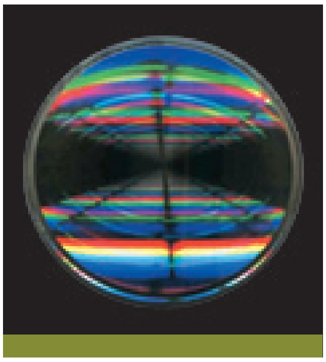
Computer-generated holograms

A flexible way to control light



In most people's understanding, holograms are those marvelous pictures that, when illuminated properly, show three-dimensional objects as if they were really there. The perfect 3D-impression stems from the ability of holograms to reconstruct the very same light field that existed when the object was available. Thus, the eye that detects only the light field emitted from an object, cannot distinguish if the object is really present or not – if the light field is the same, it looks the same.

1. Introduction

Holography can do more than producing those decorative three-dimensional light fields. Since holograms give an exact optical replica of an object, they can be used as copies, e.g. of valuable, fragile, or historical objects. The holographic copy can be examined with optical methods just like the original, eliminating the need for having the original at hands.

The concept of reconstructing three-dimensional light fields with a flat element, the hologram, is very attractive for many applications. The working principle of holographic elements is diffraction on microscopically small structures created during the recording process. Other working principles in optics are refraction on smooth interfaces between two transparent media and reflection at mirror surfaces. Optical elements based on diffraction are often referred to as Diffractive Optical Elements (DOE).

Classical holograms can only record existing light fields, i.e. the objects that produce the light field must be physically existent. Computer generated holograms (CGHs) overcome this limitation. Here, the original object exists only in the computer. The light field that stems from the computer aided designed object can be computed and since the phenomenon of diffraction is well understood the microstructures forming the required hologram can be determined. With this data, the CGH is fabricated. Since the structure sizes are down to the order of a wavelength (e.g. 0.5 µm for green light), the fabrication process is quite challenging. The advances in semiconductor manufacturing such as optical lithography have helped a lot to produce such small structures with the required precision.

One of the first applications, where CGHs have been applied, is interferometric testing of aspherical surfaces. Here a CGH defines the ideal aspheric lens shape that is optically compared to the lenses that are actually polished. Section 2 gives more details.

The principle of creating a well defined light field with a computer generated hologram is not restricted to light fields generated by real or artificial objects. In fact, CGHs can manipulate light fields in a very general way. For instance, a CGH can be designed to focus an incoming plane wave. This kind of CGHs can be used instead of refractive lenses. They are called diffractive lenses, since their working principle, as of all holograms, is based on diffraction. Diffractive lenses are very sensitive to the illumination wavelength. This can be used to design systems that change their focal length according to the wavelength. In section 3, a topography measurement system based on this effect is described.

An even more general manipulation of light fields is necessary for pattern generation applications, where the light field needs to be designed such that a given intensity distribution appears in a certain distance. Typical useful intensity distributions can be squares, circles, bars, crosses, or even company logos. Also the creation of three-dimensional intensity distributions is possible. Section 4 describes an application where a pipe of light is required to confine very cold atoms.

In some cases it would be attractive to change the CGH in real-time, e.g. to create a varying light field. This is indeed possible using consumer digital light projection technology. In section 5 principles and components for realizing dynamic CGHs are explained. Applications for dynamic CGH are given in the subsequent sections, ranging from micro-material processing in section 6 over micro-manipulation with so called optical tweezers in section 7 to new approaches in wave front sensing in section 8.

