"Large Format Digital Colour Holograms Produced using RGB Pulsed Laser Technology"

Abstract

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RGB Pulsed laser technology provides a natural way to circumvent the problems of vibration inherent in conventional CW holographic printer schemes. Using such technology we have been able to print 1-step dot-matrix digital holograms at speeds of up to 50 RGB colour pixels per second in relatively compact printer configurations. Typical hologram pixel sizes that have been employed are around 1mm diameter. Both full parallax and single parallax digital reflection holograms have been generated in this way with sizes of up to 1m x 1.5m. RGB transmission rainbow holograms have also been generated using this approach. Quicker generation of digital holograms is possible using a variety of 2-step pulsed laser printer schemes, the simplest of which consists of the contact or close copying of an original master dot-matrix hologram that has been specially processed. Other 2-step techniques such as H1:H2 schemes have required more powerful RGB pulsed lasers and yet have shown their capability of producing one-off smaller format holograms at high speed.

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1.0 Introduction

Current pulsed-laser digital holographic printers operated by Geola Group and XYZ Imaging Inc use LCD panels to encode digital data onto the printer's object beam. These panels are relatively slow, limiting the print speed to 30 RGB holopixels per second, and have small optical efficiency.

The lack of optical efficiency inherent to LCD panels leads to an energy requirement for holographic printers that has been historically catered for by the use of red, green and blue pulsed lasers that are based on relatively long laser cavities with lamp-pumped Nd:YAG crystals [1]. Despite the use of active feedback techniques [2,3,4] to tune these long laser cavities and to maintain energy stability within acceptable limits, experience has painfully shown that printer stability remains extremely critical due to the use of long-cavity laser technology. In our opinion the use of long-cavity lasers fundamentally limits the current generation of digital hologram printers to use in highly controlled environments.

More recently high resolution LCOS reflective panels have been replacing transmissive LCD panels in the projector market. Commercially available LCOS panels have typical optical efficiencies over 70% and have much improved switching times.

We will show that the incorporation of LCOS technology into a digital holographic printer allows much higher print speeds to be attained (theoretically up to 200 RGB holopixels per second with current LCOS technology). Additionally short-cavity as opposed to long-cavity pulsed laser technology may now be used: appropriate short-cavity red, green and blue pulsed lasers have much better stability characteristics and are cheaper and more compact than their long-cavity counterparts. Such lasers are also easier to operate at higher print speeds.

Initial experiments [5,6] also show that compact diode-pumped short-cavity pulsed lasers may also be used in an LCOS based RGB printer design. Although early days, our initial design calculations show that a fast desktop printer is now really possible using this design.

We also report the results of our latest research [6] concerning the generation of copy holograms by red, green and blue pulsed lasers from a tuned RGB digital reflection master hologram. Recent commercial response to the marketing of digital holograms has unequivocally shown that in order to attain a mass-market, large quantities of identical holograms must be available quickly and at a low price point. Despite the advances with LCOS technology, 1-step printers can never reasonably hope to meet these criteria. We demonstrate however that extremely fast copying by pulsed laser of a tuned RGB reflection master hologram is now a definite reality.

2.0 1 and 2-step Digital Holographic Printers

The design of most 1 and 2-step digital holographic printers is very similar. In a 1-step printer a two dimensional matrix of small juxtaposed holographic pixels (typically of the order of 1mm diameter each) is written onto a photosensitive film. Each such holographic pixel is written by highly coherent laser radiation that has been split into red, green and blue digitally encoded object beams and corresponding collimated reference beams. 1-step printers can produce both reflection and transmission holograms of horizontal only (HPO) or double parallax. The largest market for 1-step digital holograms appears to be reflective. In the case of 1-step digital rainbow transmission holograms only one wavelength of laser is required.

A 2-step printer consists of a master printer and a copier. The master printer is in almost all cases extremely similar to a standard 1-step printer. A variety of different types of copiers exist however and each may require slightly different data transformations to be employed in the master printer.

Copiers can be divided into contact copiers, small-distance copiers [9] and full-aperture copiers [1]. Contact copiers generally use a colour-tuned reflective master and generate the copy hologram by line-scanning or zone-scanning a sandwich consisting of the master hologram and a photosensitive film, with low energy red, green and blue laser emissions.

Small-distance copiers copy a master hologram onto a blank photosensitive film situated at a distance of typically a few centimeters distance using intermediate energy lasers. Finally full aperture copiers use high energy lasers to copy a master hologram in a single laser pulse.

3.0 The Case for Using Pulsed Lasers

Making 1–step digital holograms or digital holographic masters entails the recording of typically millions of small “holopixels” onto a photosensitive film in an ordered two-dimensional matrix. These holopixels must be recorded with complex object and reference beams that must be formed using a physically large optical scheme typically covering an area of several square meters. The fact that so many holopixels must be written to make a single hologram means that the writing process must be fast. Current printers operated by Geola and XYZ Imaging Inc work at print speeds of between 15 and 30 RGB holopixels per second. The prototype printer that we shall describe below has the potential to work at up to 200 RGB holopixels per second.

Generally, as the write speed of a printer increases so does the mechanical vibration present in both the film and in the optical system. If CW lasers are to be used this means that the exposure time for each holopixel must be reduced rapidly with increasing print speed. This in turn means that higher and higher energy CW lasers must be employed and that a greater and greater percentage of the laser light must be discarded to attain a small enough exposure time. At larger print speeds this equation clearly gets rapidly out of hand even with the most powerful CW lasers available.

Pulsed lasers, on the other hand, can offer nanosecond exposure times without throwing away >99% of the laser energy. We therefore realized back in late 1990s that truly commercial digital holographic printers would have to be based on pulsed laser technology.

