Metrology applications using off-axis digital holography microscopy

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Keywords: digital holography microscopy, 4D, metrology, polarization, oxide layers, MEMS, vibrations

Abstract
Off-axis digital holography microscopy (DHM) systems have evolved during these last two decades from research to commercial instrumentation. They are used in many research laboratories and production facilities as metrology instruments in a large variety of applications including dimensional, surface topography, birefringence, oxide patterns thickness, and vibration characterization. The unique non-scanning quasi-instantaneous acquisition specificity of DHM opens new 4D metrology possibilities for observation of non-static scenes, operation in noisy environments, high throughput screening, and for providing fast feedback during manufacturing processes using artificial intelligence for decision making. These aspects are discussed and illustrated in this paper with the presentation of several applications to technical samples.

1. First scientific publications and evolution of off-axis digital holography microscopy (DHM)

The first simultaneous reconstructions of both quantitative phase and intensity maps out of a single hologram acquired in off-axis configuration has been demonstrated in two seminal publications by Cuche et al in 1999 [1, 2]. The principle of this full field imaging method is shown for lens-less optical set up, as well as for reflection and transmission microscopy. The authors foreseen in the conclusion of these papers many commercial applications in both bio-imaging and material sciences.

More than 20 years later, the importance of DHM is in particular recognized by dedicated sessions at several major international scientific conferences and by an important increase in the number of scientific publications. A search on Google scholar for the exact expression ‘digital holographic microscopy’ lists more than 1000 publications in 2020 against only 11 in 1999. This present paper focus on applications. It reports a few out of the latest cutting edge DHM metrology usage of commercial systems, implemented at industrial and academic laboratories for R&D purpose, and in production facilities for quality control. It focuses on technical objects, does not include applications to biological samples, or tomographic set ups [3–9] as most of their applications are demonstrated on bio-samples as well. It concentrates on concrete applications fitting and underlining DHM unique specificities. It does not discuss off-axis DHM new approaches [10–16], or the reconstructing methods and the diversity of set ups. They are covered by review papers, for instance [17–20].

2. DHM metrology specificities

In the field of material sciences DHM are essentially three-dimensional (3D) optical profilometers. For measurement of static and quasi still objects at the scale of a few seconds, they are in direct competition with other 3D optical profilometers technologies. They have in particular a large common range of measurable samples with scanning white light interferometers (SWLI) and confocal microscopes [21]. These latter systems were already mature and well established on the market at the time of the earlier DHM development, making the commercial spread of this later more difficult. They are used mostly for shape and surface topography (roughness) characterization of static samples and scenes.
Nevertheless, DHM has made its way to the market by exploiting one of its essential differentiation with respect to these alternate systems: information is grabbed quasi instantaneously, with a single camera frame. It does not necessitate any scanning, when alternative techniques require a lateral, a vertical, and/or a phase scanning mechanism.

A first advantage of this specificity is that DHM compares sample heights with a precise and perfectly stabilized wavelength, rather than to a scanning distance, minimizing the sources of measurement non-linearities and calibration drifts. A full metrological evaluation of DHM is out of the frame of this paper, but several metrology evaluation elements are provided in section 3.

A second advantage is that multiple information can be multiplexed in a single hologram as well without scanning. Indeed, DHM enables not only to record a single wavelength information in a hologram, but to record simultaneously information at several wavelengths [17], or at several polarizations [22–25].

Section 3 shows how multiplexing information at several wavelengths enables to enlarge the absolute measurable height range to dimensions larger than a single wavelength range. In section 4, multiple wavelength information is exploited for transforming phase and intensity maps into geometrical maps.

Indeed, if this transformation is straightforward in case of homogeneous and reflective samples, it is not the case for measurements of non-homogeneous samples, or of transparent thin dielectric structured layers deposited on a reflective substrate.

Multiplexing several polarization recording provides birefringence characterization of material that can be expected by design, inherent to the material, or induced by stress. It will be illustrated in section 5 with meta-surface characterization by DHM.

The third and perhaps most recognized advantage of the absence of scanning mechanism is that with DHM, holograms are acquired, and therefore 3D topographies are measured at camera frame rate. Moreover, only a very short time duration is necessary to acquire information, enabling quasi-instantaneous measurements. This time duration is equal either to the camera exposure time, or to the sample illumination duration when using pulsed light source. Comparatively to classical photography, it enables to avoid or reduce image blurring by ‘freezing’ the object or photographer movements during the image acquisition time duration. Dynamical 3D measurement will be discussed in section 6.

