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Abstract. A one-step digital holographic printing system based on RGB pulsed-laser technology is described. The system is capable of writing full-color composite digital reflection holograms and composite digital holographic optical elements up to a size of 1.0 m × 1.5 m at hogel sizes ranging from 0.4 to 2 mm. We also show how the same pulsed-laser technology may be used to generate fast high-quality copies of such holograms. Both silver halide and photopolymer materials are used. [DOI: 10.1117/1.3596182]

Subject terms: holography; digital holographic printing; pulsed lasers; three-dimensional printing; digital holograms; hogels; holopixels; computer generated holograms.

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1 Introduction

The technique of computer-generated holography (CGH), wherein a holographic interference pattern is calculated numerically and then written onto a substrate via lithography, is well-suited to the production of small digital transmission holograms and holographic optical elements (HOE) but represents a poor choice for the generation of large reflection holograms. This is primarily due to the fundamental volume nature of the reflection grating.

A viable alternative to CGH for writing digital reflection holograms was developed in the 1990s by several groups, most notably that of Yamagushi et al.[1] This was the technique of direct write digital holography (DWDH), wherein the holographic substrate was divided into a matrix of small holographic pixels ("hogels"[2] or "holopixels"[3]) each of which was then recorded using a compact object and reference beam. Klug et al.,[4] working at the Zebra Imaging (Austin, Texas, USA), extended the technique in the late 1990s to large-format full-color reflection holography. Brotherton-Ratcliffe et al.[3,5] and Rodin et al.,[6] while working at Geola (Vilnius, Lithuania) in 1999, then demonstrated that the technique could be made to work much faster and more reliably using pulsed RGB lasers.

During the last decade, pulsed-laser DWDH has been developed and used commercially by several companies, most notably the Geola group, XYZ Imaging Inc. [(Montreal, Quebec, Canada), now Rabbitholes Media Inc.], and Zebra Imaging Inc. More recently, a dual-mode printer capable of writing holograms under both DWDH and CGH has been described by Kang et al.[7] In 2009, a pulsed-laser DWDH system was also developed allowing the rapid generation of erasable digital holograms on photorefractive polymer.[8]

During the past decade and a half, there has been considerable work on developing the materials appropriate for DWDH. Zebra Imaging Inc. initially used Dupont's color photopolymer material.[4] In the early 2000s, a consortium comprising the Lithuanian company, Geola; the Russian company, Sfera-S (Pereslavl, Zalessky, Russia); and the Canadian company, XYZ Imaging, developed a special ultrafine-grain panchromatic silver halide material that was optimized for use with pulsed RGB lasers.[9,10] Gentet,[11] working in France, also developed a similar silver halide material, as did Petrova et al.,[12] working in Bulgaria. The European Framework 6 project *SilverCross* brought many of the European teams together to successfully develop the Silver Cross panchromatic ultrafine-grain silver halide material.[13] Finally, Bayer has recently developed a new panchromatic photopolymer material.[14]

2 Printer Overview

Figures 1 and 2 show photographs of a first full-color digital holographic printing system constructed by our group (completed in 2001). The printer was designed to print reflection holograms onto glass plates (coated with a silver halide emulsion) up to a size of 800 × 800 mm at a speed of 15 RGB hogels/s using a pulsed RGB laser emitting beams at three primary wavelengths (660, 526, and 440 nm). The printer comprised three optical writing heads, one for each primary color. These writing heads form the three object beams that are focused to the writing positions of the red, green, and blue hogels on the holographic plate. Three reference beams are brought to bear from the other side of the plate to these same locations, thus forming the interference pattern characteristic of each hogel. Figure 3 shows the optical scheme of the printer.

The printer is controlled by a Dell precision workstation 530 computer with twin Intel Xeon 1.4-GHz processors, Matrix Millenium G450 graphics card, an SCSI Raid HDD of 160 MB, a further SCSI HDD of 73.4 GB, and 1 GB of RDRAM running on MS Windows 2000 Professional. An XVGA video signal connects the computer to a video splitter. This splitter drives a display monitor in addition to a CRI graphics controller card, which feeds three Sony XGA1 1064 × 768 LCD panels for object beam data encoding.

The mechanical plate stage comprises a vertical translator and a horizontal translator. The vertical translator consists of an LF6 200-mm wide rail from Isel and a 16 × 5 ball screw spindle motor with gearbox (Shrittmotorantiesbstmodule 2430 Ncm, Amph Z-Achse, Dir.Antrieb m.Bef.Flan.ZF3 reicht). The horizontal translator comprises an Isel LF4

