Lasers for holographic applications: important performance parameters and relevant laser technologies

Korbinian Hens*[a], Jaroslaw Sperling[a], Ben Sherliker[b], Niklas Waasem[c], Allen Ricks[c], Jonathan Lewis[b], Gunnar Elgcrona[d]

[a]HÜBNER GmbH & Co. KG, Heinrich-Hertz-Str. 2,34123 Kassel, Germany;
[b]TruLife Optics, The Fitting Shop Building, 79 Trinity Buoy Wharf, E14 0FR, London, UK;
[c]Cobolt Inc, 2635 North First Street, Suite 228, San Jose, California, 95134, USA;
[d]Cobolt AB, Vretenvägen 13, SE-171 54, Solna, Sweden;

ABSTRACT

There is recently an increasing interest in holographic techniques and holographic optical elements (HOEs) related to virtual reality and augmented reality applications demanding for new laser technologies capable of delivering new wavelengths, higher output powers and in some cases improved control of these parameters. The choice of light sources for optical recording of holograms or production of HOEs for image displays is typically made between fixed RGB wavelengths from individual lasers (457 nm, 473 nm, 491 nm, 515 nm, 532 nm, 561 nm, 640 nm, 660 nm) or tunable laser systems covering broad wavelength ranges with a single source (450 nm – 650 nm, 510 nm – 750 nm) or a combination. Lasers for holographic applications need to have long coherence length (>10 m), excellent wavelength stability and accuracy as well as very good power stability. As new applications for holographic techniques and HOEs often require high volume manufacturing in industrial environments there is additionally a growing demand for laser sources with excellent long-term stability, reliability and long operational lifetimes. We discuss what performance specifications should be considered when looking at using high average power, single frequency (SF) or single longitudinal mode (SLM) lasers to produce holograms and HOEs, as well as describe some of the laser technologies that are capable of delivering these performance specifications.

Keywords: Lasers for holography, SLM, laser performance, laser wavelength, tunable lasers

*Korbinian.Hens@hubner-germany.com; phone +49 561 9988-1620; www.hubner-photonics.com

1. INTRODUCTION

The basic principles of holography were discovered in the first half of the 20th century by Nobel Prize winner Dennis Gabor who was awarded the prize 1971 for his 'invention and development of the holographic method' [1]. But it was only after the laser was invented in 1960 when optical holography as a recording method and as a technique to display 3D images as an art form took off. Todays holographic applications range from security holograms on bank notes, or passports to the production of so-called holographic optical elements (HOE's). Instead of having a fixed image written into it, a hologram can also serve as a tool to route light or images through it in a customized way. For example, it is possible to make a hologram behave like a lens so that an image presented to it is magnified. Prominent examples of such HOEs are diffraction gratings often deployed in lasers or spectrometers.

Todays increased availability of more compact single longitudinal mode (SLM) lasers, along with the development of a new generation of sensitive emulsions and the availability of wavelength selectable LED based illumination sources have opened up new application areas for holographic techniques.

For instance, these technology improvements have paved the way for bringing head-up displays and associated technologies for virtual reality (VR) and augmented reality (AR) projection into the high volume consumer markets. Although high volume replication of holograms and HOEs has already been used in the security industry in the form of embossing for decades, the requirements for head-up displays mean that holograms with better resolution than what embossing can offer are needed. Lasers will likely be used to write this kind of hologram, and most likely this will be done in a form of a laser printer, akin to the current 3D printer. Developments in laser technology, emulsions and illumination sources have also led to drastic improvements in the white light holography, which is opening up new applications for holography related to ultra-realistic 3D replication of objects.

For writing single and multi-color holograms or producing high quality HOEs, weather as a master or in volume production, the performance characteristics of the applied lasers are crucial for the resulting products.

2. LASER PERFORMANCE PARAMETERS RELEVANT FOR HOLOGRAPHY

Analogue holography is based on creating a 3D image representation of an object onto a 2D holographic plate by recording the interference pattern that occurs when exposing an object with coherent light and mixing the light reflected from the object with a reference beam from the same coherent light source. The hologram is a 3D representation of the object as the interference pattern includes phase information of the reflected light.

