Use of a holographic lens for producing cylindrical holographic stereograms

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Abstract. The production of cylindrical holographic stereograms, or multiplex holograms, requires the use of a large, low f/number cylindrical lens to form a line image on the holographic film. To have an image of reasonable size for display purposes, the f/number of the lens must be quite small, on the order of f/1, and the dimensions of the lens must be reasonably large, on the order of eight inches in width and height. The optical quality of the lens must also be quite good to prevent interference fringes in the image and to minimize the number of multiple exposures in the multiplexing process. For economic reasons, adjustable, oil-filled plastic lenses are commonly used for this purpose instead of conventional optics. Considerable difficulty is usually encountered, however, in adjusting the oil lens to minimize aberrations. Making the oil lens adequately adjustable, while at the same time maintaining the oil seal, also presents mechanical difficulties. We have eliminated these problems with the use of an off-axis, holographic cylindrical lens. The lens is easy to make, requires no adjustment, and has excellent optical quality. Techniques for producing this lens and its use in making multiplex holograms are described.

Keywords: holographic cylindrical lens; cylindrical lens; holographic optical elements; holographic display.

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CONTENTS

1. BACKGROUND

Cylindrical holographic stereograms, or multiplex holograms, produce appealing, moving, three-dimensional images from ordinary motion picture films of the subject. These holograms are illuminated with white light from a common incandescent light bulb allowing inexpensive and safe holographic displays to be made for viewing by the general public.

Utilizing work in rainbow holography by Benton,[1] and earlier work in composite holography,[2-6] Lloyd Cross invented the multiplex hologram in 1973.[7] In this technique, a motion picture film is made of a rotating moving subject using conventional lighting techniques. (See Fig. 1.) The rotation of the subject provides sequential horizontal perspective information which is recorded on individual frames of the movie film.

This motion picture film is then transformed into a composite hologram consisting of individual vertical line holograms of each frame in the motion picture sequence. This transformation is accomplished with a special automated machine which uses a laser as a coherent light source. (See Fig. 2.)

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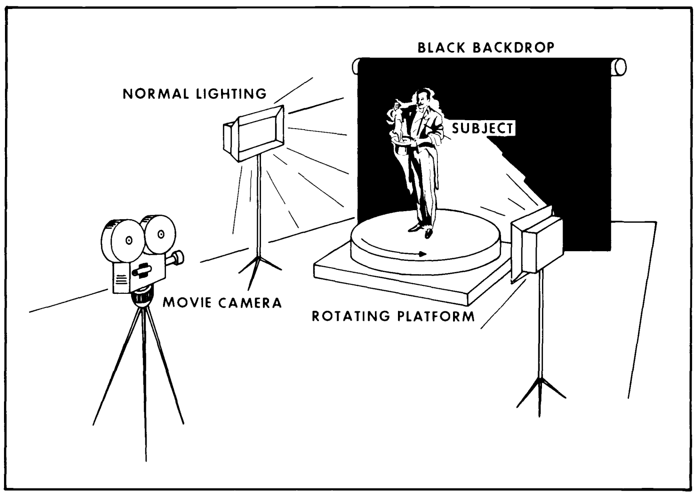

Fig. 1. Studio setup required for recording movie films used to make multiplex holograms.

It is not within the scope of this paper to describe in detail the numerous optical parameters which must be considered for each component of this apparatus. However, an understanding of the fundamental principles involved in this process will be helpful in seeing the advantages gained by utilizing holographic optical elements in the apparatus used to make multiplex holograms. Therefore, we will briefly describe the function of the basic components needed.

