1

What is a Hologram?

1.1 Introduction

First, we should define in technical terms what precisely is meant by the term “hologram” and discuss some of the important milestones in the development of the technique.

Some years ago, holography was tauntingly dubbed “the solution looking for a problem” and it has taken some time to establish the true nature of the technology and disperse some of the urban myths which it seemed to attract so readily in earlier years.

We shall mention some of the important types of hologram recording which are possible, and end this chapter with a view of the public perception of holography; explaining a number of 3D systems which are frequently labelled “holograms” by the public, but which do not realistically meet the criteria for inclusion in this category.

Before embarking on a career in holography, remember that the holographer has to be prepared for the frequent request to re-create R2-D2’s projection of Princess Leia, and also patiently to stand fast through the knowing wink accompanying the statement “Oh yes that’s the method where the broken hologram still contains all of the image!”

1.2 Gabor’s Invention of Holography

The word “hologram”, coined by Denis Gabor from Greek roots, seems to be difficult to define precisely, so the authors prefer to assume the most appropriate English meaning to be “the entire message”.

Of course, in an era where the Hellenic Institute of Holography plays a prominent role in development of new techniques for ultra-real representation of museum artefacts, the word has now ironically become “anglicised” to the extent that it now translates directly back into modern Greek as “ολόγραμμα”!

Gabor’s intention was to refer, in the name, to the unique ability of this technique to record an incoming wave of light from an object in terms of both its phase and amplitude. Gabor was working in electron microscopy when he observed that interference recording was a way to achieve recordings of ultra-high resolution without the difficulties introduced in optical systems by the limitations of recording materials, lenses and conventional optics.
The hologram differs greatly from the simple photographic recording of an image based solely on the amplitude of light arriving from the field of view of the optical system, because when we look at a black and white film exposed in an everyday camera, after applying developer, we see a perfectly recognisable “negative” image of the subject beyond the lens. In comparison, in its simplest form, the hologram recording itself, in the appropriate high-resolution silver halide film or plate, tends to be something that, at first sight, is a meaningless jumble of lines or zones in varying tones.

So, what is the “hologram”? In the etymological sense, in the early years there was a move to call the recording itself, the “holograph” and the reconstructed image, the “hologram”. This seemed a logical and useful division, as it is often confusing during discussion in the workplace, as to whether we are referring to the glass plate in the laboratory or to the image which springs forth from it when the laser is switched on.

However, this terminology appears to have fallen by the wayside, and today’s dictionary does not generally acknowledge the word “holograph” except in a separate sense with reference to the special legal value of handwritten documents.

When we look though a microscope at a silver halide holographic recording plate which has been exposed to a suitable “standing wave” of interference, and processed in a suitable developer and either “fixed” or “stopped”, we see black and white lines in what appears to be a random pattern, or at least a pattern which does not appear to relate directly to the subject of the recording.

Its fringes might well, in some cases, be predominantly linear – leading to the concept of “surface-relief holograms”. If the subject matter is relatively close to the plate, we may begin to recognise the shape of the object, but in a true “redundant” Fraunhofer hologram, it is quite impossible to relate the pattern to the subject matter (see Figure 1.1, which shows a magnified image of part of the recorded pattern in a holographic plate and, beside it, a black and white photograph of the recorded 3D image seen when the hologram was lit with helium–neon laser light).

So what is happening here?

The conditions for recording a hologram involve the use of a coherent light source. Lasers were not available in the era when Gabor invented holography, but nowadays we have a wide choice of laser types that can produce holograms, which will be detailed later.

Using a single laser, in the simplest format, we can arrange for one part of its emitted light to be incident upon a three-dimensional object. The remainder of the beam travels towards a high-resolution recording plate, and the light direct from the laser (“reference beam”) coincides near the plate with light reflected from the 3D object (“object beam”). The light reflected from the object contains information about the shape and tonality of the object and is “coherent” with the light arriving at the recording plate direct from the laser (Figure 1.2). In the vicinity of the plate these two beams “interfere” to produce a “standing wave of interference” which can be recorded in the photosensitive emulsion on the plate provided certain conditions of stability exist – by definition, this “standing wave” must not move or change during the recording process.

So what is the nature of this “standing wave”?

We are familiar with the classical experimental demonstration by Thomas Young early in the nineteenth century. By using sunlight issuing from a tiny hole in a window blind (which was a simplistic way to provide a beam of partially coherent light), he was thus able to demonstrate the wave nature of light. This was achieved by passing light
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from this single source through two adjacent narrow slits in such a way that the two waves issuing from slightly displaced sources continued towards a screen. His famous sketch in Figure 1.3 was made by the visualisation of waves on water.

Now that we are routinely able to utilise laser light, we can easily demonstrate the analogous wave effect in electromagnetic radiation. If the screen CDÉF is stationary, the extended row of spots which results demonstrates the interference of light from the two separate sources A and B.

As shown in Figure 1.3, the “wave fronts” from the two sources provide an orderly sequence of high and low intensity in accordance with the distance between the slits,
the wavelength of the light and the distance of the screen from the slits (i.e. the angle between the beams).

Of course, if we were to place a sheet of photosensitive film in the position of the line marked CDEF by Young, in an optical set-up, we could record an interference pattern provided the “standing wave” was stationary.

Nowadays, we can very easily use a laser as a fully coherent light source and Figure 1.4 shows the effect of inter-changing the laser wavelength between recordings with the same slit apertures, in this case a pair of thin (0.1 mm) lines spaced by 1.5 mm etched into a black-developed photographic plate.

