Lab instructions

Diffraction, interference and Fourier filtering

By Aitor De Andres, Rasmus Öberg and Magnus Andersson

1. Aim of the lab

During this lab you will get some practical experience on three different optical phenomena, diffraction, interference and Fourier transform, and how to apply them for real applications. Besides improving your understanding on the physics behind them, this practice will help you to learn the following:

- Basic image and data processing techniques
- Practice basic error estimations and propagation
- Writing skills to compose a scientific report
- Good practices and in laser safety

Read the whole instructions and familiarize with them before attending the lab. You don't need to understand everything before the practice, but should you have any questions please reach out your lab supervisors.

2. Theory introduction

a) Diffraction and interference

Although we tend to observe and study them together, diffraction and interference are actually two different phenomena. Let's break them up:

Diffraction is the bending of a wave (i.e. the change of its propagation direction) when it interacts with the sharp[1] edge of an object. According to the Huygens-Fresnel principle, we can understand diffraction as if the edge of the object that is illuminated would start emitting secondary spherical waves, as shown in figure 1.

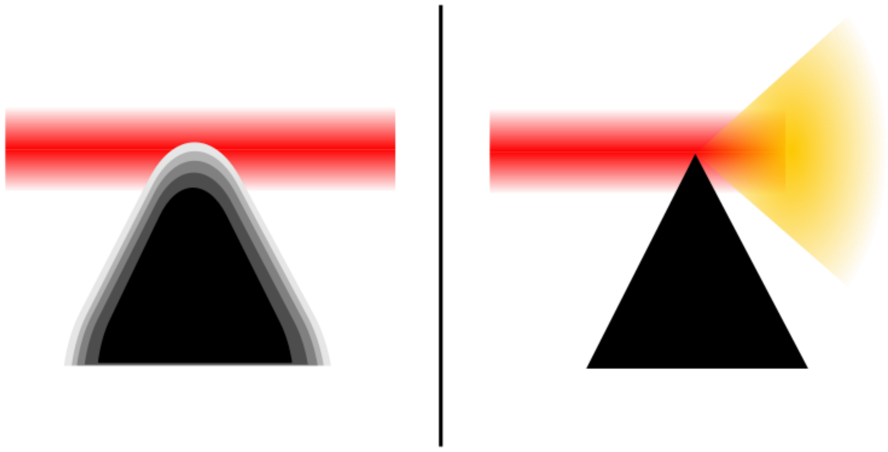

Figure 1: light interaction with a non-sharp (left) and sharp (right) object edge, showing diffraction only in the latter case. Notice that while the diffracted light has been drawn in a different color for the sake of clarity, in reality diffraction does not change the color (wavelength) of the light.

[1] In here, sharp means that the change of index of refraction between the object and its surroundings should happen in a shorter or comparable distance than the wavelength of the wave that experiences diffraction.

Interference is the linear[2] combination of two different waves when they overlap in both space and time. It occurs when the light of at least two (or more) sources interact with each other, as shown in figure 2. Notice that we are not accustomed to observe interference in our everyday lives because common light sources are not coherent (every photon has a phase independent of each other). Although still happening, the created interference patterns randomize in space, effectively washing out the fringes.

Figure 2: interference pattern created by the overlap of two (left) and three (right) laser beams. Extracted and modified from [1].

In this lab, you will generate different interference patterns using a single coherent light source. Even though we just stated that at least two sources are necessary in order for the interference to occur, we will be able to use only one because the light will undergo diffraction with the edges of an object first, effectively creating a different light emitter at every edge. Then you will be able to observe the interference created by all those (secondary) emitters.

b) Fourier filtering

You all have already studied the Fourier transform, a mathematical tool that transfers information from the time domain into either the frequency or the spatial domain. A typical example of the one-dimensional Fourier transform is the decomposition of a temporal sound-wave signal into its frequency components, as shown in figure 3, to extract information about the emitter or to remove unwanted frequencies. Although a little more mind-bending, the same concept can be generalized to study or process signals in two dimensions, like an image, as shown in figure 4.

In this practice, you will realize an optics application of the Fourier transform known as spatial Fourier filtering, where you will physically transform an image into a decomposition of all its spatial frequencies, then you will filter out some of them, and finally you will inverse transform to see what the image looks like after the process.

