Pinhole hologram and its applications

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Received August 12, 1988; accepted November 6, 1988

We propose the use of a pinhole-camera approach to make holograms. On recording the object beam passes through a pinhole, forming an image plane hologram, but on reconstruction the pinhole can be taken away. The reconstructed image can be programmed and processed by using optical information-processing elements placed in the position of the reconstructed pinhole or pinholes. Pinhole holography can also suppress intermodulation effects. We present brief theoretical considerations and experimental results for pinhole holograms produced for programmable holographic optical interconnects.

The pinhole imaging phenomenon was first described by Leonardo da Vinci (1452–1519). Near the end of the sixteenth century Giambattista Della Porta (1543–1615) invented the pinhole camera.† Lord Rayleigh showed that in certain cases a pinhole acts nearly as well as a lens.‡ Pinhole imaging techniques have been used for the production of multiple-image masks for integrated circuits§ and for image processing.¶

In this Letter we describe the first use, to our knowledge, of one or more pinholes to make pinhole holograms. When recording the hologram the pinhole plays the role of a lens, thus forming an image plane hologram. When reconstructing the hologram the pinhole can be taken away, and the reconstruction of the pinhole itself allows convenient and flexible optical processing of the reconstructed holographic image. This can be used for optical information processing and optical interconnection.

The recording and reconstruction of a pinhole hologram are shown in Figs. 1(a) and 1(b), respectively. For planar objects, such as amplitude masks, the diffracted object illumination can be replaced by a converging spherical wave to illuminate the object, instead of a diffusing surface and can provide sufficient object-beam intensity and a field of view wide enough for recording the hologram. When to(xo, yo) is a delta function, Eq. (3) gives the resolution limit of the reconstructed image of the pinhole imaging hologram. The minimum resolvable separation of the object is 1.22λd0/D, and the minimum resolvable separation of the pinhole image is 1.22λd0/D.‖

In the recording geometry we use a converging spherical wave to illuminate the object, instead of a diffuser between the object and the coherent source. This avoids the image speckle that would be caused by the diffusing surface and can provide sufficient object-beam intensity and a field of view wide enough for recording the hologram.

The optimum condition to obtain the best contrast with pinhole imaging is given by

\[ D_{\text{opt}} = 1.8\sqrt{\lambda d_i}. \]  

With a pinhole hologram the resolution of the reconstructed image may be reduced and the redundancy of the hologram may be lost, but this can be traded off against the following advantages: (1) The reconstructed image can be controlled and processed pro-
Holographic optical interconnects have been investigated for several applications in microelectronics. Programmable optical interconnects are an essential component of many proposed architectures for optical computing. We produced two holograms to demonstrate some of the characteristics of pinhole holograms and their potential application in programmable optical interconnects.

These experiments were carried out using Agfa-Gevaert Holotest 8E75HD silver-halide emulsions on 4 in. × 5 in. (10.16 cm × 12.7 cm) glass plates, processed as recommended by Agfa for transmission holography. A He–Ne laser (λ = 633 nm) was used as the light source. For recording we used the optical arrangement illustrated in Fig. 2. As test objects we used homemade amplitude transmission masks. In both experiments we used a 100-mm focal-length lens of diameter 45 mm, a 400-μm-diameter pinhole, an object distance $d_o = 58$ mm, and an image distance $d_i = 98$ mm.

For the first hologram we recorded sequentially two different masks. The first mask was recorded with the centers of the lens, mask, pinhole, and plate aligned on the Z axis of Fig. 2. The first mask was then replaced by the second mask, with its center again held at the same position on the Z axis; the

gramatically by using optical information-processing elements in the positions of the reconstructed pinhole or pinholes. (2) The pinhole hologram is somewhat like an image plane hologram, so that the intermodulation effect, which affects the efficiency and quality of the reconstructed image, can be suppressed. (3) Reconstruction can be achieved without using all the free space between the hologram and the reconstructed image. Reconstructed light from a pinhole hologram is confined within a cone, and the volume of space around the reconstructed image of the pinhole (at the sharp point of this cone) can be used to house additional elements such as spatial light modulators (SLM's). (4) The resolution of the reconstructed image can be maintained by a suitable choice of pinhole size and of the distance between the reconstructed image and the pinhole. (5) Multifacet holograms can be obtained by using a pinhole array. The selection of images can be controlled by operating a pinhole array such as a pixelated SLM.

Fig. 2. Recording geometry for a pinhole hologram.
Fig. 5. Reconstruction of the second hologram. (a) Direct reconstruction. The double image formed is caused by reflections from the air-glass interface of the plate during the recording of the hologram. (b) Reconstruction with a transmission grating in the reconstructed pinhole plane. The center is the zeroth order with positive and negative first orders on either side. Each mask point is 50 μm across, and the points are separated by 250 μm.

pinhole and the lens were shifted by 1 mm in the X direction, and the second exposure was made.

On replay, the image of each mask is reconstructed by rays traveling through the image of the pinhole that was used to record it. Figure 3 shows the reconstruction of this hologram. In Fig. 3(a) both masks are reconstructed. In Fig. 3(b) a knife edge was used to block the reconstructed image of one of the pinholes so that only one mask was reconstructed. Note that it is not necessary to replay through a pinhole to achieve this; all that is needed is to block the reconstructed image of the other pinhole so that it does not replay. Finally, Fig. 3(c) shows the reconstruction of the second mask alone, achieved by moving the knife edge so that it occludes the other pinhole image.

This hologram illustrates how pinhole holography can be combined with the use of a shutter array, such as a pixelated SLM, to produce a programmable holographic optical interconnect. Many different interconnect patterns could be recorded, each through a separate pinhole, and then one or more could be selected for reconstruction by opening or closing pixels on the SLM.

For the second example, we used the same hologram to illustrate an image-processing application. Figure 4 shows the reconstruction of the hologram described above, with a 300-line/mm transmission grating held in the plane of the reconstructed pinholes so that the mask was reconstructed in each of several grating orders. The figure shows a double-exposure photograph: For the first exposure the grating was inserted in the location of one of the reconstructed pinholes, with the other blocked by a knife edge; then between exposures the grating was rotated 90° and the grating and knife edge were interchanged. The grating split the image of the first mask horizontally into three diffraction orders and split the image of the second mask vertically in the same manner. For practical applications the diffraction grating could perhaps be replaced by an acousto-optic modulator to allow deflection by a programmable amount for scanning between the transmitted and the first diffracted order.

For our second hologram we used as an object a more complicated mask consisting of a regular array of 277 points, each 50 μm in diameter and on a pitch of 250 μm. This was recorded with the same geometry used earlier. Figure 5(a) shows a single reconstruction of this pinhole hologram, and Fig. 5(b) shows the same reconstruction but with a 300-line/mm transmission grating inserted in the reconstructed pinhole plane to replicate the mask pattern in triplicate. This is in effect a 1-to-831 fan-out element with a high resolution and signal-to-noise ratio and low cross talk. Both holograms had diffraction efficiencies of ~25%.

In conclusion, we have proposed a new type of hologram, the pinhole hologram, and have demonstrated experimentally that it shows potential for programmable holographic optical interconnect and optical information processing.

The authors wish to thank Sandra Conroy, Roy Morrison, Nick Jackson, Neal Powell, and Meilin Sanchez for technical assistance, illustrations, and photography. This research was supported by the UK Science and Engineering Research Council under grant GR/D 91797. Geraldo Mendes is funded by the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico and TELEBRAS Brazil.

Some of the results presented here were reported at Optical Computing 88, Toulon, France, August 29 to September 2, 1988.

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