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FINAL REPORT

to the

NASA Lewis Research Center

on

APPLICATIONS OF HIGH POWER LASERS

Grant NSG-3074

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ABSTRACT

The purpose of the research was to determine whether computer generated, reflection holograms can be used in conjunction with high power lasers for precision machining of metals and ceramics.

Substantial contributions were made in our laboratories during the course of the grant. Techniques for making computer generated, reflection holograms were developed and made to work at both optical wavelengths (He-Ne, 6328 Å) and infrared (CO_2, 10.6 m). These results are described in detail in the attached report.

The holograms developed under the NASA grant meet the primary practical requirement of ruggedness and are relatively economical and simple to fabricate. The technology is sufficiently advanced now so that reflection holography could indeed be used as a practical manufacturing device in certain applications requiring low power densities. However, the present holograms are energy inefficient and much of the laser power is lost in the zero order spot and higher diffraction orders. These problems are being considered in a continuation program under National Science Foundation sponsorship.

The research was conducted in the Department of Chemical Engineering at Case Western Reserve University with Professor John C. Angus as Principal Investigator. Other associated faculty were Professors Robert V. Edwards and J. Adin Mann, of Case Western Reserve University.

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I. PURPOSE AND OBJECTIVES

Purpose of the Research. *The purpose of the research is to determine whether computer generated, reflection holograms can be used to put laser energy on workpieces in desired spatial distributions for practical material removal, welding, soldering, and heat treating operations.*

Specific Objectives of the Research. There are two principal problems standing in the way of the practical utilization of high power reflection holography. The first is the need to simply and economically produce rugged holograms that can be used in machine shops. Preferably they should be used with unmodified, commercial CO_2 lasers. The second major problem arises from the desire to do multiple machining operations simultaneously. This means that one must use very high power commercial lasers. To make this practical, it is necessary to utilize the maximum amount of the available laser power and also to develop means for reducing the minimum local power density to initiate machining.

II. SIGNIFICANCE OF RESEARCH

Conventional Laser Machining. The development of high powered laser technology has permitted the use of lasers for applications in industrial processing [1,2,3]. Good reviews appear in references 4 and 5. Typical uses include welding, drilling, scribing, cutting and surface hardening. These applications have made little use of the coherence properties of laser light, but rather use the laser as an "energy hose". The usual scheme has the high powered laser light focused to a small spot. This spot is then moved over the work surface in one of several ways; by moving the workpiece, moving the laser, or by the use of moveable mirrors. The approach we are using requires motion of neither the workpiece, the laser, nor mirrors, and potentially can be used to machine shapes of great complexity.

Holographic Laser Machining. In simplest terms, we put the laser power in the desired places on the workpiece by means of the interference effects of a reflection hologram. The hologram is illuminated by a coherent, intense beam of high power laser radiation. The real image generated by the hologram falls on the workpiece.

Recent advances in our laboratory on the generation of reflection holograms by computer techniques appear to make the proposed procedure feasible. Because of the relative mechanical simplicity and energy efficiency of the process, it could have substantial cost advantages over "conventional" means of laser machining.

Applications. It is likely that the proposed technique will retain most of the advantages of conventional laser processing. Among these are: accuracy for micromaching; machining of complex or inaccessible parts;

small heat affected zone; minimal part distortion; welding of dissimilar materials; no vacuum system (as compared to electron beam techniques). Experience with conventional laser machining indicates that the method can probably be made to work on metals, ceramics, plastics and wood. Hole diameters down to .002" and depth to diameter ratios of 250 may be achieved. Experience at Ford Motor Co. indicates conventional laser cutting can produce very narrow kerf widths, viz., down to several thousandths of an inch, as well as very smooth and clean cuts [1].

Possible applications of the proposed technique include: drilling arrays of holes simultaneously; drilling holes of non-circular cross section; scribing complex patterns; simultaneous welding or soldering of complex and/or small parts; simultaneous cutting of parts from sheet stock; simultaneously machining grooves or other surface features; etching designs with minimum perturbation of underlying material; part marking; imparting surface hardness to metals in controlled spatial arrangements or cutting patterns in cloth or cardboard.

