7

Digital Colour Holography

7.1 Introduction

The earliest approach to "digital holography" sought to calculate numerically the complex wave front scattered by a virtual object [1,2]. By combining this wave front with a virtual reference beam, the resultant interference pattern could be calculated within a given medium. From the mid-1960s onwards, researchers used a combination of printing and photographic reduction methods to produce crude synthetic holograms from such calculated patterns. The technique of numerically synthesising and then physically encoding the interference pattern corresponding to a virtual object has today come to be known as computer-generated holography (CGH). The availability of comparatively cheap computational power has led to CGH now being used routinely to record high-quality transmission holographic gratings encoding either image or non-image data using electron beam lithography. Modern techniques allow the mass replication of such gratings for applications such as holographic security features and holographic optical elements (HOEs).

CGH is ideally suited to transmission holography because, in this case, the holographic information contained in the interference pattern is essentially two-dimensional (2D) in nature. In contrast, reflection holography intrinsically requires three-dimensional (3D) information; as such, no commercially realistic solution exists today for writing CGH data in the form of a reflection hologram. We have, however, seen in the preceding chapters that reflection holography is far more suited than transmission holography for the task of recording and playback of high-fidelity, distortion-free full-colour images. Historically, this led researchers to look for an alternative technique for digital holography: one that would be more naturally suited to the creation of reflection gratings.

7.2 Holographic Stereograms

As early as 1967, Pole [3] had been working on a technique that was rather different from CGH. In Pole's experiments, he was able to create a crude reflection hologram based on multiple photographs. It was intrinsically a two-step process: first, a 2D matrix of small lenslets was used to image photographs of an object taken from many different horizontal and vertical perspectives. The second step was an optical transfer of the lenslet matrix to a reflection hologram. Upon viewing this reflection hologram, the eye coincided with a virtual image of the lenslets and a 3D effect was perceived. Pole reported that the resulting "holographic stereograms" exhibited full three-dimensionality, exactly like ordinary holograms, but that the large inactive area between the lenslets caused image degradation akin to viewing an ordinary hologram through a coarse grid structure. He concluded that the optimum lenslet size would be equal to the diameter of the human eye so as to best accommodate the compromise of sampling and depth of field inherent to the new display.

In 1969, DeBitetto [4] reported an alternative system in which a masked holographic plate was sequentially exposed to different perspective view images.* This solved the resolution problem inherent in Pole's work, as with a contact aperture, the holographic exposures could be spaced with virtually no inactive area between them. Subsequent work by King et al. [5] reported the production of a white

* The images were projected with laser light onto a diffusive screen in front of the masked holographic plate.

light-viewable image plane hologram (an H_2) from a DeBitetto type (H_1) master. However, because the sequential exposure of the component holograms of a DeBitetto type H_1 required much more recording time than Pole's technique, the vertical parallax information was discarded, thus reducing the number of necessary exposures.

During the 1970s, Lloyd Cross [6] and others, inspired by the invention of the rainbow hologram [7], tackled the problem of generating holographic stereograms in yet another way. Here, transmission holography was used to produce bright rainbow holograms (without vertical parallax) using large cylindrical lenses for recording and cylindrical films for display. However, this type of system, although popular for a time, proved ultimately to be rather inferior to the DeBitetto/King approach.

By the early 1990s, most large stereograms had therefore started to be recorded as reflection holograms using the DeBitetto/King model. In 1991, Walter Spierings and his company, the Dutch Holographic Company B.V. introduced the first full-colour reflection stereograms [8] (see Chapter 1, Figure 1.45).* Although impressive, these holograms were still derived from analogue photographic data. The transition to digital data, however, was already starting. Stephen Benton and his group at the Massachusetts Institute of Technology were probably the earliest workers in this field—and certainly the most influential. In 1991, Halle et al. [9] described the ultragram. The invention allowed one to record a two-step holographic stereogram with an arbitrary transfer distance. This was the first use of digital image distortion techniques and provided a clear reason for going "fully digital". The advent of digital cameras and cheap spatial light modulators in recent years has only reinforced this doctrine. The original DeBitetto/King model is still used successfully today to produce full-colour horizontal parallax reflective holographic stereograms from digital camera or computer data.

7.3 One-Step Digital Holograms

With the advent of digital spatial light modulators (SLMs), a different avenue became available to create a high-resolution reflection hologram from computer or camera data. This was one-step or direct-write digital holography (DWDH). In analogue holography, an interference pattern is created by the superposition of the wave fronts of an object and reference wave within a photosensitive plate or film. CGH seeks to synthesise this pattern numerically. However, suppose that instead of calculating such a global interference pattern all at once, one breaks down the problem into writing only a small element of a hologram at a time. In other words, we consider the required hologram as being composed of a plurality of small microholograms arranged in the form of an (x, y) grid. The problem now reduces to writing sequentially each such microhologram. Of course, we could still calculate the interference pattern of each such microhologram via the methods of CGH and write them using electron beam lithography. However, with the advent of liquid crystal displays (LCDs), a far simpler solution became possible: a reference and object beam could be made to intersect at the surface of a photosensitive material to directly create the microhologram. The object beam is encoded with image data by being made to pass through a spatial light modulator such as a LCD and a lens system. A step-and-repeat mechanism then writes a plurality of juxtaposed microholograms (these came to be known as holographic pixels or hogels [10]).

There are many advantages to DWDH. The first and most evident is that, unlike CGH, it lends itself naturally to colour reflection holography; by using three or more laser wavelengths, full-colour reflective hogels can be written at the same physical location. The spatial frequencies within the hogels are indeed very large, but by using the natural interference process to generate each hogel, one is freed from having to use costly techniques such as electron beam lithography to attain the required high spatial resolution. Because the hogel is inevitably chosen to be small (usually in the range of 0.1 mm diameter to several millimetres) only small lasers are potentially required.

In fact, it turns out that depending on what image data is recorded, master holograms can also be generated in this fashion, hogel by hogel. These holograms can then be optically transferred to an H_2. When this is done, the technique is known as master-write digital holography (MWDH). MWDH is effectively

* These types of holograms were generated in a two-step H_1:H_2 process. The H_1 was made by laser projection of multiple analogue camera perspectives onto a diffusion screen—this process came to be known as MPGH.

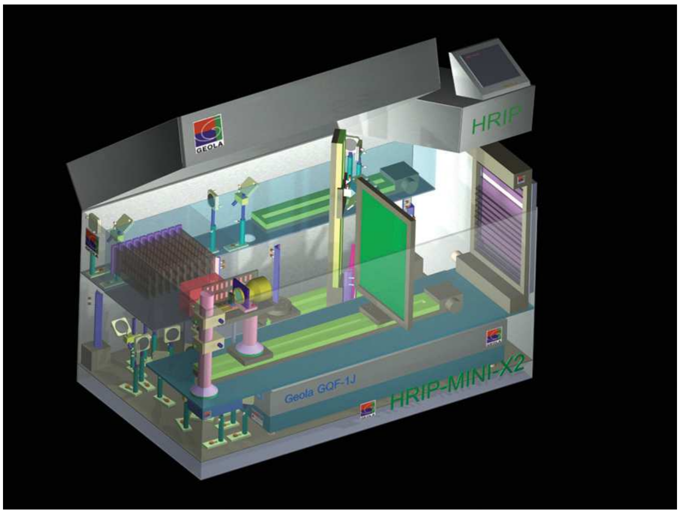

FIGURE 7.1 Early concept design (circa late 1990s) of a digital multiple photo-generated holography printer from Geola.

a DeBitetto/King full-parallax H_1 with a small square or hexagonal aperture. However, in modern systems, the aperture and the diffusion screen are usually replaced by a lens system.

In 1988, Yamaguchi et al. [11] became the first group to report experimental demonstration of DWDH. In their one-colour system, a 2D perspective sequence was generated. This was then image-processed to form an array of hogel mask frames, which were recorded on video tape and downloaded one-by-one to a twisted nematic LCD. A laser beam was used to illuminate the LCD and a lens system employed to record a volume reflection hologram of the Fourier transform of each mask. Each such hologram constituted a hogel and, by sequentially advancing the holographic plate between exposures, a matrix of abutting hogels was created. The resulting hologram reconstructed an accurate full-parallax view of the original scene. The process seemed promising, but the 320 × 240 hogel array required many hours to record.

In the late 1990s, Klug et al. [12], working at the US company Zebra Imaging Inc., extended the technique of Yamaguchi et al. to large-format, full-colour reflection holography. Zebra Imaging proved beyond a doubt that the DWDH technique was capable of generating large-format digital colour holograms of a quality never before imagined. In 1999, Brotherton-Ratcliffe et al. [13–16], working at the Lithuanian company Geola, subsequently 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 Geola, XYZ Imaging Inc.* and Zebra Imaging. More recently, a dual-mode printer capable of writing holograms under both DWDH and CGH has been described by Kang et al. [17]. In 2009, a pulsed laser DWDH system was also developed, allowing the rapid generation of erasable digital holograms on photorefractive polymer [18].

7.4 A Simple DWDH Printer

7.4.1 Optical Scheme

Some early DWDH printers used a recording scheme very similar to the original DeBitetto scheme. A simplified diagram of such a printer is shown in Figure 7.2. A continuous wave (CW) laser is used to produce a reference and object beam through the use of a polarising beam splitter (PB). The reference to object ratio is controlled by the 1/2 wave plate (WP1) and the polarisations in the two beam paths are equalised by WP2. The object beam scheme basically consists of a projection system based on an

* More recently trading under the name Rabbitholes Media Inc.

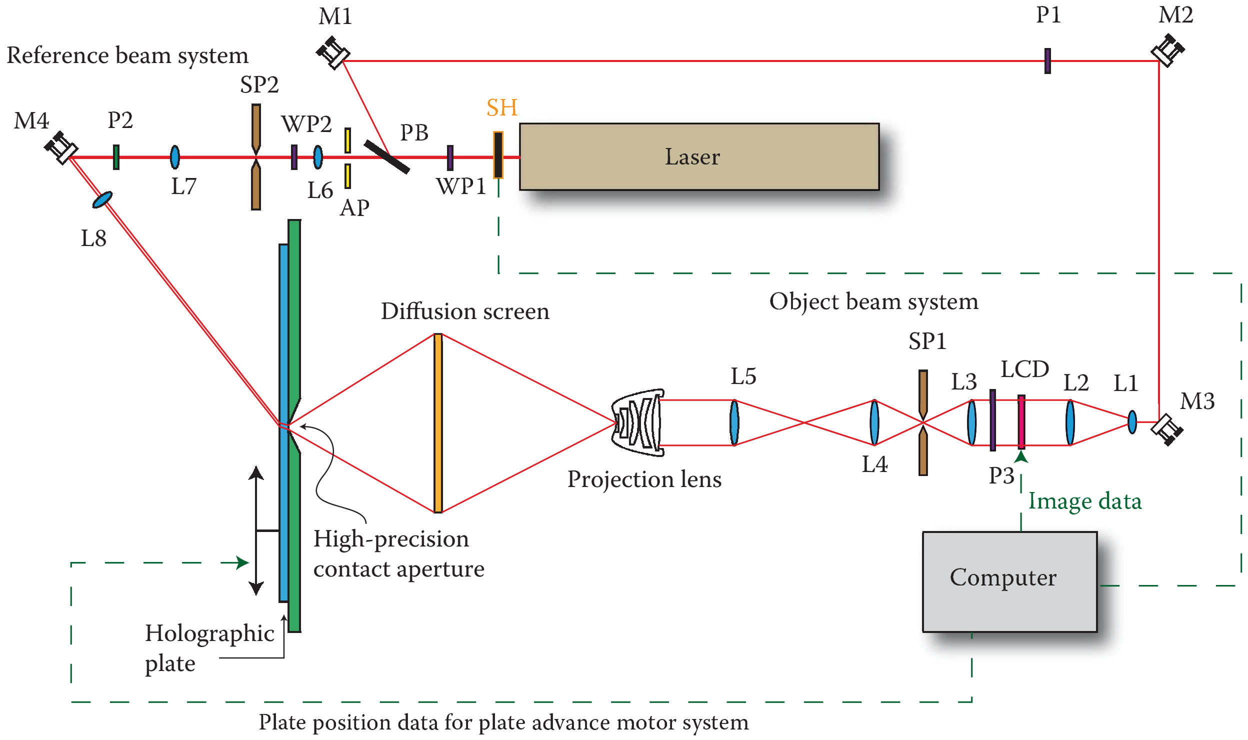

FIGURE 7.2 Simple DWDH monochromatic reflection hologram printer based on a CW laser. The object beam system comprises an LCD projector and a diffusing screen. A contact aperture is used to define the hogel. The device operates using a simple step-and-repeat sequence.

LCD panel. The beam polarisation is first cleaned up by the thin-film polariser (P1) before being collimated and expanded by the telescope (L1/L2). The LCD is a twisted nematic display, which modifies the polarisation of the radiation passing through it by its changeable birefringence. The polariser (P3) converts this polarisation change into an amplitude modulation. High-frequency noise is then removed from the transmitted object beam by the spatial filter (L3/SP1) and an image of the LCD is relayed to the projection lens (L4/L5). The projection lens then forms a high-quality distortion-free image of the LCD on the diffusion screen. Because the holographic plate is masked by a precision square contact aperture that defines the hogel, only the photosensitive emulsion directly within this hogel aperture can "see" the diffusing screen.

The reference beam system consists of three lenses: an aperture, a spatial filter and a polariser. The spatial filter (SP2) cleans out high-frequency structure in the beam and the polariser (P2) ensures a linear polarisation exactly matching the object beam. The lenses (L6–L8) and aperture (AP) define the shape of the collimated reference beam at the emulsion surface; this is usually chosen to be very close to the object beam hogel shape.

7.4.2 Speckle Blur

Because the object beam projection/diffusing system is a coherent system, it is subject to speckle. The speckle size will increase as the hogel size decreases, leading to a loss of angular resolution in the hologram. If unchecked, this will induce image blurring. Image blurring and speckle are treated in Chapter 11. The simplest solution to controlling speckle blurring is to incorporate an additional diffusing element upstream of the projection system.

7.4.3 Operation

The printer works by using a simple step-and-repeat procedure. The shutter (SH) is opened for a predetermined period of time and a hogel is written. The shutter is then closed and the holographic plate is

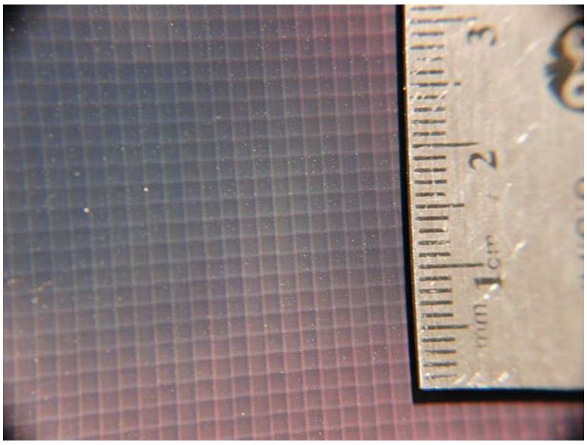

FIGURE 7.3 Magnified view of a small section of a DWDH hologram showing the matrix of hogels or elementary holograms (here, the hogels are 1.6 mm in diameter). Simple DWDH printers print one hogel at a time. At the end of each line, the printer drops to the next line and changes direction. Common hogel sizes range from just over 100 μm to several millimetres. It is also possible to print hexagonal hogels.

advanced. After a settling period, which is required for the system to reach interferometric stability, the shutter is again opened for the predetermined exposure time and the next hogel is written. The plate is moved one column at a time until a full line of hogels is finished. It then drops down a line and starts off in the other direction (Figure 7.3).

7.4.4 Image Data

The image data required by any DWDH printer can be derived from real-world images using devices such as holocams or structured light camera systems (Chapter 10). However, significant image processing needs to occur to get the data into a form ready for printing hogels. We shall discuss image-processing methods for both DWDH and MWDH in Chapters 8 and 9.

7.4.5 Deficiencies

There are several problems with this simple DWDH printer. First, the use of a contact aperture to define the hogel is difficult. Many emulsions are physically sensitive and the aperture must of course be in intimate contact with this sensitive surface. This usually means that an electromechanical system must lift the aperture away from the emulsion when the plate is moved and then gently push it back against the emulsion before exposure.* However, this takes a lot of time, and with the typical hogel size being less than 1 mm^2, even a 30 cm × 40 cm hologram can require 120,000 hogels. Another problem with contact apertures is that the final DWDH hologram can exhibit a clear grid-like structure. It can also be difficult to stop scattered light from actually recording a hologram of each aperture itself. Finally it can be difficult to guarantee exact alignment and proper contact at each exposure.

The use of a classic diffusing screen and an object beam projection system allows the recording of wide angle-of-view holograms with undistorted images. However, only an extremely small part of the object beam is actually used to expose the hogel! The result is that a large power laser is required and one ends up throwing away 99% of the power. Holographic diffusers can greatly improve this situation as they can diffuse the light into a small predetermined area that can be matched to the hogel. However, there is still a general problem with any type of diffusing system. This is the propensity of such systems to induce image blurring. The problem is that if the diffuser is too small and too close to the hogel, or if the hogel is too large, then the rays connecting a projected LCD pixel on the diffusing screen and any

* The commercial printer marketed by XYZ Imaging Inc. in 2005 actually used a system whereby the AgX film was sucked by a vacuum system onto an aperture in front of the writing optics. The function of the aperture was not to apodise the light beam in this printer but to ensure a flat film surface. There was indeed contact between the emulsion surface as it was dragged over the aperture and this caused many small scratches.

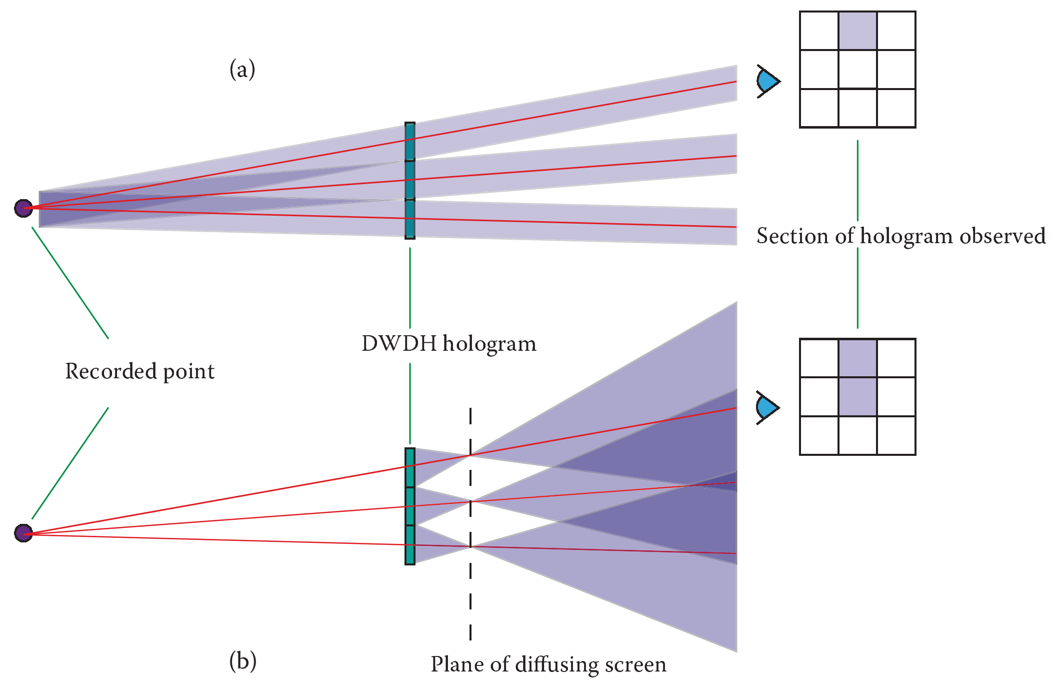

FIGURE 7.4 Diagram illustrating the induced blurring in a DWDH hologram, which occurs when too small a diffusion screen is used to write the hologram. Ideally, the ray bundles connecting a recording point with each hogel should be non-diverging as shown in (a). When too small a diffuser is used to record the hologram as in (b), the ray bundles become strongly diverging and, as a result, hogel bleeding occurs. The diagram only shows the central ray bundles for clarity—which is why there seem to be gaps in the viewing scenario in (a). In general, each hogel will be associated with just enough collimated ray bundles to fill these gaps, but then any divergence of the ray bundles in excess of the eye's angular resolution will lead to hogel bleeding as soon as the observation distance is greater than the diffuser distance.

hogel will, in general, form a cone with a relatively large angle—and the larger this angle, the greater the image blurring and the smaller the in-focus depth of the hologram (Figure 7.4). It can therefore be difficult to make compact printers capable of producing higher-resolution wide-angle holograms using diffusing screens.

