Ensuring reliable single-frequency laser performance for holography and other interferometric techniques in production environments

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ABSTRACT

Several holographic and other interferometry-based techniques have recently grown in commercial interest and feasibility, in part thanks to advancements in new laser technology that is capable of meeting the demanding optical performance requirements in these techniques. White-light analog holography is now capable of generating ultra-realistic true-color replicas of 3D objects that can be used to record and display museum artefacts. Laser-based holographic techniques have recently also drawn a lot of attention for its use in the production of holographic optical elements (HOEs) used for image projection in virtual reality (VR) and augmented reality (AR) devices. Other interferometry-based techniques, such as laser doppler velocimetry (LDV) and laser ultrasonics (LUS) are also increasingly being introduced as on-line process control tools in production environments, for example for OLED display manufacturing.

All of these holographic and interferometric techniques require single-frequency or single-longitudinal-mode (SLM) lasers in the visible spectrum with long coherence length, excellent wavelength stability and precision, as well as high, stable output powers.

As the applications of these techniques are transitioning from laboratory settings to production-scale environments the demands on performance reliability and stability over long time periods and variable environmental conditions are increasing.

Here we present how combining a robust optical assembly technology with advanced procedures for laser optimization and performance verification enables manufacturing of high power SLM lasers that deliver robust spectral performance over long time periods and in varying environmental conditions. We will demonstrate a novel automated SLM test procedure that ensures stable single-frequency performance and show wavelength stability over large temperature cycles.

Keywords: Lasers for holography, SLM, laser performance, laser wavelength, holography, wavelength stability, DPSS lasers, reliability

1. INTRODUCTION

Laser-based interferometric techniques have recently drawn a lot of attention for their use in the production of true-color holograms and the manufacturing of holographic optical elements (HOEs) used for image projection in virtual reality (VR) and augmented reality (AR) devices.

True-color holograms, such as OptoClones™ [5], have become so realistic they are now used to create 3D reproductions of precious artifacts, such as the Fabergé eggs. In situations where the actual artifacts are too fragile or valuable to transport, holograms can bring the experience of viewing these items to a worldwide audience. True-color holograms are produced using so called "white light" holography combining 3 to 5 wavelengths, where the lasers must be extremely stable in wavelength and optical power during the entire exposure. To be able to capture the precious artifacts in their own environment, the commercially available holographic imaging systems are now being made portable and are designed to withstand the stress of frequent transportation.

HOEs can be any kind of optical element, such as lenses, diffraction gratings or mirrors, that are manufactured using holographic techniques where interference and diffraction of visible light is used to record 3D features into a holographic material [4]. HOEs are being used to develop the extremely compact, free form and flexible components that are a key enabling technology for AR /VR, head-up and head-mounted displays. For example, using a plastic holographic mirror for AR headsets, in place of a traditional glass optic, decreases the weight enough to make the headset ergonomically suitable for wearing [6]. Volume holographic optical elements (V-HOEs) for wavelength selection are also being used in solar concentrators on photovoltaic cells to increase efficiency, decrease size and weight, reduce cost and improve wavelength specificity [6]. The commercial success of HOEs as a viable alternative to traditional glass optics is facilitated by the availability high power laser light sources with long coherence length, a perfect TEM_{00} beam and extreme wavelength stability and that will reliably perform in a manufacturing environment.

Holography and interferometry both utilize the amplitude modulation and phase shift induced in laser light by an illuminated object. Holography records this data into a holographic film, which, when illuminated, reproduces the effect of the object on the incident light whereas interferometry uses the data to determine properties of the illuminated object. Like holography-based technologies, interferometry-based technologies such as laser doppler velocimetry (LDV) and laser ultrasonics (LUS) place similar demands on the integrated laser light sources. LDV is a measurement technique used to analyze the movement of a particle at specific point in space and time. The particles are analyzed by collecting data at the point where two collimated beams intersect. As the particles pass through the intersection the reflected light is gathered and analyzed to measure the Doppler shift and therefore the velocity of the particles can be measured [3]. Commercially available LDV based particle analysis tools are consider essential for volume production of Organic LED (OLED) displays. In LUS a laser induced ultrasonic vibrations in a material are detected by measuring the phase shift in one arm of an interferometric vibrometer. LUS techniques are being used for non-contact defect testing of metals and composite materials. Advances in sensor and laser source robustness has allowed LUS measurement equipment manufacturers to design systems capable of transitioning from sample testing in a laboratory to on-site testing within production facilities.