Figure 2 shows a simplified sketch of the essential components needed in the apparatus. Light from the laser is split into reference and subject beams by a beamsplitter. The subject beam is directed towards a single frame movie projector where it is filtered and caused to uniformly illuminate the film gate. Anamorphic optics are used for

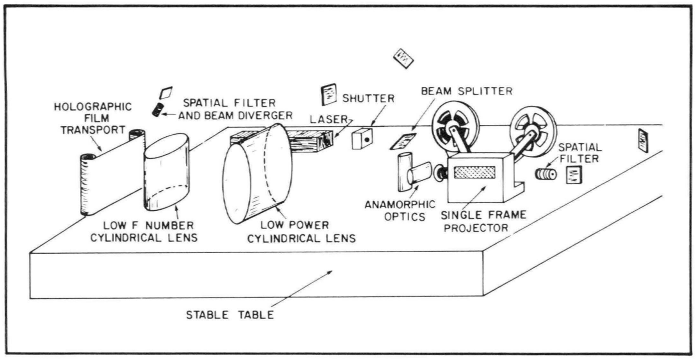

Fig. 2. Simplified sketch of special automated machine used for making multiplex holograms.

the projection lens to separate the vertical and horizontal image planes. Vertical image rays are focused onto the holographic film to allow for white light reconstruction, while horizontal image rays are focused in a plane near the location of the reconstructed image, usually near the plane of the low f/number cylindrical lens.

The large-aperture, low-power cylindrical lens is used to converge vertical illumination rays to a point coincident with the nominal viewing distance—usually two to three feet beyond the holographic film. The location of this convergence point significantly affects the vertical viewing angle of the hologram. The purpose of the low f/number cylindrical lens is to focus the illumination rays in the horizontal plane to a line at or near the surface of the holographic film.

A spatially filtered and diverging reference beam is directed toward the holographic film from directly above or below the low f/number cylindrical lens, depending on where the reconstruction source is to be located in the final display.

The sequence for recording the hologram is as follows: A strip hologram of the first frame in the movie film is recorded with an exposure time determined by the shutter setting. The next movie frame is brought into position by advancing the single frame projector. The holographic film is advanced, and a second hologram is recorded. This entire sequence is repeated until all the movie frames have been holographically recorded. The holographic film is then processed and formed to a cylindrical shape. When a white light source is placed in a position near the location of the original reference beam divergence point, the reconstructed subject appears suspended in the center of the cylinder.

2. CYLINDRICAL LENS REQUIREMENTS

A key component in the system and the primary subject of this paper is the large, low f/number cylindrical lens which is the last element in the subject beam optical path. The purpose of this lens is to focus subject illumination rays to a line near the holographic film. This lens acts as a field lens but only in the horizontal direction. It is located at or near the horizontal focal plane and has no power in the vertical direction, so it does not affect the location of these planes, as previously determined by the anamorphic projection lens.

The physical size of this lens must be larger than the image to be reconstructed. A typical image size of 8 inches requires a lens with at least an 8 inch clear aperture. To take maximum advantage of the clear aperture, horizontal image rays are focused at or near this lens.

The f/number requirement is determined in part by the maximum width the reconstructed image is to be. These holograms are usually viewed as a cylinder shape with the reconstructed image appearing suspended in space at or near the center. We show in another paper[8] that the image is located a distance from the film equal to the radius of curvature of the displayed hologram and not by the location of image planes in the system used to make the hologram. For optimized reconstruction, therefore, it follows that the cylindrical lens and the horizontal focal plane of the image should be located at this same distance in the system. Common display diameters are 12 to 16 inches. If reconstructed image widths are expected to be 8 inches or more, the effective f/number of the cylindrical lens must be less than f/1.

The optical quality must be reasonably good for a number of reasons. First, in terms of image definition and sharpness, common lens aberrations, such as spherical aberration, coma, and distortion, have little effect on the image because of its action as a field lens. These aberrations do have a pronounced effect on image brightness or hologram efficiency, because the width of the focused line determines the number of strip holograms which must be overlapped and thus the number of multiply exposed holograms that must be recorded by the film. We have found that hologram efficiency is significantly reduced when one attempts to record more than ten holograms on the same film area.

Another problem encountered when using a lens of poor quality is that aberrations, which contribute to a non-ideal focal line width, produce ray bundles near the focus which contain grossly different angular components. If one attempts to use this lens too near the focus when trying to minimize the number of overlapped holograms, successive holograms recorded can interfere in areas where rays enter the holographic film from identical angles. This produces annoying interference patterns in the reconstructed subject.