It is likely that holographic laser machining, if successful, may find first application in the electronics industry. Possible examples are drilling holes in printed circuit boards, making soldered connections and resistor trimming. It is not likely that it could be used in many operations within integrated circuits themselves because of the lack of spatial resolution, i.e., 10 to 20 μm minimum spot size vs. desired resolution of less than 1 μm. We would expect somewhat more difficulty in achieving acceptance of the method for larger scale machining operations, such as drilling arrays of large holes; however, even in very conventional plant operations, our techniques may prove to be the best alternative. This is most likely to be the case where the laser method can be shown to have

unique advantages. One possible situation is part marking or scribing where the surface or a surface layer is to be removed with minimal perturbation of the underlying material. A pulsed laser shot that does the entire job in one operation may be the best solution.

III. WORK BY OTHERS

There has been some related prior work [6,7]. Two groups have recently published descriptions of different schemes for using the coherence properties of laser radiation for machining and soldering [8,9].

A technique has been proposed by Engel for using computer generated Fresnel zone plates [8]. These plates are used to machine relatively simple repetitive patterns, i.e., arrays of small diameter holes. The plates suffer from being transmission devices which block out a substantial fraction of the laser radiation.

Researchers at Siemens have reported the use of holograms in laser soldering operations [9]. Siemens' optical hologram can be used to machine more complicated patterns; however, there are a number of difficulties. For example, any laser beam powerful enough to burn a steel surface will normally destroy the hologram. To alleviate this problem, the laser beam was expanded to a large diameter, thus reducing the power density. Consequently, the radiation could pass through the transmission hologram without immediately destroying it. The use of reflection techniques permits the construction of long lived holograms, which operate at much higher power densities.

Sweeney and Stevenson at Purdue University are pursuing closely related research to that proposed here [10,11]. In some of their work they use a computer generated grating as the output mirror of the laser. This procedure has the substantial advantage that the zero order spot is automatically returned to the laser cavity; however, the laser itself must be modified.

IV. RESULTS OF OUR RESEARCH

Summary of Results. The work performed under NASA grant NSG-3074 was highly successful. Methods for constructing computer generated reflection holograms were developed. Several methods of fabrication were successfully employed including etching of Si ships and vapor deposition on Mo substrates.

The holograms developed under the NASA grant are rugged and easy to fabricate. They have been used extensively in our laboratory environment. They could, in fact, be used for practical applications in which only low power densities are required. The present holograms are, however, quite energy inefficient. A major part of the incident laser power is lost in the central, zero order spot and in higher diffraction orders.

These and other problems are being considered under a National Science Foundation grant which was obtained after termination of the subject NASA grant.

Details of the research performed under the NASA grant are discussed in the two papers attached to this final report as Appendices.

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APPENDIX A

"Binary Phase Digital Reflection Holograms: Fabrication and Potential Applications," N.C. Gallagher, John C. Angus, F.E. Coffield, R.V. Edwards, and J.A. Mann, Jr., Applied Optics, 16(2), 413-417 (1977).

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Binary phase digital reflection holograms: fabrication and potential applications

Neal C. Gallagher, Jr., John C. Angus, Frederick E. Coffield, Robert V. Edwards, and J. Adin Mann, Jr.

A novel technique for the fabrication of binary-phase computer-generated reflection holograms is described. By use of integrated circuit technology, the holographic pattern is etched into a silicon wafer and then aluminum coated to make a reflection hologram. Because these holograms reflect virtually all the incident radiation, they may find application in machining with high-power lasers. A number of possible modifications of the hologram fabrication procedure are discussed.

I. Introduction

Off-axis holography has been used in numerous interesting applications since its development by Leith and Upatnieks.[1] Notably, synthetic aperture radar and sonar, nondestructive testing, pattern recognition, spatial filtering, and real-time signal processing are among these applications.[2-5] In this paper, we discuss a new type of computer-generated digital hologram and potential application. The computer-generated hologram, first developed by Lohmann *et al.*,[6,7] has been employed in many instances where optically produced holograms are not easily employed.[8-11]

We propose a new method of Lohmann hologram fabrication that allows the construction of holograms that reflect essentially all the light incident on the hologram. The image formed is a result of the diffraction of the phase modulated light reflected from the hologram. These holograms produce images four times more intense than binary-amplitude transmission holograms of the same size and allow the use of much higher power densities feasible, for example, for laser machining, trimming, etc.

In Sec. II, we briefly review digital hologram design considerations and how we use integrated circuit fabrication technology to make reflection holograms. Section III contains a discussion of extensions and modifications of our hologram design and fabrication procedures that may improve performance.

