Industrial Reliability in Scientific Lasers

How the introduction of HALT / HASS protocols enables the production of scientific lasers with cutting edge performance

Marco Arrigoni and Peter Vogt

By leveraging expertise from the 24/7 world of industrial lasers, the latest scientific lasers combine state of the art performance with unprecedented reliability and stability, increasing data productivity and lowering the real costs of academic research.

Ultrafast scientific lasers have always required state-of-the-art performance (e.g., higher peak power, shorter pulse duration, wider wavelength tuning) to enable ground-breaking experiments. High performance has often been achieved at the expense of ease of use and reliability, but recently this paradigm has changed quite rapidly. Performance specifications in bandwidth and energy that required complex systems only two-three years ago are now available from closed box oscillators and amplifiers offering hands-free operation and exceptional stability. At Coherent, this has been accomplished by applying our unique experience in industrial lasers also to our scientific products, and we refer to this shift in design and manufacturing scientific femtosecond lasers as "The Industrial Revolution in Ultrafast Science."

The real impact of scientific laser realibility

The cost of downtime is easy to measure in industrial applications, with the simplest method being the cost of lost productivity. This cost might range from hundreds of euros an hour in a small industrial laser job shop to millions of euros per day in a flat panel TV production line.

In a research environment, the impact of downtime is usually not as easy to quantify but it can be quite devastating for the scientific team experiencing it. Indeed, many academic users have experienced situations like:

- Graduate students unable to finish the experimental work supporting their dissertation
- Missing data for a conference paper or a time-critical grant proposal
- Inaccurate or unrepeatable data that can lead to delays in the peer review process
- Delay in the publication of a key paper, often in a very competitive situation
- Waste of post-doc or research assistant time (at a typical burdened cost of € 50,000 – 75,000 per year)

The key point is that quality, consistency and high throughput of experimental data are quintessential elements to the team or an individual investigator's success and prospects. In the case of tenure track, this data can make or break a scientist's academic career.

Industrial laser experience

Why are industrial lasers traditionally more reliable than research lasers? The simple reason is that, in commercial applications, lasers-based equipment and processes have been more expensive than other approaches and chosen only when outperforming these non-laser methods. Because of the higher capital equipment costs of these lasers, any incremental cost due to downtime would make them uncompetitive and therefore improving their reliability has been key to wider adoption. For decades, industrial laser manufacturers have continuously improved reliability through intensive programs on materials, design and testing methods, and by high volume statistics – using feedback from our thousands of lasers in diverse industrial environments.

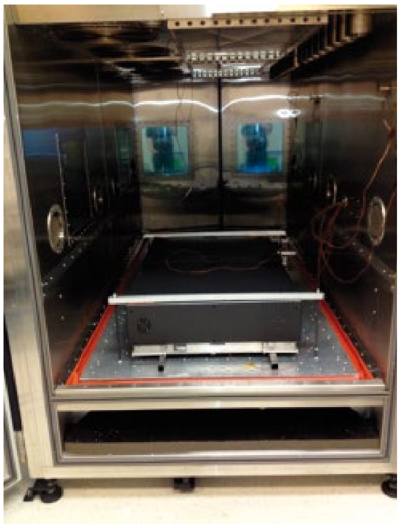

Fig. 1 The laser industry's first ever HALT / HASS chamber enables testing of even large footprint products such as this Astrella one-box femtosecond amplifier system.

Applying this knowledge, in turn, to scientific lasers has yielded a number of significant benefits. Let us consider optical surfaces as an example. Ultrafast laser oscillators and amplifiers with extremely short pulsewidths had to be opened routinely by users for periodic cleaning of the optics. The reason is that micro-contaminants accumulate on some optical surfaces ultimately leading to burn damage and optical losses. Assembling these lasers in a tightly controlled clean room setting was a first mandatory step but failed to consistently address this problem, especially with very short pulse lasers (i.e. < 20 – 40 fs).

