One-Box Ultrafast Lasers: Superior Performance ***and Reliability***

Chameleon, Vitara, and Vitesse Ti:Sapphire (Ti:S) lasers excel in applications for integrated ultrafast lasers because their exceptional performance is backed by superior reliability and long lifetimes. These result from using high stability designs and components, followed by exhaustive environmental (HALT/HASS) testing. As an example, we will discuss operations of a Chameleon laser deployed in Antarctica for Atmospheric measurements.

Introduction

The purpose of one-box ultrafast laser oscillators is to provide turnkey operation and hands-free simplicity to applications that require femtosecond pulses, without the traditionally associated complexity of optimization and maintenance. This type of hands-free performance is necessary to address applications like Multiphoton Excitation Microscopy or MPE where the lasers are operated by personnel with limited laser experience working on live animals, like in a neuroscience laboratory. Until 7-8 years ago, the majority of Ti:S ultrafast lasers required a separate green pump laser that the user had to place close to the ultrafast laser and feed into it as a pump source. Integrating the pump and ultrafast laser in the same package, adding servo controls and building the entire system in a clean environment are some of the steps necessary to provide extreme reliability, lifetime and state-of-the-art performance.

Additionally, it is possible to combine all of these attributes with extreme flexibility, as exemplified by the new Coherent Vitara. This whitepaper describes some of the key factors that contribute to the unmatched reliability and longevity of all Coherent one-box ultrafast lasers. These factors range from laser design through packaging for shipment. As a case study of design validation, we will describe the shipment and operation of a Coherent UF laser in the Antarctic, under extremely hostile conditions – well beyond its specified environmental operating range as shown in Figure 1.

Designs and Materials

We choose to define laser failure as not only any situation that leads to non-operation of the laser, but also any situation where at least one performance parameter falls outside specification, with all other parameters still being functional. Lasers are complex systems, subject to failures in electrical, software, optical and mechanical components or subsystems. While electrical and software failure mechanisms are common to devices as diverse as a home theater system or an avionics subsystem, opto-mechanical failures are peculiar to lasers, often related to extremely small deviations from the standard operating mode. These types of failures typically arise because of optical degradation of a single component, or opto-mechanical misalignment of the components with respect to each other. Therefore, the drive for reliability and longevity of one-box ultrafast lasers must begin with system and component designs whose impact needs to be fully modeled long before prototyping a new product or an updated version of an existing product.

Figure 1. *The performance of Coherent one-box lasers are designed to be tolerant of harsh shipping conditions like transportation by ice breaker ship and helicopter to the island of Dumont D'Urville in the Antarctic. Photo courtesy of Roberto Grilli, Université Joseph Fourier, CNRS, France.*

In this product environment, using highly specialized, small-batch components, over-specifying optical devices and/or system hardware would quickly and unnecessarily drive up the overall laser cost. Therefore, a key first step in the design process is a complete optical tolerance analysis for components such as mirrors, lenses and other optical surfaces. This will reveal the maximum allowable alignment change for all these optical components that will maintain performance within specification. For example, minor changes in the cavity length of the integrated Verdi pump laser will have no measurable effect on the ultrafast output and/or will be compensated by system servos. However, even sub-micron shifts that change the angle of one or more of the cavity mirrors may lead to output power losses that cannot be fully compensated even by servos. Changes in the relative alignment of components stems from long-term relaxation of residual stress, short- and long-term environmental changes and thermal cycling. These changes are to some extent unavoidable, but can be either minimized or compensated for with active or passive methods.

Dynamic (i.e., vibrational) and static movement, together with shifts in the opto-mechanical components are modeled using proven Finite Element Analysis (FEA) techniques, championed and perfected in the aerospace industry, where any unpredictable mechanical behavior can have catastrophic consequences. FEA takes into account mechanical resonances and other phenomena in modeling the motion and deformation of mechanical components in response to input forces over a wide range of amplitudes and frequencies – a range that far exceeds anything the laser can be expected to encounter during shipping, integration and even challenging operation conditions.