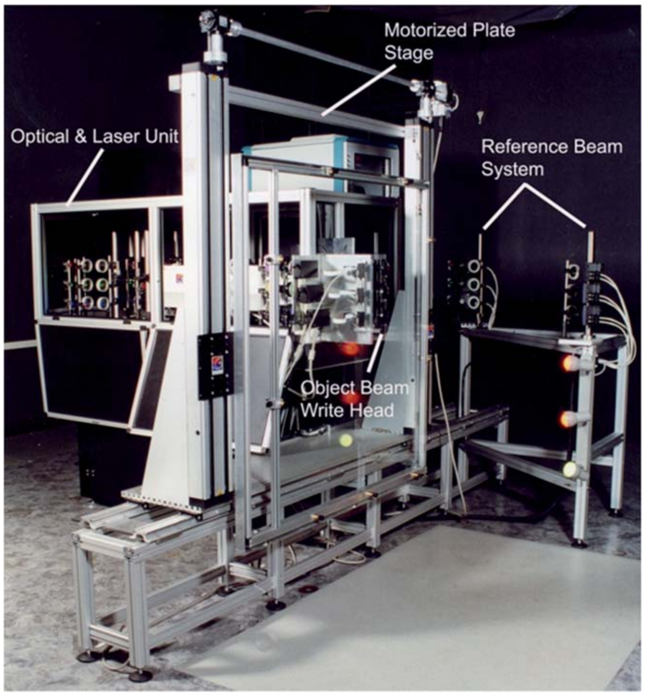


Fig. 1 Image of first RGB pulsed-laser printer produced by our group. Glass plates coated with silver halide emulsion up to a format of 80×80 cm are loaded into the motorized plate stage. The hologram is written by the sequential movement of the stage in front of the static writing head.

rail with 16×5 ball screw MS160 spindle motor. A master microprocessor-based controller controls triggering of both laser and stage motion.

Horizontal-parallax-only (HPO) holograms are created using perspective view information, which is generated either from a camera mounted on a special rail (see Fig. 4) or through commercially available computer modeling programs. The perspective information is uploaded to the control computer via a 1-GB Intranet service, where it is queued for processing. Computer software is based on a ".com" architecture and comprises two main modules. The first module—the receiver file manager (RFM)—deals with the queuing of jobs for processing. It also undertakes the pixel-swapping algorithms, optical distortion algorithms, and γ corrections required to convert the perspective view data to the actual data required by the LCDs. The output of the RFM is a folder containing the compressed LCD data files for each line in the hologram and a command sequence for every motor control required for the setup and printing of the hologram. The mathematical algorithms required for the distortion and pixel-swapping routines have been reported elsewhere.[15] The second software module is the printing and machine control, which controls printer operation, manages the print queue, and prints each hologram using the data generated by the RFM.

Fig. 2 Image of printer showing detail of object-beam write head assembly, reference beam system, and printer control rack.

2.1 *Optical Scheme*

The majority of the object beam and reference beam preparation optics are mounted on a 1.8×1.0 m enclosed optical table. Virtually identical optical systems for red, green, and blue light are mounted one on top of the other as shown in Fig. 5.

A set of three half-waveplates mounted in three precision rotation stages driven by stepper motors are used in conjunction with a set of three thin-film polarizers to control the output energy of the laser. The splitting ratios between object and reference beams are likewise controlled by a second set of motor-controlled waveplates and polarizers. Three fast electromechanical shutters are used within the laser to block emission when required.

The object beam system comprises a system for controlling the angular source size of the laser beam, LCD for encoding image information onto the beam, and a high-numerical-aperture lens system for forming the hogel. The control of angular source size is accomplished by (*i*) a telescope and motor-selectable aperture, (*ii*) a microlens array, and (*iii*) a collimating lens. The aperture plane and holographic film plane are chosen to be conjugate such that the shape of the aperture (usually square) determines the footprint of the hogel in a 1:1 manor. XGA1 LCD panels from Sony are used for image encoding. The high angle numerical aperture lens system has a diagonal field of view of ∼105 deg.[16] All aberrations apart from the fifth coefficient are effectively negligible. Correction for the intrinsic barrel distortion of the fifth coefficient is affected through software.

The reference beam system consists of a tilted aperture that is soft-imaged onto the holographic film surface defining the reference beam footprint (usually square and just a little larger than the object beam footprint). High spatial frequencies are subtracted using a pinhole within the imaging optics.

2.2 *Pulsed Red-Green-Blue Laser*

The printer was initially based on a twin ring-cavity passively Q-switched flash-lamp pumped neodymium yttrium lithium fluoride/neodymium yttrium aluminium garnet (Nd:YLF/Nd:YAG) pulsed RGB laser. The laser produced highly coherent red (659.5 nm), green (526.5 nm), and blue (439.6 nm) TEM00-like emissions of, respectively, 1.8, 3.4, and 1.6 mJ each at pulsed durations of 45 ns (green) and 60 ns (red and blue). The laser maximum repetition rate was 15 Hz. Figure 6 shows a drawing of the laser showing the layout of optomechanical components.

