Technical Information

NDT/HOLOGRAPHY

Introduction

This article is only meant as an introduction to holography and its applications. A more detailed article, which also contains a description of the properties of our photographic materials for this purpose (Technical Information No. 271) will be gladly sent on request.

1. HOLOGRAPHY

— A practical definition of holography would be the recording of an image or object using all the properties of the light reflected or transmitted by that object. The Greek words "holos" and "graphoo" from which the word holography is derived, mean "whole" and "writing".

By "all the properties of the light" we mean:

a. the intensity
b. the wavelength } of the light
c. the phase

— In **conventional photography** we only make use of the first two properties, since the image is recorded on a photographic emulsion by the intensity distribution of the light reflected by the object, using optical means (lenses and mirrors).

— In **holography**, on the other hand, we make use of the phase content of the light for recording the image information of the object, i.e. the mutual position of the various parts of the object is rendered by the phase difference of the light waves which are either transmitted or reflected by the object. This will be clarified below.

2. LASERS

For a light wave reflected by an object to contain meaningful phases there must be a fixed phase relationship between the waves emitted by the illuminating source.

— In **conventional light sources** (tungsten lamps, fluorescent tubes) the light waves are generated by the electrons of the filament or gas charge without any mutual relation in time or space. This type of light does not possess a fixed phase relationship between the emitted light waves. This is called "**incoherent light**".

— The **laser** (Light Amplification by Stimulated Emission of Radiation) is a light source with a fixed relationship between the emitted waves.

a. It has been established that the light emitted by a laser is **monochromatic**, i.e. it consists of a single wavelength or a very narrow band of wavelengths.

b. The electrons, which in a laser are at an elevated energy level, only emit energy in the form of light under the effect of a stimulant, and when this stimulant is present the energy will be emitted **simultaneously**, i.e. all **light waves** emitted by a laser **originate** at the same instant.

— Light satisfying both properties is called "**coherent light**".

— The wavelength is characteristic of each type of laser:

helium neon laser	wavelength	632.8 mμ
ruby laser	wavelength	694.3 mμ
neodymium laser	wavelength	1,060.0 mμ

Depending on the medium displaying laser properties, we speak of a gas laser (e.g. helium neon), a crystal laser (e.g. a ruby laser) or a solid state laser (e.g. gallium arsenide).

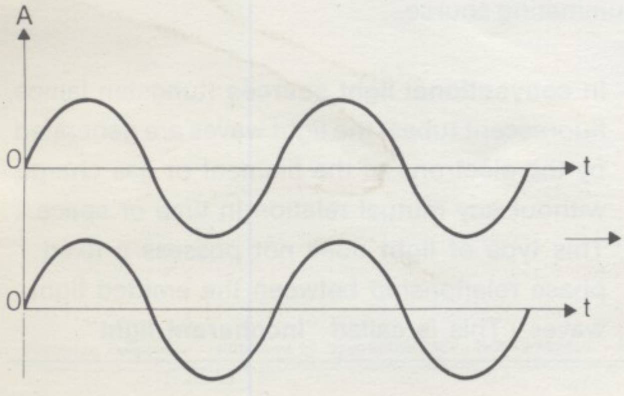
3. INTERFERENCE

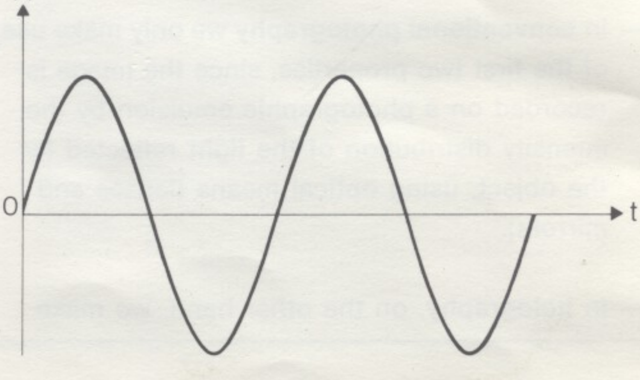
To understand the technique of holography we must remind the reader of a phenomenon which in optics is known as "interference" and which makes it possible to record the phase content of a light wave. When two waves of the same wavelength arrive together at a certain point, interference may occur, i.e. they can add together to increase the intensity at that point, cancel each other, or produce some intermediate intensity.

Maximum increase in intensity will occur when the oscillations of both waves simultaneously exhibit their maximum amplitude in the same sense and pass through zero amplitude simultaneously and in the same direction (Fig. 1). The waves are then said to be in phase.

Maximum cancellation occurs when the oscillations simultaneously exhibit their maximum amplitude, but in opposite senses, and pass simultaneously through zero amplitude but in

Fig. 1 — Two oscillations in phase mutually intensify each other; the result is an oscillation of twice the amplitude.