A final problem with this simple printer is the time required to print a hologram. Interferometric stability must be present at each exposure. This translates into a long step-and-repeat time even when a high-power laser is used. With the added complication of a contact aperture, this can lead to print times of days for small holograms. Realistically, any small disturbance within this period of time is likely to create a badly exposed hogel and can effectively ruin the hologram.

7.5 Modern DWDH Printers

Modern DWDH printers use a number of major improvements over the simple system described in the previous section. First, and most importantly, small-pulsed lasers are often used to solve the stability problems inherent to the use of CW lasers. Second, the hogel is usually formed using an optical system rather than relying on an awkward contact aperture combined with a projection/diffusion scheme. This then allows the step-and-repeat plate movement system to be replaced by a constant velocity system.

7.5.1 Use of Pulsed Lasers

The use of nanosecond-pulsed lasers in DWDH printers can completely solve the problems of interferometric stability and low printing speed that plague CW laser printers. This is of fundamental importance because this means that small-power lasers may be used to print large holograms at reasonable times. With a pulsed laser, the holographic exposure is effectively done in such a small period of time that there is no need to let the system settle.

We shall see in the next section that the problematic contact apertures often used in early printers were quickly discarded and, as such, it became possible to simply move the holographic plate at a constant velocity while a constant repetition rate laser wrote sequential hogels. The maximum rate at which hogels can be written using this system is determined by the duration of the laser pulse, τ. If we demand that within this duration, the holographic plate may only move by one-tenth of a wavelength of light, then for a hogel of diameter, δ, the maximum hogel write rate is given by the simple formula

$$f = \frac{\lambda}{10\delta\tau} \tag{7.1}$$

For a pulse duration of 40 ns, which is typical of a Q-switched pulsed laser, and a hogel size of 0.5 mm, this equates to a rate of nearly 2.7 kHz at 532 nm! The pulse energy required to expose a single hogel is also extremely small. Taking a film sensitivity value of 2000 $\mu J/cm^2$, for example, one can see that the ballpark figure for the energy per hogel is approximately 10 μJ. This assumes, of course, that one has an optical system that (unlike the diffuser system described previously) does not waste energy. If one assumes a realistic hogel write rate of 100 Hz, then the power requirement on the pulsed laser is only 1 mW!

This calculation can be compared with a CW laser system, which also functions with a constant velocity plate displacement system at a hogel write rate of 100 Hz. Here, a laser shutter must constrain the exposure time so that movement of less than one-tenth of a wavelength occurs during the exposure. The exposure must thus be limited to approximately 1 μs. To get sufficient energy for the exposure, this then requires a laser having a CW power of 10 W—or 10,000 times more than that required of the pulsed laser!

7.5.1.1 Microsecond Pulsed Lasers

There is therefore an overwhelming case for the use of pulsed lasers in DWDH printers. Notwithstanding this, there is one major problem here! Some of the best photosensitive materials for colour holography are not properly sensitive to nanosecond laser pulses. For example, dichromated gelatin is a superb photosensitive material that can be used for colour holography—but it produces poor results with nanosecond pulses. Photopolymers, which are wonderfully convenient due to their freedom from wet chemical development, can also fall into this category.

One positive indication is that some of these materials, particularly photopolymers, can show good sensitivity to multiple nanosecond pulses. Therefore, future DWDH printers may well use pulsed lasers producing emissions of a few microseconds' duration—or nanosecond pulse trains with envelopes stretching to several microseconds. Although write rates somewhat lower than 100 Hz may be required, we shall see later that there are methods for writing multiple hogels with every laser pulse. However, microsecond lasers are unfortunately more complex to produce than nanosecond lasers and usually require complex fast-switching high-voltage electronics. We have already reviewed a simple version of a pulse stretcher as applied to a ruby laser in Chapter 6. Recent work at the Geola organisation has also tentatively demonstrated the feasibility of active Q-switching systems for microsecond RGB-pulsed lasers. To date, however, no prototype printer using these longer pulse-length lasers has been tested.

7.5.2 Lens-Based Printers

Special lens systems are frequently used to replace the contact aperture and projection/diffusion scheme described above. Such lens systems create the hogel optically by focussing the light transmitted by the spatial light modulator into a narrow waist. The light distribution at the hogel then effectively becomes the Fourier transform of the distribution at the SLM. Such lens systems can also create a greatly enlarged image of the SLM downstream of the Fourier plane (Figure 7.5).

The contact aperture and projection/diffusion system can therefore be conveniently replaced by a compact non-contact optical system. The exact shape of the hogel can be precisely defined by an aperture placed at any optical plane, which is conjugate to the Fourier plane of the main objective lens.

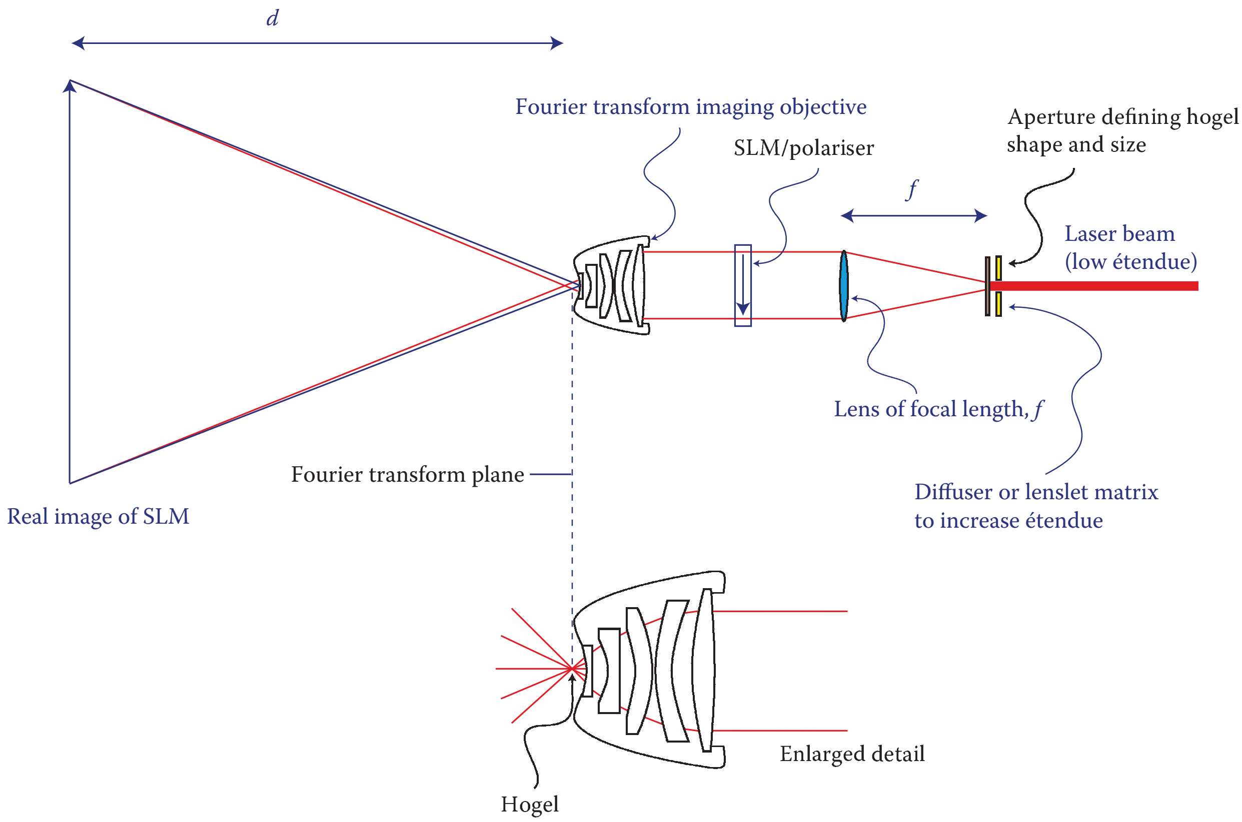

FIGURE 7.5 Lens-based hogel-forming system. Here, a Fourier transform imaging objective defines the hogel shape and also creates an image of the spatial light modulator downstream of the Fourier plane. The distance, d, should be large to avoid blurring of the hologram. The hogel shape may be conveniently defined by the shape of an aperture placed at a conjugate plane.

This type of system has great advantages. There is no need for any contact aperture and almost all the energy transmitted through the spatial light modulator is now used to record the hogel. The laser energy required is therefore extremely small. There are, however, two disadvantages we should mention. Both are related to the fact that it is difficult to design high-resolution Fourier transform imaging systems of high numerical aperture.

Unfortunately, the angular field of view of a DWDH hologram is defined by the conic angle of convergence of the focussed light forming the hogel. Usually, this angle must be large—in the order of 100° if the hologram is to be viewed from a variety of positions. This means that the numerical aperture of the Fourier transform optic must also be very large. However, as the numerical aperture increases, optical aberrations increase rapidly. These aberrations decrease the resolution of the optical system, which in turn induces image blurring in the final hologram.

It turns out that one can significantly increase the resolution of the optical system at high numerical apertures if one accepts a finite fifth coefficient (Barrel distortion) or, in other words, if one accepts that the image of the spatial light modulator produced by the optical system will become rather distorted (but not blurred). In Chapters 8 and 9, we shall discuss this problem, and in particular, we shall see how it can be dealt with in the context of image processing.

The second problem that arises through the need for a high numerical aperture system is related to the fact that higher resolution is always available from a monochromatic Fourier optical system as compared with that available from the corresponding apochromatic system. This usually results in three separate optical schemes being adopted in a DWDH printer, one for each primary colour. Such printers can be classified as triple-beam systems because they use three separate object/reference beam pairs to write three primary colour hogels in different physical locations of the holographic film. Of course, if large image depth or large fields of view are not required in a DWDH hologram, then it becomes possible to employ a single apochromatic optical system and to print single RGB hogels, one at a time.

7.5.3 Speckle in Lens-Based Printers

When a Fourier transform lens system is used in a DWDH printer, the hogel size must be controlled by the étendue of the object beam. An aperture in contact with a holographic diffuser and a Fourier transforming lens may therefore be conveniently used to define both the average étendue and the exact hogel shape. This system also provides ray averaging in that a single point at the image plane of the lens system is now connected to a single point on the spatial light modulator by multiple rays that travel different paths through the optical system. However, for small hogel sizes, too little averaging may be available due to the correspondingly small aperture size. In this case, speckle will appear at the real image of the spatial light modulator downstream of the lens system. Once again, this speckle can degrade the image by inducing image blur. Increasing the diffuser size, as can be done in a lensless printer (according to our previous discussions), is of course not an option here as the diffuser size is now directly coupled to the hogel size. One effective solution is to use a microlens array instead of a diffuser. By choosing the pitch of the lenslet matrix to be larger than a certain critical amount, lower spatial frequencies, which are predominantly responsible for the visible speckle and induced blurring, are eliminated. Of course, if too large a pitch is selected, then given that the area of the lenslet matrix is fixed by the hogel size, inefficient averaging will occur and again the image quality will be degraded. Nevertheless, for most hogel sizes, the lenslet matrix approach works well. An alternative solution that is sometimes adopted is the use of quasi-random phase plates, which are used to randomise the phase at the spatial light modulator.

7.5.4 Triple-Beam Printers

In its simplest form, an RGB triple-beam DWDH printer comprises three relatively identical optical channels—one for each of the three primary colours. Each optical channel comprises a laser emitting at a primary wavelength and an optical system for forming an object beam and a reference beam that are brought into physical coincidence at the surface of the photosensitive material where a hogel is formed.

7.5.4.1 Hogel-Writing Sequence

The hogel-writing sequence is illustrated in Figures 7.6 and 7.7. At first, the film or plate is moved at a constant speed and the lasers triggered at a constant interval such that a row of hogels is created for each of the three primary colours, each hogel being horizontally juxtaposed with respect to its neighbour. This is illustrated in Figure 7.6a.

Next, laser emission is blocked and the electromechanical system winds up the film or plate by an amount equal to the hogel diameter. The process described previously then restarts as the plate/film is moved to the right and a new line of hogels for each colour is formed under the previous line as shown in Figure 7.6b. The writing process continues in this way as illustrated in Figure 7.6c, d and e. Figure 7.6f shows the situation after the sixth line has been written.

The writing sequence continues in Figure 7.7. In Figure 7.7a, seven lines have been written. In Figure 7.7b, the eighth line of red hogels is seen to overprint the first line of green hogels. Similarly, the eighth line of green hogels overprints the first line of blue hogels. This overwriting process continues with further lines being overwritten until the blue hogels, which have already been overwritten by the green hogels, now start to be overwritten by the red hogels. As shown in Figure 7.7f, this process produces hogels that have all three primary colours.

There are several points to make about this writing procedure. Clearly, the distances between the centres of the writing locations for each colour channel have to be an integral multiple of the hogel diameter for the different colour hogels to coincide; this practically then leads to a constraint on the hogel diameter in a given printer. Typical hogel sizes are 1.6 and 0.8 mm. A typical distance between the red and green or green and blue writing locations in modern printers is 80 mm, corresponding to between 50 and 100 hogel diameters.*

* A distance between red and green writing locations of 7-hogel diameters was used for illustration purposes only in Figures 7.6 and 7.7. In modern printers, the figure is closer to 50 to 100.

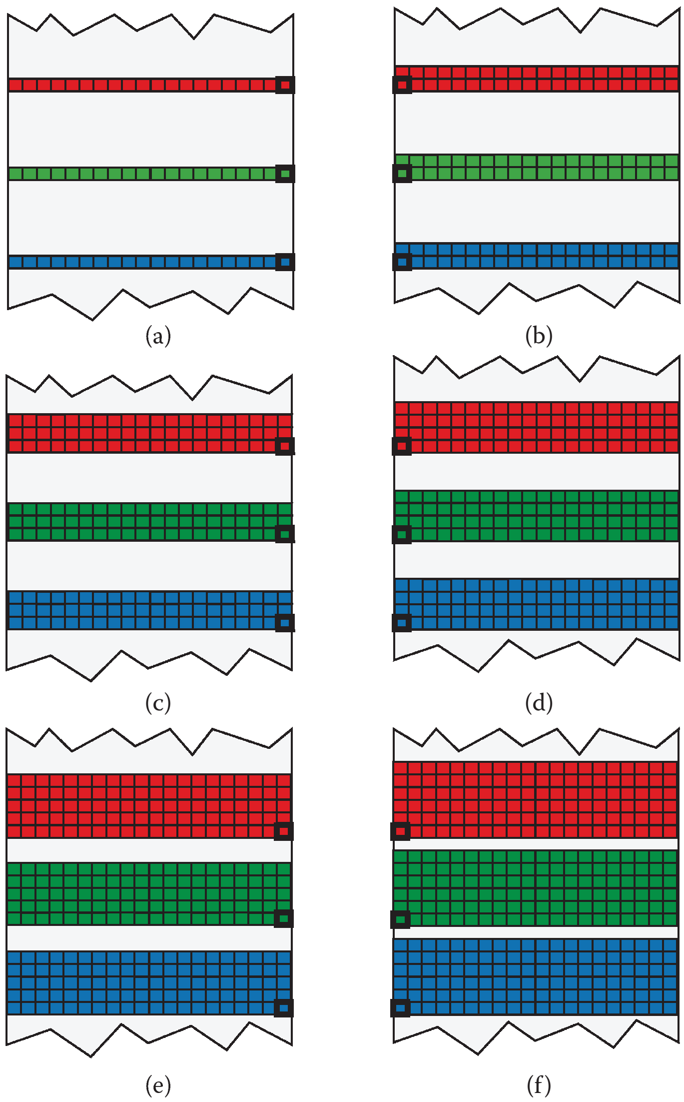

FIGURE 7.6 Hogel-writing sequence in a triple-beam DWDH printer. In (a) the photosensitive film has just been moved from right to left and a row of hogels written by each objective (the black square). In (b) the film has been moved up one step and then moved horizontally to the right while another line of hogels is written. The remaining figures show the progression of this process with three lines (c), four lines (d), five lines (e) and six lines (f) being written.

In practice, it is common for the writing process to start with the top of the photosensitive material directly under the bottom blue writing head. Writing starts only with the blue channel activated; only when the photosensitive material has moved up and the green head starts to overwrite the blue hogels is the green channel actually switched on. Likewise, the red channel is activated only when the red head actually starts to overwrite the blue/green hogels. At the end of the printing process, a similar inverse process is enacted whereby the blue and then the green heads are deactivated before the red head terminates the last line. In this way, all hogels printed contain the three primary colours.