At Coherent, we solved this problem by adapting methods used in our industrial products. In this case, the answer was in design practices as much as in manufacturing methods. Specifically, it is necessary to build and maintain a contamination-free environment within

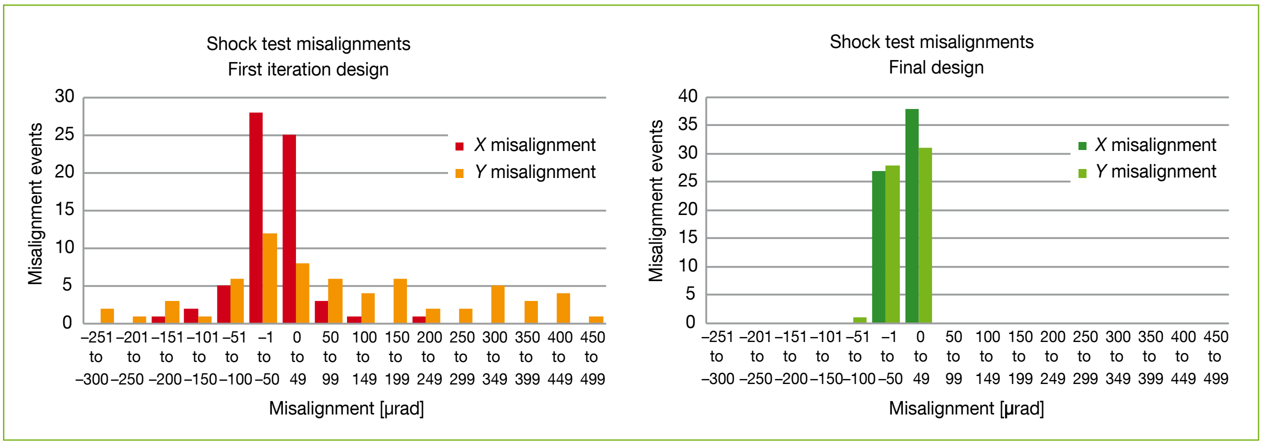

Fig. 2 Comparison of an earlier version of optical mounts with the final version used in femtosecond lasers. The final version is much more compliant with externally induced vibration and temperature change cycles.

the laser cavity. This means careful choice of materials, including minimized use of non-metals. Today, the only organics that we use are materials that our engineers have already exhaustively tested and qualified for outgassing and compatibility with exposure to high optical fields.

Experience with long-lived industrial UV lasers has also shown that our factory cleaning protocols for both the mechanical and optical components are equally important. Even trace amounts of contaminants such, as oil or lubricant, can eventually migrate from metal parts to optical surfaces, requiring cleaning or replacement of the optics.

Vertical integration

Vertical integration of the critical optical path has proved to be another important element in the industrial reliability journey. While "commoditized" components such as circuit boards and photodiodes can be sourced externally following careful design, sample test and quality screening, all critical optical components and testing processes are carried out in-house. This includes complex optical coatings, laser diodes and OPS (optically pumped semiconductor) chip manufacturing, as well as testing of non-linear and active medium crystals.

HALT / HASS – a qualitative approach to reliability

One of the most important factors in achieving industrial reliability in scientific lasers has been the adoption of rigorous HALT / HASS (highly accelerated life testing / highly accelerated stress screening) protocols and the intensive process they entail. HALT / HASS methods are well-established in other industries but only recently adopted in the laser industry. Simply stated, industrial lasers have been made reliable partly through high volume experience. These accelerated testing and screening methods are ideal for the challenge of delivering the same reliability in products such as ultrafast amplifiers where the total number of lasers produced is orders of magnitude lower.

HALT is a method where simultaneous stressors are applied during the design phase of a new product to greatly accelerate its normal aging and/or to verify its compliance with the most extreme environmental conditions to which it can reasonably be exposed. To provide ample design margin, the HALT conditions should be much worse than the specified operating and non-operating limits. Iterative cycles of HALT testing, re-design, and further HALT testing serve to eliminate any weakness or potential failure mechanism in the final design.