It is clear that increasing the distance between the slits in Figure 1.4 or reducing the distance to the screen will radically change the frequency of the fringes in accordance with “the grating equation” (see Chapter 2).
This fact will also lead us to see the advantage of the “off-axis” methods of recording holograms, later invented by Upatnieks and Leith in the USA simultaneously with the work of Denisyuk in the USSR; but it will also show the necessity for a spectacular improvement of the resolution characteristics of the films used for this more advanced form of holography. Recording materials for holography are discussed in detail in Chapter 5.

1.3 The Work of Lippmann

Gabriel Lippmann, working at the turn of the twentieth century, effectively anticipated the resolution and silver halide grain-size requirements of holographic recording materials. Using natural light, Lippmann’s technique involved the production of colour photographs by a process which bears a close relationship to today’s reflection holography. He was awarded the 1908 Nobel Prize for his work.

Essentially, he recognised the need for fine-grain silver halide emulsions and a method to process them which produced a transparent layer, rather than using the simple black metallic silver grains, which normally produce image contrast with the white background, that we associate with traditional “black and white” photography.

Lippmann produced photo emulsions with grain size of the order of 50 nm. This is difficult to do, even nowadays, for reasons explained later in Chapter 5.

By sandwiching this emulsion in intimate contact with a mirror surface in the form of liquid mercury, Lippmann was able to set up a recording process whereby a standing wave was produced by light reflected from the mirror, as it met light entering from the lens of his camera. If the camera was entirely still, the stationary wave formed by each individual wavelength of light would be recorded in the appropriate position in the photograph.

But, in common with today’s “full-colour holography”, achieved by coherent laser light, the ability of the emulsion to record a range of wavelengths simultaneously in a single zone of the recording material was limited. Furthermore, the use of incoherent light to produce a planar grating in the depth of the emulsion effectively meant that Lippmann was limited to a very thin layer of his scattering emulsion.

The natural “speed” of a photographic material tends to be proportional to its grain size, so Lippmann’s exposure times were long – requiring great stability of the equipment and the subject itself; this still presents a problem today in modern holography. Processing fine-grain emulsion is also complicated, as explained in Chapter 6; these minute crystals of silver halide may well be soluble in chemicals designed for use with more typical, everyday photographic materials.

We will return to the connections between Lippmann’s work and that of Denisyuk over 60 years later, and to the complex issues of photographic emulsion-making in subsequent chapters.

1.4 Amplitude and Phase Holograms

The first holograms were, quite naturally, recorded in silver halide material. Given its natural speed, this has obviously been the material of choice for the photographic industry for many years, only recently challenged by digital electronic technology. Only the problems outlined above, as addressed by Lippmann, regarding the resolution of the recording materials for holographic use have prevented silver from remaining the
material of choice to this day, when new materials have emerged. We discuss the alternative recording materials for holography in Chapter 5.

Silver halide, as explained in detail in Chapter 5, produces, after initial development, grains of black silver metal (which may appear tinted dark red or green in transmitted light, as we will explain later) that produce an “amplitude” record of the zones/fringes which are associated with areas of high intensity (additive or constructive) interference of the light in the standing wave recorded, and which, in turn, represent the interaction of the reference beam with the object wave.

This record is called an amplitude hologram: a three-dimensional matrix of zones of clear gelatin interrupted by grains of opaque silver metal which prevent the direct passage of light rays through the layer. This works relatively well for transmission holograms, where, as we will show later, the fringe microstructure is principally perpendicular to the layer; a predominantly superficial recording.

But if we then continue the emulsion processing with a bleaching solution, we can change the amplitude hologram into a phase-modulated microstructure. The black grains of silver which prevent the passage of light rays through the layer can be advantageously into translucent crystals of silver bromide. This is a very simple chemical step:

\[
\text{Ag} - e = \text{Ag}^+ \\
\text{Ag}^+ + \text{Br}^- = \text{AgBr}_{\text{crystal}}
\]

The loss of an electron is a simple oxidation process which can be brought about by any number of common oxidising agents (for example, a solution of ferric [iron III] sulphate). Loss of the electron results in the creation of a silver ion, \(\text{Ag}^+\), which then combines in solution with a negative bromide ion in the bleaching solution to produce translucent (pale yellow) silver bromide.

Now that we have effectively removed attenuating black material from the layer, we have a condition where light rays entering the layer are not significantly absorbed, but are now subject to diffraction at interfaces within the layer which are manifested by local “image-wise” modulation of the refractive index of the constituents of the layer.

Now, whereas silver halide is historically the most important recording material, we must consider other, later materials which directly provide phase modulation. These include dichromated gelatin (DCG), which found an important commercial outlet in hologram pendants for jewellery, and, at the opposite end of the market, the use of holograms as optical elements such as the head-up displays which were introduced in fighter aircraft in the 1970s.

The DCG medium became unfashionable later due to technical difficulties, general chemical undesirability and archival problems, and has been replaced predominantly by modern photopolymer materials in the role of direct phase-modulated materials.

### 1.5 Transmission Holograms

Simplistically, a transmission hologram is a recording where, at the reconstruction or viewing stage, the illumination source directs its light through the recording film or plate so that the viewer will interrogate the image from the opposite side to the light source, as seen in Figure 1.5.
This phenomenon is a function of the recording arrangement. Of course, the irony is immediately apparent that, as we discuss in detail in Chapter 8, the format for recording a transmission hologram, which is viewed from the side opposite to the illumination source, to enable the appropriate fringe structure to form, is a configuration where both object and reference beams arrive from the same side of the plate (the opposite is true for reflection holograms!).

The fact is that, despite a certain level of popular disbelief, a transmission hologram may be either a thin hologram or a thick (volume) hologram. This is entirely dependent upon the recording medium and we will detail in Chapter 5 why certain materials are more appropriate than others in the various hologram recording configurations, due to their ability to record either surface or volume microstructures.

