

SOPHISTICATED LIGHT SWITCHES

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If optical metrology systems reach their limits in terms of dynamic range or speed, the use of sophisticated light switches might be a way to bring more flexibility into the measurement process. Rather than just describing the action of turning on and off light, the term “switching” refers to more advanced adaptations of light such as spatially resolved intensity modulation, phase shifting, beam steering or wavefront shaping. Control over properties of light is commonly obtained using switches, modulators or spatial light modulators (SLMs). Many devices have become available on the market, with the number of addressable parameters ranging between one and several million.

The paper gives an overview of the broad field of available light modulators in section 1. Sections 2 - 4 provide an insight into a few interesting applications in which high resolution liquid crystal displays (LCDs) are used to create highly flexible tools. A phase shifting point source array and its application in an interferometer is described in section 2. Section 3 deals with a Shack-Hartmann sensor that uses adaptable microlenses. Section 4 describes the holographic optical tweezer, a flexible tool used to manipulate particles in the micrometer range.

1. Commonly used light modulators

The sensing and the control of light are the two main tasks in optical metrology. There are cases in which the mere sensing of light with a constant light source provides enough information. Often, however, a modulation of the used light provides much more information so that in the subsequent processing of the gained information the measurement result can be calculated. Figure 1 shows a brief overview of commonly used light modulators. These are divided into modulators that influence the intensity, the phase or the wavefront shape of the involved light. Another distinction can be made by looking at the number of parameters that can be influenced with the modulator. In the figure, the number of parameters is indicated by the size of the used font.

The simplest thinkable modulation of light is the switching of light sources by means of simple electrical switches, or mechanical shutters. This binary intensity modulation can be applied for calibration purposes or illumination sequences from different angles. With electronic controllers for diode lasers in fiber telecommunication the switching process is taken to extremes. Acousto-optical modulators (AOMs) are popular for fast modulation of light beams. A piezoelectric transducer is used to excite a sound wave in a transparent medium. The sound wave produces a periodic spatial modulation variation in the medium which acts as a volumetric phase grating. This grating can efficiently diffract the beam into one of the grating's diffraction orders. By varying the amplitude of the acoustic wave the diffraction efficiency is changed. The second useable parameter is the frequency (period) of the acoustic wave and thus the diffraction angle (tilt of the wavefront) of the diffracted beam. In some applications the frequency shift introduced by interaction with the moving wave is also used [1].

Piezo translators (PZTs) are part of most phase-shifting interferometers. They introduce a pure phase shift by moving the reference mirror of the interferometer by fractions of the wavelength. Some telescopes use a segmented mirror array with up to several hundred PZTs, so that static and dynamic phase aberrations can be removed. Another phase shifting device is the liquid crystal phase shifter (LCPS). The phase shift is introduced by changing the orientation of liquid crystal molecules in a thin cell by applying an electric field. Depending on the polarization of the incoming light with respect to the orientation of the molecules, the device can also change the polarization state of the light. Typical applications for such LCPSs are in the fields of phase-shifting polarization interferometry and phase-contrast microscopy.

