Facilitating advancements in holographic techniques with dedicated high power laser combiners

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ABSTRACT

Laser-based holographic techniques continue to grow into commercial markets, used in the production of holographic optical elements (HOEs), for image projection in virtual reality (VR) and augmented reality (AR) devices as well as in white-light analog holography for the generation of ultra-realistic full-color replicas of three-dimensional objects such as museum artefacts. These rapidly developing holographic techniques and holography-based technologies require reliable light sources at multiple wavelengths simultaneously, often in the same optical path.

The individual laser performance requirements for holography applications are met by commercially available, extremely reliable, single-frequency or single-longitudinal-mode (SLM) lasers in the visible spectrum with long coherence length, excellent wavelength stability and accuracy, and high, stable output powers. However, the optical alignment and beam combining necessary in multi-wavelength systems can be technically challenging and time consuming. Elaborate assembly and constant maintenance can divert valuable resources away from the more fundamental work necessary to improve quality of the holograms and HOEs. The aim is to develop a laser combiner that provides the necessary performance per laser line with robust beam alignment stability during exposure, and repeatability between exposures, which requires strict control of opto-mechanical component design and thermal management.

The performance of a laser combiner, which integrates up to four laser lines with up to 1.5 W of optical power per laser, collinearly aligned with high precision position overlap, angular overlap, and beam pointing stability, and repeatability over long periods of time, is evaluated in this paper. This laser combiner includes the laser sources, control electronics, and beam combining optics and is designed to be easily transportable, providing the ideal combined laser solution to facilitate advancements of holographic techniques.

Keywords: Holography, Laser engine, Laser combiner, Diode pumped lasers

1. INTRODUCTION

Holographic and interferometric techniques, enabled by the coherent nature of laser light, are being used in the development and production of holographic optical elements (HOEs), used for image projection in virtual reality (VR) and augmented reality (AR) devices; and creation of three-dimensional reproductions of precious artifacts made using true-color holographs, such as OptoClones™ [1].

Holographic optical elements (HOE) are of ever-increasing interest as the market demands for image projection devices in virtual reality (VR) and augmented reality (AR) expands. HOEs are manufactured by recording 3D features into a holographic material utilizing the interference and diffraction of visible light. HOEs can include lenses, mirrors, diffraction gratings and other beam shaping optics. Holographic process gives endless possibilities to the type of light weight, flexible optical elements that can be created. [2]

OptoClones™ and being used to display priceless works of art, for example Fabergé eggs. The reproductions have become so realistic that they are enabling art lovers to enjoy traveling exhibitions world-wide, while allowing the careful preservation of the actual artifacts [1]. True-color holograms are produced using a combination of 3 or more laser light sources at different wavelengths, this is otherwise referred to as “white light” holography.

The commercial production of complicated and high precision HOEs and convincing true-color holograms typically utilize not one but several high-power laser light sources. These laser sources must deliver a perfect TEM00 beams, robust wavelength and power stability, long coherence length and must be robust to environmental conditions, as well as suitable for production environments [3]. Such lasers are commercially available but optical alignment and beam path management for multiple sources can be difficult and time consuming. The work of aligning and combining laser light sources can distract from the already challenging work of producing HOEs and holograms. To make these techniques more commercially accessible, multi-color, co-linear, high performance laser combiners must be robust to a variety of environmental conditions. A dedicated high power laser combiner that delivers the proven stability performance in a single beam line removes these difficulties and facilitates focus on HOE manufacturing process development and hologram exposure optimization.

2. LASERS FOR HOLOGRAPHY

Coherence is an essential feature of laser light and it is what makes holography and interferometry possible. However, further performance parameters are required for exposing high resolution, stable and uniform holograms and HOEs with the precision required for research and the processing speed suitable for increasingly commercial applications. The critical performance parameters that determine the suitability of a laser light source for holographic applications are the power level, power stability, spatial and temporal coherence, beam shape and quality, wavelength stability and beam pointing stability.

There are many existing laser technologies that can deliver the necessary performance required for holography, including frequency converted optical parametric oscillators [4], frequency stabilized diode lasers [5], fiber lasers [6], and diode pumped solid state lasers [7]. For this discussion will focus on the compact diode pumped lasers (DPLs) with integrated control electronics and proven performance reliability [3] specifically suited for integration in a dedicated laser combiner for holography.

