrafast lasers and high-reliability laser products for 24/7 industrial applications. This new, ultra-stable Vitara design encompasses innovation at every level, from basic materials through the component level to the pump laser (an optically pumped semiconductor laser – the Verdi G series), to the final laser head architecture, backed by demanding and stringent process control and testing for every key component and assembly.

The Vitara family offers a wide choice of performance, so users can select the most cost-effective laser for their ultra-short pulse (i.e. < 20 fs) applications needs. This includes the ultra-broadband (UBB) model with adjustable bandwidth >220 nm and output pulses that can be compressed to < 8 fs. Other models offer output powers approaching 1 Watt or unique tunability from 755 nm to 860 nm, with adjustable bandwidth, all computer controlled. These models (Vitara-T and T-HP) also have the options of customized repetition rate, CEP stabilization and optical synchronization with external devices or other lasers. Finally, the streamlined Vitara-S model provides excellent overall performance for cost-sensitive applications or as a dedicated seed for Ti:S ultrafast amplifiers.

The common platform of all these models feature the same industry-leading high reliability and hands-free longevity now matched for the time by state-of-the-art performance and flexibility. Every laser is designed, built and tested so that users can count on thousands of hours of operation with no need to remove the cover. The user benefits from not having to worry about changes in beam quality and pointing, or changes in the spectral shape due to changes in lab temperature (from air conditioning or other laboratory equipment like amplifiers) or other environmental conditions. There is no need to ever tweak the laser when changing the bandwidth/pulsewidth or tuning the center wavelength. All of this means hands-free performance for years rather than tens of hours.

No Periodic Cleaning Required

With ultrafast lasers producing pulses shorter than 30-40 fs, the main reason to remove the cover is to clean the surface of the intracavity optics, especially the facets of the Ti:S gain crystal, where the intracavity pulse is the shortest and has the highest peak intensity. This is because any contaminants (organic molecules, dust) present in the laser can track along the beam to the crystal surface. The high peak power of femtosecond pulses can then activate these molecules and particles by producing excited states and even ions via multiphoton absorption. These particles tend to bind to the crystal surface causing scatter and absorption and increasing the cavity losses. The crystal facets must be cleaned, often weekly, to maintain optimum performance and also to avoid the risk of permanent damage to the surface. Unfortunately, this can happen with even the tiniest amount of contamination because of the high intracavity peak power. To put it in perspective, the peak power at the crystal surface can reach 10 PW/m^2, which is roughly 200,000 times higher than the energy flux at the surface of the sun.

This same degradation mechanism also takes place in UV nanosecond and picosecond lasers, where a single UV photon may produce the equivalent effect of multiple infrared photons. Because of this similarity, Coherent’s experience of successfully addressing contamination in pulsed UV lasers for 24/7 industrial applications turned out to be extremely useful in improving the reliability of femtosecond oscillators: in both cases the high intracavity photon flux excites contaminant particles and molecules causing them to bind to the surface of the optics. (Interestingly enough, we also used knowledge that came from NASA’s experience with UV contamination in the Hubble space telescope.)

The best approach is maintaining a pristine atmosphere in the laser cavity. A major part of this solution is using the right materials; here we saw the advantage of having engineering teams working on very diverse products but able to exchange their ideas, creativity and proven results. As a general rule, we minimize the use of non-metals, i.e., especially plastics or other outgassing materials. Beyond this obvious step, no organic material is used anywhere inside our industrial UV lasers, or Vitara, unless it has been thoroughly qualified in our own materials testing program. This testing uses different and also specially-developed analytical instruments and methods to fully measure and understand the outgassing properties of candidate materials under a range of temperature, pressure and humidity conditions.

Our experience with long-lived industrial UV lasers has shown us that cleaning protocols for both the mechanical and optical components are just as important as material selection in avoiding contamination. Even the most minute amount of contaminant such as cutting oil or lubricant can eventually migrate from remote metal and non-metal surfaces to the optical surfaces, such as the Ti:S crystal facets. So, achieving our target reliability and longevity requires state-of-the-art cleaning methods and attention to detail. This involves extensive process control.

After rigorous cleaning to ensure all potential contamination has been removed and after a complete alignment, the laser cavity is sealed to prevent external contamination during transportation and operation.

