CHAPTER V

HOLOGRAPHIC OPTICAL ELEMENTS
AND PATTERN RECOGNITION
Abstract

As a result of extensive research and development during the last twenty years holographic optical elements (HOEs) have become practical and are used in many applications. By using the fabricated experimental setup, we have attempted to record a few simple HOEs, in our laboratory. Combining a matched spatial filter and a holographic lens on a single Agfa 8E75 plate, a compact optical frequency plane correlator has been developed for pattern recognition. The recording details of the HOEs and the pattern recognition system are discussed in this chapter.
5.1 Introduction

Optical elements can be generally categorised into three basic types, viz reflecting elements, refracting elements and diffracting elements. Holographic Optical Elements (HOEs) come in the last set. In its structural sense a hologram can be considered as a record of a set of interference fringes formed between two mutually coherent beams. This system of fringes forms a complex grating which diffracts light falling on it and transforms a part of the light into a desired image. Using this technique it should also be possible to reconstruct the wave fronts coming from lenses, mirrors or gratings. Such holograms can replace some or all the optical elements in a system.

Though the seeds for the conceptual development of HOEs were sown by Dennis Gabor himself [1-3], it can be considered that the interpretation of holograms by Rogers [4] as a generalised zone plate has laid the foundation for the development of HOEs. In 1966 Kock et al. [5] analysed the imaging property of the hologram of a point source of light and its function as a lens was experimentally demonstrated by Schwar et al. [6].

Holographic counter parts of conventional optical elements have been investigated by many people. To name some -

Holographic optical elements are unique in many of their characteristics. As we have seen they are diffractive elements and hence wavelength sensitive. HOEs can serve multiple functions viz., as a lens, beam splitter and spectral filter, at the same time. The flexibility in fabrication and possibility of replication along with their added advantages such as lightness and compactness gave them increasing popularity.

The ratio of the hologram thickness to the fringe spacing determines whether a hologram is thin or thick. The interference pattern recorded in a holographic material may be either a spatial variation of absorptiveness, thickness or refractive index. Holographic optical elements of the first type are absorption elements and those of the second and third type are phase elements.
The performance of a HOE is basically determined by its aberrations and diffraction efficiency. The directions of the diffracted rays (as given by the grating equation) are determined by the surface fringe structure and hence the aberration performance depends on the hologram surface fringe structure [18]. For considering the recording of a generalized grating, we take object wave \( O \exp(i\phi_0) \) and the reference wave \( R \exp(i\phi_R) \). Then the amplitude transmittance of the recorded hologram may be written as

\[
T = \beta \left[ |O|^2 + |R|^2 + 2|O||R| \cos(\phi_0 - \phi_R) \right]
\]  

(5.1)

Illuminating the hologram with a reconstruction wave \( C \exp(i\phi_C) \), we get

\[
I = \beta \left[ C|O|^2 \exp(i\phi_C) + C|R|^2 \exp(i\phi_C) + \text{COR} \exp i(\phi_C + \phi_0 - \phi_R) \right]
\]

\[+ \text{COR} \exp i(\phi_C - \phi_0 + \phi_R) \]

(5.2)

The first two terms in the above equation form 'dc' bias and the third and fourth terms create the virtual and real images respectively. The position and the shape of the fringes formed in the hologram is determined by the phase difference between \( \phi_0 \) and \( \phi_R \).

The main task of a HOE designer is to determine an optical system, which can holographically produce a HOE, having a surface and internal fringe structure which is compatible with the desired aberration and diffraction efficiency. For the fabrication of high quality HOEs the construction optics
should also be of high quality. Any defects in this optics will be recorded in the HOE. Multiple reflections between the surfaces of the construction optics and scattered light should be minimized. Extreme mechanical stability of the optics and the supporting surface is required. The system should also be kept free from dust and other noise sources.

By using the fabricated experimental setup, we have attempted to record a few holographic lenses, mirrors and gratings. Then a pattern recognition system which uses conventional glass lenses has been developed. Matched filters [21] for complex spatial filtering have been recorded and the correlation peaks are observed. In the next step a multiple HOE which functions simultaneously as a matched filter and as the second Fourier transform lens has been recorded. The correlation peaks are again obtained.

