FP2: Digital holography

Instruction guide for the practical course

Division of Biomedical Physics
Medical University Innsbruck

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1 Overview

A so called spatial light modulator (SLM) is a miniaturized liquid crystal display (LCD), which is used to imprint a desired spatial pattern of amplitude or phase in a light field.

A common application of SLMs is the modulation of the spatial intensity of light in digital projectors. SLMs are also used for phase modulation of light, which allows for an efficient presentation of digital holograms. Further applications in technical fields and science are optical switches or multiplexers (telecommunication), wavefront shaping, or pulse shaping for ultrashort pulse lasers. At the Division of Biomedical Physics SLMs are used for controlling optical tweezers and for Fourier filtering in microscopy.

The main goal of this practical course is the introduction to the handling of SLMs and to learn the basics about the creation of synthetic phase holograms.

1.1 Requirements

Basic knowledge in: holography, Fourier optics, Fraunhofer diffraction, binary/blazed grating, coherence length, diffractive optics, Michelson interferometer, Matlab/programming basics

What you bring: own phase image on memory stick, lab book

1.2 References

- Ernst Hecht, Optics.
- Demtröder W., Experimentalphysik 2, Elektrizität und Optik
- Reynolds, The New Physical Optics Notebook: Tutorials in Fourier Optics
- lecture notes: Holography, interferometry, diffractive optics of Univ.-Prof. Dr. Stefan Bernet (Division of Biomedical Optics, Medical University Innsbruck)

1.3 Location

Attention: The practical course will take place at the Division of Biomedical Physics, Müllerstraße 44 (hospital area).

1.4 Implementation and lab report

As always it is required to be well prepared and one has to understand the physics behind the experiment. For the report it is helpful and advised to make sketches and notes during the experiment. The report should show that you understand the basics of diffractive optics and know how to control the SLMs.

1.5 Safety instructions

- Never look directly into the laser beam.
- The laser beam must not leave the working area on the optical table.
- Pay attention with reflective devices. Remove watches, jewelry, or other reflective objects.

1.6 Hints

- Please do not rotate the laser, this would result in an unwanted rotation of the polarisation.
- Please do not touch the screen of the spatial light modulator (SLM).
- The control software for the camera is called *wxPropView*.
- You do not need to prepare/bring your own MATLAB program. Nevertheless it is helpful to discuss briefly how one could implement the different tasks.

2 Introduction

2.1 A very brief outline of holography

In 1947 holography was developed by the Hungarian physicist Dennis Gabor (Nobel price in 1971). Holography is a method that allows the storage of amplitude- and phase distributions of a light field (e.g. light scattered by a real object) on a medium, the so called hologram, such that the original light field can be reconstructed completely (see figure 1).

In order to measure the phase distribution of the light field, the object wave has to be superimposed with a reference wave (often a plane wave) with known amplitude- and phase distribution. The intensity distribution of the resulting interference pattern is recorded, e.g., by a photographic film or an electronic image sensor. Interference is only observed if the (laser) light is sufficiently coherent in time and space.

There are several possibilities to regain the information of the object which is stored in the hologram. In classical holography the developed film material is illuminated with the reference wave, which needs to be positioned identically as during the recording. Due to diffraction at the interference pattern a light field is created whose properties are the same as those of the incident light field during the recording. An observer gets the impression that the light originates from the real object. The reconstruction can also be obtained mathematically with a computer, historically this approach is called digital holography.

Instead of a photographic film a SLM can be used, which also provides the possibility to display synthetic holograms, which are calculated using a computer.

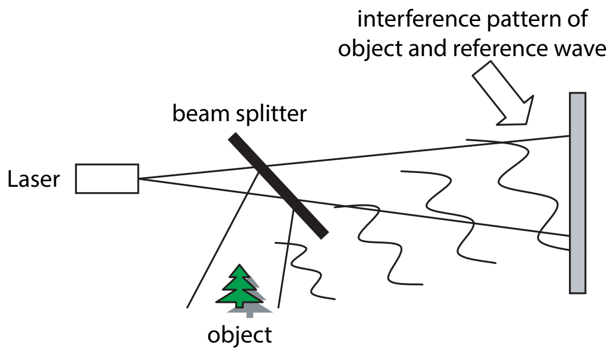


Figure 1: Schematic of recording a hologram. The beam of a coherent light source is split into a part illuminating the object and a reference wave. The object wave (containing information about the object) is superimposed with the reference wave. The resulting interference pattern is recorded on a film or a digital sensor.