The pulsed laser equation is even more compelling for full-aperture copiers where CW exposure times would inevitably be much greater than those required by interferometric stability. In addition for contact copiers and small-distance copiers the availability of appropriately energetic lasers at the correct wavelengths favours a pulsed laser solution.

4.0 The Design of Current Printers

The detailed design of current 1-step and master holographic printers is described in two PCT patent applications [7,8]. Fig.1 depicts a simplified schematic diagram of a printer. Red, green and blue pulsed lasers are employed which typically each produce several millijoules of energyat respectively 660nm, 532nm and 440nm at a pulse duration of 35-50ns depending on design. The laser outputs are highly coherent single longitudinal mode emissions and spatial structure is TEM00. The three laser beams are each split into an object beam and a reference beam by a set of motorized half-waveplates paired with polarizing beamsplitters that are controlled by the system computer. The energy of each laser emission is likewise controlled internally by the same method. This allows the system computer to control and set automatically the beam energies and the beam ratios.

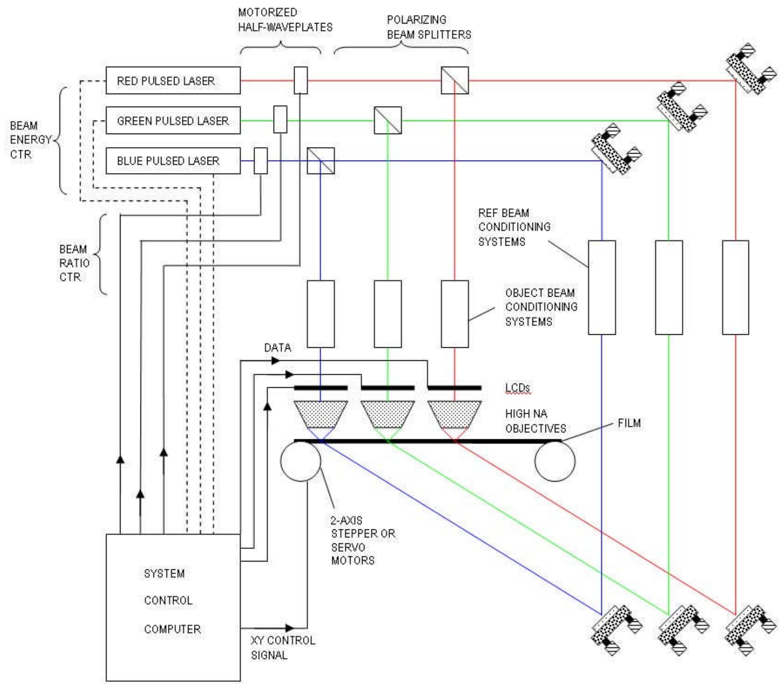


Fig.1 Simplified Schematic Diagram of a Current 1-step or Master Holographic Printer

Digital image data is encoded onto the object beams via transmissive LCD displays such as XGA1 panels from Sony. Prior to illumination of the LCD panels the object beam is conditioned by a system based on a 2D micro-lens array. By controlling an aperture directly in front of the micro-lens array differently shaped and sized holopixels may be created with ease. A correct choice of the characteristics of the micro-lens array and the associated optics is essential if a spatially uniform holopixel capable of replaying digital image data at high angular resolution is to be achieved.

Fig.2 The first RGB Pulsed-Laser Holographic Printer made by Geola in 2001

Three special high numerical aperture telecentric objectives, each having a diagonal field of view of typically 100 degrees, are used to focus down the three digitally encoded object beams to minimum beam waists which occur at or very near to the photosensitive film surface and whose footprints define the respective holopixel. The design of these objectives is such that a high quality image of each LCD is created at a distance downstream from the photosensitive film which corresponds usually to the hologram viewing distance*.

Each quasi-collimated reference beam is traditionally conditioned by a telescopic system that forms a soft image of an elliptical aperture at the photosensitive film surface. The elliptical aperture compensates for the typically 45 degree inclination of the reference beam to the film surface, thereby forming a soft circular

* the image plane of the LCD can be situated in general from the viewing plane to infinity.

footprint coincident to, and slightly larger than, the corresponding, normally square, object beam footprint.

The hologram is written when the photosensitive film or photosensitive glass plate is made to move horizontally at constant velocity as the lasers fire regularly. In this way a single line of juxtaposing holopixels are created. The film or plate is now made to move up vertically by the diameter of one holopixel and then the same process writes a second line in the inverse direction. This process continues until the hologram has been completely written row by row.

It is vitally important for the energy stability of the long-cavity pulsed lasers used in these printer designs to fire the lasers at the same repetition rate. Accordingly the velocity of the film movement must be rather constant. In addition it is necessary to synchronize properly the LCD write cycle.

5.0 The New Technology

5.1 Short-Cavity Pulsed Lasers for Digital Holography

Pulsed lasers built using long-cavities are relatively unstable because thermal and mechanical stresses are important over the dimensions of the cavity. It would therefore seem logical to construct shorter cavity lasers. There are two main problems with this idea however. The first is that the typical pulse durations of a shorter cavity will in general be shorter. This is a problem for digital holography because the panchromatic Silver Halide emulsion that we have developed produces better results at pulse durations greater than 35ns. The second problem is that inevitably the TEM00 mode volume of a shorter cavity laser will be smaller and so the output energy will be smaller. This is a problem because current pulsed-laser hologram printers use LCD panels which are relatively inefficient.