In case a single laser is used to record a hologram, either by exposing the object in real life or from a 3D CAD file, the method is commonly referred to as single color holography. Ideally that single color light source is then used to illuminate the hologram to replay a high quality 3D image of the object. In reality, holograms tend to be illuminated by incandescent sources, which typically results in an un-sharp image rendering and in a single color only.

In contrast to this white light holography typically uses 3 (up to 5) colors to write a hologram - red, green, and blue. Due to the development of new emulsions with improved sensitivity and the fact that wavelength tailored LEDs can be used to illuminate the hologram at wavelengths closely matching the recording wavelength to achieve highest clarity, white light holography gained renewed interest for applications related to virtual and augmented reality as well as ultra-realistic 3D replications.

In a more technical description a hologram can be perceived as a photograph of the light field including its phase content. In order to record this phase content of the light field a coherent light source is needed. Thus, by far the most important performance parameter requirement on a laser for holography is the coherence length. By coherent we mean that all the light waves travel in synchronization i.e. they have the same period and phase, and this characteristic is found in truly single longitudinal mode (SLM) or single frequency (SF) lasers. The coherence length of a light source is directly correlated to the spectral linewidth of the emitted light (temporal coherence), as well as the homogeneity of the phase front over the beam cross section (spatial coherence). The distance the light needs to be coherent over in order to make an interference pattern is determined by the depth of field; the larger the depth of field the longer the coherence length that is needed. Regularly a coherence length of >1m is more than sufficient. However, a larger coherence length allows for more complex holographic setups.

Besides the coherence length, there are a few other parameters which are important to be considered when selecting a laser light source for holography: wavelength, output power, wavelength accuracy and stability, power stability as well as reliability. CW lasers are commonly used for writing holograms or HOEs, however, there are potential applications for which pulsed lasers could be considered, too.

A summary of the laser performance parameters mentioned above and their characteristic impact on the quality of the hologram is given in Table 1.

Table 1: Important laser performance parameters for writing holograms.

Laser performance parameters	Characteristics
Coherence length	The coherence length is by far the most important performance characteristic to consider when writing a hologram or HOE. A coherence length >1 m is typically sufficient for writing holograms. A long (temporal) coherence length of a laser (>100's m) corresponds to a linewidth of < 1 MHz and is referred to as single longitudinal mode (SLM) or single frequency (SF).
Wavelength	Typically, 3-5 wavelengths are combined from the blue (457 nm, 473 nm, 491 nm), green (515 nm, 532 nm, 561 nm) and red (640 nm, 660 nm) parts of the visible spectrum for recording of a white light hologram. Recently tunable lasers gained in importance for holography since those can be used to highlight one particular color, or tune to the exact illumination spectrum. Their exceptional wavelength versatility, which is not limited by the wavelength coverage dictated by the energy levels and suitable transitions in a laser gain medium, provides highest flexibility for customized applications in the field of holography.
Output power and power stability	Typical laser output power levels range from a few 10 mW in the UV, up to several watts in the red. The recording speed of a hologram is directly related to the available output power of the laser, which makes this parameter especially relevant when considering systems for volume production. Good power stability is important to assure reproducible quality of a hologram when keeping the same exposure time.
Wavelength accuracy & stability	The laser wavelength accuracy should ideally be as high as possible to guarantee that holograms and HOEs will maintain their visual quality as designed. Lasers should have only little variation from unit to unit (<±0.3 nm). Furthermore, the stability over time of the laser light wavelength must stay very fixed during exposure of a hologram in order not to destruct the resolution.
Beam quality	A smooth circular beam profile (a TEM00 beam) provides even illumination during exposure and implies that the laser light source has good spatial coherence. Such lasers typically have a beam quality factor M^2 <1.2.
Reliability	Reliability becomes extremely important in volume production as all down time costs money. Thus, long-term performance tests for the laser types applied as well as the service concept of the laser supplier should be reviewed when selecting a laser for volume production of holograms or HOEs.
CW or pulsed	In general, higher output powers of CW lasers mean shorter exposure times are required for recording of a hologram. A pulsed laser can potentially write within the pulse length, which is comparatively fast. Though, the laser needs to be SLM and have high pulse energy.