These two last specificities, i.e. quasi instantaneous acquisition and camera rate acquisition, have opened a full new range of applications not possible using alternative 3D profilometry technologies. As developed at the end of this section, they are indeed necessary in many situations intrinsic either to the sample, or to the experimental configuration, or to the environmental conditions in which the sample is.

Sample deformation can be spontaneous or driven by external stimuli. It can be the result of thermodynamic changes (thermal expansion, melting, evaporation …) [26], a chemical action (electro deposition, corrosion, etching, dissolution) [27–29], mechanical forces (material release, pressure, tribology indentation …) [30–32], falling water drops [33], illumination [34, 35], or electromagnetic forces [36–48]. For such applications, the acquisition time (camera shutter) must be shorter than the time scale of the scene change in order to measure without artifacts.

Samples cannot always be stopped for being measured. It is the case for instance for on-line quality control, for very fast scanning of large areas, and for dynamical tribology [30–33]. Measurement needs to be captured ‘on-flight’, when the sample is in motion. To avoid a related blurring, image distortion, or any loss of resolution, measurement needs to be quasi instantaneous. In particular the displacement of the samples during the measurement time needs to be smaller than the lateral resolution.

Mechanical vibrations are unavoidable in many measurement environments, especially in clean room and manufacturing facilities. The other main source of environment disturbance is air turbulence produced by temperature gradients resulting in local inhomogeneities of air refractive indices, resulting in measurement distortions. They are particularly relevant when measuring at cryogenic temperature [49] or when measuring material phase transitions at high temperature, or within a heated tribometer [30]. With DHM, the potential blurring effect of both contributions is minimized as long as the acquisition time is short compared to the disturbance time scale. Moreover, in the case of turbulences, averaging over a time-sequence of acquisitions enables to minimize or even suppress measurement distortions.

These three aspects are illustrated in section 6 with several 4D metrology (3D + time) DHM application examples.

The last section of this paper concerns the applications of measurement and analysis of vibrations that are essential for the characterization of MEMS, crystal, and many micro devices [38–48]. In this field, DHM enters in competition with laser Doppler vibrometers (LDV) [50]. Similarly to the comparison with alternative 3D optical profilometers, LDV is a scanning technology. It does not measure surface topography, but a vibration velocity at a single spot area on the surface of a sample. Displacements are retrieved from the velocity measurement by a time integration. The full surface is then characterized by scanning the sample in both lateral directions. DHM measures time-sequence of 3D topographies and extract precisely from them
displacement (or vibration) maps. Indeed, each successive acquisition measures simultaneously over the full field of view, providing at each time-point typically a million of data-points. Displacement velocities can be then calculated by time derivative, preventing the measurement to suffer from a drift linked with an integration procedure. This unrivaled wealth of information reveals very quickly and efficiently MEMS response to any excitation signal with unprecedented details.

3. Basis of DHM metrology

In the nineteenth century, James Clerk Maxwell was one of the first to suggest using the wavelength as a natural gauge for length. In 1950, the standard meter in the new International System of Units (SI) referred to the wavelength corresponding to the krypton-86 (605 780 nm). The use of a precise wavelength as a reference for the measurement of lengths is well established as the ideal measurement method.

As a non-scanning technology, DHM refers purely to wavelengths for height measurements. By using ultra stable interferometric filters for selecting a precise wavelength band of a relatively broad spectrum laser source, DHM operating wavelengths are precisely controlled and perfectly stable compared to other sources of noise. The measured height values do not depend on any scanning calibration, precise positioning, absence of long term drift, repeatability of interferometric piezo-controller, or on any motorized displacement.

Indeed, it has been demonstrated in [51] that the height measurement precision is only limited by the signal to noise ratio (SNR) of the hologram. This latter depends on the camera specifications, as well as the transmittance or reflectance properties of the sample, that affects the exposure time, and consequently the acquisition SNR.

3.1. Single wavelength measurements

To illustrate the high repeatability of DHM, figure 1 shows the measurement of a VLSI Model SHS—1800 QC standard. The certified mean step height is 179 nm and its expanded uncertainty is 2 nm. Using a DHM R2200 by Lyncée Tec SA [52], operating in single wavelength mode at 666 nm, and equipped with a 2× microscope objective, the mean step height and its uncertainty are calculated following metrology practices [21]. A sequence of 50 holograms is acquired providing 50 topography maps. The step mean height is evaluated individually for each acquisition with the relation:

$$\text{Height} = \text{mean height (area1)} - \frac{[\text{mean height (area2)} + \text{mean height (area3)}]}{2},$$  \hspace{1cm} (1)

where area1, area2, and area3 are drawn in figure 1.