The first resonator, which is used for green light generation, is defined by two rear high-reflection mirrors M1g and M2g and a meniscus output coupler M5g. The active

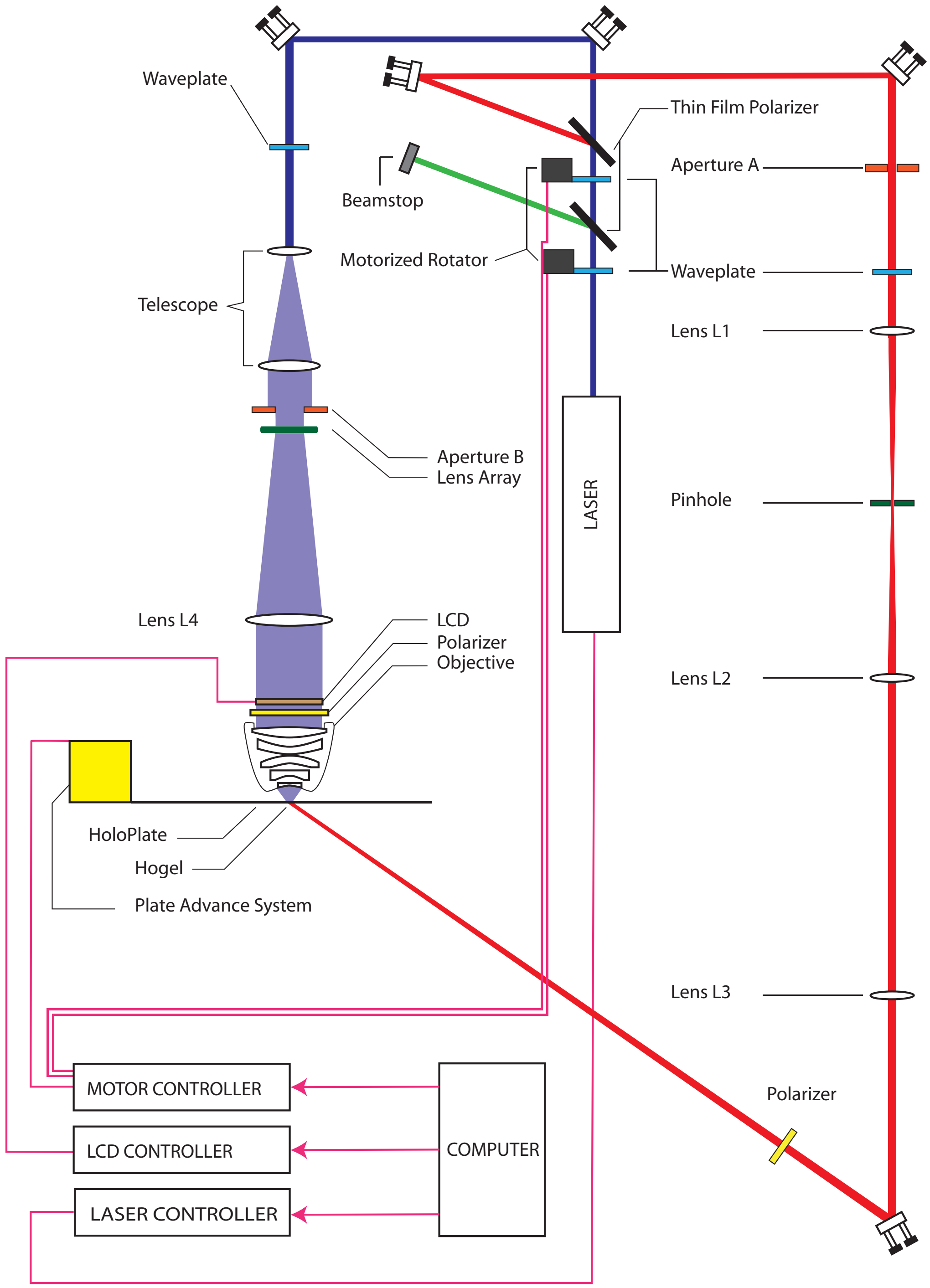


Fig. 3 Optical printer scheme for one color. Three such identical schemes exist for the three primary colors.

element (MOg) comprises a cylindrical Nd:YLF crystal with a 1% doping level lasing at 1053 nm. The crystal is bevelled at each end by 3 deg and is pumped by a 75-mm xenon flash lamp, Samarium filters and ceramic reflectors housed in a custom pump chamber. Giant pulse operation is assured by a Cr:YAG passive Q-switch (Qg) with initial transmission of 47%. TEM00 oscillation is assured by a 2.7-mm intracavity aperture A1g. The Dove prism DPg is used to improve horizontal stabilization of the vertical ring cavity. Unidirectional lasing is likewise arranged by a Faraday rotator FRg and waveplate WP1g. Single longitudinal mode (SLM) operation requires the use of two etalons: TE1g, an air-spaced etalon with FSR 3.26 GHz, and TE2g, an air-spaced etalon with FSR 50 GHz. Frequency conversion to 526.5 nm is assured by an oven-mounted potassium titanyl phosphate (KTP) crystal NCg with waveplate WP2g as required for type II phase matching.

