Light-in-flight recording: high-speed holographic motion pictures of ultrafast phenomena

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Holographic recordings have been made using lasers of short coherence and pulse length. Continuous frameless moving pictures show the wave front (pulse front) of light reflected by a mirror and focused by a lens. Light passing through interferometers has also been studied using this new method of dynamic observation. Cross sections between a thin sheet of light and a 3-D object have been recorded to demonstrate the possibilities of contouring. Finally a number of future experiments are proposed ranging from the measurements of industrial products to the study of relativistic effects.

I. Introduction

Albert Einstein wrote in his memoirs that as a young boy he pondered what a light wave would look like to an observer riding along with it. Some one hundred years after his birth it has now become possible to make observations that to a surprisingly high degree correspond to that idea. The new method is based on holography, ultrafast pulsed lasers, and the fact that interferometry is a two-photon phenomenon.

The basic idea is extremely simple. A holographic plate records an object beam only if it is simultaneously illuminated by a reference beam. If the latter consists of a picosecond laser pulse that travels along the plate it will work like an ultrahigh-speed curtain shutter. The hologram plate therefore corresponds to an infinite set of gated viewing systems triggered by the traversing reference pulse. Scanning along the processed plate produces a continuous motion picture of the object situation.

If the object consists of a flat surface illuminated by the same pulse as the reference beam, the hologram will record the motion of the light, much as if we were riding along the light waves during observation. Thus we first named the method light-wave surfing; later we changed that to light-in-flight recording by holography.[1]

The new technique to record light in flight in a strange way links together the research results of Einstein and Dennis Gabor. In 1917 Einstein predicted the existence of stimulated emission of radiation, the idea on which the laser is based. This new type of radiation was initiated simply to satisfy his equations. To establish equilibrium between the absorption and emission of spectral lines, Einstein had to introduce stimulated emission which amplifies the radiation of certain spectral lines. Not until 1960, long after Einstein's death, was his discovery practically realized in the first laser.

Holography was invented by Gabor in 1947. However, the quality of his images was inferior to that of ordinary photography and therefore there was not much interest in his work, the reason being that no light source then existed with the combined intensity and coherence that was needed. When laser light became available in 1960, Emmett Leith and Juris Upatnieks immediately applied it to holography, which they had reinvented and developed. Their experiments resulted in excellent 3-D images that astonished the world. Gabor, who by now was working in different fields, was presented the Nobel prize in 1971.

By a combination of Einstein's prediction of stimulated emission of radiation and Gabor's prediction of holography it has now been possible to fulfill Einstein's dream to see light in flight. The discoverer of this method believes that it will not only have the evident pedagogical and scientific merit in that it visualizes the dynamics of optical phenomena, but it could also be used to directly demonstrate some relativistic effects such as the apparent rotation and distortion of objects traveling at a speed close to that of light. Thus the research results of Einstein and Gabor once again intersect.

Light-in-flight recording using two-photon fluorescence[2] or ultrafast Kerr cells driven by laser pulses has been possible for some 10 years.[3] Very fast optical phenomena such as refractive-index changes in laser-

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produced plasmas have been recorded by holography using short illumination pulses.[4] However, it appears that the inherent properties of holography have never been used directly to produce a frameless motion picture of ultrafast phenomena such as light in flight. The possibility of such experiments was noted as early as 1972 in a paper describing the properties of the holodiagram[5]: One important fact that for some strange reason has not aroused the interest it deserves is that holography using a pulsed light source (or a continuous-wave light source with limited coherence length) represents a method of *gated viewing.* The hologram plate is only sensitive to information when it is illuminated by the reference beam. Thus, for example, a picosecond reference beam pulse corresponds to an extremely fast shutter, and if the reference pulse illuminated the hologram plate in an oblique angle, it should even be possible to produce a picosecond movie.

This new light-in-flight method came to mind when I was using the holodiagram to sort possible systems for optical measurements. It was like putting the methods into boxes with different labels. Some of the boxes remained empty and one of those empty boxes had been labeled gated viewing by holography.

At that time no lasers existed that were practical to use for this purpose, but I presented the method along with a number of other ideas in a sort of desperation because I feared that I would not be able to go on with my research and realize my ideas. I was able to continue my work but concentrated on sandwich holography instead because it appeared to have more direct practical uses.

When almost ten years had elapsed without anybody reacting to my remark in Ref. 5, I made a simple demonstration which was published in 1978 in *Optics Letters.*[1] The interest aroused by this preliminary experiment was greater than expected so that, after finishing my book on holography,[6] I am now determined to prove the great possibilities of using the hologram as a high-speed movie camera. This method opens a door into the new field of dynamic optics.

II. Basic Idea

In a hologram only those parts of an object will be recorded for which the path length from the laser to the holographic plate via the object does not differ from the path length of the reference beam by more than the temporal coherence length of the laser light used for the recording. If the coherence length is short, a large object will be seen during reconstruction intersected by one bright fringe of near-zero path length difference. This fringe represents the object intersected by an imaginary interference surface[6] in the form of an ellipsoid, one of its two foci being the point from which the spherical wave fronts of illumination are emitted (spatial filter A in Fig. 1) and the other focus being the point on the holographic plate used for the observation (B). Thus, to each point on the plate a corresponding ellipsoid exists in the image space representing zero path length difference between object and reference beams.

When the point of observation is moved along the holographic plate at random, the bright fringe of zero path length will move around on the object. However, the same point on the object will be within the bright fringe all the time if the point of observation (B) is moved along the intersection of the plate and a hyperboloid, its two foci being the studied point at the object (C) and the point source (A) of the reference beam or its mirror image. Thus, to each point on the object a corresponding hyperboloid exists in the space of the observation representing zero path length difference between reference and object beams. The motion, parallax, and apparent localization of the bright fringe of zero path length differences differ totally from those of ordinary holographic interference fringes which are not influenced by the angle or divergence of the reference beam.

By careful planning it is possible to optimize the geometry of the holographic setup in such a way that the utilized parts of the ellipsoids and the hyperboloids can be approximated into flat surfaces. In that case, the object is seen intersected by one flat imaginary interference surface, the depth position of which can be altered during reconstruction by changing the point of observation at the hologram plate.

Thus the light of short pulse duration or short coherence length can be used in a new holographic method for contouring. If, however, the 3-D shape of the object is known *a priori*, this new method could be used to study the shape of the imaginary interference surfaces. If the distance between object and hologram plate is long and if the object is a flat surface perpendicular to the line of sight, the intersections of the ellipsoids can be approximated into intersections of spherical wave fronts of illumination.

Thus light of short pulse duration or short coherence length can be used to study the shape of wave fronts by recording a cross section of the light in flight. By moving the point of observation so that it crosses a number of hyperboloids, it is possible to study the object at different time situations; by moving the observation continuously, it is possible to study the light in flight as a continuous high-speed motion picture. This type of holography could be compared to gated viewing, where the gating effect is caused by the fact that only light beams of the same path length will recognize one another and interfere with one another to produce the image carrying primary fringes on the holographic plate. As the inclined reference beam travels along the plate, this gating effect accompanies it, so that one side will react to younger object light rather than the other.

The relation between space and time is represented in object space (Fig. 1) by separation of the ellipsoids (d_{ell}), while the corresponding relation in the observation space is represented by separation of the hyperboloids (d_{hyp}) in the following way: $d_{\mathrm{ell}} = k \times 0.5c$, $d_{\mathrm{hyp}} = k^* \times 0.5c$, where k and k^* are constants from the holodiagram[5] ($k = 1/\cos\alpha$, $k^* = 1/\sin\beta$), where 2α is the angle between point of illumination and point of observation as seen from the studied object point (thus 2α

$= OCB$), 2β is the angle between object beam and reference beam at the hologram plate (thus $2\beta = CBD$), and c is the speed of light.

III. Light Reflected by a Mirror

A. Holographic Setup

In our experiment an opaque, white-painted, diffusely reflecting flat surface (O) was illuminated from the left at an oblique angle (Fig. 1). The path length of the object beam traveling from the spatial filter (A) in front of the laser (L) to the middle (B) of the hologram plate (H) via the middle (C) of the object surface (O) was equal to the path length of the reference beam traveling from the laser to the middle of the hologram plate via two mirrors (D and E). The plate was illuminated from the left at an oblique angle by the reference beam. Thus the left part of the hologram plate was sensitive during recording only to young object light, the age of the light being, e.g., the time of flight from the laser. The difference in age of the light recorded on the hologram plate was of the order of 800 psec.

A conventional Spectra-Physics model 170-03 ion laser was used as the light source, the coherence length of which was shortened by taking out the etalon while leaving the prism for wavelength selection in place. All strong wavelengths were tested and gave almost identical results. The object area was $\sim 1 \times 1$ m, and the exposure time was 12 sec with an output power of 2 W. The recording medium was a conventional Agfa-Gevaert Holotest 8E56 with an area of 30.3×25.4 cm. The object beam was slightly stronger than the reference beam.

Light that originates from a laser (without etalon) with a cavity length exceeding 10 cm contains a number of separate bands of frequencies (axial modes). When these different frequencies are mixed, a beating effect results, in that the light becomes intensity modulated.[6] Looking at the coherence phenomenon in this way, it is clear that the image-forming fringes on the holographic plate can only form when the object and reference beams illuminate the same place on the plate at the same time. The fringe cannot, of course, form if the path length difference is such that one component of the light has maximum intensity while the other is completely dark.

Figure 2 is a drawing of the object surface (O) with an inclined mirror (M) attached and illuminated by the divergent beam from the laser (L). The expected shape of the wave front (W_m) partly reflected by the mirror (W_r) is indicated.

Figures 3(a)–(e) are photographs taken during the reconstruction of one single hologram plate. The total difference in age of the recorded light is of the order of 800 psec. The four photographs were taken with the camera lens close to the plate and with the camera moving from left to right between each exposure so that the time lapse between them corresponds to $\sim$200 psec. In Fig. 3(a) the spherical wave front, several meters to the right of the laser, is moving across the flat, diffuse object surface. The wave front has just reached the lower-left part of the plane mirror attached perpendicular to the object surface with its normal inclined 40° to the horizontal line. Figure 3(b) shows how the wave front has reached the middle of the mirror and how the light is beginning to be reflected upward and slightly to the left. In Fig. 3(c) the wave front has just passed the mirror and all the reflected light is leaving. In Fig. 3(d) the two parts of the light front have separated completely, the reflected light leaving a hole in the main wave front.

B. Analogies Between Coherence and Pulse Length

There is no doubt that a short pulse of light is analogous with short coherence length light. By definition no predetermined phase relation exists, either in space or time, outside the coherence length. Thus no observable interference phenomena exist outside the coherence length where the phase varies totally at random. No observable interference effects can exist outside the pulse length where no phase can be defined as no light exists.

It is not obvious that the opposite statement is true, that a short coherence length is analogous with a short pulse of light. However, that is the case as long as interference effects are studied. A light source of short coherence length produces short trains of light waves. The light is coherent within each train but the phase is random in space and time between different trains. Thus this light behaves as if it had been made up of short, independent light pulses. Every light train produces observable interference effects only with in itself and behaves as if the others did not exist. As holography is an interference process (the object and reference beams interfere at the hologram plate) the holographic image behaves analogously whether the illuminating light is of short pulse duration or of short coherence length.