3. SOLID STATE LASER TECHNOLOGY FOR HOLOGRAPHY

For a long time gas lasers were widely deployed for holography, since these lasers are capable to provide the required coherence length and decent output power levels. Besides the size, power consumption and complexity of these laser systems, gas lasers can only provide a limited set of wavelengths. New generation solid-state lasers are available at a wide range of wavelengths and at power levels from 10’s mW up to multiple watts; ready to replace gas lasers. In addition to single frequency lasers based on established technologies, such as diode, DPSS, or fiber laser technology, novel tunable laser light sources based on OPO technology recently got commercially available, providing several hundred milliwatts single frequency laser light output together with an outstanding wavelength flexibility.

3.1.1 Established laser technologies

Frequency-converted diode-pumped SLM lasers (DPL or DPSS lasers)

Frequency converted diode-pumped single longitudinal mode (SLM) lasers are readily available in compact and affordable formats with fixed wavelengths from the UV to the near-IR and coherence lengths of 100’s meters [2]. DPLs are solid state lasers which are more efficient, more compact and have longer lifetimes than the traditionally used gas lasers. A large number of fixed wavelength lines in the blue-green-red region of the VIS spectrum are available (457 nm, 473 nm, 491 nm, 515 nm, 532 nm, 561 nm, 640 nm, 660 nm) with output powers on the scale of half a watt. These characteristics give the flexibility to select the most optimal wavelengths for holography depending on the emulsions and illumination source. The laser design of DPLs inherently provides excellent circular TEM00 beams, accurate wavelengths with excellent wavelength stability (Fig 1).

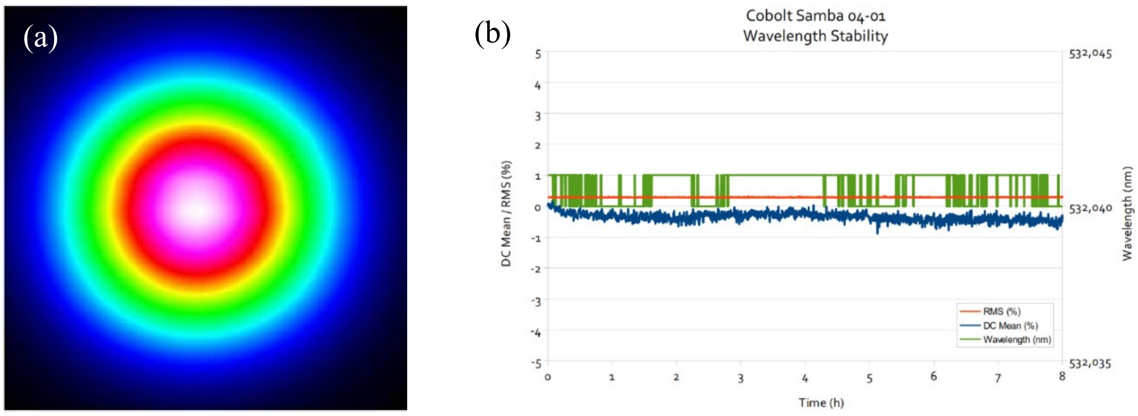

Figure 1: (a) Typical TEM00 beam profile of a DPL SLM laser. (b) typical wavelength & power stability of a DPL SLM laser (co Cobolt AB).

Single frequency or frequency stabilized diode lasers

Single frequency or frequency stabilized laser diodes are based on a different laser technology providing access to slightly different wavelengths [3]. A diffraction grating element (e.g. a Volume Bragg Grating, VBG element) with a narrow-linewidth feed-back is used with a diode laser emitter to achieve narrow-linewidth emission (corresponding to long coherence length). Typical wavelengths for such lasers are 405 nm, 633 nm and 785 nm with power levels of several hundred milliwatt. It is also possible to achieve narrow linewidth emission at higher power levels by frequency locking multi-transversal mode diode lasers. Furthermore, it is possible to reach other wavelengths in the visible spectrum with power levels suitable for holography by amplifying narrow-linewidth or single-frequency diode lasers and combining them with frequency conversion. Lasers based on this technology offer some degree of wavelength tunability, typically several 10s of nm, which means more flexibility for holographic applications.

