Holography

History:

In 1948, a Hungarian-British scientist set out to improve the resolving power of the electron microscope. While the technology of his time limited his capability of doing so, Dennis Gabor's experiments alternatively paved the path to a new form of image projection and made him the father of holography. Gabor tried to improve the electron microscope by using the electron beam to create a hologram of his magnified object which, unlike ordinary images, only records variation in the intensity of light by producing dark and light spots, Gabor's hologram also recorded the phase of light. However, while Gabor was able to effectively create his hologram, in order for the object in the hologram to be viewed, he needed coherent light. He tried to solve this problem by focusing light through a pinhole but this technique did not produce enough coherent light and also dramatically reduced the light intensity too much for practical use [1]. For a while, Gabor's formulation of holograms was nothing more than an unachievable theory. It was not until the development of lasers in the 1960s that Gabor's theory became reality and holograms could be created by utilizing the power of laser light's coherence and light intensity. Gabor eventually won the Nobel Prize for Physics in 1971 for his creation of holograms which are used to this day for art, data, and security reasons.

Introduction:

This report will go over the primary characteristics that define a holographic film. It will also go over the concept of lasers as the incorporation of such technology is fundamental to the realization of holograms. The report will then explain the system of equipment used to create a hologram and the effect of such a process such as the interference pattern created in the recording material. Appropriately, it will also discuss how the utilization of the laser will not only create the hologram but can also be used to shine on the hologram in order to recreate the recorded object in the form of an image. Finally, the characteristics of holograms will be connected and explained relative to the process that created it.

Discussion:

In modern culture, the definition of holograms is blurred and often leads to the misinterpretation of holography as any projection of an image. While there are several kinds of holograms, each with their own features and niches, in order to be considered a true hologram the device must encompass three core features. Firstly, A hologram must be a true three-dimensional image. They must show depth and parallax, meaning a changing viewing angle also results in a changing aspect, allowing the user to view the image with multiple perspectives (figure 1). Secondly, any fragment of the hologram must be capable of revealing the entire image. While it is not necessary for that holographic piece to show the same amount of depth as when it was whole, the fragment must be able to portray the whole body from at least one angle. Lastly, the image on the hologram must be scalable. A hologram must be discernible with multiple wavelengths of light and viewing the image with one wavelength compared to another should also hold the possibility of magnifying the image or shrinking it (example shown in figure 7) [2].

$$\lambda = \frac{c}{f}$$

Equation 1: Wavelength of light (λ) relative to speed of light and frequency.

Figure 1. Two photos of the same holograph depicting a mouse.

It is impossible to understand the creation of holograms without at least an elementary understanding of lasers, or light amplification by stimulated emission of radiation. While all lasers share similar qualities, having the correct type of laser is pivotal to the creation of a successful hologram. This is mainly due to the fact that various issues such as lack of laser stability, coherence insufficiency, air flow, etc. can produce indistinguishable errata in the hologram [3].

Lasers have a variety of different properties such as having controllable temporal structure, energy storage, and tractable wavelength/frequency. However, by far its most important quality, at least to the creation of holograms, is its emanation of coherent light. Instead of spontaneous emission which is responsible for most light, lasers have stimulated emission in which emitted photons are organized and identical. This creates coherent light as released photons share phase and relationship.

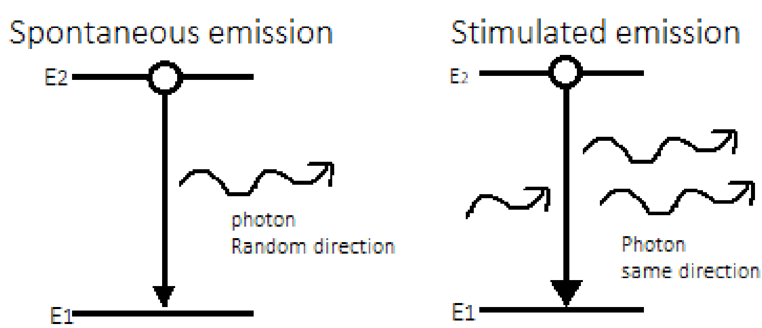

Figure 2. A photon emitting in a random direction for spontaneous emission compared to photons emitting in the same direction for stimulated emission.