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II. Digital Reflection Holograms

Lohmann's method is one of the most widely used techniques for constructing digital holograms. Several other techniques have been described[12-14]; however, for the present, we have only considered Lohmann's method.

The procedure for constructing these reflection holograms is a synthesis of digital hologram design methods with integrated circuit fabrication technology. As a result, we divide the description of the hologram construction process into two sections: Analysis and Design, and Fabrication.

A. Analysis and Design

The hologram design begins with the definition of the image we wish to reconstruct. The image is then sampled on a rectangular grid. It is not necessary for the sampling intervals along the two axes to be identical; however, in the present work we took them to be equal. This sampling procedure provides an $N \times N$ grid of image magnitude samples $\{a_{mn}\}_{m,n=0}^{N-1}$. The next step is to assign the phase to the image. The phase terms $\{\theta_{mn}\}_{m,n=0}^{N-1}$ for the sampled image $\{a_{mn} \exp(i\theta_{mn})\}_{m,n=0}^{N-1}$ may be assigned according to a number of rules.[15]

The phase has a great influence on the bandwidth and dynamic range required of the digital Fourier transform hologram; this in turn affects the quantization error and aliasing error in the reconstructed image. A detailed treatment of these considerations may be found in Ref. 15.

After the phase has been assigned to the image, we perform the 2-D discrete Fourier transform on the sequence $\{a_{mn} \exp(i\theta_{mn})\}_{m,n=0}^{N-1}$ to form the spectral sequence $\{A_{pq} \exp(i\psi_{pq})\}_{p,q=0}^{N-1}$. Using Lohmann's method, we construct the hologram for the magnitude $\{A_{pq}\}$ and phase $\{\psi_{pq}\}$ of the Fourier spectrum. The hologram plot was obtained on a Calcomp plotter using the results of the Fourier inversion. It consists of an $N \times N$ array of

rectangles; each rectangle has a height proportional to the appropriate A_{pq} and a lateral position about its center coordinate related to ψ_{pq}. The plot of the hologram is photographically reduced onto a high contrast glass plate. The photonegative can then be used as a transmission hologram in conjunction with a Fourier transforming lens to reconstruct the image. In order to determine the image formed by the reflection hologram, we first determine the image that is formed by this transmission hologram. The hologram transparency consists of a grid of rectangles as depicted in Fig. 1. Thus, the transmittance $H(u,v)$ is given by

$$H(u,v) = \sum_m \sum_n \operatorname{rect}\left[\frac{uX - (m + P_{mn})}{C}\right] \operatorname{rect}\left(\frac{vX - n}{W_{mn}}\right), \quad (1)$$

where

$$\operatorname{rect}(x) = \begin{cases} 1 & |x| \le 1/2 \\ 0 & \text{elsewhere} \end{cases}.$$

The parameter W_{mn} is related to the height of the (m,n)th rectangle, P_{mn} is related to the lateral shift of the rectangle, and C is related to the rectangle's width which is the same for all the rectangles (see Fig. 2). Using a lens or mirror to take the Fourier transform of $H(u,v)$, which produces the image $h(x,y)$, we have

$$h(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(u,v) \exp[i2\pi(xu + yv)]du dv. \quad (2)$$

We use the following identity derived from the Shannon sampling theorem[2]:

$$1 \equiv \sum_{p,q=-\infty}^{\infty} \frac{\sin\pi(p - uX)}{\pi(p - uX)} \frac{\sin\pi(q - vX)}{\pi(q - vX)}$$

in Eq. (2). We form the product $H(u,v) = (1)H(u,v)$; then, substitution of Eq. (1) into Eq. (2) yields

$$h(x,y) = \sum_m \sum_n \sum_p \sum_q J_{m,n,p,q}(x,y), \quad (3)$$

where

$$J_{m,n,p,q}(x,y) = \int \frac{\sin\pi(p - uX)}{\pi(p - uX)} \exp(i2\pi ux)du \times \int \frac{\sin\pi(q - vX)}{\pi(q - vX)} \exp(i2\pi yv)dv.$$