Frequency converted fiber lasers

In general, high power fiber lasers are typically not SLM or SF. In order to achieve SF performance of multi-Watt level fiber lasers the seed from a single-frequency master oscillator is amplified. The fibers of fiber lasers as well as amplifiers are typically doped with Yterbium (Yb), which emits between 1000-1100 nm. Laser emission in the visible spectral range can be realized by external frequency conversion. Common wavelengths are 488 nm, 515 nm and 532 nm with rather high output powers in the order of a couple of watts. Typically, the frequency converted laser output is emitted from a small frequency conversion head connected to the main laser and drive electronics via an optical fiber. The heat dissipation of this small laser head is low and thus, no active cooling is required, i.e. disturbing vibrations caused by fans while recording a hologram can be avoided.

Pulsed solid state lasers

Although, CW lasers have been the preferred sources for recording holograms in the decades after the lasers invention in 1960, the first laser used to write holograms was a pulsed ruby laser. The advantage of the short pulses is that the hologram can be written in a very short time, in principle capturing the moment of moving. The possibility of writing holograms within a single ns - 100 ns long pulse would be a big advantage for realizing volume manufacturing, enabling true 'on the fly' writing of HOEs. However, pulsed solid state lasers are not typically SLM by definition, and may be on the low side with respect to pulse energy, which is limiting the amount of commercially available pulsed lasers suitable for holography. Nonetheless, in combination with sensitive emulsions films, this could be a consideration for future laser printers and true volume production of HOE's.

3.1.2 Novel tunable cw laser light sources based on OPO technology

Tunable frequency-converted CW OPOs

Recently commercialized tunable laser sources based on frequency converted CW optical parametric oscillator (OPO) technology gained market awareness as user friendly turn-key solutions providing utmost wavelength flexibility covering most of the visible wavelength range as well as long coherence length suitable for recording holograms and HOEs [4].

Operation principle

An OPO might be considered as a light source that delivers coherent radiation very much like a laser – but with two main differences between the devices [5]: First, the OPO principle is based on a process referred to as parametric amplification in a nonlinear optical material, rather than on stimulated emission in a particular gain medium. Second, OPOs require a coherent source of radiation as a pump source, unlike lasers, which might be pumped with either incoherent light sources or sources other than light.

The basic principle common to OPOs is illustrated in Figure 2 a. To put it simple, the OPO process can be perceived as splitting an incoming pump photon of high energy into two photons of lower energy, referred to as signal and idler photons, respectively. The conservation principles of photon energy and photon momentum (phase-matching condition) apply for the overall process, but it otherwise does not involve further fundamental restrictions, at least in theory. The huge potential of OPOs thus derives from their exceptional wavelength versatility, which is in principle not limited by the wavelength coverage dictated by the energy levels and suitable transitions in a laser gain medium.

The concept of OPO was experimentally demonstrated more than half a century ago [6]. But the development and commercialization of turn-key devices has been stalled substantially due to several technical obstacles. It has been easier to overcome these obstacles at the high peak powers of pulsed devices, and thus tunable OPOs operating in pulsed mode have become readily available from a variety of suppliers. Only recently there has been comparable progress in CW OPO technology, enabling the development of commercial tunable continuous-wave OPO systems [4, 7].

The increasing availability of cost-effective, high-performance CW pump lasers in combination with the emergence of new nonlinear crystal materials and designs have mainly driven this progress in CW OPO technology. The requirements for operation of OPOs on potential light sources for pumping are quite demanding in terms of preferential single-mode operation, noise characteristics, beam quality, and beam-pointing stability. Depending on power requirements, the end user can typically utilize either high-performance, diode-pumped solid-state (DPSS) lasers (for lower powers) or fiber-laser-based solutions (for higher powers). The advent of high-quality quasi-phase-matched nonlinear materials, such as periodically poled lithium niobate (LiNbO3), whose crystal structure alters with a certain periodicity, have been very useful for the design of practical optical parametric devices.