However, in order to create that coherent light, it is vital to achieve population inversion. When enough electrons exist in the upper levels of an atom to the point where the population of the excited state is larger than that of the ground state, population inversion is achieved. Lasers need to have more excited electrons than ones in the ground state so absorption and losses can yield an optical gain and allow for the discharge of multiple photons [4]. This can be accomplished through a process called pumping where ground state electrons are excited to the third or fourth level (two level lasers do not exist) and those excited electrons would then transition to a lower level, the metastable state or E_2 as depicted by figure 3. When an incident photon comes into contact with a metastable electron, it unleashes a chain reaction of electrons transitioning to its original level, creating clone photons of identical energy which is what gives laser light its coherent attribute.

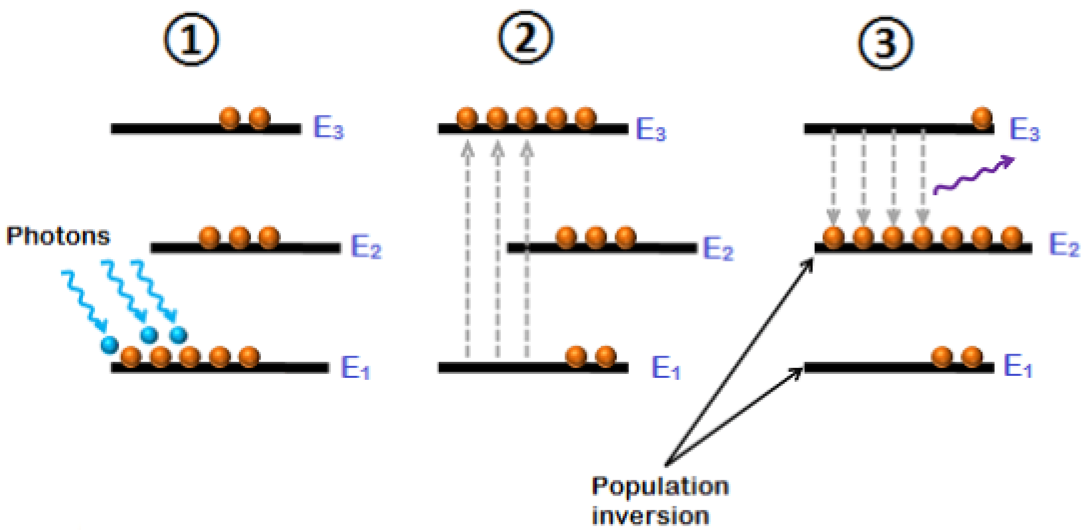

Figure 3. Example of optical pumping. Electrons are pumped with photons to help reach higher energy levels and achieve population inversion.

However, while all laser light is inherently coherent, there is a distance of which a coherent wave maintains its degree of coherence as shown by equation 2:

$$L = \frac{\lambda^2}{n\Delta\lambda}$$

Equation 2: Basic equation to calculate coherence of an electromagnetic wave.

L defines the distance where the laser light remains viably coherent, which is the absolute maximum length the laser can travel when producing a hologram. n is the refractive index of the medium the laser travels through, which in this case will be air. λ defines the signal wavelength of the laser while $\Delta\lambda$ is the difference between the highest wavelength and lowest wavelength in the laser [5].

Now that an appropriately intense and coherent light source was created, Gabor's theoretical holograms can be brought into reality. Without an explanation on the ambition of its design, the most basic apparatus to create a hologram requires a beam splitter to split laser light into two identical light beams, the object beam and the reference beam. The object beam utilizes a mirror so its trajectory can be directed onto the object so its scattered light lands on the recording medium while the reference beam is aimed to shine directly on the same medium [6]. A representation of such structure is shown in figure 4.

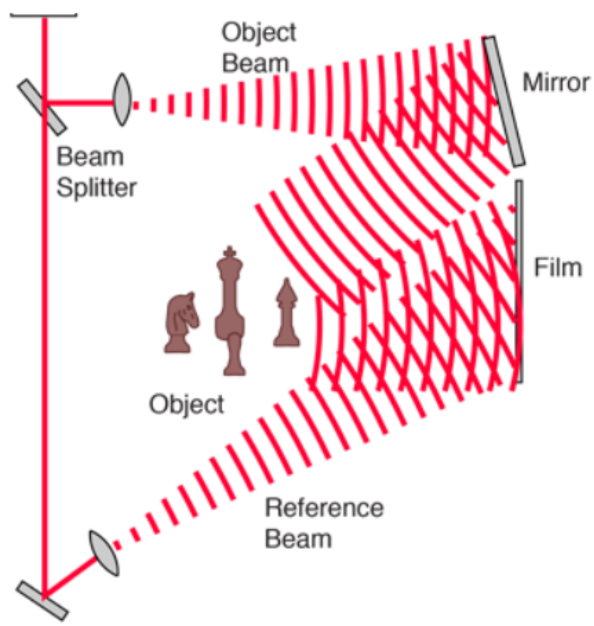

Figure 4. Beam splitter used to create an object beam and reference beam which are used in conjunction to create a hologram.