Power and Spectral Stability

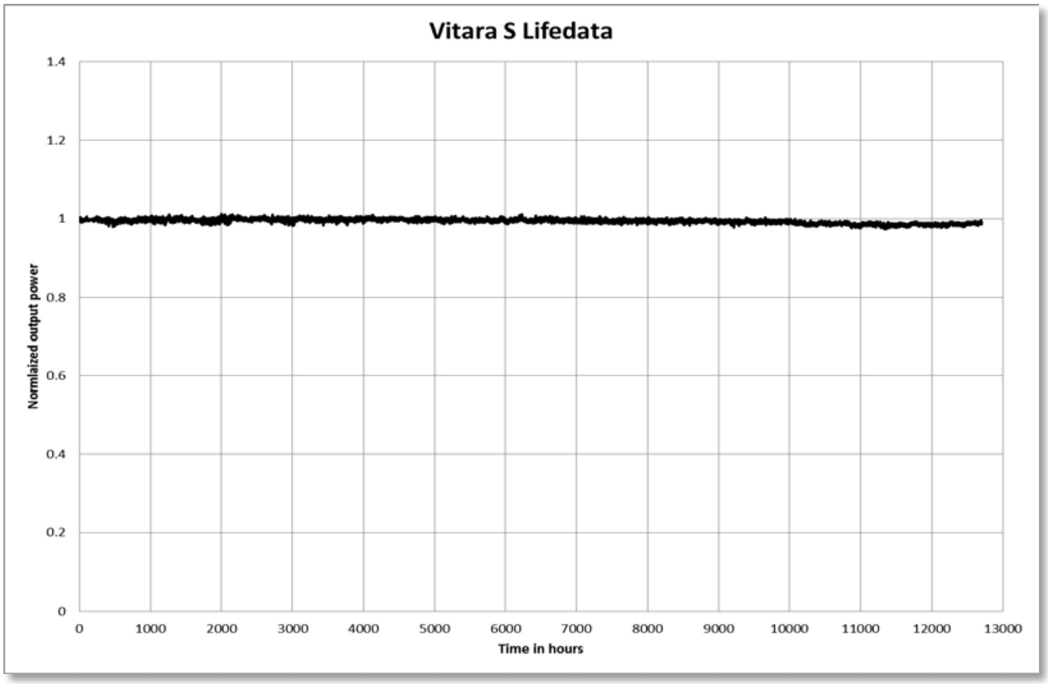

Figure 1. *This lifetest data shows the long-term stability of a Vitara-S as it passes 12,500 hours of hands-free operation.*

Figure 1 confirms the effectiveness of this approach: This lifetest of Vitara-S shows a hands-free run of over 12,500 hours without any opening of the laser head for cleaning or re-alignment. It should be noted that this laser was operated in constant pump power mode throughout the test. This is in strong contrast with the laser industry practice to show ultrafast laser performance in a light-loop mode where the pump power is increased over time to compensate for deterioration in the cavity cleanliness or alignment. The Vitara lifetest at constant pump power highlights the intrinsic opto-mechanical stability of the laser cavity and its environmental compliance.

For many applications, the spectral stability of the ultrafast laser output is just as important as the power stability. This is particularly true for very broad bandwidth lasers such as the Vitara UBB and the tunable Vitara T. In this category of lasers, spectral stability is often a more sensitive and earlier indicator of cavity degradation because the bandwidth tends to collapse even before the laser power drops. To test this stringent stability parameter, our engineers ran a Vitara-T tuned to 785 nm and set at broad bandwidth (~ 120 nm) for 27 days, monitoring the spectral stability. Figure 2 highlights how the bandwidth did not change either in width or spectral shape. Again, the laser was completely untouched during this extended period of use, and was operated in constant pump power mode so as to reveal any spectral shifts that could be masked by a light loop operation.