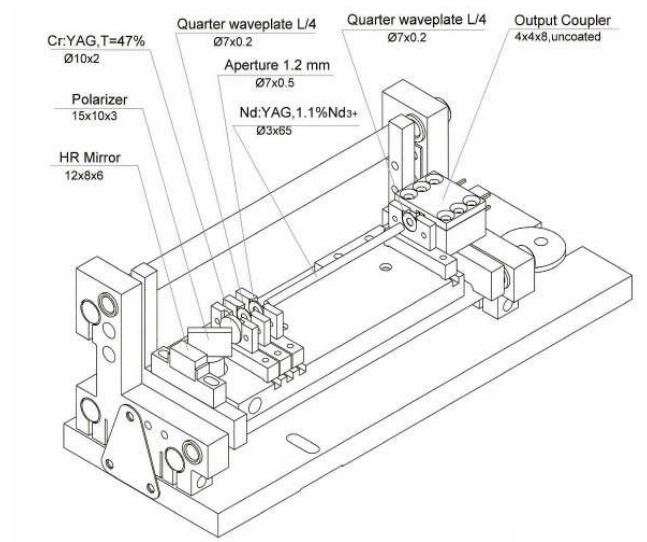


Fig.3 The 1064nm Short-Cavity Resonator

With this in mind we have investigated two types of lamp-pumped short-cavity Q-switched lasers. Both lasers use a linear resonator and Nd:YAG to produce an infrared TEM00 SLM emission. The first laser works at the usual 1064nm line of YAG and the second at the 1319nm line. Frequency doubling and tripling is used to produce a red emission at 660nm, a green emission at 532nm and a blue emission at 440nm. Our research in this field was supported by a UK government SMART award.

5.1.1 <u>Laser at 1064nm</u>

Fig.3 shows a diagram of a typical 1064nm laser resonator. A rear cavity mirror and resonant output coupler are held in L-shaped steel tilted mirror holders and mounted on super-Invar rods. Resonators of cavity lengths in the range of 128 ÷ 280mm were investigated.

Suspension of the cavity mirror holders using rigid flat springs on the rod structure allows precise X-Y alignment while isolating the sensitive resonator from baseplate temperature variations. A small stainless steel pump chamber (not shown) with diffuse ceramic reflector is mounted on a steel baseplate in-line with an intra-cavity aperture, a polarizer, 2 quarter-waveplates and a Cr:YAG passive Q-switch. The Nd:YAG active laser rod (3x65mm) is excited by a 5x45mm xenon-filled linear flashlamp with UV cut-off using Sm-doped glass. A laser power supply allowed the flashlamp operation with a repetition rate of 1 – 50Hz and a discharge energy up to 18J. The resonant output coupler comprised an uncoated parallel BK-7 glass plate in a temperature controlled oven (+/-0.01 deg C temperature stability).

With a short cavity length of 128mm we observed stable generation of TEM00 SLM output pulses with duration as short as only t = 13ns even with relatively large initial transmission Cr:YAG passive Q-switches (T = 45%). As mentioned above, it is known from earlier experiments that sensitivity and diffraction efficiency of ultra-fine grain silver halide materials have a strong decay at exposure times below 35ns. Therefore our main efforts were focused on finding experimental conditions required for stable generation of relatively long (> 40ns) pulses from the smallest length and, hence, potentially the most temperature stable and mechanically rigid laser cavity.

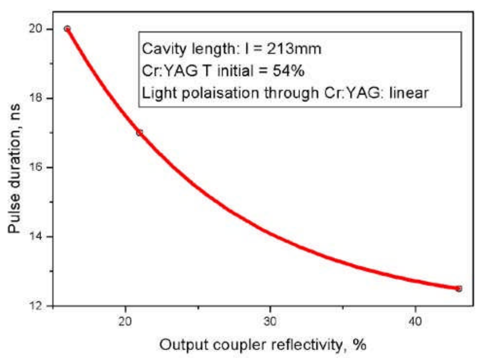


Fig. 4. Output laser pulse duration versus output coupler reflectivity for a cavity length of 213mm and a Cr:YAG initial transmission of 54%.

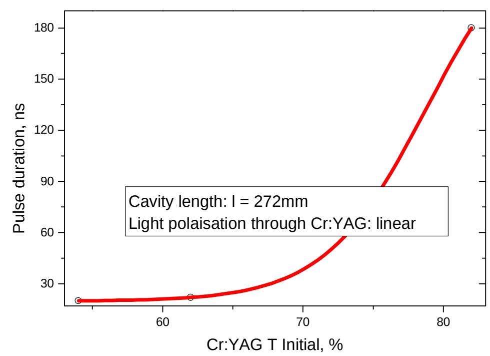


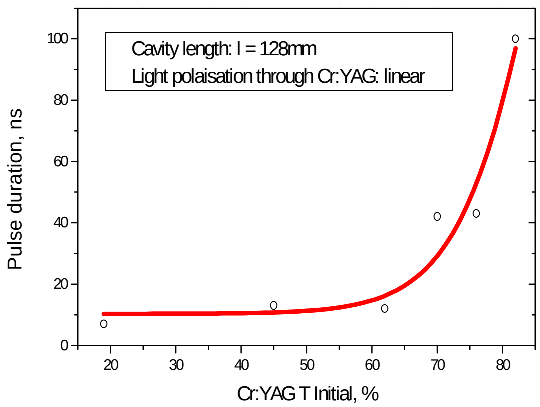
Fig. 5. Output pulse duration versus initial transmission of Cr:YAG Q-switch for a cavity length of 272mm.

Attempts to increase the reflectivity of the output coupler from 16% (uncoated) to 43% resulted in a decrease of the pulse duration even for relatively long cavities of 213mm length (Fig.4). The use of output couplers with a reflectivity less than 16%, in order to increase pulse-length, makes longitudinal mode suppression inefficient and SLM generation unstable. Higher initial transmission Q-switches lengthened the pulse duration as did a longer cavity length (Fig.5). We observed that a 2.1 times lengthening of the cavity leads to an increase of 1.8x in the pulse duration (~20ns) for an initial transmission of the Q-switch below 70%.

