MULTI-FACET HOLOGRAPHIC OPTICAL ELEMENTS†

Steven K. Case and Paul R. Haugen
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

SUMMARY

New types of holographic optical elements are demonstrated which combine some of the flexibility of computer generated holograms with the large space-bandwidth product and high diffraction efficiency of interferometrically recorded volume phase holograms. The optical elements are recorded by subdividing a volume hologram film surface into numerous small areas (facets), each of which is individually exposed under computer control. Each facet is used to produce a portion of the desired final wavefront. Three different optical elements are demonstrated.

INTRODUCTION

Holographic optical elements are an attractive alternative to conventional optical elements in systems using coherent light. The attributes of holographic optical elements include the capability of producing low f-number diffraction limited optics, and the ability to generate arbitrary wavefronts. They are also potentially easy to replicate and have low weight and compact size. Unfortunately, not all of these attributes are shared by all hologram types.

We could categorize holograms as computer generated, interferometrically generated, or generated by a hybrid technique as described in this paper. Computer generated holograms (CGH) offer the greatest flexibility in the production of arbitrary wavefronts. CGH's, however, usually have limited space-bandwidth products and diffraction efficiency. Volume phase holograms, on the other hand, can have nearly 100% diffraction efficiency into a single order and very large space-bandwidth products (necessary for low f-number optical elements), but offer limited flexibility in the production of arbitrary wavefronts.

The new type of hologram described here combines the best features of the previous hologram types: high efficiency, large space-bandwidth product, and greater flexibility in wavefront generation. The principle used to design the new hologram is straightforward. While the interference pattern required to record an entire "arbitrary wavefront" volume hologram is quite complex, the required pattern within a small area on the hologram is relatively simple such that it can be approximated by planar, spherical, or cylindrical waves. Thus our new holographic optical element is recorded by individually exposing numerous, small volume hologram facets. The wavefronts used to record each facet can be different but are produced by conventional optical elements which are positioned via computer control.

---

† This work supported by the University of Minnesota and by AFOSR/ARO Grant DAA29-81-K-0033.

WAVEFRONT TRANSFORMATION OPTICAL ELEMENTS

The first type of optical elements that we describe are used for wavefront transformations. For this system we start with a Gaussian intensity profile laser beam which we wish to transform into another shape in order to optimally illuminate some object (for interferometric testing or materials processing). In this example, we assume that we must illuminate the periphery of a hollow, square box. Such a transformation requires two holographic optical elements as shown in Fig. 1. The first hologram acts to spatially redistribute the input light beam and the second hologram produces a desired phase front on the redistributed light so that it can propagate toward a distant object.

The first hologram is recorded by subdividing the hologram surface into numerous, small squares (facets) each of which is individually exposed as in Fig. 2. The spatial frequency of the grating recorded within each facet is varied by suitably adjusting the object beam incidence angle before recording. The grating frequency within each facet is chosen such that the input beam in Fig. 1 will be suitably deflected to be spatially rearranged when it reaches the plane of Hologram #2. Design considerations for the hologram are given in Ref. 1 and will not be repeated here.

The redistributed light from Hologram #1 and a plane wave are used as the recording waves for Hologram #2. In this manner, Hologram #2 can rediffract the light arriving from Hologram #1 to produce a final output wave with the desired intensity distribution and a planar wavefront. Because both holograms are recorded in dichromated gelatin, they have nearly 100% diffraction efficiency so that the redistribution process is light efficient. In Fig. 3 we have photographed the light pattern in five equally spaced planes to show the gradual redistribution of light via our process.

SPACE-VARIANT LENS

The multi-facet hologram technique is also useful for the production of customized holographic lenses with very large space-bandwidth products. As a demonstration, we constructed a space-variant cylindrical lens capable of producing a line focus on a spherical surface.[2] The construction of a conventional lens that would perform this task would be extremely difficult if not impossible. Without multi-facet hologram approach, however, we divide the hologram film into a set of horizontal zones (facets) and specify the focal length that a cylindrical lens wihin each facet would need in order to bring a plane wave to a line focus on the object surface (see Fig. 4).