The maximum allowable misalignment analysis is also used in the selection of materials, principally the metals used in component and laser construction. All metals expand with increasing temperature and of course, different metals have different coefficients of thermal expansion (CTE). For a first-order minimization of these effects, one-box lasers like Chameleon and Vitara – or their integrated Verdi pump lasers – make extensive use of thermal stabilization. However, large changes in ambient temperature can still cause minor expansion/contraction in some locations firstly because temperature stabilization does not have infinite precision and secondly because these dynamic changes unavoidably lead to transient local temperature gradients. For this reason, Coherent selects metals and alloys to avoid mismatches in CTE whenever possible or to minimize them in all instances, particularly in the optical mounts. The design of all opto-mechanical components is validated and optimized in the test lab long before they are tested in an ultrafast laser prototype. For example, laser interferometry is used to detect angular movements as small as 5 micro-radians. These measurements are made before and after subjecting the components to vibration, shock and thermal testing as described below.

Coherent one-box lasers also make extensive use of proprietary PermAlign™ technology, long-proven in our stand-alone Verdi pump lasers that are integrated within these one-box lasers. Traditionally, lasers were built using adjustable and lockable optical mounts, which contain many separate metal parts including threaded holes, screws and flexures. In this approach, the mounts are adjusted to bring the laser into perfect alignment and locking screws are used to "permanently" fix the position of each mount. In reality, such mounts can undergo creep and small shifts due to repeated temperature cycling and/or vibrations and shocks encountered during shipping and operation. In contrast, PermAlign mounts are based on a very few components and the optics are solder-bonded on sub-mounts that are also solder-bonded on the optical reference baseplate for perfect cavity alignment. There are no locking or threaded elements or flexure points. Alignment of each optic during bonding is monitored and ensured through a laser alignment beam. PermAlign eliminates long-term shifts due to relaxation, as proven by lifetimes of tens of thousands of hours of operation logged by Verdi lasers.

HALT/HASS Testing

A major reason for the unmatched reliability and lifetime of our one-box ultrafast lasers is the comprehensive HALT/HASS testing program for each laser model. HALT (**H**ighly **A**ccelerated **L**ife **T**est) and HASS (**H**ighly **A**ccelerated **S**tress **S**creen) subject the laser to a series of overstresses, forcing weak links to emerge by accelerating fatigue. Unlike traditional single axis vibration test methods or thermal only methods, HALT/HASS testing includes random six-degree-of-freedom vibration and rapid thermal changes to exercise a combined level of stress that is more representative of extreme conditions where multiple parameters are changing at the same time.

Widely adopted in many industrial applications, HALT is relatively new to the world of scientific lasers and involves putting a laser through increasingly high levels of thermal cycling and random vibration stress, separately or in combination, while the laser is operating. Whenever a failure occurs, a physics-of-failure (PoF) analysis is conducted to determine the root cause of the problem. Failure typically involves issues related to design, materials, component, component placement, component temperature rating and cooling, and assembly issues.

The information gained from each failure is fed back from the HALT to the engineering team so that the product can be modified to eliminate these issues. Ideally, this build, test, analyze and fix (BTAAF) redesign cycle is repeated until the laser far exceeds its specified lifetime and immunity to thermo-mechanical stresses. In addition, the HALT tests reveal the operating limits – the temperature and temperature change rate beyond which the product no longer functions while the stress is applied.

The main purpose of HALT is to identify and eliminate any inherent engineering weaknesses or deficiencies, and to validate changes in design and/or suppliers to ensure the changes do not decrease the performance of the laser. The results of HALT also enable a HASS testing protocol to be established. Here, production units are randomly selected for stress testing in statistically significant numbers, as determined by HALT results.

Figure 2 *Chameleon being loaded into a temperature test oven*

As a first example, we will discuss HASS testing of Chameleon, the most widely tunable and highest-power one-box ultrafast Ti:S laser commercially available. This testing is performed using an environmental test chamber capable of subjecting the laser to several temperature cycles between -20°C and 60 °C. Temperature loggers are utilized to ensure that dwell times are sufficient to confirm the entire laser reaches the extremes, as it may take several hours to ensure that thermal equilibrium is achieved. See Figures 2 and 3. The temperature range is chosen to be substantially wider than the specified safe non-operating temperature range for these lasers, i.e., 5-40°C. For a laser to pass this test, the unit must be 100% functional upon completion of the test sequence.