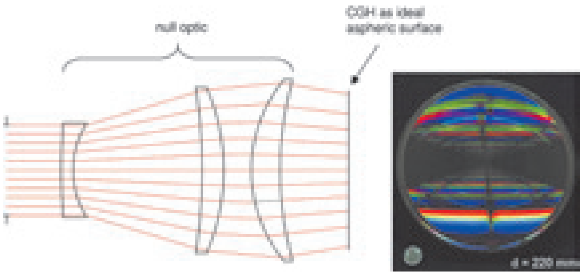
2. Computer generated holograms in aspheric lens testing

One of the first applications of CGHs was in optical testing of aspheric lens surfaces. In 1970 the first CGH was proposed and only one year later it was suggested to use CGHs in interferometric testing of aspheric lenses [1][2]. Aspheric lenses are and have been very useful components for a lot of optical systems. They allow to improve the performance of a system while at the same time reducing the size and weight. A major drawback of aspheric lenses is that they cannot be tested as easily as the standard spherical surfaces. They need a so called null lens that optically exactly fits the asphere under test. In such a null test configuration, only the deviations of the asphere from its ideal shape are measured. This simplifies to measure very small deviations of the aspheric shape from its ideal shape down to a few nanometers or less.

The null lens defines the ideal shape of the asphere and therefore must be well known. For high precision measurements the whole setup must be calibrated. Here, CGH can be used. Since a CGH can be designed as the hologram of a perfect asphere, it can be placed at the position where the aspheric surface would be. It is then measured and since it represents an ideal aspheric surface, the measurement result should give zero. A non-null measurement result is due to imperfections in the interferometer or the null optic. So, for real measurements, we can subtract this calibration function.

SUMMARY

Computer Generated Holograms (CGH) are a relatively new class of optical elements that allow a very general control of light fields not possible with conventional, refractive or reflective elements. We have shown a wide variety of applications that have been made possible with CGHs. A new and promising approach is the flexible generation of CGH with spatial light modulators (SLM). The possibility to change the holograms with video frequency or faster allows new applications such as one-shot micro material processing or flexible optical tweezers.



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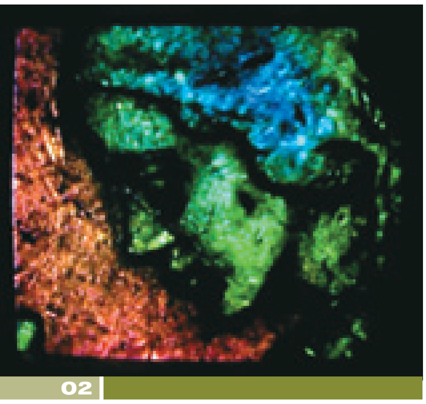
CGH replaces aspheric surface in the interferometric test setup. Left: test arm of the interferometer, right: CGH with a diameter of 220 mm and smallest structures below 1 µm.

This concept relies on a perfectly manufactured CGH. CGHs can be made with a very high precision, yet nothing is perfect, especially when a precision down to a few tens of nanometers is required. Therefore, calibration strategies have been developed that allow to determine the quality of the CGH also. For these methods the CGH is designed such that it can not only replace an aspherical surface but at the same time replace a spherical surface. For the measurement of spherical surfaces well known calibration methods exist, so the CGH can be calibrated using this auxiliary wave front.

3. Diffractive lenses for chromatic confocal microscopy

If we use a CGH in a wide, continuous spectrum of wavelengths, an intrinsic property of diffractive lenses shows up: Light of longer wavelength (e.g. red) is bent stronger than shorter wavelengths (e.g. blue). This property we have used to design a lens that varies its focal length depending on the wavelength. For many applications such as photography this so called longitudinal chromatic aberration is not desirable, since the image of say a white object gets blurred and shows colored edges. But imagine the object consists of blue parts and red parts and that the red parts are closer to the observer. This can be done by illuminating the white object on the far end with red and closer to the detector with blue light. In this case our specially designed CGH lens produces a sharp image of both parts of the object simultaneously. Although this does not really sound relevant for practical uses, it really is the basis for a very fast and robust measurement system: The chromatic confocal microscope. Here, the object is illuminated with a series of foci of different wavelengths at different focal lengths. A special aperture stop, the so called confocal pinhole, ensures, that only light from object parts that are in focus is reaching the observer. Therefore, one can see a colored image of the object, and the color in the image is directly proportional to the distance from the sensor. With a spectrometer, the color information is evaluated quantitatively. Altogether, this forms a flexible, robust, one shot height measurement system that can be miniaturized very well [4].