For recording, a thin, stationary, flexible mask containing a horizontal slit aperture is again pressed lightly against the film. Exposure is with a planar reference wave incident at approxiately 35° with respect to the film normal and a cylindrical wave. The cylindrical wave is produced by focusing a plane wave with a conventional cylindrical lens. The distance between the film plane and the focal plane for the cylindrical wave (i.e., the focal length of the holographic lens being recorded) is selected by moving the cylindrical lens relative to the film. Both the film and the cylindrical lens are mounted on mini-computer controlled translation stages. A facet is exposed via a computer controller shutter. To record the next facet, the film is translated by one facet height and the cylindrical lens repositioned to achieve the prescribed focal length for this facet. The process is repeated until all facets are exposed. The final hologram consists of 13 facets each approximately 19×3mm in size.

The experimental results in Figs. 5 and 6 show the utility of our system. Figure 5 shows the focal pattern obtained when a conventional cylindrical lens is used to focus a line on a 5.4cm diameter sphere. The top of the sphere is located one focal length from the cylindrical lens. Figure 6 shows the improved results when our multi-facet optical element is used. The focal line is now sharp and the segmenting barely visible.

IMAGE FORMATION

Our last demonstration is in the use of multi-facet holograms for the formation of images. The hologram surface is again subdivided into numerous small facets, each of which contains a grating of a specified spatial frequency. When illuminated by a plane wave as in Fig. 7, the light is diffracted to specific locations in the image plane which is located a short distance (20cm) after the hologram plane. The image is thus built up of a number of small patches of light.

As before, each facet is interferometrically recorded under computer control. The computer translates the film behind a mask so that individual facets can be sequentially exposed, and deflects the recording beam to produce the requisite spatial frequencies.

This image production method produces results similar to those from kinoforms[3] in that all of the incident light is transformed into an image. The present production technique has the advantage, however, that one only needs to control a transverse spatial frequency instead of a longitudinal phase shift.

A resultant image from this type of hologram is shown in Fig. 8. Here a 181 facet hologram is used to form a simple image.

CONCLUSION

We have demonstrated three types of multi-facet holographic optical elements which combine optical flexibility, high efficiency, and large space-bandwidth products. These elements should prove useful for a large number of custom optical applications.

REFERENCES

1. S. K. Case, P. R. Haugen, and O. J. Lokberg, "Multifacet Holographic Optical Elements for Wavefront Transformation," Appl. Opt. 20, 2670 (1981).

2. S. K. Case and P. R. Haugen, "Partitioned Holographic Optical Elements," Opt. Engin., March 1982.

3. B. Lesem, P. M. Hirsh, and J. A. Jordan, Jr., "The Kinoform: A New Wavefront Reconstruction Device," IBM J. Res. Develop. 13, 150 (1969).

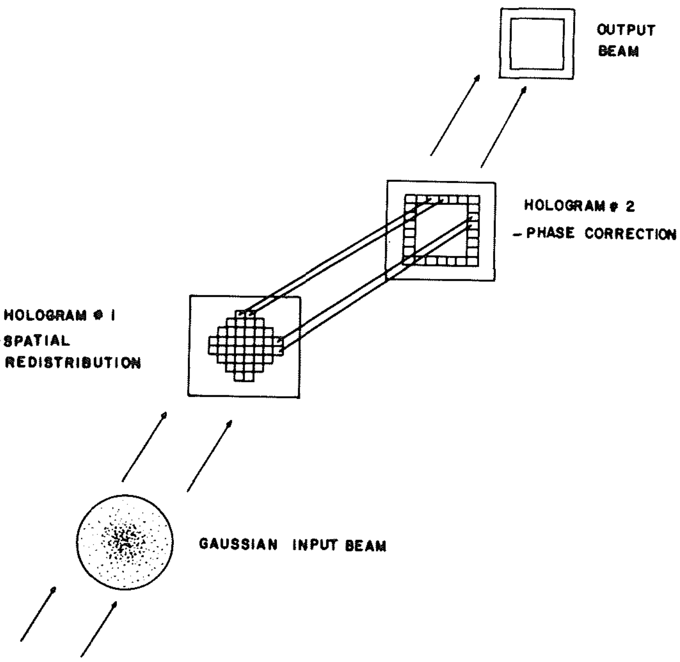

Figure 1.- Wavefront transformation via two holograms.

