Polarization-Sensitive Digital Holographic Imaging

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Polarization-sensitive digital holographic imaging (PS-DHI) is a recent imaging technique based on interference among several polarized optical beams. PS-DHI allows simultaneous quantitative three-dimensional reconstruction and quantitative evaluation of polarization properties of a given sample with micrometer scale resolution. Since this technique is very fast and does not require labels/markers, it finds application in several fields, from biology to microelectronics and micro-photonics.

digital holography, polarization sensitive imaging, state of polarization birefringence

1. Introduction

Digital holography (DH) is a fascinating alternative to conventional microscopy since it allows three-dimensional (3D) reconstruction, phase contrast images, and an improved focal depth [1][2][3][4][5]. Basically, DH consists of an interference fringe pattern between a reference unperturbed beam and an object beam, that changes its characteristics by passing through a sample. The interference pattern (hologram) is acquired by a digital sensor array. Its post-processing achieves a 3D quantitative image of the sample by a numerical refocusing of a 2D image at different object planes [6]. When DH is implemented in an optical microscope, the objective lens provides a magnified image allowing to reconstruct amplitude and phase-contrast images with a spatial resolution of less than 1μm in all dimensions [7].

Digital holographic imaging (DHI) has several interesting features including high-resolution, very fast acquisition, and 4D (3D + time) characterization of samples [8][9][10]. These properties are very useful, for example, when the specimen is moving or when the sample is subjected to external stimuli that can alter its shape and size, such as electrical, magnetic or mechanical forces, chemical corrosion, or evaporation and deposition of further materials. Moreover, DHI is a non-contact and non-invasive technique, allowing label-free quantitative phase analysis of living cells; thus, measurements do not require the introduction of a tag, so cells are not altered. This approach can provide useful information that can be interpreted into many underlying biological processes.

During the last decade, DHI has experienced several technological developments, including the integration of DHI with complementary characterization techniques (e.g., Raman spectroscopy or scanning electron microscope [11][12][13]). A further important extension of DHI is the possibility to quantitative measure the state of polarization (SoP) modified by a sample [14][15][16][17] and so evaluate its birefringent and/or dichroic proprieties, which are frequently related to the micro- or even ultra-structure of the sample itself [18]. Therefore, the characterization of these proprieties and the detection of their eventual variations, that can be due to either stress and strain in a given material or disordered microstructure in biological specimens, could lead to a better understanding of the process involved in a broad variety of applications.

Since SoP is one of the fundamental properties of light, its evaluation has attracted a growing interest in both the basic researches and practical applications of optics, intending to study novel optical phenomena and new applications. Thus, the experimental evaluation of the SoP has become a fast-rising subject. Typically, polarization imaging has been carried out with different approaches—for example by using real-time polarization phase-shifting system [19], polarization contrast with near-field scanning optical microscopy [20], optical coherence tomography [21][22], and Pol-Scope [23]. However, these techniques need different image acquisitions, generally obtained at diverse orientations of birefringent optical components (e.g., polarizers, quarter-wave, and/or half-wave plates) to retrieve the polarization state. The great advantage offered by polarization-sensitive digital holographic imaging (PS-DHI) is the possibility to use a single acquisition to retrieve the full polarization state of the sample under observation, therefore gaining in speed and simplicity.

2. Theoretical Background

The Stokes vectors and Müeller matrices allow a whole study of the polarization state for fully polarized, partially polarized and even unpolarized light, comprising the optical axis and the degree of polarization. On the other hand, the Jones vectors, that can be useful only for completely polarized light, are more appropriate for problems concerning coherent light. As a general rule, the Jones vectors are useful for problems involving amplitude superposition, while the Müeller matrices are applied for problems involving intensity superposition [24]. Different approaches of PS-DHI have been proposed in the literature, however, the basic idea is to generate a hologram of the sample through the interference between the object wave and two orthogonally polarized reference waves, producing in this way two fringe patterns. The hologram of the magnified sample is recorded by a digital camera (such as a charge-coupled device or an active pixel sensor). The numerical reconstruction of such hologram leads to two wavefronts, one relative to each reference wave, and thus, one for each perpendicular state of polarization [15]. So, the amplitude map and the phase map for each polarization component can be reconstructed. With the aim to evaluate the SoP change of the object beam due to the interaction with the sample under test, typically, two parameters are experimentally measured: the amplitude ratio β, which is related to the different transmitted intensities of the two orthogonal components and corresponds to the azimuth of the polarization ellipse, and the phase difference $\Delta\varphi$, that contains information on the different optical paths due to the refractive index anisotropy linked to the sample structure [18][25].