So far we have only discussed light of short coherence length in a general way. The limited coherence length of the light from, e.g., a simple He–Ne laser, is not at all as random as that from an ordinary incandescent lamp. A He–Ne laser emits light of many different frequencies, all with a wavelength that lies within the Doppler-broadened spectral line and at the same time fulfills the condition that the cavity length is an integral multiple of that wavelength.

A laser $\sim$30 cm long produces about five different wavelengths all of which fulfill these two conditions. Therefore the light is a mixture of the corresponding five frequencies, the differences of which all have one constant value. Thus a beat frequency is produced, which means that the light is pulsed at a high frequency. The length of the pulses produced by the beating between the most different frequencies determines the coherence length. Therefore one can say that the coherence and pulse lengths are not only analogous but in this case are also identical. For these reasons we are convinced that our argon laser without its etalon that produced 30-mm coherent light would behave just as if it produced a train of pulses with a time duration of $\sim$100 psec.

C. Practical Considerations

The experiment described was made directly on the concrete floor of a basement in an apartment house in Stockholm. As no short-pulse duration laser was available we used one with short coherence length as described earlier.

The spherical sheet of light we were going to study was ~30 mm thick. To be able to see its curvature as it intersected a flat screen, the screen had to be large. It also had to be rigid as the exposure time would be ~5 sec and the sensitivity to unwanted motion would be the same as for ordinary holography. Thus we decided to use an ordinary white-painted door as the screen. When the experiment succeeded I could not resist publishing the statement "I hope this experiment will open a door into a new field of research."

The door as well as the whole holographic setup is seen in Fig. 4. A holographic recording of the door, made when the argon laser was equipped with the etalon so that it produced light with a coherence length of several meters, is seen in Fig. 5. Thus Figs. 3 and 5 show identical situations, the difference being the coherence length of the laser light.

IV. Light Focused by a Lens

A. Experimental Conditions

My first experiment was made in Sweden using an argon laser with short coherence length. Even this primitive equipment produced, as described, results that were superior to everything published before in the field of recording light in flight. In spite of the similarities between light of short coherence length and that of short pulse length, I wished to use light that consisted without any doubt of one single picosecond pulse. To produce such a pulse with energy enough to expose my holographic scenery I needed a very powerful ruby laser. Such lasers exist but not yet commercially, and none was available for my experiment. Thus I decided instead to use a mode-locked dye laser that produced a train of picosecond pulses.

Spectra-Physics, Inc., kindly arranged for me to use their laboratory and equipment. Their picosecond laser and one researcher, Eric Marason, were at my disposal for one week. The light source was a mode-locked argon laser (model 171) which pumped a dye laser (model 375) placed in a cavity of the same length as that of the argon laser. The whole setup was referred to as a synchronously pumped mode-locked dye laser. When used to expose our holograms it produced pulses of ~10 psec (3 mm long) separated by twice the cavity length or ~2 m. For the holographic setup we needed additional equipment which was kindly lent by Joseph Goodman of Stanford University. The experiment at Spectra-Physics had to be finished in a week. Since I ran into problems that might be typical for those who want to repeat my experiments, I will explain in some detail how the work proceeded.

During the first day (Monday) all the holograms failed because the plates became too dark. The plates were seven years old [a bunch of Agfa-Gevaert 8 E 70 8 × 10″ kindly given to me by the Institute of Optical Research in Stockholm] and the developer was new to me (Kodak D19). Therefore it took some time for me to realize that the reason for overexposure was stray light from the laser, probably mostly ultraviolet. After we covered all the open parts of the laser and the cavities of the argon and dye lasers, the plates did not become black any more. Instead we had to spend all day Tuesday trying to get light energy enough to expose the plates.

On Wednesday the plates were exposed just right but there was no hologram. I began to despair because some experienced holographers had told me it would not be possible to make holograms using picosecond pulses.

On Thursday I thought the best thing would be to test the setup by making an ordinary hologram using a conventional He–Ne laser. When this experiment also failed I used the mirrors of the setup to make a Michelson interferometer. By studying its interference fringes it was found that the vibrations were much too large. The experiment was made on a large Newport air-cushioned hologram table, a device I had never used before. After some adjustments of the air valves the Michelson produced stationary fringes, the holograms made with the He–Ne laser succeeded, and we returned to the original plan using the picosecond laser.

On Friday morning we managed to make the first recordings of light in flight but the quality was extremely low. As we gradually decreased the intensity of the reference beam the quality increased, but we did not get good holograms until the intensity of the reference beam was only a tenth of that of the object beam. The quality became extremely good and the contrast just as high as that of any ordinary hologram.

B. Results

From earlier experiments I knew that for light-in-flight recordings the ratio between reference and object beams should be much lower than that of ordinary holograms (ten to one); that it should be as low as about one to ten was a surprise. One rather obvious theory was that, as only a thin line of light is recorded, only that light should be taken into account when the intensity of the object beam is measured. That light was about one hundredth of the total object light which could explain the result. The object light that arrived at the plate at those moments when it was not simultaneously illuminated by the reference beam had no influence on the recording of the hologram; it simply worked as an added incoherent illumination that darkened the plate. But could not the same be said about the reference light?

However, another theory seemed just as possible: that the beam ratio should be the same in light-in-flight recording as in ordinary holography. If we make a holographic recording of the whole screen, the thin line of the pulse front is also recorded with sharp detail and good contrast. Why should this recording deteriorate just because the rest of the screen is eliminated from the image and only that line is left? The only explanation I can find is that the rest of the screen in the first case

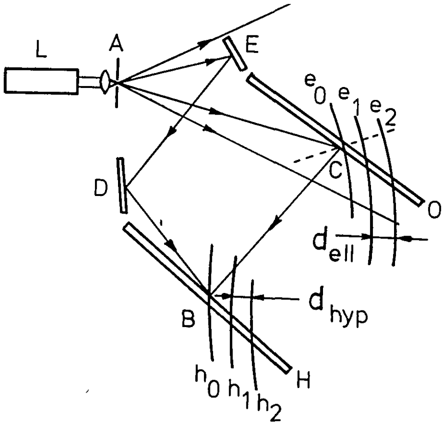


Fig. 1. L, laser; A, spatial filter; O, object; C, observed point; H, hologram plate; B, point of observation; and D and E, two mirrors. e_0, e_1 and e_2 are portions of ellipsoids perpendicular to the bisector of ACB. while h_0, h_1 and h_2 are portions of hyperboloids parallel to the bisector of CBD. From the intersection of H by h_0, only those parts on O are seen that represent its intersection by e_0, because the pathlength ACB is equal to AEDB.

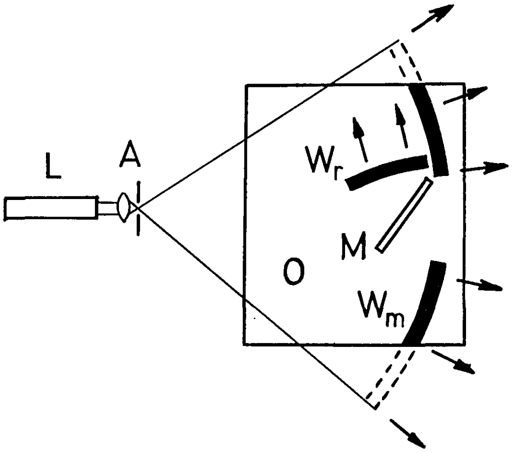
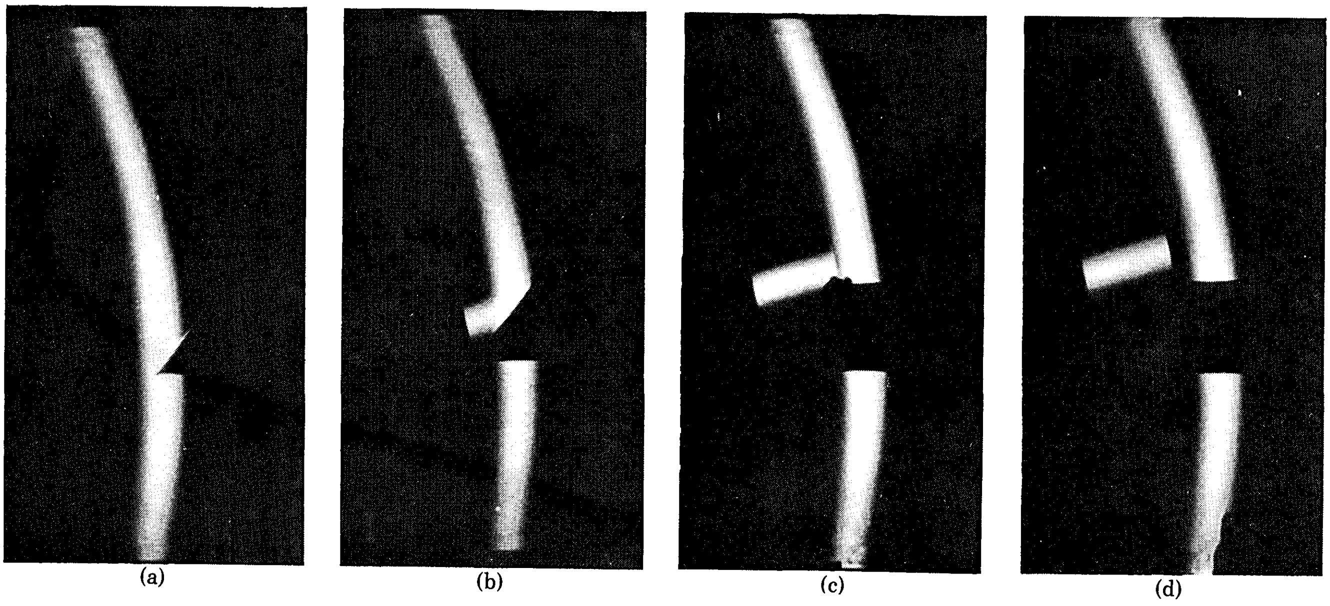


Fig. 2. L, laser; A, spatial filter; O, object surface; M, mirror; W_m, main wavefront; and W_r, reflected wavefront.


(a)
(b)
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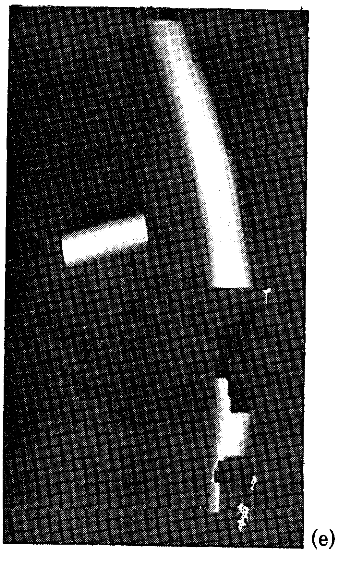

(e)

Fig. 3. (a) A spherical wavefront from an argon laser enters at the left, illuminating a white-painted flat object surface at an oblique angle. The lower left end of a tilted mirror is just reached. (b) The wavefront has reached the middle of the mirror, the normal of which is inclined 40° to the horizontal line. The light is being reflected by the mirror upward and to the left. (c) All the reflected light is separating from the main wavefront which has just passed the mirror. (d) The two components of the light have separated completely, the reflected light leaving a black hole in the spherical wavefront. (e) The main wavefront exits to the right shadowed by some optical components.