Only simple methods have been used for the simulation of the above elements and no thorough evaluation of the qualities of the HOEs recorded has been done. Considering the interests developed for the past few years on HOEs we think that the experience we gained, however small it may be, through the fabrication of these elements will be rewarding. This is reported just for completeness of presentation of the work we have done in this field.
5.2 SIMULATION OF HOEs

5.2.1 Holographic Lens

A holographic lens can be considered as an interferogram formed by a spherical wave from a point source and a plane wave reference. When functioning as a lens, the plane wave reference is the lens input, and the focus is the real image of the point source. An off axis arrangement as given in Fig 5.1 was used in our laboratory for the simulation of holographic lenses.

The beam from a 10 mw He-Ne laser is split by using the beam splitter BS of about 50% reflectivity. The spatial filters (SF) consisting of 20 X microscope objectives and pin-holes of about 20 microns diameter are arranged after the mirrors M1 and M2 to increase the uniformity of the beams. The pin-holes used here are some of the smallest pin-holes we have made. This has been used to achieve a sharp focus the simulation of holographic lens.

[22,23]. Lens L2 with a focal length 25 cm has been used for
collimating the reference beam. The path lengths of the two
beams were arranged equal. Fifteen holographic lenses with
focal lengths ranging from 10 cm to 30 cm were recorded by
using different system configurations. Also the angle between
the beams was varied in a range of 10° to 20°. Agfa 10E-75
plates were used as the recording material. During recording
the holographic plates were arranged in such way that the two
beams made almost equal angles with the plate normal. This has
been done in order to minimize the aberrations [23,24] due to
emulsion shrinkage. Emulsion shrinkage was also minimized by
deliberately over exposing the plate [23]. This reduces the
developing time, thereby reducing the emulsion distortions.
The exposure time was about 0.1 sec and 1 minute developing was
done in 1:1 diluted IPC 163 developer. The effective aperture
of the lenses varied from 2 cm² to 5 cm².

After the usual processing, the lenses were bleached
for 3 minutes in 5% aqueous solution of potassium ferricyanide
[25] to enhance the diffraction efficiency.

Fig 5.2 shows the reconstructed real focus of one of
the holographic lenses with a
focal length of 35 cm. The
intensities were measured by using
the EG & G 460-1A laser power-
meter and the diffraction
efficiencies were calculated. The
best efficiency we could obtain
was about 4%.

One of the holographic lenses has been used for
obtaining the Fourier spectrum of a wire mesh. Fig. 5.3a and 5.3b are those obtained with a good quality glass lens and with a hololens respectively. The focal length of the two lenses were equal to 25 cm. The quality of the Fourier spectrum obtained with the hololens is comparable to that obtained with the glass lens.

5.2.2 Holographic Paraboloid Mirrors

In recent years the importance of conic mirrors have got a revival due to their many new applications [8,9] such as spacecraft observatory, spectro-radiometers, laser fusion target illumination systems etc. The fabrication of such mirrors are difficult by using conventional methods. The attractive features of holographic optical elements can be utilized here and the wave front reconstruction technique can be applied to simulate different types of mirrors. Here the holographically simulated mirror (HSM) should reconstruct say, the object wave by reflection. Reflection holograms [25] can
be made by allowing the two beams to enter the emulsion from opposite sides. Different isophase layers will be formed parallel to the hologram surface and the waves reflected by these layers reconstruct the object wave. Reflection holograms of the volume phase type fabricated with dichromated gelatin have efficiencies close [26] to 100%. Holo-spherical mirrors with dimensions larger than 32 inches are used in optical simulators for the training of pilots.

Any general conic section may be represented by the equation

\[ y^2 = 2px + (e^2 - 1)x^2 \]  

(5.3)

Here \( e \) is the eccentricity and \( 2p \) is the latusrectum. If we slowly vary the value of \( e \) from \( e > 1 \) to \( e = 1 \), the situation arisen can be analysed as follows. As \( e \) comes closer to unity, the second vertex of the hyperbola will be farther from the first vertex (similar is the case with a second branch) and in the limit the hyperbola reduces into a parabola [20]. The situation can be practically realised by mixing a set of plane waves and a set of spherical waves entering the emulsion from opposite sides [20,25]. The traces of the contour surfaces resulting from the interference will be parabolas, almost parallel to the hologram surface. This family of partially reflecting parabolae function as several layers of parabolic mirrors having a common focal point.

