Extending low-coherence interferometry dynamic range using heterodyne detection

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A R T I C L E   I N F O

Keywords:
Low-coherence interferometry
Dynamic range
Heterodyne detection
Fourier transform spectroscopy
Optical coherence tomography

A B S T R A C T

Low-coherence interferometry (LCI) technique is generating considerable interest in industrial applications where there is a need for larger measurements with high resolution. Conventional Fourier domain systems reach a limiting depth of around 3 mm, mainly due to the spectrometers used as detectors. In this work, we present an optical detection system that performs the Fourier transform of the LCI signals, based on a spatial heterodyne spectrometer. This device avoids the fall-off effect of the spectrometer, allowing to reach measurable optical depths of almost 5 cm without losing resolution. We describe the theory underlying this detection system and present experimental results which are in great accordance.

1. Introduction

Low-coherence interferometry (LCI) is a non-destructive optical measurement technique able to reach a micrometer resolution in the axial direction. The main objective of LCI is the measurement of optical path difference (OPD) to find distances of interest in a sample. Currently, its main application field is in biomedical imaging through optical coherence tomography (OCT) [1]. However, this technique is in constant expansion and has interesting applications such as in art [2,3], profilometry [4], component characterization [5,6] and optical fiber sensors [7].

There are three widely used LCI systems: in the time domain (TD-LCI), in the Fourier domain (FD-LCI) and with swept source (SS-LCI). In TD-LCI the interference signal is generated moving a mirror in the reference arm of an interferometer. In those systems, the use of expensive moving systems of great precision but extremely slow are required to measure distances over one centimeter [8,9]. With the development of FD-LCI this limitations were overcome, allowing the design of more robust, compact and fast systems [10,11] without moving parts on the reference arm. In FD-LCI, the Fourier transform of the interferogram is performed to find the OPDs and therefore the lengths of interest. The state-of-the-art depth values measurable with this technique ranges from 3 mm to 4 mm. This limitations arises mainly from the spectrometer used to detect the interferogram: its diffraction grating and number of sensor pixels affects directly the signal sampling[12]. On the other hand, a strong limitation of this technique is the “fall-off” effect [13] due to the limited size of the sensor pixels, which produce the interference signal attenuation for larger OPDs.

It is of interest for many industrial applications to extend the measurable OPD of this technique. Although this is possible using swept light sources (SS-LCI) [14], the cost of the system increases dramatically. In recent years, several successful improvements were achieved to extend the axial range in FD-LCI systems, such as the generation of the full complex signal [15,16] and the use of Talbot bands [17,18]. The first one attenuates the mirror terms of the Fourier transform signal by producing phase shifted interferograms. On the second one, the two interferometer beams are laterally shifted in order to produce a Talbot band configuration that allows to enhance sensitivity and depth range. These methods have proven to be useful to double the depth range of standard systems. However, they still have the limitation imposed by the spectrometers, such as the fall-off effect due to the finite pixel size.

In this work, we studied a novel detection system for FD-LCI based on a spatial heterodyne spectrometer [19] that can be extended to FD-OCT systems carrying out a lateral scan. This device performs the Fourier transform of the LCI interferometric signal, enabling the possibility to find the distances of interest without any further processing. The main advantage was found to be the independence of the sensor used for the signal detection. This led to one of the most important characteristics of this method: avoiding the fall-off effect that limits the dynamic range in conventional FD-LCI systems. As a result, the maximum measurable distance is shown to be increased in one order of magnitude.