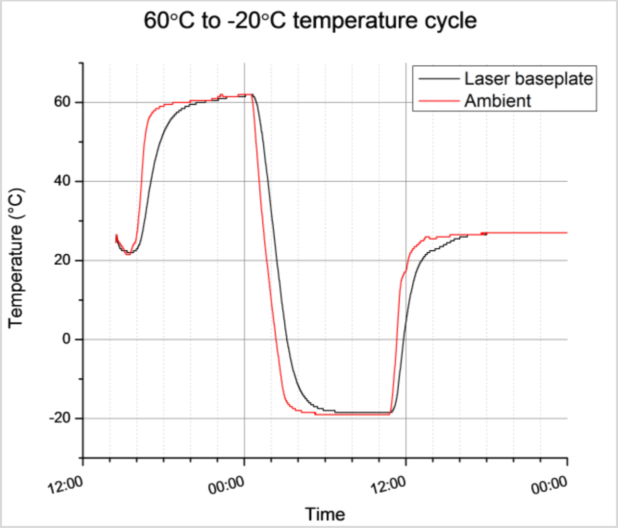

Figure 3*. In non-operating HALT/HASS tests, the laser head is subjected to large temperature changes including "soaks" of nearly 6 hours at both high and low extremes of the test range.*

Vibration/Mechanical Shock Testing

Individual components of Chameleon, and then the entire laser assembly, are subjected to shock, impact and vibration testing. If any components are redesigned in any way, this series of mechanical tests is repeated. Vibration testing is accomplished by securing the assemblies or non-operating laser on a vibration/shock table, which is then operated over a range of g-forces, and an input frequency spectrum that well exceeds those expected during transportation. The device under test is then inspected and tested to detect even minor changes in its performance due to these mechanical stresses. A video exemplifying just how rigorous this testing is can be viewed at www.coherent.com/VTest .

The results of these tests are used to identify and eliminate any inherent engineering weaknesses or deficiencies. Figure 4 illustrates an example of this. This is a plot showing the statistics for shock testinduced misalignments in a statistically large number of optical mounts of a type used in prototype versions of Chameleon. In the case of the original mount, although most of the mounts showed only very small shifts in the x and y axis angular positions (+/- 50 µrad), some mounts showed larger shifts, particularly in the y-axis. As a result, the mount was redesigned. The same tests were then performed on a large number of these new mounts. These shock test misalignment results are also statistically summarized in Figure 4, which shows how all of the new mounts now only undergo minor shifts and display a much narrower distribution of misalignment angles.

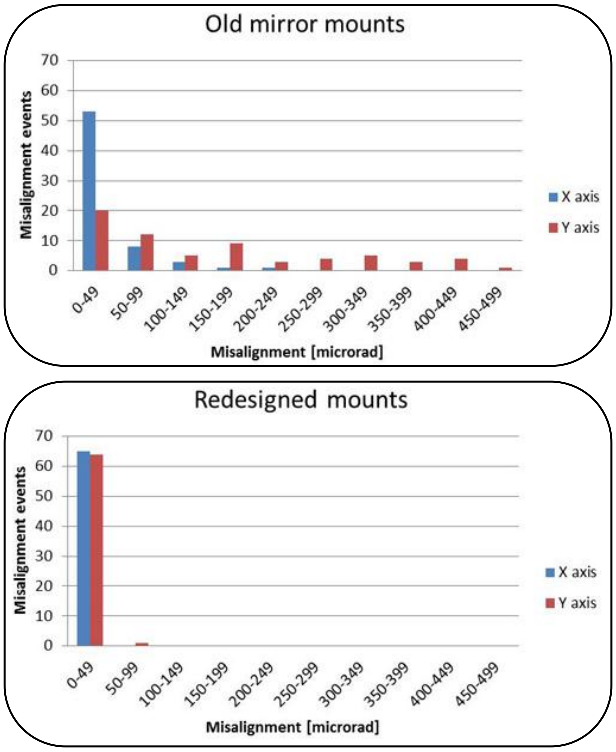

Figure 4. *These data shows misalignment test data for a large number of two different mounts. Clearly, the "Redesigned mounts" data show large decrease in the potential for significant misalignment seen with the original mount design.*

In addition to the component and laser shock tests performed on the vibration test table, every assembled laser is subjected to a drop test. While operating, the front of the laser is lifted approximately 1/4" and dropped back to the tabletop. Again, the output is re-assessed for every performance parameter to make sure there are no changes whatsoever to the laser.