In Fig. 6 we show the output pulse durations (left) and energies (right) versus the initial transmission of the Cr:YAG Q-switch for the case of an uncoated output coupler and a resonator length of 128mm. The large point-to-point discrepancy of experimental points is due to different Q-switches manufacturers (GOI, StPetersburg, Russia; Castech and Coretech, China) having different levels of non-saturable losses. An optimum initial Q-switch transmission of 76% was identified that produced pulses of 43ns duration and ~ 1mJ output energy. We observed also that the pump energies required for reliable master oscillator operation over threshold are below 10J (475V; 40μF). This implies a very good flashlamp lifetime.

We observed that Q-switches with initial transmission of higher than 82% cannot ensure stable single pulse generation. Increasing by only ~ 10V the flashlamp discharge voltage results in the generation of a second pulse following the first with a delay of approximately ~ 10 – 20 μsec. By further increasing the voltage, pulse trains may be generated. In such a case it is difficult to define the excess voltage over threshold required for reliable single-pulse operation of a flashlamp pumped system. However this observation leads to the potential construction of SLM pulse train lasers that may be useful in digital holographic printers that use photopolymer materials that are not sensitive to a single pulse in the nanosecond regime.

With a given initial transmission of the passive Q-switch, the output pulse duration is defined by its contrast. It is known that the contrast of Cr:YAG Q-switches is lower for incident light that is circularly polarized. It is therefore reasonable to change the position of a quarter wave-plate with the Q-switch crystal so as to assure that circularly polarized light is present in this crystal. This was tested initially for a Cr:YAG crystal with an initial transmission of 62% and the shortest cavity length of 128mm. An increase of ~1.7 x in the output pulse duration was observed: from 12ns 20ns. Further experiments used Q-switches with relatively large initial transmission (70 – 82%) and produced stable pulses of long duration.



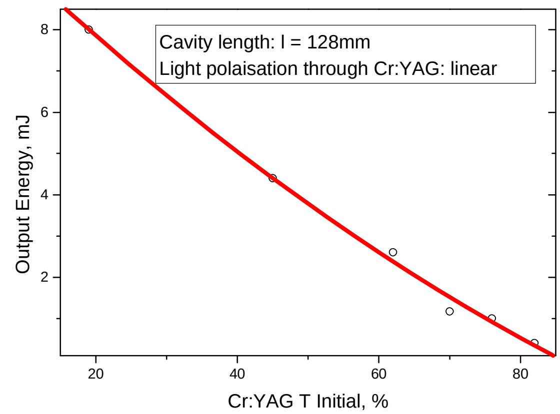
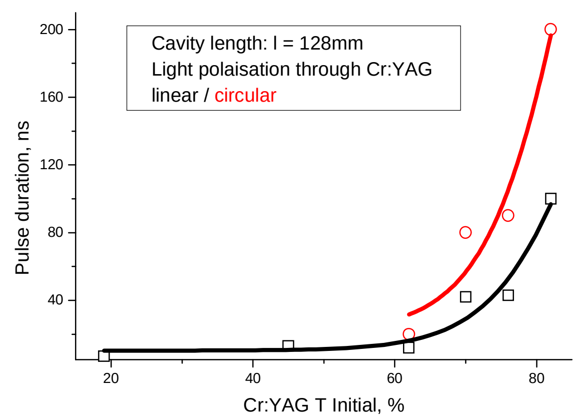


Fig. 6. Output pulse durations (left) and energies (right) versus initial transmission of the Cr:YAG passive Q-switch.

It was found that the use of circularly polarized light allows us more freedom in attaining longer pulses. These results are depicted in Fig. 7 together with results achieved with conventional linear polarization. Pulse durations as long as 200ns were achieved for Cr:YAG with 82% initial transmission with output energies ~ 0.35mJ.

Fig.7 Output pulse durations versus the initial transmission of Cr:YAG passive Q-switch for linear (black) and circular (red) incident laser light.



By temperature stabilization of the output coupler we have found that a 128mm resonator exhibits very good longitudinal mode and energy stability; the laser will operate at the same longitudinal mode for many tens of thousands of pulses. To increase this stability we have enclosed the entire resonator in a close-fitting metallic cover. We have then mounted approximately 15 miniature electrical temperature controllers in an even pattern over this cover. The controllers measure the temperature at a point and control it to a preset level to an accuracy of +/-0.01 °C. In this way the resonator is closely and completely surrounded by a surface on which the temperature is constant at every point irrespective of the ambient laboratory temperature. This leads to a very stable temperature in the volume surrounding the resonator.