[2] In here linear means that it obeys the superposition principle. In the future you might study non-linear phenomenon, where the electric fields of different waves combine to give new frequencies (colors), but this is out of the scope of this lab.

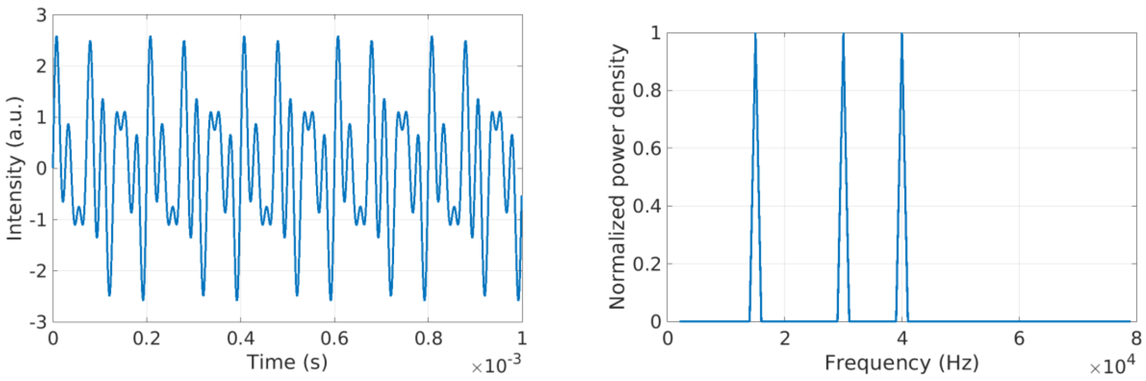

Figure 3: radio signal in the time domain made of three different sinus waves (left) and its Fourier transform showing the signal frequency components of 15 kHz, 30 kHz and 40 kHz (right). In this example, the Fourier transform rearranged the one-dimensional information from the temporal domain into the frequency domain.