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https://doi.org/10.1016/j.optlaseng.2020.106106
Received 20 December 2019; Received in revised form 9 March 2020; Accepted 19 March 2020
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2. Theory

2.1. Frequency domain low-coherence interferometry

FD-LCI is an interferometric technique that relies on a low-coherence light source to measure OPD [1]. Usually, a Michelson interferometer configuration is used, where the sample of interest is placed in one arm and a reference mirror in the other, as shown in Fig. 1. The reflections produced in the reference arm and the sample, recombine after passing through a beam splitter, generating the interference signal detected with a spectrometer. Considering the general case where there are several reflections in the reference arm and in the sample arm, the total intensity in the detector is expressed by (1), where \( k \) is the wavenumber and \( S(k) \) is the normalized light source spectrum [1]. The OPD is given by \( n_g \Delta z_{ij} \) with \( \Delta z_{ij} = z_i - z_j \), where \( z_{ij} \) is the reflection pathlength from the beam splitter. The subindex \( i,j \) takes into account the reflection of the reference arm \( (z_p) \) and the multiple interfaces of the sample \( (z_s) \) and \( R_{ij}(k) \) denotes their reflectivities. \( n_g \) is the group refractive index in a non-dispersive medium. In the case where air is the medium \( n_g = 1 \).

\[
I_{\text{tot}}(k) = S(k) \sum_{i=1}^{N} R_i(k) + S(k) \sum_{|j|=1}^{N} 2\sqrt{R_i(k)R_j(k)\cos(kn_g \Delta z_{ij})}. \tag{1}
\]

The OPD is obtained performing the Fourier transform of (1) (see Fig. 2). It is worth noticing that the distance of interest is half the OPD in this interferometer.

The maximum measurable value of the OPD [1], which defines the dynamic range of the system, can be expressed as

\[
\text{OPD}_{\text{max}} = \frac{\lambda_0^2 N_s}{4n_g \Delta \lambda}, \tag{2}
\]

where \( \lambda_0 \) is the central wavelength of the light source, \( \Delta \lambda \) the spectral FWHM in wavelength of the light source and \( N_s \) the number of illuminated sensor pixels of the spectrometer used as detector. Notice that the spectrometer plays a determinant role [20].

The resolution of this technique is given by the coherence length of the source \( \lambda_c \). Assuming a Gaussian-shaped spectrum centered in \( k_0 \) with a spectral bandwidth \( \Delta k \) (given by the half width of the spectrum at 1/e of its maximum)

\[
S(k) = \exp \left( \frac{(k - k_0)^2}{\Delta k^2} \right), \tag{3}
\]

the resolution is given by Drexler and Fujimoto [1]:

\[
\delta z = \frac{2\sqrt{\ln(2)\lambda_0^2}}{\Delta k} = \frac{2\ln(2)}{\pi} \frac{\lambda_0^2}{\Delta \lambda}, \tag{4}
\]

2.2. Heterodyne detection system

The heterodyne detection system presented here is based on the spatial heterodyne spectrometer [19], a Fourier transformed spectrometer. The design is similar to a Michelson interferometer, with diffraction gratings in place of mirrors (see Fig. 3(a)). The input signal is the light beam to be analyzed. The heterodyne detector separates the different wavenumber components of the input signal via the diffraction grating equation

\[
k \left[ \sin(\theta_L) + \sin(\theta_L - \gamma) \right] = \frac{m}{d}, \tag{5}
\]

where \( k = 1/\lambda \) is the wavenumber of input, \( \theta_L \) the Littrow angle (dependent of grating), \( \gamma \) is the angle that the output waveform makes with the normal of the detector, \( m \) is the diffraction order and \( 1/d \) is the groove density of the grating. For each wavenumber there are two wavefronts tilted in opposite directions that recombine in the detector creating interference fringes known as Fizeau fringes [19,21,22]. The output contains the overlap interferences of all the separated wavenumbers constituents of the input.

When \( \gamma \) equals zero, the observed wavenumber is known as the Littrow wavenumber and the wavefronts returning from both arms are parallel to the sensor surface. The Littrow angle can be solved in this condition:

\[
\theta_L = \sin^{-1} \left( \frac{m}{2ak_L} \right). \tag{6}
\]

The phase difference between the recombining beams is [19]

\[
\Delta \phi = 2\pi(4k - k_L) \tan(\theta_L)x, \tag{7}
\]

where \( x \) is the position along the detector, as shown in Fig. 3(a), which can be related to the optical path difference of an interferometer by

\[
\text{OPD}_{\text{het}} = 4x \tan(\theta_L). \tag{8}
\]

