Principle of holography

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1. Overview

Holography is one of the most significant discoveries humankind has ever made. Its discovery has had such a profound effect on scientific developments, that the person who discovered the process in 1947, Prof. Dennis Gabor of Imperial College in the United Kingdom, received the Nobel Prize in Physics in 1972.

So far holography is the only visual recording and reconstructing process that can record a three-dimensional scenery on a two-dimensional recording medium and reconstruct the original scenery, to the unaided eyes, as a three dimensional image. The image demonstrates complete similarity to the original scenery and depth-of-field. The image can float in the film, or in the space behind or in front of the recording medium.

This short article is intended to introduce some basic concepts involved in making a hologram. First, we will introduce the terminology: what a hologram is and what holography is. Then, we will describe how to make a simple hologram, and how to view a hologram to display a three-dimensional image. After that, we will discuss the principle of the technique by using some simple mathematics. Finally, we will introduce some applications of holography to various fields in science and technology and our daily life.

2. What is a hologram and what is holography?

Holograms and normal photographs are two forms of recording visual images on photosensitive films. The technology of making normal photographs is called photography, and the technology of making holograms is called holography. Both of them are for recording visual images. However, their principles to make a record are very much different. Just as what the two parts of the Greek word, "*holo*" (whole or complete) and "*gram*" (information or picture) imply, "*hologram*" as a whole means "whole information" or "complete picture". This means that by making a hologram not only can we record the intensity information of a scenery, but also record the phase information (i.e., three-dimensional sensation) of a real object in space. But normal photography compresses the three-dimensional scenery we see onto a plane.

Physically speaking, a hologram is a light wave interference pattern recorded on a photosensitive film that can produce a three-dimensional image when illuminated properly. A hologram diffracts light that illuminates it, and the diffracted light has the characteristics that are so similar to the light from the original object that an observer will feel as if the light comes from the original object, and even be tempted to touch the "object" with his hand. From the same hologram, the observer can see multiple images of the same object from different directions, only if he changes his position of observation.

3. How to make a hologram, and how to view a hologram?

In order to make a common hologram, we need these optical and mechanical components, a laser, a beam splitter, two lenses, two mirrors, a holographic film or plate (i.e. high resolution photosensitive film or plate), film processing chemicals, a test bench, holders for these components, and of cause, an object to be recorded. The following schematic diagram shows how these components are used to produce a hologram.

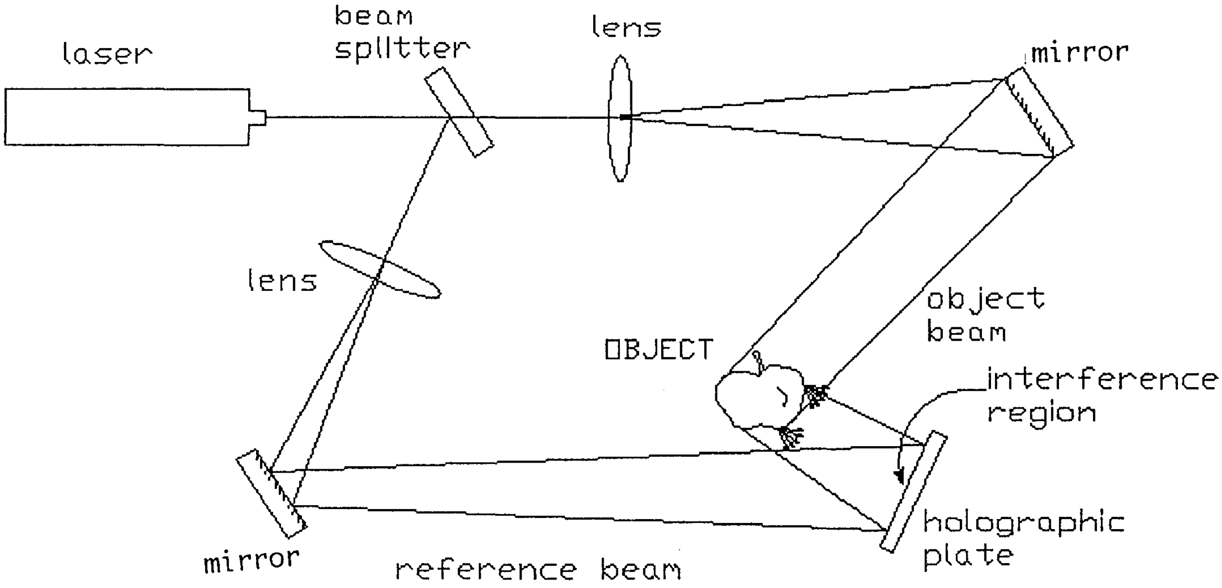

Diagram 1. Optical layout for making a hologram

As shown in the diagram, a laser beam is **split** into two beams, an **object beam** and a **reference beam**. The **reference beam** is expended by a lens and aimed **directly at the film plate.** The **object beam** is expended and aimed **at the object**. The object reflects or scatters some of the light to the holographic film.

The two beams interact, forming an interference pattern in the film. Under very stable condition, an exposure is made, the film is properly developed and fixed, and the product is a hologram. Laser light is needed because it is made of coherent waves (of same wavelength and stable phase) so as to generate the interference pattern. A stable environment is necessary so that the interference pattern will not be disturbed.

When the hologram is illuminated **using the original reference beam from its original direction**, a three-dimensional image of the object appears where it originally was, as if the object itself reappears.