The top set in figure 1 represents the class of modulators that influence the shape of the interacting wavefront. In the simplest case, a tilt is introduced to the wavefront by flipping solid mirrors about one or two axes. This is achieved by galvano-scanners. Other devices enable the control of optical power without any moving parts. Liquid crystal lenses have a laterally varying phase shift realized either with a convex or concave liquid crystal cell or with a high resistivity electrode causing a weaker electric field in the center of the lens than at its edge. Electrowetting lenses [2] operate upon the effect obtained when the contact angle of a liquid/liquid-interface with a solid casing changes as voltage is applied to the casing. Due to the fact that the two liquids have different indices of refraction, the modified shape (curvature) of the interface causes a change in the optical power of the lens. An application of these lenses is expected to be used in the next generation of mobile camera phones. Deformable membrane mirrors (DMMs) offer more degrees of freedom. They usually consist of a metallic membrane with up to nearly 100 underlying electrodes. Voltages on the electrodes generate electrostatic forces which determine the shape of the mirror. Due to their fast response time, they are often used in compensation optics for the removal of the influence of atmospheric turbulence in ground-based telescopes. Other types of membrane mirrors use thermal expansion, magnetic forces or piezoelectric actuators for the membrane deformation. The most variability is offered by spatial light modulators (SLMs) such as liquid crystal displays (LCDs) or micro mirror arrays (MMAs), basically consisting of arrays of up to millions of liquid crystal cells or movable mirrors which can be individually controlled. Operation modes vary between binary amplitude modulation (flip MMA, ferroelectric LCD with polarizers), continuous amplitude modulation (LCD with polarizers), binary phase modulation (ferroelectric LCD) and continuous phase modulation (piston MMA [3], LCD). Wavefront shaping is best achieved with the continuous phase modulators. Wavefront deviations of many wavelengths, however, can be achieved in a diffractive manner with all 4 types, whereas the best efficiencies are achieved with continuous phase modulation capability between 0 and 2π . The devices then act as flexible diffraction gratings where the local grating period determines the local deflection angle. One disadvantage of pixelated devices is the appearance of unwanted diffraction orders. It is advisable to characterize the device prior to its application [4].

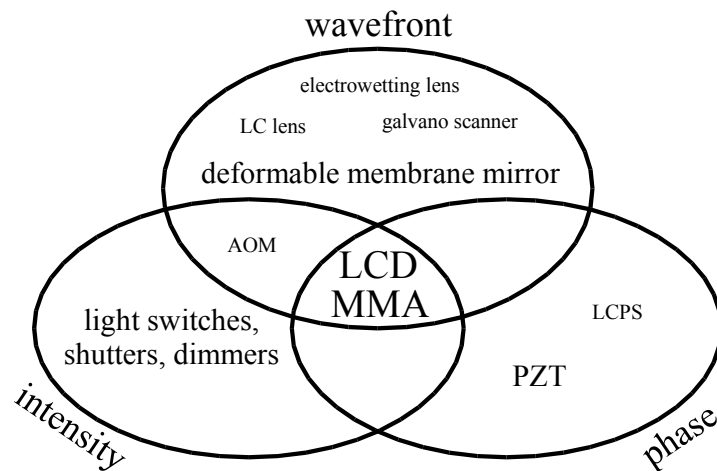


Figure 1: Overview of the most commonly used light modulators showing devices that modulate intensity phase and wavefronts. The font size indicates the number of controllable parameters (smallest for 1 or 2, intermediate for 10 to 1000, and largest for up to millions)

2. Phase shifting point source array

The phase-shifting point source array (fig. 2 left) is a device that enables free intensity regulation and independent phase shifting of point sources arranged on a regular grid. It consists of a high-resolution liquid crystal display (LCD) followed by a microlens array and an array of pinholes aligned centrally behind the microlenses at a distance that corresponds to the focal length of the microlenses. The pinholes constitute the potential positions of light sources. The illumination of the PPA is monochromatic, collimated and is aligned with a slight tilt. The LCD pixels are electrically addressed and controlled by software to be either transparent or non-transparent (in principle, any modulation would be suitable, e.g. also phase modulation). When the entire LCD is non-transparent, all point sources are inactive. Even if part of the light is transmitted by the LCD (contrast ratio of LCDs typically 1:250), it will be blocked since the tilted light is focused onto a spot next to the pinhole. In order to activate a point source, a local linear grating needs to be displayed by the LCD in front of a microlens. The grating causes several diffraction orders which generate a line of focal spots in the plane of the pinholes. The tilt of the PPA illumination is aligned in such a way that only the first diffraction order goes through the pinhole. The point source is now active. This arrangement also allows a phase-shift of the light emitted by the point source by laterally shifting the displayed grating. The amount of phase shift is calculated using the following equation:

$$\Delta\varphi = 2\pi \frac{d}{P},$$

where d is the lateral shift and P is the period of the displayed grating. The intensity of the light source can be adjusted by displaying gratings with varying diffraction efficiencies.