2.2 Digital holography

2.2.1 Spatial light modulator

A spatial light modulator (SLM) is (as the name suggests) used to modulate optical wave fronts. The SLM used in the experiment is a miniaturized LCD with 1920 x 1080 pixels. The size of each pixel is about 10 µm. A voltage can be applied to each pixel individually. Depending on the applied voltage the birefringent liquid crystal molecules are rotated. This changes the optical path length for the incident wave, which results in a phase shift (see figure 2). For a properly chosen direction of linear polarization the polarization itself stays unaffected, and the SLM acts as a pure phase modulator. The otherwise observed change of the polarization state can be used (in combination with a polarizer) for amplitude modulation. This configuration is used, e.g., in digital projectors.

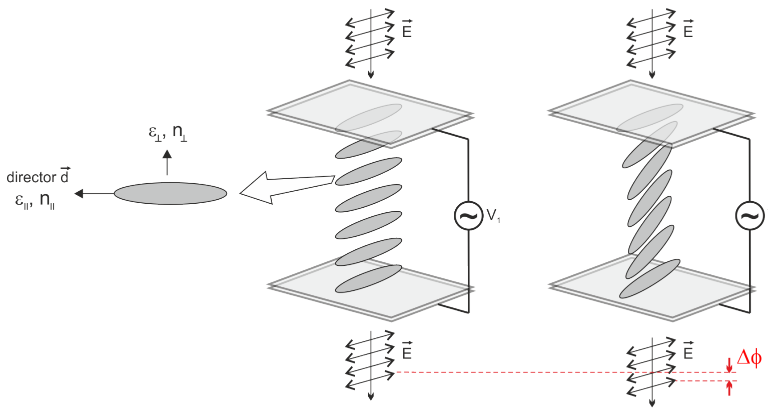
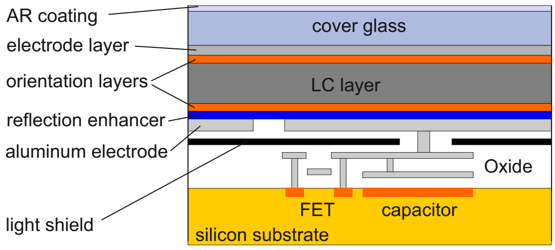


Figure 2: Principle of an SLM acting as a phase modulator. As long as no electric field between the electrodes is applied, the liquid crystal molecules are oriented parallel to the surface. Under the influence of an electric field the molecules are forced to change their alignment as shown. This changes the optical path length for the incident wave, which results in a phase shift. If the polarization is parallel to the long axis of the LC molecules, then the polarization itself stays unaffected, and the SLM works as a pure phase modulator.

Most of the currently manufactured SLMs work in reflection mode (see figure 3). The major advantage of this design is a higher density of pixels per unit area due to the fact that electrical controlling components can be hidden behind the reflective layer. Furthermore, because the light is reflected, the effective thickness of the liquid crystal layer is doubled.



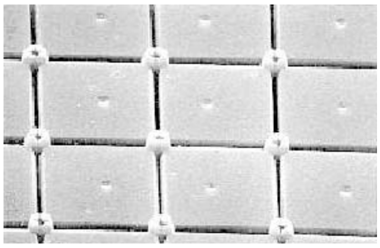


Figure 3: Left: cross-section of a reflective SLM with LCoS (liquid crystal on silicon) technology. Right: image of the SLM silicon layer.

The SLM is controlled by the graphics card of the computer. An 8-bit gray image, displayed on the computer screen, is transformed by the SLM to a phase pattern with 256 different levels between 0 and 2π.

2.3 Calculation and realization of a digital hologram

Figure 4 shows a common optical setup for using SLMs to display digital holograms.

In this configuration **no image** of the intensity distribution of the source is being produced at the target plane. Instead, the electric field in the target plane $E_T(x,y)$ is related to the field of the source $E_S(u,v)$ by a Fourier transform

$$E_T(x,y) \propto \mathscr{F}(E_S(u,v)) \propto \int E_S(u,v)e^{-i\frac{2\pi}{\lambda f}(ux+vy)}\mathrm{d}u\mathrm{d}v\,, \tag{1}$$

leaving out any scaling factors. Here f denotes the focal length of the lens and λ the wavelength.