Diode pumped lasers (DPLs) provide the high optical output power in a perfect TEM00 beam with the required single frequency performance and spectral stability needed for holography. DPLs typically consist of a pump diode, a solid-state gain medium, and a non-linear optical element. Non-linear frequency conversation, such as second harmonic generation, sum frequency generation, and third harmonic generation make it possible to produce coherent light at discrete wavelengths throughout the entire visible range from 457 nm to 660 nm. However, achieving the appropriate wavelength is not sufficient. To deliver a narrow spectrum, intra-cavity mode suppressing elements are included to allow only one single cavity mode to propagate, resulting in a robust single frequency, single longitudinal mode laser.

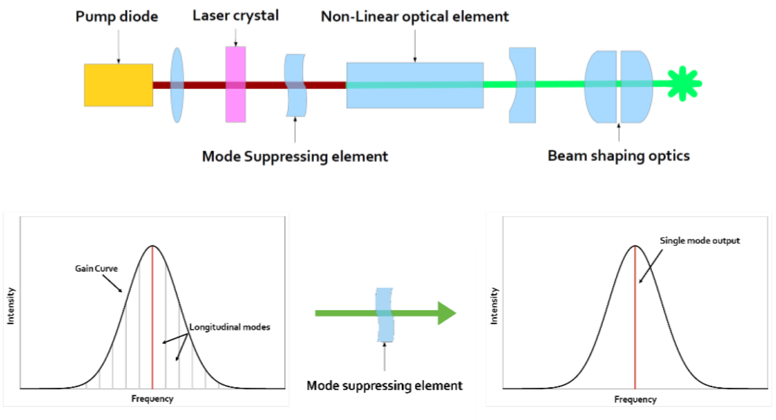

Figure 1: Conceptual diagram of a diode pumped solid state laser for holography (top) and conceptual diagram of mode suppression. (bottom) [3]

After achieving the necessary single frequency performance, the laser must be constructed with a repeatable, controlled manufacturing process. Using the patented HTCure™ technology all Cobolt lasers are manufactured for extreme reliability and robustness. The cavity components and beam shaping options are fixed to a monolithic platform with a high temperature cured adhesive and the entire optical assembly is hermetically sealed to ensure the components are permanently aligned and contamination free. Selecting the highest quality components, optimizing for themo-mechanical compatibility, actively temperature controlling critical components, as well as the platform itself, further stabilizes the cavity. Additionally, optimizing in process controls and verifying critical parameters ensures that the lasers will achieve the required performance over the expected lifetime.

3. COMPACT LASER WITH PERFORMANCE FOR HOLOGRAPHY

Building on the established performance robustness and manufacturing repeatability [3], and striving to minimize the form-factor of the packaging, the control electronics of the Cobolt 05 Series lasers has been fully integrated into the laser head. These lasers are referred to as the Cobolt 05-iE and are ideally suited for integration into a laser combiner as they require no auxiliary equipment.

Figure 2: Cobolt 05-iE laser with fully integrated control electronics, connections for the power supply and I/O connections for OEM integration or to the CE/CDRH compliant key control box.

It is known that changes in packaging can potentially impact stability, especially where thermal management is a key factor. Prior to integration into the dedicated high power laser combiner, all critical performance parameters must be verified and proven robust to changes in the operational environment. This study includes the demonstration and characterization of the Cobolt 05-iE lasers with the nominal wavelengths 457 nm, 532 nm and 640 nm. The wavelengths are specifically chosen based on common wavelengths for “white-light” holography. The exposure time and recording speed of holographic production depends on the intensity of the illumination, making the available output power of a suitable laser a critical factor in the productivity of any holography production process. The required power levels can vary from tens of milliwatts to watts, depending on the wavelength. Typically, the longer (more red) the laser wavelength the more power is required.

All lasers included in this study have > 300 mW of output power and have passed all standard factory acceptance testing, including power stability, noise, single longitudinal mode performance, beam diameter and ellipticity. Here the performance is demonstrated when operated over the entire specified ambient temperature range, using a temperature-controlled baseplate, cycled from 20 °C to 45 °C, to simulate an ambient temperature of 10 °C – 35 °C. The results of the temperature cycling measurement aims to show that the integrated electronics have not negatively impacted the expected performance both in a laboratory environment and manufacturing locations with less stringent climate control.