When Coherent engineers started to design Vitara – the newest generation ultrafast laser for scientific applications – their challenging task was to improve the technical specification in every performance parameter but also to set new standards of product reliability. The Vitara family is capable of producing pulses shorter than 12 femtoseconds, with computer controlled wavelength tuning and bandwidth adjustment, plus a series of options that make it suitable for applications as diverse as attosecond physics or operation in conjunction with Free Electron Lasers (FELs). Installation in large multiuser facilities like an accelerator or a FEL requires the highest reliability because of the very high cost of – and demand for – beam time. To satisfy the requirements of this installation as well as everyday physics laboratory conditions, Vitara is also subject to extensive HALT during the design and prototyping phase and to statistical HASS at the production stage. HASS includes simultaneous temperature and 3D vibration cycling with changes in temperature between -40 °C and +60 °C and vibration at 10g level over a wide range of frequencies, as exemplified in Figure.5. This test is performed in a Coherent environmental chamber that is dedicated to HALT/HASS procedures as shown in Figure 6.

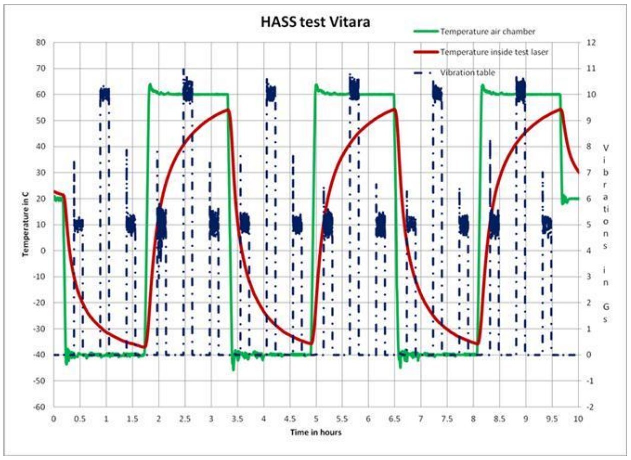

Figure 5. *Simultaneous vibration and temperature cycle testing of Vitara in the HALT/HASS test chamber.*

Figure 6. *The HALT/HASS test chamber at Coherent.*

Crating and Shipping

In many cases, the roughest environment a laser experiences is during transportation to the end user. The laser and its shipping container can be exposed to shocks, drops, vibrations, extreme temperature and humidity changes. Coherent ships lasers from facilities all over the world using a network of vetted and trusted shipping companies. Nonetheless, packaging and crating must be able to protect the laser from unexpected rough handling and special shipping conditions such as in the Antarctic application described below. Designing a good crate for a laser requires experience and a number of trial and error tests, to achieve the right balance of sturdiness, support and damping. To test the sturdiness of our crates, we dropped a fully crated Chameleon prototype multiple times and at different angles over a vertical drop of 18 inches. During these impact drop tests, an accelerometer embedded in the packaged laser was used to measure impact forces as shown in Figure 5.

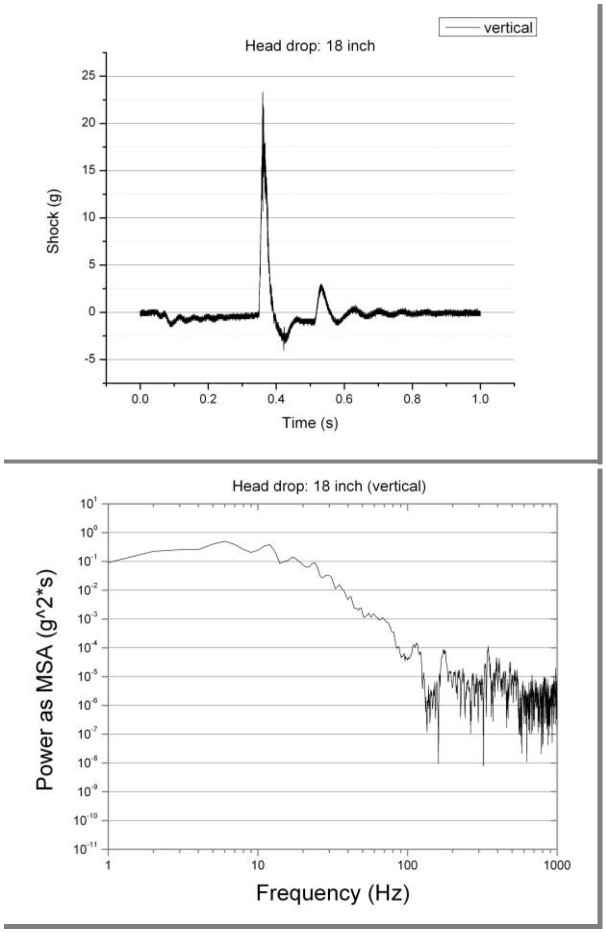

Figure 5. *Top: Raw data from the accelerometer shows that the 18-inch drop test of the crated laser head results in the laser being subjected to substantial g-forces. Bottom: Frequency spectrum of the accelerometer data.*