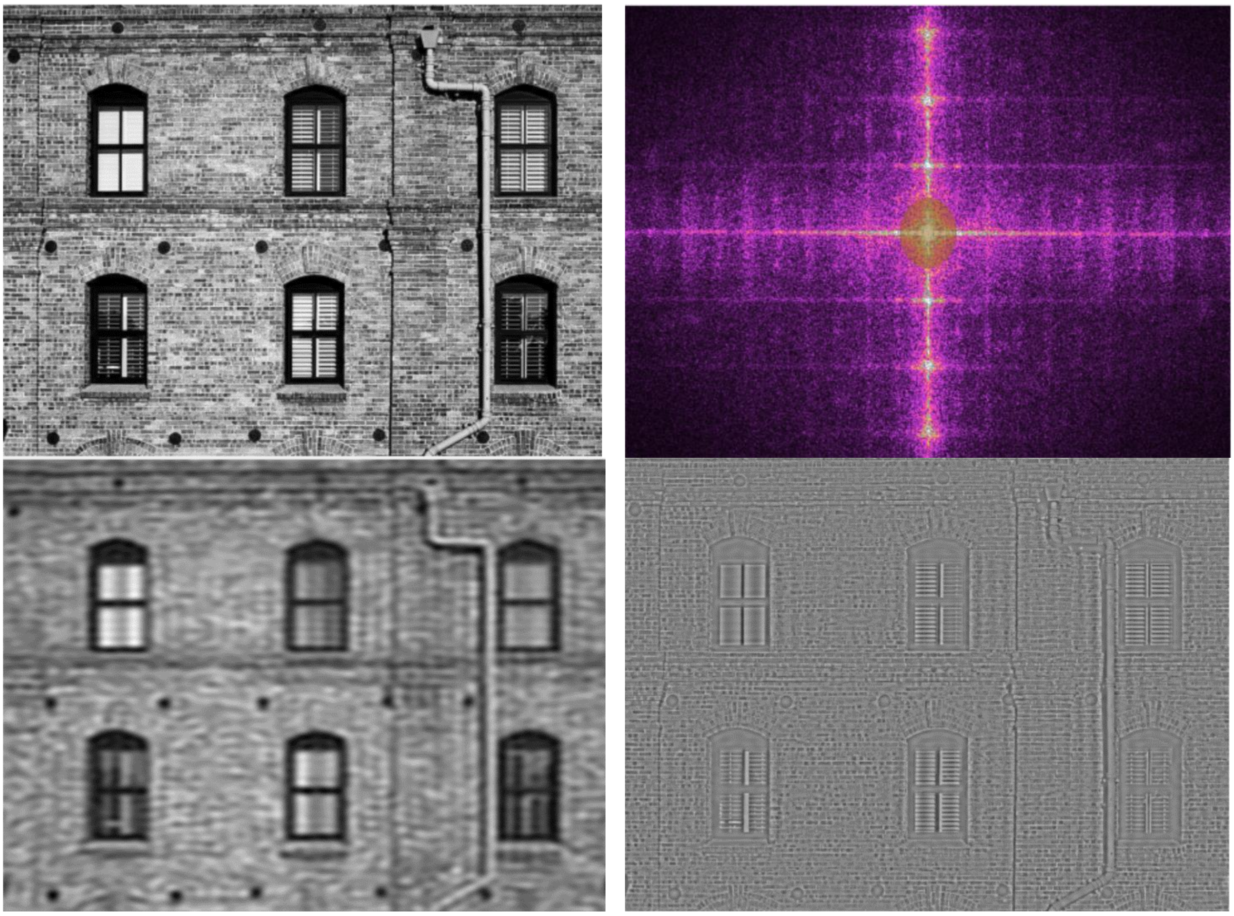

Figure 4: original image of a building made of bricks (top left) and its two-dimensional Fourier space (top right. Notice strong periodic features both vertically and horizontally in the Fourier space, which in this case originate from the periodic brick pattern of the building. Sub-figures bottom-left and bottom-right originate from inverse Fourier transforming the center region of the Fourier space (i.e. low frequencies) and the remaining outer region (i.e. high frequencies).

Let's illustrate how the spatial Fourier filter works by applying the principle described in figure 4. Figure 5 left shows the typical Matlab "peppers" image. Applying a 2D Fourier transform algorithm renders figure 4 center, where we can observe the decomposition of the image in its spatial frequencies for each dimension (vertical and horizontal). This is what we call the Fourier plane, and in our case we observe that most of the signal is around the center[3]. By inverse transforming the Fourier plane we recover the exact same original image shown in figure 4 right, as expected.

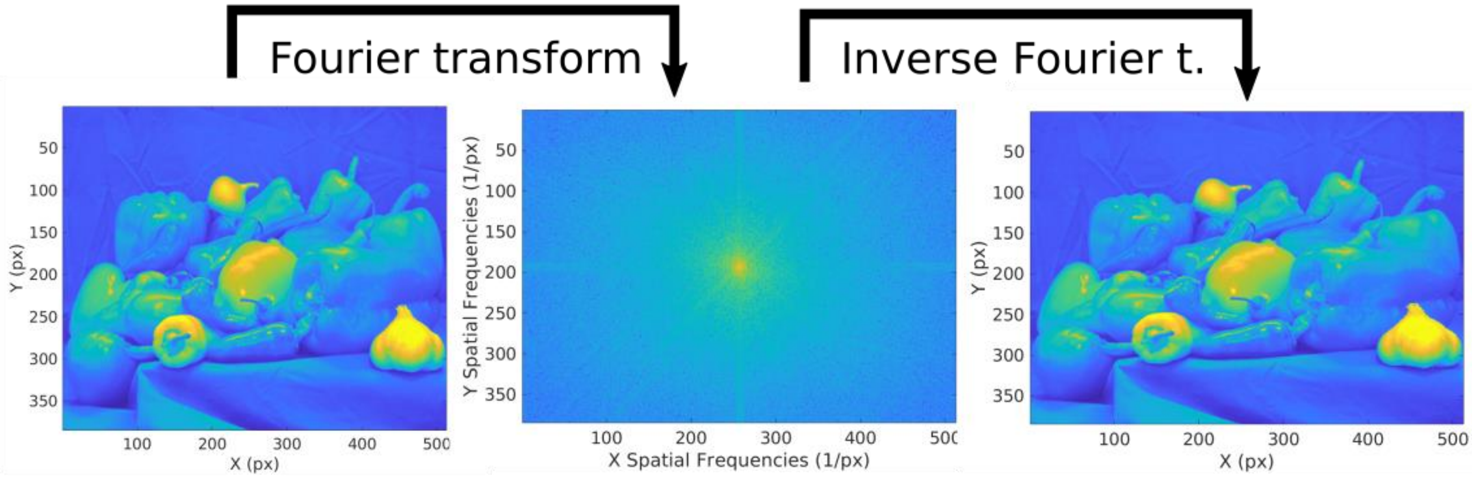

Figure 5: Original image (left) showing some peppers, which we decompose into its spatial frequencies (center) with a Fourier transform algorithm. Inverse Fourier transforming (right) renders back the original image.