3.1 Power stability

The power stability of the laser is a critical performance parameter for many applications and, as such, is verified on every manufactured laser. In Figure 3 we show the results from a Cobolt Samba 05-iE 532nm laser, at 1500 mW. The laser is mounted on a temperature-controlled baseplate and the power stability is measured while the baseplate temperature cycled from 20°C to 50°C. This first 12 hours, contain two 6 hours cycles through temperature range followed by an additional 6 hours temperature cycle (hour 12 – 18 in the figure below) in which the laser is switched ON and OFF from the mains power with and ON time of 30 minutes and OFF time of 10 minutes. The power stability is shown to be better than 2% over the entire temperature range, including a period of ON OFF cycling simultaneously with temperature cycling on the baseplate.

Figure 3: Cobolt 05-iE power stability in temperature cycling, with the laser power measurement in dark blue and the baseplate temperature in turquois (left), exampled of laser on a temperature controller (right)

3.2 Beam shape and quality

The intensity of the laser must also be consistent over the exposure time as discussed above. Additionally, the intensity should also be uniformly in space, ideally a perfectly gaussian, TEM_{00} beam with an M^2 of < 1.1 and equal in diameter regardless of orientation, having an ellipticity better than 0.90:1. The beam quality is measured at a constant baseplate temperature of 35 °C using a beam propagation analyzer and the beam shape is measured using a scanning slit beam profiler.

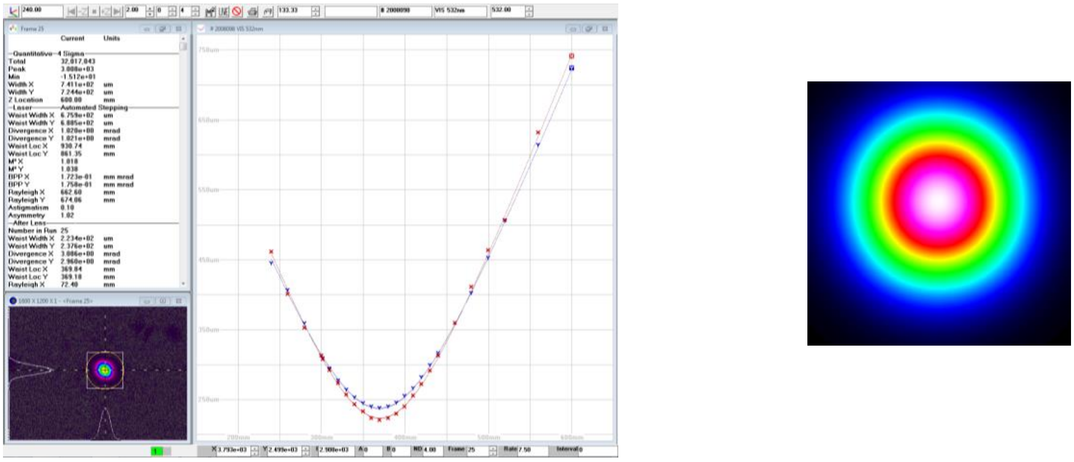

Figure 4: Beam measurements showing beam quality M^2 < 1.1 (left) and a nearly perfect gaussian beam profile (right).

3.3 Wavelength precision

To verify the wavelength precision the lasers to be integrated into the laser combiner are mounted on a temperature-controlled baseplate and the wavelength is measured with a high accuracy, high precision wavemeter at 500 ms measurement intervals while the temperature is cycled throughout the ambient temperature range. As seen in Figure 5, the lasers used in this study have shown a total wavelength variation over the entire operating range from a baseplate temperature of 20 °C to 50 °C of better than 2 pm for the 457 nm laser, < 1 pm for the 532 nm laser and < 6 pm for the 640 nm laser. The discontinuities seen in wavelength stability in temperature cycling of the 640 nm laser are not represented in wavelength stability performance at constant temperature. Under steady state conditions all of three lasers performed well within the specified wavelength stability of < 1 pm.

