On the absence of phase-recording or 'twin-image' separation problems in 'Gabor' (in-line) holography†

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Abstract. In contrast with a general belief which followed Gabor's wavefront-reconstruction imaging work in 1948, the original Gabor 'in-line' hologram recording scheme is shown to produce perfectly separable 'twin images', without any phase-recording problems, notably in high-resolution imaging and with diffused illumination.

The introduction of the optical maser by Schawlow and Townes, and of its continuous wave helium–neon form by Ali Javan and others, have brought with them a considerable new interest in the wavefront-reconstruction imaging method, first described by Gabor (1948, 1949, 1951).

Very impressive results have been obtained in a number of variations of the basic wavefront-reconstruction imaging arrangement (Leith and Upatnieks 1963, 1964; Leith, Upatnieks and Haines 1965; Stroke 1964, 1965a; Stroke and Falconer 1964, 1965; Stroke and Funkhouser 1965; Stroke, Brumm and Funkhouser 1965). Fundamentally, we showed that it was possible to reconstruct the complex-amplitude distribution in the field originating from a scattering object by forming a hologram, i.e. interferogram between the spherical waves scattered by the various object points and a 'coherent' (spherical or plane) background wave.

Recently, some variations of the basic method of wavefront-reconstruction imaging have been found to be particularly useful in some applications of 'spatial filtering' work (Cutrona *et al.* 1960, Vander Lugt 1964), along the lines first described by Maréchal and Croce (1953), and where holograms may be used as 'complex' spatial filters. In these and similar applications it appeared to be particularly convenient to bend the path of the coherent background beam 'off axis', with the help of an additional prism or mirror (or comparable displaced lens) (figure 1(*a*)) so as to make it form an angle with a 'mean' direction of the 'scattered' field, rather than having the mean direction of the scattered field form an angle with the path of the coherent background, as in the original method (Gabor 1948, 1949, 1951), where no additional prisms, lenses or mirrors were required.

In spatial filtering and similar applications, as well as in holographic imaging of specularly reflecting or of phase objects with 'extended' details (low resolution), the hologram generally consists of a very small diffraction pattern *spot* carried on a widely spread coherent background. This is in contrast to a hologram in which the diffraction pattern has been spread out over a wide portion of the photographic plate, which is the case required for the attainment of high spatial resolutions in the object and in imaging of three-dimensional objects, for example.

It was pointed out by Stroke (1964) that holograms capable of displaying three-dimensional images of macroscopic three-dimensional objects could be readily obtained if the light scattered from the objects could be made to cover more or less uniformly a large portion of a photographic film (rather than only a small diffraction spot) so as to permit one to move the eyes and head to different portions of the hologram, in correspondence to different viewing angles of the object. Diffusing objects or diffused illumination, or multi-directional illumination thus appears as a requirement for three-dimensional holography, now demonstrated in many forms (Leith and Upatnieks 1964, Stroke 1964, 1965a), and indeed

† For a general background see, for example, G. W. Stroke, *An Introduction to Coherent Optics and Holography* (New York and London: Academic Press, 1966).
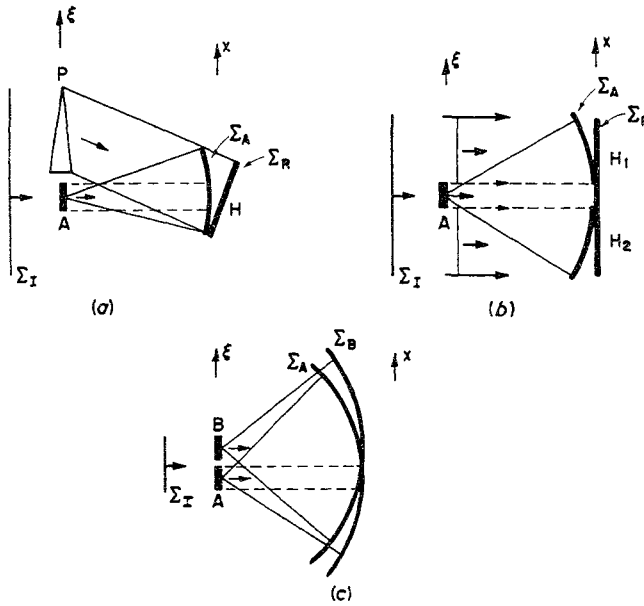
Figure 1. (a) 'Off-axis hologram recording arrangement according to Leith and Upatnieks (1963). Σ_I, monochromatic spatially coherent plane illuminating wavefront; A, scattering object; P, prism; Σ_A, wavefront scattered by point-scatterer in object; Σ_R, reference wavefront (coherent background); H, hologram; ξ, coordinate in object domain; x, coordinate in image plane.   The hologram H is formed by interference between the coherent background and the various waves Σ_A scattered by the object, as first demonstrated by Gabor (1948) (see (b)).

