USE OF LASERS IN HOLOGRAPHY CVI MELLES GRIOT

WHITE PAPER

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Introduction

Holography was invented in 1948 by Dennis Gabor purely as a research tool. At the time Dr. Gabor was interested in a way of increasing the magnification of electron microscopes and hit upon the idea of "wavefront reconstruction" - now called holography -for which he won a Nobel in 1971. Throughout the 50's holography remained a subject of purely scientific interest with no obvious applications in industry or engineering. This was primarily due to the lack of a coherent source with which to record the hologram. This problem was solved in Michigan by Leith and Upatnieks in 1963, the first group to use a laser in the recording of a hologram. These holograms, however, were only viewable in laser light and therefore were still not able to transcend into the mainstream of industrial processes or engineering techniques. In 1963 Y. Denisyuk invented a method to make holograms viewable in standard "white light", i.e. non-coherent sources, creating what is today called a "reflection hologram", while in 1969 Dr. Benton at Polaroid created another method of allowing white light viewability resulting in what is today called a "rainbow hologram". These two advances allowed holography to escape from a laboratory environment.

While the art community quickly grasped the concept of holography as an artistic medium, the industrial uses and engineering applications of holography began to emerge in the 70's and 80's.

One of the first applications of holography was the ability to create Holographic Optical Elements (HOEs). The first paper on this appeared in Nature in 1967 (Nature, 215, pp239-41). Since then HOEs have become a major tool in engineering and military. Their applications are mainly in lightweight systems for complex uses, such as Head Up Displays (HUDs) in jet aircraft. They are also found in multiple wavelength systems such as the dispersive elements in spectrophotometers.

Holographic techniques have also been used in applications where conventional techniques already existed. The holographic technique may either enhance the range of applicability or provide a more compact solution. Examples of this are the Fiber Bragg Gratings (FBGs) used in telecommunication to route optical signals, or phase masks used in such diverse fields as astronomy or microscopy where a precise phase relationship is necessary.

Another engineering application of holography is in holographic interferometry. This arose from the observation that motion of the subject during recording caused dark lines to appear in the recreated image. It was soon realized that such an effect could be deliberately used to study small distortions in an object. This gave rise to the field of Non Destructive Testing (NDT) using holographic interferometry. This technique is now widely used for testing, analysis and studies of stability in materials. Today computerized techniques allow the use of this method to be encapsulated in a container with software and embedded hardware, thus automating the system.

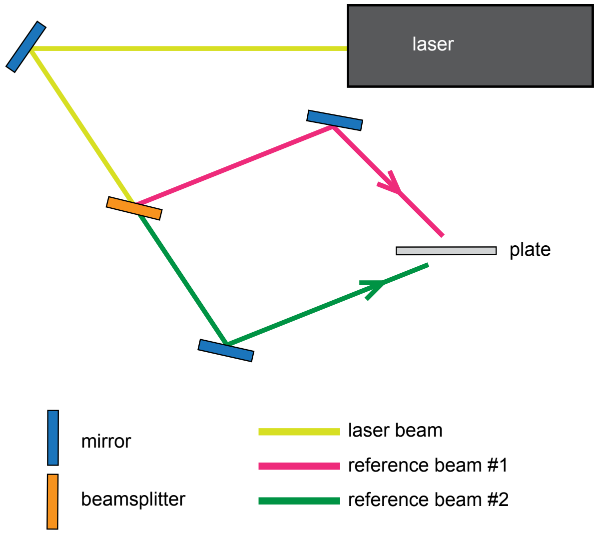
Holography entered the public space with the advent of embossed holography. This is a technique where a hologram can be imprinted onto foil, which can be adhered to paper or cards by standard embossing methods and makes it possible to mass-produce holograms cheaply. The major application today is in security, where holograms are a standard security feature on credit cards.

