Optics Communications 407 (2018) 426–431

Contents lists available at ScienceDirect

Optics Communications

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

Full field tomography using interference fringes casting of a non spatially-coherent extended spectrally modulated broadband light source

Yoel Arieli [a,*], Shlomi Epshtein [b], Alon Harris [c], Igor Yaacubov [d], Yoel Cohen [d]

[a] Jerusalem College of Technology, Havaad Haleumi 21, Jerusalem, 9372115, Israel
[b] Ben-Gurion University of the Negev, Beer Sheva, 8410501, Israel
[c] Glick Eye Center Indiana University Medical Center, Indianapolis, IN, 46202, United States
[d] AdOM Technologies, Hamlacha 1, Lod, 7152001, Israel

ARTICLE INFO

Keywords:
Full field tomography
"en face" tomography
Optical coherence tomography

ABSTRACT

A method for full field tomographic measurements using a fully non spatially-coherent extended broadband light source and a common path interferometry is described. A layered object's is being tomographed by acquiring multiple images of the object while modulating the spectrum of the extended broadband light source. In order to overcome the non spatially-coherence of the light source, interference fringes are created by amplitude division interferometry at a focal plane of the illuminating optical system and are casted on the measured object. In addition, due to exploiting one of the object's layers as a reference layer for the interference the need for an auxiliary reference beam is avoided and inherent Full Field "en-face" common path interferometry measurements are obtained. Another advantage is that by using spectrally modulated broadband illumination and obviating the reference beam, the requirement that the object should be used as one of the interferometer arms as in common dual beam interferometry is also avoided. This enables to relay the spectrally modulated light to illuminate the measured object which is just being imaged using a simplified imaging system while modulating the light. However, since there is no reference arm, the tomography of the object is calculated by a complex iterative algorithm where some knowledge on the object's structure is required.

1. Introduction

Full-field Optical Coherence Tomography (FFOCT) is an interferometric technique which directly takes full-field, "en face" tomographic measurements of an object. A typical FFOCT system consists of a spatially-coherent or partial spatially-coherent broadband light source and a Michelson or a Linnik interferometer which splits the illumination into reference and object beams. The reference and the back-reflected object light are superimposed and focused on a CCD sensor which detects the interference signal [1–4]. Due to the development of low cost, high luminance and broadband extended light sources such as Halogen lamps that are fully non spatially-coherent, it is desirable to develop a technique that can utilize them. However, in order to achieve interference fringes there is a need for limiting the light source physical dimensions such as to increase its spatial coherence on the expense of limiting its efficiency. In addition, using Michelson or Linnik interferometers with fully non spatially-coherent light sources for full field measurements requires that the reference and the object arms of the interferometers should be almost identical, otherwise the interference cannot be obtained. Thus, when tomographic measurements of a surface that is located inside an optical system such as the retina in the eye is required, the requirement that the reference arm and the measurement arm must be almost identical, makes the full field measurements using Michelson or Linnik interferometers impractical.

Bachmann et al. [5] and Epshtein et al. [6] describe an interferometry technique utilizing a broadband light source, in which the interferograms for each object's point are obtained directly when multiple measurements of the object are acquired while illuminating the object with a variable Spectrally-Modulated White Light source (SMWL). The rational of this method can be understood easily by noting that in using Fourier Transform Spectroscopy (FTS) to measure the spectrum of light, the spectrum of light is measured by using an interferometer with a moving mirror and Fourier transforming the resulted interferogram. However, since the interferometer in the FTS is actually a variable cosine spectral filter, it follows that by modulating the spectrum of the light source with a variable cosine function before illuminating the object,

* Corresponding author.
E-mail address: arieli@jct.ac.il (Y. Arieli).

http://dx.doi.org/10.1016/j.optcom.2017.08.027
Received 16 March 2017; Received in revised form 10 August 2017; Accepted 13 August 2017
Available online 19 September 2017

the interferogram is obtained directly. It should be noted that the light source's spectrum may be modulated by any kind of variable cosine modulation method and this spectral modulation obviates the need for using an interferometer with a continuous phase delay at the reference arm, as is done in Time Domain Optical Coherence Tomography (TD-OCT). Of course, one way to modulate the light source's spectrum with a variable cosine filter is to use an interferometer. The light is propagated through the interferometer that includes a moving mirror and its amplitude is divided to two light beams. The interference of the two light beams modulates the spectrum of the light with a variable cosine function according to the Optical Path Difference (OPD) between the two interferometer's mirrors. However, due to the lack of spatially coherence it is required that the spectrally modulated light will be focused to an optical fiber or a pinhole with very limited physical dimensions otherwise the light source's spectrum modulation contrast decreases.