Of course, overall transmission qualities of the lens are also important. Dust particles, smudges, and scratches present in or on the surface of the lens will contribute to noise in the reconstruction.

3. PLASTIC LENSES USED

For economic reasons, these large cylindrical lenses have been commonly constructed from clear plastic sheet such as Plexiglas. Surfaces are bent to the nominally required curvature and end plates are attached. This shell is then filled with an index matching fluid such as mineral oil to form the lens. Because of the mechanical difficulty in producing the desired lens surface curvature with plastic sheet, the lens is usually made somewhat adjustable. This is commonly achieved by mechanically pressing on the lens surface at various points near its edges, in order to change the curvature across the lens at that location. Figure 3 shows an adjustable oil-filled lens constructed by the authors for making multiplex holograms at the University of Dayton. It has a focal length and clear aperture of 6 inches and produces a usable focused line width of 1 cm. Figure 4 is a photograph of the ray cone near the focal region and represents fairly typical performance of plastic lenses that we have produced using this technique. Although this lens construction technique saves the high cost of having a lens fabricated with conventional methods and

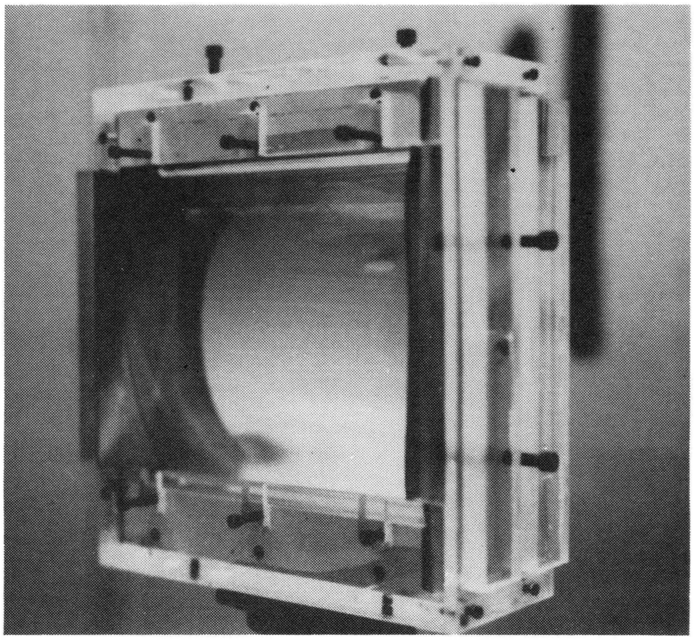

Fig. 3. Adjustable, oil-filled plastic lens used in making multiplex holograms.

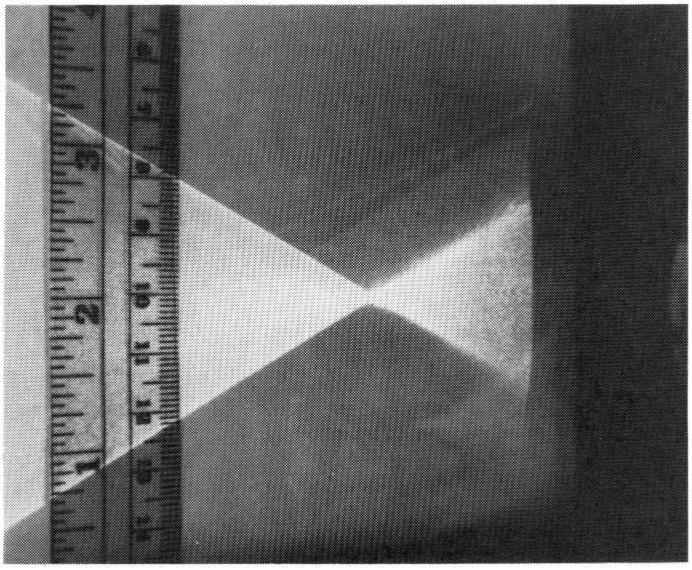

Fig. 4. Focal region formed by the plastic lens shown in Fig. 3.

