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Dinesh Padiyar, TripleTake Holographics

The Advantages of Holography to Generate Complex Optics

I would like to talk about holographic optical elements, HOEs, and their advantages in the design of AR/VR/HUDs and other complex optical devices.

Holography was invented in 1947 by Dennis Gabor to solve a problem of resolution in electron microscopes. At the time, practical resolutions were well below the theoretical resolution because of distortions in the lenses. Gabor conceived of a system of imaging without the use of lenses, but instead the use of difffraction as an imaging method. He wrote it up in Nature, 1947 as "A New Microscopic Principle"

The early holograms made by Gabor were crude, but it did prove the principle.

A serious limitation of Gabor's method was that diffraction produced two images, with one directly behind the other. This "twin image" problem made it difficult to distinguish the desired image from the background image.

An important breakthrough came with a change in method created by Leith and Upatniks at the University of Michigan in 1962 with their off-axis method. They separated a reference field from the object.

The beginnings of the use of holography as an optical element came as a result of the analysis of wavefronts and aberration by Meier and Champagne in 1967.

Today, the use of holography for imaging, AR and VR is widespread.

Essentially, in all these types of devices, the function of the device is to take an image from some digital display source, and then project the image onto a surface, such as a projection screen, the windscreen of a car, or directly to the user's eyes, perhaps with some computerised processing in the pipeline of the light between display device and final destination. This manipulation of the light field, from origin to destination may be a fairly complex optical function, involving many individual stages of manipulations of the light field as it passes through the various stages of the system. Such a function may be carried out with conventional lenses and mirrors, but the devices also have to be fairly compact and lightweight in order to fit onto a head mounted device, or glasses, or the inside of a car.

Conventional optics would make the device bulky and heavy. There are a number of solutions to this problem, including fiber optics. One such solution is Holographic Optical Elements, or HOEs. In addition, multiple elements in a conventional system, such as lenses and mirrors, can be replace by a single HOE element that include and replace all of those functions.

Holography is a method of wavefront reconstruction. That is, that any light field consists of a wavefront, which is a surface, propagating along some direction, or directions. The wavefront may remain smooth and regular coming into, and going out of the system, such as an off-axis lens, where a spherical wavefront goes through the optical system at some angle, and the system generates a spherical wavefront coming out at some other angle.

It may also be fairly complicated. both as an input to the system and the output out of the system.

The wavefronts generated by an actual object are a very complicated set of wavefronts caused by each individual point source on the object. Thus illuminating , say a porcelain cat, would generate a complex "cat" wavefront.The conventional display hologram that usually comes to mind, when talking about holograms, such as a hologram of a porcelain cat, is actually the wavefront of the cat captured by the holographic medium. When reconstructed, the hologram reconstructs the 'cat' wavefront.

However, in terms of abstract wavefronts, the hologram can reconstruct any abstract wavefront. It can, for example, reconstruct the wavefront of light going through a simpe lens, or through a set of lenses and mirrors. Such holograms are known as Holographic Optical Elements, or HOEs, because they simulate the behaviour of a set of optical elements.

Given a system, such that an image output from some digital display is to be transferred onto some other final surface through some optical system, it is possible to effectively reverse engineer the optical system. If the lightfield at the final surface is specified and the lightfield from the display is known, then the optical system can be simulated by an HOE. Thus, the entire optical system, or most of it, can then be repalced by a HOE, reducing space requirements and making it easy to install into a device, such as AR/VR glasses. Note, in this sense, the hologram is not reconstructing anything. It is altering one particular light field, the one from the display, into another particular light field the one on the screen. In this sense, the hologram may simply be referred to, as a "Light field processer". We now have a specific input lightfield, and the hologram processes it into another, specific output lightfield.

Thus a point source coming from one part of a system, which is perhaps inside of some enclosure and invisible to the viewer, can be made to seem to come from another part of the system, perhaps from behind a car windscreen.

Part of this processing of the lightfield, is that the hologram can be made sensitive to the different wavelengths, or colours, in the incoming lightfield. Thus, if the lightfield is white, but you may wish to extract only a narrow range of colours out of the lightfield, you can make a hologram that processes the lightfield unaltered in shape, but with specific colours removed or redirected.

You may also create an HOE, such that only a very narrow part of the input spectrum is passed through the hologram, and possibly focused. Thus, for example, sunlight entering the hologram is converted into a narrow range of colours and can be focused. This is known as a notch filter. Application such as solar concentrators use this function. Such functions are difficult in standard optics.