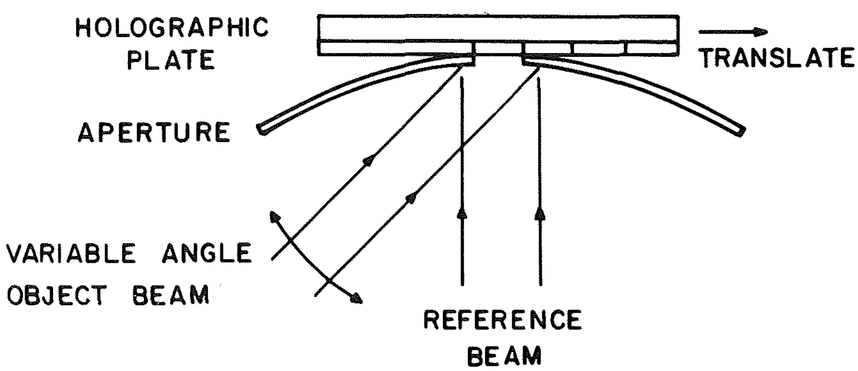

Figure 2.- Multi-facet hologram recording method.

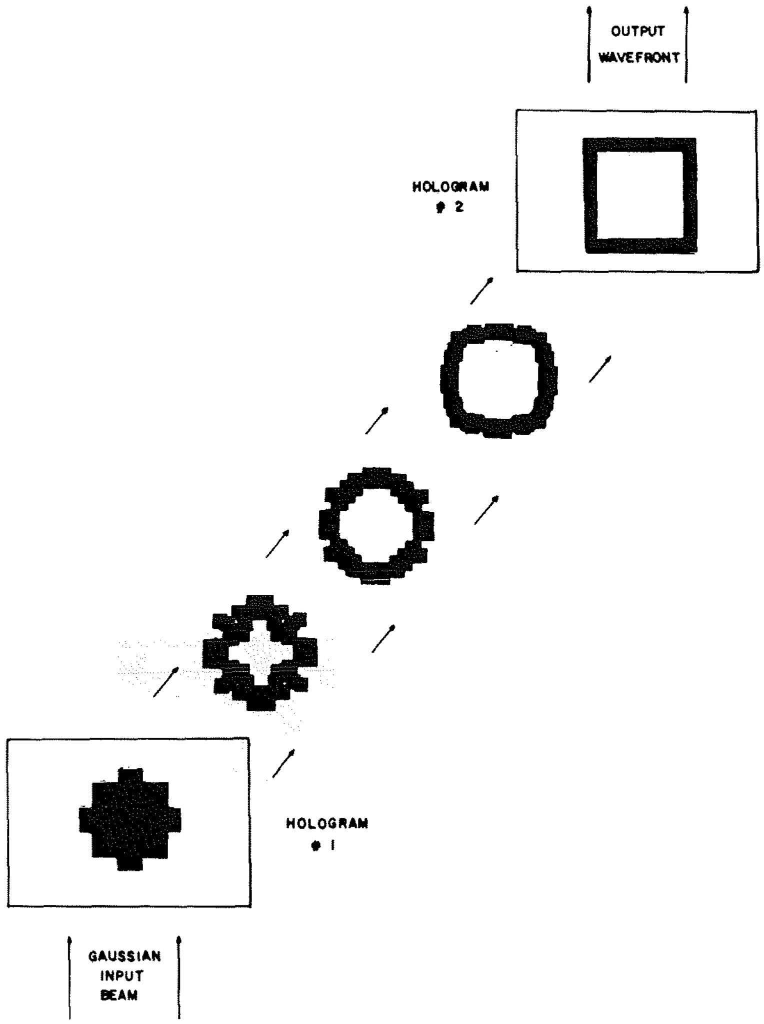

Figure 3.- Light redistribution.