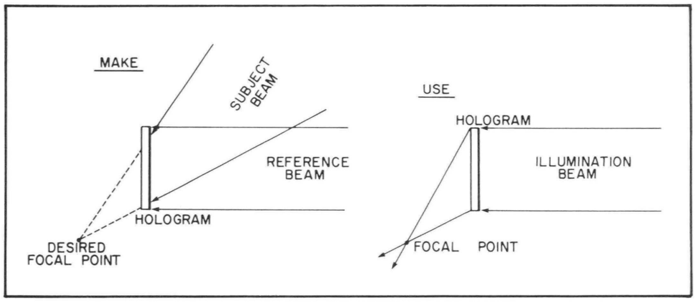

Fig. 5. Optical scheme for making and using a simple off-axis transmission HOE.

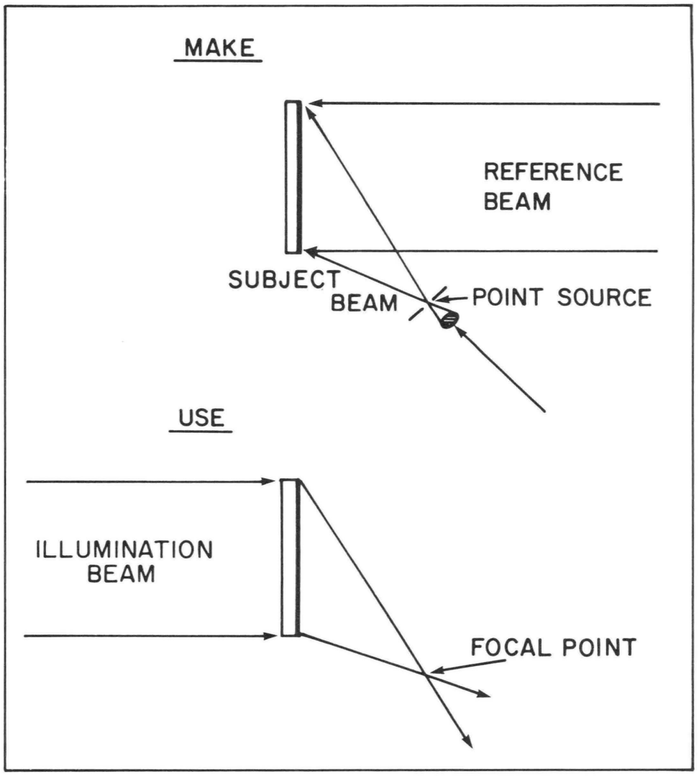

Fig. 6. Off-axis transmission HOE formed with the conjugate of the desired wavefront.

materials, performance and ease of use are compromised. The lens is difficult to construct with adequate adjustment while maintaining a good oil seal. It is also difficult to adjust for best focus while maintaining a constant line width along the full length of the lens. In addition, the lens requires periodic tuning to maintain best performance.

4. HOLOGRAPHIC OPTICAL ELEMENT (HOE)

Although for several years we successfully used the plastic adjustable lens to produce multiplex holograms for various research projects at the University of Dayton, our interests in developing methods for increasing image width and reducing distortions required that we obtain larger lenses of higher quality. These interests and our difficulties with the fabrication and use of oil-filled plastic lenses led us to consider the use of a holographic optical element (HOE) to perform the function of the low f/number cylindrical lens in the multiplex apparatus. Numerous basic holographic configurations can be used for making a HOE. These include transmission and reflection holographic techniques utilizing both off-axis and on-axis schemes. The appropriateness of one configuration over another is dependent upon the particular application being considered. A number of comprehensive articles on the construction of HOEs and analysis of their performance characteristics can be found in the literature.[9-14] Since, in our application, the HOE is used to control illumination rays and not imaging rays, design considerations are reduced to the simplest case by treating this element as a simple condensing optic. Figure 5 illustrates the fundamental requirements for making a simple transmission, off-axis, focusing HOE. Subject beam rays are caused to converge to a point congruent with the desired focal point of the HOE. A collimated reference beam is directed toward the holographic film at the desired angle of incidence. A hologram is then made by recording the interference of these two wavefronts. After developing, the hologram is used as a lens by illuminating the hologram with the original reference beam. The reference beam rays will then be diffracted toward the point of convergence of the original subject beam, thus forming the focal point of a simple lens. This focal point will contain all the characteristics of the focal region created by the original optic used in making the hologram.