Application Criteria

In order to determine the best criteria for lasers for any given application, the applications may be split into three classes:

1. HOE, or technical applications
2. Holographic Interferometry
3. Display Holography

1. HOEs



Holographic Optical Elements

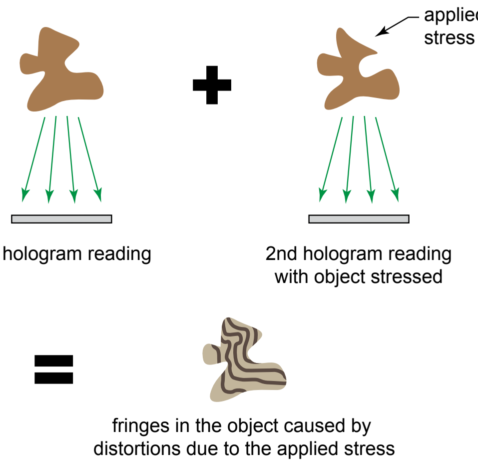
HOEs are recordings of phase fronts that create a specific phase profile within the medium that simulates the phase profile of optical components such as lenses or mirror. The layout for such a recording is fairly straightforward compared to the layout for a display hologram. This is because there is no need for complex lighting that goes along with a display piece. However, the attention to detail is far more important when creating a HOE. A small deviation from the calculated parameters might have a significant effect on the phase front being recorded, and so alters the final phase profile in the hologram. If the HOE is to be used in sensitive equipment, such faulty phase recordings may cause false readings.

Since there is no physical object, both beams impinge directly onto the recording medium. Thus, there is no need for long coherence lengths. However, mode hopping becomes more serious in HOE recording, since mode hopping creates a distorted wavefront, effectively creating different angles of incidence across the recording media. This creates superfluous fringes which rob energy from the intended diffracted beam and result in noise. Therefore a laser with good mode stability is much more important for HOEs.

While HOEs are generally exposed fairly quickly, in the order of minutes, high power is a valuable asset in recording HOEs to minimize the recording time. Small mechanical vibrations are more deleterious in HOE recording, for the same reason – formation of spurious gratings. Most media used for HOEs have a sensitivity of about 100 mJ/cm^2. A typical 500 mW laser usually results in an exposure of about 2 to 3 minutes. It would be advantageous to reduce this to a few seconds, thus a laser in the 3 – 6 W range is more appropriate.

Polarization is again an important parameter. For HOE recording, more so than for display recording, it is vital to get fringes of the highest quality. Careful alignment of polarization ensures this. If the laser is not initially polarized it may not be possible to get high class HOE recording.

2. Holographic Interferometry



Holographic Interferometry

The principle behind holographic interferometry is the addition of two sets of fringes from the same object on the same medium; the first with the object in its natural state and the second with the object distorted. In this technique a hologram is first made of an object, then the object is distorted slightly by mechanical stress or heat, for example, and then a second recording is made on the same medium. The fringes from the first set (the undistorted object field) and those from the second set (the distorted object field) are illuminated simultaneously. The illuminated hologram reconstructs both object fields simultaneously. This has the effect of two coherent object fields with a slight phase difference between each one caused by the distortion and so the object waves from the two recordings will interfere with each other. Since each object wave is essentially the same with very slight changes caused by the distortion, they will mutually interfere causing visible low frequency dark and bright lines across the face of the reconstructed object where the phase difference between each object field is π, or where the distortion is half a wavelength apart. This allows very small changes, in the order of microns or submicrons – depending on the recording wavelength - in an object to be studied. Since the object itself is unaffected by the tests, this is a powerful method of non-destructive testing at very small scales.

In practice, there are several uses of this technique. In one use – real time holographic interferometry – an object is recorded and the holographic medium is processed and returned to exactly the same position as it was recorded. With the object also in its original position, both the object and the medium are illuminated with the recording wavelength. Now the light from the illuminated object passes through the plate while the reference beam replays the original recording. If the object is now stressed, heated or distorted in real time, a series of dark fringes is seen on the holographic reconstruction.

In another technique, a recording is made as usual, but the medium is not processed. The object is distorted and a second recording is made on the same (unprocessed) medium. Now, the processed medium will replay both sets of fringes simultaneously and the final image will show up with dark fringes across it.

This technique is useful when it is important to know the exact distortion caused by a specific disturbance, for example in determining the strength of a structure by placing loads on a model of the structure. This technique has also been applied to tires, where a hologram of a tire is recorded, the tire is inflated and a second hologram is recorded. Any deviations from uniform expansion caused by areas in the material that are weaker than the surrounding material will show up as a series of dark rings on the final holographic image. This allows an analysis of the areas on a tire where the tire might blow under stress.