Let's now add some noise to the original image, which for pedagogic purposes will be rather ideal (periodic in one dimension and with a high spatial frequency), looking as a grid of dark bars. The noisy image and its Fourier transform are displayed in figure 6 left and right, respectively. Notice that now the Fourier plane contains extra features corresponding to the added noise. If those extra features would be removed from the Fourier plane, the noise would be eliminated when we inverse Fourier transform back into the image. This is indeed what the spatial Fourier filter does, and the results of this technique are shown in figure 7, where the center part of the Fourier plane is kept but the surroundings are set to zero (left) and then the original image without noise is recovered[4] by inverse transforming (right).

---

[3] In the Fourier plane lower frequencies appear in the center, while higher frequencies manifest radially further away.

[4] Notice that the quality of the recovered image is somehow lower. This is a normal side-effect associated to any kind of filtering technique: when removing the undesirable part of the signal some valuable information is also lost.

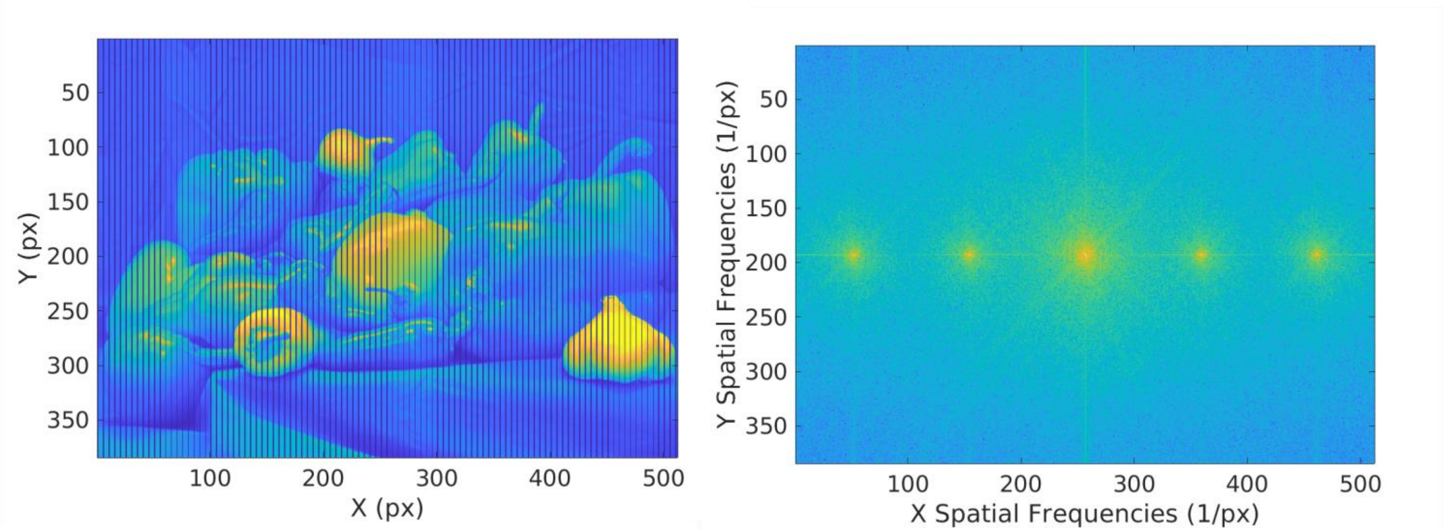

Figure 6: peppers image with periodic noise (left) and the Fourier transform of the noisy image (right).