The optical concept of a commercially available tunable CW OPO [4], designed to cover the visible range, is illustrated in Figure 2 b. The operational principle is based on a cascaded sequence of nonlinear optical processes within two cavities, referred to as OPO and SHG (second-harmonic generation).

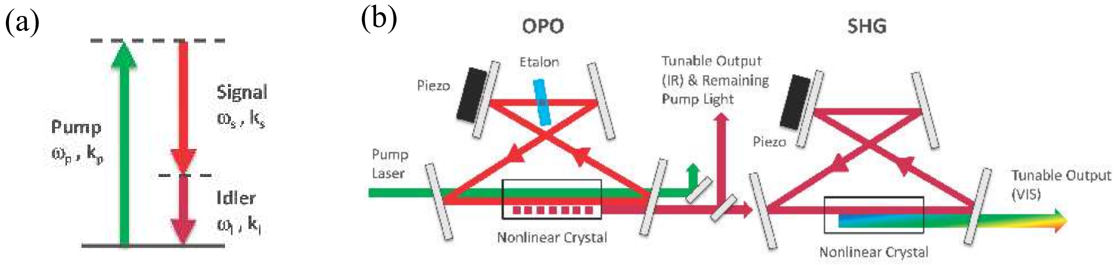

Figure 2: (a) Schematic of the parametric process in OPOs. The process can be perceived as the splitting of an incoming pump photon of high energy into two photons of lower energy (typically denoted as signal and idler). (b) Schematic beam path inside a commercial CW OPO system (see reference [7]). In a first step (OPO), a 532-nm laser pumps a nonlinear crystal to generate signal and idler photons (900 to 1300 nm). Wavelength selection and subsequent second-harmonic generation (SHG) converts either signal or idler photons into the visible range of the spectrum - 450 to 650 nm. Pump laser beam (green arrow); signal beam (dark red); idler beam (arbitrary assignment, light red). (co Hübner Photonics).

In a first step pump laser photons are split into pairs of photons of lower energy - signal and idler (Fig 2 a). For a particular operational wavelength, the OPO cavity is operated “on resonance” at either a particular signal wavelength or a particular idler wavelength (singly resonant OPO design, Fig 2 b). Broad wavelength coverage of the system is ensured by using a precisely moveable stack of periodically poled nonlinear crystals - for a particular wavelength selection, a crystal layer with a suitable poling is automatically selected, and its poling period further adjusted through a temperature-control loop. Simultaneously, the effective OPO cavity length is actively stabilized to a multiple integer of the selected operational wavelength.

While one of the generated (signal or idler) waves is circulating resonantly inside the OPO cavity, its counterpart can be extracted for wavelength conversion into the visible by another nonlinear process – the second-harmonic generation (SHG) process (Fig 2 b). The SHG takes place in a second, separate cavity by frequency doubling the primary OPO cavity output. It should be noted that this configuration is technically practicable and provides favorable operational stability, even though alternative designs, such as intracavity frequency doubling, have been successfully demonstrated in the lab [5, 6, 7, 8].

The system described above delivers high quality CW output with typical narrow linewidths of <500 kHz corresponding to typical coherence lengths well above 100 m throughout both the visible and the near infrared tuning range. An integrated Pound-Drever-Hall (PDH) frequency stabilization scheme leads to a long-term frequency stability of <150 MHz over hours being routinely achieved at typical lab conditions. For applications with highest demands, the performance characteristics can be even further improved by operating the system in closed-loop mode, i.e. in conjunction with an external wavelength measurement device (wave meter) and an optionally available software package. The achievable long-term stability essentially is given by the measurement resolution of the external wave meter device itself (Fig 3).