But, as shown in Figure 1.5, the diffractive properties of a transmission hologram work in such a way as to disperse incident white light into its component colours. The hologram acts, in its effect, in a similar way to a prism, although the colour distribution appears reversed. This fundamental property of the transmission hologram made it impossible in the early years to view the image in white light, until the incredible invention by Dr Stephen Benton in 1967 of the rainbow hologram, which we describe later in detail and which has facilitated the major commercial outlet for the technology in security applications.

So, the embossed holograms with which we are so familiar are, in fact, transmission holograms. By mounting the transmissive layer upon a metallic foil substrate, we are able to view the image from the same side as the illumination source. Similar means have been used to display large-format transmission rainbow holograms; that is, by mounting a glass or film hologram layer upon a mirror before framing the whole assembly.

1.6 Reflection Holograms

In the simplest terms, reflection holograms are those which are illuminated in the reconstruction or replay step from the same side of the plate or film as the viewer sees the image. These holograms are often called volume reflection or Lippmann holograms.
Note: The use of the term “volume hologram” works very well in the technical environment, but the authors have frequently been seriously frustrated in commercial discussions by the interpretation of this term as relating either to the quantity of holograms to be produced or to the fact that the image itself has depth or volume!

As with transmission hologram technology, the configuration for recording such a microstructure is the opposite of the viewing configuration, so that to create the required microstructure here, we must arrange for the recording object and reference beams to be incident from opposite sides of the recording medium. The result is that the fringes are typically planar within the layer and, like Lippmann’s photographs, they tend to act somewhat like a mirror, rather than showing the prism-like dispersive effect of the transmission hologram. This is why the concept has been summarised as being “like a mirror with a memory”.

This “mirror” has the quality of being monochromatic, so it acts rather like a filter to incident white light, in that a single wavelength is selectively reflected, whereas rays of all other wavelengths pass directly through the layer. This is because rays of light, shown in orange in Figure 1.6, whose wavelengths coincide with the particular selected frequency of the planar grating, constructively interfere, in accordance with Bragg’s Law, at the successive parallel index interfaces, in order to create a reflected summation of their energy, whereas other wavelengths fail to meet the conditions for constructive interference. It is important to recognise that Bragg diffraction follows a mechanism of constructive interference, whilst thin holograms actually function quite differently.

Because the reflection hologram is thus able to reflect selected light of a certain wavelength, and of course this may be in the form either of a (simple) plane wave or a complex object wave, as previously discussed, the device itself may take the form of a clear, almost colourless layer, which bears a three-dimensional or animated image, so that such an extremely simple, compact, ethereal film layer is a very attractive proposition in security applications, where it may be used to overlay conventional printed graphics, allowing an unobstructed view of printed information on a document, in the “off-Bragg” conditions of illumination.
In this configuration, we see the vital importance of the phase (bleached) hologram set-up. Interestingly, if we make an exposure in the reflection mode to a suitable silver halide film, we can develop the film to a low density and if, at that time, we dry the film and view the hologram with strong illumination, we will see a very dim monochromatic reflection image in the black silver layer. If we imagine the fringes of this “Lippmann–Bragg” hologram to be of similar planar structure to the pages of a book, albeit tilted perhaps at a small angle to the surface of the film, as shown in Figure 1.6, then, of course, a ray of light entering the layer from the surface of the film is gradually absorbed by the layers of black metallic silver as it advances into the hologram layer. What light is reflected at the interfaces of gelatin and silver metal provides us with a dim, monochromatic image of our chosen subject.

As previously described, we can convert the metallic silver into translucent crystals of silver bromide, which incidentally has an unusually high refractive index (~2.23), the importance of which will become clear. Now, the layer appears clear and light is able to pass through the whole layer with little attenuation. More importantly, the emulsion layer comprises alternating planar zones of higher and lower refractive index in accordance with the modulated concentration of silver bromide in these individual planes. We have thus produced an index-modulated microstructure. The image of this phase hologram may be extremely bright and such a grating may be close to 100% efficiency in terms of its ability to diffract light of a single specific wavelength.

1.7 Edge-lit Holograms

Stretching back to the era of Leith and Upatnieks, there is a very interesting “special case” where the structure of a holographic grating falls between the “transmission” and “reflection” modes. This phenomenon has attracted sporadic research interest including some work by the true doyens of holography such as Leith, Phillips and Benton.

Due to the fact that the volume microstructure is basically midway between the defined “transmission” and “reflection” configurations, we have a hologram which, upon receiving illumination of an appropriate wavelength at an oblique angle within the support layer, as shown in Figure 1.7, is able to direct that light in such a way as to exit...
the film through its front surface in the form of a plane wave; or indeed in the form of a complex object wave with the ability to display a 3D or animated image.

The technique has been slow to deliver results of similar quality to the highly accomplished achievements in the conventional display and security arenas. At first sight, physicists are frequently excited by the apparent reassurance that the light which is successfully launched into the substrate is constrained therein by total internal reflection (TIR) at the front surface, but the holographer has to contend with the fact that, even in the event that index-matching surface couplers in the form of adhesives can ensure the passage of light from the illuminated substrate into the volume hologram itself, its angle of incidence upon the microstructure itself is critical and must comply with the Bragg condition. The authors have reason to believe that new recording materials, lasers and optical configurations may well lead this technology into widespread commercial use in the future.

1.8 “Fresnel” and “Fraunhofer” Holograms

The generic terms “Fresnel” and “Fraunhofer” holograms represent the extreme cases that we meet on the optical table when producing actual holograms. It is useful to define the meanings here because we will see later that the proximity of the “object source” of a hologram is a relevant factor in the way we record images in master and copy holograms, and certainly influences the limits of diffraction efficiency which might be expected from any recording configuration.