The step mean height is obtained by averaging the 50 measured heights. The measurement precision is determined by calculating the standard deviation of the 50 mean height measurements.

Measured step height is 179.15 nm ± 0.03 nm. It lies perfectly in the range of the step certification and shows the high accuracy of DHM.

![Figure 1. Topographic measurement of VLSI certified step (179 ± 2 nm). Grey levels encode surface height. Measurement is obtained with a DHM R2200 [52] equipped with a 2× microscope objective and operating in single wavelength mode at 666 nm. The step height mean and standard deviation are calculated using equation (1) over the three colored rectangular areas for a sequence of 50 acquisitions. Measured values are 179.15 ± 0.03 nm.](image-url)
3.2. Multiple wavelength measurements

The unambiguous measurement vertical range of single wavelength DHM is limited when unwrapping procedure cannot be applied. Combination of several wavelengths, enables to create synthetic wavelengths (long beating frequency). It increases this unambiguous measurement range \([17, 53]\). In this later reference, dual wavelength DHM R2100 \([52]\) operating at 680 nm and 760 nm and SWLI measurements are compared and the similarity of both measurements in terms of value, as shown in figure 2. The difference between the two results lies mainly in the fact that the DHM data were acquired almost instantaneously, while SWLI one required a scan.

Using simply a synthetic wavelength provides a larger measurement vertical range, but consequently decreases the measurement accuracy. Nevertheless, by combining properly the information at different wavelengths, multiple wavelength measurement has the same vertical resolution as when operating at a single wavelength \([54]\). The procedure can be generalized to a larger number of wavelengths. For instance, on the DHM R2200 \([47]\) used in figure 3, the combination of the information at three wavelengths \((\lambda_1 = 666 \text{ nm}, \lambda_2 = 794 \text{ nm}, \lambda_3 = 675 \text{ nm})\), allows to compute phase images as two synthetic wavelengths \(\Lambda_1 = \lambda_1 \lambda_3 / (\lambda_3 - \lambda_1) = 49.95 \mu\text{m}, \Lambda_2 = \lambda_1 \lambda_2 / (\lambda_2 - \lambda_1) = 4.13 \mu\text{m}\). Using the procedure defined in \([54]\), the topography within the range corresponding to the highest synthetic wavelength \((\Lambda_1)\) is computed with a resolution similar to a single wavelength measurement: so large vertical steps can be measured by DHM with a very high precision.
The information at more than two wavelengths can be acquired in the same hologram, but practically, for many samples geometries, cross talks between the information at different wavelengths produce artifacts. Therefore, to the detriment of quasi-instantaneous acquisition, it is often preferable to limit multiplexing of information at two wavelengths in a single hologram. Measurements acquired at three (or four) wavelengths will necessitate in such cases two holograms.

Figure 3 presents the measurement of a VLSI Model SHS—4.5 QC standard, with a certified step height mean value of 4.469 µm and expanded uncertainty of 0.059 µm. As for the single wavelength example here above, the measurement precision is evaluated from the acquisition of 50 measurements. In this case, two sequences of 50 holograms are necessary, the first using \( \lambda_1 \) and \( \lambda_2 \), and the second using \( \lambda_1 \) and \( \lambda_3 \). They are acquired using a DHM R2200 equipped with a 2× microscope objective. The measured mean height and standard deviation determined using equation (1) are 4473.73 nm ± 0.05 nm. The precision of the measurement is similar on this 4.45 µm step to the one of the 179 nm one presented in figure 1. It illustrates that multiple wavelength measurements have a similar resolution than a single wavelength measurement, but for a much higher step. Here again, accuracy of the measurement is well within the standard certification values. The standard deviation is very small compared to the step height. Achieving an high resolution on a such a relatively large step is unique in 3D optical profilometry, as generally a long scanning range is synonym of larger incertitude. DHM keeps an interferometric resolution on large ranges.