The range of integration on the first integral is $(1/X)[-(C/2) + m + P_{mn}]$ to $(1/X)[(C/2) + m + P_{mn}]$ and on the second integral is $(1/X)\{-[(W_{mn})/2] + n\}$ to $(1/X)[W_{mn}/2 + n]$. We assume $W_{mn}/2 \ll X$ and $P_{mn} + (C/2) \ll X$ and discover that

$$J_{m,n,p,q}(x,y) \approx \exp\left\{i\frac{2\pi}{X}[(m + P_{mn})x + ny]\right\} \frac{\sin(\pi CX/X)}{\pi x} \frac{\sin(\pi W_{mn}y/X)}{\pi y},$$

when $m = p$ and $n = q$, and $J_{m,n,p,q}(x,y) \approx 0$ otherwise. Thus

$$h(x,y) = \frac{\sin(\pi Cx/X)}{\pi x} \sum_p \sum_q \frac{\sin(\pi W_{pq}y/X)}{\pi y} \times \exp\left(i\frac{2\pi}{X}P_{pq}x\right) \exp\left[i\frac{2\pi}{X}(px + qy)\right]. \quad (4)$$

If we restrict attention to small values of y,

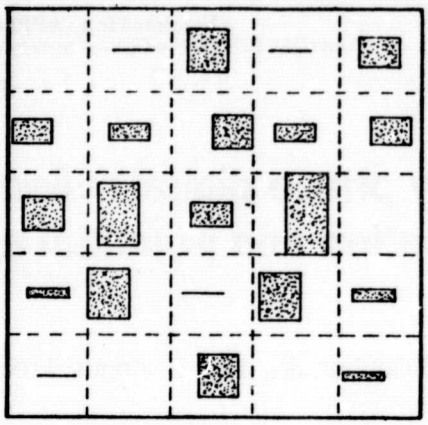

Fig. 1. Representation of Lohmann's method for constructing holograms.

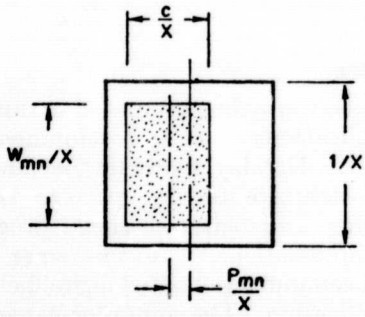

Fig. 2. The (m,n)th resolution cell.

$$\frac{\sin(\pi W_{pq}y/X)}{\pi y} \approx W_{pq}/X.$$

For convenience we pick x in a range where $x/X \approx M$, an integer. After doing this we need to pick C such that the value of the function

$$\left|\frac{\sin(\pi Cx/X)}{\pi x}\right|$$

is near a local maximum. This insures that the multiple images formed from the hologram are located near the principal diffraction maxima. Common practice has been to pick $M = 1$ and $C = 1/2$. We may now rewrite Eq. (4) as

$$h(x,y) \approx \sum_p \sum_q \left[\frac{W_{pq}}{\pi X^2} \exp(i2\pi P_{pq})\right] \exp\left[i\frac{2\pi}{X}(px + qy)\right]. \quad (5)$$

Equation (5) is the Fourier series representation for the image $h(x,y)$. If we pick W_{pq} to be proportional to A_{pq} and pick $P_{pq} = \psi_{pq}/2\pi$, we reconstruct the desired image $h(x,y)$. Detailed discussions of this method may be found in Refs. 6-9 and Ref. 16. A typical Calcomp plot is found in Fig. 3, and a typical image reconstruction is found in Fig. 4.

Fig. 3. Typical Calcomp plot of a hologram.

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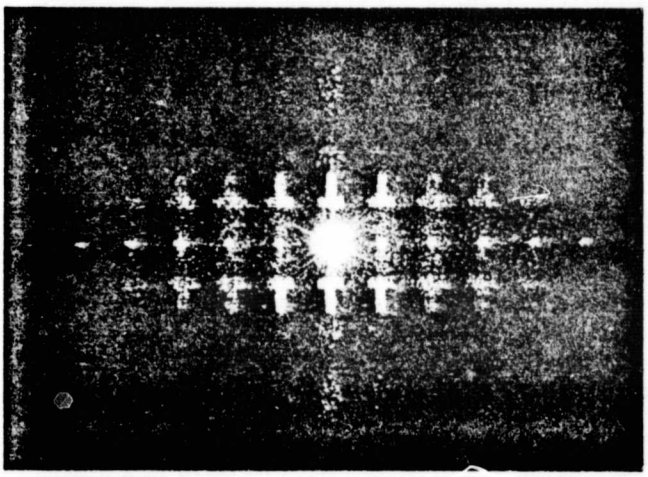

Fig. 4. Image reconstructed using the high contrast photomask as a transmission hologram.