(b) Original 'in-line' hologram recording arrangement according to Gabor (1948).   Same symbols as in (a).   In case of objects which scatter over wide angles (as seen from the object A) (which is the general case of diffusing or diffusely illuminated two- or three-dimensional objects) and the general case of high-resolution imaging, e.g. in microscopy, the original Gabor 'in-line' hologram recording arrangement shown here presents no problems of twin-image separation or of completeness in phase recording, and is indeed superior to the 'off-axis' arrangement of (a) in that it does not require the introduction of any extraneous elements, such as the prism of (a) (which may not be available in x-ray imaging, for example).

(c) 'Lensless Fourier-transform' hologram recording arrangement according to Stroke (1965), used for high-resolution holograms, both with point sources and with extended sources, and designed to solve the 'emulsion problem' and the 'source problem' in high-resolution holography. Σ_I, spatially coherent monochromatic illuminating wave; Σ_A, wavefront scattered by object point; Σ_B, wavefront scattered by source point. A and B are in the same plane.   The arrangement is designed to result in appreciably smaller path differences, and as a consequence the interference fringes in the hologram have a spacing which is appreciably wider with respect to the photographic 'grain' in this arrangement than in the Fresnel-transform hologram recording arrangements (such as that of (a)).   The 'coding' of the Fourier-transform hologram by the use of an extended source B would result in a resolution 'loss' in the image reconstruction, if it were not for the possibility of resolution-retrieving decoding by a 'correlative reconstruction' process, using either the same extended source, or an equivalently scaled source, as first shown by Stroke, Restrick, Funkhouser and Brumm (1965a, b).

in those more general cases where it is desirable to record what we may call a 'macro-hologram' (i.e. a hologram containing the holographic information in a form spread out over large areas of the photographic plate), in contrast to a 'micro-hologram', formed of only a small diffraction spot on an extended coherent background.   In comparison with the wide-angle diffraction and large numerical apertures required in high-resolution microscopy, it should be clear that macro-holograms and not micro-holograms must be formed when high resolutions in the object space are being sought. (We may immediately note that some diffracting objects, such as those studied in microscopy, and indeed in x-ray diffraction

work, will naturally tend to form macro-holograms, by diffracting the light over wide angles, corresponding to their highest spatial frequencies, and this without any 'artificial' diffusion.)

In this paper we show that when macro-holograms, of both microscopic and macroscopic objects, are required, they may indeed be produced in the original (Gabor 1948, 1949, 1951) 'in-line' hologram recording arrangement (figure 1(*b*)), in which the light scattered by the object is made to interfere with an 'in-line' coherent background, without compromising any of the basic advantages of phase preservation and twin-image separation, recently attributed to the 'off-axis' arrangements (such as that of figure 1(*a*)). In fact, experimental convenience, rather than any basic considerations, calls for an 'off-axis' reference-beam illumination in the general case.

Indeed, some recent descriptions (Leith and Upatnieks 1965) of the so-called 'off-axis' method (figure 1(*a*)) may have seemed to imply that the 'off-axis' hologram recording arrangement may be an essential improvement, required *sine qua non* for the good separation of the two reconstructed images (virtual and real), obtained by illuminating the hologram with a plane or a spherical wave. In fact, it may have been implied that Gabor's original 'in-line' method may have somehow been less 'complete' in recording both the phase and amplitude in the scattered field, or that it may present some special problems in the separation of the virtual and real twin images, when compared to the 'off-axis' method.

Experimental convenience, rather than any basic considerations, may call for the use of the 'off-axis' arrangement of figure 1(*a*) in preference to the 'in-line' arrangement. But the 'off-axis' Leith–Upatnieks hologram H of figure 1(*a*) is effectively nothing but one half (i.e. H_1 or H_2) of the original Gabor 'in-line' hologram. Diffuse illumination in holography was first suggested by Stroke (1964) and used by Leith and Upatnieks (1964).

The physics of the hologram recording method used may be readily understood in terms of the diagram (figure 1(*b*)) and in terms of the many previous publications in holography, as well as in comparison with figure 1(*a*).