The second resonator, which is used for red and blue light generation, is defined by the two rear high-reflection mirrors M1r and M2r and a meniscus output coupler M5r. The active element (MOr) comprises a cylindrical Nd:YAG crystal with a 1% doping level lasing at 1319 nm. The crystal is

Fig. 4 Commercial HoloCam System: A rotating digital camera mounted on a translating rail records several hundred to several thousand high-resolution images of the scene to be converted to an HPO hologram.

bevelled at each end by 3 deg and is pumped by a 75-mm xenon flash lamp, Samarium filters, and ceramic reflectors housed in a custom pump chamber. Giant pulse operation is assured by a V:YAG passive Q-switch (Qr) with initial transmission of 53%. TEM00 oscillation is assured by a 2.7-mm intracavity aperture A1r. The Dove prism (DPr) is used to improve horizontal stabilization of the vertical ring cavity. Unidirectional lasing is arranged by a return mirror MRr and by the Faraday rotator (FRr) and waveplate WP1r. SLM operation requires, as with the green resonator, the use of two etalons: TE1r (a quartz etalon) and TE2g (an air-spaced etalon with FSR 96 GHz). The polarizer (Pr) selects the correct cavity polarization. Frequency conversion to 659.5 nm is assured by an oven-mounted KTP crystal NC1r. The red and infrared signals are then combined in an lithium triborate crystal NC2r, where third harmonic generation produces emission at 439.6 nm. An image of the laser is shown in Fig. 7.

2.3 *Second-Generation Laser*

In order to improve the stability and repetition rate of the pulsed RGB laser source, a second-generation pulsed RGB

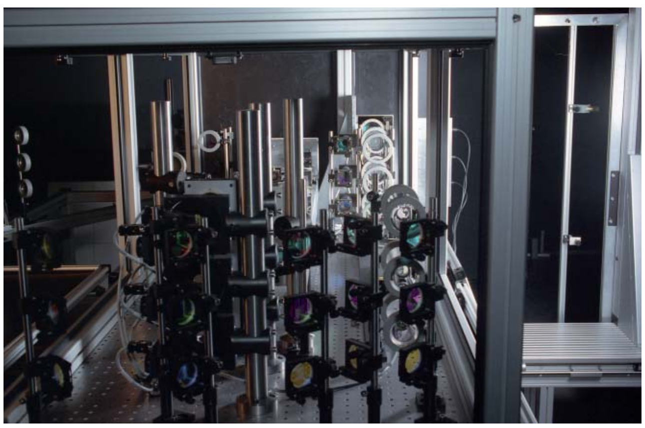


Fig. 5 Optical system of printer showing the stacking of similar optical components for each primary color.

laser was designed (see Figs. 8 and 9). This laser (the first prototype of which was produced in 2004) is based on twin linear Nd:YAG resonators and replaces the passive Q-switching at 1.3 μm by Co:MALO. Output is at 532 nm (6 mJ/35 ns), 659.5 nm (4 mJ/50 ns), and 438.6 nm (2.8 mJ/50 ns). The laser also incorporates electronic feedback of the cavity length in order to stabilize both frequency and pulse energy output.[17] Usual operation is at 30 Hz, but stable operation has been tested to 50 Hz. With appropriate pump chambers, operation should be possible with the same design at up to 120 Hz.

The laser consists of two channels. One channel (the G channel) generates 1064 nm laser light; green light (532 nm) is achieved after frequency conversion. Another channel (the $R + B$ channel) generates 1319 nm laser light; red (660 nm) and blue (440 nm) are achieved after second harmonic generation (SHG) and third harmonic generation (THG).

The optical schemes of the 1064- and 1319-nm channels are nearly identical to each other, except the position of the passive Q-switch is different. For briefness, we will describe only the 1319-nm channel in detail.

The linear cavity master oscillator of the 1319-nm channel is built using a two-mirror scheme—an output coupler M1r and high reflectivity mirror M2r. A Nd:YAG laser rod is inserted into a pump chamber with close-coupled diffuse reflector and pumped by a xenon-filled linear flashlamp. The close-coupled diffuse reflector provides uniform rod pumping and UV filtration. Transverse mode selection and thermal lens compensation is provided by an intracavity telescope (lens L1r and L2r). This telescope also helps to shorten the cavity length and increase the TEM00 mode size several times inside the Nd:YAG active rod (MOr) so that it can produce a high-output energy at low pumping level. SLM generation is achieved by the use of two etalons (TE1r and TE2r), a passive Q-switch (Qr), which is placed between the intracavity telescope (while in the 1064-nm channel, the passive Q-switch is placed near output coupler) and a rear cavity mirror operating with active feedback. To improve single longitudinal mode stability, the etalon (TE2r) is placed in a temperature-controlled oven. In addition, two quarter-wave plates (WP1r and Wp2r) are used to avoid spatial hole burning in the Nd:YAG laser rod and to improve the longitudinal mode selection.

In the 1319-nm channel, the output energy and pulse duration can be changed by moving the position of the Q-switch (Qr). The master-oscillator generates horizontally polarized output pulses [determined by polarizer (Pr) and quarter waveplate TE2r] with an energy of ~20 mJ and a pulse duration of ~70 ns; while in the G channel, fundamental output is ~13 mJ with a pulse duration of ~45 ns. The beam shutter (SHTr) provides reliable blocking of the laser beam and ensures the safe operation.