For a polychromatic source, the interferogram \( I_{\text{het}} \) at the output of the heterodyne detector is

\[
I_{\text{het}}(x) = \int_{-\infty}^{\infty} \frac{1}{2} L(k) [1 + \cos(2\pi(k - k_L)\text{OPD}_{\text{het}})] dk \tag{9}
\]

where \( L(k) \) is the spectral radiance measured at the input of the detection system. Eq. (9) shows that the interferogram at the output is the real part of the Fourier transform of the input signal. It is worth noticing that if the gratings are placed in different Littrow angles, the parallel planes for which \( \Delta \phi = 0 \) are no longer parallels to the camera. Therefore, the image on the sensor is a projection of the Fizeau fringes. Small variations around the Littrow angle for both gratings will lead to different fringe patterns as studied in [22].

2.3. Heterodyne detection for FD-LCI signals

In this work, the input signal on the heterodyne detection system is the interference signal produced by the LCI system. As this detection system performs the Fourier transform of the signal spectrum, the output will be formed by fringes corresponding to the different OPDs, as shown in Fig 2. The maximum measurable OPD will be related to the maximum
position \( x \) in the detector measured from its center (see Fig. 3(a)) and depends on the illuminated width of the gratings \( W \) [19]:

\[
\Delta x = \frac{W \cos(\theta_L)}{2 \Delta k} \quad \text{and} \quad OPD_{\text{max}} = 2W \sin(\theta_L).
\]

A typical experimental image of the output of the heterodyne detection of a LCI signal is shown in Fig. 4. The central fringe corresponds to the Fourier transform of the light source spectrum. It also corresponds to an OPD of zero. At equal distance from the central fringe on both sides lie the fringes (Fourier peaks) corresponding to the OPD of the interferometer.

The modulation inside each fringe, is caused by a tilt of the diffraction gratings on an axis perpendicular to the optical axis. When there is no tilt in the \( y \) direction, the fringes produced are perpendicular to the optical axis. The intensity profile of the experimental image is shown in Fig. 4, where each peak corresponds to the OPD of the interference signal as in Fig. 2. Since the system Fourier transforms the signal, the envelope that defines the peak depends on the input spectrum of the light source as in conventional FD-LCI. If the input light source has a Gaussian-shaped spectrum as (3) centered in \( k_1 \), the output FWHM \( \Delta x \) can be found from (1) and (8):

\[
\Delta x = \frac{\sqrt{ln(2)}}{\tan(\theta_L) \Delta k}.
\]

where \( \theta_L \) is the Littrow angle defined previously (6). Therefore the width of the fringe depends on the width of the source spectrum, but also on the spacing of the grating and the chosen \( k_1 \) (through \( \theta_L \)). It is worth noticing that for larger Littrow angles, the fringes narrow and there are less periods of the cosine wave that define the envelope.

3. Experimental setup

In order to study the detection device, a LCI interferometer with the heterodyne detection system was built as shown in Fig. 3(b). The collimated light from an extended source (SLD351, Superlum) enters a Michelson interferometer. The source is centered in 850 nm with 60 nm bandwidth. One of the mirrors is fixed (reference) and the other is mounted on a motorized linear translation stage (PT1/M, Thorlabs and CMA-25PP, Newport). A motion controller (ESP 301, Newport) is used to move this mirror, changing the OPD of the interferometer. A set of lenses at the exit of the interferometer expand the beam before entering the detection system, as the maximum theoretical measurable OPD depends on the width of the illuminated spot on the grating by means of (10). The heterodyne detection is formed by two reflective diffraction gratings (1200 L/mm) located under Littrow angle for 800 nm (\( \theta_L \approx 28^\circ \)) in a Michelson interferometer configuration. The output was acquired with a camera (DCC1645C, Thorlabs) and the image acquisition was synchronized via PC with the movement of the displacement mirror. The acquisition and image processing were done via Python routines developed by the authors.

4. Characterization

In a previous work [23], we made a preliminary study about the feasibility to use this detector in LCI systems. Several measurements were carried out to evaluate the relationship between camera size and spot size.