Fraunhofer was a German physicist active at the turn of the eighteenth century. His observation that a distant object obstructing a beam of light will produce a shadow whose periphery is characterised by surrounding lines of alternating light and dark, is an effect which becomes all too familiar when we begin to utilise lasers as a light source, and one which provides significant problems when we are masking down laser beams on the optical table or creating apertures to permit the passage of only the central portion of a laser beam into an adjacent part of the optical system.

Figure 1.8 is a photograph of a collimated laser beam falling on a distant screen. The edges of the aperture manifest themselves as a periodic sequence of lines of alternating

Figure 1.8 Sharp edges of the shadow of the model are contaminated by the effects of edge diffraction.
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high and low brightness. Of course, this effect is not limited to the edges of an aperture but equally, or more importantly, affects the edges of every detail of the graphic image. So, for example, Gabor’s slide subject which contained a text tribute including the names Fresnel, Young and Huygens, was rear illuminated such that the “edge diffraction” in the image seen on a screen beyond the slide was included in the light arriving at the recording material.

In the modern era we take it for granted that the “reference beam” will be launched from a slightly displaced position, such that it does not contain the shadow of the subject graphics.

However, looking in detail at the shadow of the model cast on a white screen by a collimated laser beam in Figure 1.8, we see the effect of edge diffraction at the periphery of the shadow, as well as the two edges of the aperture frame.

Wonderfully, unlike the simple photographic image of Figure 1.8 recorded at the recording plate where, unlike the holographic parallel, no coherent reference beam was present, a holographic recording at the same position can cope perfectly with this situation, where incident rays include edge diffraction and all other “spurious” features, and the fidelity of the hologram will thus benefit, in its ability to reconstruct the original scene, from every ray of light associated with the subject matter which arrives at the plate! The illumination of the recorded hologram, with the identical conditions of incidence to the original reference beam parameters (conjugate reference), will re-create the original wave front, with the effect that the image seen, unlike this photograph, will be a precise, sharp likeness of the subject of the recording at the precise position in which it was originally placed.

The Fraunhofer hologram is one where the object is distant from the recording medium; but to make such a statement of relative scale we need to qualify the size of the object itself. Fraunhofer’s set-up is not unlike the method which Denis Gabor used in the original demonstrations of holography. In his case, Gabor found that the presence of the conjugate real image was particularly disruptive to the view of the subject.

The “off-axis” regimes of Denisyuk and Leith and Upatnieks were later to solve that problem in a single step. The term “redundant” may also be used to describe a hologram where the object is distant from the recording medium. This definition will also allow for the oft-quoted phenomenon where a shard of a broken glass hologram contains information about the whole subject matter. It is possible to photograph an image of the whole subject of the original hologram, even if only a small glass segment is available. The photograph in Figure 1.1(b) is a view through a small part of the “redundant H1 master” pulse laser hologram, shown in Figure 1.1(a), made by the authors of the singer Billie Piper. The camera lens is close to the master, looking through the plate, whilst it is illuminated by laser light. Of course, any part of the master hologram will provide a view of the whole portrait, so it is true to say that if the glass master was broken, each part would contain a worthwhile image of the subject. The unspoken “lost information” in this case is parallax, of course – the solid angle through which the object can be seen is clearly limited by the size of the shard, in a similar way as it was originally limited to a lesser extent by the size of the whole “un-broken” recording plate; after breaking, the window of view is far smaller, but still shows a narrower view of the whole subject.

A Fresnel hologram is the opposite case, where the diffuse subject is close to the recording material. Augustin-Jean Fresnel was a French physicist at the turn of the nineteenth century who was an important contributor to the wave theory of light.
Now, in holography, every individual point on the surface of the laser-illuminated object is effectively the source of a secondary wave. A segment of every wave will arrive at the hologram recording plate in accordance with the proximity of the diffuse object. In the case that the distance is short, the wave will intersect the recording material so as to produce a wide range of angles relative to the reference beam. The emission wave of each individual point on the surface of a diffuse object incident upon the recording material thus resembles the familiar form of a Fresnel “zone plate” (Figure 1.9).

The intersection of multiple circular wave fronts, as seen in Figure 1.9, emanating from every point on the surface of an object would lead to incredible complexity in the combined two-dimensional intensity profile. We can imagine, therefore, that the combined (volume) interference pattern, which is the summation of all such points on the diffuse surface, is an incredibly complex three-dimensional pattern, and as such this hologram recording will demand a whole new level of resolution (measured as a modulation transfer function, MTF) from the recording material as compared to the relatively simple, predominantly two-dimensional structure of the Fraunhofer hologram.

In the Fresnel hologram, as was mentioned previously, it is possible, to some extent, to recognise the object matter of the hologram; this “photographic” effect may well prevent us from achieving maximal diffractive efficiency and aesthetic appearance in the hologram; and its manifestation in the film or plate surface is often referred to by holographers as “burn out”, as its amplitude tends to exhaust the dynamic range of the recording material locally and is often deleterious to holographic images.

1.9 Display Holograms

There are a number of holograms which have become icons of the technology. Exhibitions of display holograms have been held in every part of the world. In general, framed exhibition holograms are glass plate recordings which are second generation copies of original master recordings. Clearly, framed glass reflection holograms lend themselves particularly well to exhibition, as they can be lit conveniently by spotlights.
attached to the ceiling (there is no reason why they cannot be lit from the floor level; this is known as “bottom reference”).

As will be discussed in Chapter 8, master holograms can be transferred in their second generation into either rainbow transmission or reflection formats.

In Figure 1.10, my co-author’s hologram, “The Art of Science” a 50 cm x 60 cm pulse-mastered glass display, has been produced in both formats. It is possible, in the case of a transmission rainbow hologram, to use one of two techniques:

1) To organise for the plate to hang in such a way that it can be lit from the reverse side. For example, the framed hologram can be elegantly suspended from the ceiling with wires.