Once the overall design has been "frozen" for the product introduction and before starting the standard production cycle, an appropriate HASS test protocol is then defined and put into place. These stresses are not as high as during the HALT phase because the goal is to reveal workmanship and material issues without compromising the lifetime and performance of each tested unit. At first, HASS is performed on each manufactured unit, verifying that there are only negligible variations in performances before and after the HASS test cycle. Units that fail are analyzed to determine the weakness and to correct it, be it a material quality issue or a workmanship error. Once a sustainable, high pass rate is achieved, HASS is then performed on a statistically significant sample of production lasers throughout the lifetime of the product.

The industrial revolution in practice

To be effective in a complex product like an ultrafast oscillator or even a complete ultrafast amplifier, HALT / HASS has to become a completely integrated part of the laser design and manufacturing processes. HALT / HASS concepts and practices have to be repeatedly applied at every level, from components through sub-assemblies, lasers and integrated laser systems. Outsourcing a few components and lasers for occasional evalu-

Company

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Founded in 1966, Coherent, Inc., is a world leader in providing photonics based solutions to the commercial and scientific research markets, and celebrates its 50-years anniversary in 2016. The company, which is headquartered in Santa Clara, California, has R&D and manufacturing facilities at a number of locations around the world – in Europe these are in Germany and Great Britain. A global service and sales network supports customers in both industry and science. Coherent provides solutions for fields such as material processing, microelectronics, machining, medical and instrumentation.

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ation by an independent HALT / HASS testing lab will never deliver the same levels of robust reliability.

Fortunately, HALT / HASS testing hardware is commercially available, in the form of computer controlled chambers where customized, simultaneous temperature and vibrational cycling sequences can be programed. At Coherent, we invested in one of the largest of these HALT / HASS chambers (see Fig. 1). This size enables us to fully test components ranging from a new mount in a small oscillator cavity to larger footprint products, such as integrated ultrafast amplifiers.

To see how this works in practice let us examine HALT / HASS testing at three different levels:

High stability optical mounts

Fig. 2 shows an example of successful use of HALT methodology in the design of optics mounts for a femtosecond laser. In the first design iteration, about sixty mounts were tested, and a significant population of mounts showed misalignments after extreme temperature and vibration testing. Moreover, the performance of this sixty unit sample covers a wide statistical spread. As a result of these experimental findings, the mounts were redesigned. The test was repeated after each design cycle to quantify the stability in a statistical way. Fig. 2 also shows the much improved stability and excellent consistency from HALT tests of the final design iteration.

Closed box ultrafast oscillators

The terms "closed box" and "hands-free" have long been used in marketing literature as qualitative descriptions of the stability and reliability of one-box ultrafast oscillators. In practice, these characteristics have always been very dependent on the operating regime. For example, commercial one-box products such as the Coherent Chameleon series that provide "standard" 100 – 150 fs pulses with broad tunability for dedicated use in microscopy and other life sciences applications have traditionally been very reliable. These can deliver years of continuous operation with no need to ever open the laser. On the other hand, lasers producing very short pulses have typically been more maintenance-intensive. Users report that lasers from some manufacturers in this category need optics cleaning and tweaking on a weekly interval or less. Today, researchers are increasingly demanding that state of the art ultrafast lasers (i.e., broadband oscillators) also deliver the reliability of more standard laser oscillators, like Chameleon.

As already noted, key elements to achieve long and maintenance-free lifetimes are selecting the right materials, cleaning the various materials in the proper way to minimize outgassing, and sealing the cavity to avoid contamination during every day operations. Repetitive HALT iterations of component and cavity designs are then performed until the target field stability is well-exceeded. Fig. 3 shows the end result on the first generation of broadband ultrafast oscillators designed from the ground up using this new approach. This is a 12,500 hour run on the model Vitara-S operated at constant diode pump power, i.e. without any light feedback loop, indicating the absence of any degradation in the optical losses of the resonator components. Use of HALT / HASS enabled the introduction of a unique ultra-broadband laser like Vitara-T that produces sub-12 femtosecond pulses and provides center wavelength and bandwidth control. To the best of our knowledge this has been the first hands-free, flexible and broadband ultrafast laser.