The mirror of the interferometer was moved so that the OPD changed and the correspondent fringe in the image moved toward the extreme of the sensor. This displacements (Fig. 5) show a linear relation between
the position of the center of the OPD fringe in the camera sensor and 
the distance of the mirror (and the OPD) set in the interferometer, 
as expected from (8). A detailed description of one possible method to find 
the fringes center can be found in [23]. The half width of the fringe was 
considered as the uncertainty associated to the position.

When the illumination spot size is larger than the sensor area, we 
can move the camera along the spot to use the maximum dynamic range 
of the detector. This measurements are shown in Fig. 6 along with the 
calibration curve whose slope is $m = (181.3 \pm 0.8) \text{px/mm}$.

The maximum distance measured in this conditions was 22 mm, ex-
tending the dynamic range by a factor of eight compared with the con-
tentional systems that uses a spectrometer as a detector. This measure-
ment is in great accordance with the theoretical predictions, taking into 
account that the full spot size was used ($W = 2.1 \text{ cm}$), the maximum 
measurable OPD is twice of that calculated with (10).

In the above cases, the gratings were at the same distance from the 
beam splitter ($l_1 = l_2$). When that does not happen, an OPD is added 
in the heterodyne system, causing a shift on the position of the central 
fringe. If we take this OPD difference $\Delta l$ into account, the interference 
signal at the output for small $\gamma$ can be described by:

$$I_{\text{het}}(x, y) = \int_{-\infty}^{+\infty} \frac{1}{2} \left| L(k)[1 + \cos(2\pi(k - k_\perp)OPD_{\text{het}} + \Delta l)] \right| dk.$$  \hfill (12)

This adds an offset on the position of the central fringe of the output, 
causi a shift to the right or left depending on which grating is nearer 
to the beam splitter.

5. Experimental results and discussion

An evaluation of this idea was carried out by placing one of the 
gratings on a linear stage (PT1/M, Thorlabs). Considerable care was taken 
so that the system stayed aligned when moving the grating. The reference 
mirror was moved by two motorized linear translation stages, 
with a travel range of 25 mm each and 2.2 $\mu$m accuracy given by the 
actuator (LTAHSPV6, Newport). A long range measurement was made 
with this setup, reaching a maximum distance of 4.8 cm (Fig. 7). To our 
knowledge, this is the greatest dynamic range achieved by a FD-LCI sys-
tem. It presents an increase of sixteen times compared with conventional 
devices, which typically have a dynamic range in the order of millime-
tres. The half width of the fringe was considered as the uncertainty $\sigma$ 
related to the position. However, when the grating is moved an uncer-
tainty $\sigma$ related to the initial position in the sensor is added. 
Therefore, the absolute error increases in each range where the grating 
was moved, but the relative error stays constant for the whole range. 
A calibration curve was calculated, whose slope was $m = (160.7 \pm 0.1) 
\text{px/mm}$. It is worth noticing that the difference in this value, compared 
with the one calculated when moving the camera, is due to the distance 
difference between the lens and the camera in each case.

The maximum resolution of the system is not affected by the hetero-
dyne detection system, since it only depends on the light source of 
the LCI device. In our work, the resolution was theoretically calculated to be 
5 $\mu$m. This is a major advantage as the extended dynamical range does 
not compromise the high resolution of the overall system.

In order to evaluate the performance of the system along the whole 
range, the sensitivity of the device was measured. Fig. 8 presents 
the signal to noise ratio in decibels of the peak-to-peak amplitude of 
the fringe and the RMS (root mean squared) noise outside the fringe. 
The line in the plot shows a decreasing trendline from 30 dB to 25 dB. 
The bands indicates the standard deviation from the trendline. This decay 
of 5 dB in around 50 mm presents a great advantage above other systems, 
such as the ones that uses Talbot bands where the sensitivity decay 
is expected to be at least 1 dB in 1.5 mm [17]. Furthermore, the variation

![Fig. 5](image1.png) Characterization of the position of the fringe and the OPD of the interferometer showing a linear relation.