A central task in computer generated holography is to find and realize a suitable *phase* hologram, which leads to the wanted intensity distribution at the target plane. In general one can only find an approximate solution. An SLM used as phase modulator only changes the phase $\phi(u,v)$ of the electric field $E_S(u,v) = a(u,v)e^{i\phi(u,v)}$. The amplitude distribution $a(u,v)$ remains unchanged by the SLM. Even though one can invert equation (1),

$$E_S(u,v) \propto \mathscr{F}^{-1}(E_T(x,y)) \propto \int E_T(x,y)e^{i\frac{2\pi}{\lambda f}(ux+vy)}\mathrm{d}x\mathrm{d}y\,, \tag{2}$$

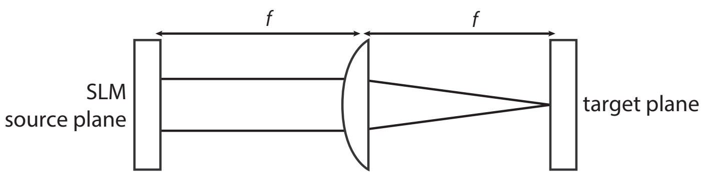


Figure 4: SLM plane (source) and the object plane (target). The field intensities $E_S(u,v)$ and $E_T(x,y)$ are related by the Fourier transform. The coordinates of the SLM plane are u and v, and x and y for the target plane.

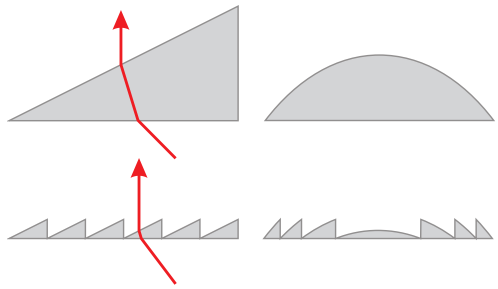


Figure 5: left: blazed grating. right: diffractive lens.

the realization of $E_S(u,v) = A(u,v)e^{i\Phi(u,v)}$ requires in general both amplitude and phase modulation.

Remark Using two SLMs allows for the control of the phase and amplitude distribution, making an exact implementation possible. In certain configurations even two phase-only modulations are sufficient. Only for a few cases a single phase hologram is enough to (in theory) realize the wanted intensity distribution exactly. Examples are holograms that act as prisms or lenses.

2.3.1 Implementation of simple intensity distributions

As a starting point one tries to generate the simple point-like distribution

$$E_T(x,y) = \delta(x - x_0)\delta(y - y_0)$$

at the position (x_0, y_0) in the target plane. With equation (2) the associated source field is $E_S(u,v) = e^{i\frac{2\pi}{\lambda f}(ux_0+vy_0)}$. This can be generated by pure phase modulation with

$$\phi(u,v) = \arg(E_S(u,v)) = \frac{2\pi}{\lambda f}(ux_0 + vy_0) \mod 2\pi\,. \tag{3}$$

This sawtooth shaped phase distribution, as shown in figure 5, is also used for so-called blazed gratings, which show a high diffraction efficiency. One can conceive that this grating emanates from splitting a prism, where parts have been removed that change the optical wavelength by integer multiples of λ. For monochromatic light these gratings are equivalent to the original prism. The same principle can be used for other optical elements like lenses (see figure 5, right). These elements are called diffractive lenses.

2.3.2 Realization of arbitrary intensity distributions

There exist different approaches to calculate phase holograms that generate a required intensity distribution. Here the Gerchberg-Saxton (GS) algorithm will be introduced.

Originally the algorithm was developed to determine the phase distribution of a propagating field by measuring the intensity distribution in (at least) two planes along the propagation direction (see figure **6**). One iteratively approaches the solution by initially assuming a certain phase distribution in plane 1 (based on an educated guess or by starting with a random pattern). The field (phase and amplitude distribution) at plane 2 can be calculated from the field at plane 1 by mathematical propagation, see section 2.3. The simulated intensity at plane 2 will differ from the measured one, due to the wrong initial assumption about the phase. The next step is to replace the calculated

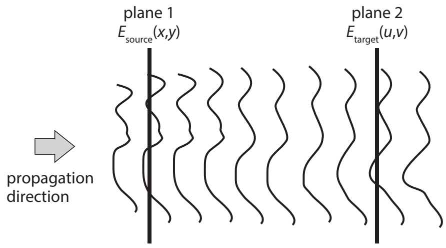


Figure 6: The phase of a propagating wave front can be determined from the knowledge of the *intensity* distribution in at least two cross-sectional planes.