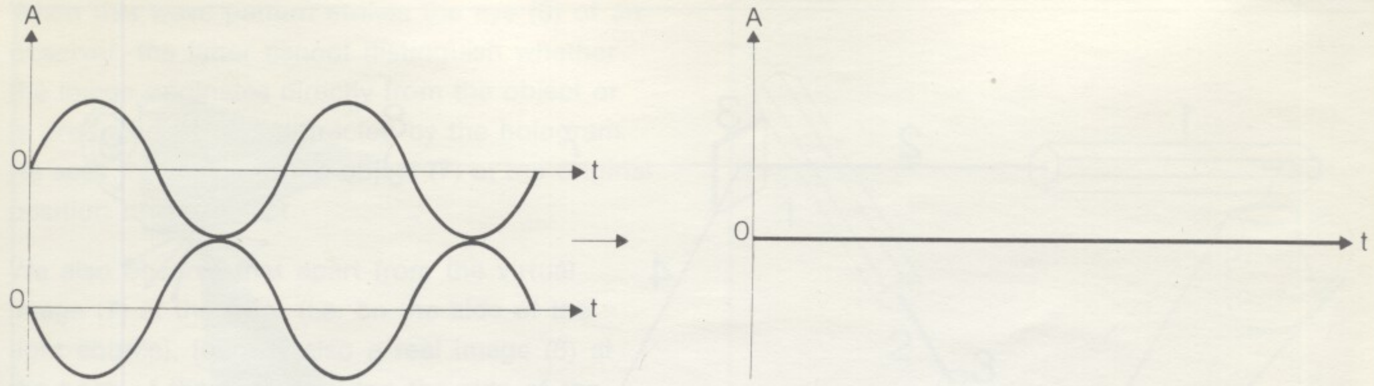


Fig. 2 — Two oscillations in anti-phase cancel each other; the result is no oscillation and the amplitude remains zero.

opposite directions (Fig. 2). The waves are then said to be out of phase or in anti-phase. For example, this will occur when one of the two waves has travelled a distance which is an odd number of half-wavelengths greater than the distance travelled by the other wave.

When two monochromatic light waves meet after having travelled different distances, all intermediate cases may occur from greatest intensity to total cancellation.

4. RECORDING TECHNIQUE

Fig. 3 shows the principle of holographic recording technique. The laser (1) emits a coherent light beam (2). This beam is partly transmitted and partly reflected by a semi-transparent mirror (3). The reflected beam is called the reference beam (4) and is distributed over the entire surface of the photographic emulsion (6) by means of a lens (5).

The transmitted beam (7) is also made wider by means of a lens (8) in order to illuminate the object to be holographed (9). At each point of the object illuminated by the light beam, the light is reflected in a diffuse manner, i.e. in all directions, and therefore also in the direction of the photographic emulsion (10).

At the photographic emulsion, all rays reflected by the object mingle with the reference beam. Since both originate from a coherent light source, interference will then occur. According to the difference in the path length between the rays of the reference beam and those of the object beam, they will exhibit more or less phase difference. If the difference in path is an even number of wavelenghts, the rays will intensify each other. If the difference in path is an odd multiple of half-wavelenghts, the rays will cancel each other, thus producing minimum density.

The same argument applies to all points of the object from where rays are reflected. We thus obtain on the photographic material places which have received a greater or lesser amount of illumination, which after processing results in places with higher or lower density, and thus "freezes" the information-carrying wavefront in the photographic material. This photographic result is called hologram (Fig. 4).

