HIGH-EFFICIENCY IN-LINE MULTIPLE IMAGING BY MEANS OF MULTIPLE PHASE HOLOGRAMS

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Received 3 May 1971

A fully transparent optical component called a multiple phase hologram is inserted into a conventional optical imaging system. By means of this artificial hologram, which in fact is a two-dimensional phase grating with special groove shape, instead of the normal single image a central block of equally bright multiplied images around the optical axis is generated.

In recent years various holographic techniques for multiple imaging have been proposed and discussed [1-5]. These techniques are based on commonly recorded holograms of arrays of point light sources. If, in reconstruction, these holograms are illuminated by a single object beam, an array of multiplied images is generated instead of the array of point light sources. There are mainly two drawbacks involved in this technique:

(i) The multiplied images are generated off-axis. This is often unfavourable in practice and leads always to aberrations in the multiplied images proportional to $\tan^2\alpha$ [3], where α is the off-axis angle.

(ii) The efficiency of the system is relatively low due to the low reconstruction efficiency of the commonly recorded thin holograms.

In order to overcome these difficulties, high-efficiency in-line phase-only holograms can be used. Fig. 1 shows the optical setup, the basic part of which is a conventional optical imaging system capable of imaging single objects with the desired accuracy. Inserting a plane grating into the exit pupil of that system leads to multiple images according to the diffraction orders of the grating. The brightness distribution amongst the multiplied images is the same as that amongst the diffraction orders, which is determined by the groove shape of the grating. In our special arrangement shown in fig. 1 it is the intensity of the Fourier transform of a single groove shape that determines this brightness distribution. So each single groove can be considered as an elementary in-line Fourier-transform hologram, the reconstruction of which yields the brightness distribution of the multiplied images, and the grating can be considered as a multiple phase hologram consisting of a two-dimensional array of small elementary holograms.

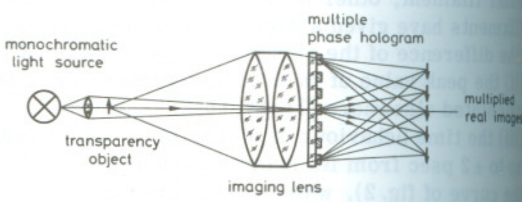

Fig. 1. In-line multiple imaging by means of multiple phase hologram.

For special applications in image multiplication, the brightnesses of the images have to be all equal, at least in a central block. Thus the desired brightnesses of the diffraction orders are given rather than the groove shape. In this case, of course, a groove shape can be found by inverse Fourier transform, but in general this will result in some complex groove shape and a grating, which will not be very efficient and will be too complicated to be realized in practice. Therefore, we restrict ourselves to phase-only structures, which yield high efficiencies, in particular to binary phase-only structures, which in fact have been realized yielding efficiencies in the range 40 - 50%.

Furthermore, we restrict ourselves to structures with transparency functions $t(x,y)$ which can be separated in the spatial coordinates x and y:

$$t(x,y) = t_1(x)\ t_2(y)\ . \qquad (1)$$

In this case, the Fourier transform $T(u,v)$ of $t(x,y)$ can be separated, too,

$$T(u,v) = T_1(u)\ T_2(v)\ , \qquad (2)$$

where $T_1(u)$ and $T_2(v)$ are the one-dimensional transforms of $t_1(x)$ and $t_2(y)$, respectively. The main computational problem, namely finding a transparency function $t(x,y)$ of the phase-only form

$$t(x,y) = \exp[-\mathrm{i}\varphi(x,y)]\ , \qquad (3)$$

the Fourier transform of which yields a given $T(u,v)$, is thus reduced to the one-dimensional problem.

In the following, only the practically more important binary case is described in more detail. It can be seen from (1) and (3) that in this case, without essential restrictions, the transparency functions $t(x,y)$, $t_1(x)$ and $t_2(y)$ in (1) can be assumed to have values +1 or -1 only.

A binary function with values +1 and -1, e.g. $t_1(x)$ in (1), has the form as shown in fig. 2. The only free parameters of this function are the transition points $x_1, x_2, x_3, \ldots$. Let us assume that a single one-dimensional groove extends from $x = -a$ to $x = a$ having transition points at $x = x_{-N}, x_{-N+1}, \ldots, x_{-1}, x_1, \ldots, x_M$, i.e. $N+M$ free parameters. Then, to a certain extent, $N+M$ given relations between the diffraction orders of the corresponding grating can be maintained by a proper set of parameters $x_{-N}, \ldots, x_M$.

For special applications, e.g. for multiple imaging of IC-mask pattern, a central, symmetrical block of equally bright diffraction orders is desired. The relations between the diffraction orders are then given by (in one dimension)

$$|T_1(u_n)|^2 = |T_1(0)|^2 = |T_1(-u_n)|^2\ , \qquad (4)$$

where the u_n ($n = 1, 2, \ldots, M$) are the abscissa of the diffraction orders in the Fourier plane.