Basically, PS-DHI approaches can be classified in two groups—(i) those which allow measurement of Jones vectors or Jones matrices and (ii) those which give information on Stokes vectors or Müller matrices. Since holography needs a uniform laser beam, especially regarding the flatness of phase front and the extended depth of field, in both approaches, (quasi)-monochromic light and perfect plane wavefronts are considered. However, the realistic intensity distribution of laser sources is described by Gaussian function, leading to problems in holographic-based applications, such as a reduced image contrast. These issues can be overcome by implementing beam shaping systems built on the base of field mapping refractive beam shapers like πShaper [26].

3. PS-DHI Applications

As described in the previous section, PS-DHI can measure the parameters β and $\Delta\varphi$, thus allows to retrieve the SoP of a beam that interacts with a specimen. The modification of the SoP in the transmitted or reflected beam gives information about the structure, the composition, or the optical properties of the specimen under study. Basically, the following two physical properties of the matter can alter the polarization state of a wave [18]:

- Birefringence—a material is considered birefringent if its refractive index depends on the polarization and propagation direction of the incoming light, i.e., it shows an optical anisotropy. When these samples are crossed by a polarized light, the amplitudes are unchanged but a modification in the relative phase occurs. Birefringence can be linear (that is, there is one axis of symmetry, called the optic axis) such as in optical wave plates/retarders and many crystals, or circular (that is, in which for an incident linearly polarized light, the corresponding outgoing polarization plane will be rotated) such as chiral fluids.

- Dichroism—a material, typically crystalline, is considered dichroic if it absorbs more light along a preferential incident plane of polarization than another plane (absorption anisotropy); as a result, when the optical beam propagates within this material, its polarization state undergoes a modification. The ratio of amplitudes of the orthogonal components of the light emerging from the sample under test provides a measurement of its linear dichroism property.

The study of the polarization state covers different applications and research fields, such as measurement of stress, geology, chemistry, display technologies, medicine and medical diagnosis, etc. Currently, it has been demonstrated that the PS-DHI technique can be used for noninvasive quantitative imaging of live cells or the evaluation of the dynamic phase difference induced by the birefringence of liquid crystals. In the following, a state of the art of the PS-DHI applications is reported in two subsections, dividing the biological from microelectronics and micro photonics applications.

4. Conclusions

PS-DHI is a flexible, useful development of DHI; indeed, only a few changes to the standard DH setup are required to obtain polarization-based imaging. However, innovative solutions were also developed. The requirement of a single-shot imaging and high processing speed significantly improve the operation of the measurement process making this approach more appropriate for real-time multiple analyses. Moreover, the full SoP and phase distribution for an arbitrary light field can be easily and quickly measured by PS-DHI based on the geometric phase.

In this context, this review paper presents a brief introduction to the basic principles underlying PS-DHI and an overview of some enhancements in its technology development. To the best of our knowledge, there are no other reviews on this topic. Therefore, it is our belief that this work could help researchers who work in this field. Even if PS-DHI is a fairly established research line (the first work proving its feasibility dates back to 1999 [17], while in the past 20 years, many works have been published to introduce improvements to the technique), there are currently only a few applications presented in the literature. Among these, the most promising are in the fields of microelectronics, photonics and biomedical imaging. Since it has been demonstrated with other more complex techniques that birefringence and, in general, SoP modification induced by biological and electronics samples can indicate their status (e.g., the healthy state of some cells [27][28][29][30][31] or the stress–strain induced in some materials [15][16]), and considering the achievements of PS-DHI in microelectronics, photonics, and biomedical imaging of the past few years, new technological developments, such as the use of quantum holography, which is a recent fascinating line of research, and new potential applications are expected in the next years.

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