Introduction to holography at undergraduate level using research-grade open-source software

C. A. Buitrago-Duque*, S. I. Zapata-Valencia, H. Tobon-Maya, A. Gomez-Ramirez, J. Garcia-Sucerquia
Universidad Nacional de Colombia Sede Medellín, School of Physics, A.A: 3840-Medellín-050034, Colombia

ABSTRACT

In this work, the content for an undergraduate-level holography workshop is presented. The session is divided into two parts: an instructional section and a hands-on application activity supported by research-grade open-source software. The first section starts with a brief theoretical review of conventional imaging, interference, and diffraction as the underlying physical phenomena. These concepts are then used for the description of the recording, processing, and reconstruction stages of analog holography, emphasizing in each case the phenomenology rather than the mathematical framework. Finally, the translation of these stages to digital holography is presented, introducing the principles of digital recording and numerical reconstruction. The contents of the instructional section are then applied in a lecturer-guided activity, in which the participants generate a computational off-axis hologram and calculate its reconstruction. All the operations are performed using the "Numerical Propagation" plugin of the open-source software ImageJ. This research-grade software allows the modeling and manipulation of complex-valued wavefields from a user-friendly graphical interface. It thus allows the participants to recreate step-by-step the recording and reconstruction stages of the holographic process, while directly identifying when each physical phenomenon is at play. The proposed content can be implemented either as a stand-alone workshop or as an applied component of an undergraduate optics course.

Keywords: Holography, undergraduate teaching, workshop, open-source software.

1. INTRODUCTION

Although commonly associated with a faraway future or science fiction, holography is a very real and current research field with a rapidly growing range of practical applications; from security and data storage to medical imaging[1,2], many modern cutting-edge technologies are supported by the holographic principle. These applications are often unknown by students as holography is not a common subject in undergraduate programs, being mostly offered as part of electives or specialized courses and programs. This limitation can be partially attributed to the equipment and technical knowledge required to successfully implement an experimental optical holography setup, and the common association of holography with high-level physics and math concepts. However, the unique combination of physics, optics, and computer science in modern holography presents a valuable opportunity for students to explore new technologies in an interdisciplinary study that should be better exploited. For many years, initiatives for introducing students of both STEM areas[3] and artistic programs[4] to holography have been developed, ranging from portable devices[5] to alternative pedagogies that waive the need for a strong theoretical background[6]. In this work, a workshop for introducing undergraduates to the general holography concepts through a hands-on digital generation and reconstruction process is presented. The first stage, where the underlying physical phenomena are briefly reviewed, allows the participants to acknowledge the general concepts of imaging, interference, and diffraction. The second stage, corresponding to a project-oriented activity to digitally generate and reconstruct a digital hologram, allows the application of these concepts. This stage is supported by open-source computational tools that waive the need for specialized laboratory equipment and arduous programming, while still allowing the participants to interact with each of the physical phenomena involved in the holography process and identify their corresponding effects on the technique.

*cabuitragod@unal.edu.co

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2. BRIEF THEORETICAL REVIEW

A full treatment of holographic imaging touches most of the major concepts of optics and photonics. However, the overall principles can be approached through the topics of conventional imaging, interference, and diffraction. These concepts are well-known to STEM students and part of the general physics syllabus for most undergraduate programs; nonetheless, this approximation to understanding holographic phenomena can be promptly extended beyond physics programs, and into other STEM and arts studies. To prevent evoking undeserved fear in prospective students, these concepts can be treated from a phenomenological perspective rather than under a rigorous mathematical formalism. As presented in the following paragraphs, such an approach is more than sufficient to convey the main aspects of holography and spark the curiosity of the participants.

The initial approach to understanding light was through the study of how our eyes work. Up to Newton's work, 'Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light'[7], light was only understood from a corpuscular behavior, meaning that its study was focused only on amplitude, or brightness, distributions. The later works of Thomas Young and Agustin Fresnel showed that, against corpuscular intuition, light superpositions could result in dark regions, leading the way to a wave behavior description to understand the interference of light. A most significant development in this direction was thus recognizing light as an electromagnetic wave, allowing the amplitude distributions described by Newton to still hold, but now recognizing that, as waves, light also carries phase information. The phase of light fields is of uttermost importance to understanding the capabilities of holography. For students who may be unfamiliar with the concept, the concepts of amplitude and phase information may need to be explained.