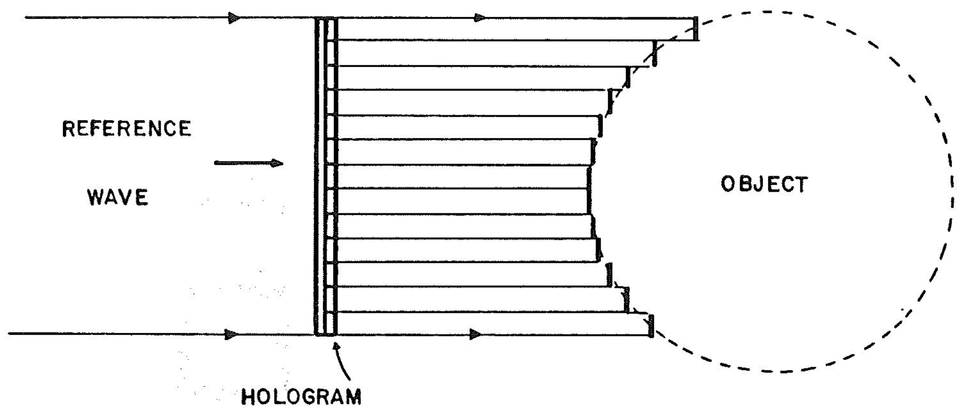

Figure 4.- Side view of multi-facet hologram producing segmented focus on object surface.

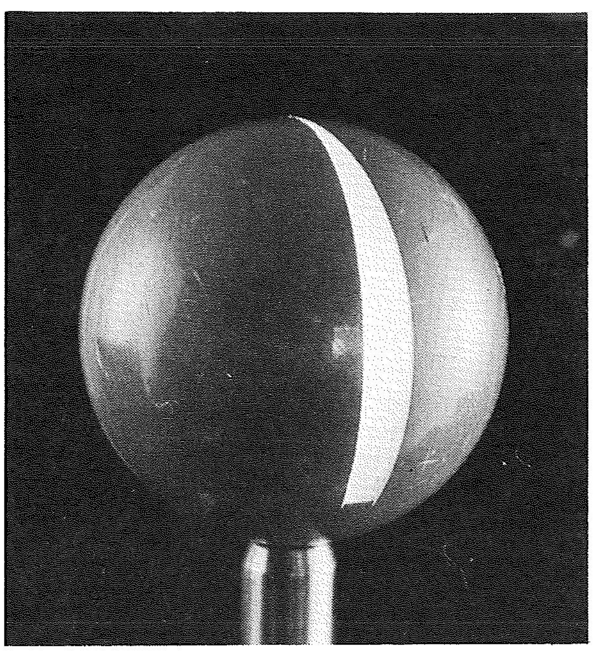

Figure 5.- Line focus formed by conventional cylindrical lens.

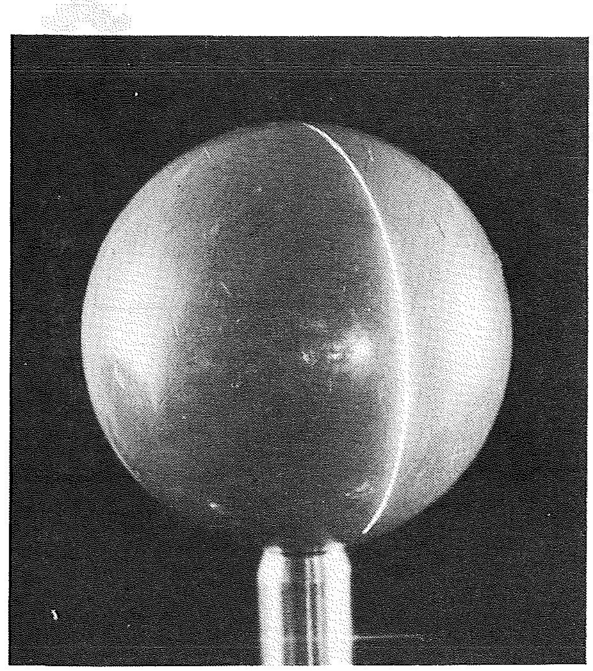

Figure 6.- Line focus formed by multi-facet holographic cylindrical lens.