The experimental arrangement we have used is given in Fig.5.4. Here a diverging beam and a plane beam are made to enter the emulsion from opposite sides. The two interfering
beams are offset by an angle $\phi = 7^\circ$. The holographic plate is kept at the bisector of the angle made by the interfering beams. Seven paraboloid mirrors with focal lengths 15, 20, 25 and 30 cm were simulated. These HSMs were bleached as described in the previous section. A photograph of the reconstructed real focus is given in Fig.5.5. The diffraction efficiency was measured and was found to be only 0.76%. 

Fig 5.4 Experimental arrangement for the simulation of holographic paraboloid mirrors.

Fig 5.5 Real focus of a paraboloid mirror.
5.2.3 Holographic Gratings

Like other HOEs holographically simulated diffraction gratings (HSDGs) have also become a potential tool for instruments designers. Even though the efficiency of HSDGs are not as good as that of ruled gratings [19], their large size, number and pattern of grooves, low scattered light and the freedom for aberration correction make them attractive.

A holographic grating is an interference pattern containing a great number of closely packed fringes. A plane grating is obtained if the interfering beams are plane and the recording of the fringes are done on a plane surface. The theory of HSDGs, their efficiency and aberrations have been discussed by several scientists viz., Kogelnik [12] Murty and Das [13], Noda et al. [27] and Mahipal Singh [28]. The scattering of input light caused by the granular structure of the recording materials and its influence on the diffraction efficiencies of planar gratings have been investigated by Syms and Solymar [29,30].

Consider the simple case of two plane waves derived from a coherent source and the beams intersect at an angle $2\theta$. In the region of interference the intensity will be a maximum at the points where the relative phase difference of the waves, say $\phi_2 - \phi_1$, satisfy the condition

$$\phi_2 - \phi_1 = 2n\pi$$

As the plane waves progress in the direction of their wave normals, the interference lines will generate planes of
maximum intensity. These planes of maximum intensity bisect the angle between the wave normals. The period of the sinusoidal intensity variation 'd' is given \[25\] by

\[2d \sin(\phi) = \lambda\] (5.5)

The period of the fringes decreases with the increase of the angle \(2\phi\). If we place a thin photographic material which can resolve \(1/d\) fringe pairs/unit distance, with its plane perpendicular to the bisector of the angle \(2\phi\), the photographic record of the interference lines (hologram) will function as a HSDG. The grooves in relief produced in the emulsion after processing will be equidistant. Imperfections, roughness etc., are very much less compared to the ruled grating, thus reducing stray-light.

The arrangement used in our laboratory to simulate a few holographic diffraction gratings is as shown in Fig.5.6. By using a 50% reflectivity beam splitter BS the beam from the laser is divided into two parts. The spatial filters SF are arranged after the mirrors M1 and M2 to enhance the beam uniformity. Both the beams are then collimated by using two good quality lenses of focal lengths 25 cm each. Path lengths of the beams were arranged equal.

The photograph of the interference pattern was recorded on Agfa 10E75 plates. Three sets of gratings were simulated by changing the angle between the beams viz., 10°, 15°, 20°. The fringe frequency in each case was measured by using a spectrometer and was found to be 273, 414 and 540 lines/mm respectively. The diffraction efficiencies of these
The diffraction orders of a laser beam, produced by one of the gratings ($2\theta = 15$) and that of a ruled grating are given in fig. 5.7a and b. It can be clearly seen that the stray light because of non-periodic errors [19] in classically ruled grating, is not at all a problem in the holographic grating.
5.3 HOLOGRAPHIC PATTERN RECOGNITION SYSTEM

5.3.1 Introduction

From the lonely domain of lens designers and astronomers, optics has now become a vital field affecting all areas of basic research and applied technology. Lasers, holography, optical Fourier transformations, and optical spatial filtering are a few of the key items that spawned lots of developments in optics. Optical spatial filtering is one of the most significant developments evolved due to the happy marriage of communications theory and optics [31].