As the applications for holographic and interferometric techniques, like those mentioned above, are transitioning from laboratory settings to production environments the demands on the laser light source performance, reliability and stability over long time periods and variable environmental conditions are increasing. Here we present how combining a robust optical assembly technology with advanced procedures for laser optimization and performance verification enables the manufacturing of high power, single frequency lasers that deliver robust spectral performance over large temperature ranges.

2. MANUFACTURING LASERS FOR HOLOGRAPHY

Holographic and interferometric techniques are, in general, made possible by the coherence of laser light. In order to make high resolution, stable and uniform holograms, or interference measurements, there are several critical performance parameters that influence the suitability of a light source. The light source must be spatially and temporally coherent over the entire depth of field, typically > 1 m, which can be specified as single frequency emission and verified by measuring the single longitudinal mode (SLM) performance. As the required exposure time and recording speed in hologram production is directly related to the intensity of the light source the output power of the laser is an important factor. Required power levels range from tens of milliwatts at shorter wavelengths to watts at longer wavelengths. When industrializing any application repeatability and process stability become more important and the power must not only be sufficiently high for exposure but stable over the entire recording time. A smooth, circular beam profile provides uniformity of illumination during exposure. An ideal beam is perfectly gaussian with exceptional beam quality, an M^2 of < 1.1 and ellipticity better than 0.95:1. There are several laser technologies capable of delivering these performance parameters, including fiber lasers, frequency converted optical parametric oscillators and frequency stabilized laser diodes [1] but this discussion is limited to the specific suitability of frequency converted diode pumped lasers (DPLs) and their proven performance reliability.

Diode pumped lasers deliver high optical power in a perfect TEM_{00} beam with the spectral performance and stability described above as essential for holography and other interference-based technologies. A typical diode pumped laser consists of a pump diode, a solid-state gain medium or laser crystal, and a non-linear optical element. Additionally, some DPLs contain mode suppressing elements and beam shaping optics. A conceptual diagram of a diode pumped laser can be seen in figure 1.

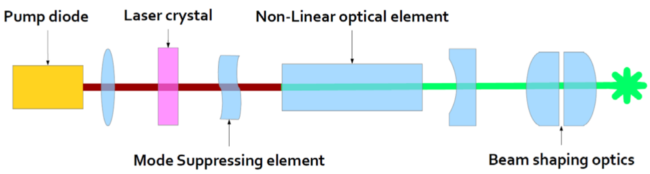

Figure 1: Conceptual diagram of a diode pumped solid state laser for holography.

By employing nonlinear optical processes such as second harmonic generation, sum frequency generation and third harmonic generation, discrete wavelengths covering nearly the entire visible spectrum from 457 nm to 660 nm can be achieved, with the flexibility to develop additional wavelengths as the application needs evolve. Generating the desired wavelength does not necessarily guarantee the required spectral purity. To further narrow the emission spectrum, an intracavity mode suppressing element can be included during manufacturing. The mode suppressing element allows only a single cavity mode to propagate and results in robustly single frequency laser, this concept is illustrated in figure 2.

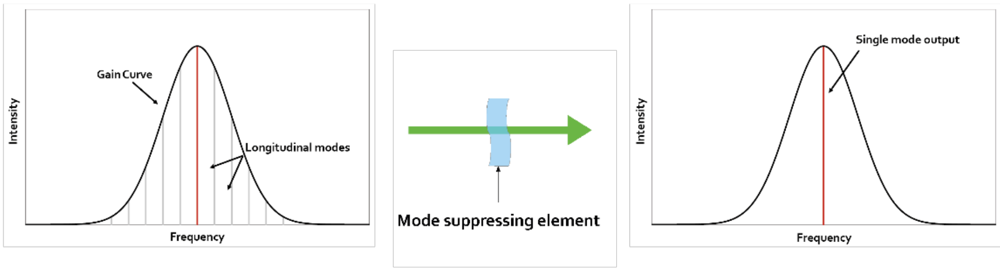

Figure 2: Conceptual diagram of mode suppression.