7.5.4.2 Basic Systems in RGB-Pulsed Laser Triple-Beam Printers

Figure 7.8 shows a schematic optical and control diagram of a DWDH printer manufactured in 2001 by the Geola organisation for the production of large-format RGB horizontal parallax-only (HPO) reflection holograms (Figure 7.8). We will use this printer to illustrate how a modern pulsed laser triple-beam DWDH printer works before going on to discuss more complex variants. For clarity, Figure 7.8 shows only one colour channel. In the printer itself, there are three such colour channels (red, green and blue) which are schematically identical. The printer is designed to print reflection type hogels onto silver halide plates of a size up to 800 mm × 800 mm, using three pairs of object and reference beams powered

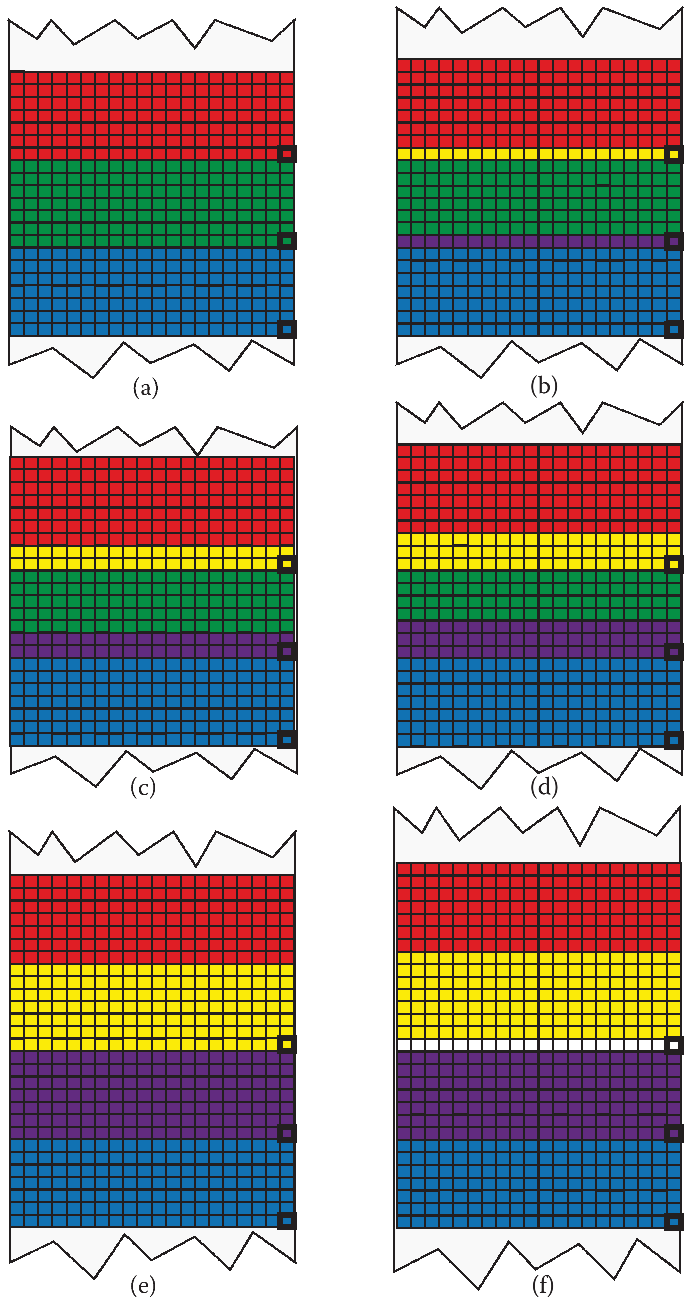

FIGURE 7.7 Hogel-writing sequence continued from Figure 7.6. In (a), seven lines of hogels have been written in each colour. In (b), the different colours start to overlap. Now a line of red hogels has been written over the green and a line of green hogels over the blue. By (e), additional lines have been written, and in (f), the first line of overlapping red, green and blue hogels (shown in white) is produced.

by an RGB-pulsed laser operating at 15 Hz. As with all triple-beam printers, each object and reference beam pair is made to intersect at a given location on the photosensitive film.

7.5.4.2.1 Control and Video Image Stream System

The printer is controlled by a DELL precision workstation 530 computer with twin Intel Xeon 1.4 GHz processors, Matrix Millennium G450 graphics card, an SCSI Raid HDD of 160 MB and an additional SCSI HDD of 73.4 GB and 1 GB of RDRAM running 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 1024 × 768 LCD panels for object beam data encoding. The printer includes many motorised microrotation and microtranslation stages for the

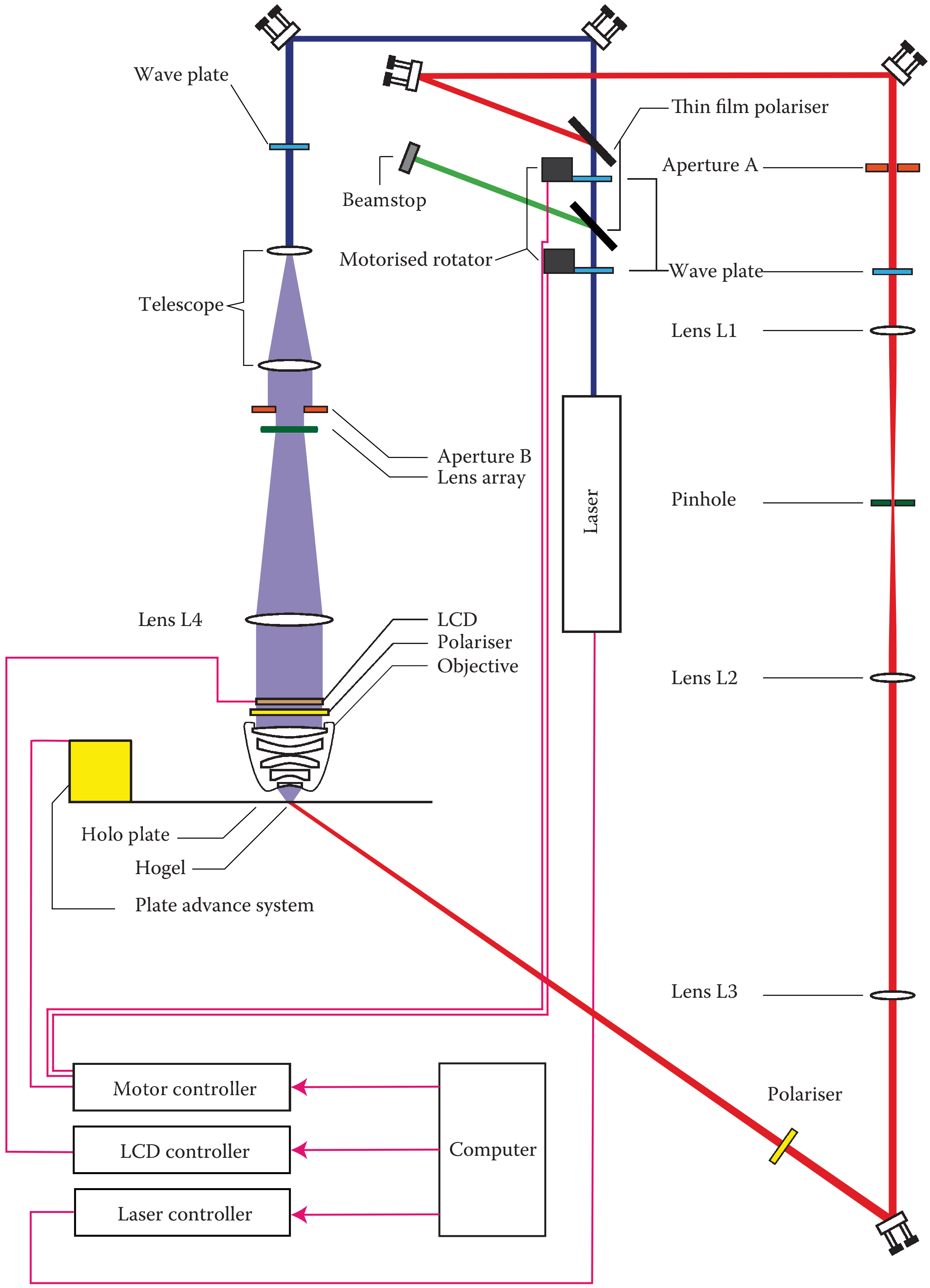

FIGURE 7.8 Optical and control schematic for the 2001 RGB-pulsed laser DWDH printer manufactured by Geola.

automatic adjustment of beam energies and ratios, in addition to electromechanical shutters. Controllers for these components are mounted with the main control computer in a large control rack (Figure 7.10).

7.5.4.2.2 Mechanical Plate Displacement System

The mechanical plate movement system comprises a vertical translator and a horizontal translator. The vertical translator consists of an LF6 200-mm width rail from the German Company Isel Germany AG

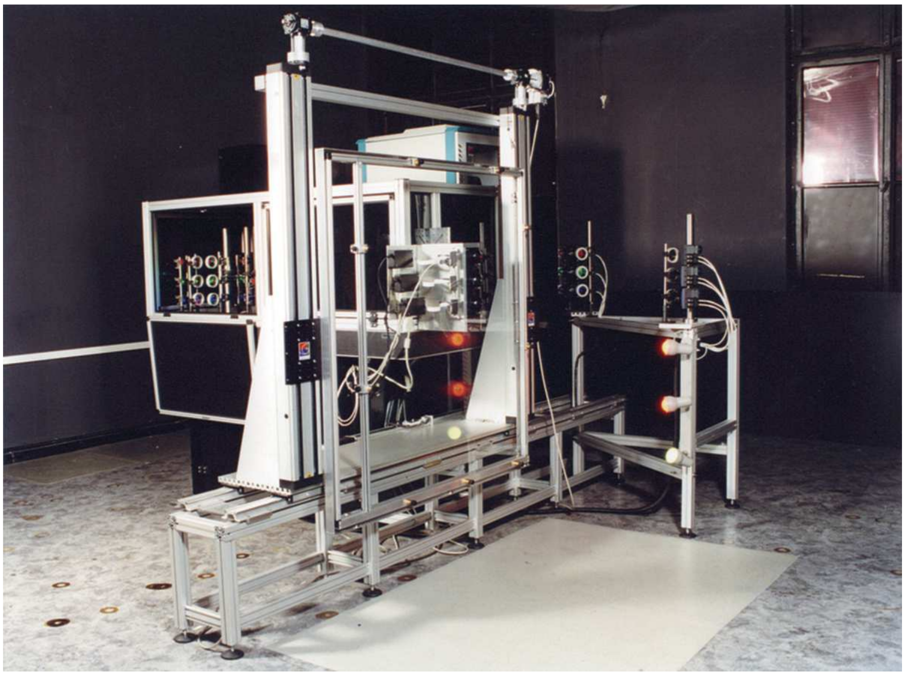

FIGURE 7.9 Photograph of the 2001 RGB-pulsed laser DWDH printer manufactured by Geola. Note the large plate-holder with 2D electromechanical displacement system in the foreground. To the right of the photograph can be seen the reference beam system. In the background are the main optical unit and laser (left) and the electronic control rack (right).

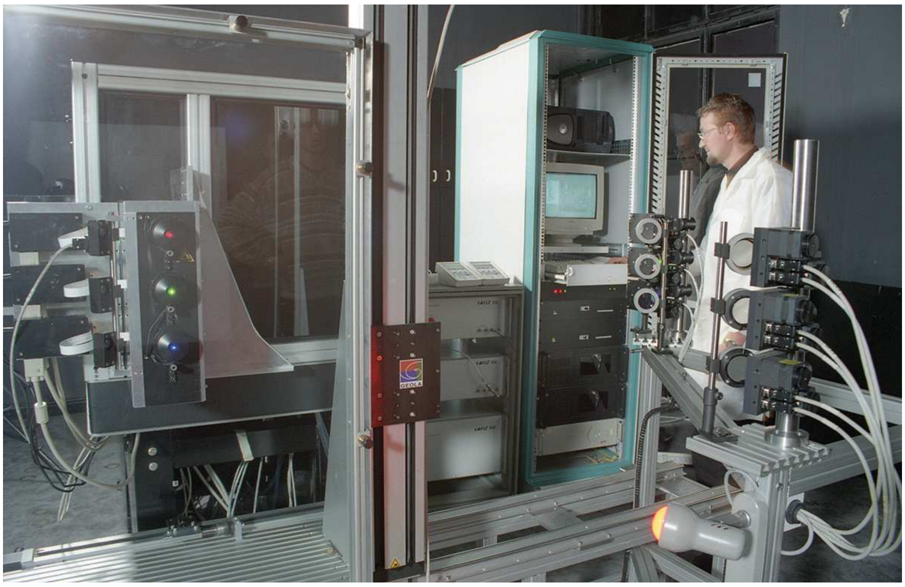

FIGURE 7.10 Photograph of the main control rack of the 2001 Geola printer showing the computer (top) and electronic controllers (bottom). To the left can be seen a separate smaller rack for the laser power supplies.

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 rail with 16 × 5 ball screw MS160 spindle motor. A master microprocessor-based controller (mounted in the main control rack) controls the triggering of both laser and stage motion.

7.5.4.2.3 System Architecture

The printer is limited to producing HPO holograms.* HPO holograms require much less memory storage and this allows a simplified computer system to be used, with image files being uploaded over a network.

* In later models, this was upgraded to also allow the creation of full-parallax holograms.

Holograms are created using perspective view information, which is generated either from a holocam (Chapter 10) or through commercially available computer modelling 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 RFM—deals with the queuing of jobs for processing. It also undertakes the pixel swapping algorithms, optical distortion algorithms and gamma 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 will be covered in Chapters 8 and 9. The second software module is the PMC, which controls printer operation, manages the print queue and prints each hologram using the data generated by the RFM.

7.5.4.2.4 Laser and Optical System

The optical system of the Geola printer is built around a dual ring-cavity neodymium RGB-pulsed laser emitting separate red, green and blue beams at wavelengths of 660, 526.5 and 439.5 nm. The pulse energies available are between 3 and 5 mJ at each colour and a repetition rate of 15 Hz is standard. We have already reviewed this laser in Section 6.5.1.

The laser beam is first attenuated to a desired level through a 1/2 wave plate and Brewster angle polariser pair. The wave plates for each colour channel are mounted in precision electromechanical rotation stages that are driven by stepper motors. These motors are controlled by standard motor controllers that are in turn connected to the printer's dedicated control computer. Calibration tables are defined which allow the control computer to quickly select a given red, green or blue laser energy. Excess unwanted energy is absorbed in a beamstop.

A similar 1/2 wave plate and Brewster angle polariser pair is used to divide the main laser beam into a reference and object beam. In Figure 7.8, the reference beam is coloured red and the object beam is coloured blue. The wave plates are mounted as before in precision electromechanical rotation stages; with appropriate calibration, the control computer is then capable of commanding not only an exact laser energy for a given colour but now also an exact reference energy and an exact object energy. Two further fixed wave plates, one in the reference beam and the other in the object beam, are used to tune the polarisation to the desired direction. Figure 7.11 shows a photograph of the main optics unit of the Geola printer with the energy and ratio control system visible in the foreground to the left.

7.5.4.2.5 Object Beam Subsystem

A simple telescope (Figure 7.8) expands and collimates each laser beam. The beam then illuminates a microlens array that is apodised by the aperture (B). The function of the lens array is twofold. First, it creates a light source that has a larger étendue, which is directly controllable by the size of aperture (B). Second, it produces a clean approximately top hat spatial distribution. The focal length of the lenslets in the lens array is chosen to create a gradual expansion of the object beam and lens (L4) is positioned at a distance of approximately one focal length from the lens array. This ensures that in the case that aperture (B) is very small, the beam after (L4) is collimated.

The object beam now illuminates a Sony XGA1* twisted-nematic LCD panel where the digital image data are encoded onto the object beam. The LCD panel has an active area of 38.8 mm by 27.6 mm and a resolution of 1024 × 768 pixels. A polariser is required to convert the data, which is written initially by the LCD as changes in the polarisation vector, to amplitude modulation.

The final element in the object beam system is a high numerical aperture Fourier transforming objective lens system. This acts to strongly focus the object beam down to form the hogel and is a key part of the system. It must create a high-fidelity image of the LCD at a distance equal to or greater than the expected viewing distance of the final hologram and must have a Fourier plane at approximately 5 mm downstream of the lens. The conic angle of focus from the objective to the hogel is 105° in the Geola

* In later versions of the printer, the three XGA1 LCDs were updated to higher resolution Sony LCX028ALT panels. These were then mounted in ovens to assure operation at a higher hogel write rate of 30 Hz.

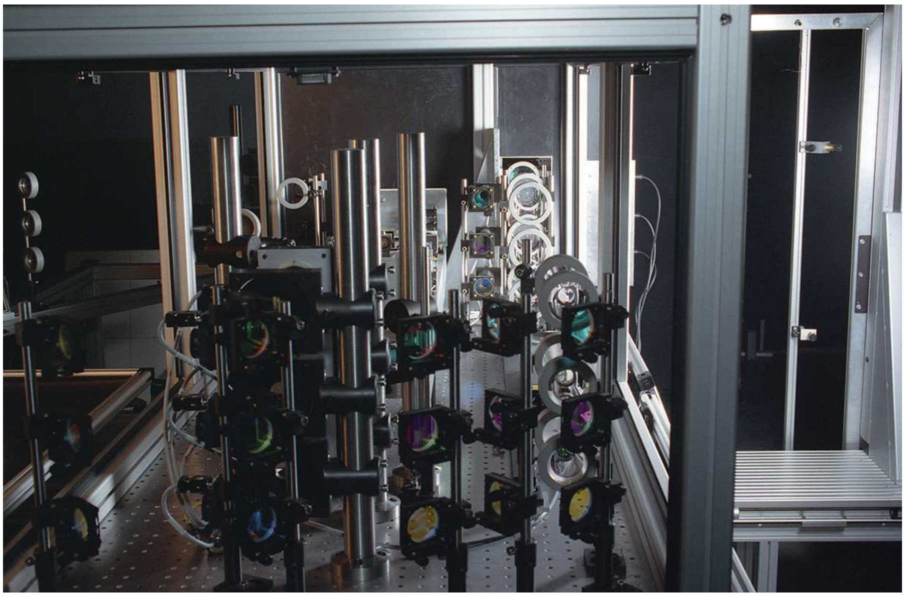

FIGURE 7.11 Photograph of the main optics unit of the 2001 Geola printer showing how the three colour channels are stacked one on top of the other. The laser is visible towards the rear left and the energy control systems are situated in the left foreground. Also visible to the right behind the large glass plate are the three hogel-writing optical objectives. The optics and motorised rotation stages visible to the left form part of the triple reference beam system.

printer and this fixes the intrinsic field of view of the hologram at 105° (Figure 7.12). For hogel sizes from 0.8 to 1.6 mm, the objective has a resolution capable of resolving the LCD pixels at all angles.

The footprint of the object beam at the surface of the photosensitive material is determined by the shape and size of the aperture (B). This is because aperture (B) is at essentially a plane conjugate to the emulsion plane. To see this, remember that the objective lens system produces a Fourier transform of the LCD plane at the emulsion plane. However, the Fourier plane of (L4) is at the lens array and so L4 approximately induces an inverse Fourier transform of the lens array plane at the LCD plane. The two transforms therefore cancel leading to the emulsion plane and the lens–array plane being conjugate. This is a useful feature in that aperture (B) can be controlled automatically to change the hogel size.

7.5.4.2.6 Reference Beam Subsystem

The function of the reference beam optical system in the Geola printer is to produce a clean collimated beam of the correct polarisation that illuminates the hogel from a given fixed angle with a defined spatial distribution. A 1/2 wave plate is used to rotate the polarisation to the desired angle, and a polariser is used to remove any elliptical component. Generally, one wants to minimise reflection from the photosensitive

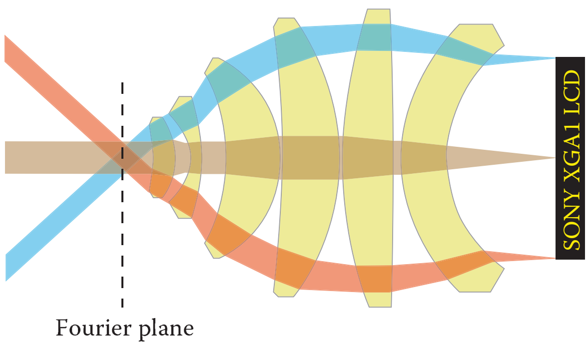

FIGURE 7.12 The 105° hogel-writing objective lens system used in the 2001 Geola printer. Note that the hogel is formed at the Fourier plane. Note also that the ray bundles emanating from a specific LCD pixel pass through the hogel as approximately collimated beams.

material or from the glass or film onto which it has been coated. The polarisation of the electric field is therefore usually chosen to be in the plane parallel to the photosensitive material. If Brewster's angle is chosen as the incidence angle, this then eliminates any unwanted reflections completely. The axial object polarisation must of course be tuned to exactly the same angle as the reference polarisation to achieve maximum interference.