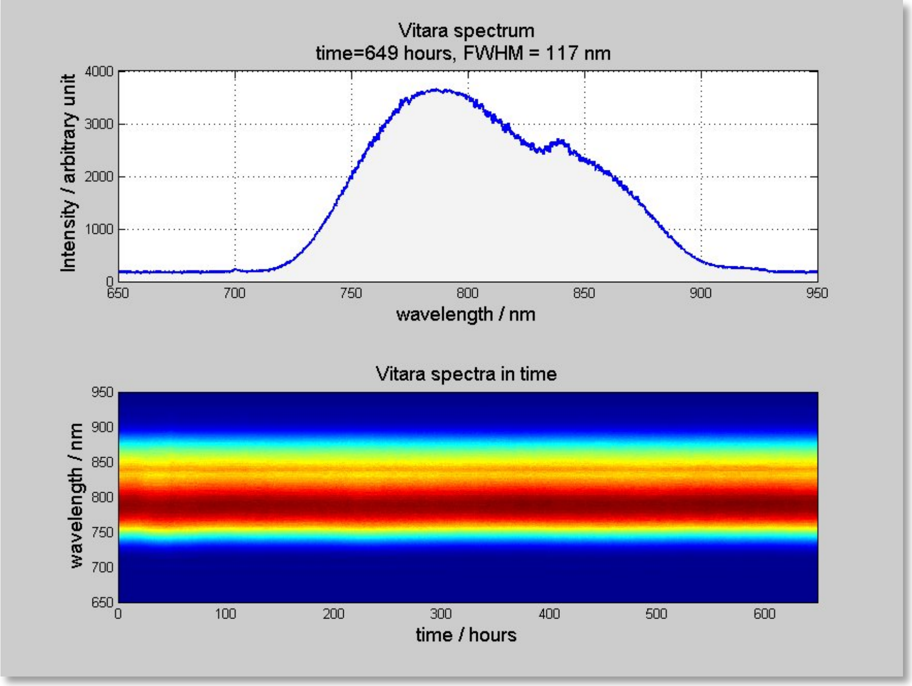

Figure 2. *The spectral profile of the output from this Vitara-T was essentially unchanged over 27 days of continuous operation. The laser was operated in constant pump power mode and was completely untouched during this entire period.*

Ultra-stable Design – No Tweaking Zone

After optical surface contamination, the next most common cause of power/spectral instability is shifts in internal cavity alignment, leading to a need for removing the laser cover to perform periodic "tweaking" of the internal opto-mechanical components. Eliminating this problem is primarily an issue of design and testing. The design of all opto-mechanical components to make sure every optical mount and assembly well exceeds the required level of stability.

Figure 3 shows beam pointing stability data that confirms the success of this approach. These data cover 50 hours of continuous operation of a Vitara-T. The standard deviation over this entire period is only 1.4 µrad in the X direction (i.e., XZ plane) and 2.6 µrad in the Y direction. This deviation, measured in the far field, is only 0.3% of the beam divergence (~ 1 mrad).

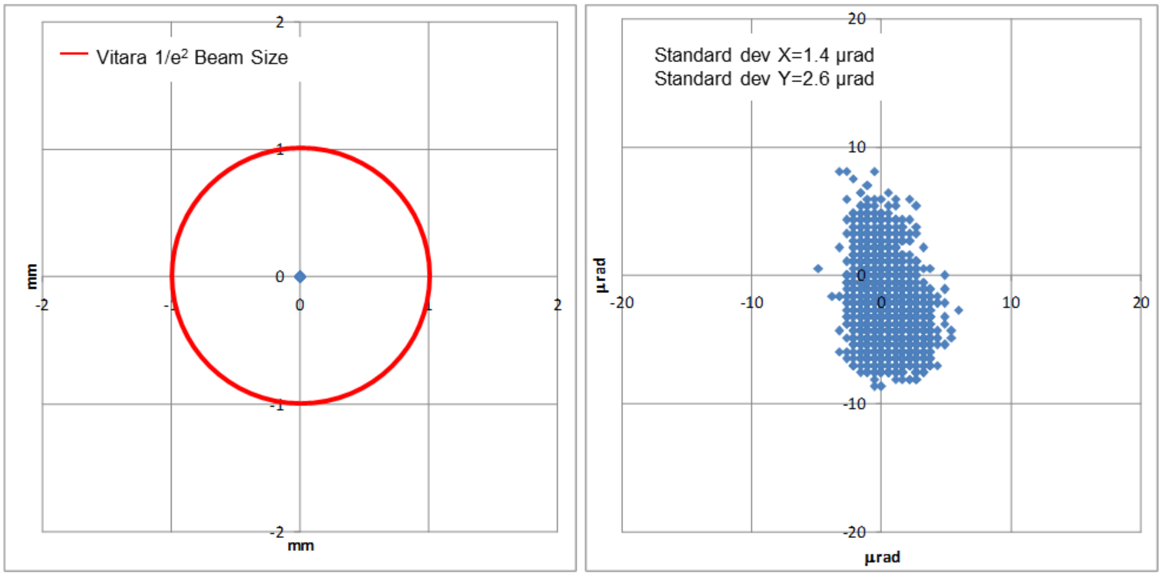

Figure 3. *These data shows the high beam pointing stability of a Vitara-T as measured over a 50 hour period of continuous operation.*