2) To mount the hologram on a mirror such that it is treated as a “reflection hologram”. This does, however, require that the processing of the plate uses a technique that provides a clear and predominantly colourless layer. It also introduces the possibility that the hologram and mirror assembly may require index matching to avoid “Newton’s rings” (wood grain interference).

In more recent years, the digital holograms made by companies such as Zebra and XYZ Inc. have introduced new technology in which the image comes about by quite different means, and we shall describe this technology later. These techniques lend themselves to “tiling”, where a large image can be assembled from a number of smaller component plates. The difficulty of producing large-format holograms is considerable; generally, 50 cm x 60 cm has become the observed size limit. Formerly, in the 1980s, Agfa Gevaert produced one-metre-square recording plates on 6 mm glass, and also supplied rolls of film on a triacetate base of one metre roll width. Of course, handling such large and heavy recording material presented significant difficulties in the holography studio and the chemistry laboratory!

For the purposes of our intention in this chapter to define the conventional techniques of holography and its associated terminology, it is appropriate to introduce everyday terms used in conventional holography. It is widely accepted that we refer to a first generation recording of subject matter or artwork as the “H1” and further image transfers as “H2” and “H3”. (Only counterfeiters need concern themselves with H4!)
The basic configuration of these optical arrangements is shown schematically in Figure 1.11. To summarise the typical procedure, the object or artwork (a three-dimensional item or model or a graphic display) is illuminated with laser light, and the coherent reference beam arrives simultaneously to produce a standing wave of interference, which is thus recorded in the “H1 transmission master”, shown in Figure 1.11(a).

This plate is regarded as a permanent archival record of the subject matter. In Figure 1.11(b), this “H1” plate, with its “redundant” image displaced far from the

Figure 1.11 (a) First generation (H1) recording of a real object; (b) second generation (reflection) “image-planed” recording (H2); (c) the “contact copy” configuration for mass production.
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A surface, is illuminated by a laser (preferably of the same wavelength as the originating laser) from the opposite surface of the plate, to produce a real image of the subject, displaced from the surface. (The real image has the property of “pseudoscopia”)

A second, unexposed recording plate is then placed a similar distance from the H1 as was the original object, and a new coherent reference beam is introduced to record a new image of the original “H1” recording, as a second generation hologram; hence its title, “H2”. In the case where the second reference beam is incident from the side opposite to the H1 master, as shown in Figure 1.11(b), a reflection hologram will result. If, however, the second reference beam is directed from the same side of the plate, a second generation (H2) transmission hologram is recorded.

This “H2” usually has the quality of being “image-planed.” We generally now select the position of the subject of the hologram to be astride the recording medium to achieve the mysterious and exciting illusion for the viewer where the 3D subject appears to be situated partly in front of the display and partly behind the film or plate. In Chapter 10, we will refer to our hologram “Chelsea Library”, where the image has a depth of more than two metres and intersects the film just beyond its mid-point, with spectacular effect. In my time at Applied Holographics, James Copp produced an incredible image of branches from a tree whose H2 transfer allowed an incredible real image projection when illuminated by laser. It was possible when viewing the hologram to walk into the scene, with the surreal effect that that twigs in the extreme projection appeared to project literally into the viewer’s eye (without pain!).

In certain applications, for example for mass production purposes, the “H2” hologram, which, as previously suggested, could be either a glass or film layer, may be used as a second “master” hologram, as shown in Figure 1.11(c).

It is possible to use this hologram as the subject for contact copying. Film is typically laid upon the “H2” in order to allow a single laser beam to transfer the image from the “H2” into the new film layer, to produce the third generation “H3” image. This effect is explained more fully in Chapter 8.

1.10 Security Holograms

Holography has found its primary commercial application in the security industry. The general observation that any technique is frustratingly difficult to perfect means that an opportunity exists to use the product as a badge to mark a genuine product, provided a significant barrier is presented to those who may wish to attempt to counterfeit the device.

Holography offers such a barrier, not least because during the route to a mass-produced product there is a plethora of opportunities for error; only the most experienced holographer will avoid such pitfalls.

Applied Holographics was formed by Larry Daniels and Hamish Shearer in 1983 in order to exploit the use of reflection holography in display applications, but there was a rapid change of emphasis as soon as the potential as a security device was recognised by the security industry. The roots of that company in reflection holography were necessarily adjusted in favour of embossed holography after ABNH released the VISA dove in 1984.

Applied had, by that time, successfully commissioned its ruby pulse replicator “The HoloCopier” based upon fine-grain film produced by Ilford Ltd. Commercially,
however, there was no option but to concentrate on the embossing method, in the light of the cost advantages of thermoplastic foils over silver halide, and also bearing in mind the existing compatibility between the printing industry with existing “hot-foil” products, which, in turn, offered a link to surface-relief embossing. Actually, that link was made rather less simple by the relatively small margin of temperature between the embossing and “hot-stamping” processes.

Embossed holography has been in the vanguard of security printing since that date and a large industry has developed. In recent years there has been a serious increase in the incidence of counterfeiting and it was suggested by David Pizzanelli for Smithers-PIRA [2] in 2009 that volume reflection holograms in photopolymer film would be the leading disruptive technology of the present decade (the exponents are running out of time!).

Embossing is a process which utilises surface-relief diffractive images to be pressed at very high speed on a roller system into cheap thermoplastic foil. Because the result is a definitively thin diffractive microstructure (transmission hologram), it disperses incident light into its individual colour components. Utilising Benton’s “rainbow” technique, holographic images reflected from the silver foil substrate appear incredibly bright in aesthetically attractive, iridescent colours. The technique is capable of producing very large quantities of low-cost foil holograms, and for this reason, the security industry has used embossed holograms in the form of adhesive labels and hot foil for over thirty years, with English banknotes bearing characteristic holograms made by De La Rue Holographics since the millennium. Only now is counterfeiting becoming a serious problem for embossed holography, and the security industry is calling for new solutions, which might well involve full-colour reflection holograms, as previously suggested by PIRA.