(02) shows a measurement example. CGH enable the wide measurement range and design flexibility of such systems. [5]



02

Detail of a coin, as seen by a chromatic confocal sensor. The height of the object is coded as color at each pixel. This allows one shot height measurements.

4. Manipulating matter with light: confining Bose-Einstein condensates

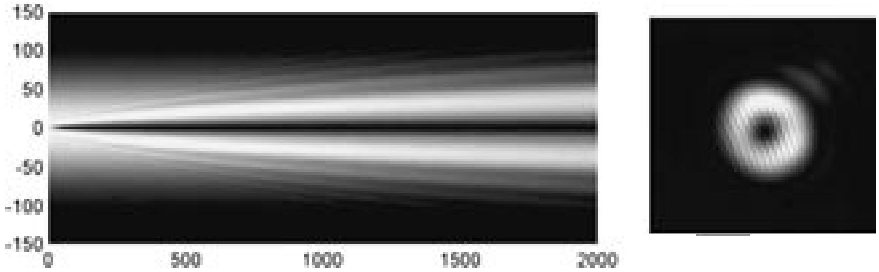
It is a fascinating effect, that microscopic particles feel a force in a light field with an intensity gradient. This effect can be used to trap matter in suitable light fields. Computer Generated Holograms are ideally suited to generate the necessary light fields. **(03)** shows the light field that is generated from a Gaussian laser beam with the help of a high efficiency CGH. In **(04)** experimental results of Bose-Einstein condensates travelling along the 1D path defined by the light pipe are shown. The condensate is trapped inside the dark area, which helps reducing the impact of the trapping light field on the condensate.

5. Dynamic computer generated holograms

We have so far only discussed applications that require static optical elements. By writing CGHs not permanently onto glass or other substrates but using a dynamic changeable medium of course a lot of new interesting applications become feasible.

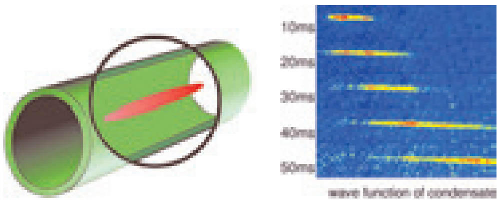
Ideally one would like to have a modulator that can be used as a direct replacement for conventional DOEs written in glass. Unfortunately such devices are not available. Resolution is limited to about 10 microns, which is about a factor of ten worse than what one achieves with static DOEs, for all electrically addressable elements. Even worse, the number of addressable pixels lies in the range of only one to two million pixels. Compared to the billions of “pixels” that are stored on a conventional recorded hologram this is not very promising. Finally the light efficiency of the available modulators is quite bad (in the range of some ten percent). By using a dynamic DOE you are therefore losing a lot of light which is a problem for some applications.

In spite of these problems there are still applications where today’s modulators are an interesting alternative to static systems. Before we show some of these applications we want to give an overview over the different types of modulator technology that are used for dynamic DOEs.



03

Light field generated with a CGH. The graph shows a cross-section of the light field immediately after the CGH, propagating from left to right. Well visible is the desired dark area on the optical axis. Right: Intensity in a plane parallel to the CGH.



04

Bose-Einstein condensate trapped inside the light pipe. Left: schematic drawing of the geometry, right: Bose-Einstein condensate travelling along the light pipe.

Generally one has to distinguish between optically and electronically addressable elements. From the standpoint of usability of course electronic addressing is favorable. With a large (more than some hundred of thousands) number of pixels this unfortunately means that an active addressing matrix has to be used. For elements that work in transmission this results in a significant amount of space at the pixels that is used for the electronics and which results in an overall reduced transmission of the elements because at the position of the electronics (transistors, capacitors, and wiring) light transmission or modulation is not possible. The smaller the pixel size the more severe is the problem because one cannot shrink the addressing electronics below a certain limit of a few microns.