3.3. Measurements with vertical range larger than the depth of focus

When increasing vertical range, sample height is often larger than the objective depth of focus. DHM is not an infinite focus technology in the same sense as confocal and SWLI technologies that somehow slice optical sections of sharp focus. Indeed, as DHM captures the complex wave front, the wave field can be propagated and the focus can be made sharp on any location on the surface of the sample, providing an infinite focus, or extended depth of focus (EDOF) [55–59]. An example of a micro-lens sample measurement using a DHM R1000 [52] operating \( \lambda = 682.5 \) nm, mounted with a 50×, 0.75 NA objective is shown in figure 4. Data are validated by a comparison with AFM measurements. When applying EDOF, both are in very good agreement.

4. Thin transparent layers metrology

Hologram reconstruction provides phase and intensity maps. Metrology generally expects a geometrical information on the surface topography. For homogeneous samples, conversion of a phase map into a topography is straightforward. But when sample material is not unique, or not homogenous, the transformation from optical to geometrical information is no longer straightforward. In the case of layers of semi-transparent materials and reflective layers, often encountered in micro-technology, multiple reflections occur at the different interfaces. Nevertheless, the resulting intensity and phase maps depend on a limited number of parameters: the refractive indices and thicknesses of the different layers. Using several wavelengths, the problem is similar to spectral reflectometry, where the reflected amplitude versus the wavelength spectrum is exploited to determine film thicknesses by fitting procedures. Usually, the measurement is performed on a laser sport, which size defines the lateral resolution. It can be scanned...
Figure 5. Reflectometry DHM R2200 topography measurements for a SiO\textsubscript{2} deposition on a Si wafer (a) and for a SIMS (40 nm Au, 100 nm SiO\textsubscript{2} and Si) (b) and the respective profiles comparison with a Tencor Alphastep 200 profilometer.

Figure 6. Quantitative phase measurements at the image plane with a DHM R1000 equipped with a 100\times objective, for an RCP (right-handed circularly polarized) incident light and a LCP (left-handed circularly polarized) reference arm. (a)–(d) SEM images of a nano antennas array (partial view). The scale bar is 500 nm. (a): lens (b) slow linear variation (c) fast linear variation (d) vortex beam generator. (e)–(f) Corresponding phase contrasted images of a full array of nano antennas. The scale bar is 10 \(\mu\text{m}\). The limits of the grey scale are \(-\pi\) and \(\pi\). (i)–(l) Corresponding unwrapped phase. The limits of the color bars correspond to the phase functions used to design the structures. (m)–(p) Cross section along the transparent vertical plane. The measured data are compared to the theoretical phase functions.

laterally point by point to provide a 2D map. A reflectometry measurement using the basic same principle can be also applied in DHM by measuring reflected wave-fronts (both amplitude and phase) at different wavelengths in order to evaluate layer thicknesses of different layers. The principle is demonstrated in [60, 61] for SiO\textsubscript{2} patterns deposed on Si wafer, for SIMS characterization with three layers (Au-SiO\textsubscript{2}-Si) and for thin water surfaces. Figure 5 shows, for the two first cases, that measurements using a mechanical profilometer and DHM R2200 [52] are identical. Such a comparison is not possible on the water example, as the nature of the samples does not allow the use of a mechanical method.

5. Polarization metrology

Liquid crystal displays, optical telecommunication devices, MOEMS, photonics crystals, are a few examples of samples for which birefringence is a central and key property that need to be characterized. Birefringence analysis is also used for analysis of forces and stress analysis during manufacturing. It can be measured using DHM, both in transmission and reflection configuration [22–25]. DHM has been used in particular for characterization of meta-surfaces [62, 63]. In figure 6, the polarization of the reference arm of DHM R1000 with a 100\times magnification is adjusted to left-handed circularly polarization to interfere only with the meta-surface diffused wavefront. Indeed, a meta-surface, or a meta-device, is a substrate structured with subwavelength-scale patterns in the horizontal dimension. They modulate the behaviors of electromagnetic waves in the 3D space. As many of these devices are active, or as the processes investigated happen quickly, the ability of DHM to record instantaneously information at several polarization is essential for birefringence measurements.
6. 4D metrology

The three 4D metrology examples of this section illustrate the needs of in-situ, controlled environments, and real time measurements.

6.1. In-situ and real-time chemical etching

In situ monitoring and controlling etching processes is an important need in micro and nano structuring of materials and thin films. Conventional methods are mainly laser end point detection and optical spectrometers. Both of them monitor thickness or composition of etched layers and materials, but neither of them provides in-situ real time 3D topography measurement of the etching process with sub-micron lateral resolution.