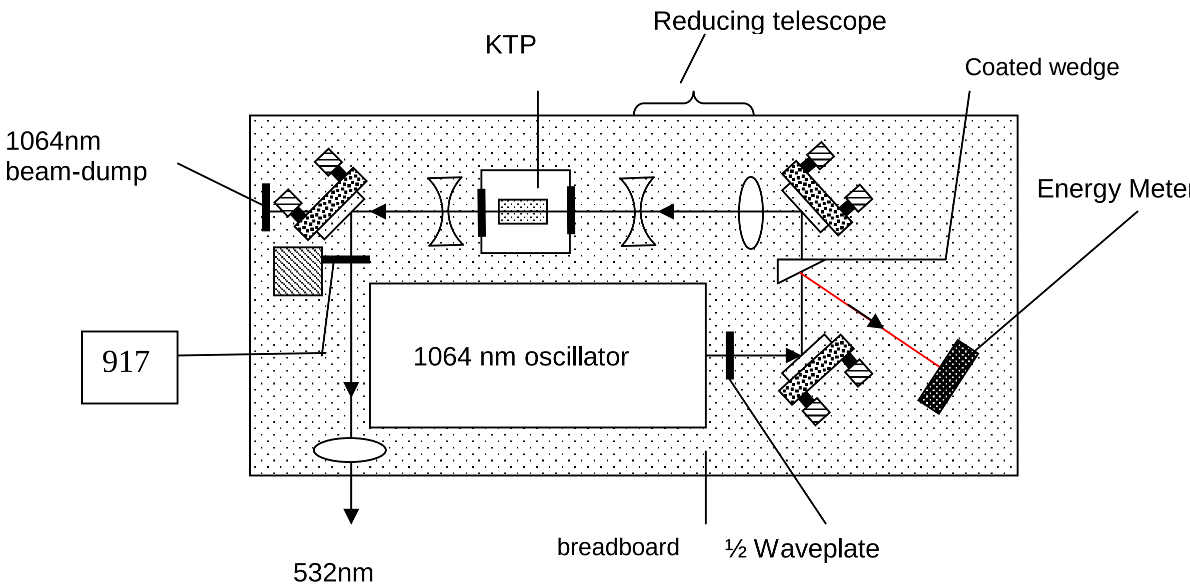


Fig.8 Schematic for a short-cavity lamp-pumped 532nm Laser

To further stabilize the resonator we employ a thermally heated rear mirror mount that can be used to control the cavity length via computer. By measuring standard deviation of the laser energy emitted and scanning the rear-mirror temperature we are able to set a cavity length every few days that is exactly matched to a given longitudinal mode. Under these conditions we have achieved stable lasing at the same longitudinal mode for many tens of millions of pulses. Peak-to-Peak energy stabilities of less than +/-3.5% for 100 million pulses have been achieved.

In order to make a green laser emitting at 532nm a small type II KTP crystal mounted in an oven maintained at 35.4°C is used. The schematic for a 532nm laser is shown in Fig.8. Typical output characteristics are an energy of 400µJ at a pulse duration of 40ns and a repetition rate of up to 50Hz. Similar stability characteristics as those reported above for 1064nm are observed.

5.1.2 Laser at 1319nm

Exactly the same technique as we applied for 1064nm may be used to make a 1319nm laser. Instead of Cr:YAG we have used either a V:YAG crystal or a Co:MALO crystal. We use the same

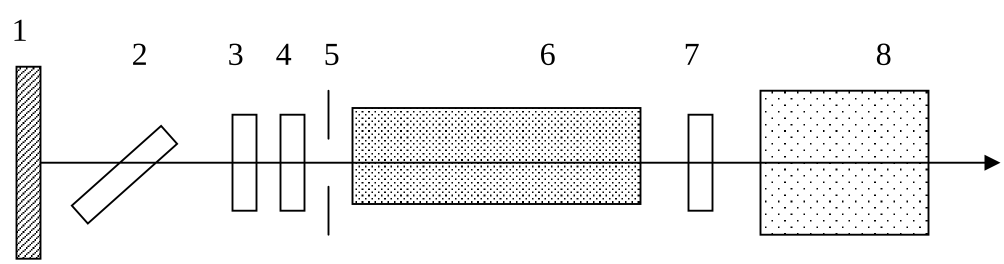


Fig. 9 1319nm Cavity Scheme : (1) HR Mirror, (2) *Polarizer, (3)* Co:MALO, T=80%, (4) Quarter waveplate L/4, (5) Aperture 1.0mm, (6) N d:YAG, Ø3×65mm, 1.1% Nd^{3+}*, (7)* Quarter waveplate L/4, (8) Output Coupler (Coated Etalon,6.5GHz, R=36%@1319nm) - Cavity Length: ~128mm/ Threshold: 1293V.

physical resonator as before and the same lamp power supply. Because of the lower gain of the 1319nm line a higher reflectivity tuned output coupler is used. Optics must generally be AR coated where appropriate for 1064nm as well as 1319nm. If this is not done then the more powerful 1064nm line may oscillate parasitically. The Nd:YAG rod is also cut at a 3° angle for the same reason. Finally it is important to use a relatively long pump pulse as a short pump pulse will favour the 1338nm line of Nd:YAG. Fig.9 shows an optimized resonator scheme for the 1319nm channel. As with the 1064nm laser we find that we may tune easily the output pulse duration by using different initial transmission Q-switches. For the optimum parameters of Fig.9 we obtain the an energy at 1319nm of ~1.2mJ at a pulse duration ranging between 40-48ns (depending on exact Q-switch). Typical energy stabilities for a resonator without active temperature stabilization of the laser cover or rear-mirror mount are RMS over 1000 pulses: 0.67%, PTP over 1000 pulses: 3.7%. With full temperature stabilization we again obtain single-mode highly-stable lasing for tens of millions of pulses.

In order to make a red laser emitting at 660nm a schematic identical to Fig.8 is used except that a type II LBO crystal replaces the KTP. Typical output characteristics are identical to the 532nm laser.

In order to make a blue laser emitting at 440nm we mix the red 660nm signal with the 1319nm signal in a type I LBO crystal using critical phase matching. This entails using two LBO crystals mounted very close to one another. Accordingly a very similar schematic to Fig.8 can also be used for a blue laser. Typical output characteristics for the blue laser are again very similar to the 660nm laser except that a smaller conversion efficiency limits the energy to typically 300µJ. Since a blue laser first entails the production of a red emission and then mixing this signal with the infrared, a blue laser will always produce a residual red signal. By adjusting the incident polarization to the non-linear conversion optics, a co-linear red-blue laser may be made with a variable red/blue ratio.