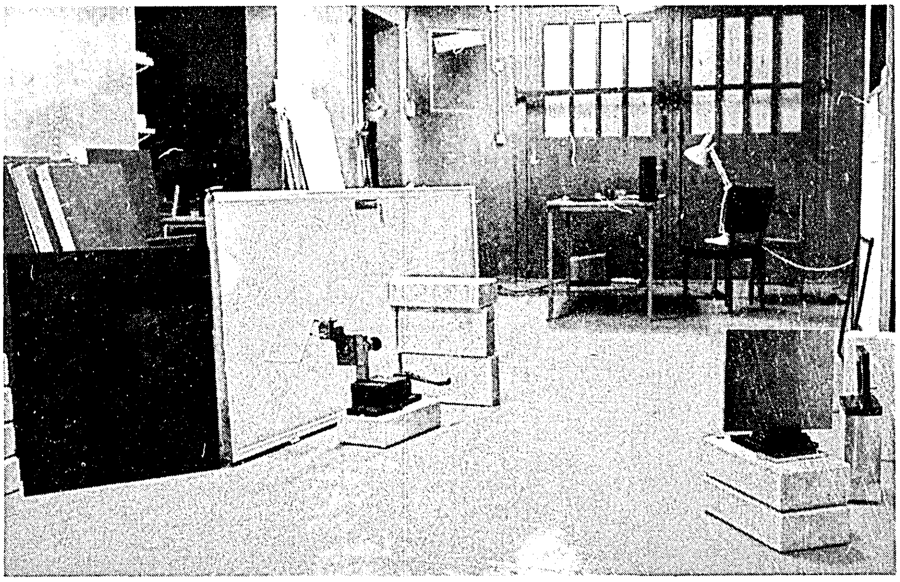


Fig. 4. The experimental set up that produced the photos of Fig. 3 The white-painted object surface (O of Fig. 2) is an old door. It was chosen because it was large enough to reveal the curvature of the 30 mm thick spherical sheet of light. It was also mechanically rigid enough for the five seconds exposure and white-painted to give sufficient scattering of the light. To the door is fixed the mirror (M of Fig. 2). The large square black surface to the left is the reference mirror (E of Fig. 1) while the mirror (D of Fig. 1) and the hologram holder are seen far to the right.

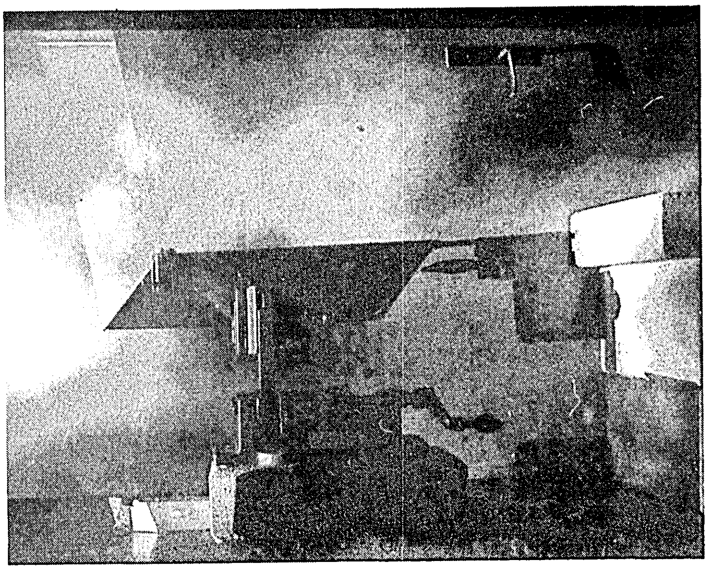
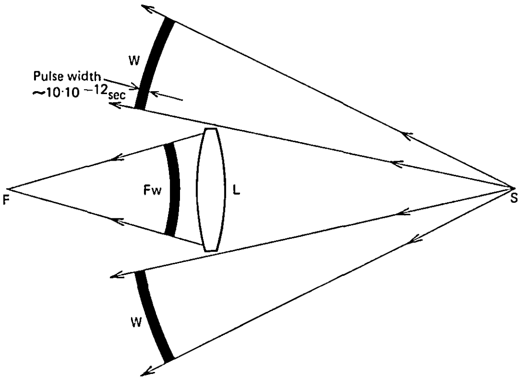
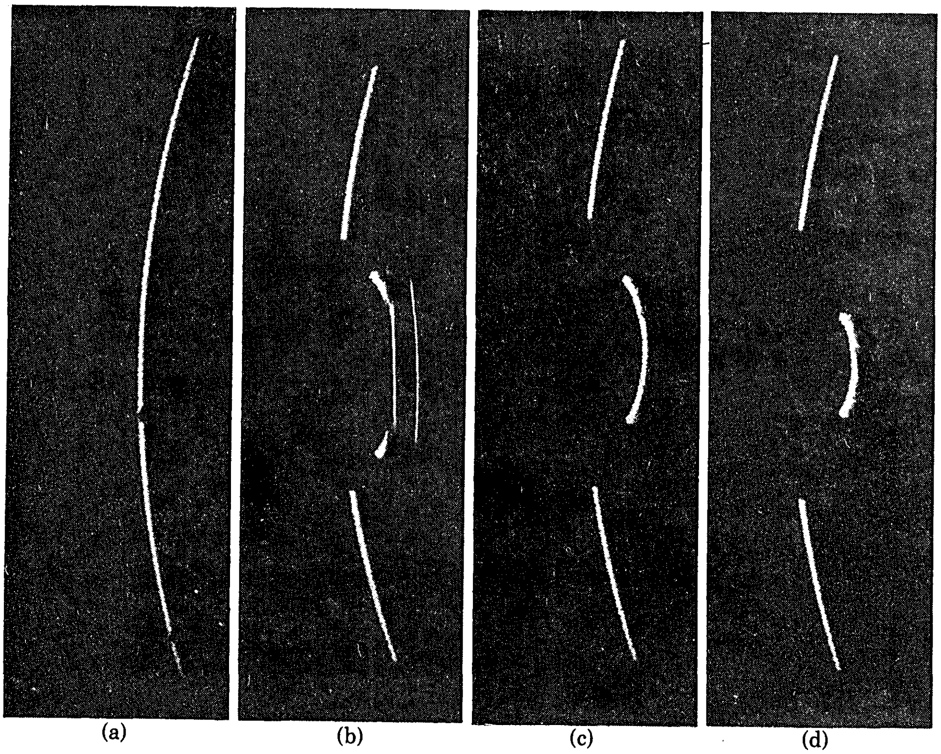


Fig. 5. The door with its mirror as holographed with continuous laser light of long coherence length. The difference as compared to Fig. 3 is certainly very striking.



S = Light source
L = Lens
Fw = Focused wave front
W = Main wave front
F = Focal point

Fig. 6. A diagram showing what is to be expected when a spherical wavefront (W) emanating from the point source (S) is focused by the lens (L) towards the focal point (F). Light moves slower through glass than air, therefore the wavefront that has passed through the lens (Fw) is delayed. As the lens is thickest in its middle the originally convex wavefront is transformed into a concave one.


(a) (b) (c) (d)

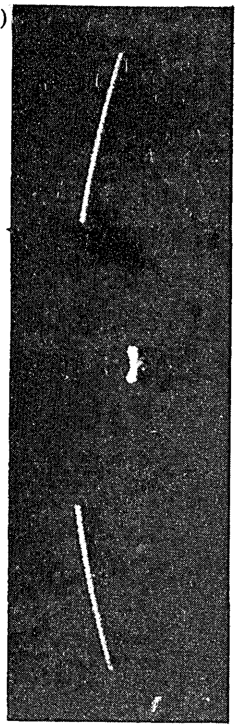

(e)

Fig. 7. (a) The practical result of the experiment described in Fig. 6. A three millimeter (10 picoseconds light pulse) thick pulsefront representing the spherical wavefront travels from right to left. It sweeps almost parallel to the observation screen and has not yet reached the cylindrical lens. (b) The wavefront has just partly passed through the lens (which is not seen in the photo). Only the top and bottom parts of Fw (Fig. 6) have yet reached out of the glass. (c) The light has left the lens and is focused towards the focal point. Observe the resemblens to the diagram of Fig. 6. (d) The length and the radius of curvature of the wavefront are decreasing as it travels away from the lens. (e) This exposure is made just before the wavefront has reached the focal point.

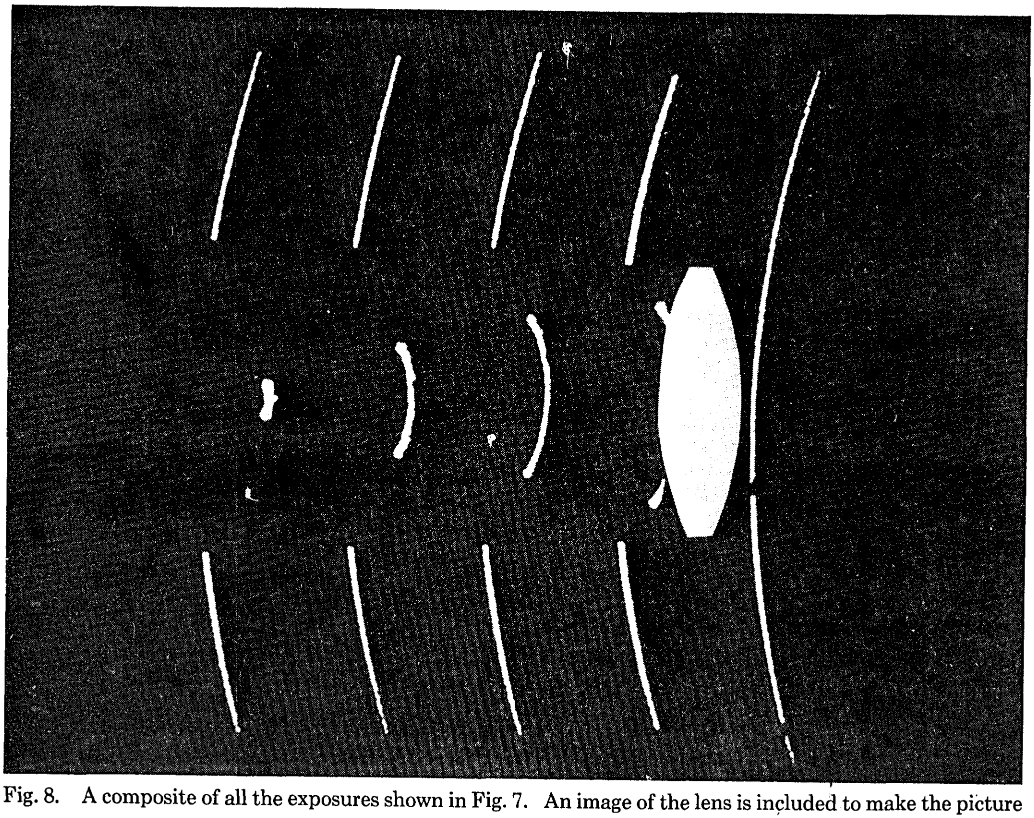


Fig. 8. A composite of all the exposures shown in Fig. 7. An image of the lens is included to make the picture more clear.