The solution to this problem is to use the light modulator in reflection. The addressing is done from behind so that a large effective area of the pixel really can be used optically. With liquid crystal displays these reflective elements today are mostly fabricated on a silicon basis. Therefore such elements are called LCoS (liquid crystal on silicon) displays.

Additionally it is often difficult (especially at long wavelengths) to achieve a full 2π phase modulation. This results in a reduced diffraction efficiency and the appearance of unwanted higher diffraction orders. In principle it is possible to design modulators that have a full 2π phase modulation but this is not advantageous for commercial amplitude modulating displays. Therefore if one wants to use consumer elements one has to live with an additional amplitude modulation and a reduced efficiency.

Another promising reflective modulation technology is based on micromechanical elements. Most noticeably are the so called digital micromirror devices sold by Texas Instruments. Unfortunately the Texas Instruments elements only modulate intensity. Therefore the diffraction efficiency is quite bad compared to – also available (but more expensive) – phase modulating devices.

Optical addressing completely circumvents the problem of the fill factor due to the electronics. On the other hand such elements somehow are exotic and are not manufactured for the mass market. Additionally the optical setup of a system is getting more complex and expensive since one needs an additional electronically addressable modulator for controlling the optically addressed modulator. A very rough comparison of the different available technologies is given in **(t01)**.

As is shown in **(05)** there are lots of disadvantages but only one advantage of modulator based DOEs compared to static DOEs. This advantage is of course the possibility to change the function of the DOE very fast (depending on the technology the maximum frequencies are between ten Hertz and a few thousand Hertz).

6. Dynamic CGH for micro material processing

(07) shows one example where this is employed. It is a setup for holographically writing structures on a microscopic scale into material. A laser is first expanded by a lens before it hits the modulator, in this case a 640 x 480 pixels Epson LCD panel.

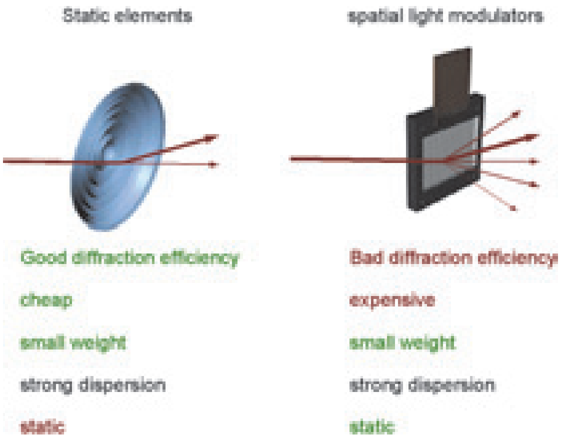
After being modulated by the diffractive element written into the LCD the beam is Fourier transformed by the second lens. The Fourier transform of the light field behind the LCD is written into the material. By proper design of the DOE one can write more or less arbitrary patterns into the material. The pattern to be written is reconstructed by the lens. No mechanical scanning is necessary to change the patterns. All is done (even defocusing onto different depths) by electronic addressing of the LCD [7].

An example is shown in **(08)**. Compared with simple

ZUSAMMENFASSUNG

Computer-generierte Hologramme (CGH) werden heute in einer Vielzahl von Anwendungen als optische Elemente eingesetzt. Durch die Möglichkeit, Licht nahezu beliebig ablenken zu können, sind die Elemente sehr flexibel sowohl in Beleuchtungs- und Abbildungssystemen als auch in speziellen Messanwendungen einsetzbar.