The film or recording material can be made with several different types of matter but the most common one is made with silver halide attached to a transparent substrate which is typically glass or plastic. Silver halide emulsion is primarily used for holography as a high resolution and photo-sensitive material is necessary to hold all the intricate details of a hologram, although alternatives exist in dichromate gelatin, photopolymers, and etc [7].

$$Ag^{+}NO_{3}^{\ -} + NH_{4}^{\ +}Br^{-} =\downarrow Ag^{+}Br^{-} + NH_{4}^{\ +}NO_{3}^{\ -}$$

Equation 3: Double composition reaction between a nitrate solution and a soluble halide solution.

The conjunction of the dual laser beams at the film creates an interference pattern which is the basis of its visual comprehension. These fringes are created from waves that have the same amplitude but varying phase. When those waves meet, the ones that share phase create constructive interference which is responsible for the light spots in the hologram and waves that have opposite phase create destructive interference which is responsible for the dark spots in the hologram. Like the example in figure 6, the film essentially acts as a collection of diffraction gratings with patterns that control how much light passes through each section.

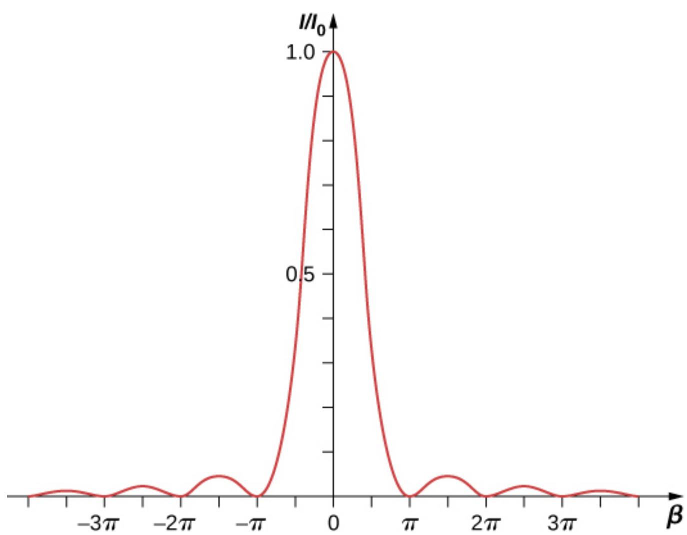

Figure 5. Single slit diffraction graph.

Figure 5 represents the intensity I/I_0 of the grating based on the angle of the light source β. The highest intensity exists at 0 radians with the intensity rising and falling with waning intensity as the angle increases/decreases.

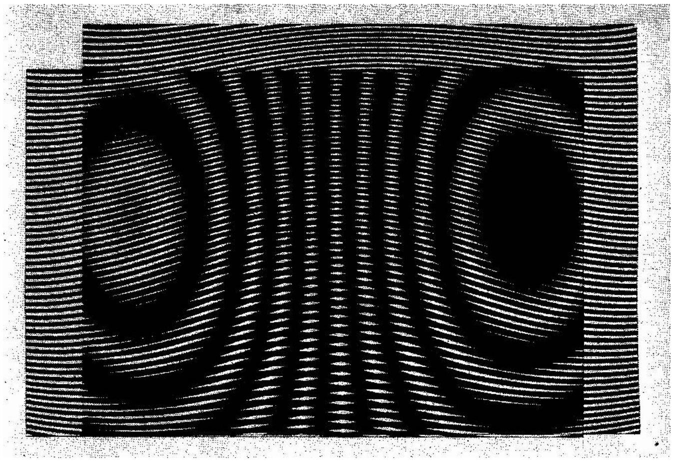

Figure 6. Film with an interference pattern.

However, while the hologram can be created from such means, the visual information supplied from the recording material will be nonsensical and bear little resemblance to the recorded object. In order for the hologram to serve any practical use, a key is needed in the form of the original light source. The laser originally used in the manufacture of the hologram needs to be present during the observation of the film so that the procedure that created the film can be reversed in order to recreate the visual aspects of the object [8]. On the light source side of the hologram, a virtual image visible to the observer will appear while a real image that can be photographed will appear on the other side.