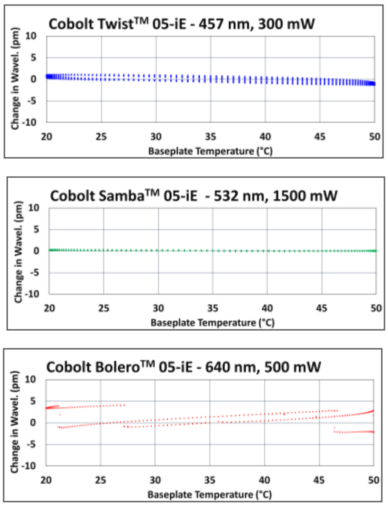

Figure 5: Wavelength stability of Cobolt 05-iE Laser at 457 nm, 532 nm and 640 nm, prior to integration into the laser combiner

3.4 Single longitudinal mode performance

The coherence length is an important consideration when determining if a laser is appropriate for holographic applications. Diode pumped solid state lasers with intracavity mode suppressing elements are expected to have an actual linewidth of << 1 MHz, corresponding to well over 100 m of coherent length. By verifying the SLM performance we can ensure that there are no deviations in the expected linewidth and thereby the expected coherence length of a given laser. To ensure that the SLM performance is robust enough to tolerate system integration the lasers can be with a measured with a scanning Fabry-Perot interferometer, with a 10 GHz free spectral range, giving a resolution of about 67 MHz (which corresponds to approximately 1.4 m of coherence), depending on how coherence lengths is calculated), while mounted on a temperature-controlled baseplate. Below we see a typical result, showing a perfect single mode performance, indicated by the green color, throughout the entire temperature range of 20°C to 50°C and within the operating range around the nominal power, in the results show below the laser is emitting at 532 nm and 1500 mW.

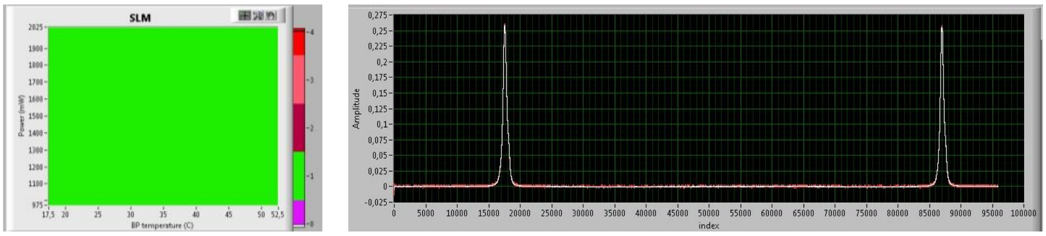

Figure 6: SLM window scan demonstrating single frequency performance over the entire ambient temperature range and through the a power range around the nominal operating power.

3.5 Beam Pointing Stability

In addition to the above requirements for suitability in holographic application, a laser must have superior beam pointing stability to be a good candidate for a beam combining system. To measure the beam pointing stability the lasers are placed on a temperature-controlled baseplate with a beam camera at least one meter from the aperture. The centroid beam position is continuously measured over the entire temperature cycle of three time 6 hours from 20°C to 50°C. To remove the influence of bending and movement of the temperature-controlled baseplate from the laser beam pointing results an additional beam is reflected off the temperature-controlled baseplate and the pointing stability of the reflected beam is subtracted from the measured laser beam pointing stability. Below is a typical result from a Cobol 05-iE laser, specified to be < 10 µrad/°C.

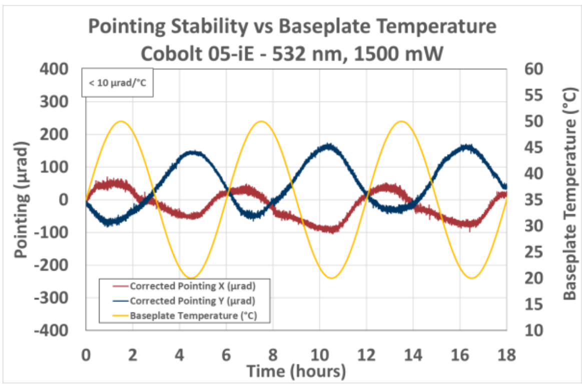

Figure 7: Beam pointing stability of Cobolt 05-iE Laser, prior to integration into the laser combiner.