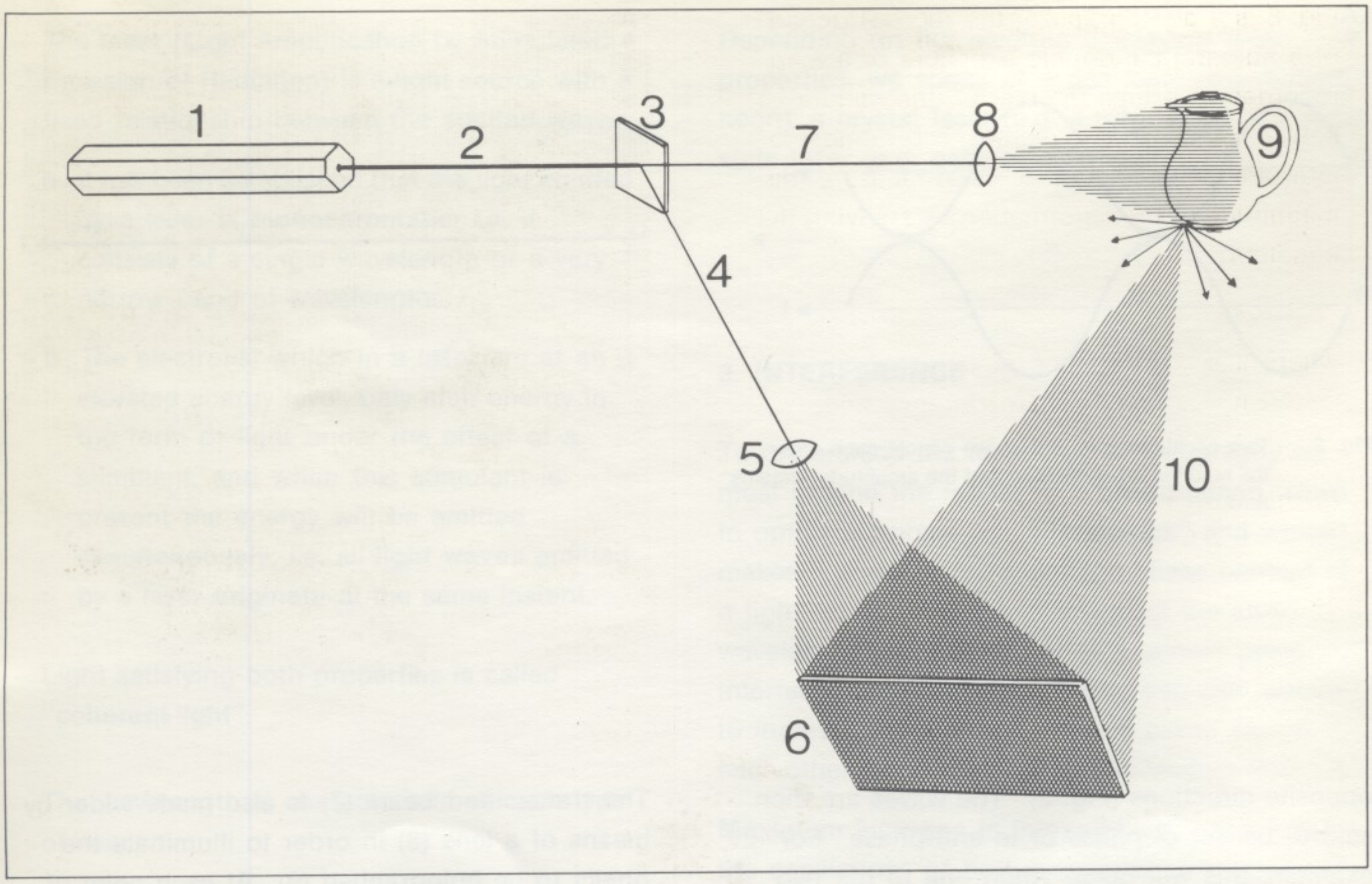
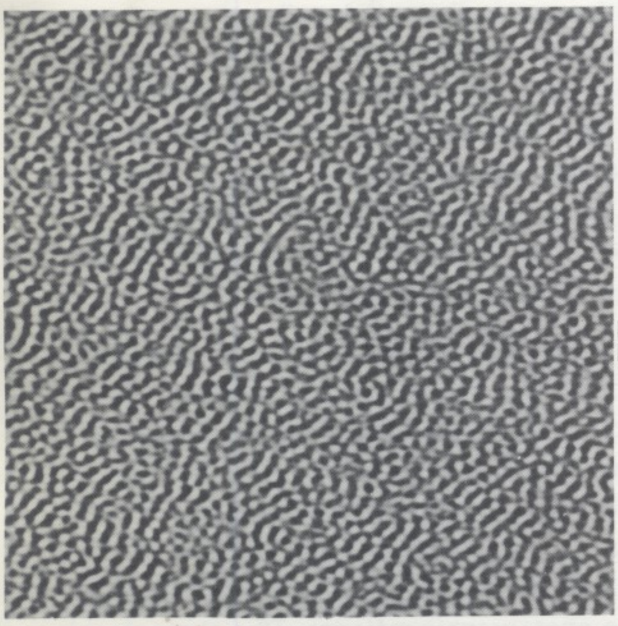


Fig. 3 — Principle of the arrangement for making a hologram.



5. RECONSTRUCTION OF THE IMAGE

By this is meant the making visible of the image by means of suitable illumination of the hologram. Fig. 5 shows the principle of the arrangement.

The laser beam (2) is made to fall at approximately the same angle as the reference beam during recording on the hologram (4) by means of a laser (1) and a lens (3). The successive clear and dark lines of the hologram (see Fig. 4) now act as a diffraction grate for the reference beam. The rays which have been diffracted by this grate and which may vary in intensity, now form a wave pattern (5) behind the hologram, which is identical with the one which would have passed through the photographic material if it had been transparent instead of light-absorbent. This empirical fact can be explained mathematically.

When this wave pattern strikes the eye (6) of an observer, the latter cannot distinguish whether the image originates directly from the object or is produced by rays diffracted by the hologram. He sees the image of the object (7) at the original position of the object.

We also observe that apart from the virtual image (7) at the front (i.e. on the side of the light source), there is also a real image (8) at the back of the hologram (on the side of the observer).