We have calculated a large number of sets $x_1, x_2, \ldots, x_M$ with $x_n = -x_{-n}$ (symmetry) the corresponding transparency functions $t_1(x)$ of which have Fourier transforms satisfying (4). For each M, i.e. for $2M+1$ equally bright central diffraction orders of the one-dimensional grating, there exist various solutions $x_1, x_2, \ldots, x_M$, which, however, have different "linear" efficiencies η_1 defined as

$$\eta_1 = \frac{\text{radiant flux in the equally bright central orders}}{\text{total radiant flux passing the grating}}\ . \qquad (5)$$

The corresponding efficiency η of the two-dimensional grating, i.e. the multiple phase hologram, is given by

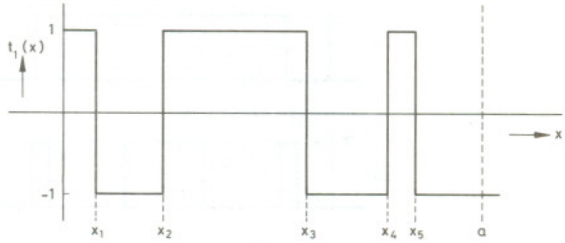

Fig. 2. Form of a binary function having values +1 and -1 only.

$$\eta = \eta_1\ \eta_2\ , \qquad (6)$$

where the "linear" efficiencies η_1, η_2 correspond to distributions $t_1(x)$, $t_2(y)$, respectively.

Fig. 3 shows some calculated binary phase-only groove shapes which, arranged in a grating, exhibit central blocks of equally bright diffraction orders. The diffraction orders are shown schematically on the right-hand side of fig. 3 where also the linear efficiencies defined by (5) are noted.

Just for comparison, fig. 4 shows some calculated continuous phase-only groove shapes, the corresponding diffraction orders and efficiencies. The efficiencies for the multiple phase holograms, η, defined by (5), are almost a factor of 2 higher than in the corresponding binary case, but the still unsolved problem is realizing the corresponding two-dimensional gratings.

We have realized some binary multiple phase holograms which are deduced from two identical one-dimensional structures thus yielding a quadratic block of equally bright multiplied images. The manufacturing process is the following: first a black-and-white mask is made containing a few two-dimensional structures. Fig. 5 shows such an original mask containing four two-dimensional grooves derived from fig. 3d. This original pattern is then multiplied by a step-and-repeat process yielding the black-and-white mask of the whole grating. From this mask binary phase gratings are made by copying the mask on photoresist layers on a high-quality glass base the optical thickness of the layers being $\frac{1}{2}\pi$ resulting in a phase shift of π.

Fig. 6 shows multiplied images produced in the optical setup of fig. 1 using a multiple phase hologram deduced from the structure shown in fig. 5 and fig. 3d. We have measured that the 15×15 central diffraction orders contain 41% of the total radiant flux compared with 40% from calculation.

The light illuminating the single object (fig. 1)

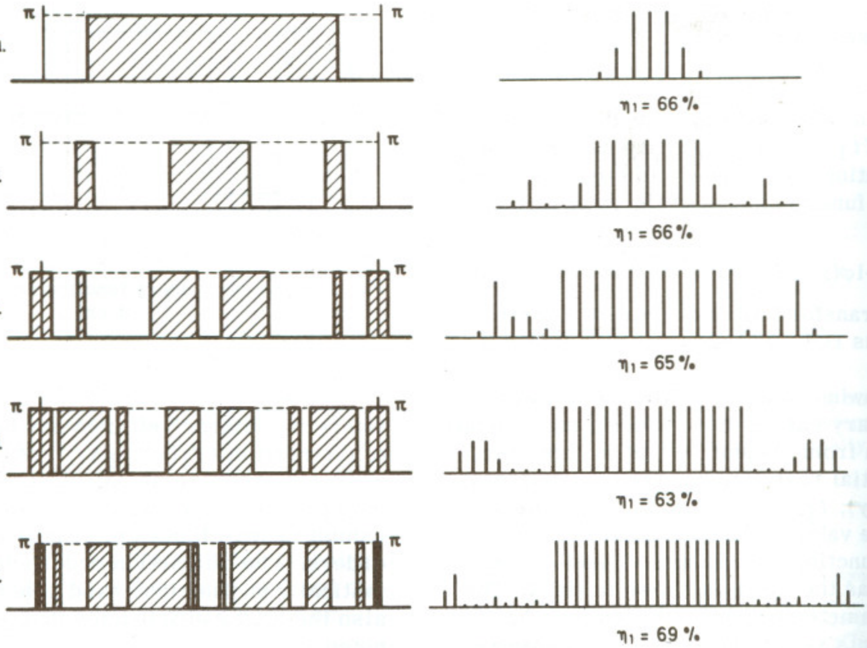

Fig. 3. Some binary groove shapes and corresponding diffraction patterns of gratings exhibiting 3, 7, 11, 15 and 19 equally bright central diffraction orders.