4. DEDICATED HIGH POWER LASER COMBINER FOR HOLOGRAPHY

Multi-color or "white light" holography may require 3 or more different lasers. Optical alignment can be cumbersome and time consuming. To overcome this, laser combiners provide a compact and easy-to-use interface for development and manufacturing of holograms and holographic optical elements. The stability of the commercially available lasers discussed above can be delivered combined into a single beam line to allow for maximum flexibility in processing while maintaining a rigorous control of the exposure parameters. The three combined lasers are mounted on a common baseplate which also houses the beam combining optics and any further beam delivery accessories, such as acousto-optical modulators or electronic shutters. The beam combing optics consist of a vertical translation prism and a beam steering mirror for each beam respectively. The emission from all combined lasers is then routed out of a common aperture. The electrical interfaces and software control interface for the lasers integrated in the combiner is also combined into a system interface on the laser combiner enclosure. All required laser safety features are also implemented on the laser combiner at a system level, so the laser combiner can be treated as a single laser device with emission at three (or more) different wavelengths.

Figure 8: C-FLEX Laser Combiner with three Cobolt 05-iE lasers, 457 nm, 532 nm and 640 nm, shown with optional acousto-optic modulators in red, mounted between the laser heads and the combiner optics, which can be used for attenuation of the laser lines independently and without sacrificing stability. [8]

The beam overlap and position stability are critical for the ease of use of any laser combiner, and just as critical for a dedicated high power laser combiner for holography. The beam line is composed of three or more individual lasers beams that have been made colinear to facilitate experimentation and production of multi color holographic exposures, where the key advantage is that the user will not have to make adjustments to the exposure position when changing colors. As discussed above, the laser performance is a key factor in the suitability of the laser combiner for holographic applications. The performance of the laser combiner as a system requires further performance controls in terms of critical system parameters such as beam position and angle overlap, beam pointing stability at a constant baseplate temperature and the beam pointing stability with temperature which have been evaluated on the C-FLEX and are discussed in the sections below.

4.1 Laser performance within the laser combiner

Once integrated into the laser combiner the standard laser specifications remain wholly intact. Demonstrating the extreme wavelength stability over time of the integrated laser is specifically interesting for holography applications. A 532 nm laser with 1500 mW output power is integrated into the laser combiner, the laser combiner is mounted onto a temperature-controlled breadboard at 25 °C and the wavelength is measured with a high precision, high accuracy wavelength meter continuously for 6 days. The total instability of the wavelength over the 6-day period was measured to be < 1 pm.

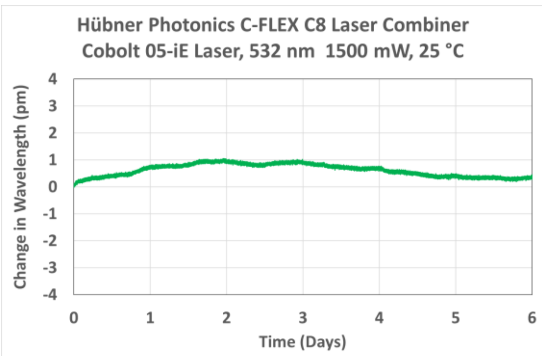

Figure 9: Wavelength stability of Cobolt 05-iE Laser after integration into the laser combiner.

4.2 Laser combiner beam position and angle overlap

The laser beam position overlap, and the beam angle overlap of the laser combiner are optimized during manufacturing to achieve the best possible alignment prior to shipment. The beam line is set inside the laser combiner with a two-pin hole system to define the reference beam as beam originating farthest from the aperture. Then the centroid position is measured for each beam at approximately 10 cm from the aperture and at least 1 meter from the aperture. The laser combiners integrated opto-mechanics are used to, simultaneously, fine align the beam position at the aperture to better than 50 µm beam-to-beam overlap and the beam angle to better than 150 µrad beam-to-beam angular overlap.

4.3 Beam pointing stability at a constant baseplate temperature

To show the beam pointing stability under fixed environmental conditions the laser combiner is mounted on a water-cooled bread board, and the temperature is maintained at a constant 25 °C throughout the measurement. The centroid beam position is measured with a beam camera at one meter from the exit aperture of the laser combiner, the change in the beam position in micrometers is taken over the distance to the camera in meters and reported as the beam pointing stability in microradians.