B. Reflection Hologram Fabrication

The present binary-phase reflection holograms were constructed by etching a high contrast photoreduction of the plotter output into polished silicon wafers. A $\lambda/4$ thick silicon oxide layer was first grown on the silicon, where λ is the wavelength of the light used for image reconstruction. The wafer was coated with a standard commercial positive photoresist, which was then exposed to uv light through a negative transparency of the holographic pattern. The exposed resist was chemically removed, leaving the pattern in resist on the surface. The silicon oxide layer was etched down to the silicon by a buffered HF etch. After the resist was washed away, the holographic pattern was left etched in the wafer. An aluminum coating approximately 0.5 μm thick was next applied to the surface by vapor deposition at near vertical incidence. This produced a surface that was highly reflective at both visible and ir wavelengths. The typical size of a hologram for use with 0.6328-μm radiation was 1 cm × 1 cm. The hologram was a 64 × 64 array so each cell had linear dimensions of 156 × 156 μm. Since the width of each cell, $2C/X$, was always twice the width of the rectangles, C/X, each etch pit is nominally 78 μm wide. The height of the rectangle, W_{mn}/X, of course varied according to the value of A_{mn}, but except in rare cases was well above the estimated resolution of the etching process of approximately 2 μm.

We have stated that the image formed by such a reflection hologram is four times more intense than an image formed by a transmission hologram of the same size. It is now straightforward to determine the image formed by the reflection hologram. First, suppose that the photonegative transmission hologram with transmittance $H(u,v)$ produces the Fourier transform image $h(x,y)$. Now, we want to establish the relationship between the reflectance of the hologram $R(u,v)$ and the transmittance of the photographic mask $H(u,v)$. The magnitude of $R(u,v)$ is identically equal to one; however, the phase of the light reflected from the etched pits differs by one-half wavelength from the phase of the light reflected from elsewhere on the hologram. Consequently, we can write $R(u,v)$ as

$$R(u,v) = H(u,v) + [1 - H(u,v)]\exp(i\phi)$$
$$= [1 - \exp(i\phi)]H(u,v) + \exp(i\phi), \quad (6)$$

where $\phi = \pi$ when the pits are etched to the proper depth of $\lambda/4$. This expression can be most easily understood by recognizing that the reflection hologram is essentially the superposition of two binary transmission holograms, one the negative of the other with a phase difference of ϕ. Upon taking the inverse Fourier transform of Eq. (6), we have

$$r(x,y) = [1 - \exp(i\phi)]h(x,y) + \text{central order spot.}$$

Ignoring the central order spot, we have after setting $\phi = \pi$

$$r(x,y) = 2h(x,y).$$

This shows that the image formed by the reflection hologram has twice the field strength of that formed by the transmission hologram; consequently, the image intensity is four times greater. The rectangles in the holograms described here are pits; however holograms where $\phi = -\pi$ phase difference, i.e., mesas instead of pits, will act identically. It should be noted that holograms etched to a depth different than $\lambda/4$ will still produce images, but because of reduced diffraction efficiency the images will be much less intense.

Figure 5 contains several scanning electron microscope photographs taken of a reflection hologram etched to a depth of about 2.5 μm for use with 10.6-μm ir radiation. In Fig. 6 we find typical reconstructed images. These are from a reflection hologram etched to a depth of about 0.15 μm and used with a He–Ne laser operating at 0.6328 μm.