In figure 7, a metallic sample is coated with a polymer resist patterned with two trenches of different width. It is placed in liquid electrolyte and current is applied to perform electrochemical etching. The measurements are performed with a DHM R-2200 [52] through the transparent window of the etching chamber during the process. The objective has a magnification of 20× and a working distance of 10.8 mm. Both etching depth and surface roughness are monitored with interferometer resolution in real-time and in-situ by DHM, without need to stop the process and to take the sample out of the etching chamber [29]. Although the DHM used for this application has a camera operating at 195 frames per second, the time scale of this application is relatively slow. But the presence of bubbles and gradients of material associated with the etching process requires a short acquisition time of 100 µs for this application.

6.2. Ball-on-disk vacuum tribometer with real time and in situ measurement of the wear track by digital holographic microscopy

Ball-on-disk tribometers are test instruments designed for precise and repeatable wear testing. Continuous monitoring of the wear track is essential to detect when important events, such as material removal happens. DHM has been combined with a ball-on-disk vacuum tribometer and enables real-time and in-situ measurements of the evolution of the wear track under various temperatures (up to 800 °C), vacuum, and atmospheric conditions (figure 8). It measures at 34 frames per second, with an acquisition time of 100 µs. The system can operate up to a linear speed of 10 cm s⁻¹ with a 40× magnification objective. This one has a working distance of 30 mm, providing enough clearance to perform the measurement through optical port. This one is coated to reflect IR to prevent any damage on the objective when the sample is heated at 800 °C. The system was tested and validated by correlating measurements of the wear track measured by the DHM with the ones characterized using SEM and confocal microscopes [30, 31]. It solves the problem of taking the sample out of the chamber and replacing it in the exact same position relative to the ball-on-disk.

6.3. Surface topography measurements simultaneously to laser texturing

Interference lithography enables complex surface structuring of azobenzene-containing films for creation of surface relief patterns with varying heights. For understanding and controlling their formation dynamics and response to different types of light fields, a lithography set up has been combined with a DHM-R2100 [10, 47]. It enables real time, in-situ observation, and control of surface-relief grating formation on azobenzene-containing films, as shown in figure 9. The DHM measurements, performed at 195 frames per
second, with an acquisition time of 0.5 ms, and a 20× objective with a 3 mm working distance, have been validated using an atomic force microscope.

The applications of this section illustrate how real-time topography measurements can be exploited to give a quasi-instantaneously feedback to the control system of a process, that can be etching, mechanical ablation, laser structuring, polishing, or many other micro- or nano-manufacturing processes. It may include artificial intelligence for taking decisions and adjusting the process parameters, such as its time duration, laser beam intensity and shape, intensity of an electrical or mechanical action, among others.

7. Vibration Metrology

Consequently to the full-field and single shot fast acquisition specificities of DHM, many of its applications are naturally found in the MEMS domain [38–48].

Despite the technology evolution, cameras have, and will always have, a limited maximum acquisition frame rate, especially when a certain imaging resolution of at least one million of pixels is expected. A second limitation lies in the exposure time that necessary decreases when frequency increases. To preserve the same amount of light collected at each acquisition independently of the acquisition frequency, illumination intensity must be increased in inverse proportion with the camera shutter duration decrease. Eventually, laser power cannot be increased above a given threshold to prevent sample damages.

When the movement of a sample can be repeated identically over time, the laser pulsed stroboscopic synchronization technique provides a solution to these technical limitations. This approach enables the use of standard, non-high-speed cameras with higher imaging quality than high speed sensors, and of lasers with low power, and compatible with reasonably priced tabletop DHM systems.

The acquisition principle is shown in figure 10. The excitation signal represented in this example is a so-called burst, composed by two periods of a sinus wave, followed by a constant voltage period. This signal
Figure 10. Laser pulse stroboscopic synchronization principle.

