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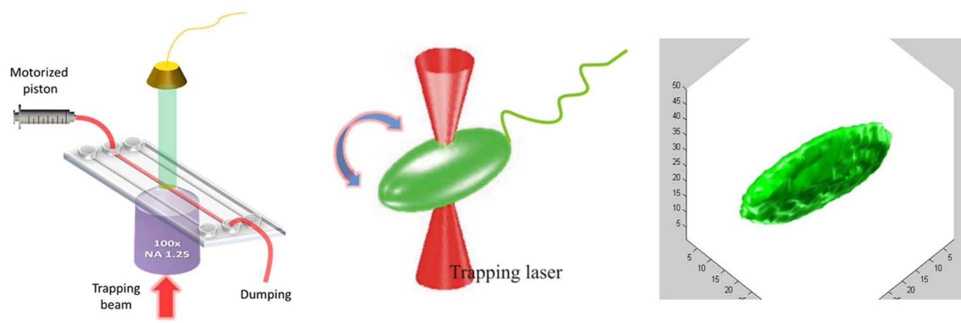

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Breakthroughs in Photonics 2013: Holographic Imaging

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Abstract: Although holography is topic that goes back to the 1950s, the research in this field continues to be very active worldwide. A continuous growth is confirmed by the publication of more than 2000 papers each year in archival journal on different holographic issues. Here we describe shortly what appeared to us to be the most significant achievements reached in 2013 on holographic imaging.

Index Terms: Digital holography, 3D imaging, infrared holography, incoherent holography, on chip microscopy.

1. Introduction

The continuous advancements in holographic imaging has been very fruitful in 2013 by revealing very fascinating results in different fields of application. Holographic 3D imaging for microfluidic platforms at Lab-on-a-Chip scale has been demonstrated an important route for biomedical applications showing impressive results. Moreover, holography at mid-IR wavelengths has seen important developments for homeland-security as well as for Non Destructive Testing of aerospace composites. On the opposite side of the spectrum, EUV and X-ray have pushed further important visualization issues at nanoscale. Anyway, independently from the adopted wavelength, a key-role is played, since the advent of the digital era, by the numerical processing of numerical holograms in order to improve performances for all the various imaging purposes.

2. Lab on Chip Biophotonics

Microfluidics and lab-on-chip are expanding research subjects where high-throughput and label-free imaging is of fundamental importance. In 2013, several exciting improvements have been done on holographic imaging. In fact, by combining holography with lab-on-chip devices quantitative, high resolution, and marker-free studies of biological unstained samples was made possible. Combining the Optical Tweezers (OT) capabilities with Digital Holographic (DH) microscopy, quantitative 3D reconstructions was achieved thus solving the problem of biovolume estimation and 3D rendering of motile cells [1]. Actually, the most common and well-established methods to calculate biovolume are based on more or less complicated geometrical models. Experiment*s* for measuring biovolumes need isolation and sorting of the cells. Cumbersome observation procedures at microscope are requested [2]. DH allows quantitative phase-contrast and label-free imaging that can be of great help in