![Fig. 6](image2.png) Dynamic range reached using the entire light spot. The calibration curve has a $m = (181.3 \pm 0.8) \text{px/mm}$ slope.

![Fig. 7](image3.png) Large dynamic range acquired changing the distance between the gratings. Calibration curve with slope $m = (160.7 \pm 0.1) \text{px/mm}$.

![Fig. 8](image4.png) Sensitivity of the system measured over the whole measured range.
in the whole range and in the partial ranges between movements of the grating can be explain by misalignments of the overall system. With better translation systems in the LCI system and in the heterodyne detector this alignments can be improved and thus the sensitivity.

The studies performed with the heterodyne detection system for LCI signals were in great accordance with the theoretical predictions. The relation between the OPD in the interferometer and the position of the fringe at the output keeps constant along the spot size, which allows a simple calibration of the system.

The key of this method lies on the proper choice of the Littrow angle and the spot size that enters the detector. A larger \( \phi \) will result in narrower fringes on the sensor. As a consequence, there will be less cosine waves forming the OPD fringe which would difficult the determination of its center.

This device has several interesting features. The main advantage is the possibility to reach high dynamic range almost sixteen times greater than conventional systems. This is mainly due to the independence of the pixel size of the sensor used, avoiding the fall-off effect present when spectrometers are used. In addition, the output could be analyzed directly, without the need to perform computational processing of the signal, since the Fourier transform is made by the detection system.

Another characteristic worth to be highlighted is the independence of the size of the sensor used, since the output spot could be enlarged or focus to fit the sensor width with a lens without losing information. Of particular interest is the enlargement of the spot, as it leads to a better precision on the fringe position. In this case, more pixels of the sensor are used to sample the cosine wave that forms the peak and the envelope could be better defined. In this system, suitable choose of the Littrow angle is useful too. It is worth noticing that there is a compromise between the Littrow angle chosen and the maximum OPD measurable from (10).

One downside regarding this device is the loss of intensity in the detection system. In a Michelson configuration with a 50\(^\circ\)::50\(^\circ\) beam splitter, the estimated intensity loss in the output is at least 50\%. Considering that the input light of the LCI passes through two of this configurations, the expected loss is around 75\%. This issue may become relevant in cases where the reflectivity of the sample decreases with depth. In addition, the size of the gratings has to be considered when designing, as the incoming spot width has been shown to play a determinant role in the maximum measurable OPD.

6. Conclusions

In this work we have presented a novel detection system for LCI signals that Fourier transform the signal. This heterodyne detection system provides a powerful tool for extending the dynamic range of the FD-LCI systems, enabling measurements at least one order of magnitude greater that conventional ones, without compromising the high resolution that characterizes LCI techniques. In addition, this device does not represent a significant increment on the cost of the system as it happens with other developments (SS-LCI).

The main advantage of this novel device, arises from the fact that the detection system performs the Fourier transform of the signal, which allows to overcome the limitations of the traditional FD-LCI systems, such as the fall-off. The results of this work show a strong dependence of the maximum measurable value of OPD with the width of the illuminated spot on the gratings, which is in great accordance with the theory.

We think that our findings might be useful for industrial applications, in areas such as dimensional metrology, were there is a need for long range LCI systems at low cost. This system could be of particular interest for the automotive industry, where characterization of metalworking and windshields can be performed. In the biomedical area, this long range could be useful where conventional OCT systems are limited as in measuring the depth of the anterior chamber or the axial eye length [24].

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Leslie Judith Cusato: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft. Santiago Cerrotta: Conceptualization, Validation, Writing - review & editing. Jorge Román Torga: Funding acquisition, Validation, Resources, Writing - review & editing. Eneas Nicolás Morel: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing - review & editing.

Acknowledgments

This work was supported by the National Technological University (UTN) [grant number PID ASUTNDE0004898]. L.J. Cusato acknowledged a doctoral scholarship from Comisión de Investigaciones Científicas (CIC). E. N. Morel and J. R. Torga are members of the National Scientific and Technical Research Council (CONICET).

References

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