The positive lenses L1 and L2 constitute a Kepler telescope. This telescope changes the diameter of the laser beam by a factor

$$M = f_2 / f_1 \tag{7.2}$$

where f_1 and f_2 are the focal lengths of L1 and L2, respectively. The separation of L1 and L2 must be chosen as

$$s = f_1 + f_2 \tag{7.3}$$

to ensure beam collimation. By placing a pinhole at the focus of L1, the beam may be cleaned very effectively and higher spatial frequencies removed. In practice, the focal length f_1 is chosen to be 20 to 50 times larger than the laser beam diameter to minimise aberrations and also to avoid breakdown of the air at the pinhole due to the presence of a high electric field. The focal length of L2 is then determined by the required beam magnification and the separation (s) is fixed by beam collimation.

The function of the two remaining elements in the reference beam system, aperture A and lens L3, is to shape the footprint of the reference beam at the hogel to a desired form. Without these elements, the reference beam would strike the photosensitive material at the incidence angle, forming an elliptical shape, the eccentricity of which is determined by this angle. This is not what is required because, ideally, the reference beam footprint should be matched to that of the object beam. In practice, one actually wants to make the reference beam just a little larger so that the object beam never falls outside the reference footprint. For a 0.8 mm diameter hogel, the reference beam footprint is therefore chosen to be a circle of 0.9 mm diameter, which leads to a small bleed from hogel to hogel.

The desired reference beam footprint is accomplished by arranging lens L3 so that it forms an approximate image of aperture A at the surface of the photosensitive material. The shape of aperture A is then designed such that the required (usually square) distribution of light is obtained at the hogel.

The Kepler telescope relays an image of aperture A by a distance

$$R = -d + f_1(M+1) + \frac{f_1 M\left(f_1(M+1) - Md\right)}{f_1 + 2M\left(f_1 - d\right)} \tag{7.4}$$

where d is distance from aperture A to L1. By choosing d carefully, the relayed image of aperture A can easily be positioned to the right of the Kepler telescope. Then, it is simply a question of choosing the focal length (f_3) and position of the positive lens (L3) such that the relayed image is in turn imaged to a location approximately coincident with the hogel. To do this, one simply uses the Gaussian form of the thin lens equation

$$\frac{1}{t'} + \frac{1}{t} = \frac{1}{f_3} \tag{7.5}$$

where t and t' are, respectively, the (positive valued) separation between the relayed image and L3 and that between L3 and the hogel. If t and t' are chosen to be too large then diffraction will wash out the image at the hogel completely. On the other hand, if they are chosen too small, then the reference beam will not be sufficiently collimated.

Because the hogel is created by the coherent interference of the object and reference beams, it is important that the optical path lengths of both object and reference beams are as similar as possible. Although the intrinsic coherence length of the laser is theoretically greater than 1 m, any discrepancy in the path lengths will in practice tend to reduce the overall diffractive efficiency of the hogel.

7.5.4.2.7 Energy Requirements

The 2001 Geola printer required approximately 1 mJ of energy per pulse per primary colour channel to print 1.6 mm diameter hogels using a panchromatic silver halide material having a sensitivity of approximately 1000 μJ/cm^2. This is, in fact, much bigger than the theoretically required energy of approximately 30 μJ—largely because many of the optical systems were simply not optimised.

7.5.4.2.8 Alignment

Triple-beam printers are fundamentally more difficult to align than apochromatic single-beam printers. The problem is that in triple-beam printers, the virtual image of the red, green and blue spatial light modulators, downstream of the writing objectives, are separated by the distance between the objectives. Although it is relatively easy to align the actual objectives in the x, y and z directions, it is rather more difficult to ensure the correct orientation of the emerging light.

An effective alignment process for triple-beam printers is to focus in the objectives to form an image of each SLM, for example at 50 cm from the Fourier plane. A graticule is then loaded onto each of the SLMs and a high-energy object beam is used to project an image of this graticule onto an exactly perpendicular target. By taking digital photographs of the target with the three projected graticules and analysing these using a computer, the optical system may be aligned very accurately. It is important to point out that it is not sufficient that the objectives alone point in the same direction. One must also ensure that the SLM is exactly centred with respect to the objective and is not at an angle. In the case that the alignment is not done properly, holograms will show misaligned red, green and blue images. Almost always, an iteration process is required to ascertain whether alignment has been successful. This entails recording a test hologram of a grid structure and analysing whether a given colour channel needs readjustment. In film printers, it is imperative that the normal vector of the emulsion surface at the red, green and blue hogel write locations be the same, otherwise even a perfectly aligned optical system will lead to displaced colours. Although it is possible to numerically recalibrate a physically misaligned optical system by predistorting the SLM image data, this generally introduces some noise into the final 3D image and, as such, it is always strongly recommended to properly align the optical system.

In apochromatic and monochromatic printers, alignment is much easier because there is only one hogel write location and one writing objective. One therefore only needs to verify that a good image is present downstream of the Fourier plane. Colour slip is immediately obvious and can be corrected for by looking at the projected image while adjusting the optics.

In addition to the alignment of the object beam system, in all DWDH printers, the footprint of each object beam must coincide with the corresponding reference beam footprint at the holographic film surface. If this does not occur, then at best, a full hogel will not be formed, and at worst, there will be no hologram at all. For small hogel sizes, it can be quite tricky to ensure proper object/reference alignment. The usual way of doing this is to replace the square aperture used in the printer object beam system (which produces a square hogel) with a very small circular aperture. This essentially forms a very dim "point hogel" which scatters on the emulsion surface (one usually uses old film or an old plate). By reducing the energy per pulse, it is safe for an observer to then look into the writing objective where a luminous point will appear at a certain location at the emulsion surface. This is the centre of the hogel. It is then relatively easy to align the reference beam such that the point appears exactly in the centre of the larger reference square. When glass plates are used, it is vital that the system be recalibrated for the exact thickness of the glass used. It is useless aligning the object and reference writing beams at one thickness and then recording with a slightly different thickness plate—Snell's law will act to misalign the system and hogels will not be recorded properly.

7.5.4.2.9 Conjugate and Non-Conjugate Operation Geometries

Lens-based printers usually produce an image of each spatial light modulator downstream of the hogel. In contrast, diffusion screen systems always produce an image upstream. We have already discussed that a problem with diffusion screen systems is that the screen must be relatively large and at a good distance from the hogel if image blurring is not to result. In both lensless and lens-based hogel-forming systems, one has the choice of replaying the hologram with a conjugate or non-conjugate reference beam

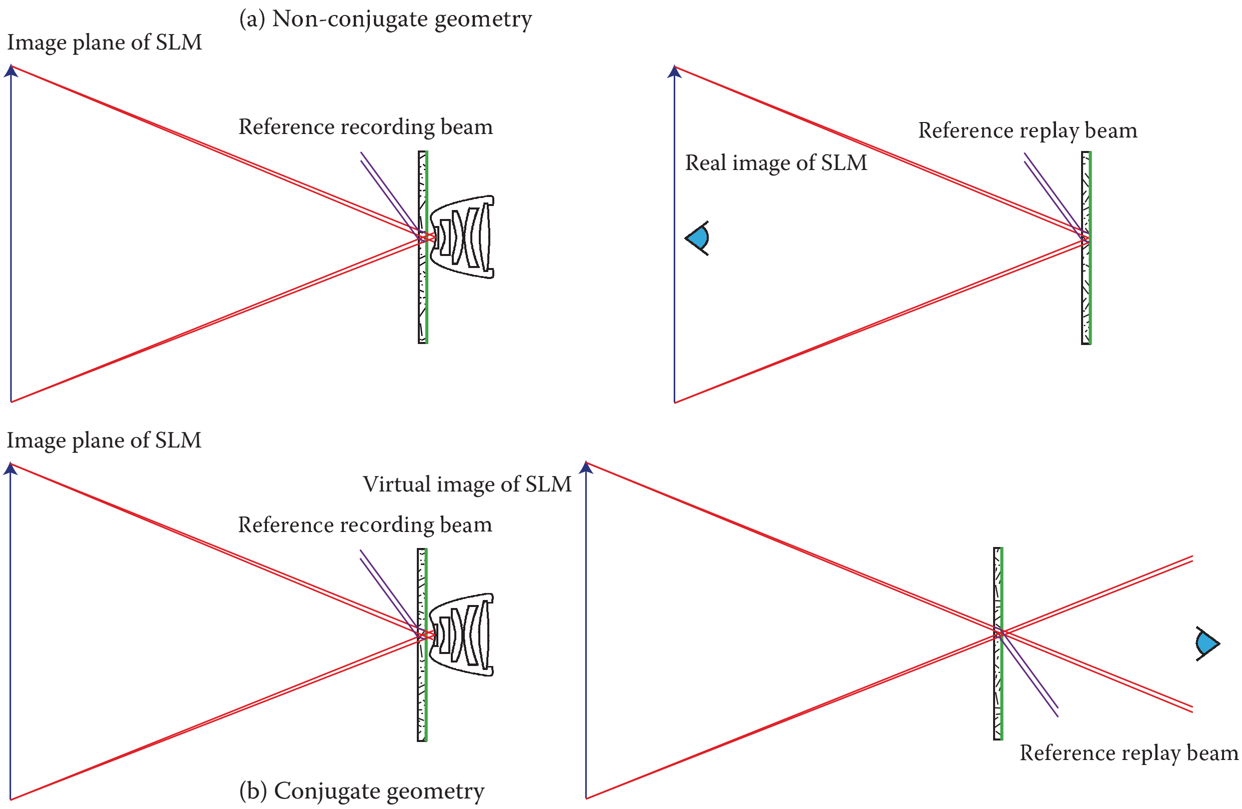

FIGURE 7.13 (a) Non-conjugate and (b) conjugate recording/replay geometries in a lens-based DWDH printer.

(Figure 7.13). If the image plane of the SLM is upstream* of the hogel at recording, then a non-conjugate reference beam at replay will produce a virtual image of the SLM behind the hologram. Likewise, a conjugate replay beam will produce a real image of the SLM, for each hogel, in front of the hologram.

The choice of which geometry to use is related to the printer construction. In the 2001 Geola printer, the glass holographic plates are always mounted with the emulsion facing towards the hogel-writing objectives. This is essentially a necessity, as the large plates are generally of a thickness that is greater than the distance between the physical end of the objectives and the Fourier plane. After processing, the sensitive emulsion surface must be at the rear of the hologram—blackening is then applied both to protect the emulsion and to improve the viewing characteristics of the hologram. This means that illumination of the hologram must be by a non-conjugate beam. When a diffusion screen system is employed, the same logic would dictate that a conjugate replay geometry be used.

If the image plane of the SLM is at a relatively small distance from the hologram and the hologram is to be viewed close-up, then it is generally better to ensure that a real image of the SLM is located on the viewing side of the hologram at replay. This will lead to the best image quality. However, it is often the case that the image plane distance can be made very large, and in this case, the choice of conjugate or non-conjugate replay geometries simply depends on the most convenient way to record and replay the hologram. In Chapters 8 and 9, we will see that the image transformations necessary to convert perspective view information into the SLM mask file information depend critically on whether the printer is designed for conjugate or non-conjugate operation.

7.5.4.2.10 Laser Stability Issues

By far the largest problem encountered with the 2001 Geola printer was related to the OEM RGB-pulsed laser. Although the laser's stability was relatively good from an absolute point of view, the occasional bad pulse often ruined a hologram after hours of writing—simply because a hologram could contain nearly one million hogels. For this reason, a new type of laser was developed by XYZ Imaging Inc. and Geola Technologies

* Note that Figure 7.13 shows the case of the image plane of the SLM being located downstream of the hogel.

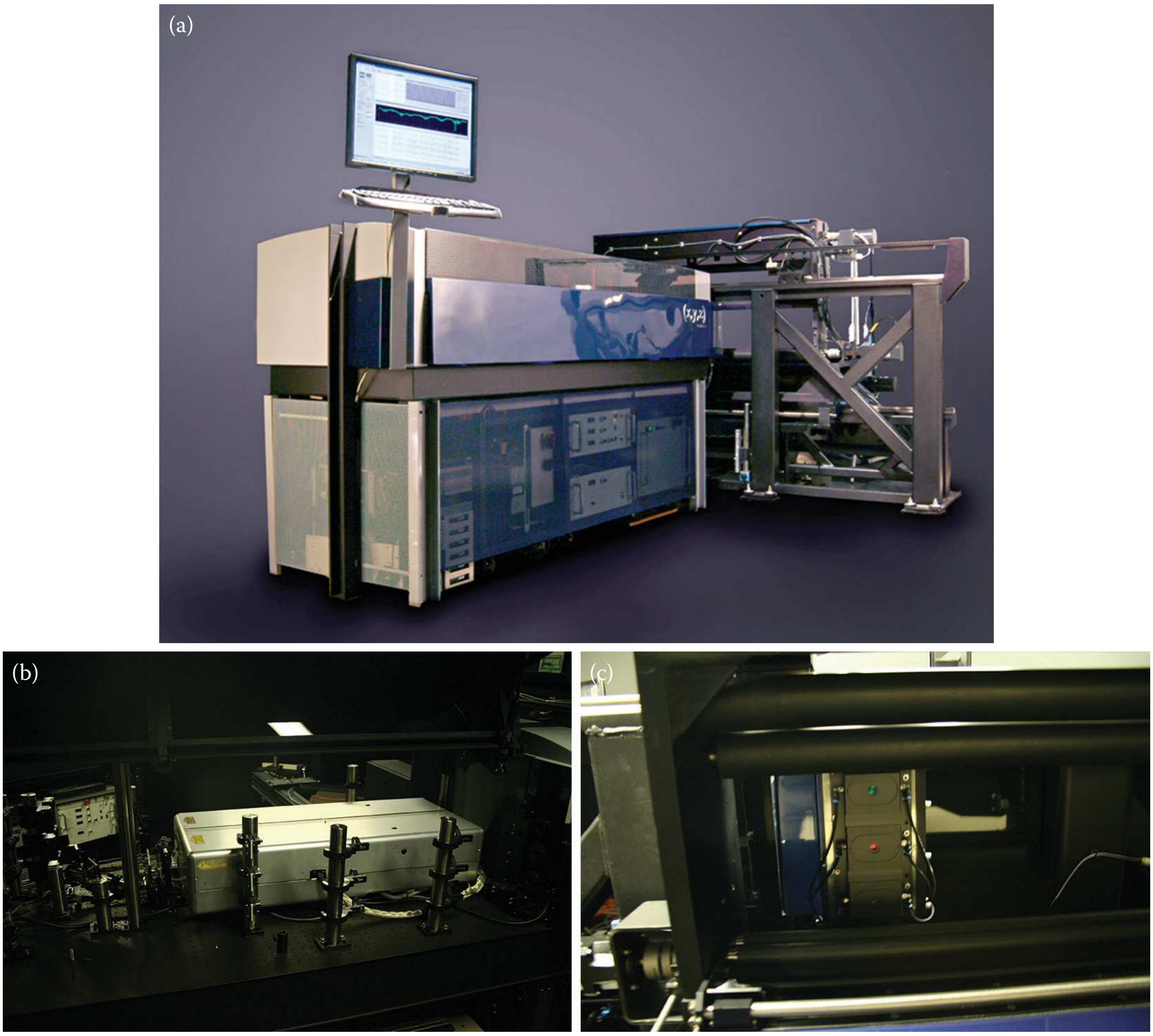

FIGURE 7.14 (a) Commercial DWDH triple-beam printer made by XYZ Imaging. (b) A shot of the interior showing the optics and the RGB-pulsed laser. (c) The three hogel-writing objectives, each surrounded by a vacuum unit, whose function is to pull the film flat at exactly the correct distance from the object. In practice, the optimum distance is a little downstream of the Fourier plane.

Ltd. This laser was built around twin linear telescopic cavities, rather than the initial ring cavity geometry. Another passive Q-switch, Cobalt MALO, was used in the 1319 nm channel and Nd:YLF was abandoned for Nd:YAG. This laser (see Section 6.5.2 in Chapter 6) was capable of operation at faster speeds—initially up to 30 Hz. The final piece of the puzzle was an active cavity length stabilisation scheme (see Appendix 3), which dramatically improved laser stability and allowed large DWDH holograms to be routinely produced.

7.5.4.2.11 Commercial DWDH Printers Based on 2001 Geola Printer

In 2004 to 2005, the company XYZ Imaging produced a commercial DWDH triple-beam printer based on the original Geola design (Figure 7.14). This was a film-based device* capable of writing DWDH holograms up to 1.1 m in width at hogel sizes of 0.8 or 1.6 mm. To keep the film at exactly the correct distance from the writing objectives, a vacuum system was used to suck the film onto a flat surface immediately in front of the three objectives (Figure 7.14c). XYZ Imaging also developed an automatic chemical processor. Photographs of holograms produced on the XYZ Imaging printer and on various other DWDH printers are shown in Chapters 10 and 14.

* The printer was designed to work with panchromatic silver halide film produced by the Russian Company Sfera-S.

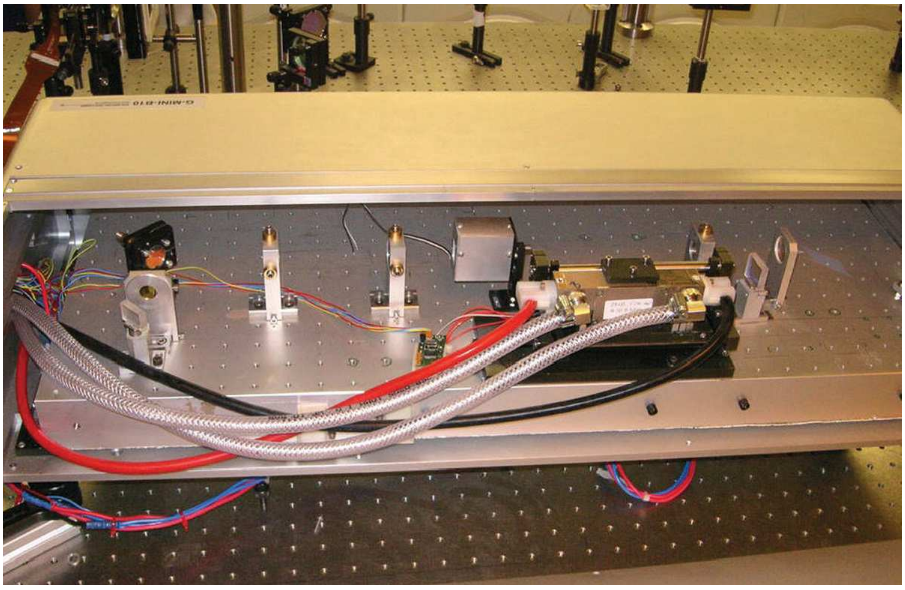

FIGURE 7.15 Short-cavity 532 nm Nd:YAG pulsed laser used in a 2006 prototype DWDH printer based on an LCOS display at Sussex University. The actual laser is visible in the centre of the picture. The optics in the larger laser case, are for frequency doubling and beam collimation. The main printer optics are visible in the background. The laser delivered stable pulses up to an energy of 1 mJ at a repetition rate of up to 50 Hz.