In Figure 10 we see the measured beam pointing stability in microradians in a 16-hour test, where there is less than 30 µrad of angular deviation per beam. This corresponds to less than 30 µm of displacement of the centroid beam position on a target at 1 meter. It is useful to remember that the lasers in this study have a nominal beam diameter at the laser head aperture of 700 µm with a full angle divergence of 1.2 mrad for the 457 nm and 532 nm laser and 1.4 mrad for the 640 nm laser. At the distance 1 m from the laser combiner aperture the beam diameter of the laser is between 1400 and 1500 µm, which makes the pointing stability within 2 % of the full beam diameter.

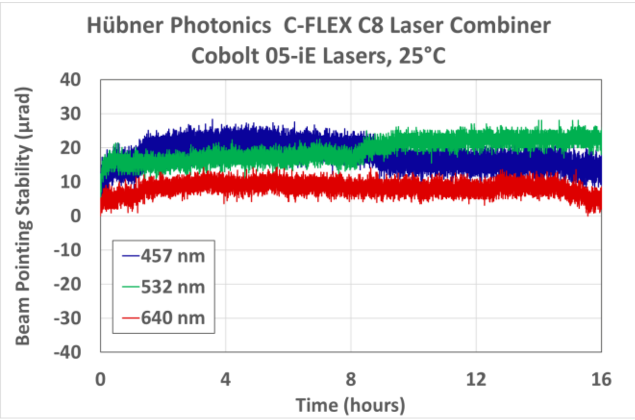

Figure 10: Laser combiner beam pointing stability, per beam, at a constant baseplate temperature

4.4 Beam pointing stability at a varying baseplate temperature.

Further, the beam position and angle deviation is measured with respect to the temperature of the baseplate of the laser combiner. The water-cooled bread board which is set at different temperatures from 20 °C through 45 °C, the specified operational range for this system, and the change in beam angle with respect to temperature is measured. The beam centroid position is acquired in a continuous way as the baseplate temperature is stepped from one set point to the other. The measurement of each laser is started with the laser combiner baseplate at 20 °C and the relative angular deviation is normalized to the initial beam position at the start of the measurement. The beam angle deviation in Figure 11 represents the angular deviation dependance of each beam and the laser combiner baseplate temperature and not the beam-to-beam angular overlap.

As expected, the 640 nm laser, in the farthest position from the aperture, shows the largest in-combiner beam angle deviation, 15.6 µrad/°C, which is well within the specified < 20 µrad/°C. Counter intuitively the laser in the second position from the aperture shows the least temperature dependent angular beam deviation. This could be in part due to the extreme pointing stability of the laser itself, or due to a lower bending of the baseplate in the center than on either side, this remains to be seen.

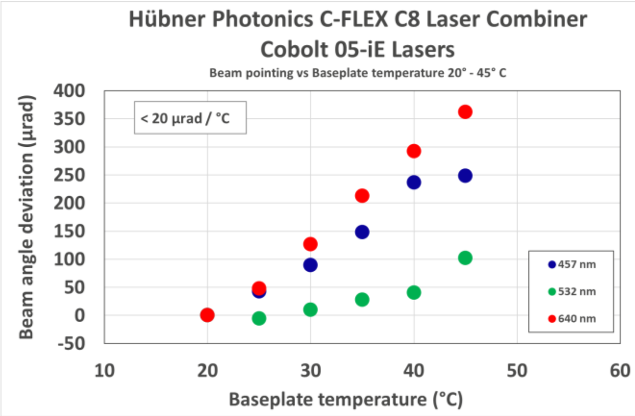

Figure 11: Laser combiner beam pointing stability, per beam, at a different baseplate temperatures. The 640 nm laser is integrated farthest from the aperture.

5. CONCLUSION

By integrating three high power single frequency visible lasers with a perfect TEM00 beams and extremely stable and robust spectral performance onto a single platform, we are able to meet the significant performance demands of the growing field of holography with a precision-aligned co-linear “white light” laser combiner. This high-power laser combiner is transportable and includes all laser control electronics, and beam combining optics and communication hub within a single enclosure, providing the ideal laser light source to facilitate advancements of holographic techniques.

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