The output beam from the output coupler is reflected by a 45-deg mirror (M3r) before passing through an antireflection-coated window to reach another 45-deg mirror (M4r). A photodiode captures the reflected beam, providing information about pulse shape and output energy; these are used for active feedback control and monitoring.

The half-waveplate after the mirror M4r changes the horizontally polarized output beam by 45 deg, which is necessary for SHG conversion. The negative lens L3r and positive lens L4r together form a telescope for beam condensation, which allows high conversion efficiency in the SHG and THG crystals.

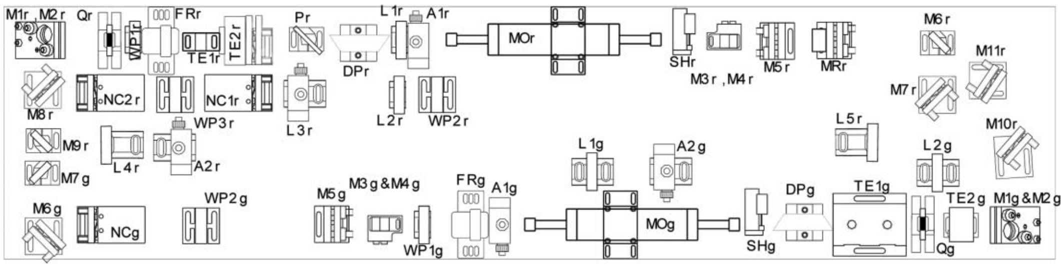


Fig. 6 First-generation dual-ring cavity pulsed RGB laser producing nanosecond emissions in red, green, and blue.

The SHG crystal is a type II [1319(e) + 1319(o) $\rightarrow$ 660(e)], noncritical temperature phase-matching crystal, whose phase-matching temperature for 1319 nm is $\sim$42°C. The crystal is cut along the Z-axis ($\theta = 0$ deg, $\varphi = 0$ deg). Because of the absence of walk-off effects in noncritical phase matching, it is possible to use a longer crystal to achieve higher conversion efficiency. In our case, the crystal is purposely placed with its SHG beam (660 nm) horizontally polarized.

The THG crystal is a type I [1319(o) + 660(o)$\rightarrow$440(e)], phase-matching crystal, whose phase-matching angle is ($\theta = 90$ deg, $\varphi = 21.1$ deg). In this case, the THG beam (440 nm) is vertically polarized. The ratio of blue (440 nm) and red (660 nm) beam output energy can be adjusted by slightly rotating the half-waveplate WP3r.

Directly after the nonlinear crystals, the fundamental, red, and blue beams are mixed together. The red beam is separated out and magnified by beam splitter M5r&M6r and telescope L5r&L6r, while the blue one is treated by M7r&M8r and L5r&L7r. The remaining fundamental beam is dumped by beam diffuser Mrs.

The optical scheme of the G channel is almost the same as the R + B channel, except the position of passive Q-switch is different, and only one nonlinear crystal is used for frequency conversion. A KTP type II phase-matching crystal is employed to convert the 1064 nm infrared laser light into green light.

2.4 *Improvements to Printer*

The printer design described above has been used by XYZ Imaging Inc. as a basis to produce a commercial digital holographic printer (Fig. 10). In this commercial printer, the glass stage has been replaced with a film advance system and the Sony LCDs have been updated to Sony LCX028ALT panels mounted in ovens to assure operation at 30 Hz. A number of such systems are now in commercial operation (e.g., see Refs. 19–21).

2.5 *Printed Holograms and Holographic Optical Elements*

Since its development in 2003, we have written DWDH holograms onto the panchromatic PFG03CN silver halide material produced by Sfera-S. The high stability of the pulsed-laser technology described above allows the routine printing of high-quality large holograms and holographic optical elements onto glass or film at hogel sizes from 0.4 mm to >2 mm. The holograms are free from "bad" hogels, even in relatively noisy operational conditions. This is of course in complete contrast to CW-based printing systems, where the slightest environmental noise leads to a substandard hologram. Figure 11 shows an example of a large-format HPO hologram produced at our labs at a hogel size of 0.8 mm. The perspective view data have been generated by computer. Figure 12 shows an example of an HPO hologram produced by a camera-on-a-rail or Holocam system. In addition to image holograms, high-quality digital HOEs have been produced for autostereoscopic real-time 3-D displays.[18]

2.6 *Finer Hogel Resolution*

Smaller DWDH holograms require smaller hogel sizes. The printer technology described here has no problem in coping reliably with hogels down to 0.4 mm diam. Figure 13 shows a hologram of 0.4 mm hogel size and a zoom of the actual hogels. Figure 14 shows zoomed hogels of 1.6 mm for comparison.