7.5.5 Printers Based on Liquid Crystal on Silicon Displays

John Tapsell [19], working at Sussex University in 2006, converted an old monochromatic DWDH printer supplied by Geola to work with a liquid crystal on silicon (LCOS) device. Marcin Lesniewski designed a telecentric afocal reversing system for the printer so that his 105° Fourier transform objective, which was used in the XYZ Imaging commercial printers, could be used with a BR768HC LCOS panel from Brillian. The printer used a short-cavity 532 nm, 30 ns pulsed Nd:YAG laser (Figure 7.15) of the type described in Section 6.5.3.1. The 768 × 1280 LCOS panel measured 17.91 mm diagonally and had a 12 µm pixel pitch. The fill factor was 92% with a reflectivity of 71% and a frame rate of 120 Hz. Small monochromatic DWDH reflection holograms were recorded with the system with a write rate of up to 40 Hz and a hogel size down to 300 µm. Very little energy was required and the 2000:1 contrast ratio available from the LCOS display produced a better quality image than available with comparative tests using an XGA1 Sony LCD panel. Figure 7.16 shows a diagram of the Sussex printer.

Geola Technologies Ltd used the experience gained from working on the LCOS printer at the engineering school of Sussex University in 2006 to come up with a concept design for a large-format RGB triple-beam DWDH LCOS printer. This design was subsequently used as the basis for the construction of a commercial printer built by the Centre for Laser Photonics in North Wales* for the production of metre-square full-colour reflection master holograms. Figure 7.17 shows a schematic of the design and Figure 7.18 shows a 3D visualisation.

The use of LCOS panels in DWDH printers is relatively simple. The slightly increased complexity of the object beam optical system is well merited due to the clear advantages offered by these panels in terms of higher switching speed (up to 200 Hz), better contrast (typically 2000:1) and superior efficiency (>70%). Table 7.1 lists the lenses used in the telecentric afocal reversing system and the Fourier transforming objective employed in the triple-beam printer.

* The Centre for Laser Photonics was a joint venture between Geola Technologies Ltd and Optropreneurs Ltd., which was operational between 2006 and 2010.

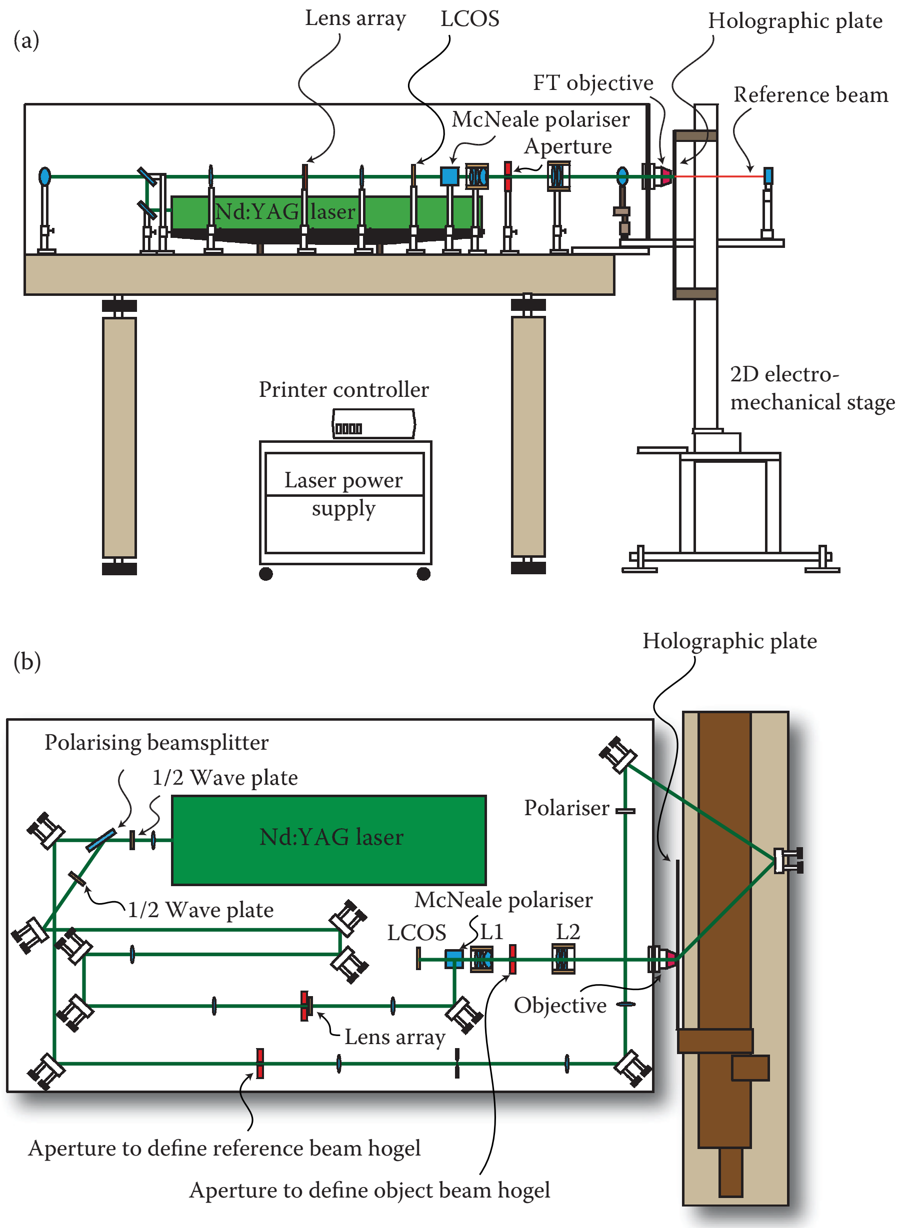

FIGURE 7.16 Sussex University LCOS printer. (a) Side view of the printer and (b) optical schematic. Note that the lens systems (L1 and L2), together with a meniscus field curvature correction lens next to the LCOS, form an afocal telecentric reversing system.

7.5.6 Printers Incorporating Variable Reference Beam Systems

All the printer schemes that we have reviewed above have used static reference beams. This is the simplest case to arrange optically. However, a static reference beam means that the written DWDH hologram must be replayed with a collimated light source if one is to avoid injecting any aberration into the hologram. However, this is rarely practical—in practice, the hologram must be illuminated by a point source relatively close to the display. One solution around this problem is to numerically predistort the image data to exactly counteract the induced aberration. We shall derive the equations needed for this purpose in Chapter 11 and discuss their solution in Appendix 4. For colour reflection holograms, both chromatic and geometric predistortion of the image data are required. Unfortunately, there is a rather strict limit on how much predistortion can be applied successfully and it gets more difficult the larger the hologram and the greater its field of view. Therefore, although numerical predistortion can certainly help, it is only very

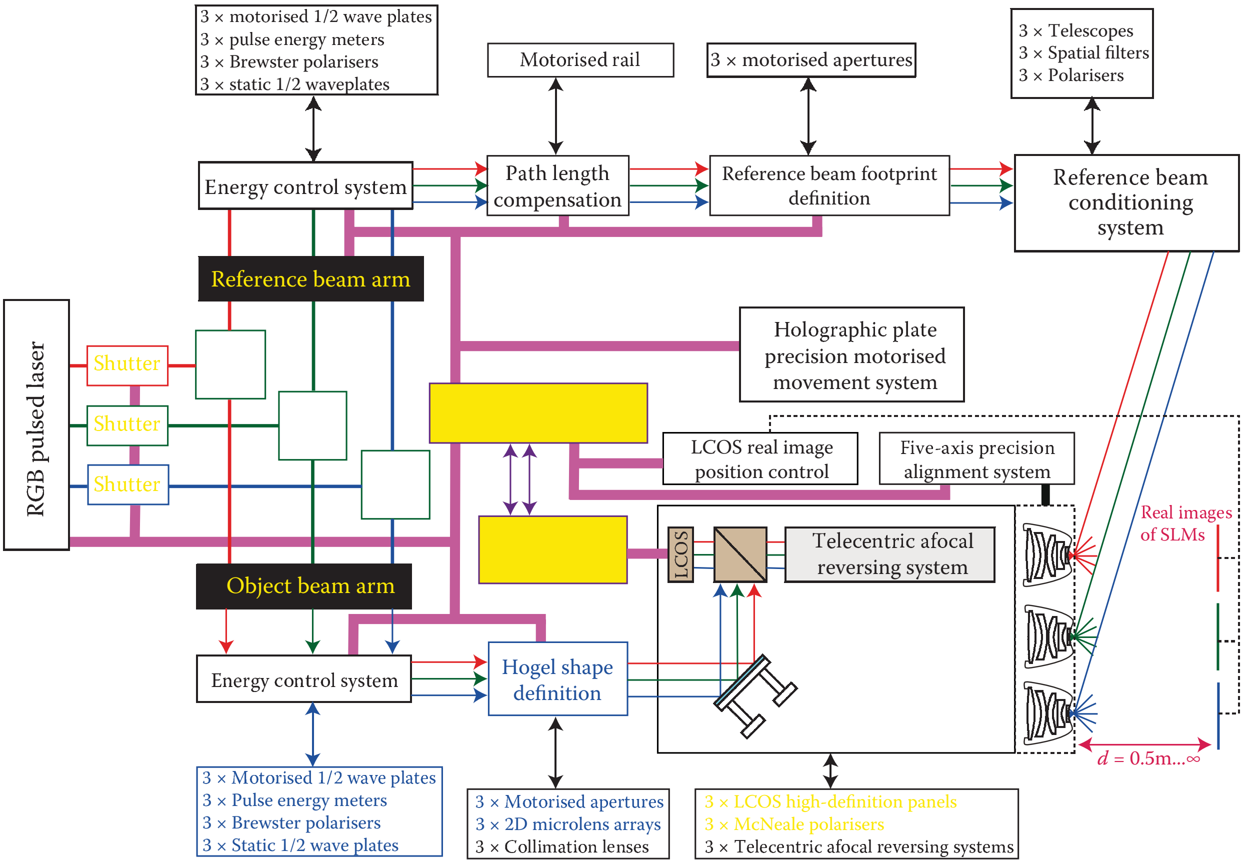

FIGURE 7.17 Systems schematic for a large, triple-beam DWDH LCOS printer that was built by the Centre for Laser Photonics in Wales. The design includes separate computers for image display and machine control for eventual operation at 120 Hz. The main trigger signal is originated by the LCOS controller and this is used to drive the main mechanical stage and the laser. A five-axis alignment system is used for easy alignment of the three objectives.

rarely capable of completely solving the problem of induced aberration due to a disparity in the reference recording and replay geometries.

The solution is to incorporate a variable-angle reference beam system into the printer. Each hogel can then be recorded using a software-selectable altitudinal and azimuthal angle. By choosing these angles carefully for each hogel, any type of macroscopic reference recording beam may be synthesised. In this way, a hologram may be produced so that it replays perfectly for a given location of the illuminating point source. In addition, under certain circumstances, small variations of the reference angle at each hogel may be combined favourably with numerical image predistortion to enhance the angle of view available from a given printer.

The downside to variable-angle reference beam systems is that they are rather more complex than static reference beam systems and can, if not designed properly, induce various problems including blurring and dimming into the hologram. The basic issue is that the object and reference beam footprints at the emulsion surface must overlap quite precisely. For small hogels (and they can go down to <250 μm), it can be a difficult enough task to arrange for proper footprint matching with a static reference beam, let alone for a 2D variable reference beam.

The simplest solution is to use a 2D-gimballed precision rotation stage to deflect the laser beam to a second 2D-gimballed rotation stage, itself mounted on a 2D translation stage. A computer then calculates the rotation angles and translation distances such that the reference beam strikes the hogel at given altitudinal and azimuthal angles. Of course, as the angles change, so the footprint at the emulsion surface also changes—this then needs to be compensated by the 2D rotation of a square aperture upstream of the hogel placed within a weak image-relaying system.* Figure 7.19 shows a schematic of this system.

* An LCD may also be used here as a programmable mask of variable shape.

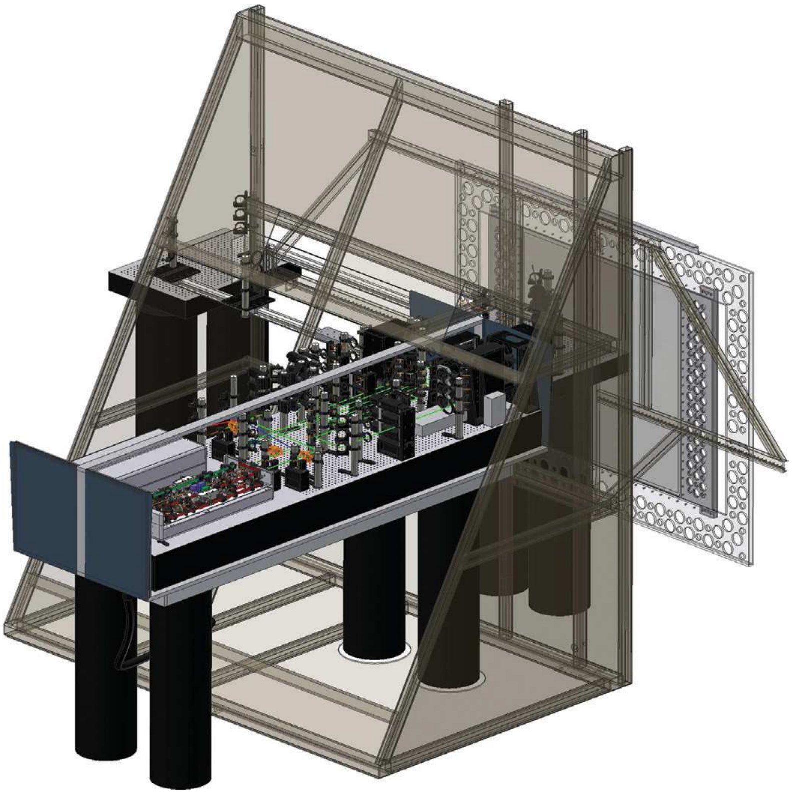

FIGURE 7.18 3D computer drawing of the large LCOS printer from Figure 7.17. Note the two lasers at the rear of the optical unit. The intention was to use a pulsed chromium forsterite laser for the red channel (627 nm) and to use an additional dual-channel 446 nm/532 nm pulsed Nd:YAG laser for the red and blue channels. In the actual printer, this design was modified to include only a single standard 440/532/660 nm RGB laser.

To work properly, this scheme must be very compact as the precision of the beam footprint alignment scales strongly with size.

Another type of variable reference beam system is based on a lens system and a single small-angle 2D-gimballed precision rotation stage as illustrated in Figure 7.20. Here, the centre of the reference beam is always aligned with the centre of the object beam and a small change in rotation angle produced by the rotation stage leads to a much larger change in angle at the hogel. The advantage of this type of system is that the footprint alignment is much more stable. The disadvantage is that if a large range of angles is required, then aberration in the lens system can induce blurring into the hologram. In addition, the footprint shape often changes in a non-linear way at large angles, requiring the use of an SLM as the apodising element. Figure 7.21 shows a photograph of a lens-based variable reference beam system in a recent triple-beam printer.

7.5.7 HPO Printers

The SLM mask file patterns used in triple-beam printers to print DWDH HPO holograms (ignoring numerical distortion correction for finite optical objective distortion and viewing window functions) are independent of the vertical coordinate. Horizontal information (as typified by the central row in the SLM) is essentially repeated in all rows within the viewing window. The vertical coordinate of the SLM is thus used in a very simplistic manner in these printers to induce a vertical divergence of rays at the hogel.* However, it is possible to use the vertical coordinate of the SLM to encode multiple hogels; to do

* Of course, when a full-parallax hologram (or indeed a rainbow hologram) is being written, this is not the case.

TABLE 7.1

Lens Parameters for the Telecentric Afocal Reversing System and Fourier Transform Objective Used in the Triple-Beam RGB DWDH Printer Manufactured by the Centre for Laser Photonics in Wales (2009)

	Green Channel		EFL = −7.669		Red Channel		EFL = −7.671		Blue Channel		EFL = −7.716	
No.	**Radius (mm)**	**Clear diameter (mm)**	**Separation (mm)**	**Material**	**Radius (mm)**	**Clear diameter (mm)**	**Separation (mm)**	**Material**	**Radius (mm)**	**Clear diameter (mm)**	**Separation (mm)**	**Material**
1	Plane	2.301	4	Air	Plane	2.301	4	Air	Plane	2.318	4	Air
2	−20.34	9.562	3.07	S-SF6	−19.476	9.563	3.15	S-SF6	−21.69849	9.627	3.05	S-SF6
3	−9.616	11.63	1.93	Air	−9.3	11.678	1.8	Air	−10.03	11.678	2	Air
4	−7.6	12.36	1.45	S-SF6	−7.465	12.309	1.54	S-SF6	−7.852	12.474	1.45	S-SF6
5	−26.03	17.598	3.45	Air	−25.54	17.781	3.36	Air	−29.51541	17.734	3.45	Air
6	−25.027	24.134	7.45	S-SF6	−25.36	24.173	7.5	S-SF6	−27.31236	24.774	7.53	S-SF6
7	−16.144	28.39	0.3	Air	−16.144	28.396	0.3	Air	−16.707	28.995	0.3	Air
8	−201.01914	37.924	7.8	S-SF6	−131.52	37.312	7.64	S-SF6	−142.99318	38.172	7.87	S-SF6
9	−35.57	39.759	0.3	Air	−34.04	39.35	0.3	Air	−34.95308	40.243	0.3	Air
10	59.7	42.1	7.03	S-SF6	60.9	42.341	7.16	S-SF6	63.76992	42.852	6.83	S-SF6
11	1310.14201	41.384	1.27	Air	−568.9	41.829	1.28	Air	−1469.7098	42.281	1.3	Air
12	27.27	38.142	6.15	S-SF6	27.27	38.281	6.15	S-SF6	27.29649	38.636	6.15	S-SF6
13	20.51	32.078	14.72777	Air	20.51	32.205	14.82	Air	20.51	32.379	15.27	Air
14	Plane	46	246.59396	Air	Plane	64	246.59396	Air	Plane	64	246.59396	Air
15	693	64	4.33	S-SF5	693	64	4.33	S-SF5	693	64	4.33	S-SF5

16	224.9	64	7.33	S-BK7	224.9	64	7.5	Air	224.9	64	7.33	S-BK7
17	−304.8	64	0.5	Air					−304.8	64	0.5	Air
18	693	64	4.33	S-SF5	693	64	4.33	S-SF5	693	64	4.33	S-SF5
19	224.9	64	7.33	S-BK7	224.9	64	7.33	S-BK7	224.9	64	7.33	S-BK7
20	−304.8	64	250.1	Air	−304.8	64	250.1	Air	−304.8	64	250.1	Air
21	Plane	50.895	73.58	Air	Plane	50.895	73.58	Air	Plane	50.895	73.58	Air
22	−29.51	35.98	15.2	J-BAF7	−29.51	35.98	15.2	J-BAF7	−29.51	35.98	15.2	J-BAF7
23	−37.1	45.5	0.4	Air	−37.1	45.5	0.4	Air	−37.1	45.5	0.4	Air
24	483.10001	47	6.4	J-SK4	483.10001	47	6.4	J-SK4	483.10001	47	6.4	J-SK4
25	−110.15	47	0.2	Air	−110.15	47	0.2	Air	−110.15	47	0.2	Air
26	129.42	47	9.8	J-SK12	129.42	47	9.8	J-SK12	129.42	47	9.8	J-SK12
27	−80.91	47	4	J-SF14	−80.91	47	4	J-SF14	−80.91	47	4	J-SF14
28	Plane	47	50	Air	Plane	47	50	Air	Plane	47	50	Air
29	Plane	30	30	S-BK7	Plane	30	30	S-BK7	Plane	30	30	S-BK7
30	Plane	30	36.68504	Air	Plane	30	36.68504	Air	Plane	30	36.68504	Air
31	−65.845	30	2	S-SF5	−65.845	30	2	S-SF5	−65.845	30	2	S-SF5
32	Plane	30	1.15834	Air	Plane	30	1.23033	Air	Plane	30	1.67108	Air
	Thickness	807.707			Thickness	807.779			Thickness	808.279		