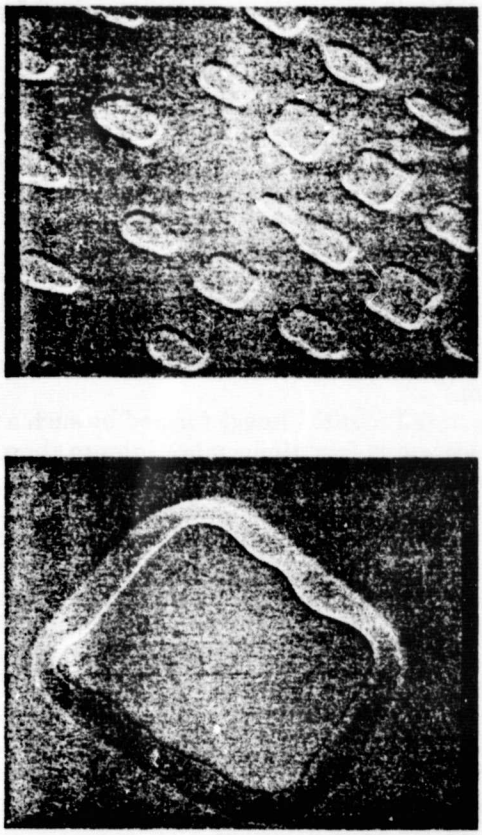

Fig. 5. Scanning electron micrographs of etched silicon wafer. The rectangle pits are approximately 0.007 cm wide.

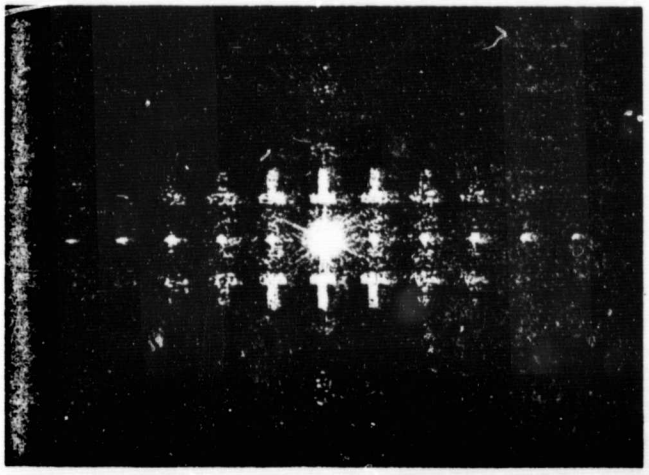

Fig. 6. Image reconstructed using the reflection hologram constructed with the same photomask that produced the image in Fig. 4.

III. Modifications and Extensions

The fabrication of the hologram as an aluminized silicon wafer provides a number of advantages not available with standard transmission holograms; however, there are additional improvements that may be gained by modifying the hologram computation algorithm, plotting procedure, or fabrication technique. Presently, we employ the computation algorithm described in Refs. 17–19; however, there remains the possibility for the refinement of this algorithm (see, for example, Refs. 20 and 21); these refinements could result in reduced image reconstruction errors. At present, we use the Lohmann plotting procedure. As was mentioned earlier, there are other hologram plotting techniques worth consideration, notably, the methods of Lee, Severcan, and Haskell merit consideration.[12–16] Gabel has investigated the relative merits between Lohmann's method and Lee's method; however, he did not use the optimum quantization schemes for the holographic signal representation.[17–26] Because the type of quantization scheme employed can have a great effect on the quality of the reconstructed image, it may be enlightening to review Gabel's analysis with these additional considerations.

There are a number of improvements possible in the fabrication procedure. It may be possible to improve the quality of the reflection hologram by modifying the etching process and the substrate etched. For example, sputter etch techniques may prove superior to chemical etching. Also, substrate materials other than silicon may have significant advantages. Directly etching the hologram into an aluminum mirror seems especially attractive. The hologram could be etched into a mirror with a positive focus which provides the focusing power required to reconstruct the image, thus eliminating the need for a separate focusing element. Another very significant advantage of this approach is that it may permit the use of much greater power densities for potential applications in holographic laser machining.

Another alternate scheme is to make a reflection kinoform rather than a hologram.[17,27] With a kinoform all the energy can, in principle, be placed in a single image rather than in multiple images plus a zero order spot as with a hologram. However, this leads to complications in fabrication. With kinoforms, one does not use the magnitude information from the Fourier spectrum. Only the phase information of the Fourier transform is imposed on the incident light. Unlike the Lohmann hologram rectangles, each element of the kinoform has the same area; however, the elements must be etched to different levels. This implies a more complex multimask etching procedure to produce the reflector.

Finally, for high power applications one will wish to utilize reflector geometries that are less susceptible to degradation by the beam. One will likely wish to avoid geometries with sharp corners, for example.

IV. Discussion and Summary

We have presented a new technique for the construction of binary-phase digital reflection holograms.