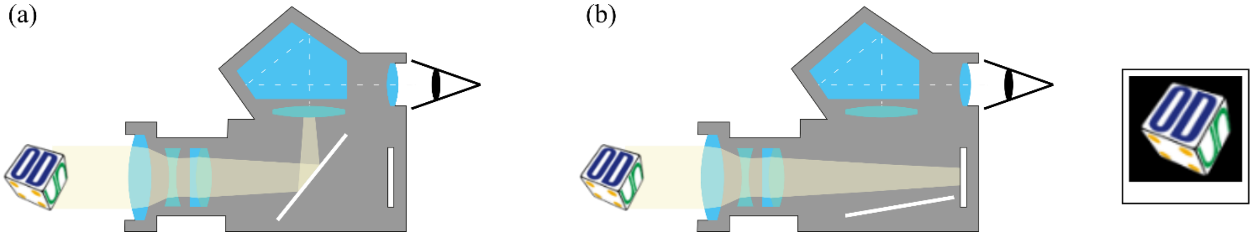


Figure 1. Process for taking a picture in an analog camera (a) observation of the scene (b) recording the scene.

To understand the role of phase information, it can be useful to think of conventional photography. When photographers want to take a picture, they look through the system to determine what image they want to capture as in Figure 1.(a). When they are ready, the picture button is pressed, and the mirror moves downward to let the scene illuminate the photographic paper or digital sensor, as in Figure 1.(b). The intensity of the light is recorded, and the picture is created by the varying levels of brightness. However, there is a difference between rotating a photo frame and viewing the same scene through a window from different perspectives. From Figure 2, it becomes immediately clear that the ability to distinguish depth is lost in the photo.

Figure 2. Light information of a Scene: (a) The direct view of the scene. (b) Rotation of a scene with only amplitude information. (c) Rotation of a scene with amplitude and phase information.

Physically, the phase corresponds to the oscillation state of the light wave. However, there are no detectors capable of directly recording this information. Indeed, all the images we see on a computer screen or in photographs contain only amplitude information; that is, how bright, or intense, each portion of the image is. The phase information, the mark of the wave nature of light, is lost. Fortunately, there are ways in which the phase information may leave a mark on the intensity distribution; in particular, its value shapes interference and diffraction phenomena[8]. For example, when two light waves are in phase, they can create constructive interference that makes objects appear brighter. When two light waves are out of phase, they can create destructive interference that makes objects appear dimmer. It is thus possible to codify, in intensity changes, the phase variations of a wavefield. Under this principle, in 1948, Dennis Gabor proposed a two-stage method that would revolutionize technology: holography[9]. His proposal lies in recording a hologram, a light-sensitive plate where the phase and amplitude information of an object is encoded by light. This information can be later decoded to retrieve all the complex information of the object of interest.

The first stage, known as the recording of the hologram, is shown in Figure 3(a). A beam splitter divides a laser light beam into two paths. The first path directly illuminates the object of interest, and the light reflected by this object propagates to a plane where the photographic plate is located. At the same time, the second path serves as a reference, with the light directly illuminating the plate without modification. The interference between the light reflected by the object and the reference beam occurs over the photographic plate and is recorded by it.

The second stage consists of recovering the object illumination, as shown in Figure 3(b). The same optical setup is used for this step, and only the reference path is needed since the object is no longer present. The reference light illuminates the developed photographic plate recorded in the first stage, and this plate acts as a diffraction grating, thus generating a diffraction pattern. This pattern contains all the phase and amplitude information of the object of interest. If an observer looks through the hologram in the direction where the object was located, it will appear as if the object is there, and since the amplitude and phase information are recovered, a 3D view of the object can be observed and perceived.