Designing a system that will deliver the required performance is the first challenge. The second is developing a manufacturing process to ensure that the design is realized in each delivered instance. For the final challenge, these performance parameters must be guaranteed over the expected lifetime of the laser and in a wide range of operating environments. This is achieved by securing the highest quality components, documenting and controlling the process steps, determining the optimal in-process controls and designing measurements to thoroughly verify each key performance parameter.

All Cobolt lasers are manufactured with patented HTCure™ technology which facilitates the extreme reliability of performance and exceptional spectral stability. The optical components of the laser cavity, as well as those for beam shaping, are mounted on a single platform, fixed with a high temperature cured adhesive and hermetically sealed to ensure that the laser cavity is permanently aligned. All materials are carefully selected for thermo-mechanical compatibility. The critical optical components, as well as the platform, are actively temperature stabilized to optimize and control performance. Further, the laser head capsule is thermo-mechanically decoupled from the outer mechanics providing isolation from fluctuations in ambient temperature and the influence of those fluctuation on the laser performance. HTCure™ laser manufacturing technology is well established and proven to be reliable and maintenance free over years of operation.

3. DEMONSTATION OF PERFORMANCE

Once the processes are refined and repeatable it is still imperative to verify that all essential parameters have been achieved simultaneously and without trade-off. To demonstrate the reliability and robustness of performance, representative samples of commercially available high-power visible wavelength lasers were removed randomly from the production line and included in this performance survey; no special preparations are taken in the selection.

The lasers included in this study are Cobolt 05-01 Series lasers [2] with nominal wavelengths of 457 nm, 491 nm, 532 nm, 561 nm, 640 nm and 660 nm. All lasers included in this study have > 100 mW of output power and have passed all standard factory acceptance testing, including power stability, noise, beam diameter and ellipticity. While laboratories are often climate controlled and relatively stable in ambient temperature, industrial manufacturing locations can vary dramatically in temperature from day-to-day or facility-to-facility. To characterize the performance in all possible ambient temperature conditions the lasers can be mounted on a temperature-controlled baseplate as seen in figure 3 and temperature cycled from 20 °C – 50 °C, corresponding to an ambient temperature range of 10 °C – 40 °C.

3.1 Output power stability

Power stability is critical for many applications and is considered an essential factory acceptance test. Each manufactured laser is measured at a constant baseplate temperature to verify the steady state power stability as well as with a temperature cycled baseplate to characterize the effect of the ambient temperature on the output power. The typical test result of the lasers in this study can be seen in figure 3, demonstrating power stability of better than 1 %. The measurement duration on the x-axis, the variation in the measured output power shown on the primary y-axis in dark blue and the temperature of the baseplate shown on the secondary y-axis in light blue. The lasers are equipped with an internal power regulation circuit that controls the pump diode drive current in order to actively maintain the set output power.

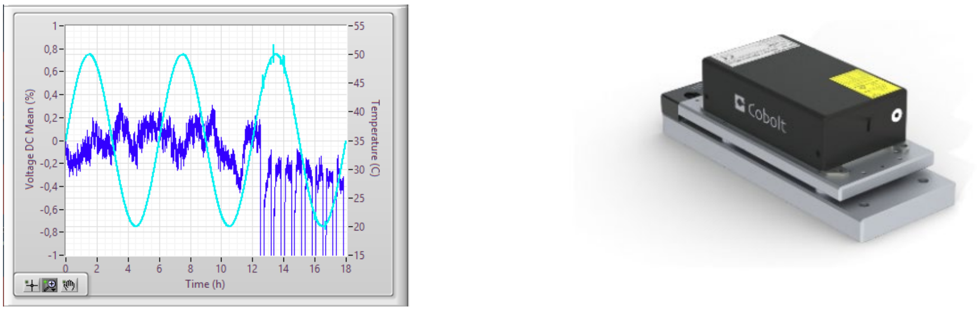

Figure 3 : Typical factory acceptance test for power stability demonstrating better than 1% power stability over 18 hours where the final 6 hours cycle includes and ON OFF test (left).