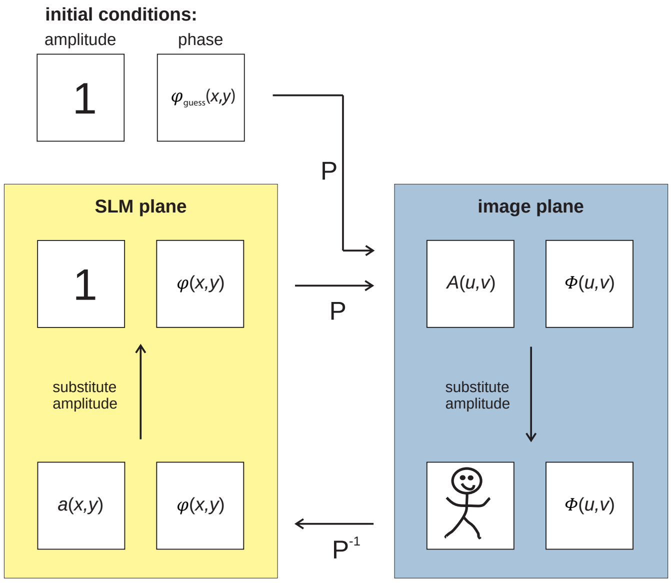


Figure 7: Application of the Gerchberg-Saxton algorithm to calculate a phase hologram.

amplitude distribution by the measured one, keeping the phase unchanged, and propagate this field back to plane 1. There one also replaces the calculated amplitude by the real one, which completes the first iteration. With every iteration the resulting field will be closer to the real one. Depending on how close the initial choice of the phase distribution was to the real one, the iteration will converge to the true solution, or a local optimum.

The GS algorithm can also be used to find a phase hologram that generates a desired intensity distribution. The principle of this method is illustrated in figure 7. Usually one assumes a constant homogeneous intensity in the plane of the hologram. The intensity in plane 2 corresponds to the desired target distribution. Given that this can not be achieved by only using phase modulation, one gets a phase hologram that generates the wanted target intensity only approximately. Typically there is also a fine-grained structure observable, the so-called *speckle pattern*.

3 Instructions for experimentation

3.1 Optical setup and implementation of a grating

In the beginning the basic optical setup as shown in figure 8 needs to be implemented. As the available LCoS-SLM works in reflection, a (non-polarizing) beam splitter is used to separate the in- and outgoing beam. The imaging lens with focal length $f = 200$ mm is positioned at a distance $f = a + b$ relative to the SLM and the screen at a distance f after the lens (adjust positions such that beam is focussed at screen). On the SLM a blazed grating with a period of 2-10 pixels shall be displayed (Matlab program to generate the desired pattern on the SLM will be provided).

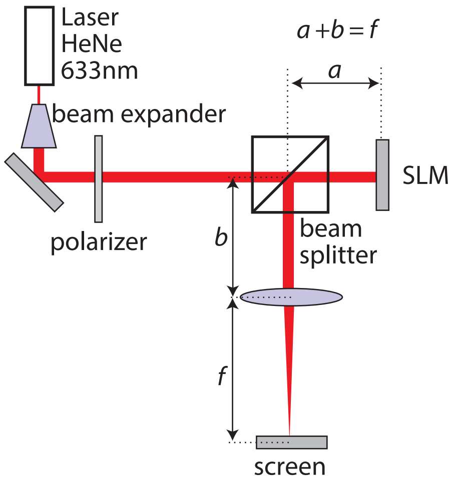


Figure 8: Optical setup

Tasks

- Document the diffraction pattern (position, intensity) for different grating periods. What intensities are expected theoretically?
- Measure the distance between the diffraction orders and calculate the pixel size of SLM. (Note: diffraction angle $\alpha_i \approx \tan\alpha = x_i/f$, where x_i denotes the position of the i-th diffraction order at the screen, and f the focal length of the lens. Wavelength of HeNe laser is 633 nm.)

3.2 Implementation of a diffractive lens

Based on the Matlab program to produce a grating, a modified program should be written to create the phase pattern of a diffractive lens. This pattern shall shift the position of the focus by a distance $z_0 = 50$ mm.

Hint: Realize a source distribution $E_S(u, v) = \exp\left(i \frac{\pi}{\lambda f^2}(u^2 + v^2) z_0\right)$.

Tasks

- Validate the program by measuring the focus position with and without the lens hologram.

- What limits the maximally achievable focus shift z_0?
- What happens when the phase pattern is moved on the SLM?
- How does one achieve that the focus is at the position (x_0, y_0, z_0) relative to focus of the 0th order?

3.3 Generation of multiple independent foci

The goal is now to not only generate one single focal point at the screen, but to produce two points, i.e., the desired intensity distribution is given by

$$I(x,y) \propto \delta(x-x_0)\delta(y-y_0)+\delta(x-x_1)\delta(y-y_1).$$

Tasks

- How can two phase holograms, each of which creates a single spot, be combined to a single phase hologram that creates two spots in the focal plane?
  Hint: What's the difference between $\exp(i\phi_0)\cdot\exp(i\phi_1)$ and $\exp(i\phi_0)+\exp(i\phi_1)$?
- What problems are observed?