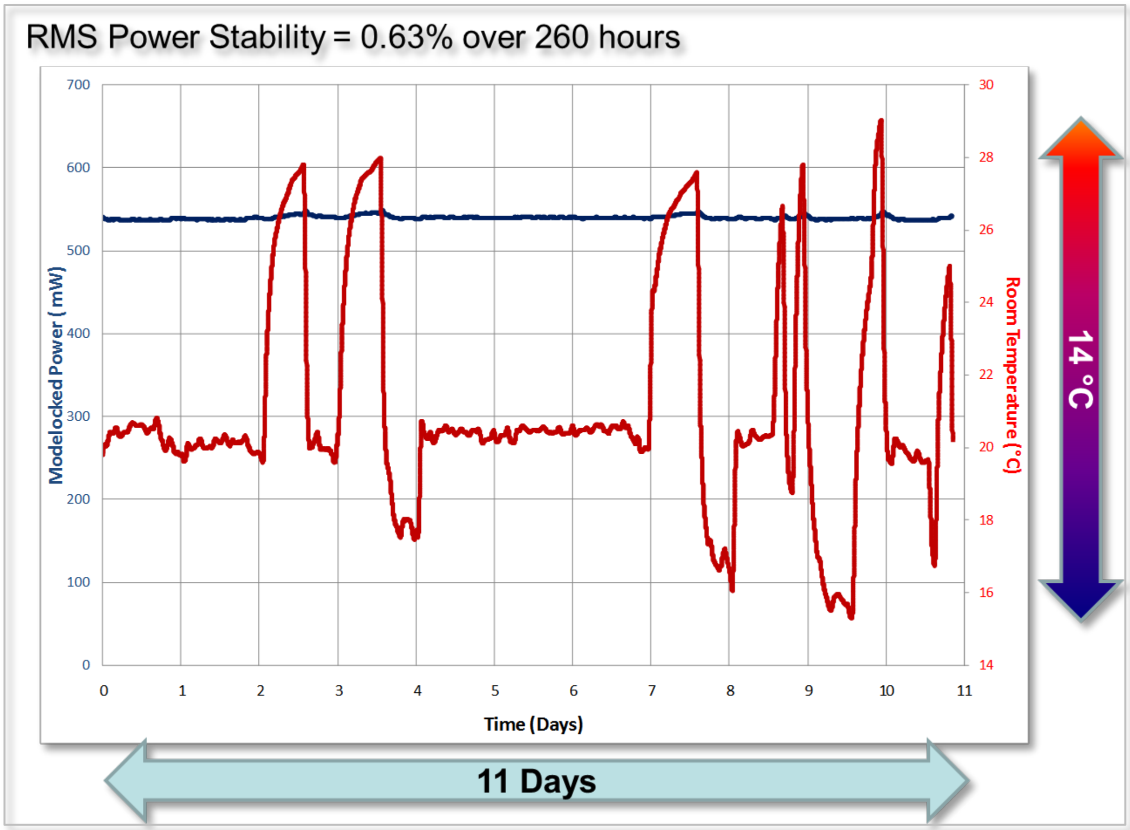

Figure 4. *Vitara-T environmental temperature test. These test lab data confirm the laser head design is immune to changes in room temperature; they show that large random temperature changes have negligible impact on the output power of the laser over an 11 day period. These temperature swings far exceed the worst case diurnal range for a modern lab with thermostatically controlled conditions.*

While the pointing test was performed under typical laboratory condition, we also test all the Vitara models in more stringent conditions, by changing the laboratory temperature by unusually high amounts. An example of this test is show in figure 4, where a Vitara-T was operated for over 11 days under a temperature swing of 14 °C. One of the reasons why we tested the laser under temperature transients lasting tens of hours is that each optical component and subassembly has time to completely thermalize and undergo the full temperature swing. In contrast, tests lasting 2 or 3 hours do not allow all the laser components to experience the measured temperature change.

HASS Testing Delivers Laser Reliability

Achieving the desired long-term stability and reliability in the Vitara platform also required numerous iterations in a program of Highly Accelerated Stress Screening (HASS), a well-known approach used in many industries to confirm design compliance to environmental changes. In brief, HASS involves putting a product through increasingly high levels of thermal cycling and random vibration stress, separately

The information gained from each failure is fed back from the HASS team to the engineering department so that the prototype product can be modified to eliminate these weaknesses. In the case of Vitara, this build, test, analyze and fix (BTAAF) redesign cycle was repeated until the laser far exceeded its specified lifetime and immunity to thermo-mechanical stresses – see figure 5. Only at that point did we finalize the design for release to manufacturing.

