Optics Communications 318 (2014) 88–94

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Extended range phase-sensitive swept source interferometer for real-time dimensional metrology

Yi Shen [a], Zhihua Ding [a,*], Yangzhi Yan [a], Chuan Wang [a], Yaliang Yang [b], Yudong Zhang [b]

[a] *State Key Lab of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China*
[b] *The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China*

ARTICLE INFO

Article history:
Received 26 June 2013
Received in revised form
17 December 2013
Accepted 23 December 2013
Available online 4 January 2014

Keywords:
Dimensional metrology
Low coherence interferometry
Phase unwrapping
Swept source

ABSTRACT

The measurement of center thicknesses and airgaps along its optical axis is crucial to a mounted optical system. Aiming to real-time dimensional metrology, an extended range phase-sensitive swept source interferometric system is developed. To yield high precision of measurement, reference interferometer sharing the same swept source with the measurement interferometer is introduced and a phase-sensitive approach based on phase-comparison between measurement signal and reference signal is exploited. The proposed phase-comparison method is theoretically developed and its merits over standard phase-sensitive approach are experimentally confirmed. In contrast to the standard phase-sensitive approach, the sensitivity under signal to noise ratio of 45 dB achieved by the phase-comparison method is improved from 222 nm to 25 nm and the processing time is shorten by 90%. Measurements of glass plates are performed to evaluate the performance of the developed system. Submicron precision about a range of 30 mm is realized by the developed system equipped by a commercial available swept source operating at a sweeping rate of 10 kHz. The developed system holds potential application in real-time contact-free on-axis metrology for the fabrication and testing of complex optical systems.

1. Introduction

The measurement of center thicknesses and airgaps along the optical axis of a mounted optical system, such as the lens system for microscopy, photography or lithography is crucial to optics manufacturing industry and modern optical instrumentation [1]. Low coherence interferometric sensor (LISE) is thus developed to meet such requirement. Extended range is feasible for LISE due to its high-precise mechanical-driven delay line calibrated by an additional internal laser interferometer [2]. However, relative long time taken by mechanical movement in LISE makes it unsuitable for real-time applications. To speed up the measurement, spectral interferometry without moving component is a potential candidate. Fourier domain detection in a spectral interferometer can provide increased phase stability over time domain detection in LISE if without additional hardware for real-time compensation [3,4]. Unfortunately, the measuring range of a spectral interferometer is usually limited to several millimeters by the spectral resolution of a spectrometer mostly using grating as the disperser in conjunction with a line-scan CCD [5]. Although spectral resolution of 0.002 nm over a free spectrum range of 50 nm using an orthogonal dispersive spectrometer is reported recently to realize an imaging depth over 80 mm in optical coherence tomography (OCT), but the slow frame rate (30 Hz) of two-dimensional CCD obstructs current system for real-time application [6]. An alternative to spectral interferometry is swept source interferometry, where a swept source with fast frequency sweeping rate around tens to hundreds Kilohertz is adopted. Again, the measuring range is usually limited to several millimeters by the instantaneous coherence length of the commercial available swept source due to challenge in compromising between high sweeping rate and narrow instantaneous line-width [7]. Most recently, a swept source OCT using vertical cavity surface emitting laser light source is demonstrated to enable imaging ranges from a few centimeters up to meters at a high sweeping rate [8]. This ultralong-range OCT based on the novel swept source enables completely new applications that were previously impossible. However, a narrower instantaneous line-width means longer coherence length and introduces a broader autocorrelation artifacts resulting from multiple reflecting interfaces of the sample under measurement if balanced detection is not perfect. To remove such autocorrelation artifacts, frequency shifting approach has been applied [9,10], but filtering out the broadband autocorrelation artifacts requires a very high carrier frequency. What is more, aliasing could be more serious under case of longer coherence length if the sampling rate for the detected signal is limited. Therefore, for the specific application of the measurement of center thicknesses and airgaps along the optical axis of a mounted optical system, it is desirable to extend the measurable range without increase of the coherence length of the swept source.

---

[*] Corresponding author. Tel.: +86 135 887 03473.
E-mail addresses: zh_ding@zju.edu.cn, witchball@gmail.com (Z. Ding).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.12.065

A technique allowing for substantial increase of measuring range for optical low-coherence reflectometry is proposed by use of a recirculating delay line [11]. Similar recirculating approach is adopted in swept source OCT [9]. In this Letter, we report an extended range phase-sensitive swept source interferometric system for real-time dimensional metrology. The measuring range of the system is extended by use of two active recirculation loops configured in a measurement interferometer feeding by a commercial available swept source with a modest coherence length of 12 mm. A reference interferometer sharing the same swept source with the measurement interferometer is introduced to provide reference signals for all sweeps. Phase-sensitive approach based on phase-comparison between measurement signal and reference signal is proposed to distance determination without wavenumber calibration, and a measurable optical path difference (OPD) uncertainty of 25 nm under signal to noise ratio (SNR) of 45 dB is realized. The proposed phase-comparison method achieves higher precision and speed over the standard phase-sensitive approach. Measurements of glass plates are performed with the developed system, and submicron precision about a range of 30 mm is confirmed for the swept source operating at a sweeping rate of 10 kHz (kHz).