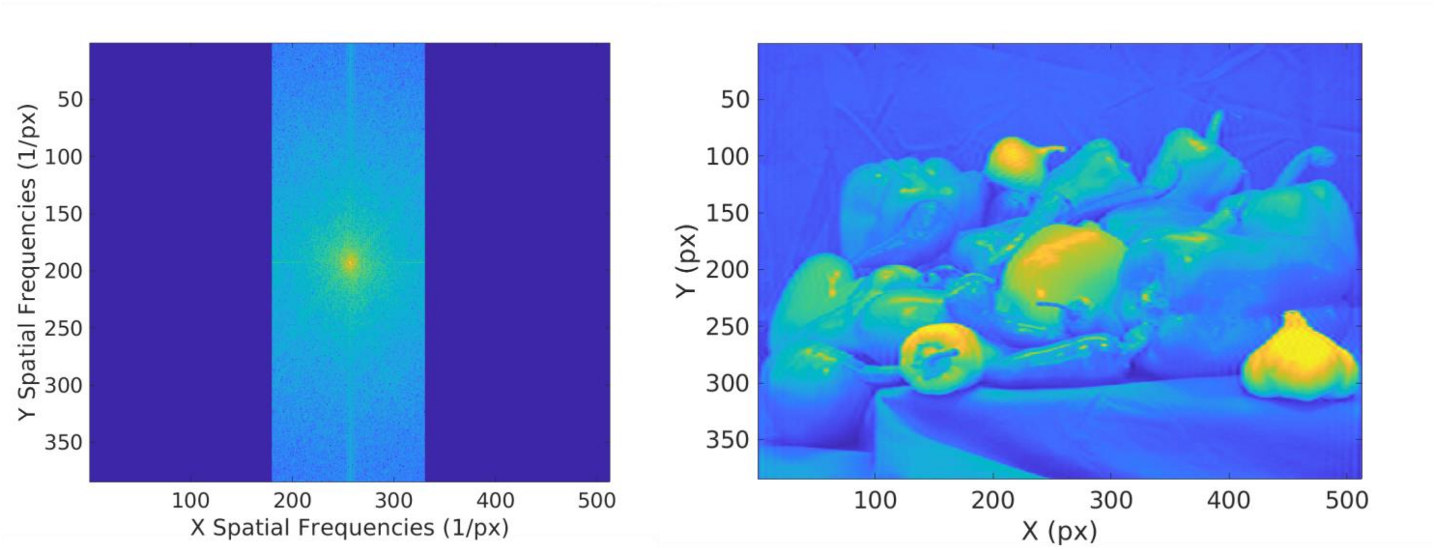

Figure 7: Fourier plane where everything except the center region was filtered out (left) and the result by inverse Fourier transforming (right).

Unlike the previous example with the peppers image, where computer algorithms were used to digitally perform and demonstrate the technique, during the lab you will physically implement the spatial Fourier filter on an image. This is possible because nature likes to do Fourier transforms in several situations. One of them relevant to us is the focusing of a light beam: it happens that focusing a collimated laser beam corresponds to performing a Fourier transform, and re-collimating it afterwards corresponds to inverse Fourier transforming, as shown in figure 8.

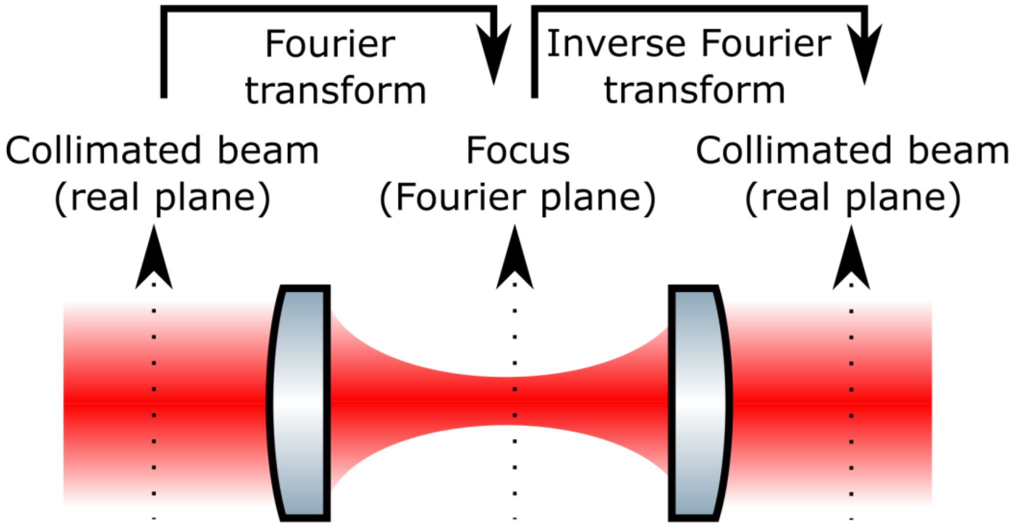

Figure 8: Diagram showing the collimated and focused planes of a laser beam, corresponding to the real and Fourier planes, respectively.