3.4 Representation of arbitrary intensity distributions

The aim is to produce a phase hologram of a specific intensity distribution using the Gerchberg-Saxton algorithm (program will be provided). Bring an image on a memory stick (black and white image, size approx. 500×500 pixels). Well suited for a holographic reconstruction are e.g. drawings made up of (few) lines.

Tasks

- Document the generated intensity distribution with a digital camera (replace the screen by the camera, use an attenuator).
- What are the differences between the original and the generated images?
- How does the number of iterations in the Gerchberg-Saxton algorithm influence the outcome? Compare the result after 1 and 10 iterations.

3.5 Recording of a digital hologram

To measure the phase of a wavefront an interferometer must be set up as shown in figure 9.

After aligning the setup, place a transparent phase object (e.g. nail polish or adhesive tape on glass slide) before the SLM. The interference pattern of the reference beam and the distorted wavefront contains information about the phase of the wavefront and therefore about the thickness of the phase object. For a complete capture of the wavefront three interference patterns (I_1, I_2, and I_3) with different relative phases between the two beams (0, $2\pi/3$ und $4\pi/3$) need to be recorded. The phase shift of the object can be reconstructed using

$$\phi = \arg(I_1 + I_2 e^{i\frac{2\pi}{3}} + I_3 e^{i\frac{4\pi}{3}}). \tag{4}$$

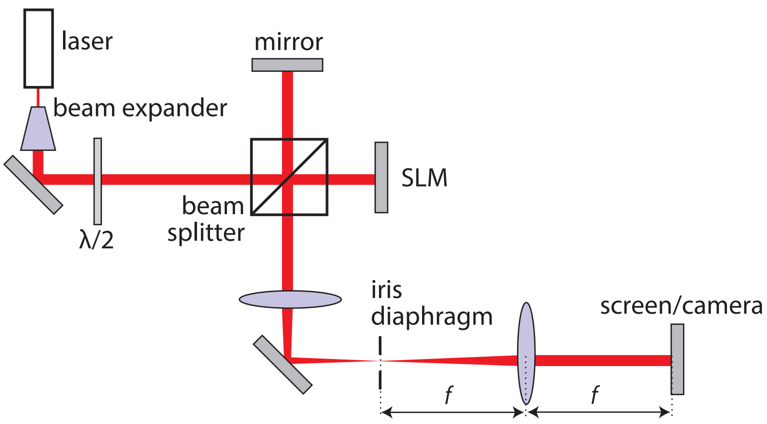


Figure 9: Optical setup for recording a digital hologram.

The so called "phase stepping" of the relative phase is often realized by a mirror mounted on a piezo actuator. In our case it is sufficient to shift the grating at the SLM, as the phasing of a beam diffracted by a grating is dependent on the gratings position. Moving the grating by one pixel causes a change in the phase of $2\pi/G$ where G denotes the (lattice) period of the pixel of the SLM.

By displaying the negative of the measured phase at the SLM, the wavefront distortions can be corrected. This demonstrates the basic principle of adaptive optics, which is widely used in astronomy or microscopy to compensate the effects of atmospheric turbulences or aberrations caused by biological specimens.

Instructions for aligning setup

1. Block the reference beam going to mirror.
2. Display a blazed grating with a period of 3 pixels and a circular mask on the SLM.
3. Place an iris diaphragm at the focal plane of the lens, such that only the first diffraction order passes through.
4. With another lens (focal length $f = 100\,\text{mm}$) create a (demagnified) image of the SLM on the screen. Use distances for lens and screen as shown in figure 9.
5. Unblock the reference beam and align it such that it coincides with the beam coming from the SLM (check at focal plane). Interference fringes should be visible at the screen.
6. Replace the screen with a digital camera. Adjust the position of the camera until the pattern on the SLM is imaged sharply.
7. Place a test phase object (transparent nail polish or tape on a glass slide) close to the SLM but **do not touch** the surface of the SLM. The fringes will appear distorted due to small variations of the thickness of the test object.

Tasks

- Determine the phase of the distorted wave front:

  Take three images I_1, I_2, I_3, where the pattern on the SLM is shifted by one pixel after each exposure. From these images calculate the phase distribution using equation (4).

- Correction of the wavefront distortions with the SLM:

  Display the inverted and properly scaled phase pattern on the SLM (program will be provided). After applying the correction, straight parallel inference fringes should be observable.