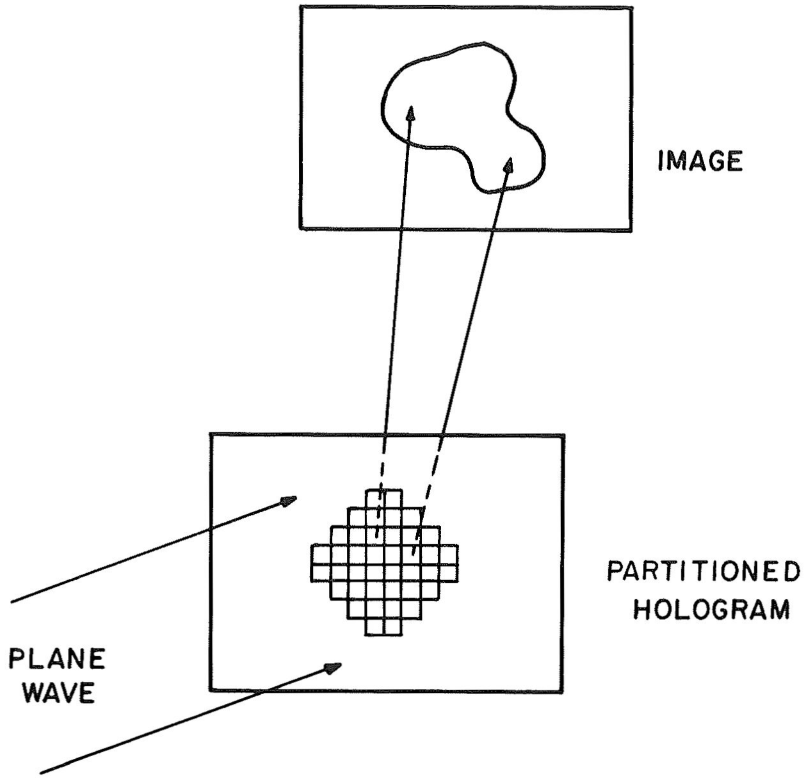

Figure 7.- Image formation.

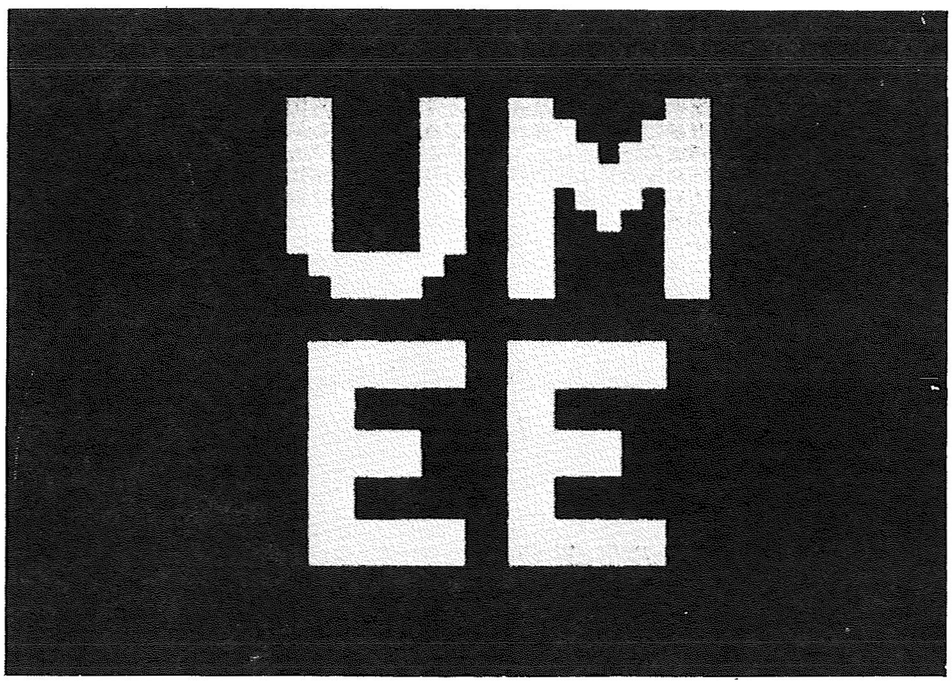

Figure 8.- Output image.