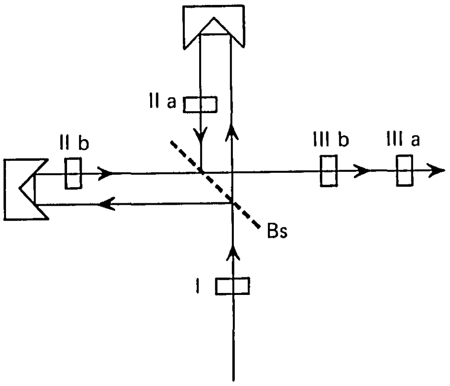


Fig. 9. Light of short coherence length, representing a pulse length of some 100 picoseconds, enters the Michelson interferometer at I. The beam-splitter (Bs) divides the single pulse into two pulses (IIa and IIb). The two pulses travel different pathlengths and thus they will be time separated after recombination (IIIa and IIIb). The prisms at the ends of the two interferometer arms were in the final experiment substituted by mirrors.

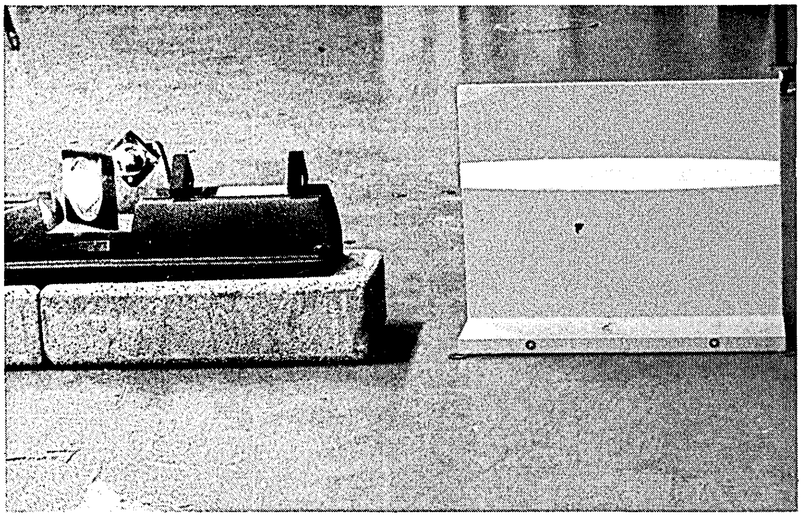


Fig. 10. The Michelson interferometer of Fig. 9 is seen to the left while the obliquely illuminated observation screen (O of Fig. 1) is seen to the right. The bright band on the screen is the continuous collimated light from the interferometer as it looks in an ordinary photograph.

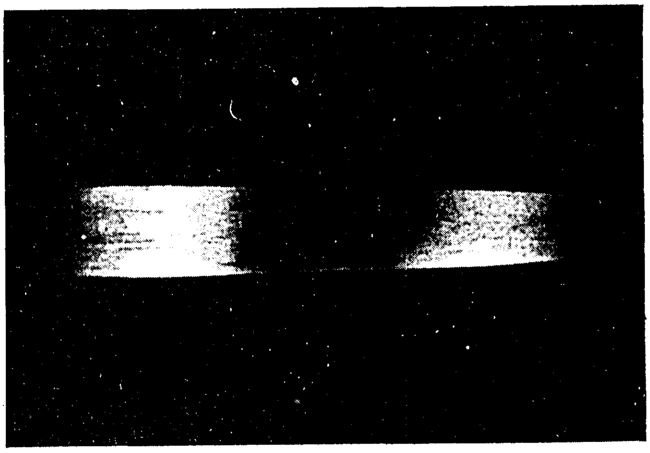


Fig. 11. The single pulse entering the interferometer is divided into two pulses that are so separated in time that they do not reach each other (they are mutually incoherent). Thus no fringes are seen either in a static or a dynamic observation.

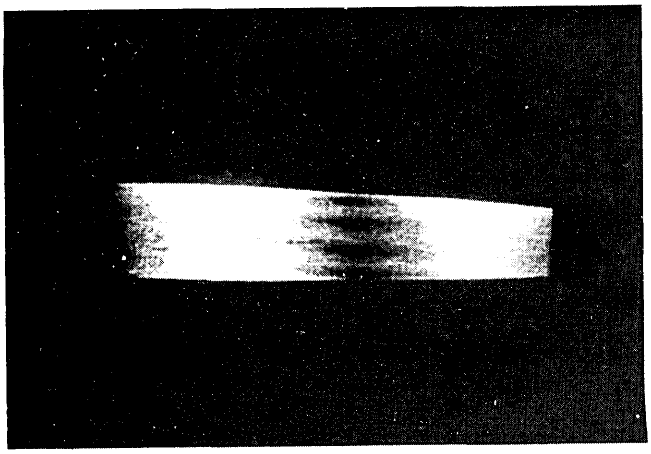


Fig. 12. The two pulses are just touching each other. As they travel with the speed of light from left to right the weak fringes in the center of the composite pulse are drowned by the bright zones in its front and back parts. Thus no fringes are seen in a static observation (the two light components are mutually incoherent). Still they are easily detected in this dynamic observation.

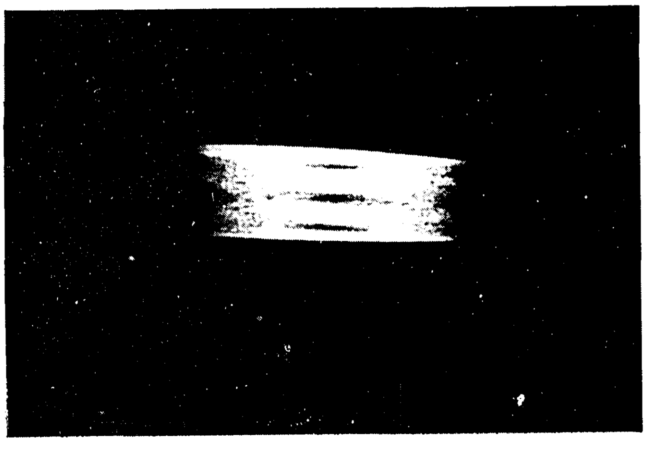


Fig. 13. The two pulses cover each other to about fifty percent. The fringes in the center are of high contrast in this dynamic observation. As the pulses pass by from left to right the time-averaging effect almost conceals the interference fringes so that they become very weak and difficult to distinguish when ordinary static observation is used. Thus one concludes that the two pulses are almost out of coherence.

also produces a sort of a reference beam for the total hologram. Whatever is the explanation the experiment works very well with a weak reference beam, and the darkening of the plate caused by the noninterfering object beam produces no apparent negative influence on the image quality.

During Friday afternoon everything worked perfectly and all the plates recorded excellent holograms. This result was indeed fortunate as the laboratory closed at 5 p.m. and I had to leave the U.S.A. on Saturday.

Some examples of the recording of a short light pulse that passes through a positive lens are seen in Figs. 6 and 7. The diagram of Fig. 6 shows the expected result of the experiment. The spherical wave expands from the point source (S) and moves to the left. The curved line (W) represents the spherical wave front intersected by the flat observation screen—not a door in this case but a white-painted plate of aluminum ~20 × 30 cm. A cylindrical lens (L) is fixed with its axis normal to the screen so that it focuses the light which arrives almost parallel to the screen surface.

As light travels slower through glass than through air the light that has passed through the lens (Fw) will be delayed compared to the original wave front (W); the lens being thickest at its center the light that passed through this part was delayed the most. Thus the originally convex wave front was transformed into a concave shape. As the wave travels perpendicular to its wave front the concave shape means that the light is traveling toward the focal point (F) which is in the center of the curved line.

The photographs of Fig. 7 show how extremely well the experiment verified the expected results. Pictures taken at earlier moments (photographed further to the right through the hologram plate) and at later moments (photographed further to the left) clearly show the focusing effect of the lens. Figure 7(a) is made just before the spherical pulse front enters the lens. Figure 7(b) shows how the light waves have left the lens at its thinnest parts while they are still inside the center of the lens. Figure 7(c) shows the situation when it is most like that of Fig. 6, while Figs. 7(d) and (e) show the light moving toward the focal point. Figure 8 is a composite of all the photographs with an image of the lens added to make the picture clearer.

This demonstrates how the wave front (Fw) travels toward the focal point (F) at the same time as its arc becomes shorter and its radius of curvature decreases. In future experiments it would be interesting to study in detail what happens at the focal point. Does the radius of curvature increase again before that point and go to infinity before the curvature changes its sign?

V. Michelson Interferometer

The experiments described so far have demonstrated the dynamic behavior of a light pulse reflected by a mirror or focused by a lens. In the following we shall show some preliminary experimental studies of interference.

What we usually see in an interferometer is a more or less static image, a sort of time average of the interference phenomenon. This statement is true even when the interferometer is used to study vibrations and other movements that from a mechanical point of view are very fast. Compared to the speed of light and the frequency of the light waves, however, such mechanical movements are approximately stationary. Thus let us use our new methods to study conventional interferometry with a time resolution corresponding to a few millimeters travel of the light waves. The experimental setup is seen in Fig. 9.

A. Two Pulses that do not Reach Each Other

For these experiments we used the analogy between light of short coherence length and that of short pulse length, as described in Sec. IV and demonstrated by photographs in Secs. III and VI.

The interferometer of Figs. 9 and 10 was first adjusted so that the path length of one arm was much longer than that of the other. One of the mirrors was slightly tilted in such a way that a few interference fringes should form. Using ordinary static observation no fringes were seen (Fig. 10), and the simplest interpretation of this fact was that the coherence length of the laser light was shorter than the difference in path length via the two arms of the interferometer.

Using the dynamic observation (Fig. 11) it was, however, clearly seen that the single entering light pulse was divided into two departing pulses by the interferometer. The distance in time between the departing pulses (*IIIa* and *IIIb* in Fig. 9) depends on the difference in the time it took for the pulses to pass the two different arms. Thus the distance between the pulses is equal to the difference in path length, and the photograph in Fig. 11 could be used to measure the position of one of the mirrors of the interferometer in relation to the other.

Looking at Figs. 9 and 11 it is easy to understand why no interference fringes are seen when static observation is used. The two pulses arriving at different points in time do not reach each other and cannot interfere.

B. Two Pulses that Touch Each Other

One of the mirrors of the interferometer (Fig. 9) was moved to decrease the difference in path length. The translation was, however, stopped before any fringes could be seen directly. Using dynamic observation, however, it was clearly seen that the two pulses now arrived so close in time that the trailing edge of the first one just slightly overlapped the leading edge of the second one (Fig. 12). In the area where the two pulses overlap some interference fringes were seen.

One of the mirrors of the interferometer was moved until weak interference fringes just began to appear when the outgoing light was observed in the conventional static way. The simplest interpretation of the weak interference fringes was that the difference in path length had now decreased so that it was just slightly shorter than the coherence length of the laser light.

Studying Fig. 13 it is easy to understand that the low fringe contrast when conventional static observation was used is not caused by the fringes themselves. The explanation is that the fringes (at a certain fixed point in space) exist for such a short time compared with the time of the fringe-free light. When the pulse of Fig. 13 sweeps by with the speed of light, the dark fringes in its middle are drowned by the light in its first and last parts. In the area where the two pulses overlap very sharp interference fringes were seen. The contrast of these fringes was as high as if the path length difference had been zero.

Thus conventional static observation produces some sort of time-average fringes, while dynamic observation can be used to separate the interference fringes from stray light caused by fringe-free light existing at other points in time. The moire analogy to Fig. 13 is seen in Fig. 14. Finally one of the mirrors of the interferometer was adjusted so that the interference fringes became as sharp and rich in contrast as possible. The obvious interpretation of this optimization was that, in this situation, the two path lengths of the interferometer were close to zero.