2. Experiment setup

Fig. 1 depicts the schematic of the extended range phase-sensitive swept source interferometric system. The system consists of a measurement interferometer and a reference interferometer sharing a common swept source. The commercial available swept source (HSL-2000, Santec Inc.) operating at a sweeping rate of 10 kHz is employed to provide a tuning range of 115 nm from 1267 nm to 1382 nm with instantaneous coherence length around 12 mm. The 90% of the output power from the swept source is sent into the measurement interferometer and directed into sample arm and reference arm through a 50/50 fiber coupler. In order to extend the measuring range of the measurement interferometer, recirculation loops with mismatched optical path lengths are implemented in both sample arm and reference arm to provide multiple stepped OPDs simultaneously. The mismatched OPD is adjusted to be 16 mm through an optical delay line (OD). As optical path lengths of both recirculation loops are far beyond the coherence length of the swept source, returning light from sample arm and that from reference arm with different times of passage through two recirculation loops cannot interfere while those with the same times of passage can. For every pass of the light through two recirculation loops, the zero OPD position of the measurement interferometer is shifted to the depth direction in the sample by half of the mismatched OPD, i.e. 8 mm. Therefore, interferences origin from different depth ranges of the sample are realized simultaneously without movement of reference arm. To resolve these interference signals corresponding to different times of passage in two recirculation loops and thereafter encode them to depth information without ambiguity, two acousto-optic frequency shifters (AOFS1 and AOFS2, Brimrose Inc.) driven by voltage controlled oscillators under different frequencies ($f_1 = 55$ MHz for AOFS1, and $f_2 = 70$ MHz for AOFS2) are adopted in both recirculation loops. The use of two AOFSs instead of one favors the dispersion balancing between two recirculation loops. The role of AOFS in each recirculation loop is shifting the optical frequency of the light upward by the driving frequency. As the driving frequency applied to two AOFSs is different, a carrier frequency of $N \times \Delta f$ is produced in the interference light at the fiber coupler before the detector, where N is the number of light recirculation in two recirculation loops, and $\Delta f = f_2 - f_1 = 15$ MHz, is the carrier frequency obtained in one recirculation by two AOFSs. As described in Ref. [9], the frequency is related to OPD by $(2\pi\rho\Delta f/\gamma\Delta k)$, where Δk is the tuning bandwidth in wavenumber, γ is the sweeping rate, and ρ is the duty cycle. Using system parameters ($\Delta k = 412\ rad\ mm^{-1}$, $\rho = 0.85$, $\gamma = 10$ kHz), the OPD corresponding to the carrier frequency of 15 MHz is calculated to be ~20 mm. In considering of the coherence length (~12 mm) of the swept source adopted in our system, such a carrier frequency is enough to isolate interference signals corresponding to different N in frequency domain. Therefore, interference signals from different depth ranges corresponding to different N are frequency coded without depth ambiguity. Semiconductor optical amplifiers (SOA, Inphenix Inc.) are used in recirculation loops to compensate for losses. Two optical isolators are placed at the output of the SOAs to protect their operation from stray reflection. Two circulators are adopted in both reference arm and sample arm to send and collect light to and from the reference reflector and the sample under measurement. The interference signal from the measurement interferometer is detected by a balance detector (PDB450C, Thorlabs) with a bandwidth of ~150 MHz and sampled by one input channel of a 12-bit DAQ card

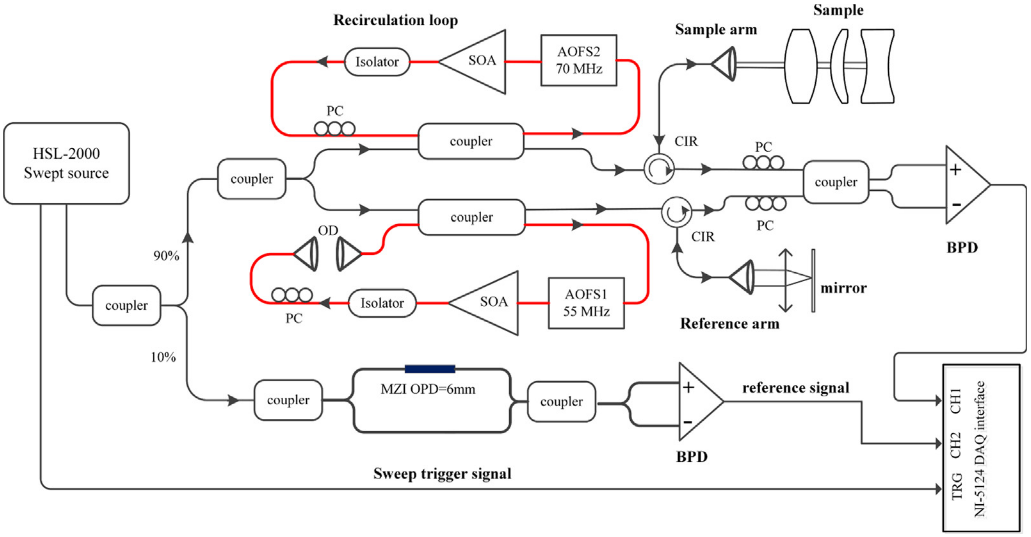

Fig. 1. Schematic of the extended range phase-sensitive swept source interferometric system. Coupler: 50:50 fiber coupler; PC: polarization controllers; AOFS1, 2: acousto-optic frequency shifters; SOA: semiconductor optical amplifier; CIR: circulator; OD: optical delay line; MZI: Mach–Zehnder Interferometer; BPD: balanced photodetector; CH1: channel 1; CH2: channel 2; TRG: trigger channel.