The established methods of applying hot foil to banknotes, credit cards and packaging will need to be replaced with wholly new techniques for secure application of reflection holograms. The introduction of photopolymer as a recording medium for volume holograms has tended to displace from favour the idea of silver halide mass production pioneered by Applied Holographics in the 1980s.

At that time, Du Pont were discussing such a photopolymer material with AH, and Du Pont Authentication Systems Inc. went on to produce the material “Izon”, which has famously protected products such as Nokia batteries and AMD hardware from counterfeit. Bayer Materials Science (now Covestro) has introduced its “Bayfol HX” material, which is a polychromatic recording film capable of high diffraction efficiency in a full range of colours, by the use of red, green and blue lasers to produce volume reflection holograms.

As we shall see in Chapter 5, one of the inherent problems of mass producing reflection holograms is the need to match the remarkable production speed at which embossed holograms can be pressed into thermoplastic foil. However, new developments, especially in laser technology, may well progress reflection holography into a new era of commercial usefulness.

### 1.11 What is Not a Hologram?

One of the frustrations commonly expressed by holographers is the continual receipt of enquiries that refer to techniques which cannot be considered to be holograms. 3D imaging is certainly not limited to holography; in the same way that holography is not necessarily limited to 3D imaging.
During the era of the original release of George Lucas’s epic *Star Wars* films, as previously mentioned, the authors recall that holographers were inundated with requests to duplicate the effect shown in the scene where robot R2-D2 projected a 3D animated image of Leia (with sound!). But although labelled “a hologram”, this imaginary technique does not fit easily into the scientific definition of Gabor’s method of 3D imaging.

So, for the avoidance of doubt, we would like to address a number of categories of 3D imaging which are regularly referred to as holograms but which we feel do not necessarily fall in line with Gabor’s invention to any great extent; and in some cases, not at all!

### 1.11.1 Dot-matrix Holograms

Clearly there is an open-ended zone of technical debate as to what constitutes a hologram. A prime example arose automatically within the industry in the 1980s when techniques such as “dot-matrix holography” were added to the portfolio of security hologram techniques. A dot-matrix “hologram” is a digitally originated array of dots wherein the individual units of exposure comprise an $x$–$y$ matrix of plane gratings with various directional and colour qualities (Figure 1.12).

Such an array, although originally produced with lasers at Applied Holographics, could technically equally comprise an array of mechanically ruled gratings, and in the case of the *Kinegram*, originally produced by Landis and Gyr, similar effects are created by other mechanical means; or, in the case of CSIRO, by *electron beam lithography*. But because these techniques became involved with existing embossed holography work, and in the case of Applied Holographics were frequently combined as a mixed technique with “classical holography”, they have been labelled “embossed holograms” with universal approval.

![Figure 1.12](image-url) Reconstruction of a dot-matrix hologram.
1.11.2 Other Digital Image Types

In general, it is true there is something of a conflict between the terms “digital” and “hologram” in its fundamental sense (the entire message). Later, we discuss the techniques of digital reflection holography used by Zebra Inc. These holograms, in common with a similar technique later shown by XYZ Inc., appear to have the advantageous capability, since the surface matrix is divided into small pixels which are individually written, to produce hologram panels which could be aggregated together after exposure to produce very large 3D displays.

In common with the “one-step” methods invented by Haines for embossed holography, these “holograms” are essentially an array of pixels whose individual properties are predicted by ray-tracing techniques so as to enable each pixel to provide to the viewer the expected view of a large 3D subject when the viewer’s eye is looking directly at that particular point in the surface matrix, from a certain viewing position. For these reasons, a pixel at the edge of an adjoining panel can be organised to coordinate spatially with the adjacent pixel in the next panel of a “tiled” array, thus inviting the possibility to build a matrix of panels capable of displaying a very large aggregated 3D image of an object.

1.11.3 Holographic Optical Element (HOE)

A holographic optical element is an optical device which has a similar effect to a conventional optic but takes the form of a thin film. We refer to a “holographic” element simply because we use the materials and techniques of conventional image holography to create the product. For example, a dispersive grating as used in a spectrophotometer to divide light from a white source into its separate colour components can be made by a mechanical ruling device. It is convenient and very cheap to produce a highly efficient linear grating by laser imaging on a photosensitive material and the manufacturer then also has the opportunity to incorporate the hi-tech “holography” buzz-word in the specification.

Whereas the above-mentioned techniques, when they apply to plane mirror optics, do not appear to fall in line closely with Gabor’s original concept of the word “hologram”, these are all important technical developments which have basically arisen because technologists have exploited his invention and, of course, they all have the common theme that their mode of operation can be defined as “diffraction”.

However, there are techniques for 3D imaging which are far more difficult to classify as holograms. But the word “hologram” has captured the imagination of the public to such an extent that we have to accept that the following techniques are all frequently labelled as such!