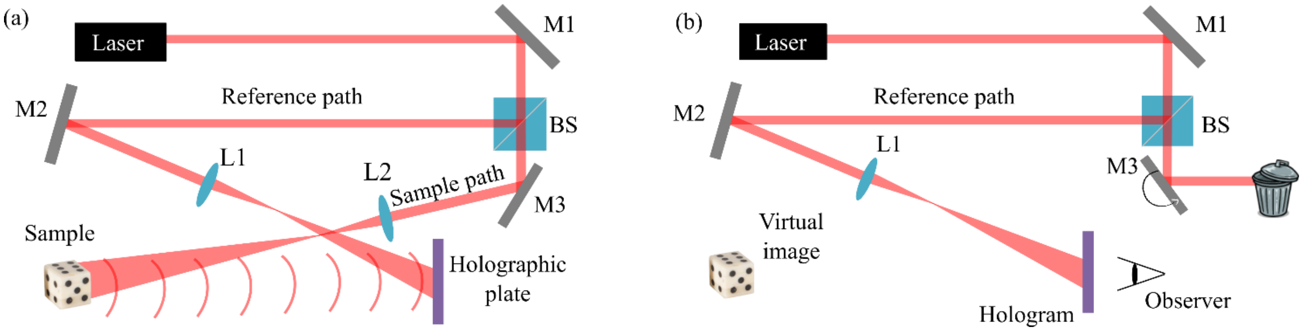


Figure 3. Analog holographic setup. (a) Hologram recording setup. (b) Analogic reconstruction setup. BS is a beam splitter, M1, M2, and M3 are mirrors, L1 and L2 are lenses.

Taking advantage of the capability of recording and recovering 3D information from objects, an imaging branch, analogous to photography, has grown rapidly, seeking to improve the quality and display of recorded objects. Currently, it is common to hear that museums exhibit holographic collections, or for archaeological excavations, holograms are recorded before transporting the pieces to ensure that the information of the objects is not lost in case of the objects being damaged during their manipulation. Another branch utilizes holography for measurements. Since the phase provides information about light wave oscillations, more precise sensors for different applications have been developed, allowing for the extraction of nanometer-scale information from the recorded objects.

The analog approach of holography using a holographic plate has interesting characteristics, such as the quality and resolution of the recorded hologram and the 3D visualization of the object. However, the need to always impress the interferogram onto different photographic plates, which are single-use, makes the analog technique impractical and inefficient for measuring and characterizing applications. The advent of digital technologies has provided a solution to this issue. In a digital holographic approach, the plate is replaced by a digital camera, and the hologram is now a digital image containing the information of the interference between the object and reference paths recorded during the first stage. Now, since the hologram is digital, an optical setup is not necessary for the reconstruction stage. Instead, a numerical reconstruction is performed. The digital hologram is numerically illuminated by the conjugate reference wave, and this numerical wavefield is numerically propagated to the plane where the object is focused. This modification in the technique has the advantage of allowing multiple uses of the digital sensor as the hologram is a digital image stored in a computer. Additionally, it provides all the capabilities of image processing available to the digital world, but as this information is displayed using a 2D screen which operates with changes in the intensity, it losses the capability to directly show the 3D information of the reconstructed object, even though the phase information is recovered.

3. LECTURER-GUIDED ACTIVITY: DIGITAL HOLOGRAPHY SIMULATION

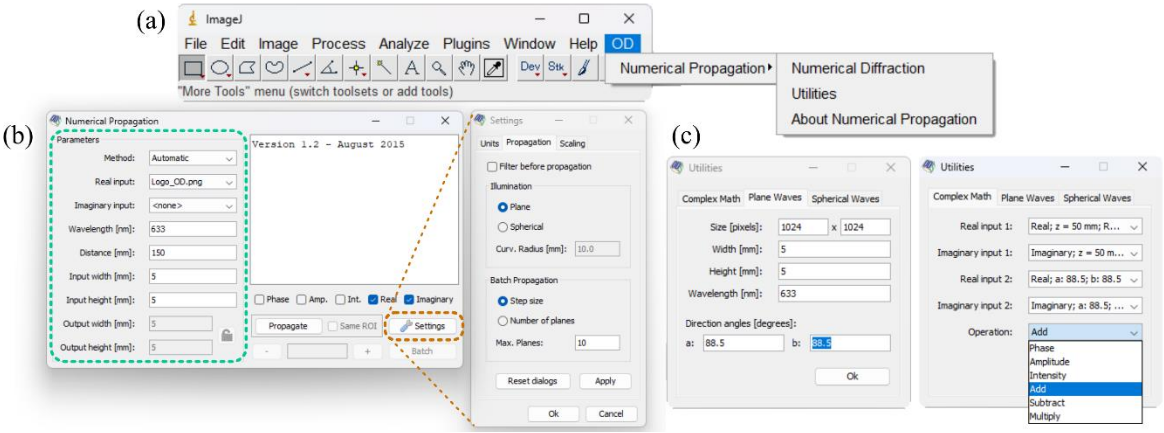
The contents of the instructional section can now be applied in a lecturer-guided activity to generate a computational off-axis hologram and calculate its reconstruction. All the operations will be performed using the *Numerical Propagation*[10] plugin for the open-source software ImageJ[11]. The ImageJ project is open-source software for processing and analyzing scientific images, which can be freely downloaded from the project's webpage (https://imagej.net/). This environment has been widely adopted in the scientific imaging community because of its easy adaptability to new processing needs through the incorporation of custom-made plugins. Particularly for computational optics applications, the *Numerical Propagation* plugin allows the computational calculation of diffractive processes via angular spectrum, Fresnel-Fourier, and Fresnel-Bluestein methods[12] implemented through a user-friendly graphical interface; it additionally allows several complex-field operations, like the digital generation of reference wavefields and complex-valued mathematics. This plugin is also open-source and can be freely downloaded from the developer's GitHub repository (https://unal-optodigital.github.io/NumericalPropagation/). Similarly, for more specialized holography applications, plugins for the operation of Digital Holographic Microscopy systems[13,14], or general complex-field manipulation tools[15], can also be found. In preparation for the workshop, it is thus encouraged to prepare the system of each participant with an ImageJ installation equipped with the *Numerical Propagation* plugin by following the instructions on the respective web pages.