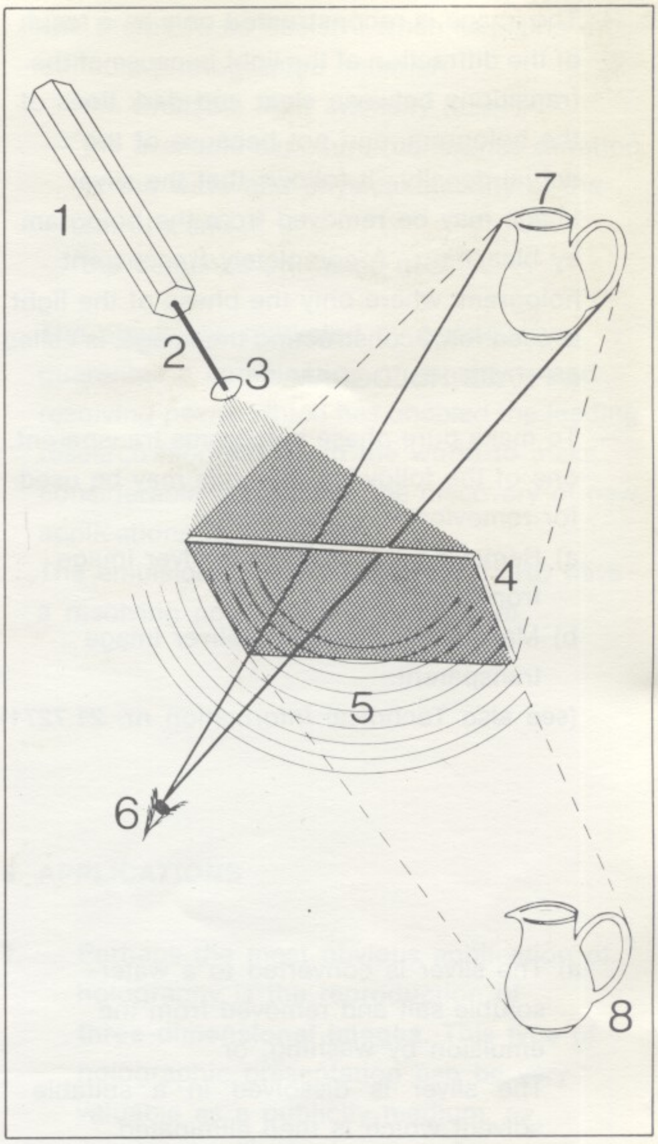


Fig. 5 — Image reconstruction.

6. PROPERTIES OF THE RECONSTRUCTED IMAGE

a. The reconstructed **image** is in fact **three-dimensional** because each point of the photographic material ''sees'' the object from a different viewpoint. When the observer moves with regard to the photographic material, each time he will see the image from a different perspective, namely the perspective which was ''seen'' by that particular part of the photographic emulsion.

b. **Every small part** of the photographic material **contains** all elements of **the image**, of course only as ''seen'' from the same angle of view (Fig. 6). The hologram may be cut into small pieces and it will still be possible to reconstruct the entire image from each piece. The only limiting factors are the resolving power of the photographic material and the angle at which the eye sees the hologram.

Application: STORAGE OF DATA IN AN EXTREMELY SMALL SPACE.

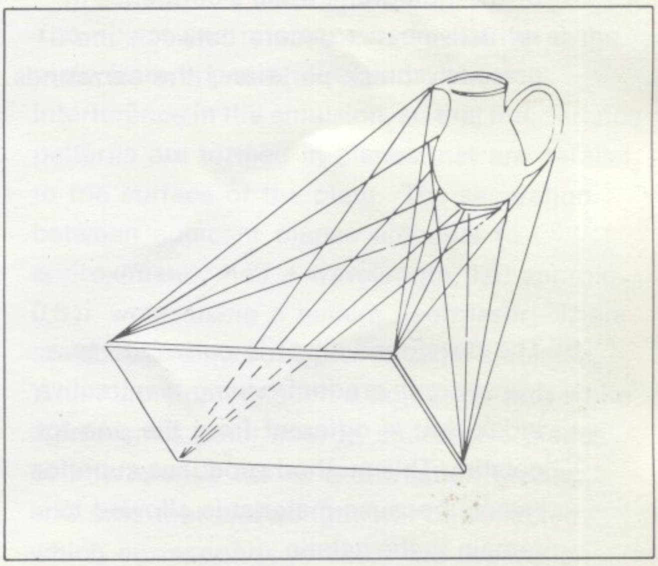


Fig. 6 — Each location on the photographic material ''sees'' the object from a different viewpoint.

c. — The image is **reconstructed** only as a result of the diffraction of the light because of the transitions between clear and dark lines of the hologram, and not because of the actual density. It follows that the silver image may be removed from the hologram by bleaching. A completely transparent hologram, where only the phase of the light is used for reconstructing the image, is called a PHASE HOLOGRAM.

— To make pure phase holograms transparent, one of the following methods may be used for removing the silver image:
a) Removing the developed silver image from the emulsion, or
b) Making the developed silver image transparent.
(see also Technical Information nr. 21.7271).

a) The silver is converted to a water-soluble salt and removed from the emulsion by washing, or
The silver is dissolved in a suitable solvent which is then eliminated.
This method converts the original silver image to a relief image, for, by removing the developed silver from the emulsion, the thickness of the emulsion will vary in accordance with the original density of the hologram, while a difference in refractive index occurs between the originally black parts and the surrounds.

b) The developed silver is converted to a transparent product having a refractive index that is different from the one for gelatin. This method produces superior results because material is allowed to remain in the gelatin.

If the intensity of the emergent light of the first order be I_d and that of the incident light I_t, the ratio $\frac{I_d}{I_t}$ is called the **diffractive efficiency,** which is a measure of the transparency of the reconstructed image.

The great advantage of phase holograms lies in the fact that their diffractive efficiency is much higher (approx. 40 per cent) than in the case of near opaque amplitude holograms (approx. 5 per cent).

d. As the light source used for reconstruction is monochromatic, the **image** will also be **monochromatic.**

e. Since interference during reconstruction only relates to locations on the photographic material that are relatively close together, the light source only needs to have a limited degree of coherence and a laser is nog required. A sufficiently approximate **monochromatic point source** will be suitable. For example, a mercury vapour lamp with a monochromatic filter for extracting a single spectral line possesses sufficient coherence. This type of light source has been successfully used for **recording** holograms of simple objects.