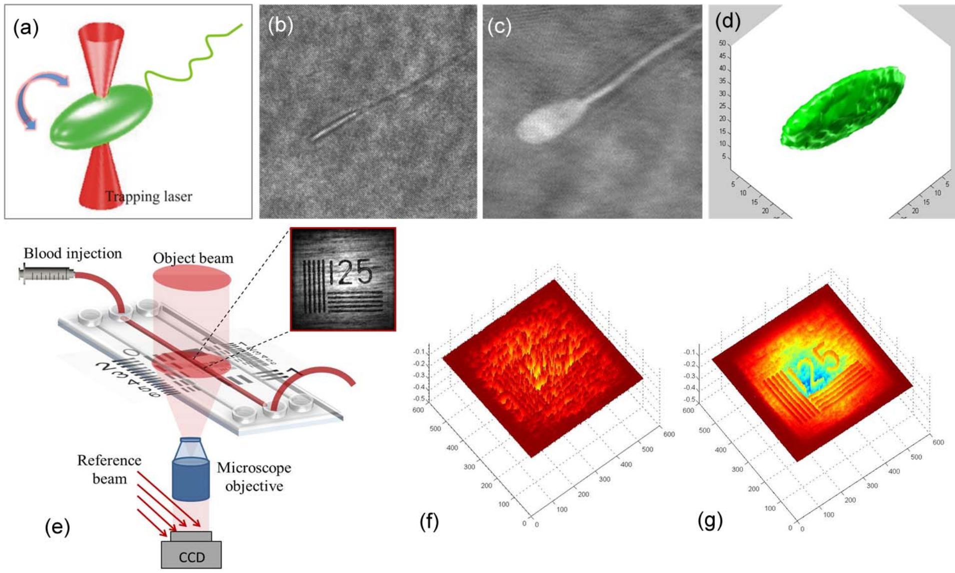

Fig. 1. Biovolume estimation experiment [1]. (a) Simulation of spermatozoon trapping. (b)–(d) SFS estimation from the QPM sequence. (b) Frame of the holographic sequence. (c) Starting QPM corresponding to the angle 0°. (d) Visual hull reconstruction computed by the SFS algorithm. (e)–(g) Experiment in a turbid medium [17]. (e) Blood is injected inside a microfluidic channel at tunable velocity. (f) A single DH reconstruction is not sufficient to guarantee clear imaging through a low-speed blood flow (flow speed at $v = 10\ \mu$m/s), while (g) clear vision of the target through a low-speed blood flow is achievable by incoherent combination of multiple DH reconstructions.

visualizing low-amplitude contrast objects [3]–[5]. The experimental apparatus described in [1] allows simultaneous trapping and holographic imaging of the sample. Under particular conditions of optical trapping power and distance from the chamber walls, the specimen is put in rotation [6] and images of different parts of the cell can be recorded without mechanical contact. During the rotation a holographic sequence is recorded and for each hologram of the sequence the Quantitative Phase Maps (QPMs) are calculated. The new concept is to estimate the biovolume of the cell by exploiting many QPMs, and applying the Shape-From-Silhouettes (SFS) algorithm. SFS is a very powerful method for estimating the 3D shape of an object from its silhouette images [7]. This procedure is attractive because the silhouettes can be computed quickly and with great accuracy. Fig. 1(a)–(d) shows the 3D reconstructions obtained for a bovine spermatozoon. Biovolume of the sperm head can be easily calculated from the 3D reconstructions, as shown in Fig. 1(d) [1].

Staying on the topic of biophotonics applications, several efforts have been spent in resolution and depth-of-field enhancement in terms of experimental arrangements and, as well as, numerical processing [8]–[10]. In particular in ref. [11] was presented a superresolution method which allows lateral phase resolution below the 100 nm barrier exploiting the well-known concept of synthetic aperture in microscopy [12]. Super-resolution item has been investigated also in experiment dealing with partially coherent digital in-line holography as in case of [13]. Authors in [13] realized a field-portable microscope able to produce lens-free color images over a wide field-of-view. Moreover, further impressive results were obtained on the concept of on-chip microscopy [14], [15]. A different topic concerning the ability of holographic microscopy to see through turbid media was established in [16], [17] in 2013. It was demonstrated that DH can detect, in a quantitative way, phase and/or amplitude objects hidden by turbid medium where traditional microscopy techniques fail. In particular, multiple-hologram reconstructions were processed to recover the phase information of cells flowing behind a scattering layer in a microfluidic channel [16]. Moreover it was demonstrated the ability of DH to see through a true blood flow [17], as shown in Fig. 1(e)–(g). A test resolution target (125 lines/mm) can be clearly imaged through blood by one single DH recording if the blood flow overcomes a threshold speed.

In 2013, for the first time the confocal microscopy concept has been combined with the digital holography one [18]. The researchers experimentally realized 3D imaging of biological tissues from holographic recording of the scanned spot. It was proved the ability of the method both in transmission and reflection recording schemes. Another active research area concerns the clinic application of holographic imaging as demonstrated in [19], where tympanic membrane displacement was measured by optoelectronic holography. In order to enlarge the imaging capabilities of DH, Smith and coworkers proved that nonlinear optical contrast mechanisms can be used for biological specimen imaging by exploiting the coherent scattering of second harmonic light from the volume of the whole sample [20]. Finally, in 2013, interesting and useful research on using a low-cost compact DH to combat Malaria infections, which can have a broad compact in areas with limited access to healthcare, has been published [21].