Using dynamic observation it was clearly seen that the two pulses covered each other completely and that the combined pulse was covered by interference fringes along its total length (Fig. 15). This fact thus proved the assumption that the difference in path length was close to zero.

C. Pulse Forming

Let us now look at Fig. 13 (or the moire analogy of Fig. 14); observe the area where the two pulses overlap. Dark horizontal interference fringes have formed in the middle of the complex pulse. If we study a horizontal intersection along a bright interference fringe we see that the entering pulse has transformed into an outgoing pulse almost double the original length. This experiment demonstrates that there has been an elongation of the pulse or an elongation of the coherence length of the light.

Let us now return to Fig. 13, but this time we shall study a horizontal intersection along a dark interference fringe. In this case we see that the entering pulse has split into two outgoing pulses of shorter length separated by the original pulse length. The shortening of the pulse is caused by destructive interference in the area where the two pulses overlap. Thus it is possible with this method from one single entering pulse to produce two outgoing pulses that are much shorter than the original pulse. In this way it should be possible to produce extremely short pulses, e.g., of the order of 0.01 psec.

Figure 16 shows diagrammatically what happens when two pulses interfere destructively. The original pulse entering the interferometer (Fig. 10) is split into two pulses that pass through its two arms. The difference in path length results in that the two outgoing pulses arrive at slightly different points in time. Further on, the interferometer is so adjusted that the two pulses are 180° out of phase, which in Fig. 16 is indicated by drawing one pulse negative in relation to the other. Destructive interference occurs where the two pulses overlap. The light will therefore be extinguished in the middle of the pulse while its front and back parts will remain bright.

What has happened is in fact that the outgoing complex pulse shape represents the derivative of the original pulse, its sharp front and back have caused the two short pulses. For example, let us assume that one single pulse of infinite length enters the interferometer; out will come just one short pulse representing its front.

Pulses can not have edges of unlimited sharpness. A more probable pulse shape is the Gaussion intensity distribution of Fig. 17. A practical result of a laser pulse that has passed the interferometer with different arm lengths is seen in Fig. 18. In this case the mirrors were so adjusted that there was destructive interference through the whole center of the pulse where no fringes formed. The two pulses of Fig. 18 are each about half of the length of the original pulse.

D. Result

An interferometer can be used to produce two pulses out of one or one pulse the length of which is double that of the original (constructive interference). It can also be used to produce two pulses that are shorter than the original separated by its length (destructive interference). In the latter case it can also be used to produce pulses representing the derivative of the original pulse shape.

A short pulse can be divided into two shorter pulses representing the front and back edges of the original pulse. Only the front (or the back) of a pulse of infinite length will pass through the interferometer. Fast variations in light intensity will pass through while continuous light will be stopped. Such a strange situation can occur that a continuous flow of light is always stopped by the interferometer while an interruption in the flow of light will result in a short flash of light leaving the interferometer.

Observing interference fringes dynamically makes it possible to look at the contrast of interference fringes as a time-averaging phenomenon. Doubtless this fact has pedagogical and logical advantages. Dynamic observation stops the light in its flight so that high-contrast sharp fringes are seen where static observation discloses only very weak fringes or even no fringes at all. Finally, dynamic observation makes it possible to observe and measure the difference in path length, something that is not possible when conventional static observation is used.

VI. Fabry-Perot Etalon

A. Thick Plate

"It is extremely dark in this room, the light must have been switched off for a long time." This remark is a well-known joke in Sweden. With the following simple experiment I wanted to demonstrate that such a statement can be based on practical experience.

The experiments described so far were all made with a Michelson interferometer, but they could have been made using a Fabry-Perot interferometer, an etalon, a plane–parallel glass plate, or an antireflection (or reflection) coating. Let us start by studying the reflection from a glass plate that is so thick in comparison to the coherence length (or the pulse length) of the light that the front part of the pulse reflected by the back surface does not reach the back part of the pulse reflected by the front surface.

The experimental setup is seen in Fig. 19 and the result in Fig. 20. A single pulse traveled toward the glass plate, while from the plate a train of pulses is emitted as the original pulse is reflected back and forth between its two surfaces. Three of these pulses are seen in Fig. 20. The pulses are covered by weak interference fringes on their front and back parts indicating that they slightly touch each other. Using ordinary static observation only a constant light is seen without the slightest sign of interference fringes (Fig. 19). The interpretation is that the coherence length (pulse length) was short compared with the path length difference.

Dynamic observation demonstrates that the one single pulse has been transformed into a train of pulses. It also results in interference fringes appearing that before were totally drowned by the brighter fringe-free light as the pulses travel with the speed of light. Figure 20 also discloses that the coherence length of the light has become at least three times longer (if we ignore the disadvantage that it has been interrupted by incoherent areas). Similar methods of lengthening the coherence length were demonstrated by Mottier[7] in 1972 using the white-painted inside walls of a box instead of the mirrors of the etalon.

B. Thin Plate

Finally the experiment was repeated using a thinner glass plate, which resulted in the short pulse being transformed into one single long pulse. The different reflected pulses covered each other in such a way that no interval was seen (Fig. 21). This experiment demonstrates that a short pulse can be lengthened by multiple reflections in an etalon. It also shows how the coherence length of laser light is increased. Thus we find that an etalon can increase the coherence length of laser light, not only if it is placed inside the cavity of the laser but also if it is placed outside—a fact that is philosophically satisfying. The experiment also demonstrates that light can be emitted from an etalon long after it has been switched off, thus proving the statement in the beginning of this section.

VII. Contouring

A. Theoretical Possibilities

As mentioned in Sec. II, light-in-flight recording by holography can also be used for measurement of the 3-D shape of objects. If the wave front (pulse front) of a short pulse is flat, it will produce a thin flat sheet of light. The intersection of this sheet by a 3-D body will on its surface produce a thin line representing a cross section. It is advantageous if this cross section represents a flat surface, which will be the case if illumination and observation are collimated or made from large distances.

Thus light-in-flight recording by holography can be used as a contouring method that differs from other methods (e.g., shadow moire or two-wavelength holography) in that it does not produce a set of fringes but just one single fringe. This has the great disadvantage that one single image represents just one single cross section. However, it has the great advantage that this single cross section can be moved about in depth. By moving the point of observation behind the hologram plate from left to right the intersecting sheet of light can be moved forward or backward. Determination of fringe order number by finding the zero fringe no longer represents any problem as only the one single zero-order fringe exists. Therefore this new way of contouring has great advantages especially when the observation and calculations must be made by computers.

Lasers producing pulses shorter than 1 psec already exist and soon there will be lasers in the 0.3-psec region representing pulse lengths of 0.1 mm. Using heterodynelike methods it should not be a problem to find the center of the contouring line with 10% precision which corresponds to ~10 μm. Using such equipment the 3-D shape of, e.g., a propeller, a turbine blade, or an automobile body could be measured with high accuracy. This way one could say that light-in-flight recording by holography represents a radar method that works in the region of micrometers instead of meters or kilometers like ordinary radar.

B. Practical Results

To demonstrate the possibilities of this new technique we made the following experiment. A stationary propeller from an ordinary fan (Fig. 22) was illuminated by short pulse length laser light (the same mode-locked laser was used as described in Sec. IV.A). The illumination and observation directions were approximately parallel to the shaft of the propeller. The holographic setup is seen in Fig. 23 where, however, the distance between propeller and hologram plate is greatly reduced compared with the real situation.

Reconstruction of the hologram disclosed the propeller intersected by a thin sheet of light the thickness of which was equal to half of the pulse length. The ideal case would be if this intersecting sheet of light had been flat, which would be the case if illumination and observation were collimated or made from infinite distances. In the actual experiment the intersecting surfaces were parts of ellipsoids of the holodiagram, one focal point (A) being the point of illumination, the other (B) the point of observation at the hologram plate. As the object (C) and the separation between A and B were small compared with the distance from C to A and B, the intersecting sheet of light could be approximated into a section of a sphere with almost zero curvature.

For every certain distance from the left of the hologram plate a corresponding cross section in depth exists so that by moving the observation point sideways behind the plate the cross section moves in depth. Three photographs were made from the single reconstructed hologram with the camera in the positions B_1, B_2, and B_3. The corresponding cross sections S_1, S_2, and S_3 are seen in Figs. 24(a), (b), and (d).

Figure 24(a) shows the circular hub of the propeller with its hole for the shaft. Two of the rather unsymmetrical blades are also seen just touched by the light sheet S_1. Figure 24(b) reveals how the hub has passed out of the light into darkness, while instead the central joint of the four blades is intersected. Its out of flatness is easily detectable and measurable. The intersection of the four blades reveals their inclinations and their symmetrical errors. When the intersection is continuously moving past the propeller one gets the impression of a beautiful flower that opens up and starts rotating.

To produce a thin intersection of the object it is important that the observation aperture be small (at least as small as the pulse length along the plate). To demonstrate this we produced Fig. 25 which is a photograph identical with that of Fig. 24(b) except that the aperture used in the camera is much larger. Figures 24(a)–(d) were all exposed with a camera aperture of 11, while Fig. 25 was made using an aperture of 4. The reason the last photograph produced such broad lines of low contrast is that different parts of the lens observe the object as it was recorded at different points in time when the light sheet reached different depths.

The best way to make the photographs of the reconstructed image is either by photographing the virtual image using a vertical slit aperture at the plate surface or by using the real image, illuminating the plate by a laser beam which is preferably elongated along a vertical axis. When the virtual image is photographed it is of great importance that the camera lens be close to the hologram plate; if it is not the intersecting plane appears inclined. The reason for this tilt is that different parts of the object are observed through different parts of the plate. Thus they are recorded at different points in time when the light sheet reached different depths. This chance of tilting the intersecting plane by changing the separation between camera and hologram plate can be advantageous during the evaluation when carefully planned.

VIII. Future Developments

A. Focusing Effect

It is of great interest to look closer at the focusing effect of a positive lens or mirror. The radius of curvature of the concave wave front leaving the lens will decrease with distance to the lens surface as the light approaches the focal point. After passing this point the wave front is convex and its radius of curvature will again increase. However, close to the focal point the wave front will pass along a channel where its radius of curvature will either be infinite or indeterminable. It would be of great interest to find out which is the case.

If the radius of curvature becomes infinite it would be interesting to study at which points the two places exist where the radius of curvature has minima. It also would be interesting to compare the focusing effects of an ordinary positive lens (concave wave front) with those of a Fresnel lens (concave pieces of wave fronts). Interesting experiments in this direction have been performed by Bartelt *et al.*[8] They demonstrated that a prism tilts the wave fronts while a grating does not. These experiments were made using a method quite different from light-in-flight recording by holography but which in many ways produces similar results.

The strange phenomenon of light not moving perpendicular to its wave front appears to most people almost impossible by definition. Thus it might be better to use the word pulse front instead of wave front, since pulse front is what we see. The curvatures of the individual wave fronts have not yet been seen, and it might be that the pulse front is not analogous to the wave front when the latter has been chopped by a grating. However, it might also be that they are analogous. The questions that arise when the microscopic and macroscopic shapes of the wave fronts are not identical are discussed in Ref. 6.