7. PHOTOGRAPHIC MATERIALS

It will be clear from the above discussion that photographic materials for holography must possess the following two properties to a very high degree:

a. Sufficient colour sensitivity over a well-defined range of wavelengths,
b. Very high resolving power.

a. Colour sensitivity

In order to record the light from a laser, the material must be sensitized for this monochromatic radiation. Since most panchromatic materials have already passed through their maximum sensitivity at 632.8 mμ and certainly at 694.3 mμ, special sensitizers have to be used. Agfa-Gevaert supplies a range of specially sensitized emulsions which allow exposures of a fraction of a second.

b. Resolving power

a. The separation on the hologram between a line of high density and one of low density corresponds to the difference in path length between the reference beam and the object beam of half a wavelength, or an odd multiple of half a wavelength.

If Θ = angle between reference beam and object beam when symmetrically incident on the photographic material, the separation d between two dark lines on the hologram is:

$$d = \frac{\lambda}{2 \sin \frac{\Theta}{2}}$$

where λ = wavelength of the laser used. At 45° this is a separation of 0.8μ. This can only be rendered by a photographic emulsion with a resolving power of 1,250 lines/mm. With a smaller angle between reference beam and object beam, a lower resolving power will suffice.

It is well known that high sensitivity and high resolving power are contrary demands on a photographic emulsion. The following factors will therefore be decisive when selecting a suitable photographic material:

— the available light intensity (laser),
— the available exposure (coherence duration of the wave and physical stability of the set-up), and
— the demands on image quality.

The emulsions marketed by Agfa-Gevaert guarantee a combination of sensitivity and resolving power which has enabled the leading research laboratories in the world to make considerable progress in the discovery of new applications of holography.
The emulsions 8 E 56 HD and 8 E 75 HD have a resolving power of 5,000 lines/mm.

8. APPLICATIONS

1. — Perhaps the most obvious application of holography is the reproduction of **three-dimensional images**. This type of holographic presentation can be very valuable as a publicity medium, as spectacular illustration material in schools, etc.

— A special form of holography is **white-light holography**, also called **reflection or Bragg holography.**

The object and reference beams arrive at the plate from opposite directions, causing interference in the emulsion, so that interference patterns are formed in planes that are parallel to the surface of the plate. The separation between adjacent planes amounts to approximately half a wavelength, i.e. approx. 0,3μ when using a helium neon laser. There are about twenty such planes in the emulsion. When illuminating such a hologram with white light from a point source, successive planes of interference act as a diffraction grating, and only that wavelength will be reflected which corresponds to twice the separation

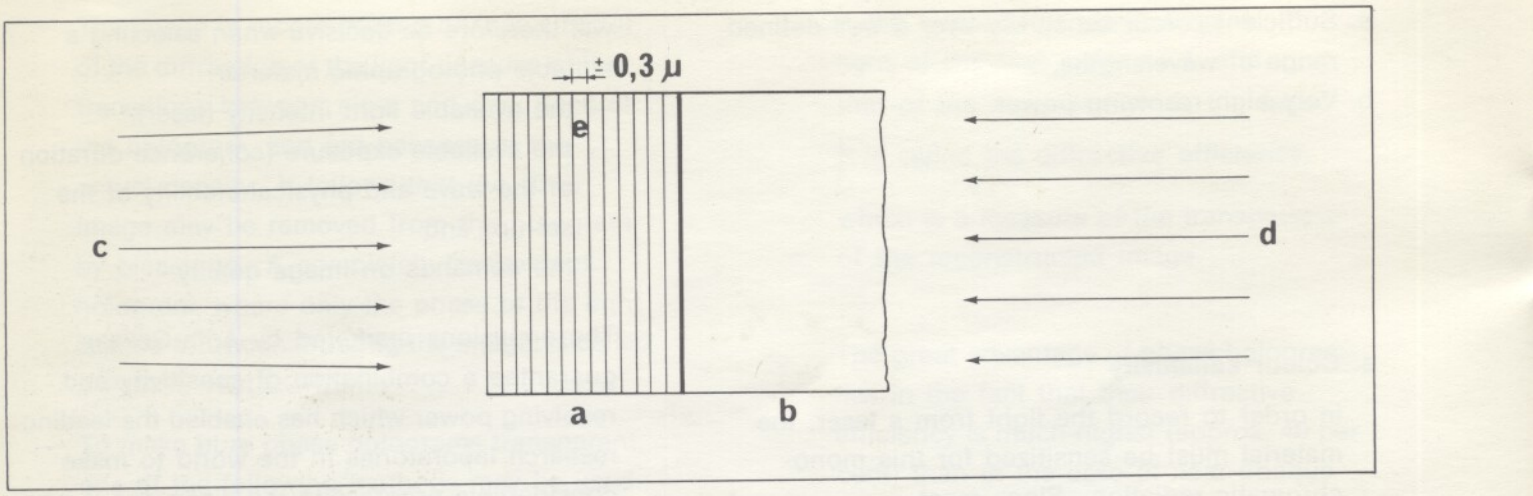


Fig. 7 — Section through a Scientia 8 E 75 plate for Bragg holography
a. emulsion, thickness 6 µm
b. glass base, thickness 1.2 to 1.4 mm
c. object beam
d. reference beam
e. basic interference pattern throughout the thickness of the emulsion

between two interference pattern planes. The result is not only a three-dimensional, but also a monochromatic image, although the light source will be composed of all visible wavelengths.

Sufficient monochromacity of the image requires a minimum emulsion thickness of 6 µm. Chemical processing causes some shrinkage of the emulsion, which in turn causes a colour shift from red towards green for a helium neon laser. This effect can be remedied by after-treatment.