Im Artikel werden verschiedene Spezialanwendungen von CGHs beschrieben. Insbesondere wird auf die Vermessung asphärischer optischer Flächen, die Vermessung von Wellenfronten und die konfokale Mikroskopie eingegangen. Ebenfalls besprochen wird die Möglichkeit, spezielle Lichtfelder zum Einfangen von Atomen, Zellen und mikromechanischen Teilen durch die CGHs zu generieren. Die CGHs können sowohl als statische Elemente (z.B. in Plastik oder in Quarz) als auch als frei programmierbare dynamische Elemente (basierend auf Flüssigkristalldisplays oder Mikro-elektromechanischen Systemen) realisiert werden.



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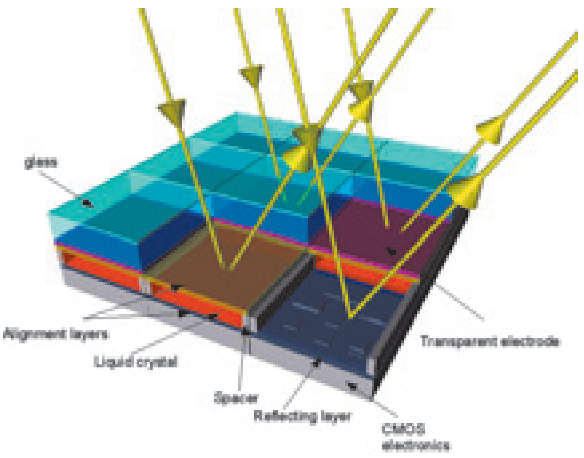
Static versus dynamic diffractive optical elements.



06

Liquid Crystal on Silicon (LCoS) reflective display.

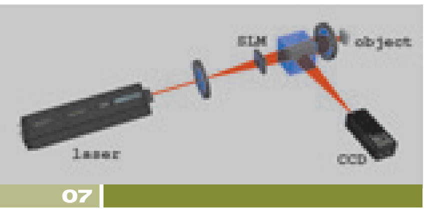
Comparison of different SLM technologies

	OALCD	LCD in transmission	LCoS	DMD
Overall efficiency	30 … 40%	5 … 10%	5 … 20%	5.00%
Number of Pixels (Millions)	0.5...100	1 .. 2	1 .. 2	1 .. 2
Speed	30 Hz	50 Hz	200 Hz	10 kHz
Price (incl. addressing)	7000 EUR	1000 EUR	1000 EUR	2000 EUR

t01

imaging one saves a lot of energy because with pure imaging lots of the light (the black area of the pattern to be written) is lost because it will be filtered by the modulator. With the DOE approach this light is not lost. All the light falling onto the modulator is redirected (by diffraction) to the illuminated areas of the pattern. Still the efficiency is bad (only some ten percent) if we compare this with a mechanical scanning approach.

But getting rid of mechanical moving elements can be a great advantage especially if we work on the microscopic scale since precision and repeatability are greatly enhanced. An application where this turns out to be especially important are optical tweezers.

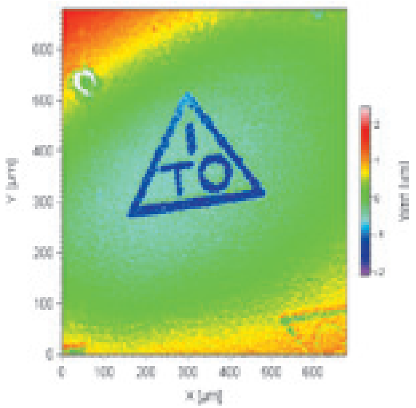


07

Holographic material processing with a dynamic hologram.

7. Dynamic optical tweezers

Again, a light modulator is used in the Fourier plane as shown in **(09)**. It is a setup for manipulating (trapping and moving) small particles like cells or microsystem parts. By changing the holograms (computation of the holograms is possible in video real-time) one can control a lot of traps, as shown for 7 particles in **(10)** (up to 100 is feasible) in three dimensions without mechanical motion and with high repeatability. Additionally by adapting the hologram it is possible to correct for aberrations caused by the optical system or the specimen [8].