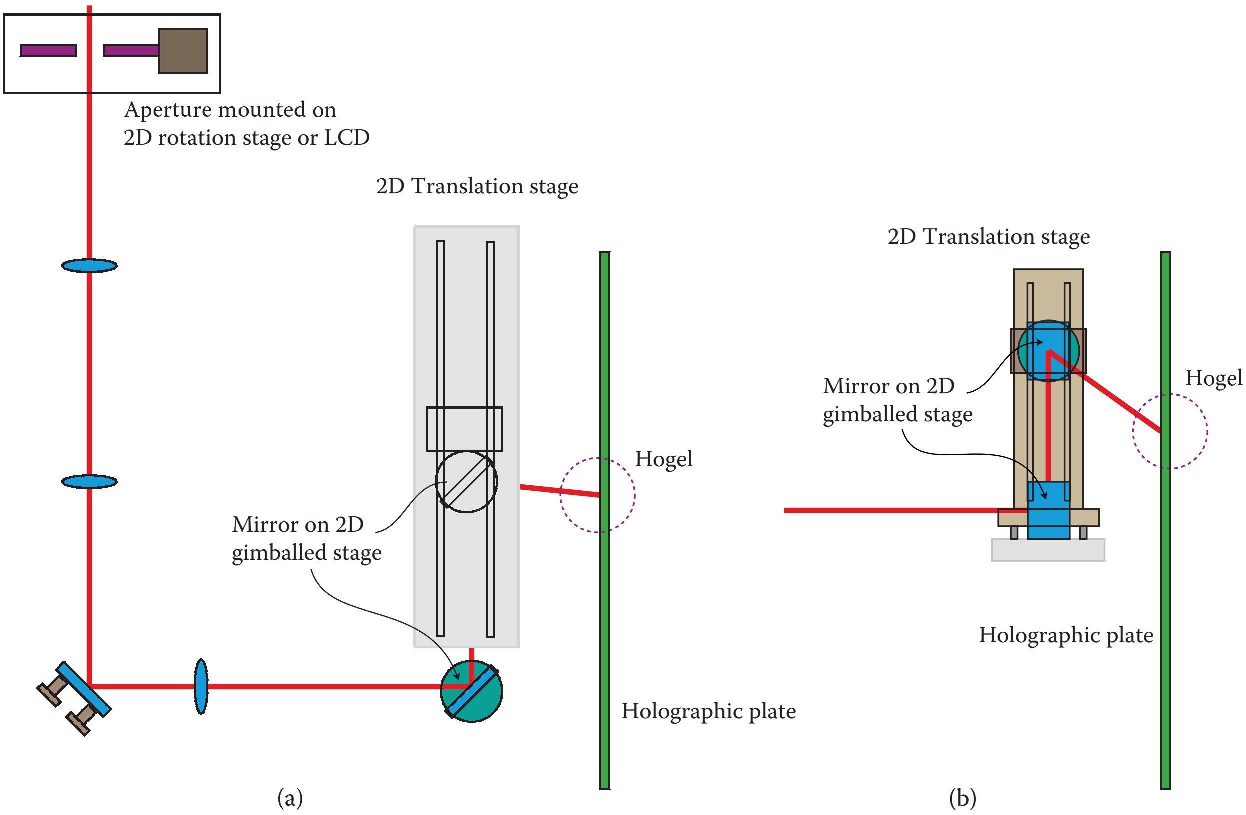

FIGURE 7.19 Simple optical scheme for automatically changing the reference beam angle (altitude and azimuth) at each hogel—view from the top (a) and from the side (b). Note that for fast printing, each motor controller must be preprogrammed with exact position data versus time. Before hogel-writing commences, the motors will need to backtrack a little and then start an acceleration sequence. Thereafter, the velocity of each stage will, in general, be a non-linear but smooth function of time. This ensures that the reference beam attains the correct angles and proper footprint alignment at each hogel at just the correct time without introducing mechanical transients into the system.

this, one must delegate the job of creating a vertical divergence of rays at the hogel to another system. The Fourier transforming objective then becomes a cylindrical lens system and the form of the hogel becomes an elongated column, the length of which, in the simplest variant, is equal to the SLM panel height, although a telescope may easily be used to modify this. A vertical diffusing element must be used in contact with the holographic emulsion and a modified "elongated column" reference beam must be employed. Klug and Kihara [20] described a variant of this system in 1995.

In 1998, Shirakura et al. [21], working at Sony Corporation, designed and built an integrated one-step CW laser HPO DWDH monochrome reflection hologram portraiture printer using this concept (Figure 7.22). The system consisted of a charge-coupled device (CCD) camera for image capture, a high-speed image processing device and a desktop DWDH HPO digital holographic printer. The portraits were delivered as an HPO 3D image (78 mm × 59 mm) and recorded on DuPont photopolymer film (HRF700XO71-20). The CCD camera unit moved along a straight track from right to left, driven by a stepping motor. There was another stepping motor in the camera unit to move a 2/3 in. CCD unit anti-parallel to the direction in which the camera moved; these two motors were synchronised so that the optical axis was always pointing directly at the object.

The hologram was recorded by projection of the digital images through a 510-K pixel thin-film transistor monochrome LCD using one-dimensional image compression with a cylindrical lens. The images displayed on the LCD were calculated from the perspective images available from the camera. The CCD camera recorded 295 2D images (640 pixels by 480 pixels) which were captured in 7.5 s of shooting (30 frames/s). A 400 mW frequency-doubled CW Nd:YAG laser of 532 nm was used as the recording light source in the tabletop printer, which measured only 1100 mm × 700 mm × 300 mm. Each column hogel (0.2 mm × 78 mm) was exposed onto the photopolymer in 0.25 s. A diffuser was attached to the LCD to

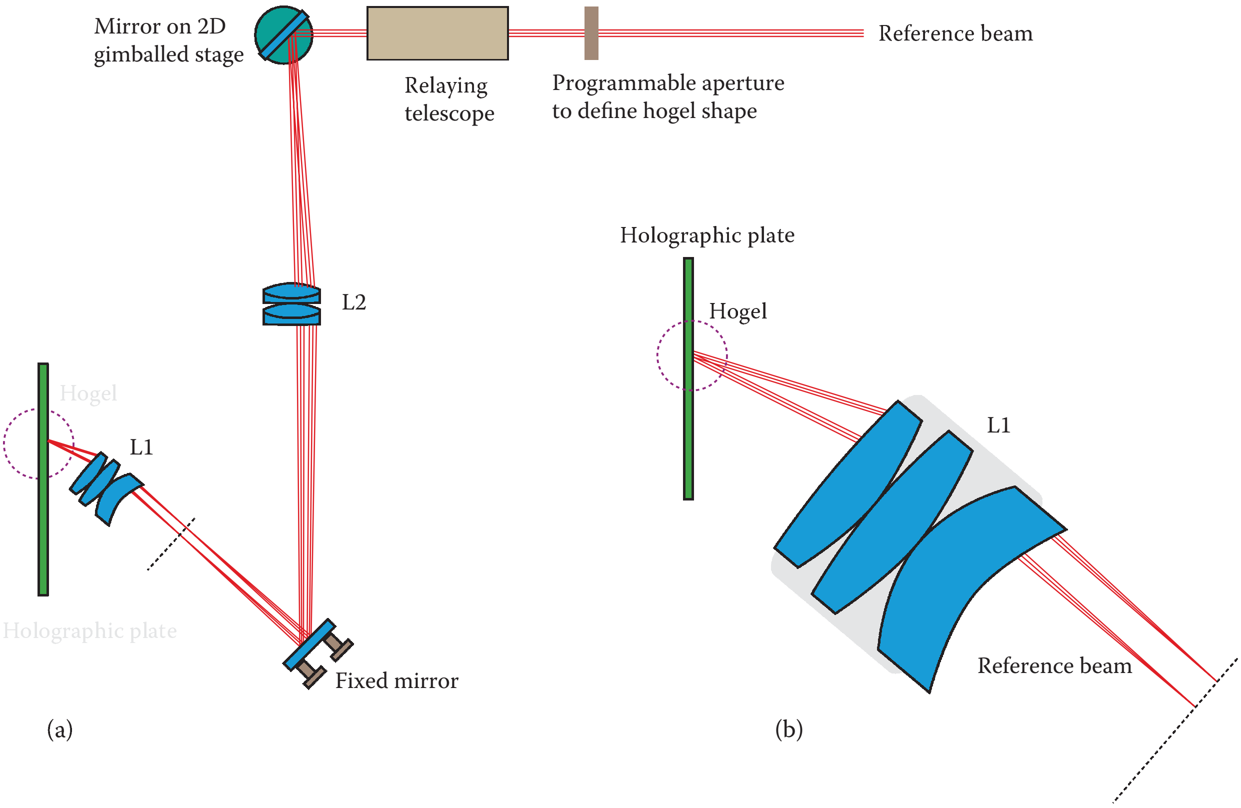

FIGURE 7.20 Lens-based optical scheme (a) for automatically changing the reference beam angle (in altitude and azimuth). Details of the main reference objective and the rays affecting the hogel under two different angles of incidence are shown (b). A typical system may be able to achieve a variation ±25° at the hogel (in both vertical and horizontal angles) for an angular variation at the gimballed rotation stage of ±1.5°. Due to intrinsic aberration of systems that can cope with large angle variations, a programmable aperture such as an LCD may be used in junction with a relaying telescope to ensure a proper hogel shape at all times.

make the beam intensity more uniform within the width of an elemental hologram and a slit, placed at an optical plane conjugate to the film plane, was used to form the hogel. The cylindrical focussing lens gave the holograms a horizontal field of view of 57°. A vertical diffuser in contact with the film likewise ensured a vertical viewing angle of 40°. The entire printing time of the 295 column hogels took only 147 s.

Clearly, a triple-beam pulsed laser DWDH printer designed using this concept could be expected to print HPO holograms much faster than the type of DWDH printers we have been discussing up until now. Nevertheless, in practice, it can be difficult to stop the hologram from looking "banded" and there are issues associated with the use of a contact diffuser.

7.5.8 Single-Beam RGB Printers

Single-beam DWDH printers can be constructed using apochromatic lens systems if resolution or angle of view can be sacrificed. Often, source size and chromatic blurring significantly limit the available depth in a display hologram. One may not then need the increased resolution available from a monochromatic system, and as such, it makes sense to design the printer using a single hogel write head. As we have discussed previously, this enormously simplifies the task of aligning the component colours.

7.5.8.1 Screen-Based Hogel Formation Systems

When limited depth in a hologram is acceptable, a lensless solution forming a single RGB hogel can also be used. In fact, we began our discussion of DWDH printers by presenting just such a system, based on a diffusion screen (Figure 7.2). We did, however, mention that there were several problems associated

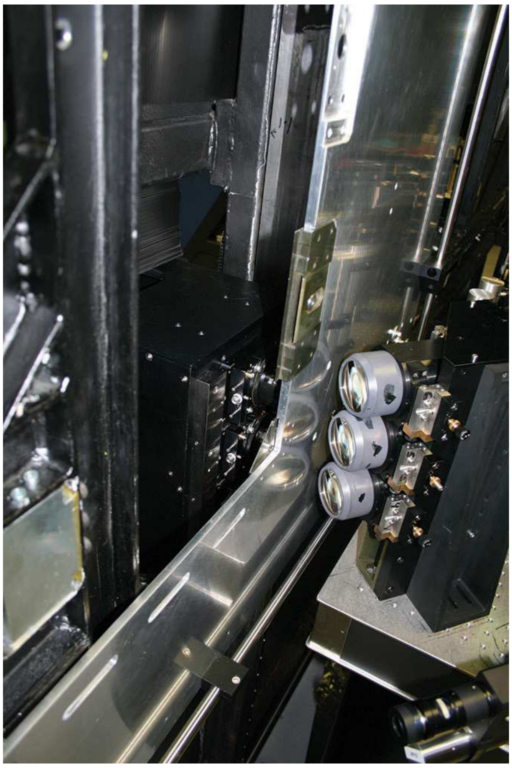

FIGURE 7.21 Photograph of a lens-based variable reference beam system in a modern large-format DWDH printer. To the left of the plate carrier (just visible) are two of the three object beam Fourier transform lenses. To the right of the plate carrier are the three lens systems for the reference beam angle control.

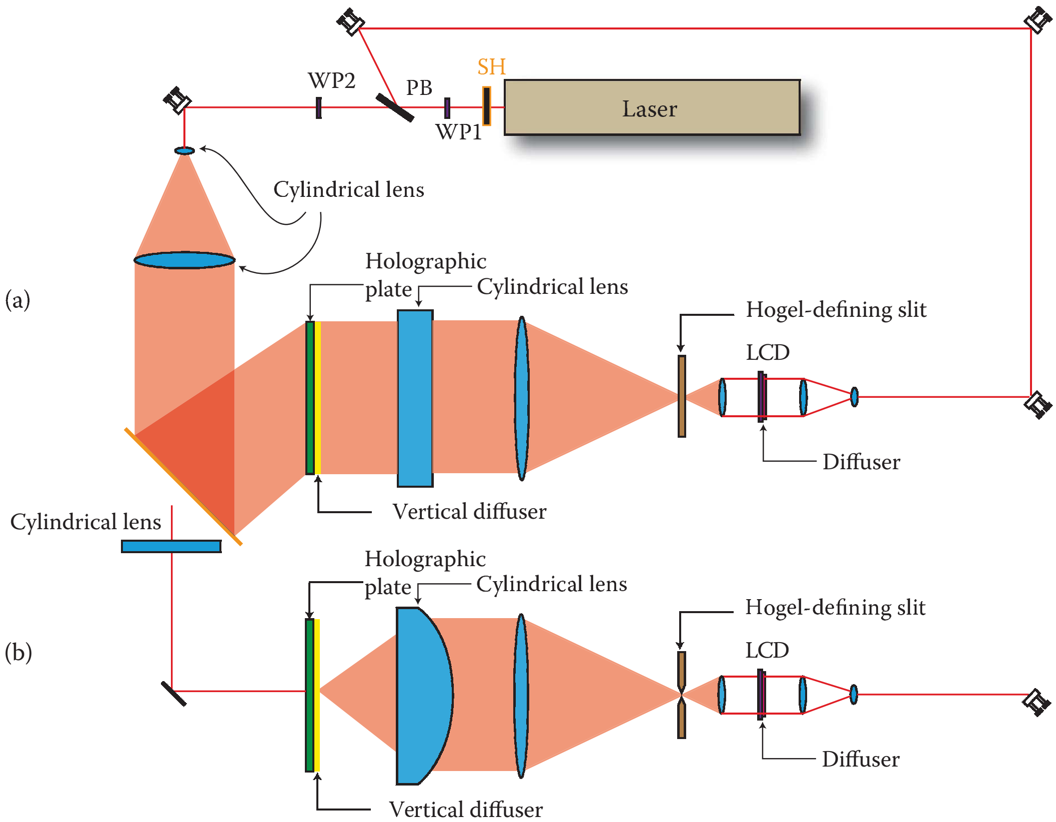

FIGURE 7.22 Simplified optical schematic of the 1998 Sony Corporation portrait printer, which printed small monochrome DWDH HPO reflection holograms as elongated "column" hogels using a 400 mW CW Nd:YAG laser in under three minutes. (a) Side view and (b) overhead view.

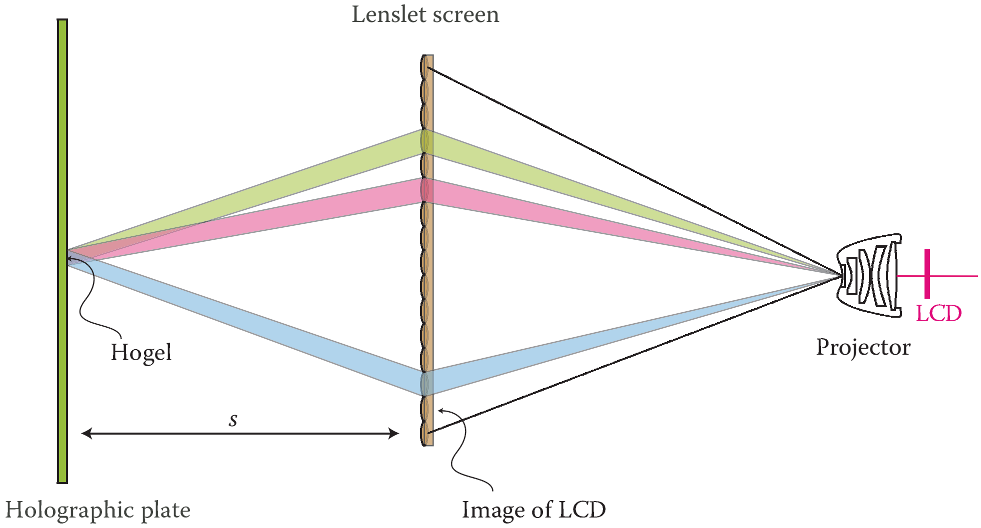

FIGURE 7.23 Diagram of an object beam hogel formation system based on a lenslet array. The size of the lenslets is greatly exaggerated.

with the simple diffusing screen. In particular, one needs a contact aperture to form the hogel; also, the energy efficiency is extremely poor. However, both these issues can be resolved by using a lenslet matrix to focus a 2D real image into a hogel (Figure 7.23). Nevertheless, there are two remaining problems. The first is illustrated in Figure 7.24. If the lenslet screen is too close and the lenslets are too large, then there will be viewing zones with no images. This produces the effect of image points flickering as an observer walks past the hologram. To avoid this, the lenslet size must be reduced, but this introduces a divergence into the ray bundles connecting each lenslet to each hogel. Any such divergence of a large enough magnitude will introduce blurring into points within the hologram beyond a certain depth. As we shall study in Chapter 11, a general paraxial formula for the critical depth, beyond which (interior) blurring occurs due to any form of ray bundle divergence is given by

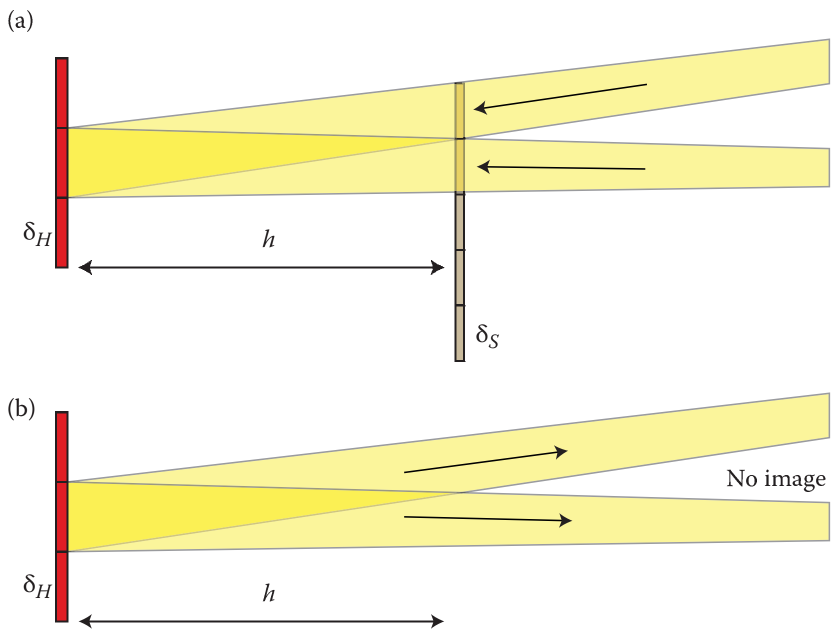

FIGURE 7.24 Diagram illustrating (a) the recording and (b) playback of a hogel using a lenslet screen. If the lenslet screen is too close, and the lenslets are too large, then there will be viewing zones with no images.

$$\begin{aligned} d &\sim \frac{h\delta\theta_{\text{Eye}}}{\delta\varphi - \delta\theta_{\text{Eye}}} \qquad \forall\delta\varphi > \delta\theta_{\text{Eye}} \\ &\sim \infty \qquad\qquad\qquad \forall\delta\varphi \le \delta\theta_{\text{Eye}} \end{aligned} \tag{7.6}$$

where h is the viewing distance from the eye to the hogel, $\delta\varphi$ is the ray bundle divergence and $\delta\theta_{\text{Eye}}$ is the angular resolution of the human eye. In the limit that the lenslet size is much smaller than the hogel size, which will usually be correct for a close screen, the ray bundle divergence induced in the present case is simply $\delta\varphi = \delta_H/s$, where s is the screen to hogel distance.