The interferometer shown in fig. 2 (right) was equipped with a PPA. Together with the collimation lens, the PPA generates reference waves with varying tilt angles and also provides the phase shift for standard phase shifting interferometry algorithms. In this way a common problem in aspheric testing - the inability to evaluate regions with too high fringe densities - could be greatly reduced since the fringe density depends on the angle between object wave (the one reflected by the surface under test) and reference wave. Several measurements with different reference wave tilts are combined to reveal the overall surface shape. Due to the fact that no mechanical actuators are used in this setup, the results are highly reproducible. Furthermore, the different reference waves can be calibrated to each other by switching on two reference waves at once and phase-shifting one of them while the object wave is blocked. More details about the method are given in [5].

The fields of coherent fringe projection or digital holography offer other possible applications for the phase-shifting point source array.

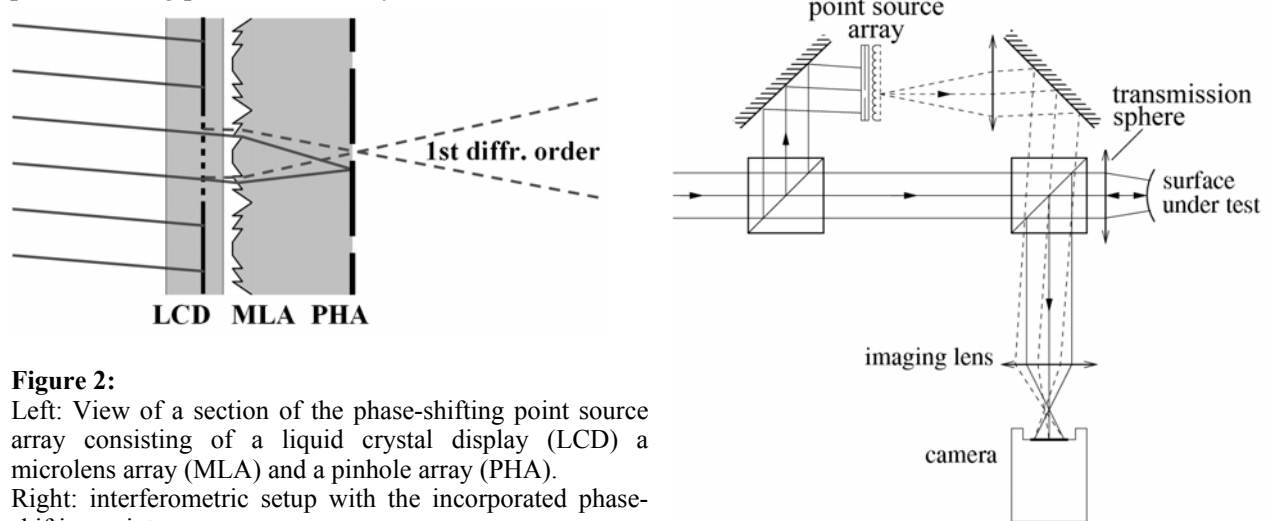


Figure 2:

Left: View of a section of the phase-shifting point source array consisting of a liquid crystal display (LCD) a microlens array (MLA) and a pinhole array (PHA).

Right: interferometric setup with the incorporated phase-shifting point source array.

3. Adaptive Shack-Hartmann sensor

A Shack-Hartmann sensor (SHS) is a wavefront sensor used in a wide range of applications such as adaptive optics in astronomy, laser beam analysers and non contact measurements.

In a conventional SHS, a static microlens array is used. The wavefront is sampled by the microlens apertures and brought to a focus on a camera chip. The focus positions are measured and compared to the focus positions measured with a plane reference wavefront. The displacements are proportional to the local wavefront tilts which are used to calculate the wavefront shape.

In the adaptive SHS [6] the static microlens array is replaced by a spatial light modulator that displays freely programmable diffractive microlenses. In our experimental setup we use a high resolution liquid crystal display (LCD, 1024x768 pixels) in amplitude modulation. In the basic setup each microlens is a Fresnel zone plate. 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, favours measurement precision but limits the maximal measurable wavefront slope.