3.1 Simulating the recording of a digital hologram

As presented in the previous section, in the recording stage of an experimental holography setup the sample under study is illuminated by a laser beam, producing a wavefield that propagates through free space towards the recording screen. At the screen plane, this diffracted field interacts with an unperturbed reference wave, producing an interference pattern whose intensity distribution corresponds to the recorded hologram. The process can thus be summarized in three steps: 1) Diffraction of the laser-illuminated sample information towards the detector plane, 2) Interference between the diffracted field and an unperturbed reference wave, and 3) Intensity recording of the resulting pattern.

For the first step, the participants are directed to select an image of their preference. While almost any input works, the best results are achieved with monochromatic images (or, equivalently, color images that do not lose much contrast when converted to a grayscale representation) with high-contrast features. The selected image will represent the object to be recorded, with the white regions corresponding to high-intensity points and black portions to the absence of light; consequently, it is convenient to use white-background images to increase the signal-to-noise ratio of the results. The selected image can be opened in the ImageJ environment by either drag-and-drop or via de 'File > Open…' menu option. Once the image is ready in ImageJ, direct the participants to the "Numerical Diffraction" tool of the *Numerical Propagation* plugin. To access it, use the menu path 'OD > Numerical Propagation > Numerical Diffraction', as shown in panel (a) of Figure 4. Panel (b) of the same figure illustrates the graphical user interface (GUI) of the plugin. This new window has all the fields needed to recreate the diffractive process of the object wave in the section titled "Parameters". For the present example, the selected image was a 1024 x 1024 line-art logo of the Opto-Digital Processing research group, to which a physical dimension of 5 mm x 5 mm was attributed. The propagation method was left for automatic selection, with an illumination wavelength of 633 nm and a distance from the sample to the screen of 50 mm. To the right-hand side of the window the output information can be selected; as further complex-valued processing will be needed, the real and imaginary components were selected as output. Notwithstanding the aforementioned values, the selection can be tuned as needed to show, for instance, the effect of changing the illumination wavelength, the propagation distances, and the sampling conditions. Additionally, in the settings menu, which can be accessed using the button towards the lower-right portion of the GUI, further customizations can be made, like changing the illumination from a plane wave to a spherical wavefront with a custom curvature radius.

Once the diffracted object wavefield is ready, the reference wave must be prepared. To do so, the "Utilities" tool of the *Numerical Propagation* plugin can be used. This element can be accessed from the menu path 'OD > Numerical Propagation > Utilites', as shown in panel (a) from Figure 4. The Utilities GUI allows the user to numerically generate the complex representation of either a plane or a spherical wavefront. For this case, a plane wave was prepared using the same pixel count, physical size, and wavelength as the object wave to ensure their physical compatibility. The direction angle fields allow the introduction of a custom tilt to the wavefront, thus allowing the simulation of any holographic configuration, from Gabor's in-line[9] architecture (perpendicular incidence of the reference field to the screen, corresponding to direction angles of $a = b = 90$ °) to the Leith-Upatnieks[16] off-axis setup. The latter will be implemented in this case, as it has the convenience of separating the diffraction orders in the spatial frequency regime, allowing their easy isolation by Fourier spatial filtering[17]. The specific angle for a fully-off-axis configuration will depend on the selected parameters[18]; however, the plugin will let the user know the possible range of values without exceeding the sampling theorem limit. For the case at hand, a value of $a = b = 87.53\,°$ was used. Varying the angle of the reference wave can be used to illustrate its effect on the interference fringes and the positioning of the diffraction order components in the Fourier spectrum.