5.2 An improved Digital Holographic Printer

Fig.10 shows a schematic diagram of an improved fast digital holographic printer suitable for writing master or 1-step holograms holopixel by holopixel. This printer is based on 3 LCOS panels and red (660nm), green (532nm) and blue (440nm) short-cavity pulsed lasers as described above. For clarity Fig.10 only shows the printer schematic for a single colour laser emission. Since the printer schematic is the same for each three colours, only one colour has been shown. Physically the beam-paths for each three colours are stacked identically one on top of the other.

A small cavity TEM00 SLM laser (101) emits a pulsed laser beam (3mm diameter, 0.4mJ for 660nm) which traverses the motorized ½ waveplate 102. The laser beam then continues on to the Brewster-angle polarizer 104 where it is split into a reference and object beam. Further downstream two energy meters (147,145) measure the energies in these two beams. By activating the stepper motor 103 the system control computer can accurately control the reference beam energy.

5.2.1 <u>Object Beam Arm</u>

The object beam originates at the polarizer 104 and immediately traverses the ½ waveplate 120 which is controlled by the stepping motor 121. It then traverses the Brewster angle polarizer (down-facing) 148 where excess energy in the wrong polarization is dumped. The mirror 122 now guides the object beam onto a series of two mirrors (149,128) which are mounted on a precision translation stage 124. This stage is mounted on precision rails (126,127) and is controlled by the stepping motor 125. The system control computer can control the beam path length of the object beam by controlling this motor. As the rail moves back and forth the beam directions remain invariant but the beam path length changes. This allows the object and reference beam paths to be exactly matched.

The object beam is then reflected by the mirrors 128 and 129 before traversing a coated wedge 144. This wedge is cut at 10 degrees and its rear-surface is anti-reflection coated (660nm for red object beam, 440nm for blue object beam and 532nm for green object beam). The wedge allows most of the object beam to traverse it unchanged whilst reflecting a few percent to the GEM-SI-

7511 energy meter 145 (commercially available from Geola Group). This energy meter is calibrated to read the object beam energy and is connected via USB cable to the system control computer.

The object beam now continues to the aperture 130 and to a microlens array (131). The shape and size of the aperture determines the shape and size of the final holographic pixel (116). Usually a square shape is used. An aperture dimension of 9mm x 9mm corresponds in our printer to a holographic pixel size of 1mm x 1mm at the photosensitive film 117.

We have used various microlens arrays depending on the LCOS display panel used. For the BR768HC display panel (available from HOLOEYE and made by Brillian) we use a lens array of 50mm in diameter, made from BK7 (or K8) and containing rectangularly packed 0.2mmx0.23mm lenslets each with a radius of curvature of 0.65mm. On illumination by the squarely apodised object beam the lens array produces a beam of rectangular beam profile downstream. This profile is chosen (through the design of the lens array) to fit the LCOS display 137.

The object beam downstream of the lens array is conditioned by the lens(es) 146 and then reflected by the mirror 132 onto a McNeale type polarizing beamsplitter (139) whereupon the light is reflected and passes through a field curvature correction lens (138) to illuminate the small LCOS panel (137). We have used several panels but prefer the BR768HC panel which measures 17.91mm diagonal, has a 12 micron pixel pitch, a fill factor of 92%, a reflectivity of 71% and a frame rate of 120Hz.

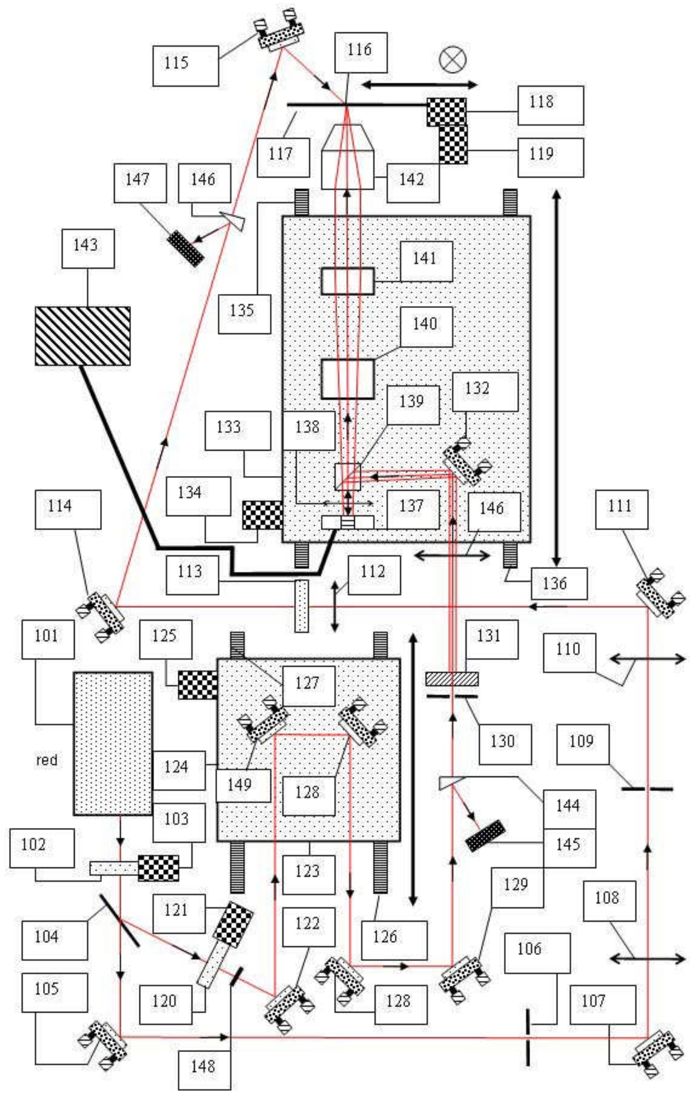


Fig.10. Holographic Printer based on LCOS and short-cavity laser technology

The object beam that is reflected from the LCOS panel is modulated by a digital image which is supplied by the system control computer and is derived from pixel-swapped image data.