The measurement dynamic of the conventional sensor is limited by the fact that spots leave their sub-apertures (defined by the center of the microlens and its size) when large wavefront slopes are present (fig. 3). An unambiguous assignment of the spots to their microlens is not possible. There are special spot search routines that try to solve this problem. The adaptive sensor solves this problem by switching on or off single lenses or groups of lenses in order to identify the corresponding spots. The measurement dynamic is thereby increased.

Precise measurements require a precise determination of focal spot positions. This is not always possible because curvatures in the incoming wavefront cause blurred focal spots. With the adaptive sensor these curvatures can be considered in the design of each microlens. However, an approximate knowledge of the wavefront shape is necessary. This knowledge can be gained by making a preliminary measurement with uncorrected lenses. The adapted microlens design results in a point-like focal spot (see fig. 3). Therefore the measurement accuracy is increased.

Very strong curvatures in the wavefront could result in an overlap of neighbouring focal spots. The adaptive sensor can overcome this problem by adding a well-defined tilt to the microlens hologram. This increases the dynamic range.

The intensity of focal spots can strongly differ due to an inhomogeneous illumination. This decreases the signal-to-noise ratio for dark spots. The intensities of the spots can be balanced by adjusting the efficiency of the diffractive microlenses. The camera can then be used with the maximal possible signal-to-noise ratio.

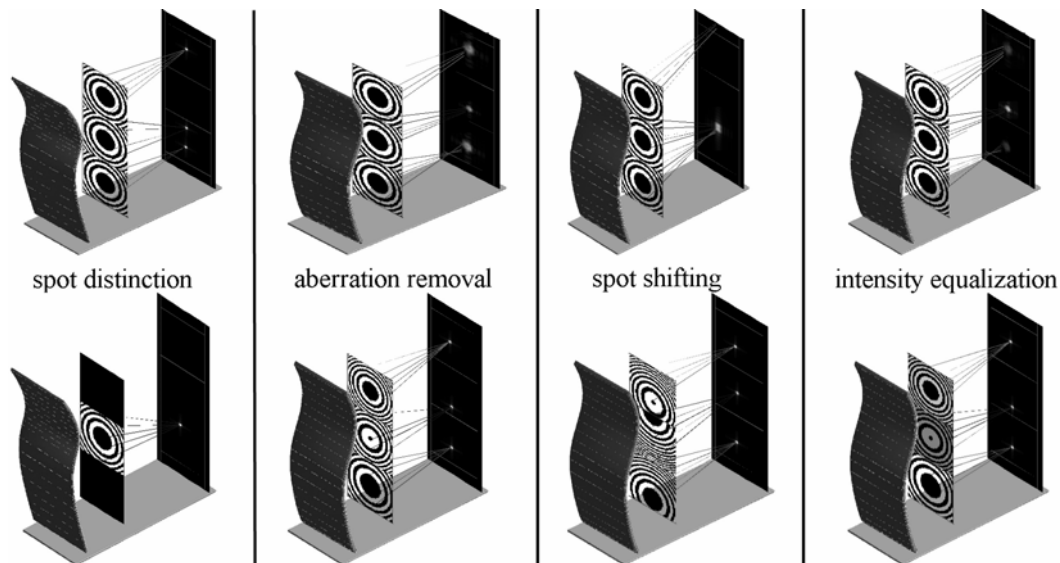


Figure 3: Features of the adaptive SHS.