Method: Automatic
Real input: Logo_OD.png
Imaginary input: <none>
Wavelength [nm]: 633
Distance [mm]: 150
Input width [mm]: 5
Input height [mm]: 5
Output width [mm]: 5
Output height [mm]: 5

Version 1.2 - August 2015

☐ Phase ☐ Amp. ☐ Int. ☑ Real ☑ Imaginary

☐ Filter before propagation
Illumination
● Plane
○ Spherical
Curv. Radius [mm]: 10.0
Batch Propagation
● Step size
○ Number of planes
Max. Planes: 10

Size [pixels]: 1024 x 1024
Width [mm]: 5
Height [mm]: 5
Wavelength [nm]: 633
Direction angles [degrees]:
a: 88.5 b: 88.5

Real input 1: Real; z = 50 mm; R...
Imaginary input 1: Imaginary; z = 50 m...
Real input 2: Real; a: 88.5; b: 88.5
Imaginary input 2: Imaginary; a: 88.5; ...
Operation: Add

Figure 4. Accessing the *Numerical Propagation* plugin tools from the ImageJ environment. (a) Main ImageJ interface. (b) The GUI of the plugin for numerical propagation of complex fields. (c) Tools for the operation of complex-valued fields.

Once the plane wave to be used as reference is generated, the same Utilities GUI can be used to emulate the second step; that is, the interference between the object and reference waves. To do so, the 'Complex Math' option, shown in panel (c) of Figure 4, allows the calculation of an image-based complex-valued addition. Selecting the appropriate Real/Imaginary pairs, this operation results in a new complex-valued field corresponding to the amplitude superposition between those fields. The squared modulus of this final complex-valued field, which can be calculated using the "Intensity" operation in the same tool, corresponds to the final step: The holographic recording which, in its interference fringes, codifies both the amplitude and phase information of the diffracted wavefield. Figure 5 summarizes the input, output, and intermediate images of the hologram simulation process.

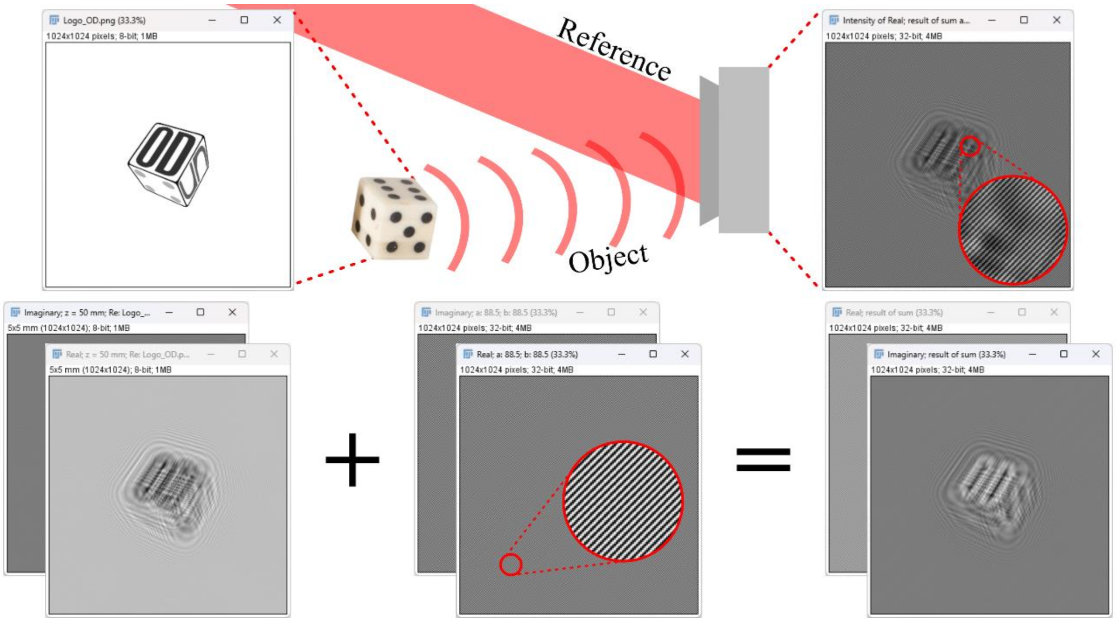
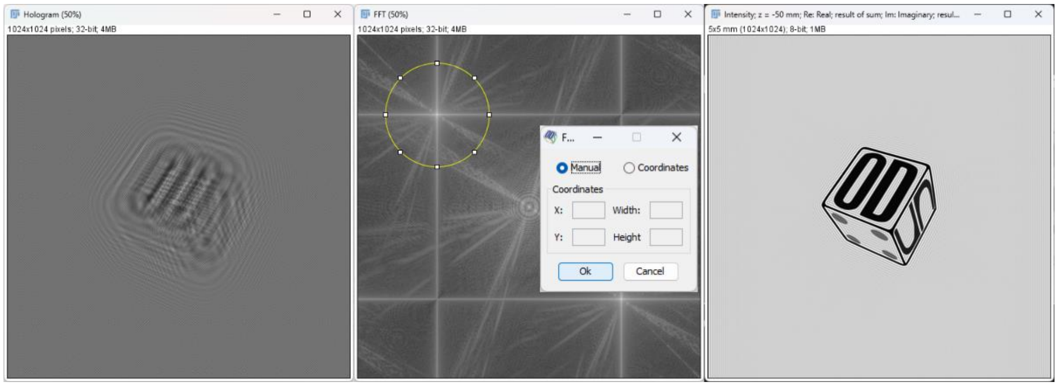