As an example, let us take a hogel diameter of 0.5 mm. Then, if we place the screen at a distance of s = 5 cm from the hogel, at a viewing distance of h = 0.5 m, we will observe blurring at a distance of d = 6 cm into the hologram. This is clearly not very acceptable. At a distance of s = 15 cm, things are rather better. Resolvable image blurring then starts at approximately d = 22 cm for h = 0.5 m. Decreasing the hogel size makes things even better. If one goes to a hogel size of 250 μm, then a screen placed at 15 cm will only induce image burring at a depth of more than 75 cm for h = 0.5 m. However, we must be careful here because decreasing the hogel size will induce a second type of blurring—digital diffractive blurring. The critical distance at which digital diffractive blurring operates (for wavelengths, λ) is given by

$$\begin{aligned} d &\sim \frac{h\delta\theta_{\text{Eye}}}{\lambda/\delta_H - \delta\theta_{\text{Eye}}} \qquad \forall\lambda/\delta_H > \delta\theta_{\text{Eye}} \\ &\sim \infty \qquad\qquad\qquad \forall\lambda/\delta_H \le \delta\theta_{\text{Eye}} \end{aligned} \tag{7.7}$$

We shall discuss this type of blurring in Chapter 11—but basically, it is caused by the innate diffractive property of a small source (the hogel). Plugging in the numbers for the case of interest, we obtain a value for d of 44 cm for h = 0.5 m.* Therefore, for a 250 μm hogel, digital diffractive blurring is more limiting at h = 0.5 m than the blurring induced by a close recording screen. In fact, digital diffractive blurring gets worse as you get closer to the hologram, and thus, one wants to avoid using too small a hogel. By ensuring that the hogel size is greater than or equal to 0.5 mm, this type of blurring is eliminated for the human observer with normal eyesight.

As long as the field of view of the hologram is not too great, it can therefore be feasible to use a lenslet screen to form the hogel. Good quality small-hogel (albeit relatively shallow) holograms can be made in this way within the design remit of a compact printer. However, we will now illustrate why this technique is not so appropriate for the case of ultra-realistic holograms of great depth and field of view. Let us again take a hogel diameter of 0.5 mm; anyhow, we cannot use a smaller diameter without incurring digital diffractive blurring. We now demand no induced blurring from any viewing distance. However, to guarantee this, we need to place the screen at a distance of at least 500 mm from the hogel. At a field of view of 130°, this leads to a screen that is more than 2 m wide!

Holographic diffusers and holographic optical elements may also be employed usefully as hogel-forming devices. These elements are usually used as a more convenient form of the lenslet matrix screen. Most screen-based hogel production techniques have two main potential advantages. The first is that they can usually be used in an apochromatic or single-beam printing system. The second is that, even for high fields of view, they have the potential of not inducing any image distortion into the hogel. In high-numerical aperture, lens-based systems, one must inevitably tolerate such induced distortion, which is caused by a finite fifth Seidel coefficient.

7.5.9 Ultra-Realistic Printers

Ultra-realistic printers are DWDH printers capable of producing full-colour high virtual volume (HVV) displays. HVV holograms are digital full-colour reflection holograms which, when illuminated correctly,

* We assume that the average human eye can resolve 1 mm separations at a distance of 1 m.

exhibit essentially no perceivable image blurring or distortion. For a printer to be capable of writing HVV displays, it must have the following characteristics:

- Rigid high-precision printing medium such as photosensitive glass plates
- High-precision 2D electromechanical plate translation stage
- Hogel-writing SLMs with a sufficiently high pixel count
- Hogel-forming optical system with a sufficiently high resolution and sufficiently high numerical aperture
- Reference beam system with a sufficiently low divergence

In addition to these constraints, the photosensitive material must be capable of supporting a high spatial frequency, of not changing its physical size upon processing* and of producing a good diffractive response—this is especially needed if the field of view at replay is required to be large as in the case of holographic window-type displays. The image data and image processing must also be able to produce a data set that either matches the optical resolution of the printer or betters that of the human eye. For an HVV hologram to actually generate a proper "HVV" image, the hologram must be illuminated properly. This means that the diameter of the illuminating source must be smaller than 1 mm for every 1 m that the source is diagonally distant from the hologram. The spectral width of each colour illuminating the hologram should also be less than 1 nm. Any larger than this and there will be induced chromatic aberration (unless Bragg selection is able to mitigate this—which is unlikely). However, much below 2 nm, speckle blur becomes a concern. We shall see in Chapter 13 that speckle may be essentially eliminated using devices that induce a fast temporal modulation in the phase of the illuminating light.

The 2001 Geola printer, which we described previously, is not an ultra-realistic printer. It uses an LCD having a horizontal pixel count of 1024 and a paraxial field of view of 86° (note that the non-paraxial field of view is nearly 105° due to a finite fifth coefficient at large angles). This endows each hologram written with an angular resolution of approximately $\delta\varphi = 1.8$ mrad—which is nearly two times the human eye resolution. Following Equation 7.6, the maximum clear depth that the holograms can display is given by the paraxial rule

$$d \sim \frac{h\delta\theta_{\text{Eye}}}{\delta\varphi - \delta\theta_{\text{Eye}}} \tag{7.8}$$

which, for a viewing distance of $h = 1$ m, comes out at approximately 1.25 m.

The 2001 Geola printer could be potentially modified by replacing the 1024 × 768 LCD display with a 1080p panel. This would solve the SLM insufficiency problem for paraxial viewing because the resolution of the Fourier lens system is easily sufficient to resolve the 1080p panel. However, at higher angles, the resolution falls below the pixel size and again blurring due to insufficient objective resolution is injected into the hologram, fundamentally limiting the virtual volume.

In thinking about the design of the ultra-realistic DWDH printer, we come up against two conflicting processes. On the one hand, we generally wish to increase the field of view of the hologram. This is certainly the case for "holographic window"-type displays in which the idea is to mimic a window. To do this, we are obliged to use a higher numerical aperture objective. However, on the other hand, we must now increase the resolution of the objective to be able to resolve more SLM pixels. Further work needs to be done in investigating how far both conditions may be satisfied in a single compound lens system. Current objectives made at Geola use SF6 glass. It is possible that by using higher index glasses, a higher numerical aperture might be attained at sufficiently high resolution.

However, even if this were the case, current HD SLMs do not have the pixel counts required for large fields of view. We shall see in Section 14.4.1 of Chapter 14, that at least four 1080p panels are required to write an HDD hologram with a field of view of 100° × 120°. Although it is possible to tile these displays together using prisms and a variant of the telecentric afocal reversing system described previously, the

* Although a physical change in the thickness of the emulsion and a change in the refractive index on processing can be compensated for using numerical image processing algorithms, this inevitably leads to the introduction of some noise.

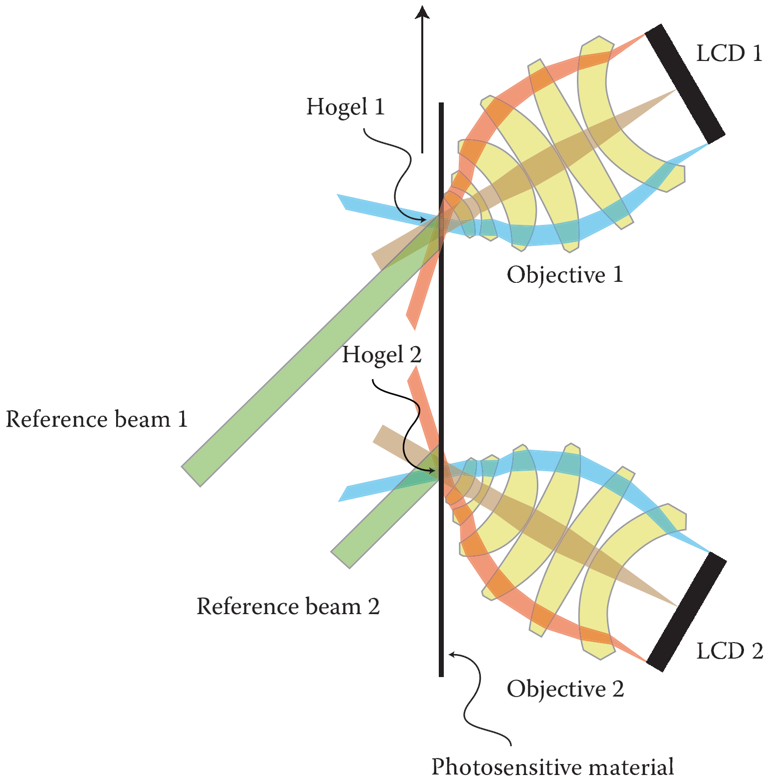

FIGURE 7.25 Writing a very-wide angle hologram using multiple objectives. Objective 1 writes hogel 1 and objective 2 writes hogel 2. Then, as the film advances, hogel 2 is overwritten by objective 1 again. In this way, hogels can be built up in several steps.

proposed UHDTV 4320p standard, which has a pixel count of 7680 × 4320, would certainly make the optics rather simpler.

7.5.9.1 3N-Objective Printers

Beyond a certain field of view, it becomes impractical to write HVV holograms using single compound lenses for each primary colour. With a sufficient index modulation in the photosensitive material (see Chapters 11 and 12 for the theory behind this), one can, however, envisage writing hogels in angular segments as illustrated in Figure 7.25. The idea is basically an extension of the RGB triple-beam printer concept—except that here, one would use, in the simplest variant, an array of 2 × 3 objectives, two for each colour. These two objectives would be angled such that, together, a greater horizontal field of view could be covered. Special care is needed with the numerical image processing in the overlapping regions, as the rays from the two SLM/objective systems do not of course align. In some cases, it may therefore be better to use a 3 × 3 system (or a $3^2 \times 3$ system in the case of 2D angle extension) rather than a 2 × 3 system.

7.5.10 DWDH Transmission Hologram Printers

Geola has run a number of research projects using DWDH transmission printers since 1999. All these devices have been monochromatic pulsed laser printers operating at either 532 or 440 nm. The optical schematic is just the same as in Figure 7.8, with the single exception that now the reference beam impinges onto the hogel from the same side as the object beam. It can often be a little tricky getting the reference beam in, as there is not much space between the physical end of the objective and the photosensitive plate. For wide-angle objectives, one usually uses an angle of incidence that is a little larger to cope with this. Alternatively, the reference beam can be brought in through the main objective as shown in Figure 7.26.

The main interest in DWDH transmission holograms is that full-colour rainbow, achromatic and mixed rainbow–achromatic holograms may be generated from digital data in a single printing step using

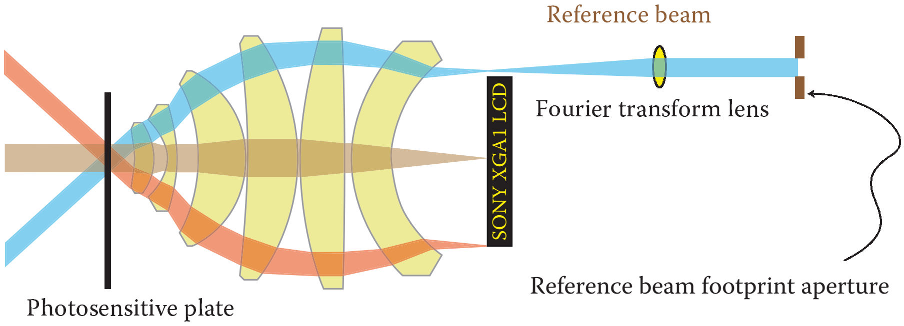

FIGURE 7.26 DWDH transmission hologram hogel formation. Here, the reference beam is actually brought in through the Fourier transform objective.

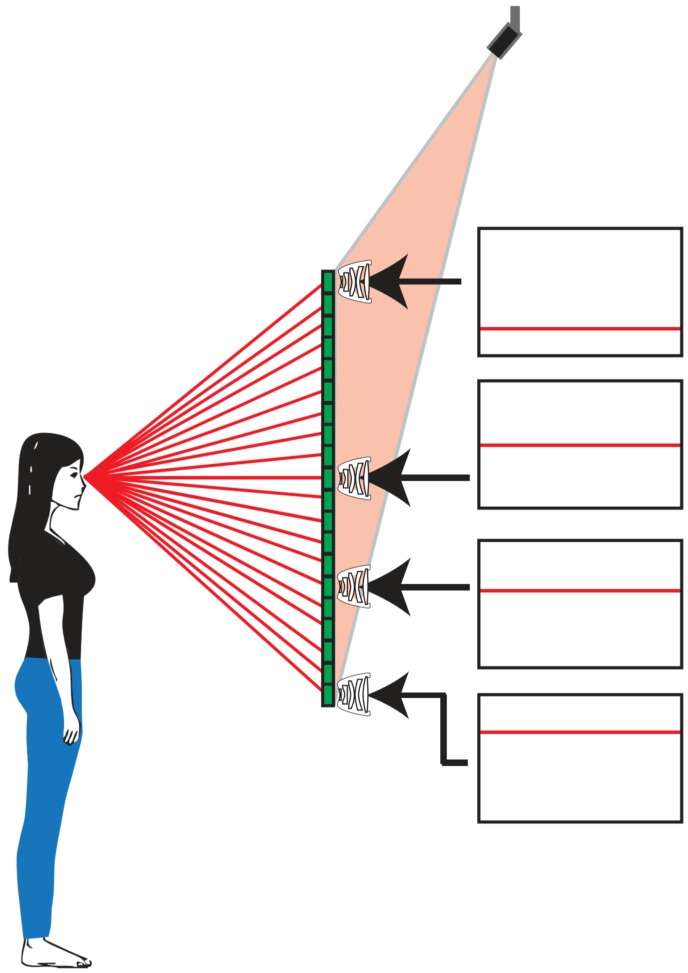

FIGURE 7.27 A 1-slit DWDH rainbow transmission hologram is seen here illuminated by light of only one colour. The observer, as positioned, sees a monochromatic holographic image. On illumination by white light, this image is available at different heights where it replays now with different colours. The four rectangles to the right of the diagram illustrate the data displayed on the printer LCD when the indicated hogels are written. The LCD data for each hogel is in the form of a line which is modulated by image data specific to that hogel. The vertical height of a given line on the LCD is determined by the vertical height of the hogel in the hologram in such a way that a rainbow viewing slit is synthesised as shown. The technique can be extended to any number of rainbow slits (using only a single colour laser) to produce full-colour DWDH rainbow transmission or achromatic transmission holograms.

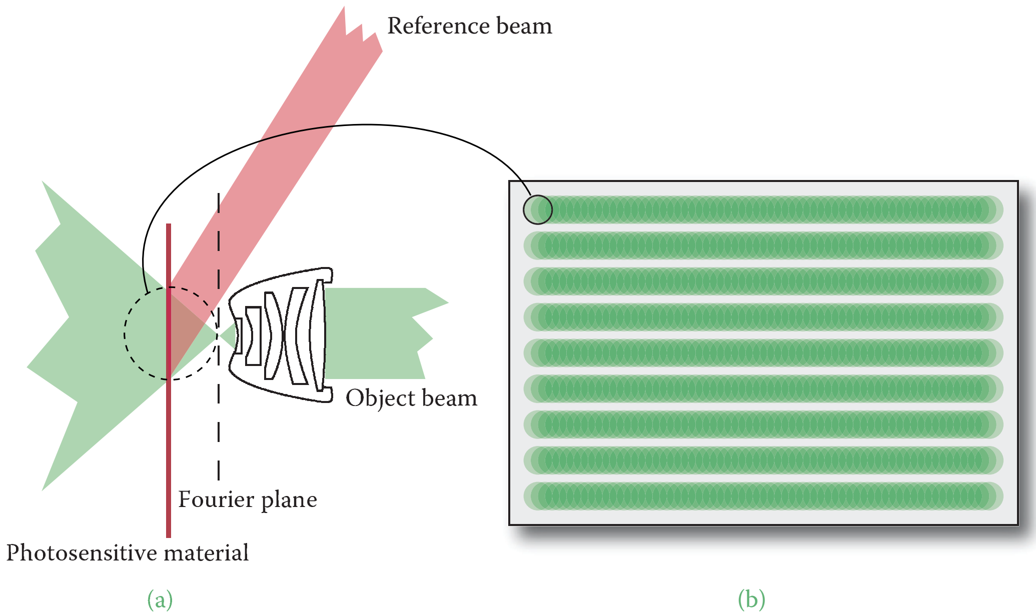

FIGURE 7.28 MWDH often uses overlapping hogels away from the Fourier plan (a). Typical hogel footprints, (b), are shown here for an MWDH transmission H_1 hologram designed for transfer to a HPO reflection H_2 to be illuminated by broadband illumination. Note the distance between hogel lines—dispersion in the vertical direction makes the gaps invisible in the final H_2. Note also the circular hogel shape—in MWDH one is not constrained to use a square or hexagonal footprint.

only a single-colour laser (see Figure 7.27). In principle, these printers are much simpler than the triple-beam reflection hologram printers. By introducing the reference beam into the writing objective, one essentially only has optics on one side of the photosensitive material—and by only needing one laser, the optical scheme can be made very small. Alignment of the reference and object beam is also much easier. Variable reference beam systems can also be incorporated with relative ease. Very compact printers, the size of normal photocopiers, should be achievable using this technique if processing-free materials, such as monochromatic photopolymers, are used. In Chapter 8, we shall study the image-processing algorithms required to write full-colour rainbow and achromatic (i.e., black-and-white) holograms.

Small transmission rainbow and achromatic DWDH holograms have applications in document security. The Geola organisation is currently able to produce such holograms using a 440 nm pulsed laser at a hogel size of 250 μm. The holograms are then transferred to photoresist to make the embossed shims.