The digital data is encoded onto the object beam by the LCOS panel as a phase modulation. When the object beam passes back through the McNeale polarizer (139) this phase modulation is converted to an amplitude modulation. This amplitude modulated object beam then passes through a special telecentric afocal reversing system (140, 141) before being “focused” to the holographic pixel (116) by the high numerical-aperture telecentric objective lens system having an FOV of greater than 100 degrees (142).

The LCOS panel (137), the field curvature correction lens (138), the telecentric afocal reversing system (140, 141), the McNeale polarizing cube (139) and the mirror 132 are all mounted on a precision translation stage (133) with rails 135 and 136, controlled by a stepper motor 134. The system control computer can use the motor 134 to adjust the distance at which a focused real image of the LCOS panel appears in space behind the photosensitive medium. This is usually chosen to correspond to the viewing distance of the hologram being printed.

A Proflux thin-wire polarizing beamsplitter can also be used instead of the McNeale type. We prefer the McNeale polarizers as they damage less easily.

5.2.2 Reference Beam Arm

The reference beam originates at the polarizer 104 and is reflected by the mirror 105 to the aperture 106. This aperture is generally elliptical. An image of this aperture is formed by the lens system comprising the lenses 108, 110 and 112 at the photosensitive film surface 116. Since the reference beam intersects the photosensitive film at an angle (usually close to 45 degrees) the final reference beam footprint is circular rather than elliptical.

The reference beam passing through the aperture 106 reflects off the mirror 108 and then passes through a small pinhole 109 (typically 0.2-0.8mm). This pinhole acts as a spatial filter and cleans up the beam. Note that the energy is so low that no electro-optical breakdown occurs. Since the pinhole removes high spatial frequencies it also softens the image of the aperture 106 at the film surface 116. In this way a nicely Gaussian circular reference beam is created at the holographic pixel location.

The reference beam continues to propagate from the pinhole (109) through the lens, 110. It is then reflected off the mirror 111 and traverses the lens 112. A polarizer 113 removes any unwanted polarization. The beam is then reflected off the mirror 114. A wedge 146 now reflects a few percent of the object beam back to a GEM-SI-7511 energy meter 147. This allows the system computer to monitor the reference beam energy. Note that the back side of the wedge is AR coated. The reference beam now continues on to the mirror 115 where it is reflected to intersect the photosensitive material 117 at the holographic pixel 116. The (usually) circular reference beam (301) is made to be a little larger than the (usually) square footprint (302) of the object beam at the photosensitive material surface. The centre axial rays of both the object and reference beams intersect at the surface of the photosensitive material.

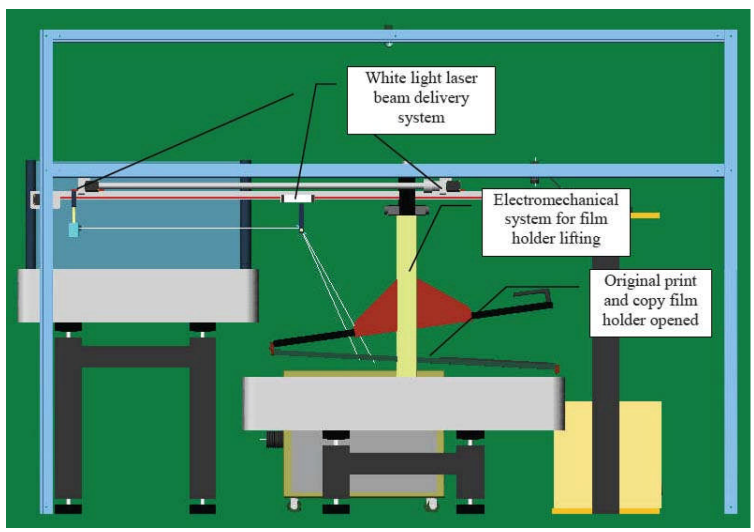


Fig.11. Spot-scanning Holographic Copier - Side View

5.2.3 Results

Using the above printer, we have printed high quality reflection holograms with holopixel sizes ranging from 0.25mm to 1mm on glass plates coated with the PFG-03CN emulsion at up to 50Hz. The limitation in speed is purely due to our control electronics, our laser power supplies, our laser pump chamber design and the large two-dimensional ISEL translation stage that we use for moving the photosensitive material. We have more than enough energy from our short-cavity lasers. It is clear that we can increase the print-speed to the LCOS panel limit of 120Hz. With the latest VAN LCOS panels commercially available from Sony, print speeds approaching 200Hz should be possible.

5.3 Creating the Holographic Copy

We have recently investigated two ways to copy a tuned RGB reflection master hologram. The first is by 2-dimensional spot scanning using a long-cavity RGB pulsed laser. The second is by line-scanning using the same laser. Of the two methods we find line scanning to be less operationally problematic although both methods are clearly capable of producing high quality copy holograms. The laser we have used produces TEM00 SLM emissions at 660nm (3mJ), 532nm (4mJ) and 440nm (2.5mJ) at repetition rates up to 30Hz at at pulse durations of around 40-50ns. Figs.11 and 12 show side and top illustrations of our spot-scanning set-up.