Figure 11. Phase and amplitude vibration maps of a micro-mirror supplied by Lemoptix SA, Lausanne, Switzerland, excited by a sine wave at 19 kHz (a)–(c) and 491 kHz (d)–(f). (a) and (d) are the 3D topographies measured consecutively at the excitation signal phase with steps of 15°. (b) and (e) are the amplitude vibration maps, and (c), (f) are the vibration phase maps. Diameter of the mirror: 1 mm, objective 5×, working distance 14 mm, measurement performed using a DHM-R2100 [52] and with a 2.5× objective.

is repeated over time. Laser pulse trains are precisely synchronized with this signal, with well controlled delays applied for the successive holograms acquisition. The number of samples per excitation period can be in this way precisely controlled. There is no need for a high-speed camera and integration of multiple laser pulses for each sample ensures optimal hologram illumination without the need of a high-end powerful laser source that may arm samples.
Figure 12. Capacitive micro-machined ultrasonic transducer (CMUT) by Philips, Eindhoven, Netherlands, excited by a burst signal composed by two periods of a sine wave at 5 MHz. (a) Excitation burst in blue and three randomly selected areas vertical displacement in red, yellow, and green. (b) 3D topography time sequence (represented sampling: one measurement over two during the first four microseconds of the CMUT response). (c) Four remarkable frequency maps obtained by DFT over the time-sequence of topography maps. Measurement performed with a DHM R2100, \( \text{diameter of the membrane } 120 \, \mu\text{m}, \) objective \( 20 \times \) water immersion, working distance 3.5 mm.

The output of a stroboscopic acquisition scheme is a time-sequence of 3D topographies that can be exploited as is or further processed for investigating time and frequency responses. Traditional Bode plots and Fourier transform has been used by the author of this paper in [47] to analyze the response (displacements) of an individual small area of the surface of the analyzed samples. This approach is generalized in this section by replacing individual area analysis by the calculation of full field amplitude and phase maps. These representations are interesting because they are also the ones used by the finite element simulation programs used to predict the properties of MEMS.

Phase and amplitude vibration maps are extracted from the time sequences of topographies. The amplitude map displays for each pixel the difference between the minimum and the maximum of the vibration, and the phase map displays the difference of phase between the excitation signal and the response of the device. It is illustrated in figure 11 for a micro mirror excited by a sine waveform at 19 and 491 kHz.

According to Nyquist-Shannon theorem, and assuming sinusoidal vibrations of the sample, three samples per period are sufficient to extract vibration maps on the example of figure 11. The vibration time-sequence can be restored from the two vibration maps, i.e. the phase and amplitude of the vibration for each pixel. With this approach and representation, vibrations are characterized with an optimal number of recording, and a minimal need of data storage.

For investigating the frequency response of a microsystem, a first solution consists in exciting it with a sine waveform and sampling a full period of the excitation period, and to sweep step by step the excitation frequency over the relevant frequency range. Frequency resolution is given by the sweeping step. An alternative to this approach is to excite the system with a waveform encompassing multiple frequencies (chirp, burst, transient), and to perform a discrete Fourier transform (DFT) of the time-sequence to retrieve the microsystem response in the frequency domain. Frequency resolution depends on the number for samples per period and maximum sampling frequency [47]. This second solution is illustrated in the figure 12 for an ultrasonic transducer, with membrane diameter of 120 \( \mu\text{m}, \) measured with a DHM R2100, \([52]\), and a water immersion objective \( 20 \times \) with a working distance 3.5 mm. It generalizes the conventional single point frequency analysis into mega-pixel vibration amplitude maps calculated for each DFT bins/channels.

In this section, the presented applications show that off-axis DHM provides a very efficient analysis both in the time and in the frequency domain. Time sequences of topographies are measured at precise phases of the MEMS excitation signal, and enable to calculate amplitude and phase vibration maps. Data are
determined over the full field of view, providing mega pixel digital resolution and diffraction optical resolution. Such specifications enable investigation of complex structures and resonant modes difficult to address using a LDV scanning system measuring a limited number of spots over a grid.

8. Conclusions

Off-axis DHM technology is no longer a research topic in itself. Latest developments lie mainly in the technological improvements of electro-optical components, such as higher speed and improved quality cameras. DHM systems have been consolidated into commercial systems and they are used daily for research in academic and industrial laboratories and for quality control in production environments. Their functionalities cover a large range of metrology applications, including dimensioning, calibration, polarization, and semi-transparent layers investigations. With their 4D ability, they provide a new insight on many phenomena investigated previously only by performing endpoint measurements. The off-axis DHM evolution lies now in the new metrological application developed by DHM users.

Latest trends include fast interpretation of measurements to provide feedback to manufacturing and material processing, involving artificial intelligence to control manufacturing and processing tools, machine learning for decision making, and integration of complementary measurement modalities.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to thank all the past and present Lyncée team members who allowed for the development of the DHM systems on which the results presented were obtained.

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