3. IR Holography

The massive production of new generation of thermographic sensors has recently conveyed growing interest in the extension of DH to the infrared (IR) region of the electromagnetic spectrum. Indeed, employing a long IR wavelength allows the hologram recording of large size objects, and makes the acquisition of the interference pattern less sensitive to vibrations. Moreover, the available coherent and high-power CO_2 laser sources make possible to expand the object beam to achieve a larger field-of-view, so that wide areas can be covered. Thanks to these features, new applications of IRDH have been explored in the fields of industrial inspection and security [22]–[24]. In [22] and [23] a set-up combining an IR laser source and a handy microbolometric array sensor has been designed to perform large space reflector metrology, realizing a compact IRDH device mounted on a tripod, as shown in Fig. 2(b). In [24] a lensless IRDH configuration has been adopted to visualize moving subjects through smoke and flames, demonstrating for the first time the possibility to record human-size holograms on a digital support. Out of focus hologram recordings, followed by numerical focusing, avoid the need for zoom-lenses, which are responsible for the saturation of the sensor elements due to the flame emitted radiation. Since this is incoherent with the reference wave, it does not contribute to the formation of the fringe pattern on the sensor and the useful signal of the target can be recovered. Fig. 2(a) shows a conventional thermographic image of a man standing behind a flame, which is not visible at all as the IR sensor is blinded. On the contrary, in the IRDH reconstruction no blind areas are present and the man can be clearly detected. These results can open the route for exploiting IRDH in real-world scenarios, e.g., to search and rescue survivors in case of fire accidents.

4. Incoherent and Exotic Wave Holography

A breakthrough achievement in DH has been presented in 2013 by M. K. Kim, showing the fascinating possibility to record holograms under incoherent illumination obtaining for the first time full-color, three-dimensional images of daylight-illuminated outdoor scenes [25]. Differently from Fresnel incoherent Single Channel Holography (FISCH) [26], two mirrors with different curvatures and a piezo-actuator for phase shifting purposes are employed to record holograms by self-interference without using any SLM. The simple set-up could pave the way to the production of holographic color cameras to be widely exploited by the general public (see Fig. 2).

On the other side, coherent extreme ultraviolet (EUV) and X-ray sources, as well as with electron sources has recently been applied to study problems in different scientific areas allowing to reach high spatial resolution. For example, Zhang *et al.* [27] demonstrated the first general tabletop EUV coherent microscope that can image extended, non-isolated, non-periodic, objects with a 100 nm resolution. The authors exploited a CDI (coherent diffraction imaging) technique, by using a curved EUV mirror to focus the light onto the sample, in order to reconstruct both the amplitude and the phase of an object starting from the information contained in the intensity of its far-field diffraction pattern.