In 1964 Vander Lugt [21,32-33] succeeded in the optical realization of a complex matched spatial filter by combining the concepts of radar processing and holography. Pattern recognition is the identification of a given pattern of data with in a mass of extraneous signals. Considerable research has been done for military applications, but recent advances suggest development of systems with potential commercial applications. An updated summary of the present status of optical data processing has been treated and reviewed by Casesent[34-37]. The rapidity of processing data in parallel and in real time has captured the imagination and brought out the inventiveness of many researchers [38-44]. A holographic technique which can detect and identify images of target objects despite distortions in image scale, angle of view or rotation was reported [45] in 1986. This method, developed at the Imaging Technology Division of Sandia National Laboratories, is effective even if the target is partially obscured. Over the past five years interest in Optical Pattern
Recognition appears to have still increased. Tien-Hsiu Chao and Hua-Kuang Liu [46] reported the use of coherent optical correlation technique for real time tracking of multiple objects making independent movements. Recently a special issue of Optical Engineering [47] which puts together the current research activities on optical pattern recognition has appeared. Various theoretical issues related to correlation filters and important aspects related to practical implementation of correlators are discussed in it.

5.3.2 Initial Experimental Setup and the Basic Principle

Using glass lenses as the Fourier transform elements we have initially constructed an experimental optical correlator as shown in Fig.5.8. The variable beam splitter VBS enables control over the beam balance ratio. The folded paths from VBS to mirrors M2 and M1 are used to maintain equal beam path lengths. The angle between the beams is arranged to be
\( \theta = 20^\circ \). A variable attenuator \( A \) is also arranged in the object beam path to facilitate its intensity variation. \( S \) is a mechanical shutter with 'T' setting and having a maximum speed at 1/150 sec. Two spatial filters consisting of 20 microns pinholes and 20X microscope objectives are arranged after the mirrors \( M_1 \) and \( M_2 \). Two lenses (\( L_1 \) and \( L_2 \)) with focal lengths 25 cm and 15 cm are used for collimating the object beam and the reference beam respectively. Lenses \( F_{L1} \) and \( F_{L2} \), both of focal lengths \( f = 40 \text{ cm} \) are used as the Fourier transform elements. The solution flow system described in Chapter III has been used for the \textit{in-situ} processing of the hologram.

We represent the input, transform and output correlation planes by \( P_1, P_2 \) and \( P_3 \) respectively with spatial coordinates \((x_1, y_1), (x_2, y_2) \) and \((x_3, y_3)\). If \( \lambda \) is the wavelength of the laser used we can denote the spatial frequency coordinates of the transform plane \((u, v) = (x_2/\lambda f_1, y_2/\lambda f_1)\), \( f_1 \) is the focal length of the FT lenses. We use the upper case variables to denote the Fourier transform of the spatial functions. Suppose we initially form a matched spatial filter of the spatial function \( h(x_1, y_1) \). This can be done by placing \( h(x_1, y_1) \) at the plane \( P_1 \) and taking hologram of its transform \( H(u, v) \) formed at the plane \( P_2 \) by \( F_{L1} \). After the processing we block the reference wave and a transparency with amplitude transmittance of \( g(x_1, y_1) \) is placed in the input plane looking for the correlation.

The light distribution \( U_2(x_2, y_2) \) in plane \( P_2 \) due to the complex Fourier transform of \( h(x_1, y_1) \) can be represented [25] by
\[ H(u,v) = \frac{1}{1 - \lambda f_1} \int \int h(x,y) \exp[-2\pi i(ux + vy)] \, dx \, dy \] (5.6)

The light amplitude at the hologram forming plane \( P_2 \) due to a plane reference wave incident at the angle \( \vartheta \) to the signal beam can be represented by

\[ U_r = R_0 \exp(-i2\pi \alpha x_2) \] (5.7)

where the spatial frequency \( \alpha \) associated with the reference wave = \( \sin(\vartheta)/\lambda \). After the hologram recording and processing its transmittance is.