Integrated ultrafast amplifiers

Surely no commercial laser system is more challenging in terms of stability and reliability than a femtosecond amplifier. While some researchers prefer an open architecture system that may allow them to make configurations and operational changes, many applications prefer a turnkey system with simple on/off functionality and reliability to pump various types of non-linear processes like parametric amplification or terahertz pulses generation. For example, these lasers are increasingly used in two-dimensional spectroscopy where intrinsic experimental complexity greatly benefits from the laser behaving like a true black box.

An integrated, Ti:sapphire, chirped pulse amplifier (CPA) system incorporates an ultrafast oscillator with its green pump laser, a regenerative amplifier, a pulsed 532 nm pump laser and a stretcher / compressor assembly. At Coherent, each of these lasers, plus their critical components, are designed from the beginning with rigorous use of HALT / HASS protocols which are then applied to the complete amplifier both at the design and manufacturing stages.

Fig. 4 shows the HASS protocol used to test this first generation of ultrafast

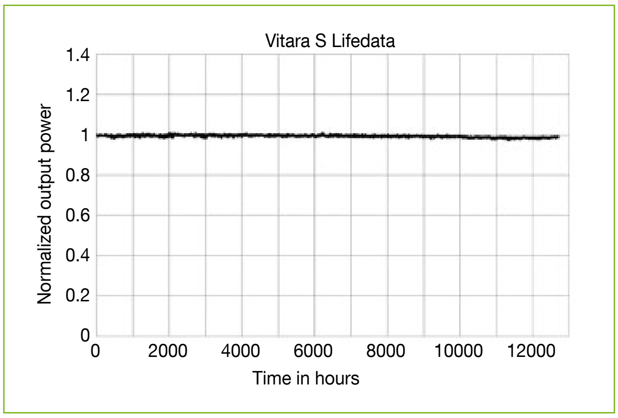

Fig. 3 Vitara-S life test run at constant pump power.

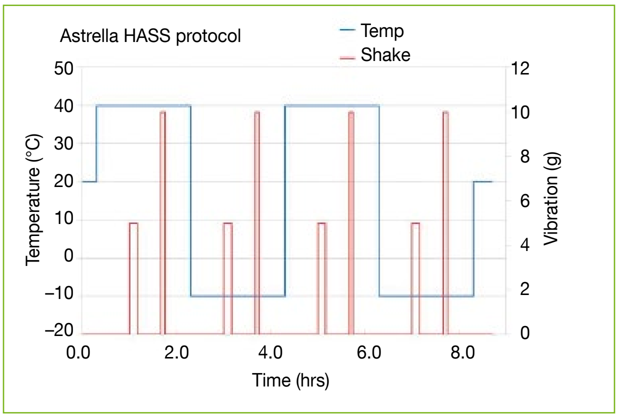

Fig. 4 The HASS test protocol current used for every single unit of a new type of short pulse (< 35 fs) ultrafast amplifier – Coherent Astrella.

amplifiers designed and manufactured completely to these new industrial standards. As can be seen in the figure, this protocol combines different intensity bursts of vibration, together with extreme temperature swings of 50 °C in two-three minutes. The system must show no significant change in output parameters at the end of these tests or it is rejected for shipping.

The end result for the laser user? As described in a recent case study, university researchers are successfully using one of these lasers to conduct two-dimensional spectroscopy in experiments requiring up to 48 hours of uninterrupted data acquisition!

Summary

In conclusion, the introduction of the HALT / HASS protocols to the scientific laser design cycle in the last three years, combined with industrial laser experience and vertical integration for critical components has enabled the production of scientific lasers with both cutting edge performance and industrial reliability and lifetime – truly enabling an industrial revolution in ultrafast science.

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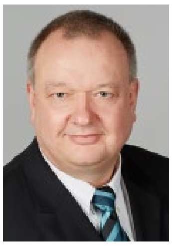

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