4. Holographic optical tweezer

Optical tweezers use a focused beam of light to trap particles which have a size ranging from a few hundred nanometres to several tens of micrometers. Due to the non-contact character of optical tweezers they are very suitable for handling microbiological objects. Moving the trapped particles is possible by steering the focussed beam by means of mechanical actuators such as tiltable mirrors and movable lenses. Multiple traps can be established with beam splitters and the same number of mechanical actuators for each optical path. However, systems become quite complex if three or more traps are desired. The use of two acousto-optical modulators (AOMs) is one way of generating multiple traps [7]. The deflection angle of the (AOMs) is quickly switched from one trap to next, so that for each trap a pulsed optical trap occurs. Our approach, the holographic optical tweezer (see fig. 4), features even more flexibility. We incorporate a spatial light modulator (SLM) such as a micro-mirror array (MMA) or a liquid crystal display (LCD). Like optical tweezers with AOMs, holographic optical tweezers offer the ability to move many particles independently of each other without using mechanically moving parts. Furthermore, they allow us to move the particles also along the optical axis. The steering of the focal spots is done by placing the SLM in the Fourier plane of the focal spot and displaying "holograms" such as linear blazed phase gratings or Fresnel zone plates for the lateral or the axial motion respectively. A combination of both allows a motion in any direction in 3D space. Multiple traps are generated by displaying holograms that are calculated using a complex addition of the single trap holograms. The SLM can also be used to remove aberrations in the optical system so that a small focal spot is guaranteed [8]. Likewise, an artificial spot deformation is possible by modifying the single trap's hologram. Adding astigmatism, for example, generates a focal line. Adding a phase spiral results in a doughnut-shaped spot (intensity ring) which shows an increased trapping efficiency in some cases and can be advantageous when used with biological objects with light sensitive parts in the center.

The current work at the Institut für Technische Optik concentrates on force measurements and using the graphical processing unit (GPU) of the graphics board for rapid hologram calculations.

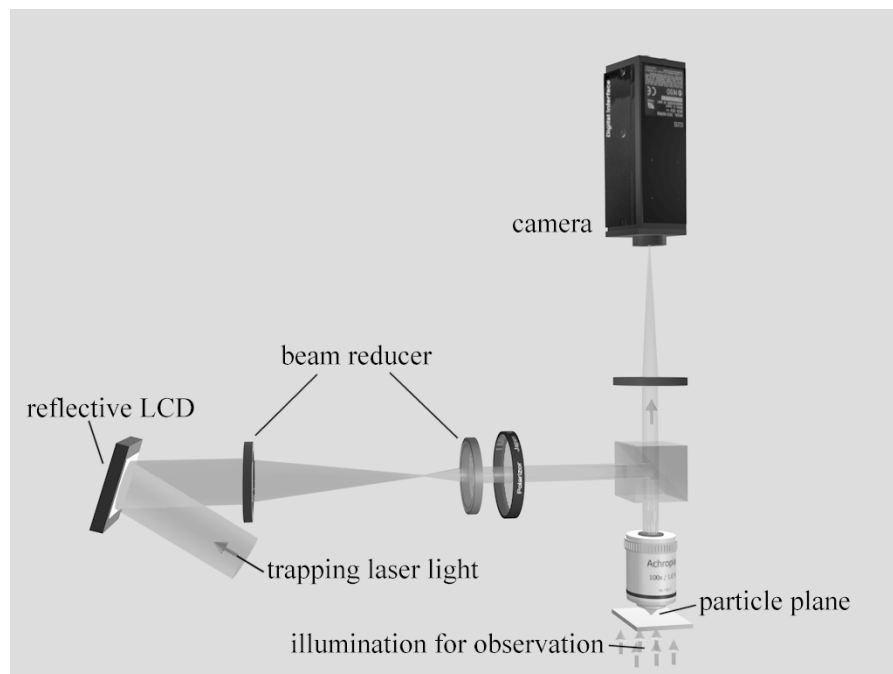


Figure 4: Sketch of the holographic optical tweezer setup. Particles are trapped and manipulated in the particle plane. All functionality is achieved by displaying holograms with the LCD.

5. Summary and Conclusion

As the three examples have shown, light modulators, especially the high resolution spatial light modulators with millions of individually-controllable pixels such as LCDs or MMAs, offer the possibility of bringing more flexibility into a great range of applications. Though some of the devices modulate only the amplitude or the phase up to a maximum phase shift of about one wavelength or less, complex phase functions with up to several hundred wavelengths of phase shift can be achieved when the devices are used as flexible diffraction gratings. A fact that must be considered is that the periodic pixel structure of the elements generates unwanted diffraction orders which also limit the amount of usable light.

Acknowledgements

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