1.11.4 Pepper’s Ghost

The holographer has to endure the misplaced universal admiration of friends, upon their return from a USA vacation, for the “holograms” in Disneyland. In the main, these “holograms” are a variation on the theme of a well-known technique in the field of exhibition displays and theatre, which is commonly known as “Pepper’s Ghost”. Documentation of such principles is recorded as far back as the sixteenth century in the writings of Giambattista della Porta, an Italian scholar whose most important publication was entitled *Natural Magic*. But John Henry Pepper, a lecturer at the Royal Institution in the nineteenth century, gave his name to the modern iteration of the method.
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Ironically, it was his colleague, Henry Dircks, who invented a specific display technique which he found it impossible to implement in theatre, but Pepper was able to modify the idea in order to make it feasible to apply the technique widely. In accordance with its title, the method was originally used to create the illusion of a ghost on stage. An actor dressed in ghostly attire was hidden from the audience, brightly lit, in a confined area below the front stage level (in the orchestra pit). His reflected virtual image, on an angled glass plate, which filled the full aperture of the stage, its edges concealed on all sides, and whose presence was thus not perceived by the audience, appeared behind the glass plate, equidistant with respect to the actor’s proximity to the glass, as shown in Figure 1.13. Thus, a three-dimensional virtual image of the “ghost” was apparently cast onto the stage area; an ethereal, floating, animated image through which the on-stage actor was able to walk!

There were problems, of course, with perspective effects, keystone distortion, image inversion, etc. and Pepper’s system, for example, included a first mirror to aid with such difficulties.

Recently, this method has received excellent publicity from London Theatre and even TV news coverage of the world’s first “Hologram Protest March” in Madrid. TV, newspaper and internet coverage of this event explained that the Spanish Civil Rights cause was advanced by use of a projection of this type featuring marching protestors. Involvement in a live demonstration for such a cause would involve the likelihood of arrest – the “hologram” was able to protect the individuals from such a fate!

At the other end of the size scale, we are seeing iPhone users encouraged to buy a new device which attaches to the screen in the form of an inverted pyramid. This appears to display an animated floating image when the screen itself displays an image from specialist software. Again, in this case, the reflection of the screen appears as a virtual image apparently within the volume of the pyramid, enabling the viewer to perceive a floating image from any oblique viewing position when the phone is laid upon a table.

![Figure 1.13](image-url) Schematic of the original theatre manifestation of “Pepper’s Ghost”. 
1.11.5 Anaglyph Method

“Anaglyph” is a term which, like “hologram”, is rooted in Greek origin, but which refers to relief carving. In modern terms, the use of viewing glasses with red and cyan lenses for the two eyes allows us to view printed images which have two stereographic views encoded in red and green ink. But the original print looks quite confusing when viewed without the glasses; the apparently “blurred” red, cyan and brown image is unsatisfactory to the unaided eye of the viewer.

The recent boom in 3D cinema projection has been achieved by a similar method. Here, the spectacles are a little more elaborate and comprise neutrally coloured polarising filters. The screen itself is made from a surface which retains the polarisation of the incident projected beam (“silver screen”). Circular polarisation instead of linear polarisation is used, as this is more sympathetic to members of the audience having the ability to tilt the head whilst viewing comfortably without disruption.

During my employment at 3M Research, Mike Fisher was a physicist in the photographic unit. He was one of the leading stereo photographers of that time and his twin-lens SLR camera had been custom-made from a pair of high-quality 35 mm film cameras. His accounts of sawing through two expensive SLRs to produce a single stereo camera enthralled our 3M coffee-room audience. He recorded colour slides in the camera and demonstrated a projection system with a twin-lens polarising projector involving remarkable lap-dissolve facilities. At that time, a reel-to-reel tape recorder provided a sound track and digital triggers to the projection system. Displays of the stereographic photography provided a remarkable experience for regular meetings of the company’s technical forum. The London Stereographic Company was formed in 1854 and still exists under the directorship of Brian May and Elena Vidal [3].

Over the years there has been a range of commercial, purpose-made cameras for stereo photography, and although the Nimslo camera is no longer made, second-hand cameras with four lenses which would image sequences of 35 mm film are still relatively easily available.

In printed form, when a simple two-channel stereographic figure is presented in the form of twin images to the viewer’s eyes in an appropriate manner, there is absolutely no difficulty in seeing a 3D image as a fusion of the pair of images without any viewing device.

Figure 1.14 shows such a pair of simple geometrical figures, which can be viewed autostereoscopically with a little effort. The viewer must position the stereo pair directly in front of the eyes and ensure that the left eye focuses solely upon the left print and that the right eye concentrates only upon the right print. This is done by staring into the distance. After a few seconds, the stereographic 3D image will appear to the viewer in

Figure 1.14 Stereo.
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the void between the frames. Moving closer or farther from the page will enable the viewer to find an optimal position.

Now, the brain is telling the viewer that she sees three cubes, the central one of these is three-dimensional, and note that on either side of the 3D cube at the base is a logo “Figure 1.14 Stereo”. The logo “3D CUBE” that appears on the surface of the central perceived 3D image, shows the destructive effect of tilting the head whilst viewing the pair, as mentioned above with respect to 3D cinema.

Any suitable pair of photographs comprising sequential perspective will offer a three-dimensional view in this way, as shown in Figure 1.15. The position of the axis of rotation of parallax defines the extent to which the image appears to project forward.

The traditional anaglyph presentation is a graphic display in coloured inks which can be differentiated by coloured gels in viewing glasses. The binocular vision of the viewer is then able to ensure that each eye sees a slightly different picture without any need to train the viewer’s eyes in a special viewing technique. The technique is easily applied to photographic reprint images, but, as mentioned, the problem for this technology is that the image tends to appear confusing without the viewing aid; bear in mind, however, that exponents of the technique could equally argue that holography appears confusing without suitable lighting!

These stereographic methods cannot realistically be called holograms – but, in fact, holography could help here in some cases.

A very simple two-channel hologram can easily be made where the viewer will effortlessly be able to see the 3D image in full colour provided that he or she keeps a central viewing position such that the left and right eyes are restricted by the hologram viewing properties to see only the appropriate information for the binocular stereo effect.

Of course, more complex holograms explained later can quite easily dispose of the need to restrict the viewing conditions as well as adding far more parallax data to the image. The limiting quality of the anaglyph methods is that only a single perspective is represented; unlike the holographic stereograms explained in Chapter 9, there is no variation in perspective of the 3D image as the viewer moves from side to side.