Where an optic is not available to produce the desired wavefront, the conjugate of this wavefront can often be produced. By taking advantage of the hologram property of conjugate reconstruction, a HOE can often be produced with the desired optical characteristics. Referring to Fig. 6 to illustrate the above, a spatially filtered point source is positioned at the desired location of the focus of the HOE. The point source wavefront interfaces with a reference beam, and a hologram is recorded. After development, the HOE is used by illuminating the hologram from the conjugate direction of the original reference beam. This characteristic makes the fabrication of a cylindrical holographic optical element to make multiplex holograms particularly attractive and relatively easy.

Figure 7(a) is an optical diagram of the setup used for making an off-axis transmission cylindrical HOE suitable for making multiplex holograms. Light from the laser is split into subject and reference beams by the beamsplitter BS. The reference beam is directed toward the holographic film at the desired angle of incidence by mirrors m_3 and m_4. This angle is determined by the clearance required around CL_3 and its mount. SF_1 and L_1 spatially filter, expand, and collimate the beam to uniformly illuminate the holographic film. The subject beam is directed toward spatial filter SF_2 via m_1 and m_2, where it is caused to diverge and uniformly illuminate a short focal length cylindrical lens (CL_3). This lens produces a low f/number cone of rays which forms the conjugate of the desired line focus of the HOE. A small diameter glass or plastic rod serves the function of this lens admirably. A cone angle of f/0.5 can be obtained with a glass rod when properly illuminated. However, care must be taken to select a rod with good optical quality. The length of rod illuminated determines the length of the focal line of the final cylindrical HOE, and

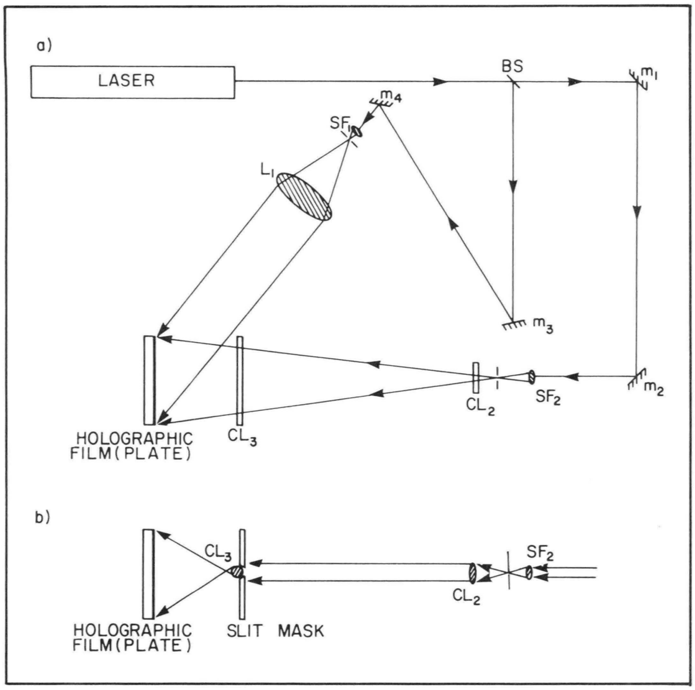

Fig. 7. Optical diagram of arrangement used for making off-axis cylindrical HOE suitable for use in making multiplex holograms.