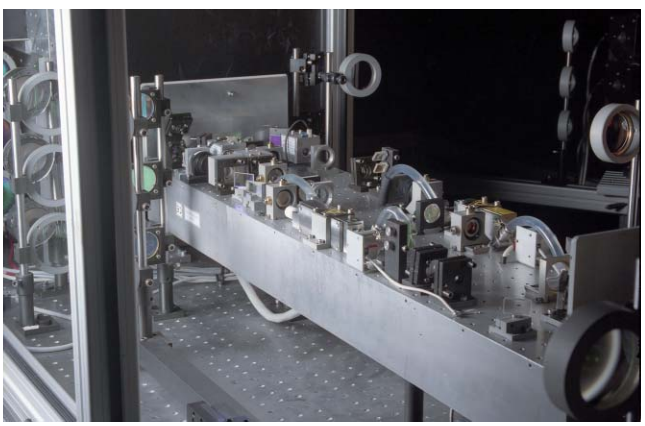


Fig. 7 Image of first-generation pulsed RGB laser based on twin-ring cavities using Nd:YLF and Nd:YAG.

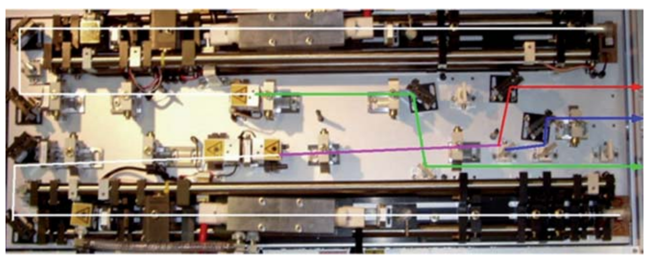


Fig. 8 Image of second-generation pulsed RGB laser based on twin super-invar linear cavities using Nd:YAG. Infrared beam-paths are marked in white. Arrows represent red (top), blue (center) and green (bottom) emissions. (Color online only.)

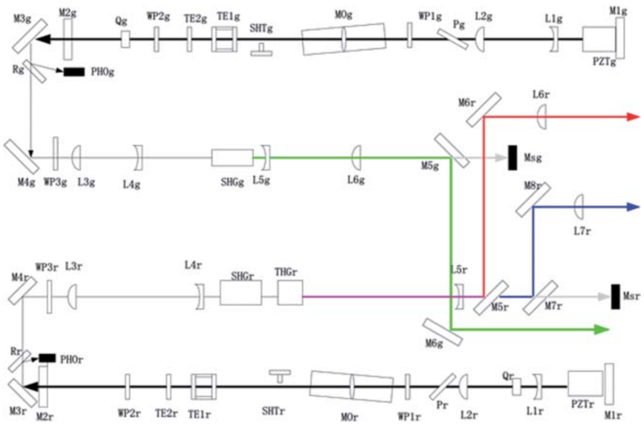


Fig. 9 Optical scheme of the second-generation RGB pulsed laser.

2.7 *Full Parallax Holograms*

HPO holograms can be produced easily from perspective data generated by Holocam systems or computer design programs. HPO holograms are also desirable on many occasions for large displays because, often, the vertical parallax is not so obviously perceived. However, for smaller holograms and for many types of HOEs, full parallax is essential. Full-parallax images do however require much more processing. Computational image planing of the perspective data generated by commercial design programs is also costly in resources. For example, using the optical parameters of our printer at a maximum field of view, a 1×1 m HPO hologram at hogel size 1 mm requires an uncompressed memory storage of 3.6 GB. At full parallax, this increases to 4.3 TB. One solution is to use in-house render packages or to use configurable real-time renderers designed for the games industry in order to circumvent the need of a computationally changing the image plane; but the fact remains that the best quality renders are often only available from commercial render engines designed for the high-end imaging markets and TV/cinema—and these generate data that require memory-intensive computational image planing. In order to effect this image processing in a reasonable time, we use a farm of eight PCs. Computational image planing must be treated by splitting the problem into sections (usually lines) because, even with modern computers, it is not possible to load the whole problem into memory at the same time. One application for full-parallax holograms is 3-D maps. To the unaided eye, a full-parallax full-color reflection hologram made with a 0.4-mm hogel is fairly in-