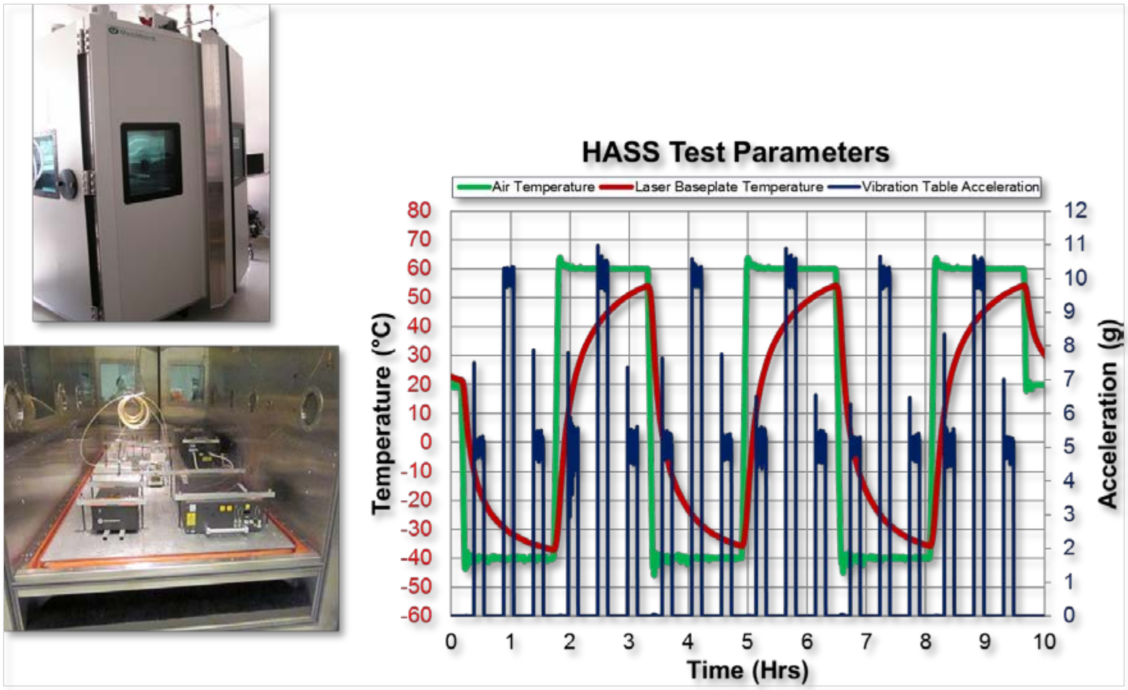

Figure 5. *Example of Vitara HASS testing. The alignment of the laser must be unchanged after 10 hours of 100 °C temperature swings and simultaneous 5 and 10 g acceleration.*

Manufacturing Testing of Every Laser

The purpose of HASS testing is to identify and eliminate any inherent engineering weaknesses or deficiencies. In addition, the results of HASS testing are also used to generate a manufacturing test protocol that each Vitara laser has to pass prior to being shipped to customers.

Specifically, all production Vitara lasers are subject to many hours of intense thermal cycles and shock stress testing. After each laser is fully assembled, aligned and meets our internal specification, it is cycled between -40 and +60 °C; then each optical mount is tapped with a calibrated force (higher than a 10 g shock) and the output power measured again. Following this step the laser is cycled again - this time between -10 and +60 °C - and must perform without any re-alignment.

Conclusion

Over twenty years ago, Ti:S ultrafast lasers popularized femtosecond research enabling its transition from laser-expert spectroscopy laboratories to biology and material processing applications. The last decade saw continuing improvement of Ti:S technology resulting in sealed and hands-off lasers capable of producing ~100 fs pulses with over a 400 nm tuning range (Chameleon). Yet, designing and manufacturing hands-free ultra-broadband lasers (i.e. sub-20 fs) proved elusive as this regime of operation brings specific challenges related to contamination and alignment. Finally, Coherent's Vitara laser platform has taken on this challenge and is the first ultrafast laser family to deliver both cutting-edge performance, together with unmatched completely hands-free reliability.

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