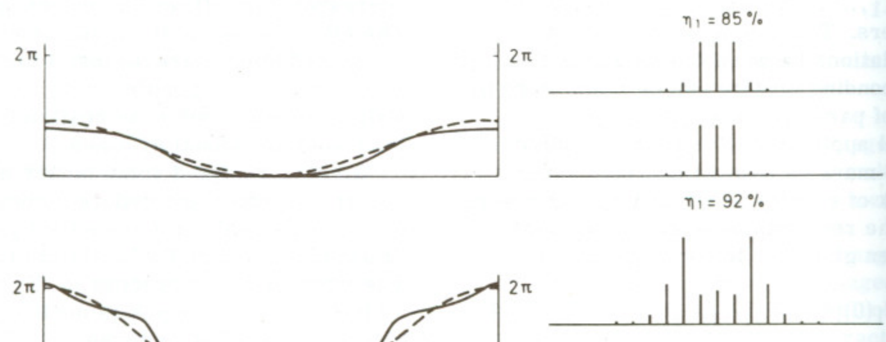

Fig. 4. Some continuous groove-shapes and diffraction patterns of corresponding phase gratings. The dotted lines represent sinusoidal groove-shapes. The diffraction pattern of the corresponding sinusoidal phase-gratings are shown in the upper parts of the right-hand side. By a proper choice of the phase modulation, the three central diffraction orders can be made equally bright (η_1 = 85%). By a slight modification of the sinusoidal form, central blocks of equally bright diffraction orders can be achieved. The solid lines represent such groove-shapes for central blocks of 3, 7 and 13 equally bright orders, as shown in the lower parts of the right-hand side, exhibiting linear efficiencies of 92%, 94% and 96%, respectively.

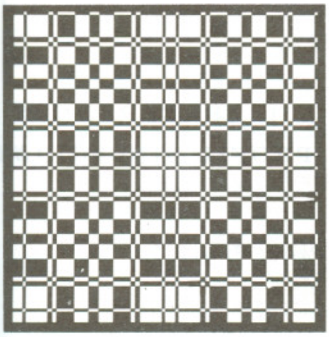

Fig. 5. Structure of a binary multiple phase hologram exhibiting a central block of 15 × 15 multiplied images.

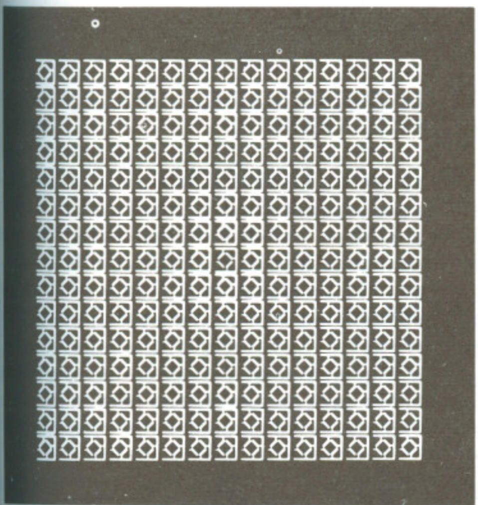

Fig. 6. Central block of 15 × 15 multiplied images.

has to be sufficiently monochromatic, since we are utilizing diffraction and want to avoid dispersion, and should be spatially incoherent in order to avoid speckles in the multiplied images. For example, light from a single line of a low-pressure mercury lamp can be used, but for real applications the light level is too low. For these applications we are therefore using laser light which is made spatially incoherent by a rotating ground glass diffusor in front of the object.

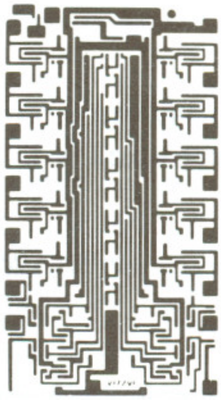

Fig. 7. One of the multiplied images of a single IC-mask pattern. This image with an actual length of 3 mm was obtained in chromium by etching.

We have made some detailed investigations into the use of multiple phase holograms for producing real multiplied images of IC-mask patterns in chromium layers by etching. The chromium plates were coated with Shipley AZ 1350 photoresist on which the multiplied images were projected using a CRL-Argonlaser (250 mW at the 4579 Å-line). The exposure time of the resist was about 2 minutes. Fig. 7 shows one of the multiplied images etched in chromium.

The authors wish to thank H. G. Tietje and M. R. J. de Bont for realizing the photomasks and E. Klotz and C. Clausen for skilfully performing the experiments. The work was sponsored by the "Bundesministerium für Bildung und Wissenschaft der Bundesrepublik Deutschland" under contract number (IA 7-5939-DV 3.303).

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