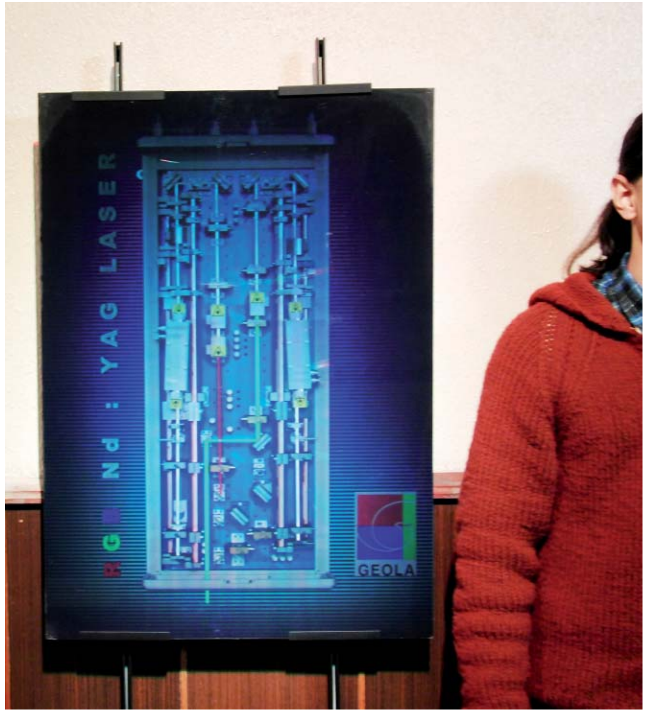
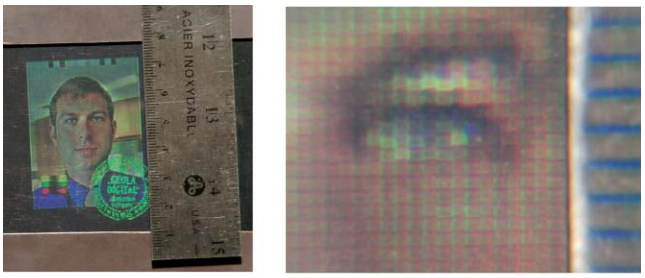


Fig. 11 Example of a large-format DWDH hologram. The hogel size is 0.8 mm, and the image has been generated entirely by computer from the original 3-D design drawing of the second-generation laser described previously.

Fig. 10 Commercial digital holographic printer produced by XYZ Imaging Inc. This printer, modeled closely after the printer in Fig. 1, comprises a second-generation pulsed RGB laser manufactured by Geola Technologies Ltd. and is capable of a print speed of 30 RGB hogels/s onto silver halide film.

Fig. 12 DWDH hologram with 1.6 mm hogel. Image produced by a Geola commercial Holocam system.



(a) (b)

Fig. 13 (a) A 0.4-mm hogel DWDH hologram 5 cm high with (b) zoomed detail of component hogels.

distinguishable from a real analog hologram under similar lighting conditions.

2.8 *Copy Holograms*

Even at a printing speed of 30 RGB hogels/s, a 1×1 m 0.8-mm hogel hologram requires >10 h to print. For the technology to become commercially interesting, one either needs to increase the laser and print speed dramatically or one needs a technique to copy the holograms produced. Print speed may realistically be increased by a certain amount. Our pulsed-laser systems can be redesigned to work at up to 120 Hz with flash pumping. Beyond that, diode-pumped laser solutions may be expected to produce repetition rates of, really, as high as required. However, SLM technology does not at this moment exist to practically produce a printer with a repetition rate of >200 hogels/s. To go faster than this requires multiple write heads, which, although possible, will increase the price point of any printer rather dramatically.

Here, we present results of recent experiments (2006–2010) that we have carried out to produce high-quality holographic copies of digital master holograms produced by our digital holographic printing technology. We use the same second-generation RGB pulsed laser to accomplish such copying. Figure 15 shows the optical scheme of an experimental copier, and Fig. 16 shows the copier apparatus. The master hologram must be processed in a special way. This is because the maximum replay wavelengths of the master hologram must match the exposing laser wavelengths.

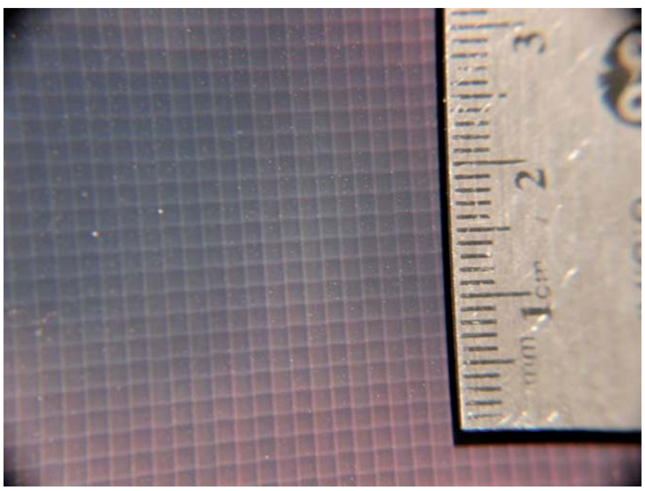


Fig. 14 Zoomed image of 1.6-mm hogels.