3.2 Beam shape and quality

Consistency of beam size and shape is a critical system interface parameter for any illumination source. The integrated, permanently aligned beam shaping optics of the lasers in this study deliver a perfect TEM_{00} beam. The beam is collimated, with a divergence of < 1.2 mrad at 532 nm (divergence is wavelength dependent) and an ellipticity in all cases of better than 0.95:1. The beam is measured with a scanning slit beam profiler to determine ellipticity and diameter. A beam propagation analyzer is used to verify that the beam quality is ideal with an M^2 of < 1.1. The divergence of each lasers is measured during manufacturing with the beam profiler while assembling the beam shaping optic but can be additionally verified with the beam propagation analyzer once the entire laser package is complete. A typical M^2 measurement result and beam profile image can be seen in figure 4.

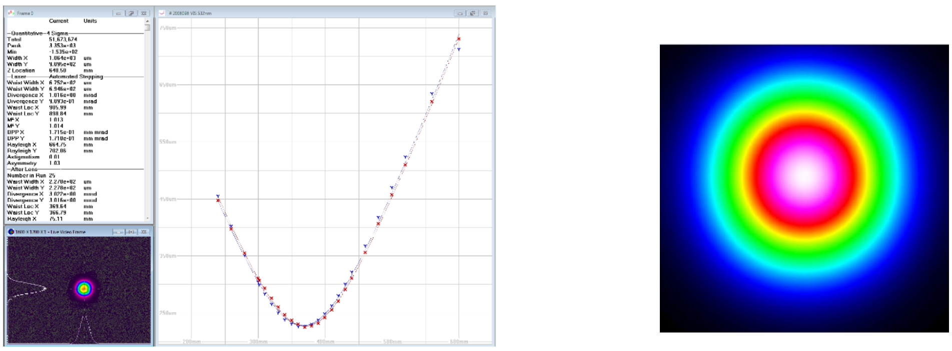

Figure 4: Beam measurements showing beam quality $M^2 < 1.1$ (left) and a nearly perfect gaussian beam profile (right).

3.3 Single longitudinal mode performance window

The most essential performance parameter for writing a hologram or an HOE is the coherence length. By measuring the single longitudinal mode performance, it can be inferred that the linewidth, and thereby coherence length, of the laser is within the design constrained expectations. In the case of the diode-pumped solid-state lasers included in this study the actual linewidth of the emission is expected to be << 1 MHz, which corresponds to more than 100 m coherence length. Though it is not a direct measurement of the line width, and is limited by the resolution of the scanning Fabry-Perot to 67 MHz (which corresponds to approximately 1.4 m of coherence), verifying the single longitudinal mode performance provides evidence that the laser coherence length will be at least sufficient for holographic and interferometric application.

Understanding the importance of dependable coherence length for the commercialization of holography, an automated test setup was developed to control both the ambient temperature and the laser parameters and create a matrix of possible operating conditions within the life cycle of the laser. The laser is mounted on the temperature-controlled baseplate. The beam is focused into a scanning Fabry-Perot interferometer with a free spectral range (FSR) of 10 GHz. A combination of partially reflecting prisms and neutral density filters are used to attenuate the beam. The interferometer signal is observed with an oscilloscope. At each set point the oscilloscope trace is recorded and analyzed with the Cobolt SLM Test acquisition program. A diagram of the test setup can be seen in figure 5.

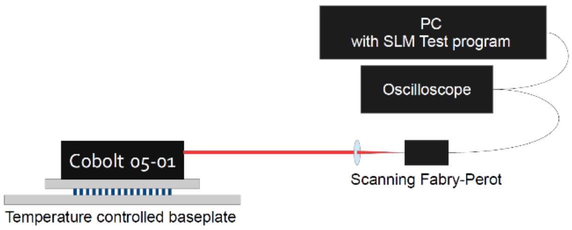

Figure 5 : Measurement setup diagram SLM Verification versus ambient temperature

The Cobolt SLM Test acquisition program reads the nominal set points for the laser pump-diode drive current, or the optical output power, from the Cobolt Monitor control software and then uses this information to create the measurement window around the nominal set point values. For each temperature set point the drive current is ramped through a range above and below the current value that corresponds to the nominal output power. A typical measurement result can be seen in Figure 6. The left image shows the SLM Test result matrix with the baseplate temperature on the x-axis and the laser drive current on the y-axis. In this example the temperature step size is 5 °C and the current step size is 50 mA. A single peak was observed on the oscilloscope at each measurement set point, as indicated by green on the color scale. The center image shows the amplitude of the peak on the Fabry-Perot trace monitored during each measurement and indicates how the power increases with current. A sample of the captured oscilloscope trace can be seen in the image on the right. If the SLM window for a measured laser is not perfect, this automated test makes it feasible to optimize the temperature settings of the critical components within the laser capsule to improve the SLM window without interrupting the flow of the manufacturing process.