Holographic interferometry is easily digitized by capturing a set of fringes on a ccd array and storing them in a memory. Since the spatial frequency of the mutual interference fringes from the two recordings of the object is fairly low, this can be accomplished with standard ccd's. The distorted object's wave is also captured and the computer subtracts the two waveforms to give the final phase difference.

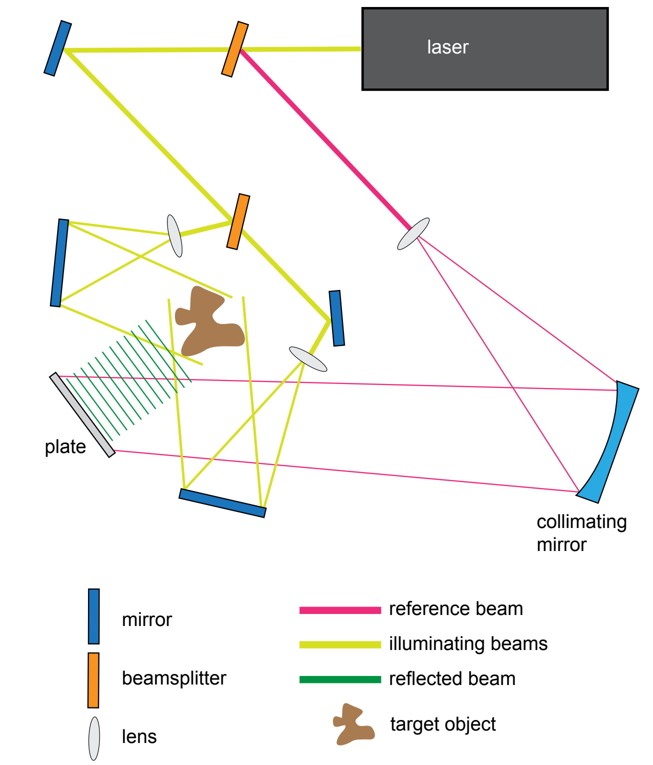
In interferometry, it is important that the fringes are well defined. Thus, while the actual object being studied usually does not have much depth, the coherence properties of the laser need to be fairly good. Polarization is important since there needs to be a fairly high fringe contrast. The recordings are usually made on a electro-optic crystal, which are usually blue sensitive.

The ideal laser for interferometry would be a blue-green pulse laser, such as a doubled / triple YAG, for quick capture of very fine or transient distortions.

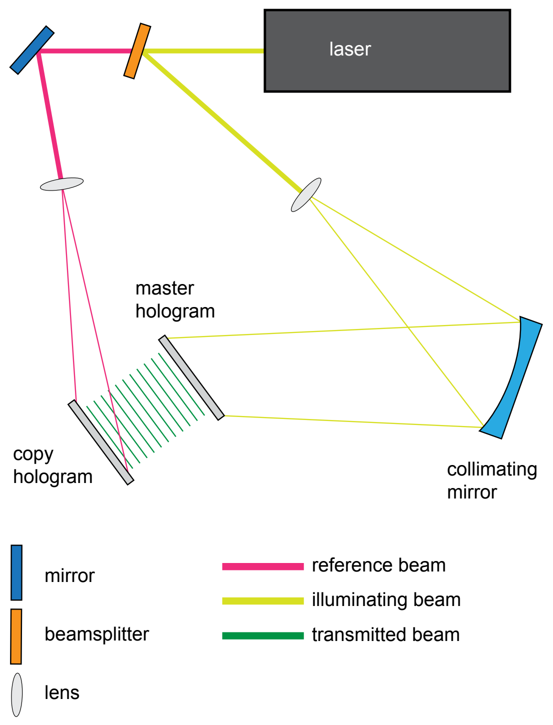
3. Display Holography

Display holography covers those applications of holography where a 3D image of a real object or a photographic recording of an object or scene is recorded into a holographic medium, such as silver halide. Viewing the hologram involves lighting the medium which then reveals the image/ scene recorded.