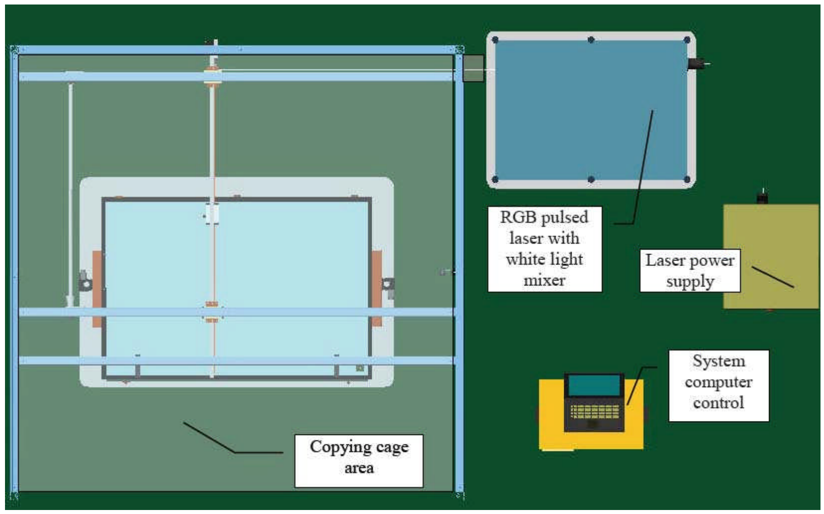


Fig.12. Spot-scanning Holographic Copier - Side View

So far our prototype copier can only copy holograms up to around 50x50cms. A tuned film RGB reflection master is placed on a heavy glass sheet attached to an optical vibration isolation table. The PFG03CN film to be copied is then placed on top and another heavy glass sheet (typical 10-15mm thick) is lowered onto the sandwich. An achromatic collimated laser beam having a circular footprint of a diameter of around 4cms is then made to scan the entire surface of the hologram sandwich in a 2-dimensional manner. The 2-D computer controlled servo-stage that moves the achromatic beam across the hologram surface is mounted on a platform independent of the film holder. In our line-scanning experiments we replaced the 2-D stage with a 1-D stage and used optics to form an appropriate thin collimated achromatic line beam. For the brightest results we find that there is an optimal pulse energy and overlap ratio. This means that at least several laser pulses are needed to achieve bright holograms at the reference/object ratios characteristic of contact copying using PFG03CN.

Since laser exposures are made to overlap considerably, the master hologram and unexposed film must not move relative to each other. In both spot and line scanning this criterion applies to neighboring lines. In line-scanning however the lines are much thinner (typically a few mm) for the same laser energy. Hence line-scanning is less sensitive to film movement and ambient vibration.

Typical copy-times using either spot or line-scanning for a 50x50cms hologram are under 10 minutes. Typical brightness and quality of the holograms are very similar to those of the master holograms.

One of the most difficult things that we have found with copying is the proper production of a tuned reflection master. Without this the copies are poor. In order to generate such tuned masters the humidity and temperature at the time of writing the master hologram must be precisely controlled and special attention must be taken with the chemistry. Normal 1-step reflection holograms naturally shrink by 20 to 30nm and although this makes them look brighter they are then useless for copying. We also find that being able to precisely adjust the humidity at the time of copy can help us to fine-tune the play-back signal. To optimize the final copy brightness appropriate chemistry must additionally be used so as to shrink the final copies to replay at 20-30 nm smaller wavelengths.

Geola hopes to be operating a commercial copier based on line-scanning and a long-cavity pulsed RGB laser by the time of publication. We are also working on an integrated 2-step printer in which the same short-cavity RGB pulsed laser used to generate a reflection master is also used to create a spot-scanned copy.

5.4 Amplification of RGB Laser Emissions

Amplified RGB emissions are useful for various types of holographic printer. In particular H1:H2 RGB reflection hologram printers require a full aperture copy to be generated. For A4 H2 formats single-colour pulse energies in the region of 250mJ are required with PFG03CN.

Green emissions of virtually any energy are available using lamp-pumped amplification of the 1064nm line employing Neodymium doped glass. In addition high energy emissions are also available using Nd:YAG amplification. High energy red and blue emissions are more difficult to obtain due to the intrinsic low gain of the 1319nm line in Nd:YAG (around 6 times lower than the 1064nm line).

We have performed extensive experiments with lamp-pumped amplification of 1319nm emissions from both short and long cavity 1319nm pulsed nanosecond lasers (TEM00 & SLM). We have used both 2-pass and 4-pass schemes with and without liquid SBS mirrors at repetition rates of up to 50Hz. Our results for amplification of emissions from short-cavity lasers are poor as the starting energy is too low. In particular, starting with a signal of 1.2mJ at 32ns we achieve only 8.5mJ after 2-pass amplification using 2 4mmx65mm Nd:YAG 1.1% doped rods in series with maximum pumping levels. Using a 4-pass scheme with the same two amplifiers we achieve 18mJ at 40ns. At these energies all liquid mirrors that we tried were below threshold.

Amplification of long-cavity 1319nm emissions (17mJ at 50ns TEM00, SLM, 30Hz) has been much more successful. At these energies, using a single 6mmx100mm Nd:YAG rod doped at 1.1% and 2-pass amplification with a $SiCl_4$ liquid mirror we attain 50mJ with a very acceptable beam profile. Typical reflectivity of the SBS mirror is 60% and we attain a 1-pass gain of 2.4x. Amplification with 2 amplifiers of 4mmx100mm in series instead of the previous one amplifier gives a 100mJ signal of good profile. Without SBS mirrors we have achieved over 150mJ using a 2-pass telescopic scheme with one 4mmx100mm amplifier and one 6mmx100mm in series. However in this case the beam profile is unacceptably bad.

It is now very clear how to scale this technology up. 250mJ emissions at 660nm and 440nm should be possible using two slightly larger 2-pass amplifiers, each with SBS mirrors. We are also currently looking at 4-pass amplification again in the context of long-cavity lasers: starting with a higher energy allows one to achieve threshold in an SBS mirror after the first stage of amplification; the hope is that SBS 4-pass schemes may then be able to produce a higher energy more efficiently and with an acceptable profile. Whether this turns out to be true or not we shall report at the conference.

6.0 References

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