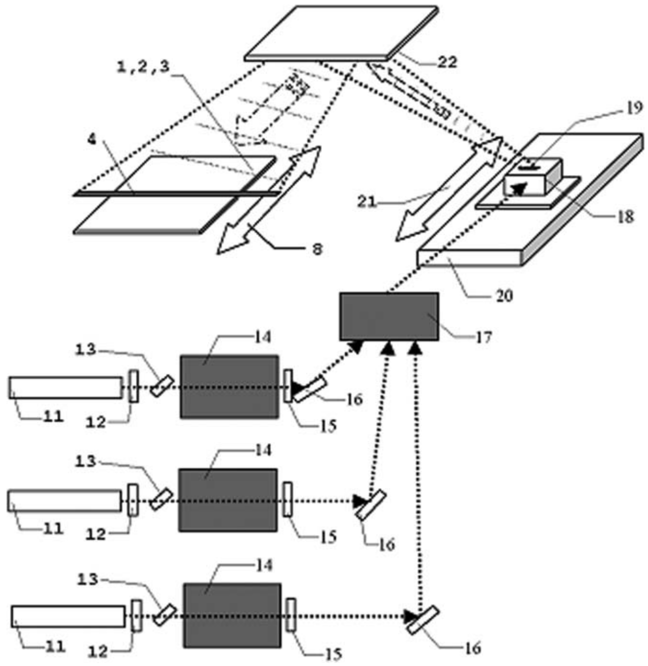


Fig. 15 Optical scheme of hologram copier.

With reference to Fig. 15, each of the beams (11) passes computer-controlled wave plates (12) and polarizers (13). By rotating the waveplates (12), we adjust the desired color balance of the hologram copy. Afterward, the beams are then cleaned with spatial filters (14). The polarization correctors (15) compensate the polarization. Then the beams are directed by the mirrors (16) to a three-color combiner-deflector (17). Next, the beams are shaped by the shaping/deflection system (18). This system forms the white beam into the shape of a narrow elongated oval slit. This beam is then reflected by the flat mirror (22), where it illuminates the nonexposed light-sensitive material (1) as a reference beam. Part of the beam is however transmitted through the material and onto the master hologram, where it generates a diffractive reflection forming the object beam.

The zone illuminated by the laser beam slit (4) is transverse to the scanning movement of the slit. The laser radiation shaping/deflection system (18) is fixed on the computer-

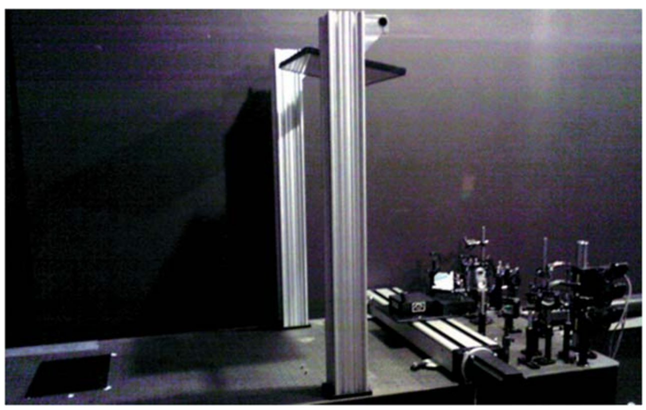


Fig. 16 Copier apparatus. The copy and master plates are visible to the left. The RGB pulsed laser is mounted on a separate optical table.

Fig. 17 (a) Master hologram 0.8-mm hogel 20×30 cm, (b) three-color copy on PFG03CN silver halide, and (c) three-color copy on photopolymer.

controlled translation motion mover (20), which assures its even movement in direction (21). At the same time, the translation motion mover (20) assures the coherent light radiation movement in direction (8), which is perpendicular to the projection of the coherent lighting beam that illuminates the master hologram. This assures the even exposure of nonexposed light-sensitive material and master hologram, causing the even recording of the reconstructed master hologram data.

Our experimental results show that existing silver halide photoemulsions (we have tried both PFG-03CN from Sfera-S and the SilverCross emulsion) do not allow the production of full-color contact copies having a diffraction efficiency greater than the diffraction efficiency of the master hologram. The best result that we have been able to achieve is a color copy with a relative diffraction efficiency of (as a percentage of the master diffraction efficiency) 100% in red and green and 50% in blue. Nevertheless, the quality and brightness obtained are still clearly adequate for commercialization. In addition, this situation should be improved by using different silver halide photoemulsions, which we hope will be developed in the near future. We observe that if the copy is made only with two colors, its diffraction efficiency can reach 150% of the master hologram efficiency (using AgX).

Panchromatic photopolymer material from Bayer was also used to record high-quality copy holograms. Relative diffraction efficiencies in red and green of well over 100% were obtained. Figures 17(a)–17(c) show the experimental results. We are currently scaling up our tests to record meter-by-meter size copy holograms with time scales of several minutes.

3 Conclusions

A digital holographic printing system and a rapid holographic copying system, both based on unique RGB pulsed-laser technology, have been described. High-quality highly diffractive large-format, full-color "spot-matrix" composite digital reflection holograms have been written with hogel diameters ranging from 0.4 to >2 mm. The speed of printing appears clearly superior to CW solutions. In addition, printing with a pulsed laser is insensitive to environmental noise, making commercial operations realistically possible. High-quality HOEs have also been printed for autostereoscopic real-time 3-D displays. Copying with the same pulsed RGB laser technology demonstrates that a commercial copy quality can be attained on both existing silver halide emulsions and existing photopolymer materials.

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