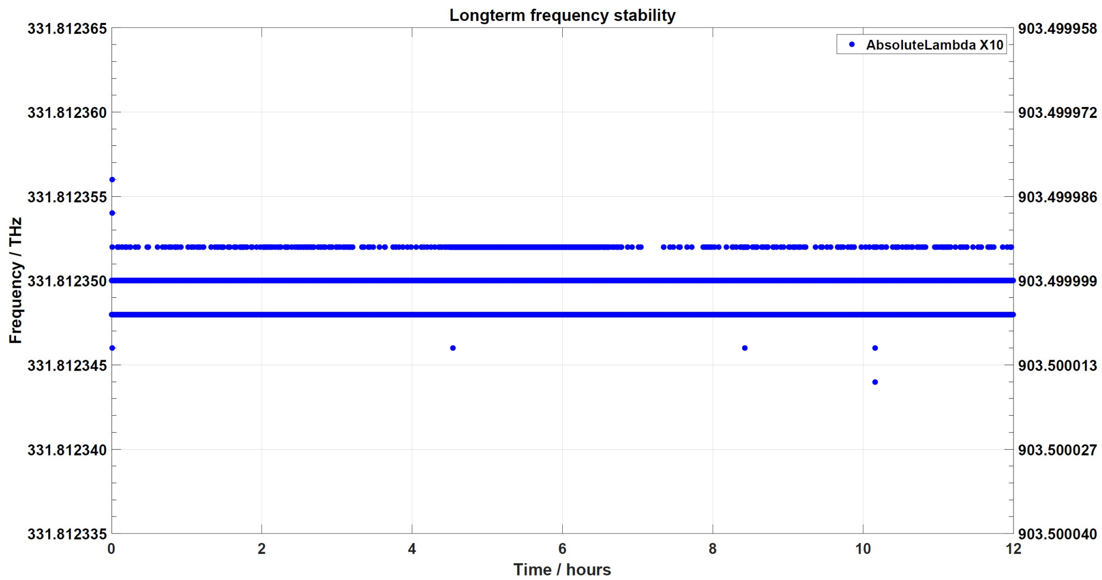

Figure 3: Long-term frequency stability of the CW OPO output in closed-loop operation. Employing a software module in conjunction with a high performance wavemeter, a frequency stability of ±2 MHz over hours is achieved.

Benefit for holography

The unique design of a CW OPO as described above means that any wavelength in the range 450 nm – 650 nm (however there is degeneracy at the pump wavelength) can be accessed from a single laser unit with powers up to half watt level. In addition to this the tunable infrared output (900 nm – 1300 nm) as well as the remaining pump laser light at 532 nm is accessible simultaneously. The flexibility in wavelength selection that this offers can allow for complete customization of the writing wavelength, making the hologram more difficult to copy and thus extremely attractive for security applications. Being able to match recording and replay wavelengths by using a tunable CW OPO, allow for new flexibility and new approaches to make complex holograms or HOEs at improved quality. Shrinking effects of polymer films, which gain more and more importance in mass production of holograms and HOEs, as well as angular dependencies, which can be different between recording and replay of a hologram, can be compensated by detuning the recording wavelength on purpose when using a tunable laser light source, allowing for complex holographic applications, related to virtual reality and augmented reality. Alternatively, the wavelength flexibility can act as a complementary 4^{th} or 5^{th} wavelength in RGB pallet of fixed wavelengths for the creation of ultimate replication white light holograms i.e. in documentation of artefacts. This additional 4^{th} or 5^{th} wavelength can be used to highlight the color unique of that artefact. Using a proprietary silver halide material in combination with a tunable OPO has proven to achieve diffraction efficiencies of 80% [9]. The good linewidth intrinsically provided by the OPO cavity design (< 500 kHz) resulting in a several hundred meters coherence length is useful, as it allows flexibility in setting up complex holographic setups.

4. CONCLUSION

Beside fixed wavelength lasers, being either diode pumped lasers, frequency stabilized diode lasers, and frequency converted fiber lasers, either operating CW or pulsed, also recently commercially available tunable CW OPOs can be used for writing holograms and holographic optical elements (HOEs). By far the most important performance characteristic required is long coherence length, which can be provided by the types of laser light sources mentioned above. Additionally, good power stability, wavelength accuracy and stability and last but not least excellent reliability need to be considered when selecting a laser for holographic applications. Tunable CW OPO systems that recently got commercially available can contribute substantially to new flexibility in holographic designs for emerging applications, such as production of optical elements for AR and VR devices, and help in general to improve the flexibility and quality when recording holograms or HOEs.

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