B. Pulse Shape

It would be of great value to study the passing of short light pulses through optical fibers. In a leaky fiber the pulses could be seen like trains traveling along the fiber. If there are cracks or other disturbances in the fiber, reflections would be seen as trains moving in opposite directions. Thus the quality of fibers, connections, and switches could be studied.

Pulse broadening could easily be seen that is caused by rays at different angles traveling different path lengths in a multimode fiber. By placing a screen perpendicular to the fiber at its output end the mode pattern could be viewed and the different modes studied by using their separation in time. The result would be similar to that of Ref. 9.

Studies of the pulse shape in the time domain will give higher resolution than any other known method. Thus pulses of extremely short duration could be studied and their variation in time could be measured in different cross sections of the pulse. The pulse studied could be sent into a scattering volume instead of onto a scattering flat screen. In that case not only a cross section of the pulse could be observed but also its total volume, thus producing a sort of 4-D holography where time is one of the dimensions. Pulse broadening, e.g., in fibers, and pulse shaping, e.g., using the interferometric methods of Sec. VIII, can be observed.

It is important to take into account that, if light-in-flight by holography uses the observed pulse both as object pulse and reference pulse, the recorded pulse shape will be the autocorrelation of the observation pulse. If, however, the reference pulse is an original short pulse while the object pulse is that pulse reshaped, e.g., doubled and lengthened, the recording will represent the true shape of the object pulse. If the coherence length of the pulse, however, is shorter than the pulse length, the former instead of the latter will be recorded.

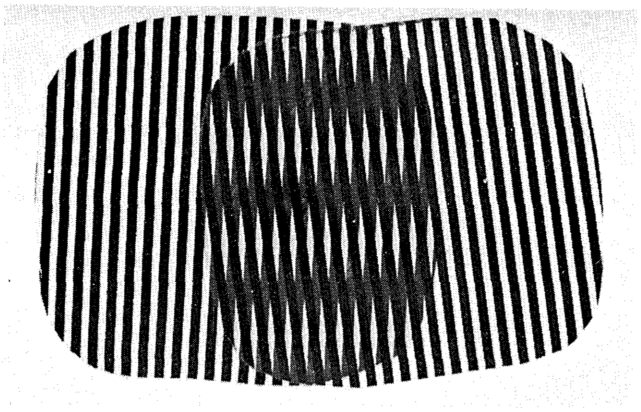


Fig. 14. The moiré analogy to the photograph of Fig. 13. The two pulses travelling from left to right with the speed of light are represented by two sets of almost vertical grids, the lines of which represent the wavefronts. Where the two grids intersect (the back part of the first pulse and the front part of the second pulse) a moiré pattern is formed representing the interference fringes.

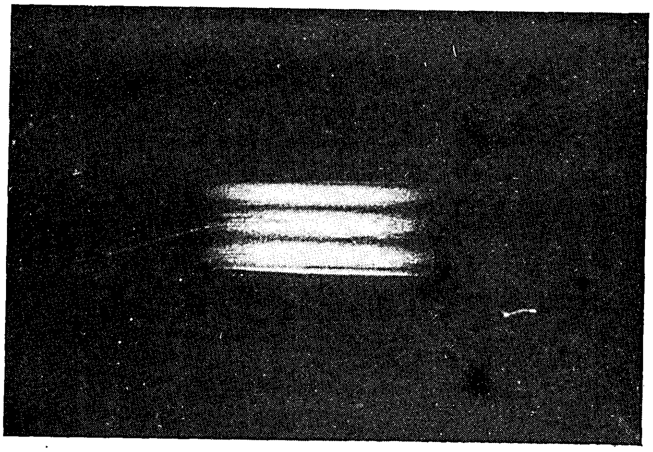


Fig. 15. The two pulses overlap completely because there was no pathlength difference. The fringes are of a high quality both when a dynamic or a static observation is used. Thus the two light components are mutually coherent.

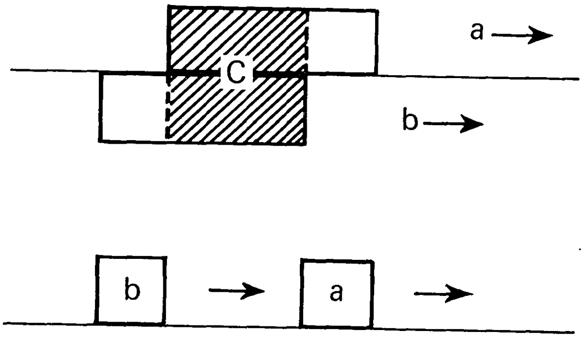


Fig. 16. Pulse (a) and pulse (b) of Fig. 9 are out of phase which is visualized by drawing the intensity of one pulse upwards, the other downwards. Where the two pulses overlap (C) the light is destroyed by destructive interference. Thus, two shorter pulses are formed out of the single original pulse. The separation of the centers of the two pulses is equal to the original pulse length.

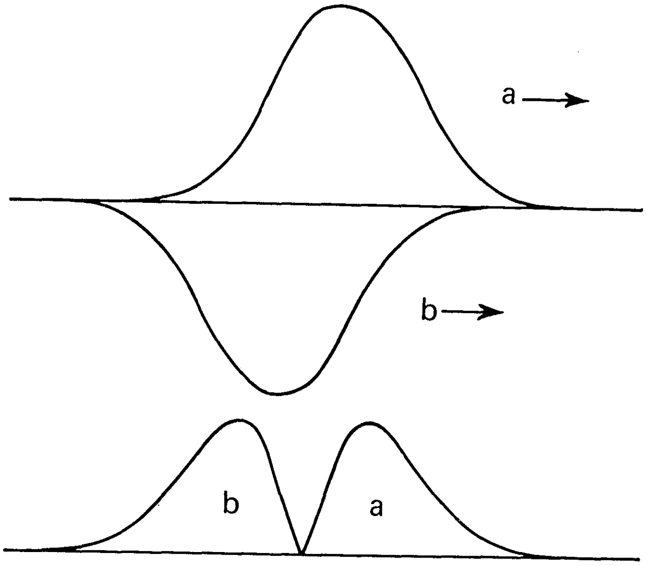


Fig. 17. A short light pulse usually has a Gaussian intensity distribution instead of the square distribution of Fig. 16. The destructive interference of the pulse (a) and its slightly delayed and phaseshifted twin (b) results in two pulses separated by a thin band of darkness.

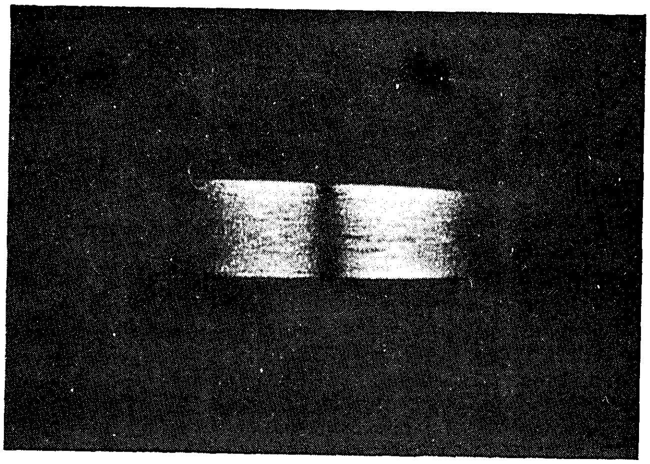


Fig. 18. The practical result of the experiment described in Fig. 17. The two light pulses are each of about half the length of the original pulse while their separation (the distance between their points of maximal intensity) is more than the difference in pathlengths.

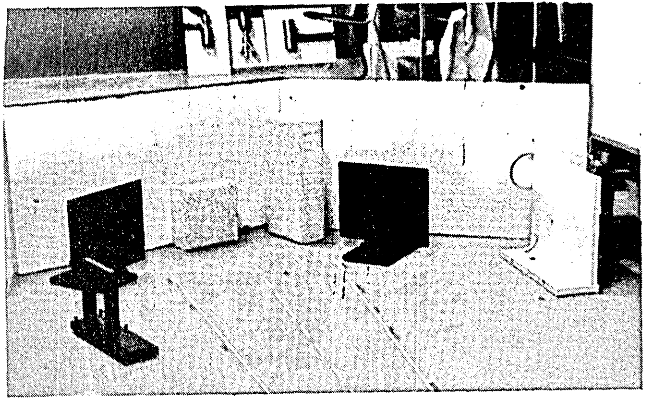


Fig. 19. Experimental set up to demonstrate multiple reflections in a Fabry Perot etalon. The circular etalon is placed at the far end of the observation screen (O of Fig. 1) seen to the right. The horizontal bright band is the studied reflected light. Far to the left is seen the holder of the hologram plate (H of Fig. 1) while the two black square surfaces represent the two mirrors E and D of Fig. 1.

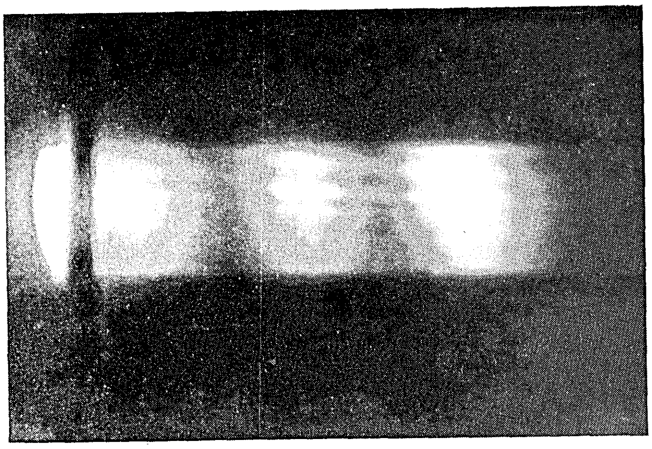


Fig. 20. Three of the reflections from the etalon at left are seen on the observation screen of Fig. 19. One single entering pulse has resulted in that at least three pulses leave the etalon which thus emits light long after being illuminated.

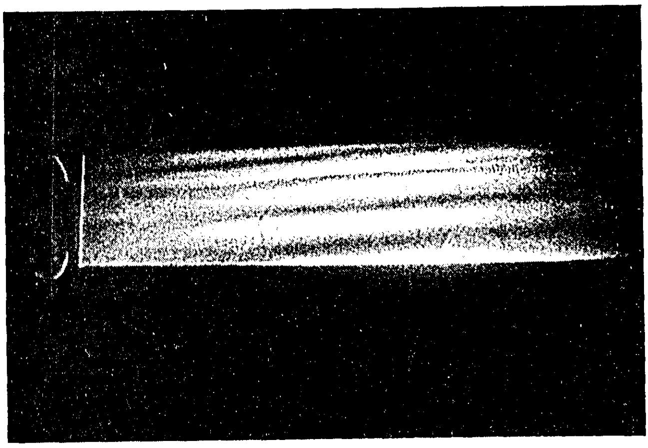


Fig. 21. The different reflected pulses will overlap to produce a continuous light if the spacing of the etalon is shorter than the entering pulse. Fringes are formed by interference of the different reflections. The reflected lightpulse is some four times longer than the entering single pulse. Thus, the etalon can be used to increase the pulse length or the coherence length of light.