Figure 5. Simulation of an off-axis hologram. The input image is numerically diffracted and superposed in amplitude with a numerical plane wave, generating a complex-valued interference pattern, whose intensity is the desired hologram recording.

3.2 Reconstruction of the off-axis hologram

The image obtained in the final step of the above-described procedure corresponds to the computer-generated off-axis hologram. To retrieve the object information from this image, the *Numerical Propagation* plugin can be once again used. As described in the previous section, the reconstruction stage of a holography setup is commonly done by illuminating the hologram with the reference wave, which recreates the object wavefront as originally impinging on the recording medium. In digital holography, the retrieved complex-valued field at the detector plane can then be numerically propagated to the object plane to obtain the in-focus sample. While this process could be recreated by generating the reference wave in the Utilities tool, adding it to the hologram, and calculating the resulting diffraction pattern, a much simpler approach has been known for many years: Commonly attributed to Takeda et al.[17], a quick reconstruction method can be pursued by Fourier spatial filtering the hologram without exact knowledge of the reference wave used during the recording stage. For this process, it is only needed to filter the spatial frequency spectrum of the hologram to isolate one of the diffraction orders and calculate the diffraction process for only these frequencies.

The Fourier-filtering reconstruction procedure can be fully applied inside the *Numerical Propagation* plugin. To do so, ensure that the option "Filter before propagation" is enabled in the 'Propagation' tab of the Settings menu (see Figure 4). Selecting the hologram as the real input and, using the same propagation parameters as the simulation, run the calculation (633 nm of illumination wavelength, 5 mm x 5 mm of physical size, 50 mm of propagation distance, and automatic method selection). A new window with the Fourier spectrum of the hologram will appear, allowing the user to select the desired region to filter out. The selection can be done with any of ImageJ's integrated tools. In Figure 6 the selection of a circular region around one diffraction order is shown. After the region is selected, press "Ok" in the accompanying emerging window for the diffraction calculation to follow. The result should be the in-focus information of the complex-valued wavefield that was selected as output. Given the properties of the object used for the simulation, the result in Figure 6 shows only the Intensity information; however, any other property, like the phase distribution, real/imaginary components, or the field amplitude could be equally computed.



Hologram (50%)

1024x1024 pixels; 32-bit; 4MB

FFT (50%)

1024x1024 pixels; 32-bit; 4MB

Intensity; z = -50 mm; Re: Real; result of sum; Im: Imaginary; resul...

5x5 mm (1024x1024); 8-bit; 1MB

Figure 6. Reconstruction of the computer-generated off-axis hologram.

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