The acquired data is then subjected to Fast Fourier Transform analysis to obtain a frequency spectrum showing the maximum expected shipping forces in each frequency band. This data is used as key input in the design of the non-operational vibration table “shake” testing protocol previously described. This entire testing protocol is repeated every time we introduce a design improvement to these lasers, no matter how small.

A Chameleon in Antarctica

While most ultrafast lasers are designed to operate with extreme stability, some applications require them to do so under extremely demanding conditions. During January and February 2012, an atmospheric monitoring application at the French Antarctic base on the island of Dumont D’Urville required both. A Chameleon Ultra II laser was used to monitor trace radicals in the Antarctic atmosphere at concentrations of one part per trillion. Measurements of IO and BrO radicals, together with NO_2 provide valuable information on the oxidant capacity of the atmosphere leading to a better model for studies of the atmospheric sulphur cycle [1] The study was accomplished using a state-of-the-art technique called modelocked Cavity Enhanced Absorption Spectroscopy (CEAS) [2] developed at the Laboratoire Interdisciplinaire de Physique (LIPhy) in Grenoble (FRANCE).

In modelocked CEAS, the laser output is coupled into a high-finesse resonant cavity in air where the laser pulses interact with the radical under study. Because of the high-finesse, the equivalent path in air of the laser pulses is ~10 km, resulting in a signal level sufficient for spectral analysis with a dispersive grating and a CCD detector. However, this technique requires a very stable coupling between the laser and measurement cavity length and superb pointing stability from the laser.

Figure 7. *After a long multi-modal shipping journey to the French Antarctic base on the island of Dumont D’Urville, a Chameleon laser operated was successfully operated at a lab temperature of only 5 °C. Here it was used to make mode-locked CEAS measurements of trace atmospheric components at concentrations less than a part per trillion. Image courtesy of Thomas Paris, Dumont D’Urville Station, Antarctica.*

The challenges to the laser started well in advance of the actual experiment, as the Chameleon made its way to Antarctica. The tortuous journey included conveyance in the hold of the icebreaker ship Astrolabe, shown in Figure 8, that was stuck twice in the Antarctic ice pack.

Figure 8. Chameleon was transported towards Antarctica by the icebreaker ship Astrolabe.

The laser was finally lifted out of the ship by helicopter and the final stage of the journey was by sled. Nonetheless, the laser worked perfectly to all specifications immediately after unpacking. In the cramped lab, the temperature soon rose to an unpleasant 40^{o}C due to the heat generated by all the lab equipment but the laser continued to work. However, some of the other equipment could not be successfully operated at this high temperature so the decision was made to open a window in order to decrease the temperature inside the room. This resulted in changes of 8-10^{o}C during the day as the external temperature varied.

In spite of these changes, ML-CEAS measurements within the shot-noise limit were possible for periods of 10 minutes at a time. As a result, the free radical concentrations could be tracked at levels less than one part per trillion and the wide spectral coverage of this femtosecond CEAS setup enabled also simultaneous tracking of atmospheric nitrogen dioxide (NO_2).

Conclusion

As ultrafast lasers are increasingly adopted for applications outside of the traditional domain of applied physics, reliability and uptime have become at least as important as performance excellence. At Coherent, we have recognized that reliability needs to be built into every aspect of the laser design cycle, from initial concept to the shipping container. Examples of environmental testing and screening were provided for various ultrafast lasers and especially for Chameleon, the most popular ultrafast one-box Ti:S laser, with over 1300 installation worldwide. The result of this thorough process is epitomized by the operation of a Chameleon in an Antarctic base after being exposed to every sort of unconventional and challenging shipping and operating conditions.

REFERENCES

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[2] Gherman T.; Romanini D. Modelocked Cavity-Enhanced Absorption Spectroscopy. Opt. Express 2002, 10, 1033