1.11.6 Lenticular Images

Plastic moulded lenticular screens comprise a thin layer of thermoplastic which is pressed with an array of adjacent cylindrical lenses. Various profiles for the lenses are possible. We see from the schematic in Figure 1.16 that each individual “lenticule” has
the ability to guide a ray of light from any vertical line at its focal plane towards the field of view wherein a slitted window of view will be created.

Thus, the artwork is presented as a separate printed sheet, or could be printed directly on the reverse side of the thermoplastic array in the form of “slices” of view of a subject featuring different perspectives or animations. Each linear feature will create an adjacent window of view for the viewer’s eye. The moment of alignment of a lenticular array sheet with corresponding printed or photographic artwork is an unforgettable experience, as the unconvincing, processed, flat artwork springs forth to be experienced for the first time as an integral 3D image. By the lenticular technique, we can organise for the viewer’s eyes to experience two related views of the subject matter which may be arranged to convey stereographic or animation data to the viewer (or both). In Figure 1.16, the left eye sees the third channel of artwork across the scene; simultaneously, the right eye receives the image displayed in the second channel.

Using modern printing and lens embossing techniques, the designer can choose an appropriate quantity of channels in the printed matter to achieve the most effective result. A simple animation such as the security graphic in the British driving licence requires only two channels of information, whereas my co-author’s portrait of David Bowie, shown in Figure 1.17, contains multiple channels recorded as a photographic sequence to enable the recreation of an animated 3D image.

1.11.7 Scrambled Indicia

Micro-lens arrays can also be produced in thermoplastics in much the same way as the lenticular method described above. Alfred V. Alasia, who died in 2010, founded Graphic Security Systems Corporation and used such lens arrays to produce the effect known as “scrambled indicia” [4] where a filter in the form of a lens array, when overlaid on a security document, was able to reveal to the viewer equipped with the correct viewing key, hidden information in a printed security device. This method was used in US postage stamps. The general technique also has the ability to produce 3D images. The lenticular and micro-lens array techniques are inferior to holography in terms of resolution capabilities, but, of course, are less demanding in terms of lighting conditions for reconstruction of an apparently deep three-dimensional image.
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1.11.8 Hand-drawn “Holograms”

William J. Beatty published a document called *Hand-drawn Holograms* and this describes a method by which some intriguing 3D effects were created by a scribing technique.

This is based upon an effect with which we are all familiar. When driving the car with a windscreen which refuses to clear adequately, the motion of the wiper blades tends to smear dirt in curved lines across the screen. Similar effects appear on the car bodywork if a polishing cloth contaminated with grit is used so as to scratch the paint surface as the cloth sweeps across the paint in a curved line.

If these patterns are viewed by the light of street lamps, we perceive three-dimensional curved lines appearing to sweep into the distance and a repetition of their rotational motion as we drive past successive light sources.

Beatty harnessed this effect in such a way as to encode the scribed pattern by using a pair of dividers with a sharp stylus point to gently score the surface of a shiny plastic or metal sheet with a sequence of circumferential lines centred on the locus of a simple image such as an alphanumeric character. This method is described [5] at http://amasci.com/amateur/holo1.html

I achieved excellent results by following this description and the result is a white, three-dimensional image. The key is the action of the stylus of the dividers utilised on
the plastic layer. Gentle manipulation of the stylus point tends to burnish a smooth curved v-groove with an angled reflective edge in the plastic layer.

During viewing, the point source of light is reflected from a single point of one of the curved v-shaped groove edges towards the viewer. If the viewer moves, then this highlighted position moves accordingly. A v-shaped curved groove representing an arc centred on successive adjacent points tracing the graphic which is the subject of the intended image will, of course, present a slightly different highlight, and the integral effect of all these curves is to represent a function of the original subject; with the ability to include three-dimensional effects.

The white reflected image in this method results from the fact that this is a non-diffractive technology. It is an interesting opportunity to compare in this way the effects we see from the reflection from the surface relief associated with a vinyl disc and a CD recording, as shown in Figure 1.18(a) and (b), where the line spacing gradually approaches the frequency that we associate with holograms and where diffraction of the visible wavelengths begins. There is a hint of colour in the light reflected from the vinyl grooves in (a) and in (b) a distinct rainbow effect with which we are all familiar. This is because the spiral track of pits on a CD has spacing of 1.6 µ, whereas the vinyl record grooves are of the order of 100 times greater spacing.

1.11.9 “Magic Eye”

In the 1990s a company was formed under the banner N.E.Thing Enterprises Ltd to exploit the technique of single image random dot stereograms (SIRDS) which is credited to Hungarian expatriate Béla Julesz working at Bell Laboratories in the 1950s (simultaneously with laser pioneers Townes and Schawlow).

During that era, the 3D images achieved cult interest in the Far East and millions of books were sold. The company later changed its name to Magic Eye Inc.

The books, such as *Magic Eye* [6] provide a non-technical, illustrative range of images using the SIRDS technique.
As we saw with the “stereo pairs” in Section 1.11.5, the method demands that the viewer controls their eyes in such a way as to stare “through” the printed image. This effectively creates two independent channels of image data, which differ slightly. The images transmitted to the brain of the viewer from the left and right eyes contain lateral displacement for certain groups of dots or vector components. As a result, the brain interprets these differences as depth cues.

The result is that it is relatively easy to produce 3D scenes that typically comprise a patterned rear plane which forms a background to a planar or three-dimensional feature in the mid-ground, behind the surface of the printed paper.

Notes

3 The London Stereographic Company. www.londonstereo.com
5 William J. Beatty http://amasci.com/amateur/holo1.html