4. The principle of holography

As one form of electromagnetic wave, light can be represented, for convenience, by using a complex function, for example, $\tilde{A}(x, y, z) = A(x, y, z)\exp\{-j\Phi_a(x, y, z)\}$, where $\tilde{A}$ is the complex function representing the distribution of light wave in three-dimensional space, A is the amplitude of $\tilde{A}$, Φ_a is the phase of $\tilde{A}$, (x, y, z) are the three-dimensional coordinates, and j is the imaginary unit symbol. With this representation, the intensity of light can be conveniently expressed by $\tilde{A}\tilde{A}^* = |\tilde{A}|^2 = A^2$, where $\tilde{A}^*$ is the complex conjugate of $\tilde{A}$.

To simplify the issue, let us set up a two-dimensional (x, y) coordinate system on the surface of the film, so that only two variables will be enough to describe the spatial distribution of light wave. Suppose on this coordinate plane the amplitude distribution and the phase distribution of object light, $\tilde{O}(x, y)$, are $O(x, y)$ and $\Phi_o(x, y)$ (i.e., $\tilde{O}(x, y) = O(x, y)\exp\{-j\Phi_o(x, y)\}$), and the corresponding quantities of reference light, $\tilde{R}(x, y)$, are $R(x, y)$ and $\Phi_r(x, y)$ (i.e., $\tilde{R}(x, y) = R(x, y)\exp\{-j\Phi_r(x, y)\}$. We also assume that the two beams of light are coherent, so that we can perform the amplitude addition of them. Thus, the intensity of the added light wave on the film is

$$\begin{aligned} I &= (\tilde{R} + \tilde{O})(\tilde{R} + \tilde{O})^* \\ &= (\tilde{R} + \tilde{O})(\tilde{R}^* + \tilde{O}^*) \\ &= \tilde{R}\tilde{R}^* + \tilde{R}\tilde{O}^* + \tilde{O}\tilde{R}^* + \tilde{O}\tilde{O}^* \\ &= R^2 + \tilde{R}\tilde{O}^* + \tilde{O}\tilde{R}^* + O^2 \end{aligned}$$

With this intensity, if we make an exposure to the holographic plate and then process the plate properly so that the relation between the amplitude transmittance and the exposure magnitude of the plate is in linear response region (this is what we mean above by saying that the film is properly developed and fixed), then the amplitude transmittance of this plate is proportional to the intensity, i.e.,

$$t = C_0(R^2 + \tilde{R}\tilde{O}^* + \tilde{O}\tilde{R}^* + O^2),$$

where C_0 is a proportional constant. For convenience, we can let $C_0 = 1$.

Now, if we place this processed holographic plate to where it was when the exposure was made, and use **the original reference beam**, $\tilde{R}$, to illuminate the plate, then the transmitted light wave just after the film will be equal to $\tilde{R}$ multiplied by t, i.e.,

$$\begin{aligned} \tilde{T} &= \tilde{R}t \\ &= \tilde{R}(R^2 + \tilde{R}\tilde{O}^* + \tilde{O}\tilde{R}^* + O^2). \\ &= R^2\tilde{R} + \tilde{R}\tilde{R}\tilde{O}^* + \tilde{R}\tilde{O}\tilde{R}^* + O^2\tilde{R}). \end{aligned}$$

Each of these four terms has its own significance, but it is the third term that we are interested in the most, as this term is $\tilde{T}' = \tilde{R}\tilde{O}\tilde{R}^* = (\tilde{R}\tilde{R}^*)\tilde{O} = R^2\tilde{O}$, which is equal to the original object light distribution on the plate multiplied (or modulated) by R^2 (i.e. the intensity distribution of the reference beam). If the reference beam is a plane parallel beam (or any other slowly varying waveform), i.e., $\tilde{R} = \exp\{-j\Phi(x, y)\}$, then we have $\tilde{R}\tilde{R}^* = R^2 = 1$. Thus, we have $\tilde{T}'(x, y) = \tilde{O}(x, y)$. What is this? This is just the original object light distribution on the plane of the film!

5. Applications of holography

Because of its capability of recording and reconstructing three-dimensional images, holography has found applications in many areas, for example, in fine arts, in medical science, and in optical information processing. The following are some examples.

In some art exhibitions, or on covers of some magazines, probably many of us have seen some kinds of holograms, which express ideas of their creators very vividly because they present complete three-dimensional visual sensation. In some museums, people can take advantages of holography to make holograms of some valuable but fragile art works or ancient goods, and display these holograms to the public, rather than display the real objects. In this way, visitors can still see the three-dimensional scenery of the objects, while the treasuries do not have to be exposed to bright illumination, or environmental contamination. Because holography requires special optical equipment, some carefully designed holograms can be printed on important documents, passports, for example, to make counterfeit much more difficult.

Here we have only introduced a few applications of holography that can be seen in our daily life. In scientific research and development, holography is finding more and more applications. Engineers have used holography to accurately measure very small deformation caused by temperature change of some fine structures (semiconductor integrated circuits, for example). Scientists are making significant progress in building X-ray lasers. The time will come that in hospitals doctors will take three-dimensional X-ray holograms, rather than normal two-dimensional X-ray photographs, for patients so as to make diagnose faster and better. Researchers have produced real-time holographic recording medium in laboratories. When the response time and the spatial resolution of the medium are further improved and data transmission rate becomes fast enough, it will become possible for us to watch holographic TV programs at home. We can expect that in the near future holography will play more important role not only in scientific research, but also in out daily life.

References

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