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By use of standard integrated circuit fabrication procedures we have constructed Lohmann-type reflection holograms on silicon wafers that produce high quality images. The hologram design algorithms are not discussed in detail in this paper as they are well documented in the referenced literature. All the holograms that we have so far constructed have contained 64 × 64 sample points. This size hologram is satisfactory for many research applications; however, in situations where truly high quality images are required, it will most likely be necessary to use 128 × 128 or 256 × 256 arrays of sample points.

One very interesting potential application for digital reflection hologram is in high-power laser machining. Because the hologram is nearly 100% reflective, it is ideal for this application as it would absorb very little energy from the laser beam. Thus, high power can be delivered to selected regions on a workpiece simultaneously. Such development could be an important application of holography.

The support of this research by the NASA Lewis Research Center, Cleveland, Ohio under grant NSG-3074 is gratefully acknowledged. NSF support for the development of computational algorithms and information coding schemes for computer generated holograms under grant ENG 76 09443 is also acknowledged with thanks. The wafer etching was performed by Robert W. Rugh.

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APPENDIX B

"Infrared Image Construction with Reflection Holograms,"
John C. Angus, Frederick E. Coffield, Robert V. Edwards,
J. Adin Mann, Jr., Robert W. Rugh, Neal C. Gallagher,
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Infrared image construction with computer-generated reflection holograms

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Computer-generated, reflection holograms hold substantial promise as a means for performing complex machining, marking, scribing, welding, soldering, heat treating and other materials processing operations simultaneously and without motion of workpiece or laser beam. The use of holography for machining was first discussed by Moran.[1,2] Computer-generated transmission zone plates used to machine repetitive arrays of small holes were described by Engle *et al.*[3] and transmission holograms for soldering by workers at Siemens.[4] Sweeney et al.[5] reported ir beam shaping with a computer-generated grating replacing the output mirror of an ir laser. In this Letter, we describe images from an unmodified, commercial CO_2 laser and holographic reflectors fabricated using standard photoresist techniques. The all-metal reflection holograms are particularly suitable for use at the high power densities required for machining operations.

A computer generated 64 × 64 element Lohmann hologram was produced as described earlier.[6] A photographically reduced transparency of the hologram was used to make a mask which, in turn, was used with conventional photoresist techniques to produce the reflector. Several successful methods of fabrication were employed. In one, a $\lambda/4$ thick layer of aluminum was vapor deposited onto a polycrystalline silicon mirror blank. A 1-μm thick coating of Shipley AZ-1350J photoresist was spin coated at 5000 rpm and exposed to uv through the mask. After removal of the exposed resist, the aluminum was etched with phosphoric-nitric-acetic acid down to the silicon substrate. The 4096 rectangles of the hologram appeared as raised aluminum mesas above the flat silicon plain. A 5000-Å layer of aluminum was then deposited to provide uniform reflectivity. The reflector itself was 3 cm × 3 cm in lateral dimensions. A completed hologram is shown in Fig. 1.

The laser was an unmodified Coherent Radiation Everlase 150, producing a nominal maximum power output of 150 W TEM_{00}. The output beam was reflected from a flat (solely for geometrical convenience) to a beam expander comprised of two concave mirrors with a 0.3-m and 1.52-m radii of curvature, respectively, with a separation of 1.4 m. The expanded beam was reflected from the hologram, which was placed just after the second mirror. In this arrangement, the beams were slightly nonparallel to the optical axis, but any coma introduced by this effect was negligible compared with other sources of error (see below). An absorbing aperture intercepted all radiation that fell outside the rectangular hologram. The image fell about 1.6 m from the second mirror. Image position and size could be changed by moving the second mirror. All reflecting surfaces, except for the hologram, were off-the-shelf, commercial molybdenum reflectors.

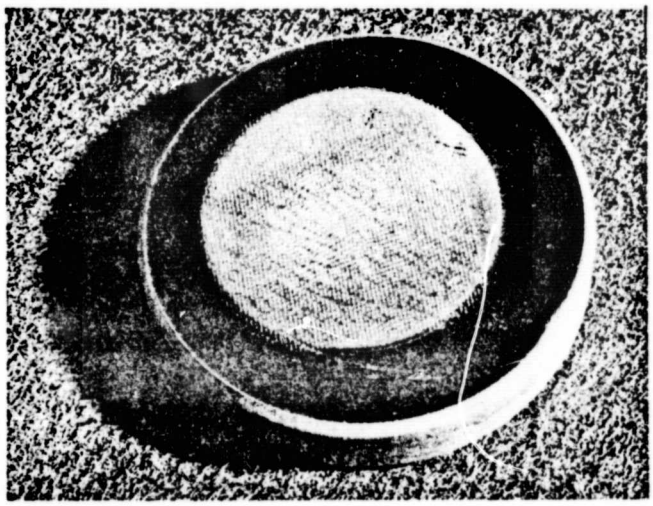

Fig. 1. Reflection hologram produced on commercial silicon mirror blank; the raised mesas are visible within the light circular area of the final aluminum deposition. Mirror diameter is 5.08 cm.