Large transmission rainbow and achromatic DWDH holograms have potential applications in advertising and display. They are particularly useful as shop window displays as the images can project outside the shop and into the street. With reflection holograms, a light is needed on the same side as the viewer so this is not possible.

Finally, it is possible to write full-colour, full-parallax transmission holograms using either a single-colour laser or by using three lasers in a triple-beam configuration. However, such holograms must be illuminated by three different colours from substantially different angles to eliminate the cross-talk images. As we shall see in Chapter 11, the volume transmission hologram has greater angle selectivity than the corresponding reflection hologram, allowing angle discrimination to be used more easily.

7.6 MWDH Printers

MWDH is the technique of writing first an H_1 hologram using digital image data and then optically transferring the H_1 to a white light-viewable H_2. In many ways, MWDH is similar to the technique of multiple photo-generated holography pioneered by Spierings and van Nuland [8]. However, no diffusion screen is used, hogels are written as spots rather than long, thin rectangles and digital data replace the photographs. MWDH can also be used to create full-parallax holograms of great depth, which is difficult to arrange using multiple photo-generated holography.

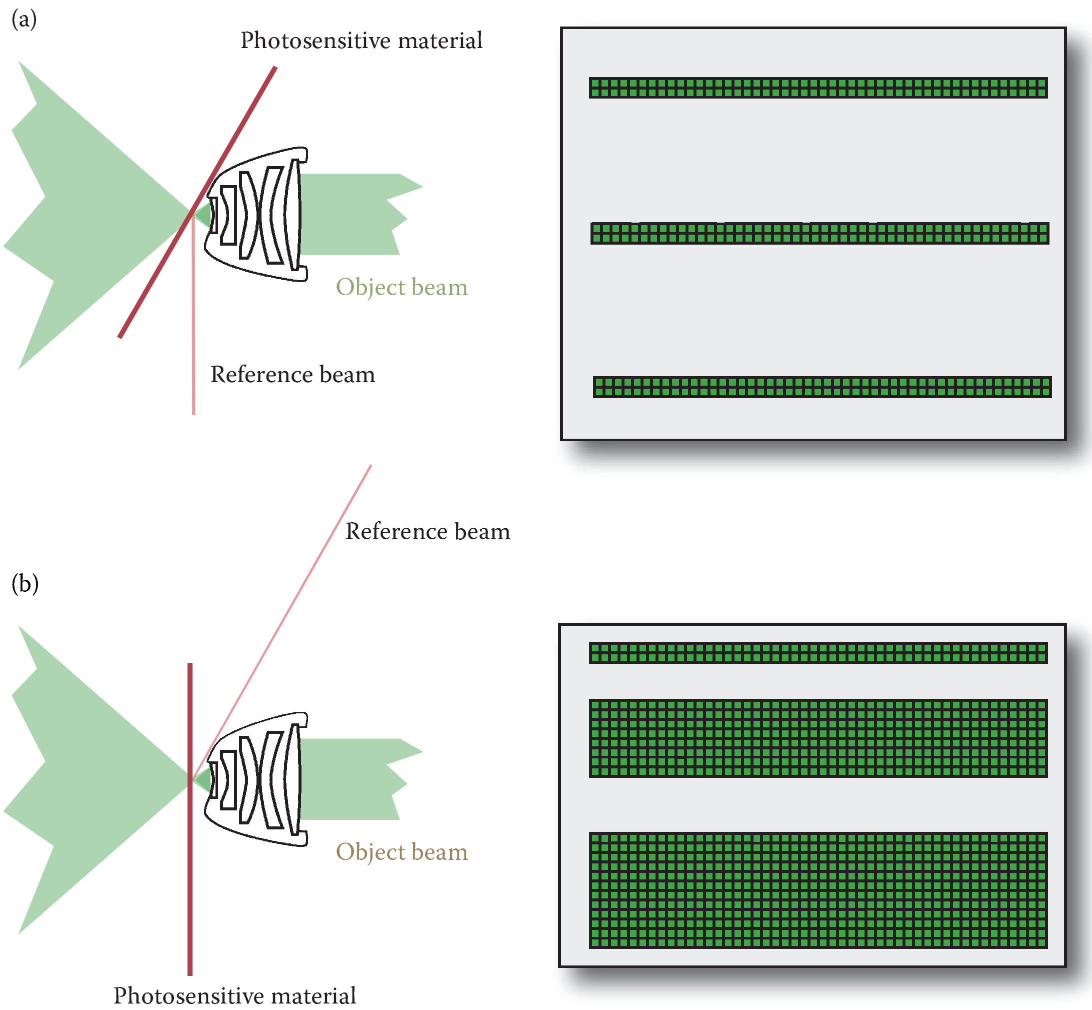

FIGURE 7.29 Writing an MWDH transmission H_1 rainbow master hologram with a monochromatic laser using a plate holder tilted at the achromatic angle (a) and a standard perpendicular plate-holder (b). In (a), the red, green and blue "slits" are the same width because the H_1 is tilted at the achromatic angle. In (b), two of the slits are much thicker as multiple rows of hogels are used to synthesise virtual slits at the correct distance behind the plate. When viewed under laser light, these wider bands would therefore seem to contain an image of a slit behind the hologram. Note of course that the size of the hogel has been greatly exaggerated in the diagram.

From an optical point of view, an MWDH printer is virtually the same as a DWDH printer. The major difference is therefore in the image data. Often, the data required by the SLM(s) in an MWDH printer are just the perspective view data available from a tracking camera. In a DWDH printer, the hogel data must be calculated from the perspective view data by a mathematical algorithm that changes the optical plane. The optical transfer from H_1 to H_2 fulfils this role in MWDH.

Basically, any type of hologram may be made using MWDH or DWDH. The decision as to which technique to use usually comes down to the speed of printing and the ease of copying. A 0.5 mm hogel DWDH hologram, 1 m × 1 m, takes 11 hours to write at a hogel write speed of 100 RGB hogels per second, but if the hologram is an HPO hologram, then the corresponding H_1 hologram can take only a very small fraction of this time to write. This is because an HPO hologram does not usually require such a high vertical hogel density.*

Copying of DWDH holograms is usually done through a contact–copy method. However, with this method, it is not possible to adjust the ratio of the object and reference beams at the copy—as this is defined by the diffractive response of the master hologram. However, certain materials may require a

* This is the case when a broadband illumination source is used.

higher modulation to record a proper copy hologram. The H_1/H_2 distance transfer process solves this problem completely, making it more suitable sometimes for the rapid production of copies. The disadvantage of course is that a full-aperture transfer requires a lot of energy, whereas the contact scheme can be accomplished by line-scanning using a small laser.

In general, MWDH and DWDH are complementary techniques. With full-parallax data, it is possible to transform a full set of perspective view data to any optical plane. In this way, computational and optical image-plane transformations can be combined as desired. This can be useful, for example, to optimise a copy geometry. By using an optical image plane transformation rather than an entirely computational one as in DWDH, the pattern of hogels on the physical plate becomes defocussed and the quality of the hologram can be increased.

Another technique used in MWDH is to write overlapping hogels downstream of the Fourier plane (shown in Figure 7.28). Because an optical transfer will be used to convert the H_1 to an H_2, the loss of diffractive efficiency caused by this overlap does not really matter. The quality of the final H_2 holograms can be somewhat increased using this technique. Another advantage is that for transmission systems, where it is not possible to bring the reference beam through the writing objective, there is now extra space to accomplish this.

Like DWDH printers, MWDH printers can produce either transmission or reflection holograms. Most often, MWDH is most appropriate for transmission holograms written using a monochromatic laser. Here, full-colour rainbow and achromatic holograms can easily be produced using a plate holder that is tilted at the achromatic angle (Figure 7.29). Alternatively, a standard perpendicular plate holder may be used if special image processing transformations are employed. Geola makes commercial H_1/H_2 transfer systems using green-pulsed lasers for formats up to 1 m × 1.5 m (Figure 6.12). One should also note that full-colour transmission or achromatic holograms can be produced using only a single "slit" with MWDH if an RGB laser is used in place of the monochromatic laser.

7.7 Copying Full-Colour DWDH Holograms

As we have already mentioned, printing full-parallax, ultra-realistic DWDH holograms is slow! For the technology to become commercially interesting, either the laser and print speed must be increased dramatically or one needs to develop a technique to copy the DWDH holograms produced. Certainly, print speed may realistically be increased by a certain amount. Current pulsed laser systems can be redesigned to work at up to 120 Hz with flash pumping. Beyond this, diode-pumped laser solutions may be expected to produce repetition rates that can be actually as high as required. However, no SLM technology exists at this moment to practically produce a printer with a repetition rate of greater than 200 hogels per second. To go faster than this requires multiple write heads that, although possible, will increase the price point of any printer rather dramatically.

Here, we present the results of recent experiments (2006–2010) carried out by the Geola organisation to produce high-quality holographic copies of digital master holograms written with a DWDH printer [22]. A standard RGB-pulsed laser (the same as that used to record the DWDH master holograms) was used in the line-scanning contact copying system. Figure 7.30 shows a simplified optical scheme of the experimental setup.

So that a good quality copy may be produced from a reflection master, it is vital that the DWDH master hologram replays at exactly its recording wavelengths. To ensure this, the emulsion must be processed in a special way and care must be taken with regard to ambient humidity and temperature during the entire process.

With reference to Figure 7.30, each of the laser beams (11) passes through computer-controlled wave plates (12) and polarisers (13). By rotating the wave plates (12), the colour balance of the hologram copy may be adjusted. The beams are now cleaned by spatial filters (14) and a proper polarisation is ensured by polarisation correctors (15). The beams are then directed by mirrors (16) to a three-colour combiner-deflector system (17), after which they are shaped by a shaping/deflection system (18) into a narrow elongated and slightly oval achromatic slit. This achromatic beam is then reflected by the flat mirror (22) to illuminate the non-exposed photosensitive material (1) as a reference beam. Part of the achromatic beam

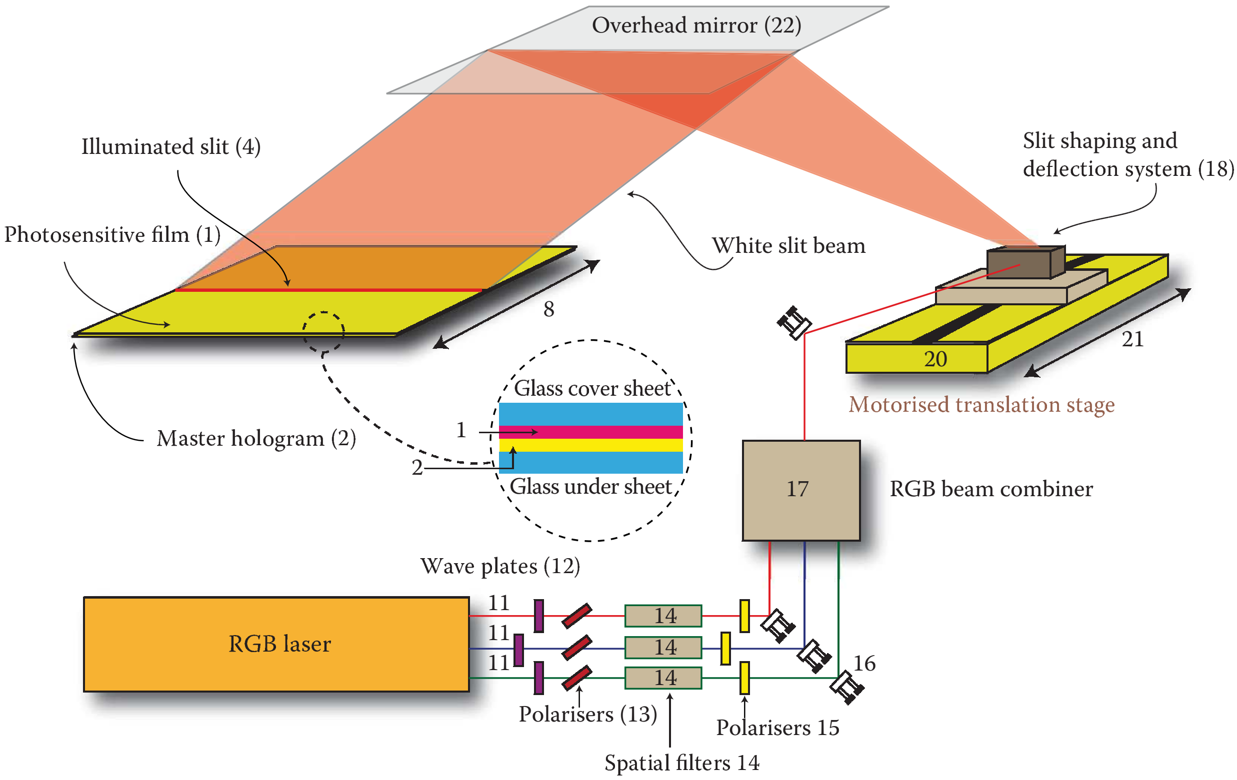

FIGURE 7.30 Simplified optical scheme of a line-scanning RGB film hologram contact copier. The system, which uses multiple pulses from an RGB-pulsed laser, produces RGB reflection film copies from a DWDH master (film) reflection hologram.

FIGURE 7.31 (a) Master DWDH hologram, 0.8 mm hogel, 20 × 30 cm; (b) three-colour copy on PFG03CN silver halide; (c) three-colour copy on Bayer Photopolymer. (Hologram image designed in 3D StudioMax. Courtesy of Razvan Maftei, 2005.)

is, however, transmitted through the photosensitive material and onto the master hologram (2) where it generates a diffractive reflection forming the object beam.

The zone illuminated by the laser slit beam (4) is transverse to the scanning movement of the slit. The laser radiation shaping/deflection system (18) is fixed onto the computer-controlled linear translation stage (20) to ensure an even movement in direction (21). At the same time, the linear translation stage (20) ensures movement of the light slit in direction (8), which is perpendicular to the longitudinal axis of the illumination slit. This ensures an even exposure of both the non-exposed photosensitive material and of the master hologram, giving, in turn, an even recording of the reconstructed master hologram.

Experimental results showed that existing silver halide photoemulsions (Geola tried both PFG-03CN from Sfera-S and the SilverCross emulsion) do not allow the production of full-colour contact copies having a diffraction efficiency greater than the diffraction efficiency of the master hologram. The best result that Geola was able to achieve was a colour copy with a relative diffraction efficiency (as a percentage of the master diffraction efficiency) of 100% in red and green and 50% in blue. Despite the less than perfect result in blue, the quality and brightness obtained were still judged adequate for commercialisation. An interesting observation is that if the copy is made with only two colours, its diffraction efficiency can reach 150% of the master hologram efficiency (using AgX).

A panchromatic photopolymer material from Bayer was also used to record high-quality copy holograms. Here, relative diffraction efficiencies in the red and green of well over 100% were obtained. Figure 7.31a, b and c show the experimental results for both AgX and photopolymer. All of Geola's work has thus far concentrated on AgX film masters. The use of glass-plate masters should, of course, substantially improve the image quality. Additionally, the use of SHSG processing could significantly improve copy efficiency.

REFERENCES

1. B. R. Brown and A. W. Lohmann, "Complex spatial filtering with binary masks," *Appl. Opt.* **5**, 967–969 (1966).
2. L. B. Lesem, P. M. Hirsch and J. A. Jordan, "Scientific applications: Computer synthesis of holograms for 3-D display," *Commun. ACM* **11**, 661–674 (1968).
3. R. V. Pole, "3-D imagery and holograms of objects illuminated in white light," *Appl. Phys. Lett.* **10** (1), 20–22 (1967).
4. D. J. DeBitetto, "Holographic panoramic stereograms synthesized from white light recordings," *Appl. Opt.* **8**, 1740–1741 (1969).
5. M. King, A. Noll and D. Berry, "A new approach to computer-generated holography," *Appl. Opt.* **9**, 471–475 (1970).
6. L. Cross, "The Multiplex technique for cylindrical holographic stereograms," in SPIE San Diego August Seminar (1977) [Presented but not published].
7. S. A. Benton, "Hologram reconstructions with extended incoherent sources," *J. Opt. Soc. Am.* **59**, 1545–1546A (1969).
8. W. Spierings and E. van Nuland, "Calculating the right perspectives for multiple photo-generated holograms," in *Int'l Symposium on Display Holography*, T .H. Jeong ed., Proc. SPIE **1600**, 96–108 (1992).
9. M. Halle, S. Benton, M. Klug and J. Underkoffler, "The Ultragram: A generalized holographic stereogram," in *Practical Holography V*, S. A. Benton ed., Proc. SPIE **1461**, 142-155 (1991).
10. M. Lucente, "*Diffraction-Specific Fringe Computation for Electro-Holography*", Ph. D. Thesis, Dept. of Electrical Engineering and Computer Science, MIT, (1994).
11. M. Yamaguchi, N. Ohyama and T. Honda, "Holographic 3-D printer," in *Practical Holography IV*, S. A. Benton ed., Proc. SPIE **1212**, 84-92 (1990).
12. M. Klug, M. Holzbach and A. Ferdman, *Method and apparatus for recording 1-step full-color full-parallax holographic stereograms*, US Patent 6,330,088 (filed 1998, granted 2001).
13. D. Brotherton-Ratcliffe, S. J. Zacharovas, R. J. Bakanas, J. Pileckas, A. Nikolskij and J. Kuchin, "Digital holographic printing using pulsed RGB lasers," *Opt. Eng.* **50**, 091307-1-9 (2011).
14. D. Brotherton-Ratcliffe, F. M. Vergnes, A. Rodin and M. Grichine M, *Method and apparatus to print Holograms,* Lithuanian Patent LT4842 (1999).

15. D. Brotherton-Ratcliffe, F. M. Vergnes, A. Rodin and M. Grichine, *Holographic printer*, US Patent 7,800,803 (filed 1999, granted 2010).
16. A. Rodin, F. M. Vergnes and D. Brotherton-Ratcliffe, *Pulsed multiple colour laser*, EU Patent EPO 1236073 (2001).
17. D.-K. Kang, M. A. Rivera and M. L. Cruz-López, "New fully functioning digital hologram recording system and its applications" *Opt. Eng*. **49**, 105802-1-9 (2010).
18. P.-A. Blanche, A. Bablumian, R. Voorakaranam, C. Christenson, W. Lin, T. Gu, D. Flores, P. Wang, W.-Y. Hsieh, M. Kathaperumal, B. Rachwal, O. Siddiqui, J. Thomas, R. A. Norwood, M. Yamamoto and N. Peyghambarian, "Holographic three-dimensional telepresence using large-area photorefractive polymer," *Nature* **468**, 80–83, (4 Nov. 2010).
19. J. Tapsell, "*Direct-write digital holography*", PhD Thesis, Univ. of Sussex, UK (2008).
20. M. Klug and N. Kihara, "Reseau full-colour one-step holographic stereograms," in *Fifth Int'l Symposium on Display Holography*, T. H. Jeong ed., Proc. SPIE **2333**, 411–417 (1995).
21. A. Shirakura, N. Kihara and S. Baba, "Instant Holographic Portrait Printing System," in *Practical Holography XII,* S. A. Benton ed., Proc. SPIE **3293**, 248-255 (1998).
22. I. Lancaster, "Geola builds holographic copier," *Holography News*, Vol. **23**, (3) 4, (2009).