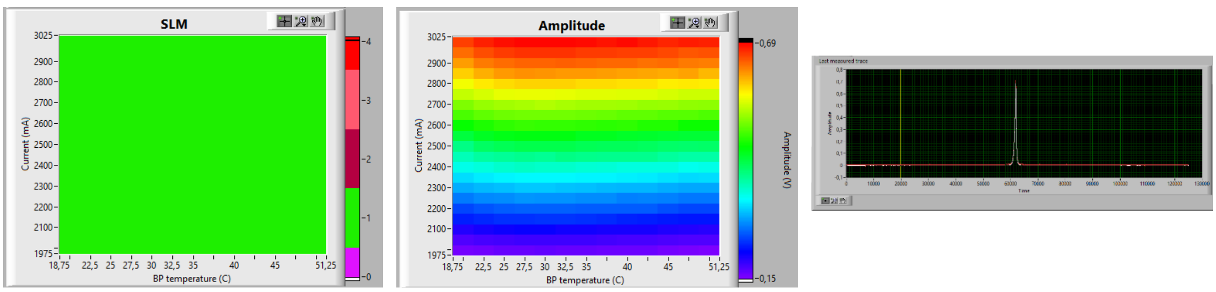

Figure 6: The Fabry-Perot single longitudinal mode measurement (right) is repeated for the entire operation range, well above and below the nominal power set point and while stepping the baseplate temperature in 5°C increments from 20 °C to 50 °C. The number of peaks in determined (left) and the amplitude of the measure peak is monitored (center) at each measurement point within the SLM window scan.

3.4 Center wavelength stability and precision

Wavelength stability and precision are imperative for the repeatability and resolution of holographic exposures or interferometric measurements. Figure 7 shows the exceptional wavelength stability of better than 0.2 pm peak-to-peak that has been demonstrated for the commercially available lasers in this study with wavelengths of 457 nm, 532 nm, 640 nm and 660 nm. The measurement is performed using a high precision wavemeter with better than 0.01 pm resolution and 0.2 pm absolute accuracy, at a constant baseplate temperature of 35 °C, over 4 continuous hours or operation. The same extreme level of wavelength stability shown in figure 7 at 35 °C is expected regardless of ambient temperature, given that the ambient temperature is constant during operation.

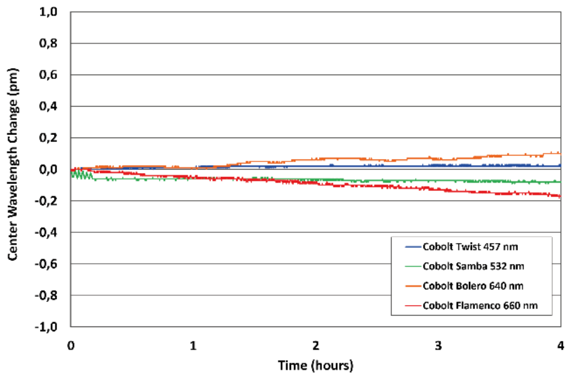

Figure 7: The center wavelength of each laser deviates < 0.2 pm over 4 hours of continuous operation at a fixed baseplate temperature.

In order to move from the strict environmental controls available in a laboratory experiment into industrial and commercial production facilities it is of great importance that the light source should perform at the end user as it does in factory testing or development scenarios. To verify that lasers continue to deliver superb performance under variable environmental conditions the laser is mounted on a temperature cycled baseplate that is cycled over a temperature range of 20 °C - 50 °C. The wavelength, in air, is measured at least once per second for 8 hours while the temperature is incremented at a fixed interval. A diagram of the test setup can be seen in figure 8.