A photograph of the actual recording arrangement used in our work is shown in figure 2† with the object (the phrase 'image separation') and the hologram in the position used for the recording. A photograph of the hologram is shown in figure 3.

The two well separated images (*real* in front of the hologram and *virtual* behind the hologram) photographed by a camera looking, from a suitable angle, through the hologram at a plane 6328 Å laser wave is shown in figure 4. (In figure 4 the granularity in the well-separated images is characteristic of the spatial coherence in the laser beam, as seen through the small aperture of the camera lens, used to record, with sufficient depth of field, both the virtual and real reconstructed images as well as the hologram, all simultaneously.)

Figures 5 and 6 show the virtual and real images, respectively, as photographed with the camera looking at the hologram, as in figure 4, but now using a wide lens aperture so as to obtain focusing on either the virtual or the real image and good resolution, as well as also avoiding the granularity effect of figure 4.

A reconstruction of the real image, obtained by 'lensless' recording of the real image on a photographic film, using the self-focusing property of the Fresnel hologram is shown in figure 7.

It should be clear from the preceding discussion, and from the figures 1 to 7, that the 'in-line' hologram recording arrangement presents no unusual problem either of phase recording or of any 'twin-image' separation, while also being the most straightforward macro-hologram recording arrangement described so far.

We may note, in conclusion, that the attainment of very high resolutions, such as those required in high-resolution microscopy, at visible as well as at x-ray wavelengths, and the need for recording the high spatial frequencies in the 'interference fringes' in the holograms may require a 'lensless Fourier-transform' hologram recording arrangement, such as that shown in figure 1(*c*) and first described by Stroke (1965b) for the case when B is a point source, rather than the arrangements of figures 1(*a*) or (*b*). We may also note that there is no need to use point sources to produce either the plane or the spherical reference waves in

† Figures 2–7 printed as plate at end of issue.

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any of the arrangements of figure 1; indeed, we have recently shown (Stroke, Restrick, Funkhouser and Brumm 1965a, b) that 'source-effect' correlation-compensation methods allow the resolution to be retrieved, *a posteriori*, from the 'coded' hologram recorded with a suitable extended source B, used in place of the point reference source.   In the absence of a resolution-retrieving source-effect compensation, every image point in the reconstructed image would be spread out, by correlation, to the width and structure of the recording source. The source-effect compensation may be accomplished by using in the reconstruction also an extended source, for instance the same source as used in the recording, or a suitably scaled and structured source (Stroke, Restrick, Funkhouser and Brumm 1965a, b).