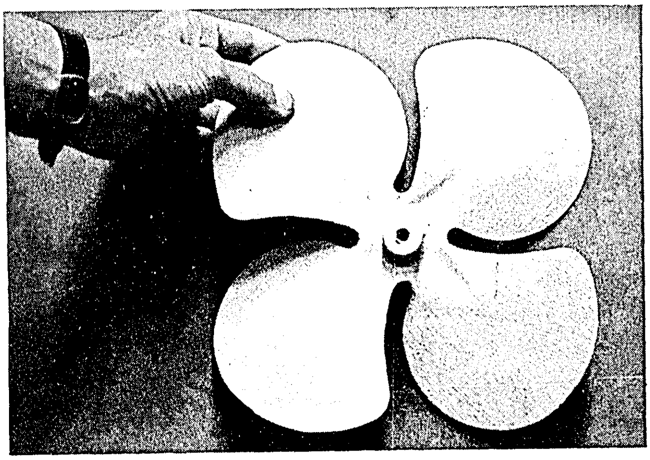


Fig. 22. The propeller of an ordinary fan was used for our contouring experiment. It was made of pressed steel sheet and had become rather deformed and unsymmetric by hard handling. To simplify the recording the propeller was covered by retroreflective paint. During exposure it was, of course, not hand-held, but rigidly fixed.

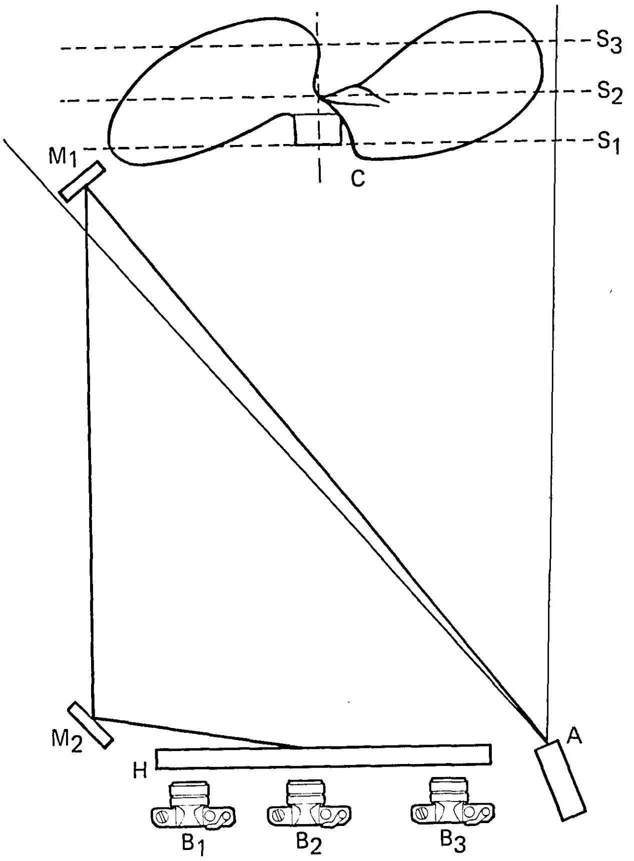
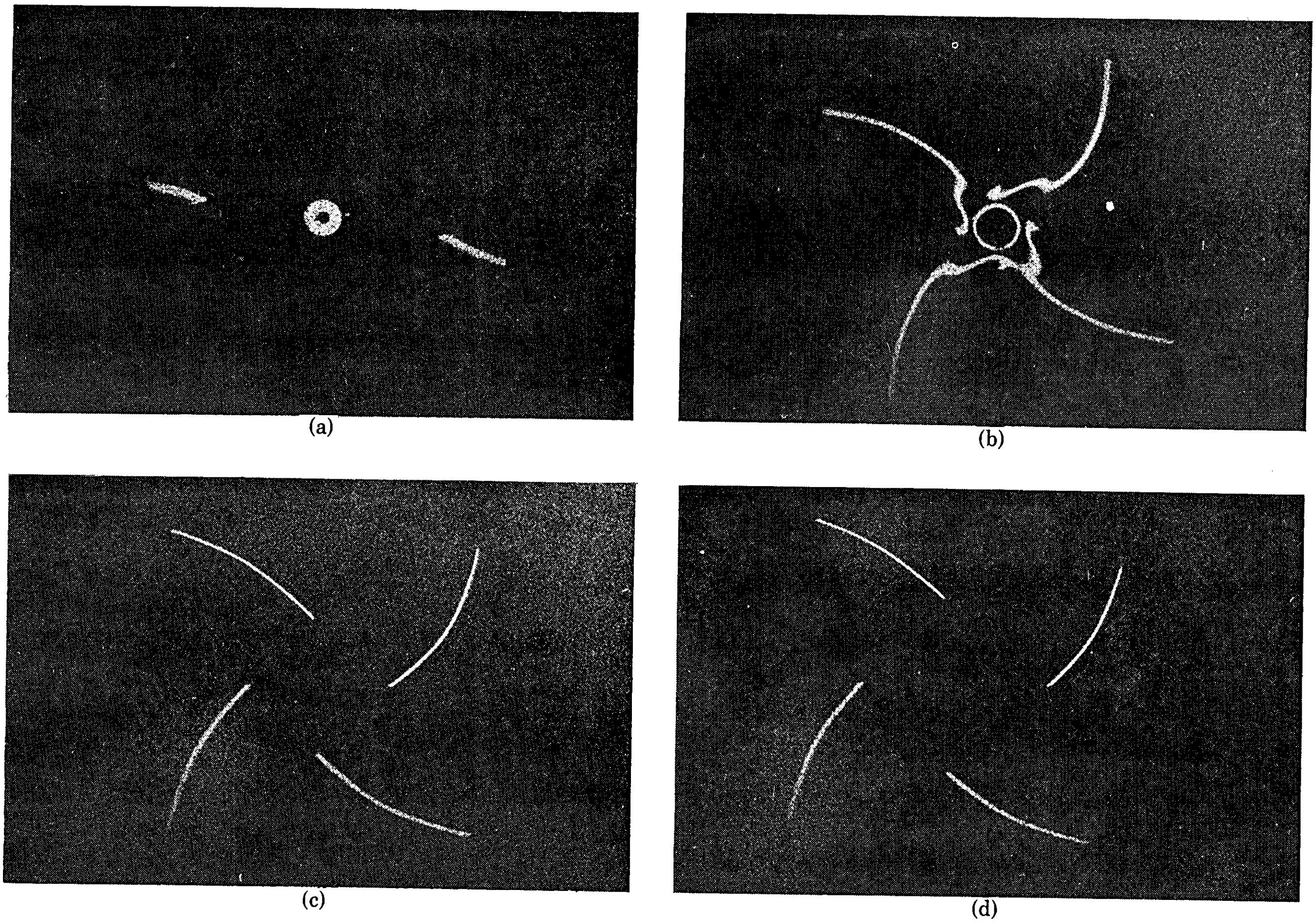


Fig. 23. A schematic view of the holographic set up. The propeller (C) of Fig. 22 is illuminated by the divergent beam from the picosecond laser (A). The reference is reflected by the two mirrors (M_1 and M_2) towards the hologram plate (H). In the actual experiment the distance between H and C was much longer compared to the size of H and C than shown in this drawing.



(a) (b) (c) (d)

Fig. 24. (a) This photo was during reconstruction exposed with the camera positioned at B_1 which corresponds to the crossection S_1 (Fig. 23). The sheet of light has just reached the hub of the propeller and two of its blades. (b) The camera at B_2 of Fig. 23 produced the crossection S_2. The hub has just passed out of the light into darkness while instead the four blades and their central joint are intersected. (c) The light sheet has passed the central joint and crossections of the blades reveal their three-dimensional shape. (d) The intersection S_3 photographed with the camera at B_3 shows how the light sheet has passed further on and soon will leave the propeller altogether.

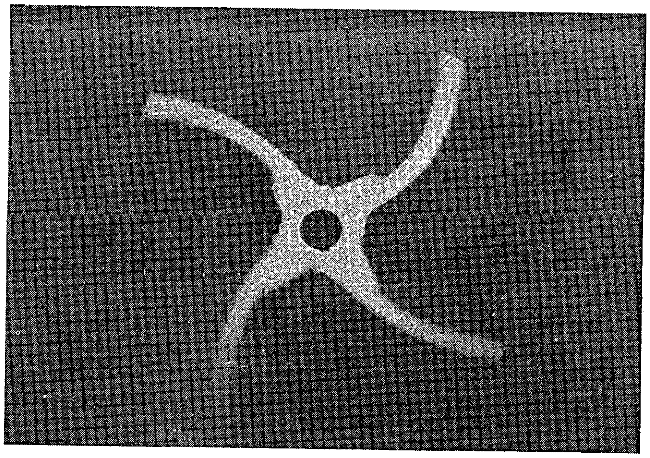


Fig. 25. This photography is identical to that of Fig. 24 b, but with the exception that, when the reconstruction was recorded the aperture of the camera was increased from 11 to 4. In the latter case the lens covered a larger area of the hologram plate, which represents a larger time duration. Thus the originally short illumination pulse (some 3 picoseconds) appears enlarged to about 20 picoseconds.

C. Interaction Between Light and Matter

If one single pulse, e.g., from a ruby laser, is used instead of a train of pulses (as described in Sec. IV), not only optical but also mechanical events can be studied. The first thing to look at could be a laser pulse penetrating a piece of metal. It would be possible to study how a long pulse hits the surface, how its front part is used to make the hole, and how its remaining part passes through. The result will be that a pulse shorter than the original one leaves the pierced metal.

Other mechanical ultrahigh-speed phenomena such as explosions and detonations could also be studied. In such cases the pulse itself is not observed; the laser light is only used to illuminate a mechanical event. Because of inertia, mechanical motions are orders of magnitudes slower than light. It is therefore of interest to make the illumination pulse long to increase the duration of observation, while the reference pulse should be short to increase the time resolution.

The duration of the illumination pulse could be increased using a delay line consisting of diffuse screens or multiple reflections as described in Sec. VI. The duration of the recording could be increased by forcing the reference pulse to spend more time transversing the plate. This could be done by making the plate longer (using some meters of holographic film), by moving the pulse along a zigzag path reflected by mirrors at each side of the plate, or by using several reference pulses with a certain path length difference between each. The velocity of light could also be slowed down by submerging all or parts of the holographic setup in a liquid of high refractive index.

Another experiment that will be of great interest to study in this way is the implosion of deuterium pellets to produce hydrogen power. Six extremely powerful laser beams illuminate the pellet from all directions to heat it to the $\sim 10^8$°C needed to start the fusion reaction. It is important that all the beams hit the target symmetrically and simultaneously; these conditions can be studied with light-in-flight recording by holography. The hologram could either be recorded using a separate light source or the illumination could be by the main heating pulse itself, while the reference pulse could be a part of that same pulse maybe frequency-doubled and shortened, e.g., using the interferometric method of Sec. V.

D. Optical Fibers

The main limitations to the bandwidth of optical fibers are the aberrations in transit time caused by different path lengths for different rays. The rays launched parallel to the fiber have the shortest path length along its central part, while those launched at increasing angles must travel longer paths in a zigzag course. Thus the length of a short pulse that enters the fiber increases during its travel so that it will leave transformed into a longer pulse. To eliminate this pulse broadening the fiber can be given such a small diameter that only one single mode can exist. Another solution is to distribute the refractive index so that the rays that enter at larger angle, and therefore travel farther, pass through material of a lower refractive index which means that its velocity is higher. Thus this higher speed of light can compensate the increased path length so that the end result is that all rays arrive at the same time independent of angle.