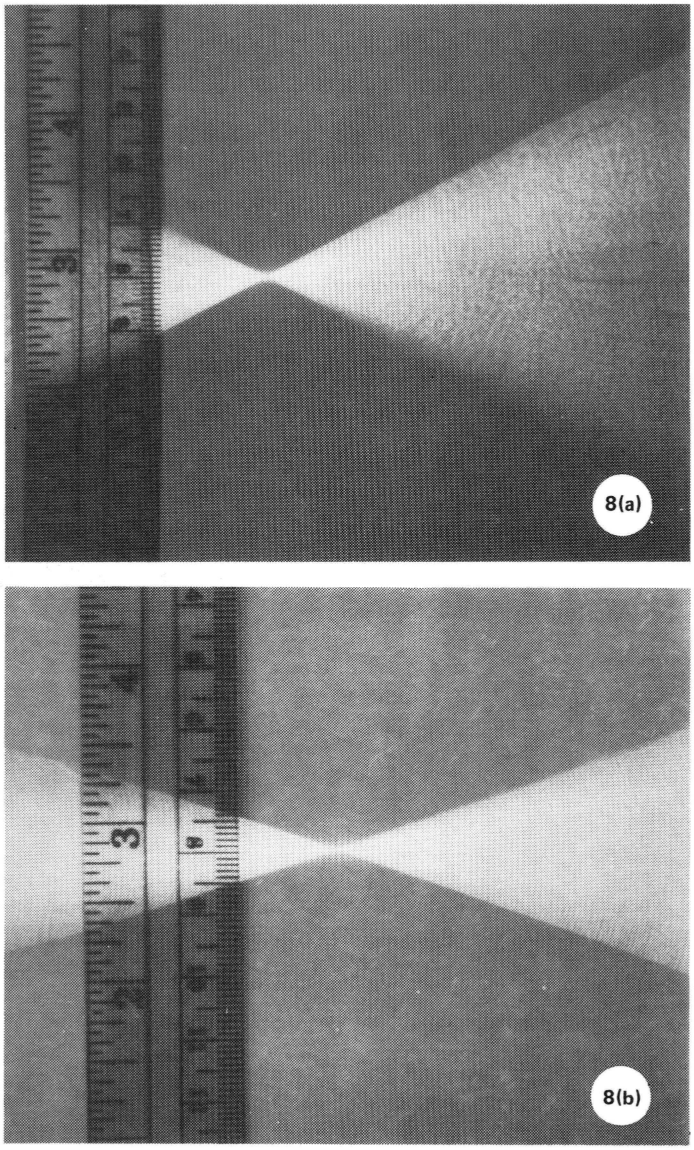

Fig. 8. Characteristics of the focal region of (a) the six inch f/0.75 and (b) eight inch f/1.0 holographic cylindrical lenses.

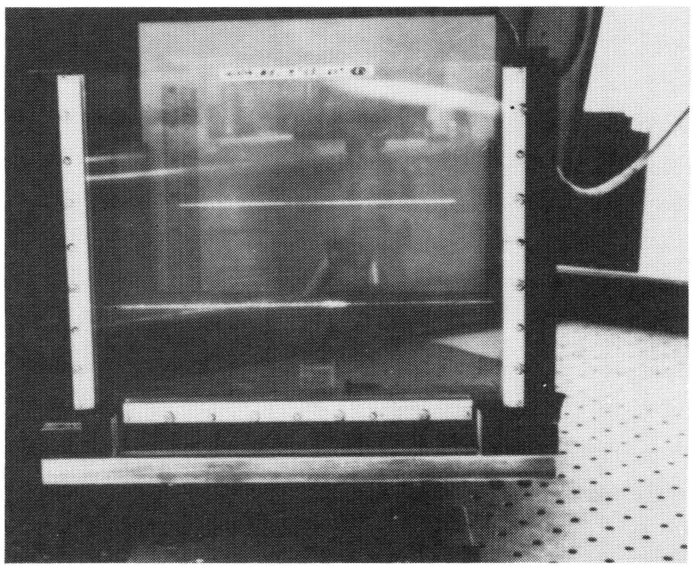

Fig. 9. Eight inch focal length holographic cylindrical lens and its line-focusing characteristics.

this length determines the maximum height of the multiplexed holographic image in the final display. CL_3 is made parallel to the holographic plate to maintain a constant f/number along its length. The distance between CL_3 and the holographic plate determines the focal length of the HOE. Referring to Fig. 7(b), which is a side view of the optical path between m_2 and the holographic film, CL_2 is a cylindrical lens which collimates the diverging wavefront from SF_2 in the vertical direction. This is done to increase efficiency in the subject beam path. An adjustable slit mask is used at CL_3 to prevent light from reaching the film around this element. It also serves to limit the aperture of CL_3, controlling the quality of the focused line and the f/number of the ray cone leaving CL_3.