\[ T(x,y) = |U_2 + U_r|^2 \]
\[ = R_0^2 + |H|^2 + R_0 H \exp(i2\pi \alpha x_2) + R_0^* H^* \exp(-i2\pi \alpha x_2) \] (5.8)

In the second stage we block the reference beam and if we keep the transparency \( g(x_1,y_1) \) at \( P_1 \), then the amplitude distribution falling on the hologram in plane \( P_2 \) is \( G(u,v) \) and that leaving the plane is \( G(u,v) T(x_2,y_2) \). Lens \( FL_2 \) then forms the Fourier transform of \( G(u,v) T(x_2,y_2) \) at its back focal plane, or finally we get [49] in the plane \( P_3 \).

\[ U_3(x_3,y_3) = R_0^2 g\delta(x,y) + [h \otimes h g] \delta(x,y) + R_0 [h^* g^*(\delta(x_3 + \alpha f_1, y_3)] + R_0 [g h^* \delta(x_3 + \alpha f_1, y_3) \] (5.9)

* implies convolution and \( \otimes \) implies correlation.

The first two terms will be centered on-axis in the plane \( P_3 \). The third term, the convolution, starts from \( P_2 \) at an
angle $\phi$ and appears at $(0, \alpha f)$ in the output plane $P_3$. The last term containing the correlation emerges from the plane $P_2$ at an angle $-\phi$ and appears at $(0, -\alpha f)$ in the output plane $P_3$. If the function $g$ contains the reference signal $h$, then a bright spot of light in the output plane $P_3$ appears due to the correlation. The location of this spot in plane $P_3$ is proportional to the location of the reference function $h(x, y)$ in the input function $g(x, y)$.

In our experiments the reference function used was the word HOLOGRAPHY (Fig. 5.9). In actual experiments the hologram recording position was slightly defocussed by about 2 cm (about 5% of $f_1$) to improve the dynamic range [49] of the recording medium. The recording medium used was Agfa 8E75 plates which had got a resolving power of about [25] 3000 lines per mm. Fig 5.9 Reference function. This type of plates [50] provide uniformly good diffraction efficiency in a spatial frequency range of 500 to 2500 lines/mm. The exposure time given was 1/25 sec. One minute developing was done in IPC 76 fine grain developer. The correlation plane pattern obtained when as input transparency as shown in Fig. 5.10 has been used is given in Fig. 5.11. The locations of the correlation peaks are proportional to the locations of the word HOLOGRAPHY. The spots with lesser intensity are the erroneous cross correlations. This is due to

102
the similarity in the general shape of the letters. Binns et al. [39] suggested the use of high signal to reference beam intensity ratios to increase the discrimination between similar patterns.

Fig 5.11 Correlation plane pattern.

5.3.3 A Compact Optical Correlator

In any optical frequency plane correlator, its size and weight are two important features [23,48] which have to be considered. Both of these parameters can be reduced by combining the matched spatial filter and the Fourier transform lens on a single plate [48]. For this a multiple function holographic optical element has to be recorded. Fig.5.12a shows the arrangement for the experimental realization of the above said factors, resulting in a compact optical frequency plane correlator. This is similar to the conventional system described in Fig.5.8 except in the fact that a converging reference beam is used rather than a plane wave. This results in the recording of the matched filter and the Fourier transform lens on the same plate. Lens CL2 has been kept at a distance of 56 cm from the hologram.
5.4 RESULTS AND DISCUSSION

A set of simple holographic Optical Elements such as lenses, mirrors, gratings, complex matched spatial filters and multiple function HOEs are stimulated by using the experimental setup we have developed. A qualitative analysis of the performance of these HOEs has been done and was found to be satisfactory. Two optical frequency plane correlators have
been developed and the recognition peaks are obtained. The performance of these correlators are found comparable in their ability to recognize words.

The major feature of the latter frequency plane correlator system is the use of a converging reference beam. This enabled the recording of both the matched spatial filter and the transfer function of the Second Fourier transform lens in the same hologram and resulted in the reduction in size, weight, number of optical components necessary and the complexity of the system.
References