Conversely, you can break up the input light field into colour components, and then have the hologram magnify or diminish any particular components, thus processing the colour of a scene. That is, a single lightfield input may give rise to several output lightfields, depending on the design specifications. An example of this is multi-spectral imaging. The ground surface or water is illuminated with white light. The reflected light is passed into an HOE which splits the reflected lightfield into it's component colours. Each colour component can be sent into different directions, onto either different screens, or, selectively, into further lightfield processors. The proportion of colours in the scene then give information, either of the air between the light source, say from a drone, aircraft or satellite, or of some parameter of the surface.Such a multispecteral imaging system is now being used by farmers to study the health of plants and evaluating soil productivity by analysing the reflectivity of plants as a function ofwavelength.

The hologram itself can consist of just a sheet of thin plastic, in terms of placement within an optical device, and so may also be made conformal. That is, it can form a skin around the inside of any surface, such as a helmet. The processing is then constrained to a narrow surface or skin, within the helmet. This makes the hologram extremely fliexible, and capable of a wide array of possible applications. Such as these.

A hologram is recorded, by using two lightfields, the expected input lightfield, and the expected output lightfield. There are two basic modalities in recording a hologram: reflection and transmission.

In a reflection mode, the hologram is recorded by two light fields originating on either side of the hologram. The output lightfield from the HOE is then on the same side of the HOE as the input lightfield. This mode may be used for AR/VR glasses, Heads Up Displays (HUDs) in cars or aircraft. Here are some possible applications of reflection HOEs. This is the view through an Air Force HUD.

The advantage of reflection holograms are compactness, wavelength control and angular control. The entire optical system can be housed within a helmet, or a pair of glasses or in or under the dash of a car. Very precise control of colour allows good colour rendition. So that the colours from the HOE can be exactly tuned to the source illuminations in the display. In addition, angular selectivity allows for precision in the positioning of the eyebox.The efficiency for reflection holograms can be very high -up to 100%. The extremely high color senitivity can also be a disadvantage. By that, I mean that the hologram must be recorded with the expected input gamut as part of the design. If the actual input gamut is not close to the expected input gamut, loss of resolution and colour rendition will result. This loss of resolution gets worse as the variation of the two gamuts increases. Efficiency also drops.

In transmission mode, the hologram is recorded by two lightfields originating form the same side of the HOE. The output lightfield is then on the other side of the input lightfield.This mode is used in holographic lenses.

It is possible to make very fast lenses, which would be bulky using conventional optics, into a very thin package. This is a holographic lens with an f# < 1. It may also be possible to make lenses for 3D projection systems and holographic waveguides.

A holographic waveguide consists of an input hologram that diverts incoming light into a slab of glass. The angle through which the light is diverted is the total internal reflection, thus, the light bounces around inside the slab. At some point, an output hologram draws this light out of the slab, and diverts it towards the destination.

The glass slab need not be straight, curved waveguides are a possibility. This is usually used in glasses, with cameras on them, in this case the final destination is then the eye.

Here is the actual device. Light enters from a remote laser on the left, is launched into the slab by an input hologram, then bounces around in the slab, and then couples with an output hologram to exit on the right.

In this mode, the advantage of a transmission hologram is that it's relatively easy to transfer the light field into another device or hologram. The disadvantages are dispersion and aberrations. Dispersion refers to the break up of colours as a source passes through an HOE. In the reflection mode, only the design colours are allowed to interact with the hologram, all other colours being absorbed within the hologram. However, in a transmission hologram, all the colours of the input lightfield are proceessed, but are output at slightly different angles. This causes unwanted colours in the input light field to create a coloured halo around the image from the display. Aberrations describe the distortion of the lightfield caused by errrors in the input lightfield. If the input lightfield veers away from the designed spec, the output lightfield is aberrated, causing a distortion of the image from the display.

What is the future of HOEs? At the moment, nanostructure liquid crystal components are being placed within a pre-recorded holographic Bragg structure. These can be turned 'on' or 'off', allowing the hologram to transmit/process lightfields, or block them. This allows the hologram to be both a lightfield processor and a switch . This is limited, at present, to the scale of the nanoparticles. As nano-materials get smaller and more powerful, it may be possible to do real-time optical processing on wavefronts by dynamically altering the structure of the hologram. Possibly, this might be a step towards optical computing.

In conclusion, HOEs provide a flexible, low cost, solution to many problems of complex optical functions, and should be considered in any optical design.