2. Another application is the detection or measurement of small deformations by means of holographic **interferometry.**

This method consists in holographing the object to be examined by incident light, but dividing the exposure into two equal parts. The object is first exposed for half the normal exposure time; the object is then slightly modified and the second exposure is given.

These small modifications can be produced by:
— forces (e.g. differences in pressure or temperature) that act on the object;
— deformation proper to the object (e.g. growth of plants).

Because
1. both holograms are recorded on the same plate, and
2. there is only a small number of different points in both recordings,

the reconstructed wavefronts will differ slightly from each other and cause macroscopic interference (not to be confused with holographic interference!). It is obvious that this interference contains information on the deformation. Let us illustrate this by means of a few examples.

It is self-explanatory that the location of both the object and the recording material must remain exactly the same during both exposures, except in so far as the modification in question belies this.

A. Fig. 8 is a photograph of the reconstruction of a holographic double exposure of a tulip recorded at a time interval of one minute between the two exposures. The number of interference lines enables us to measure the magnitude of the deformation by applying the equation:

$$x = \frac{n\lambda}{2}$$

where x = deformation of object
n = number of interference lines
λ = wavelength of laser light.

In this case the deformation is approx.

$$\frac{5.0.6}{2}\ \mu = 1.5\ \mu$$

The form of the interference pattern gives information about the direction and distribution of the deformations.

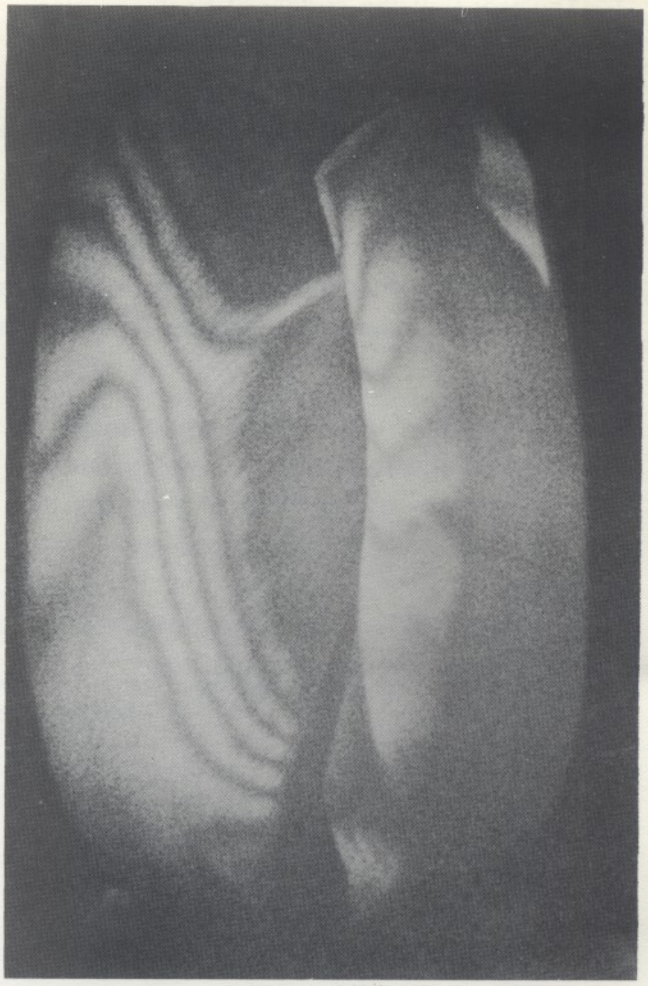


Fig. 8 — Double hologram of a tulip.
By courtesy of Prof. Dr. W. Martienssen of the University of Frankfurt/Main.

B. — Fig. 9 illustrates another application of interferometry. Two recordings were made on a single plate or film; the first of a car tyre at normal pressure and the second of the same tyre at a higher pressure.

The change in pressure causes deformation:
— expected regular expansion
— local objectionable expansion.

It is these contours that as local interference fringe patterns immediately show their presence.

— It is sometimes preferable to exactly superimpose the reconstructed image of a singly exposed hologram on the original object. With this method also, interference fringe patterns become readily visible.

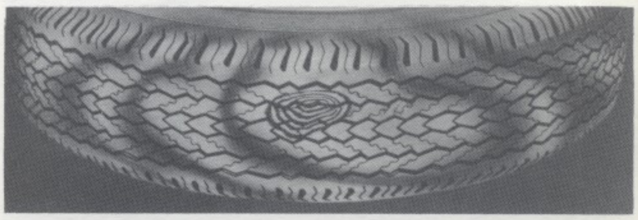


Fig. 9 — Holographic analysis of motor car tyre deformation for the detection of structural defects.

C. The fact that the supply of heat can also cause deformation, which can most easily be detected by means of holography, is illustrated by the interferometric application of holography to a phase object. A phase object is an object that does not show differences in optical absorption between its various components or states, but differences in refractive index. For example, air is a phase object.

When producing a double hologram of air with a temperature gradient, for instance in the proximity of the flame of a candle, the temperature distribution of the air is clearly rendered by the interference of both recordings, the first with the extinguished candle and the second with the candle lit (fig. 10).