5. CYLINDRICAL HOE PERFORMANCE

Cylindrical holographic lenses were produced with both argon and HeNe lasers at wavelengths of 0.5145 μm and 0.6328 μm on 8 by 10 inch Agfa 10E56 and 8E75 glass plates. The developing procedure used was the standard D-19 process. Holograms were bleached with a solution of potassium ferricyanide and potassium bromide. For increased printout stability, they were postbleached in iodine. Diffraction efficiencies in excess of 50 percent were routinely obtained. Lenses with focal lengths of 6 and 8 inches were made with clear apertures of 8 inches. Figure 8 shows the performance near the focal region of both these holographic lenses. Figure 9 shows the line focus characteristics of the 8 inch focal length lens. Little difficulty was encountered in obtaining a focused line width of less than 1 mm. This allowed us great flexibility in controlling the strip hologram line width. Bright multiplex holograms were produced using these HOEs with vertical line hologram spacings as small as 0.5 mm. Figure 10 is a photograph of a hologram recently produced using a cylindrical HOE as the final optical element in the subject beam path.

6. CONCLUSIONS

In this paper we have discussed techniques for making a low f/number, large aperture, cylindrical holographic optical element and demonstrated its use in apparatus making multiplex holograms. Described were optical elements produced by this method, having clear apertures of 8 inches and f/numbers as low as f/0.75. These optical elements produced focused line widths of less than 0.5 mm

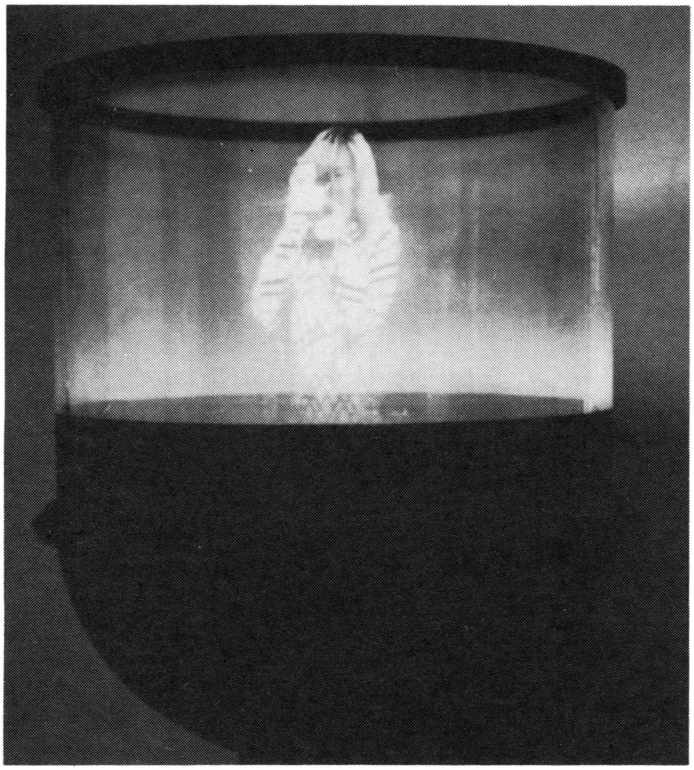

Fig. 10. Cylindrical holographic stereogram made with cylindrical HOE.

using collimated or near-collimated illumination and had efficiencies greater than 50 percent. They were easily produced (using simple optics, standard holographic equipment and materials) and have replaced the adjustable plastic lens in our apparatus. This technique also provides a method for producing the specialized optical elements required for maximizing image width and correcting horizontal distortions in cylindrical holographic stereograms.

7. ACKNOWLEDGMENTS

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