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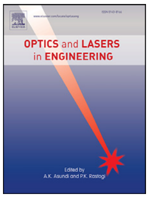

A compact real-time high-speed high-resolution vibrometer, surface profiler and dynamic focus tracker using three wavelengths parallel phase-shift interferometry

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ABSTRACT

The combination of simultaneous parallel phase shift interferometry with three wavelengths illumination and three spectral quad detectors integrated into a compact optical system is presented, achieving a real time, high speed, sub-nm axial resolution and repeatability tracking of axial position over tens of micrometers including sharp step profiles. The prototype system is tested and demonstrated for the applications of fast vibrometry up to 400 kHz rate, surface profiling and dynamic focus tracking and correction. The methodology, algorithm and calibration procedure along with the new compact and low-cost system design relying on off the shelf components, are described in detail.

1. Introduction

Non-contact high-speed high-resolution axial position measurement\tracking over a wide axial range is a key technological ability, at some cases an enabler, for various fields and applications both in academia and industry. The most obvious high technological value applications for axial position measurements are surface profiling or 3D imaging of various types of samples from different fields. An additional class of applications is made possible, if the technique enables real time measurement and tracking of the axial position, making possible a real time (RT) study of the sample or RT utilization of the measured data. One example can be a real-time feedback channel for dynamic focus tracking and focus correction in real time imaging and precision measurement systems with narrow depth of field that are common in the metrology industry [1]. Another can be real time study of processes in dynamic samples such as biological entities, or evaluation of a complex sample status during its production. Meeting the needs of these applications, any contending measurement technique must stand in a demanding list of requirements: nm and even sub-nm axial resolution and repeatability; measurement rates of hundreds of kHz to MHz rates of acquisition for point measurement or tens of frames per second for full field measurement systems; ability to capture within a single 3D frame or between sequential single point position samples topography changes of the order of several tens of μm over a working range of several hundreds of μm and a lateral field of view (FOV) of the same scale or more; real time measurement capability; and finally all in a compact and low cost system.

The sub-nm resolution requirement narrows almost absolutely the measurement\imaging approach to interference based measurement techniques, more specifically to a class of 3D imaging known as coherence probe microscopy. This class of methods, that applies short temporal or spatial coherence gates, was developed at first to monitor the fabrication processes of semiconductors by metrology equipment manufacturers [2], for surface profiling and step height measurement [3], and with the appearance of the more modern optical coherence tomography (OCT) methodology was utilized later for various applications in ophthalmology, biology and more recently in process control and metrology [4]. More advanced full field modalities of OCT (FF-OCT) [5–8], even enable the acquisition of the interference signal over the entire field of view and require no lateral scanning therefore improving the speed of 3D scene acquisition and tracking [9]. However, obtaining each of the 3D data over a single point or the entire FOV requires an acquisition of several (typically 4) interference images that are phase shifted one with respect to the other, and are usually taken sequentially [10,11]. This fact results in a factor of 4 decrease of the potential 3D imaging speed now limited by the speed of phase shift introduction, in one case the speed of the piezoelectric transducer (PZT) that actuates the mirror in the reference arm of the interferometer. In addition, the non-simultaneous acquisition of phase shifted images may result in measurement errors, as the sample may change a bit between acquisitions of phase shifted images per 3D scene due a dynamic nature of the sample (e.g. biological samples), vibrations in the system and instability of the interferome-

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ter. To address this limit, parallel phase shifting techniques have been suggested, acquiring all phase shifted signals using parallel detectors [12–16], however to the best of our knowledge a previous work of ours [17] was the first to present the full field enface image at a single shot.

All the above phase shifting interferometry (PSI) techniques, as well as others so called frequency-domain methods such as digital holography microscopy (DHM) [18,19], off-axis interferometry [20,21], and diffraction phase microscopy [22,23], are inherently limited to sample topographies in phase imaging or inter-step movements in point sensing that present smaller variations than a single interference fringe. A single interference fringe translates to half the illumination source's central wavelength. For optical wavelengths, specifically in the visible domain or the near IR or near UV, this translates to only several hundreds of nanometers. This inherent constraint, also known as phase wrapping, severely limits the suitability of all the above techniques for many applications that require handling surfaces or tracking motion patterns that can produce steep μm scale variations. Due to the implications of this constraint, many methods have been suggested for extending the axial range beyond the limit of a single fringe, also known as phase unwrapping methods. To name a few of these techniques: the most common minimum-norm methods [24–31], path following methods [32–34], network programming [35], cellular automata [36], and more recently genetic algorithms [37]. All of these methods manipulate the measured phase data or map and aim to correct it by unwrapping the phase at the locations where a change larger than a single fringe occurred. At the bottom line, they differ one from the other by their accuracy of phase unwrapping and correct calculation of the real unwrapped axial position change or topography, immunity to noise, and most importantly in our case – the execution time of the unwrapping algorithm, as these sometimes-complicated algorithms are demanding in calculation resources and run time. None of these methods can provide rung time that is of the scale of several milliseconds for a full field 3D map required for a video rate 3D imaging or single point position finding in kHz to MHz rate, required by the applications we target. Another class of phase unwrapping techniques, the multiple wavelength approach, which avoids the heavy calculations required to unwrap the measured phase by synthetically extending the effective single fringe length, or the effective wavelength to the required scale of few to tens of μm. This is achieved by combining the measured phase from two or more illumination sources with different central wavelengths taken sequentially, allowing the synthesis of a beat wavelength with a desired μm scale fringe size, yet at some cases on the expense of measurement resolution and noise. This approach has been implemented first in holography [38,39] and, later, in PSI [40,41], DHM [42–44], off-axis interferometry, and fringe pattern profilometry [45]—in all of them a considerable increase of phase unwrapping speed is achieved. By using 3 wavelengths rather than the more common 2 wavelengths, we achieve the desired high-speed measuring while maintaining the sub-nm accuracy of the single wavelength approach. In our unique optical system design and algorithm described in this text, not only the 3 phase shifted interference signals are acquired simultaneously, but also all of these signals for all 3 wavelengths are acquired at a single shot (hence we name it π-$\lambda\varphi$ to stand for parallel interferometry (PI or π) at different wavelengths and different phases) enabling fast axial position calculation and sub-nm resolution—fully answering the previously mentioned demanding list of requirements of all targeted applications.