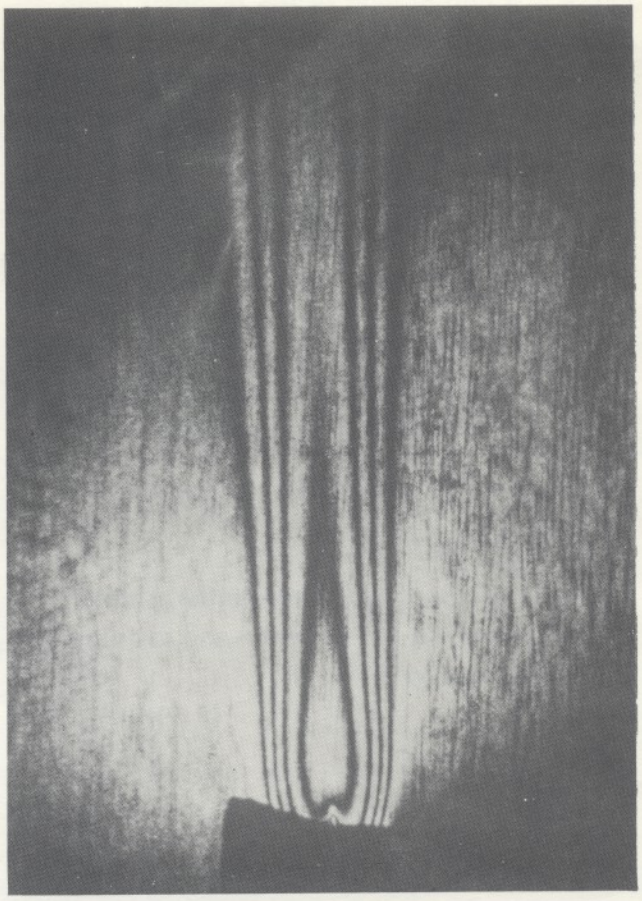


Fig. 10 — Temperature distribution in the air in the proximity of the flame of a candle as an example of the interferometric application of holography to a phase object.
By courtesy of Mr. P. Smigielski, Institut Franco-Allemand de Recherches, Saint-Louis, France.

3. One of the most interesting applications of holography is no doubt **character recognition.**

This original method for reading characters, data sorting and similar computer operations, can be particularly useful.

Fig. 11 shows a schematic presentation of an appropriate arrangement.
V is a transparent sheet containing the data to be processed (drawing or text). V is situated in the focal plane of lens L_1, which, after illumination of V by a laser, transforms each image point of V into a parallel beam.
In optics, such an operation is an application of a Fourier transform.

The light beam strikes at H a "spatial filter", which is actually a hologram containing the data to be retrieved, i.e. the data with which that of the light beam must be compared.

It can be shown mathematically that under the described conditions, only those light beams will continue their path unaffected, whose information exactly corresponds to that of hologram H, while beams of non-corresponding information will be scattered by the hologram.

The transmitted light beam (when present) is then focused on screen S by means of lens L_2 into a light spot, whose position corresponds to that of the respective information contained in the original.

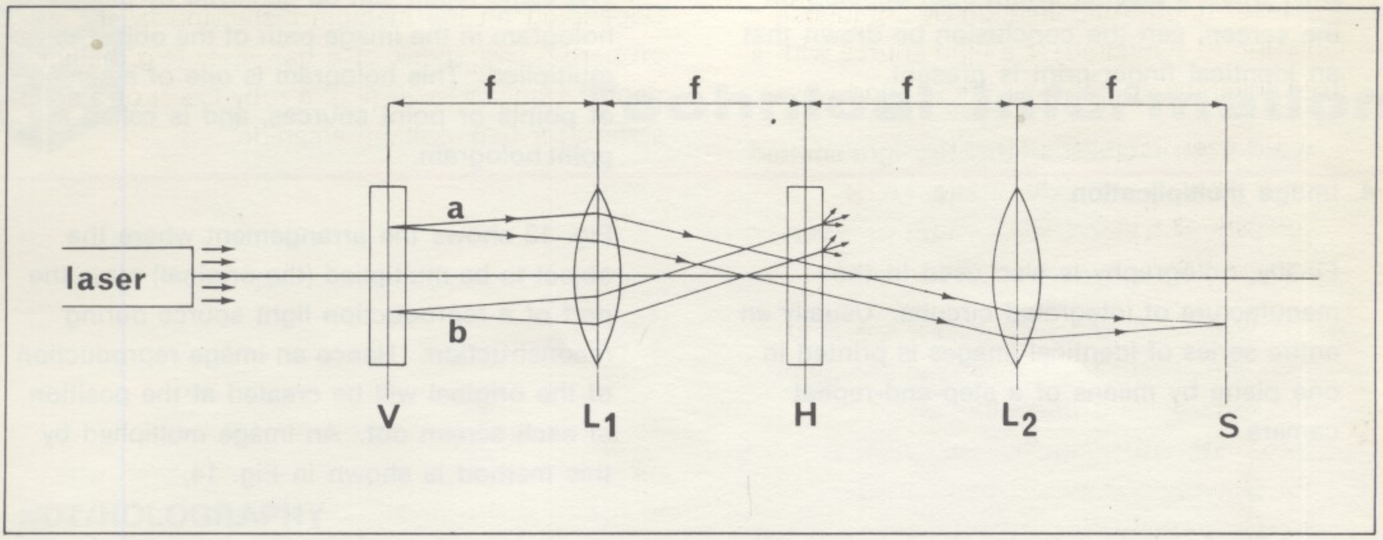


Fig. 11 — Character recognition

a. The information of this beam **corresponds** to that of spatial filter H; the light beam is transmitted unaffected and is **focused** on a screen into a point by lens L_2.

b. The information of this light beam **does not correspond** to that of the spatial frequency filter; the light beam with its inherent information is **dispersed** in all directions by the spatial filter.