08

Holographic ablation of a pattern into Fe2O3 by a ruby laser.

8. Wavefront sensing with adaptive CGH

Another application of spatial light modulators lies in the field of wave front sensing. The Shack-Hartmann sensor is used to measure a wave front in a wide range of applications such as adaptive optics in astronomy, laser beam analyzers and non-contact measurements.

The conventional sensor consists of a static microlens array and a camera. In the adaptive sensor **(11)** the static microlens array is replaced by a spatial light modulator (2) that displays freely programmable diffractive microlenses. The wave front to be measured (1) is sampled by the array of microlenses (2) and brought to focus on the detector device (3). The displacements of the foci in comparison to the position of the focuses of a plane wave are proportional to the local wavefront tilts which are used to calculate the measured wavefront shape. In our example, beam (B) is clearly tilted because of the displacement of the focus (green arrow) on the detector device.

The use of an dynamic element makes the adaptive sensor very flexible. Sensor parameters such as focal length, aperture size and number of microlenses can be modified according to the measurement task. A long focal length of the microlenses, for example, favors measurement precision but limits the maximal measurable wave front slope [9].

In addition, the measurement restrictions of the conventional sensor concerning maximum measurement dynamic and accuracy can be overcome by adapting the microlenses to the wave front to be measured. It is, for example, possible to correct wave front aberrations which makes the determination of the exact focus position in the static sensor impossible. •

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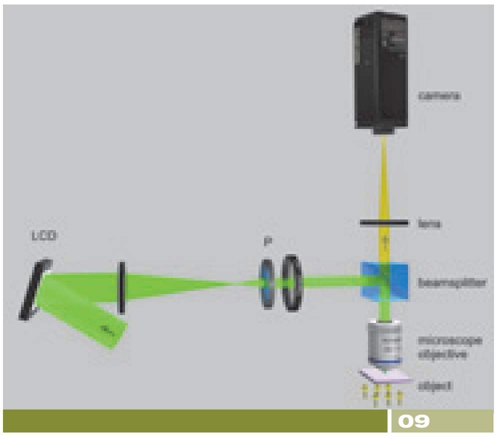
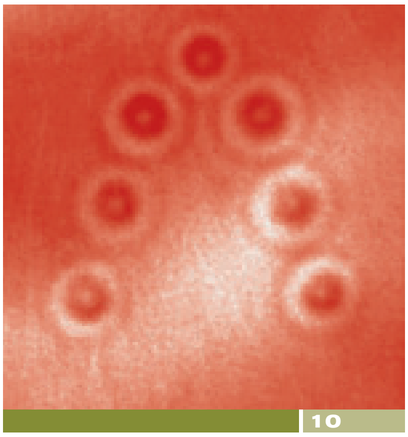
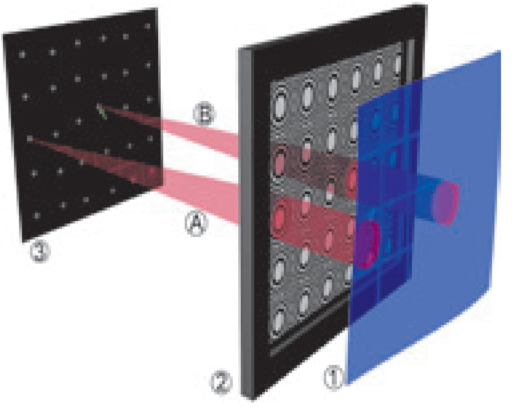


09 *Setup for a holographic tweezers systems.*



10 *Trapping of seven particles by holographic tweezers.*



11 *Adaptive Shack Hartmann sensor with exemplary beam propagation: 1) wave front, 2) transmissive SLM, 3) detector device with focuses from the microlens array, A) untilted beam of a single microlens, B) tilted beam of a single microlens.*

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