Infrared images, burned in thermally sensitive plastic sheet are shown in Figs. 2 and 3. In Fig. 2, the letters *ASE* of the word *CASE* are clearly visible, as well as the strong zero order spot. The missing letter *C* was in fact present, but at a lower level. It should be noted that the individual letters in Figs. 2 and 3 are 1.1 cm and 0.9 cm tall, respectively. Consequently, the power density is not large. The power in each of the four letters *CASE* was 0.7W, 1.3W, 1.75W, and 1.3W, respectively. Possible sources of the fall off in intensity of the *C* are the detour phase error or the expected sin x/x variation in image intensity.

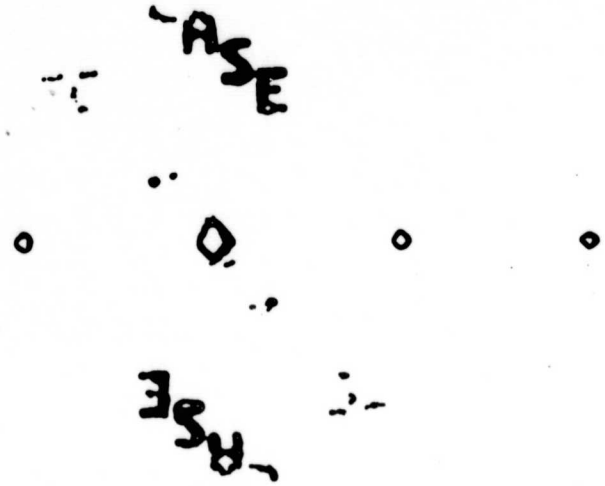

Fig. 2. Infrared image *CASE* formed on thermally sensitive paper. Note the intense zero-order spot and higher order images.

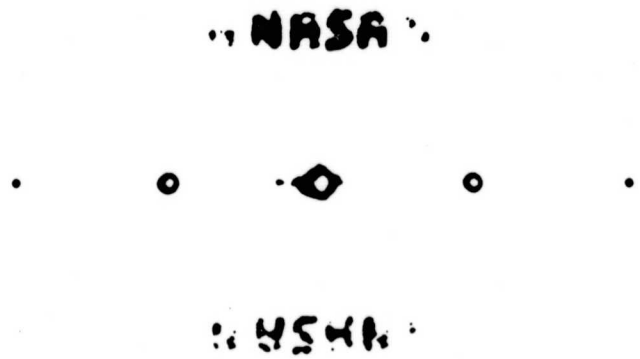

Fig. 3. Infrared image *NASA* formed on thermally sensitive paper.

The total power in the two first order images was 10 W; the zero order spot contained 35–40 W, underlining one of the problems with the process as currently implemented. The power in the image was, however, sufficient to easily burn through 0.0175 cm plastic sheet and to leave a permanent charred image on wood. Theory would indicate a maximum diffraction efficiency of 41%.[7] Possible sources of the lower efficiency include deviation in mesa height from $\lambda/4$, imperfections in the surface finish, and imperfect replication of the hologram on the reflector. For the reflector used to produce the image shown in Fig. 2, the height of the mesas was 2.65 μm $\pm$0.3 μm, as measured by a piezoelectric film thickness monitor, Talysurf probe, and optical interference techniques.

The etching procedure leads to some imperfections in the replication of the hologram. A simple way to avoid the problem with etching is to vapor deposit metal through a patterned photoresist layer directly onto the mirror substrate. This procedure eliminates the etching step entirely and gives steep-sided mesas. A reflection hologram for use at 6328 Å was successfully fabricated with this technique, using aluminum on a molybdenum mirror blank, and produced excellent visible images. Microscopic examination indicated faithful reproduction of the smallest rectangles on the hologram surface.

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