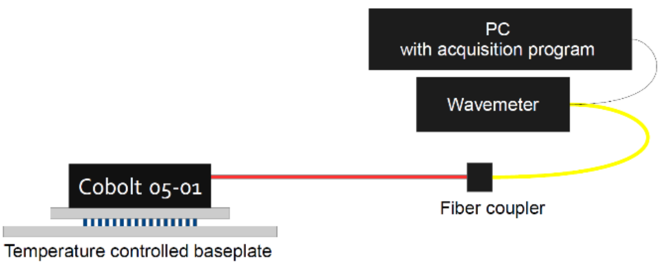

Figure 8 : Measurement setup diagram - center wavelength versus ambient temperatures

The center wavelength precision at difference baseplate temperatures is demonstrated to be better than 1 pm peak-to-peak for the 532 nm, 561nm, and 660 nm lasers; < 2 pm for the 491 nm laser; < 4 pm for the 457 nm laser; and < 6 pm for the 640 nm laser, as seen in figure 9. Discontinuities in the 640 nm laser wavelength data, that are not seen in any of the other wavelengths, can be explained by lower thermal conductivity of certain components as well as a higher thermal load on the platform. Continuous improvements in manufacturing aims resolve these issues over time. Despite these discontinuities in temperature cycling, at a constant ambient temperature the wavelength stability of the 640 nm laser is demonstrated to be as good as the other wavelengths.

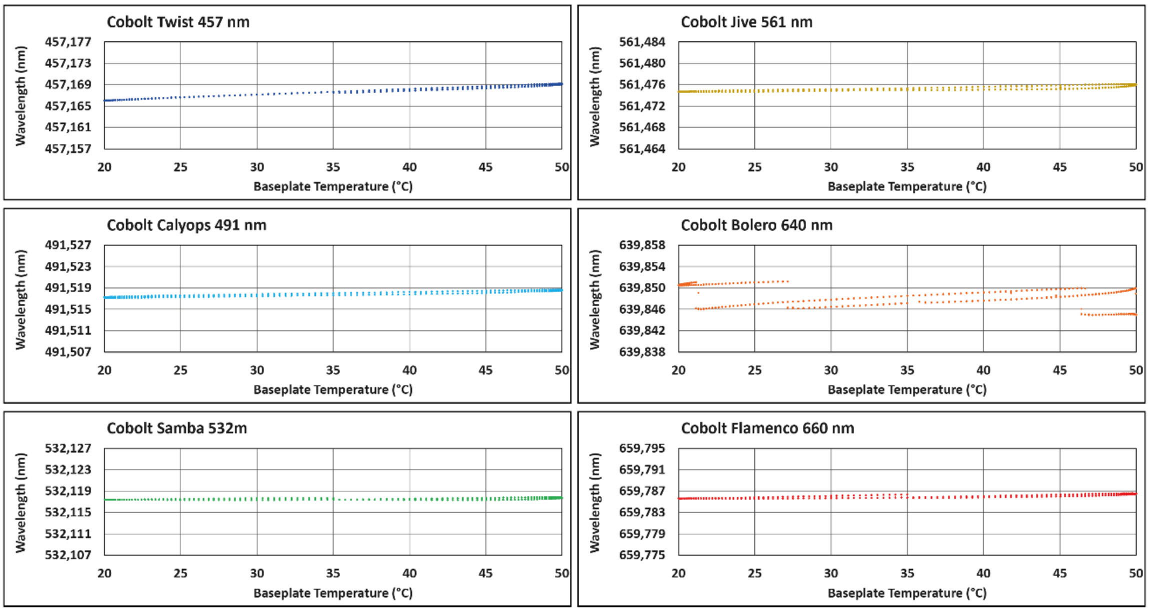

Figure 9: The center wavelength of each laser deviates between < 1 pm for 532 nm, 561nm, and 660 nm; < 2 pm at 491 nm; < 4 nm at 457 nm; and < 6 pm at 640 nm (pk-pk) in continuous operation while the baseplate is temperature cycled over 30 degrees variation in ambient temperature.

4. CONCLUSION

The combination a robust optical assembly using proprietary HTCure™ technology, strict process control and advanced procedures for laser performance optimization and verification ensures a reliable method for manufacturing of high power, single frequency, single longitudinal mode lasers across nearly the entire visible spectrum, from 457 nm to 660 nm, that deliver high quality beam, power stability and spectral performance over years of operation and over large temperature ranges. A secure supply chain of suitable light sources is a key to bringing the advanced devices and measurement techniques that are enabled by holography and interferometry to a wider commercial or industrial market.

5. REFERENCES

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