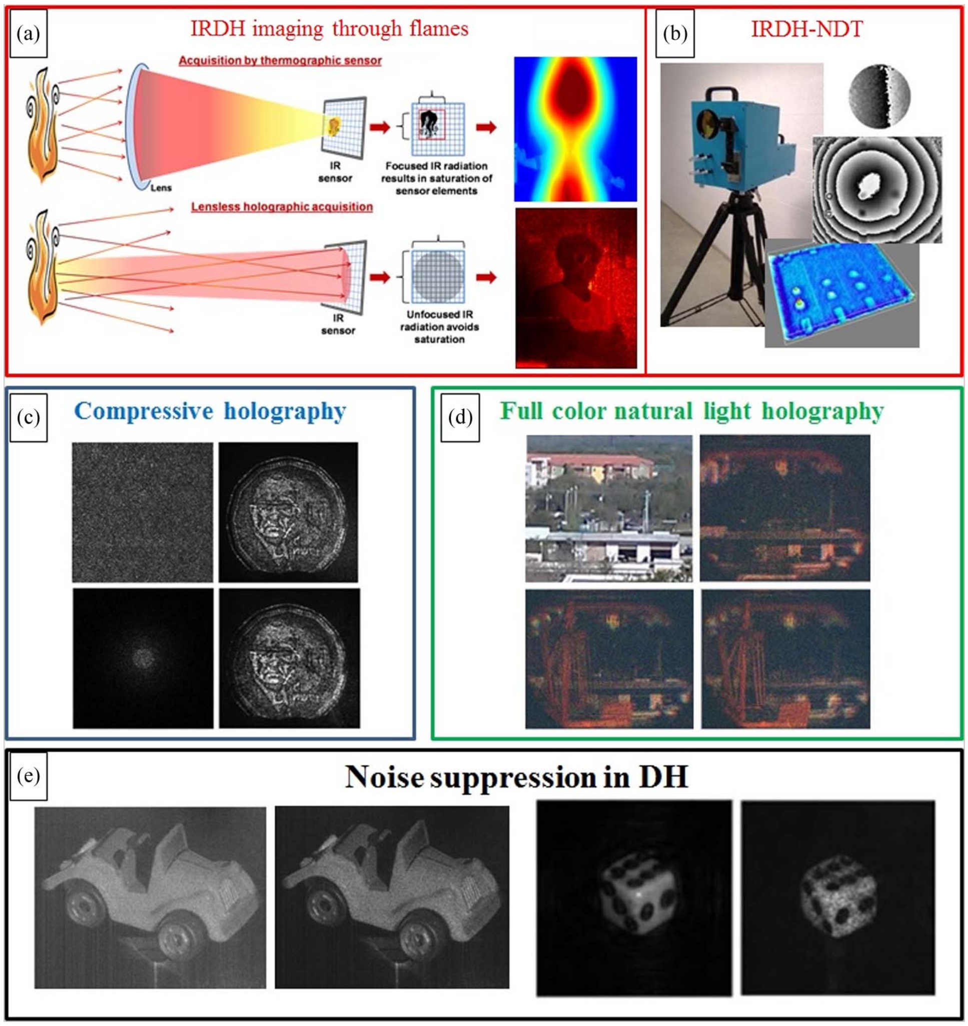

Fig. 2. (a) IRDH imaging through flames [24]. (Top) Focused flame emitted radiation blinds the detector in common IR imaging. (Bottom) Out of focus IRDH recordings with a lensless setup avoids the saturation of the sensor. Hence, a man hidden behind a flame can be clearly imaged. (b) IRDH set-up realized on a compact tripod based device to perform non-destructive testing of large objects [22], [23]. (c) Compressive sensing paradigm applied in DH [34]. On the left, Fresnel hologram of a Coin (top) and its 8% variable density random sampling (bottom). On the right, the corresponding reconstruction without (top) and with compressive sensing (bottom). (d) Hologram recording under daylight illumination provides full color images of real-world scenes [25]. (Top-left) Photograph of an outdoor scene. (Top-right) Full color DH reconstruction. (Bottom) Hologram propagation at different distances, where a toy boat (right) and the distant buildings (left) are in focus. (e) Two different noise suppression methods in DH. The denoised car is obtained by using the method in [37], while the denoised dice is the results of the optical scanning holography paradigm [33].

Moreover, in [28], a traditional holographic experiment in the EUV using a table top system is performed using an extended object. The authors obtained high spatial resolution results (similar to Zhang's experiment) with additional advantage to get time-resolved (1 ns) resolution holographic recordings.

In [29] and [30], the spatial distribution of magnetic domains is imaged with X-ray holography with spatial resolution better than 70 nm. Longchamp *et al.* [31] imaged a freestanding graphene sheet of 210 nm in diameter with 2 A$^{\circ}$ resolution by combining coherent diffraction and holography with low-energy electrons, with kinetic energies of the order of 100 eV that have the further advantage to not damage biological molecules.

5. Numerical Processing

DH allows to obtain the complex amplitude distribution of the object wavefront quantitatively and analyzed digitally. Due to this fact, many fantastic applications have been demonstrated, such as 3D object recognition, digital holograms recorded under photon counting conditions [32] and near-perfect 3D dynamic display by using optical scanning holography [33].

To obtain full benefits using these imaging techniques, a pre/post processing on the digital holograms is essential. In the pre-processing scenario, the compressive sensing (CS) paradigm provides an accurate object reconstruction framework [34]. The most important contribution of the CS in DH is the imaging of phase objects by single—pixel detector [35]. The key of CS is the ability to sparsely represent an object, which concept is a crucial aspect for several methods that have the purpose of improving the holographic information visualization [36], i.e. in the post-processing scenario. In the latter, an important contribution is provided by denoising techniques based on multiple holograms [37] and smart filtering approach [38]. In Fig. 2 an overview of the principal results mentioned above is reported.

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