3. Lab protocol: instructions to follow during the lab

For this practice it will be very useful that each group brings a camera to the lab (the one of your smartphone is perfectly fine). If you don't have one or are not happy to bring it, your supervisor will happily help you to take pictures in the lab whenever needed. Please notice that you can do both lab parts (diffraction & interference, Fourier filter) in either order. Try taking notes during the practice about the setup that you are using in each experiment, it will help you to write your report later on.

a) Diffraction and interference

i. Remove all lenses and pinholes from the beam path, should there be any.
ii. Insert one diffraction object in the beam path, and project the interference pattern on a screen with a millimetric diffusing paper.
iii. Take a picture of the diffusing screen with the pattern on it. Try to make the picture as sharp as possible and placing your camera in the smallest angle that you can (i.e. place your camera in the front of the screen, not in the side).
iv. Repeat steps ii. and iii. until you have data of at least the following objects: a single slit, a double slit, a grating and a circular aperture. You can chose the size of the apertures, but **remember to write down which ones you have used** for the data evaluation later on.

b) Fourier filtering

i. Remove all diffraction objects from the beam path, should there be any.
ii. Expand the beam by constructing a Galilean telescope with two lenses (one negative and one positive). Mind that the beam should be as well collimated as possible after the telescope. Check this by measuring the beam size close by and far away from the telescope. When collimated, the beam size should stay the same as it propagates.
iii. Insert a transparent plate with a printed image of a moose in the expanded beam. Attach another plate with a noisy periodic pattern to the semitransparent plate. Double-sided sticky tape will be handy here.

iv. Image the moose plate with a single lens on a diffusive screen. Notice that there will be a focal spot between the imaging lens and the screen. Tip: use a rather long focal length for the imaging (around 300 mm).
Insert a pinhole close to the focus of the imaging lens. Align the focus to be precisely in the pinhole using the tip and tilt nobs of the mirror located after the imaging lens. Check how the image of the moose changes while you do it. Play with the alignment until you are satisfied. Afterwards, take a picture of the resulting (filtered) image. Then, remove the pinhole to see the unfiltered image, and take also a picture of it.

4. Data analysis and report: instructions to follow after the lab

Before the lab, you will attend a short seminar where different image analysis techniques will be shown. Using these techniques, extract the information from the images that you took during the lab. After that, write a lab report using the guidelines of standard scientific writing that you will have learned you during the lectures. Make sure that your report includes the following:

- The measured intensity vs angle for every diffraction pattern (i.e. one graph for the pattern of each diffraction object).
- The retrieved slit size that you calculate from each diffraction pattern, and a comparison with the expected value (the value written in the slit). Remember that both quantitates (the experimental and the expected) should have an estimated error. Notice that estimating the error has a specific and well defined procedure, it's not something up to your criterion. A summary of how to estimate the errors should be available in Cambro/Canvas.
- The comparison between the non-filtered and Fourier filtered image.

Bonus (including any of these parts will likely decrease the number of iterations until your report is approved):

- Calculate numerically the theoretical interference pattern that you should get for every diffraction object and plot it on the same graph where you show each experimentally measured pattern. This will provide easy comparison between the two.
- Include a "proficient" sketch of your experimental setup in the "materials and method" section. Although you are free to use any method, we recommend you to use a scalable vector graphics (SVG) compatible software, such as Inkscape (which is open-source, multiplatform and free). In Cambro you will be able to find a .svg document with standard optical components that you can use. Learning how to use it is an investment that will be for sure useful to you later on in your career.
- For the advanced: write a computer script (recommended in Matlab) that performs the spatial Fourier filter on your non-filtered image. Then, compare the result of the two filtering methods (computational vs physical).

If you have any questions about any of the points (including the bonus), feel free to contact your lab supervisors, we are here to help you learn :)

5. References

[1] R.P. Photonics encyclopedia, "https://www.rp-photonics.com/holography.html", accessed on 2020 Feb 02.

[2] Frank L. Pedrotti, "Introduction to Optics", Third edition, Pearson Prentice Hall, 2007