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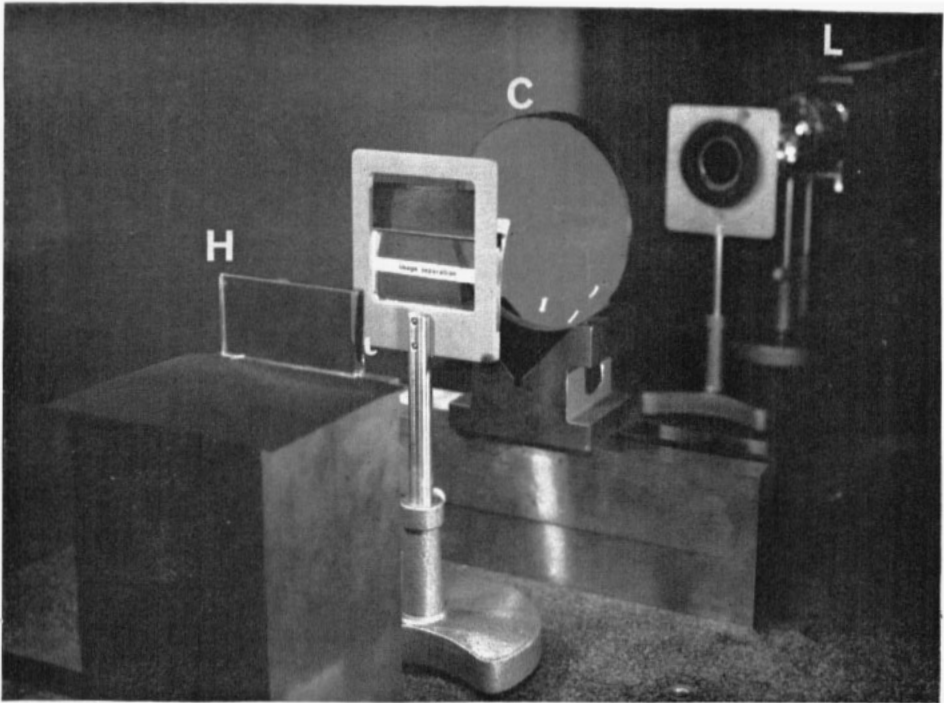
Figure 2. In-line hologram recording arrangement (according to figure 1(*b*)) used to record the hologram (H) of the object 'image separation' shown. (L is the 6328 Å He–Ne laser used to illuminate the object with a wave, through the collimator C.)
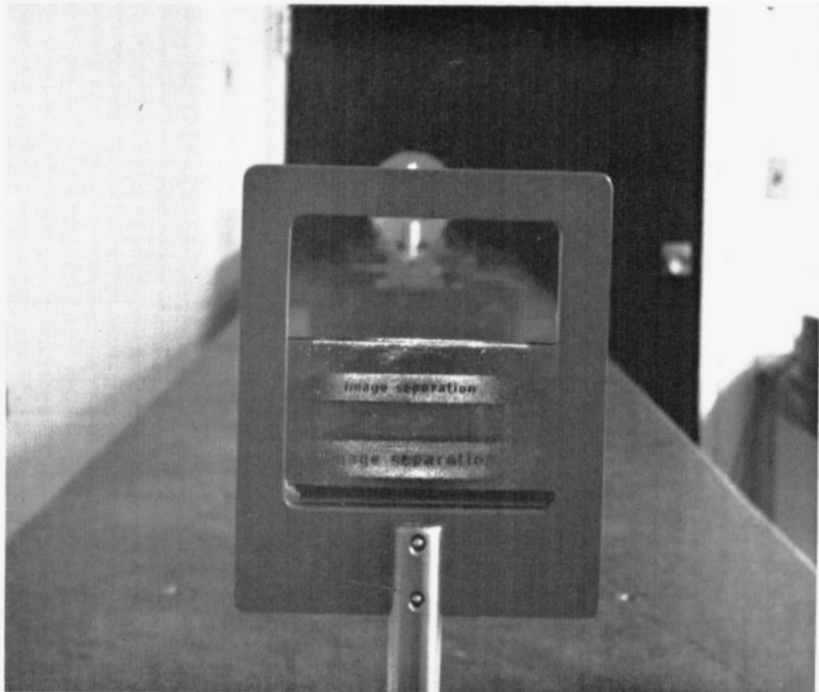

Figure 4. View through the hologram, showing the well separated virtual (top) and real (bottom) images, together with the hologram (the photograph is completely unretouched). The laser, used to illuminate the hologram, appears in the background (see text).
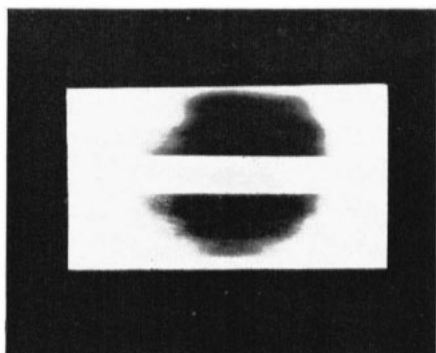
Figure 3. Photograph of the 'in-line' holo-gram H, recorded in the arrangement of figure 2, showing the two parts H_1 (top) and H_2 (bottom), each of which is an 'off-axis' holo-gram (compare figures 1(b) and 1(a))

Figure 5. Photograph of virtual image (see figure 4) as seen through the hologram (see text).

Figure 6. Photograph of real image as it appears (here in the form of an aerial image) in front of the hologram (see figure 4 and text).
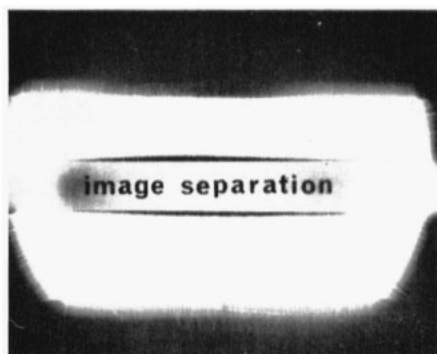

Figure 7. Lensless photograph of the real image, obtained by placing a photographic plate in the plane where the real image (see figure 4) is formed by 'self focusing' by the hologram (see text). In the general case each 'off-axis' part H_1 or H_2 of the 'in-line' holo-gram of figure 3 may be used to form a com-pletely separated real image without any problem.