We have shown, e.g., in Fig. 7, that light-in-flight recording by holography can be used to study the shape of wave fronts, the delay of pulses, and the length of pulses. In the photography of Fig. 7 the resolution is of the order of a picosecond, but there is no reason not to believe that a hundreth or a thousandth of a picosecond could be resolved in the near future.

For further development of optical fibers it is of great importance to be able to measure the delay and broadening of pulses. Preliminary results studying a 2-m long fiber with the light-in-flight method have proved that wave fronts similar to those of Fig. 7 can be made visible and measurable. The advantage over other methods is its high resolution and that an image is produced that reveals the 3-D distribution of pulse delay and pulse broadening.

E. Relativistic Effects

The relativistic effects are of importance first at speeds approaching that of light. Therefore it is obvious that the light itself (moving with the speed of light) would be an excellent object to study some of Einstein's predictions. However, as light is not made up of matter it might be that it does not follow all the rules of deformation at high speed as ordinary objects are expected to do. Let us discuss some of the relativistic effects and see which could be expected to show up using light itself as the object to be studied.

No speed is higher than that of light in vacuum (c). It would be easy to demonstrate that a rotating light beam can move laterally at a speed higher than c. It also could be proved that interference fringes (or speckles) can move laterally or longitudinally at a speed higher than c. These effects, however, do not at all contradict Einstein who stated that no information can exceed the speed of light. Even if there are no theoretical reasons to expect any contradiction of the speed of light postulate, it would be of importance to have it verified by experiments while being open to surprises.

To study the speed of light in matter would also be interesting, for example, to demonstrate how it depends on refractive-index variations, the velocity of the refracting material, or the polarization in, e.g., a double-refraction crystal. It also would be of great value to study if and how the light velocity depends on the amplifying effect of, e.g., a ruby crystal.

As a result of the Lorentz contraction an object traveling at high speed appears shortened. To explain how the speed of light always appears constant it is, according to Einstein, necessary to accept that measuring rods become shorter in their direction of travel. An object that travels at the speed of light should appear to be of zero thickness. There is not much doubt that this statement is true for material bodies; neither is there any doubt that it is not true for light. If it were true for light pulses, every pulse would appear to be of zero length. Thus there must be a large difference between how material bodies and light pulses appear relativistically. This fact is not surprising as light can reach C while matter cannot; however, one can still expect some geometrical concepts to be identical.

Thus light pulses are not shortened by relativistic effects simply because they do not need to compensate for any apparent difference in the speed of light as they themselves represent that speed. Light pulses, therefore, cannot be used to demonstrate the Lorentz contraction.

An object traveling at relativistic speed will appear rotated. Let us assume a flat surface, say 1 m^2, moving perpendicular to its surface and flying past an observer. The light from the edge that is furthest away will reach the observer slightly later than that from the closest edge. If the object moved with the speed of light, the result would be a delay of the light representing a path length of 1 m. During that time the object has moved 1 m and therefore the closest edge appears to be 1 m in front of the other. The object appears rotated ~45°.

This apparent rotation has already been verified experimentally. It can, for example, be easily observed when side-looking radar is used. In Ref. 3 an experiment was made with two parallel short light pulses in a dispersing medium photographed by a high-speed camera using ultrafast Kerr cells driven by laser pulses. It was clearly seen that the most distant pulse appeared delayed.

There are good reasons to believe that, for the apparent rotation of fast-moving objects, material bodies and light pulses behave in an analogous way. Thus, the fast-moving flat material surface could just as well be interchanged by a flat wave front or pulse front, the motion of which is studied in a dispersing medium, e.g., Plexiglas. As the wave front moves with the speed of light its apparent rotation can easily be studied using the light-in-flight method. The experiment will, however, give more than that. It will also demonstrate that the originally flat surface not only appears rotated, it will also appear deformed in the shape of a rotational symmetric paraboloid, the axis of which will be parallel to the direction of the entering light and the focus of which will be the eye of the observer. The reason is simply that the paraboloid represents the surface of constant path length for light that it scatters from the light source (at infinite distance) to the observer.

If a spherical wave front is studied instead of a flat one, the result will be that it appears deformed into an ellipsoid, one of its focal points being the point source of light (A) the other being the point of observation (B). The reason, of course, is that the shell of the ellipsoid represents the surface of constant path length for the light that it scatters from A to B. Thus, the ellipsoid into which a spherical surface appears deformed as it travels with the speed of light is just one of the ellipsoids of the holodiagram. It is gratifying to find that this holodiagram, initially designed to simplify the making and evaluation of holograms, can also be used to study relativistic effects. It can, of course, be questioned whether the apparent rotation and deformation of objects traveling at a speed close to that of light really are true relativistic effects. They simply depend on the way of observation: the speed of light and the position of the observer. This fact, however, is also true for other relativistic effects, such as time dilation, the increase of mass with velocity, and contraction of fast-moving bodies. Thus there are good reasons to believe that the experiments described in this paper represent only a few of all the secrets in physics that could be visualized by light-in-flight recording by holography.

IX. Conclusion

The new measuring techniques described in this paper have many advantages over conventional methods of high-speed photography. They produce 3-D continuous moving pictures of the light in flight. The time resolution is extremely high because no mechanics are involved and no electric capacitance or inductance exists. If the hologram plate is tilted in relation to the normal of the hyperboloids, each unit length on the plate could represent an even shorter time than that corresponding to the inverted value of the speed of light.

By forcing the reference beam to travel zigzag over the plate or along a long hologram film, one could increase the time capacitance of the method by some orders of magnitude. By using the short picosecond or femtosecond pulse(s) from mode-locked lasers or using lasers with more than one wavelength, it is possible to increase the resolution to the micrometer range.

By special design of the experiment (for example, enlarging the illumination pulse using scattering or reflecting surfaces) not only light travel could be filmed and even measured interferometrically but also other ultrahigh-speed events, such as the implosion of deuterium pellets for fusion. For this reason a laser capable of producing single picosecond pulses is needed. Such a laser was not available to me at the time of my experiments.

The key to experiments like light-in-flight recording by holography is the extremely short light pulses that can now be produced by lasers. For my experiments I chose to use holography because it is easy to work with, it produces 3-D images, and it also produces images where the time domain is represented by the distance along the hologram plate. However, any other method using a two-photon reaction can be used instead of holography. If there is a need for an image, four-wave mixing or phase conjugation could be substituted for holography. It is also possible to use many speckle method types.

If there is no need for an image it is enough to determine whether the two pulses overlap, e.g., by looking for interference fringes on a photographic plate or in a crystal. Nonlinear effects other than interferometry can be used as, e.g., the Spectra-Physics model 409 rapid scanning autocorrelator with which it is possible to measure and study pulses in the picosecond range.

It is hoped that these introductory experiments will stimulate interest and open a door to the new possibilities of recording light in flight to study the temporal dynamics of interferometry, reflection, refraction, diffraction, and the behavior of light passing through optical fibers and integrated optics. This new technique might become a powerful tool for the understanding of optics and other ultrahigh-speed phenomena. It also opens up the possibility of studying the shape of 3-D bodies by contouring with just one movable fringe. In this way the radar method of mapping landscapes can be turned into a tool to measure industrial products with micrometer precision.

The experiments described in this paper were all carried out by the author at the Royal Institute of Technology, Stockholm, at Lasergruppen Holovision AB, and at the Spectra-Physics Facility Laboratory, Mountain View, Calif. The work was sponsored by the Swedish Board for Technical Development whose interest and support is gratefully acknowledged. Finally I want to thank the School of Mechanical Engineering who by founding a professorship in Production Metrology have greatly increased the possibility of my continuous research in this important field.

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BOOKS

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Diffraction Gratings. By M. C. HUTLEY. Academic Press, New York, 1982. 330 pp. $49.50.

A diffraction grating is a phenomenon in the instrumental world of physics that has its own mystique. Despite the tremendous advances in ruling engines since Fraunhofer's time, one still never knows what to expect from a grating until ruling is completed and tests have been made. Even with the advent of the holographic grating, touted as an end to the tyranny of the ruling engine, the outcome of the fabrication process is never certain.

Not an awful lot has been written about diffraction gratings themselves. Perhaps the first full-length (almost book-length) article was written by George Stroke [*HANDBUCH DER PHYSIK, Vol. 29*, S. Flugge, Ed., (Springer-Verlag, Berlin, 1967), p. 426 *et seq.*] In 1980, *THE ELECTROMAGNETIC THEORY OF GRATINGS*, edited by R. Petit, appeared from the same publisher and contained a number of articles on gratings. The slant was largely mathematical, and it added the mystique of higher mathematics to the mystique of gratings. Now we have a new book, much less mathematical in nature, that tries to dispel the aura of the supernatural surrounding gratings. The author, at the National Physical Laboratories, Teddington, has been closely associated with gratings, especially holographic gratings, and is eminently qualified to write on the subject.

The introduction (Chap. 1) is quite short and gives a thumbnail history of gratings, grating ruling, and recording of interference gratings, sometimes referred to as holographic gratings.

The theory of the grating, how and why gratings disperse radiation, is given in Chap. 2. Both phase and amplitude gratings are discussed. The general grating equation is derived, and dispersion, resolution, free spectral range, etc. are presented. Blazing, perhaps the most important characteristic of modern gratings, is described. The chapter ends with, first, a Fourier transform, and second, a quantum mechanical, description of gratings.

In Chap. 3 the author discusses the use of gratings in spectroscopic instruments. This chapter is mostly concerned with the throughput of the different types of instrument such as spectrometers, spectrographs, and monochromators. There is also a section comparing gratings and prisms.

The manufacture of gratings is the subject of Chap. 4. The formation of grooves and the accuracy with which they must be placed occupies the first few pages. A discussion of ruling engines and their characteristics is contained in succeeding pages and gives an excellent idea of the complexity and precision associated with these machines. The bulk of the remainder of this chapter is concerned with manufacturing interference (holographic) gratings. The last few pages are devoted to replication, a most important aspect of grating manufacture; without replication the cost of ruled gratings would be astronomical.

In Chap. 5 the spectroscopic properties of gratings are discussed, how well the grating performs, and what tests are used to evaluate its performance. The resolving power is intimately connected with the perfection of the diffracted wave front which is evaluated by interferometry. Spectral impurity arises from a number of sources—diffraction by the grating boundary, grating defects, and stray light. The measurement of stray light is extremely difficult, and the author devotes a number of pages to this subject alone. A discussion of measurements of efficiency and groove profile concludes this chapter.

A very interesting aspect of gratings—anomalies—is discussed in Chap. 6. There are Rayleigh anomalies and anomalies caused by surface plasmon oscillations. The author also includes a section on the effect of dielectric overcoatings on anomalies.

Concave gratings are taken up in Chap. 7. Without the imaging properties of concave gratings, much of the spectroscopic research in the vacuum ultraviolet and soft x-ray regions would not have been possible. The different grating mountings and associated aberrations are discussed, and there is a section on the use of interferometric gratings that have been corrected to reduce the effects of aberrations. Ruled gratings can also be corrected, to a certain extent, by modifying ruling engines, a practice so far occurring only in Japan. There is a section on efficiency measurements of concave gratings. The chapter closes with a discussion of wave-front testing of concave gratings.

X-ray gratings (Chap. 8) is largely a discussion of the properties of concave gratings used at grazing incidence. Operation at grazing incidence is necessary in the x-ray and soft x-ray regions because of

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