The hologram is usually created on a large, vibration-isolation table which can be of the order of 6 feet to 8 feet. The laser beam is split, by some kind of partial mirror/beamsplitter, into two beams. Each beam traverses different paths through various optical elements such as lenses and mirrors and finally impinges onto the recording medium. Interference fringes resulting from the interaction of the two beams is then recorded as the final hologram. In order to get the maximum contrast of the interference fringes, it is important to ensure that the two beams are mutually coherent at the recording medium. This is usually only possible



Display Hologram Master



Display Hologram Copy

USE OF LASERS IN HOLOGRAPHY

if the difference in path lengths is within the coherence length of the laser. However, if the coherence length is small, it is difficult to place the optics for each arm in such a manner to ensure path lengths are equal or within the small coherence length. It would be far easier if the coherence length were of the order of several meters, thus foregoing the need for care in placing the optics. For most situations, a coherence length of about 5 meters is sufficient. The coherence length is a function of the longitudinal mode which in turn is a measure of the frequency spread, or bandwidth in the beam. The narrower the bandwidth, the longer the coherence length. The coherence length L is given by,

$$L = \lambda^2 / \Delta\lambda$$

where λ is the central wavelength and $\Delta\lambda$ is the spread in wavelength. Note that for the same $\Delta\lambda$, the coherence length is increased as the wavelength is increased, thus a red laser has a longer coherence length than a blue one for the same bandwidth. Also, the addition of an inter-cavity etalon narrows the bandwidth and significantly increases the coherence length, but at the expense of perhaps 50% less power.

Another important factor is the transverse mode at the aperture. This needs to be TEM_{00} to ensure that the illumination of the scene and the recording medium is uniform. Large gas lasers that are water cooled have a tendency to "mode hop", i.e. the transverse mode jumps into higher orders during the recording. This results in a serious degradation of the image. Thus, it is important that the laser is stable with regard to the TEM_{00} mode.

The fringe contrast is at its maximum when the two recording beams are linearly polarized in the same direction. Therefore polarization is also an important factor for display holography.

Display holography in the industrial arena tends to take a long time, sometimes over days, and comprises of several recorded holograms. A more powerful laser will reduce the recording time of any one hologram, improving productivity. Also, high power/short exposures results in better uniformity over the entire set of recordings used for a given project. Typically lasers in the 500mW range are used. Note that this figure alludes to the power at the recording wavelength. In multi-wavelength lasers, the laser power is usually given as the sum of powers over all the wavelengths.

Industrial holographers record on photoresist, which is blue sensitive (350nm – 470nm), thus the lasers they need to use are the equivalent of HeCd, Ar or DPSS in the deep blue region.

Preferred Characteristic	HOE	Holographic Interferometry	Display Holography
Power	300 mW	Pulse/1W	100 mW or more
Stability	Good for short periods	Good for short periods	Very good for long periods
Beam shape	Round	Round	Round
Coherence length	1m	1m	5m
Mode	TEM_{00}	TEM_{00}	TEM_{00}
Polarization	Polarized	Polarized	Polarized
Automatic power adjustments	Necessary for periods ~ 10 mins	Necessary for periods ~ seconds	Necessary for extended period (> 8 hrs)
Cooling	Air	Air	Air
Power Supply	110/240	110/240	110/240
Size	small	Very small	small
Wavelength (nm)	457, 488	442, 457, 488	457
warm-up time	less than 1hr	15 mins	15 min

About the Author - Dinesh Padiyar

Dinesh Padiyar graduated from London University in 1977 with a BS in Mathematical Physics and a MS in Theoretical Physics. After graduation, he worked in Standard Telephones and Cables as a hardware/software design engineer, where he worked on the first digital telephone system in the UK.

Dinesh switched to holography in 1982 to take advantage of the opportunities in optical technologies then beginning to emerge. His first position was a Research Physicist at London Holographics, where he researched into a viewing system for dispersion compensation holography, with some theoretical work on colour holography. In 1986, he came to the US.

In the US, he was appropriated into the Reagan Star Wars program and researched into various aspects of holography as an engineering and scientific tool. In this capacity, he researches were carried out in Laser Safety goggles for the US Army, X-ray holography for space applications, Head Up Displays for the US Air Force and telecommunications using coherence as modulation technique.

In 1994 he joined American Banknote Holographics, where he was a member of the New Technologies Committee investigating and testing new technologies for security holograms.

He started his own company in 2000, Triple Take Holographics, as an R and D company, incorporating a display holography section. He is now investigating new and novel display systems for glasses-free 3D and researching into a new colour space for holography. His present investigations also include a new mathematical theory of holography involving non-linear chaos theory.

Memberships: Past - IHMA, SPIE Present - OSA