In this paper, we focus on a single point measurement technique and system, not only to demonstrate and discuss in full detail the parallel phase shift and 3 wavelengths phase unwrapping algorithm we have previously presented [46, 47], but also to present a new much faster, compact, simple and elegant system design implementing it - resulting in a considerable reduction of costs, making the technology more accessible. This algorithm and system design concept can be later extrapolated to a full field imaging system in relatively straightforward manner for example by relying and improving the system design we have presented previously for a high-speed 3D microscopy system with 1 and 2 wavelengths illumination taken sequentially [17,48]. Furthermore, though single point measurement systems can be used for surface profiling by a fast raster scan of a sample as we demonstrate here, they have a wide variety of utilizations on their own enabling the tracking of axial movements and vibrations.

Some of the more prominent applications, out of the numerous scientific industrial and medical applications to which vibration measurement is important, include testing and characterizing the performances of loudspeakers [49], measuring the mechanical vibrations induced by cardiovascular dynamics in order to diagnose cardiovascular diseases [50,51] and monitoring and analyzing mechanical systems in order to reduce acoustic emissions in order to achieve performance closer to tolerances at higher speeds [52]. More demanding applications require high frequency vibration monitoring over large axial steps such as analysis of micro electro-mechanical systems (MEMS) for resonant frequency, stiffness and damping [53,54]. Over the years, several techniques have been developed for tracking axial movements, and have resulted in high performance industrial systems for various applications. The most widespread technique is the Laser Doppler Vibrometry (LDV) that relies on acousto-optic modulators (AOM) [55,56]. Though these LDV systems do present impressive performance, they suffer from inherent AOM-associated drawbacks. To name a few: the requirement for the modulating frequency of the AOM to be much larger than the measured vibration frequency limits the measurable maximal vibration; difficulties in calibrating and aligning due to the AOM sensitive nature; high power consumption by the electronic systems; short lifetimes due to the mechanical nature of the AOM and a high cost. Other vibrometry systems that do not rely on AOMs, avoiding the above-mentioned drawbacks, include self-mixing laser diode velocimeters [57–59]; however, to the best of our knowledge, they have not yet achieved sub-nanometer resolution or the capability to measure vibration frequencies above several kHz and therefore present limited performance relative to PSI-based systems.

2. System design

In Fig. 1(a), a photograph of the optical setup is presented. The illumination head of the system is composed of three single-mode fiber pigtailed laser diodes (LDs) with 1 nm FWHM and central wavelengths of $\lambda_1 = 635$ nm, $\lambda_2 = 642$ nm, and $\lambda_3 = 685$ nm, producing 8, 20, and 15 mW respectively (LP635-SF8, LP642-SF20 and LP685-SF15, all from Thorlabs). The end face of each fiber is positioned at the focal plane of a fiber collimator, providing highly collimated laser beam with a 3.2 mm diameter. Each collimator is mounted in a kinematic adapter that allows a control over the pitch and yaw (KAD11-F, Thorlabs). The adapter is mounted on an *XY* translation mount that allows a 5 mm movement in each axis (ST1XY-A, Thorlabs) relative to the optic axis of the system positioned at the middle of a cage frame comprising the system skeleton. The three collimated beams are combined to a single beam using a "beam unification unit" that includes two 50/50 beam splitters (BS). The 642 nm and 685 nm beams are combined using the first BS, and the resulting beam is combined with the 635 nm beam by the second BS. Since the output polarization of the LD is almost linear, a simple rotation of the collimators about the optic axis allows aligning the polarization of all three LDs along the linear wire-grid polarizer positioned at a 45-degree angles relative to the axes of the PBS at the heart of the interferometer, allowing maximal power coupling of all 3λs entering the interferometer.

The 3λ collimated beam then passes through an additional 50/50 BS. Half of the incoming light passes to the polarization based Michelson interferometer, while the other half is directed to a perpendicular direction, where a Hartmann–Shack (HS) sensor is placed only at the alignment process of the system. The HS sensor monitors the position of each beam, allowing a precise alignment and unification of all the beams. At the heart of the polarization Michelson interferometer, a polarized beam splitter (PBS) reflects the S polarization component of the beam toward