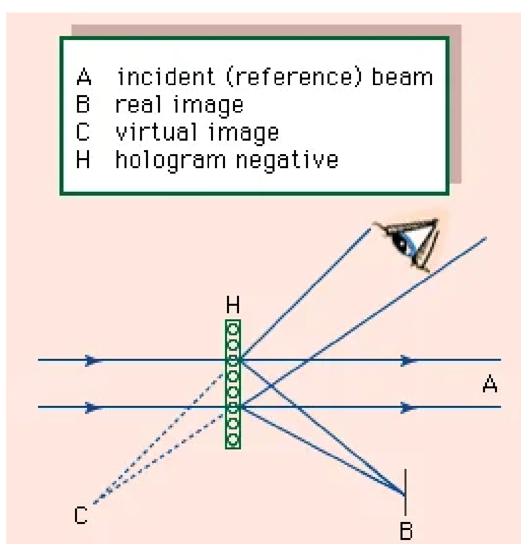

Figure 7. Visual representation of the images created when the observer views the hologram.

With the film drawn and coherent light source provided, the final product is a piece of film that abides by all the rules that encompass a hologram. If the observer were to move around or change their viewing angle, their perspective of the image will alter to fit their movement giving the effect of a truly three dimensional object. In contrast to a regular image which only records the intensity of light, the hologram also records the phase of light which allows it to hold its defining parallax feature. The documented phase is also responsible for any subsection of the hologram being able to represent the entire image. While the array of perspectives is proportional to the size of the subsection, the holographic piece will nevertheless function as an appropriate representation of the recorded piece. Finally, by using an interference filter, the observer can view the hologram with certain wavelengths divergent from the original laser so the image appears to not only have a different color but also appears to have a different size.

$$\lambda = \lambda_0 \sqrt{1 - \frac{sin^2\alpha}{n^2}}$$

Equation 4: Wavelength of light emitted by an interference filter using original wavelength λ_0, spacer index n, and angle of incidence α.

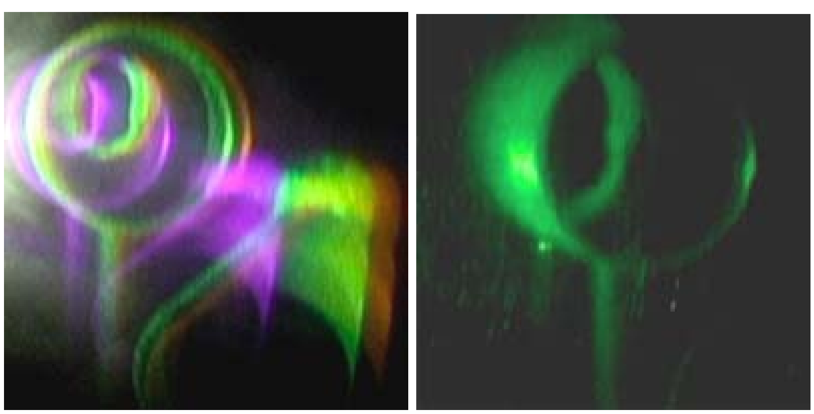

Figure 8. Left: Hologram being viewed with blue, green, and yellow-orange light. Each light magnifies the image to a different degree. Right: Hologram being viewed with only green light.

Conclusion:

While the field of holography is still growing and there are many advancements to be made, the technology has come a long way since Dennis Gabor when the invention was forced to be nothing more than a theory. With the realization of lasers, apparatuses can now be designed in order to create holograms by using intense coherent light to etch interference patterns into recording materials such as silver halide emulsion. Utilizing that same coherent light, the process can be reverse engineered to create a film that holds an image that far exceeds the average photograph by adding in dimensions, depth, and evolving size.

References

[1] The Editors of Encyclopedia Britannica. “Holography,” Britannica. https://www.britannica.com/technology/holography

[2] “Holography,” Hyperphysics. http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/holog.html

[3] Richardson, M. J., and Wiltshire, J. D. “The Hologram: Principles and Techniques,” Wiley-IEEE Press, 2017.

[4] Amann, M-C. “Semiconductor Lasers”, The Technical University of Munich.

[5] The Editors of Encyclopedia Britannica. “Coherence Length,” Britannica. https://www.britannica.com/science/coherence-length

[6] Senior, M. J. “Fibre Optics and Laser Instruments,” Rohini College of Engineering & Technology.

[7] “How are images recorded in a hologram,” Holocenter. https://holocenter.org/what-is-holography/image-recording

[8] Ling, S. J., Sanny, Jeff, and Moebs, William. “University Physics Volume Three,” BC Campus, 2019.