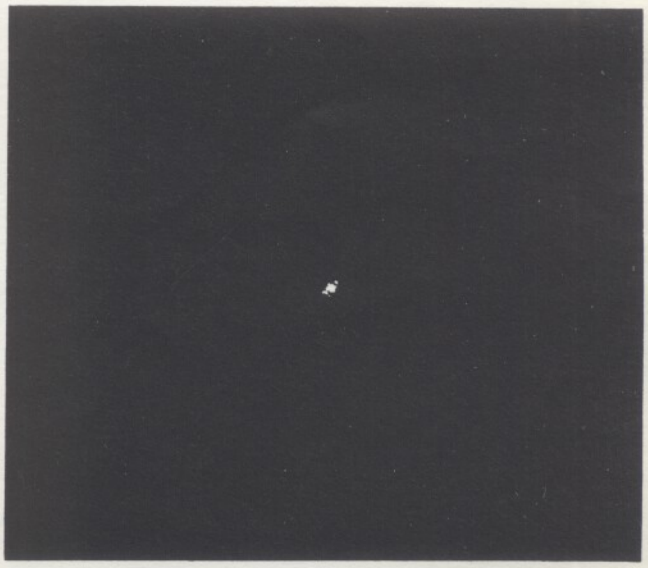
This method is used in a highly original manner for the identification of finger-prints.

Fig. 12 shows:

a. a photograph of a finger-print, and

b. one of the corresponding light beam focused into a bright spot.

Fig. 12 — Identification of finger-prints
By courtesy of Prof. Dr. W. Martienssen of the University of Frankfurt/Main.



Only when a distinct bright spot appears on the screen, can the conclusion be drawn that an identical finger-print is present.

4. Image multiplication

Finally, holography is also used in the manufacture of integrated circuits. Usually an entire series of identical images is printed in one plane by means of a step-and-repeat camera.

The same result can be achieved by placing a hologram in the image path of the object to be multiplied. This hologram is one of a screen of points or point sources, and is called a point hologram.

Fig. 13 shows the arrangement where the object to be multiplied (the original) plays the part of a reproduction light source during reconstruction. Hence an image reproduction of the original will be created at the position of each screen dot. An image multiplied by this method is shown in Fig. 14.

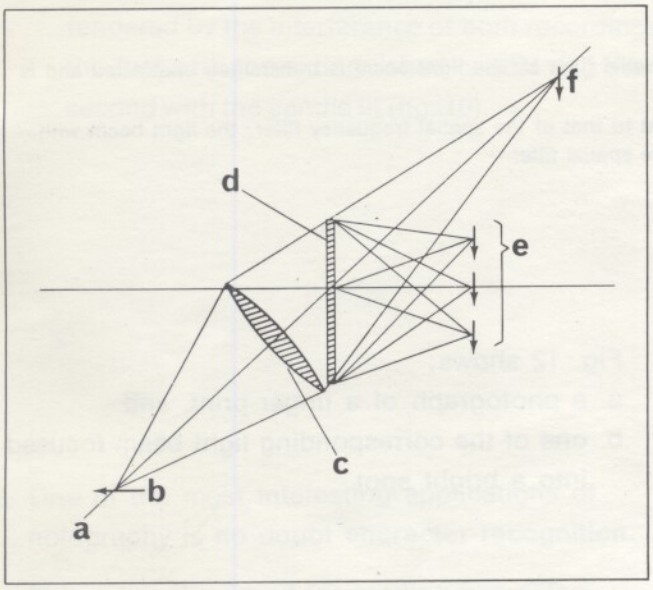


Fig. 13 — Schematic arrangement for image multiplication. By courtesy of Dr. G. Groh, Philips Zentrallaboratorium GmbH, Hamburg.

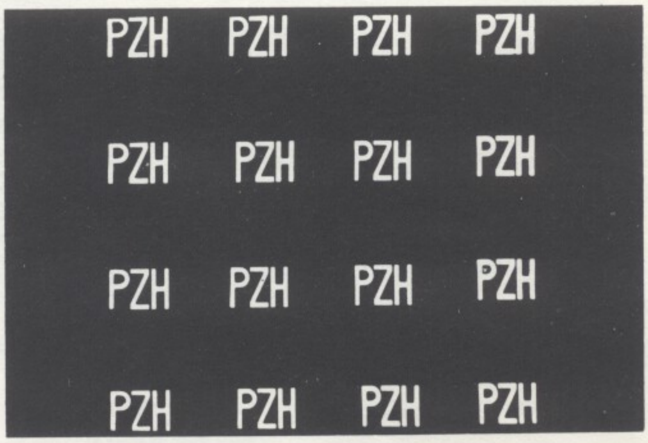


Fig. 14 — Image multiplication by means of a point hologram. By courtesy of Dr. G. Groh, Philips Zentrallaboratorium GmbH, Hamburg.

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