In this article, we extend the use of the SMWL to a full field optical coherence tomography using an interferometer for modulating the light source without the need for limiting the physical dimensions of the light source even for a fully non spatially-coherent extended light source. Accordingly, there is no need for focusing the spectrally modulated light to an optical fiber or a pinhole and thus a regular light source may be used and the efficiency of the optical system increases. In addition, we also obviate the need for a reference arm of an interferometer in conjunction with the measured object by using one of the 2D object's layers as the reference layer for its other layers. Utilizing these techniques, the spectrally modulated illumination and the absence of the need to use a reference beam, the requirements that the object should be used as one of the interferometer arms and should be identical to the reference arm are avoided. In this arrangement, a full field "en-face" OCT measurements of transparent samples become simplified since the illumination light can be relayed to the object by a separate illumination system while the object is being measured using an ordinary imaging system. Another advantage obtained using the SMWL technique as described here, is that the plane being measured in the 3D space can be simply controlled by controlling the illumination system, that is, when a multi surfaces object is measured, the signal from a certain surface being measured is detected while the signals from other surfaces are ignored.

2. The "en-face" spectrally modulated white light source tomography

The basic suggested optical system of the SMWL, is a regular imaging system where the object to be measured is illuminated by a fully non spatially-coherent extended broadband light source that its light is spectrally modulated by an interferometer.

In OCT generally, a beam splitter splits an incoming light from a point light source to two beams, whereby one beam is directed to the object and the other beam is directed to a reference mirror. The light reflected from the object in the interferometer object's arm interferes with the light reflected from the mirror in the reference arm. However, in order to obtain interference from a fully non spatially-coherent extended broadband light source, the reference arm of the interferometer must be almost identical to the object's arm otherwise no fringes are obtained and this requirement is almost unachievable for an arbitrary object.

In order to overtake these requirements and to enable utilizing a fully non spatially-coherent extended broadband light source for a full field OCT measurements, we suggest the following arrangements. The first arrangement is to use the SMWL technique to modulate the spectrum of the illumination light by a Michelson interferometer according to the OPD between the two interferometer mirrors. In order to achieve interference fringes even for a fully non spatially-coherent extended light source, a lens is added after the interferometer. In the focal plane of the lens, all the optical rays from the light source passing through a certain focal point are added together and have the same OPD, thus, interference fringes are obtained at the focal plane of the lens even for this case. As the OPD of the interferometer varies, the interference pattern at each point at the focal plane changes and the spectrum of the light at each point at the focal plane is modulated by a varying cosine function. The resulted interference pattern at the focal plane of the lens is imaged on the object to be measured by a relay system. This illumination technique, although is more complex than a standard OCT illumination, it has several advantages. One advantage is the ability of separating the measuring interferometer and the tested object and thus avoiding the requirement that the reference arm of the interferometer should be almost identical to an arbitrary tested object. Another advantage is the ability of using a regular fully non spatially-coherent extended light source such as Halogen lamp without the need for limiting its physical dimensions. The third advantage is that by controlling the focal length of the relay system, the location of the image plane of the interferometric fringes and thus the tomography measurement plane in the 3D space is also controlled, enabling the determination of what surface of a multi surfaces object is being tomographed. The focal plane of the relay system can be controlled simply by varying the corresponding distances of one or more lenses in the system and determining its effective focal length. It should be noted that though other fringe projection tomography systems exist [7,8], these methods are based on triangulation measurements which are suitable only for macroscopic measurements and not on interferometry as the current method.

In order to avoid the need for the reference arm in conjunction with the object a requirement which seriously restricts the usable of the system, a second arrangement is suggested. Instead of using an additional reference arm, one of the layers at the measured layered surface is used as the reference layer for all other layers at that surface. In this case, the imaging system gathers the reflected light from all different layers at a certain point of the measured layered surface of the object into the same image point on the detector and the light rays from all layers interfere. The interference obtained at each image's point on the detector is similar to the interference that is obtained when a reference mirror is used, except that the reference layer is one of the surface's layers. Thus, this approach obviates the need for a reference arm and enables an easy realization of full field tomographic measurements. However, it should be noted that by using one layer of the surface as the reference, only the tomography of the layered surface is measured, i.e. the thicknesses of the different layers relative to the chosen reference layer, and not the absolute topography.

The tomography of the layers structure of the object is obtained by acquiring multiple images of the object's surface while modulating the spectrum of the light source by moving one of the interferometer's mirror continuously and increasing the OPD between the two interferometer mirrors. However, only when the reflectivity of the first or last object's layer is much higher than the others, this layer serves as the reference plane and the tomography is obtained directly by the interferogram. Otherwise, the reconstruction algorithm is much more complex than the conventional one, since a specific reference layer cannot be selected from the many layers of the sample. A reconstruction algorithm will be described briefly below.

Since there is no need for the reference arm, a major simplification of system is achieved, the system tolerance requirements are relaxed and thus many "en face" applications are optional candidates for using the current tomography method.

3. The optical system of the full field spectrally modulated white light source tomography

In order to investigate the suggested tomography method, an imaging optical system for this full field tomography using the extended SMWL method was built and is shown in Fig. 1.

The illumination path includes a Philips halogen reflector bulb, an EKE 150 W light source condensed by ACL5040 Thorlabs condenser lens

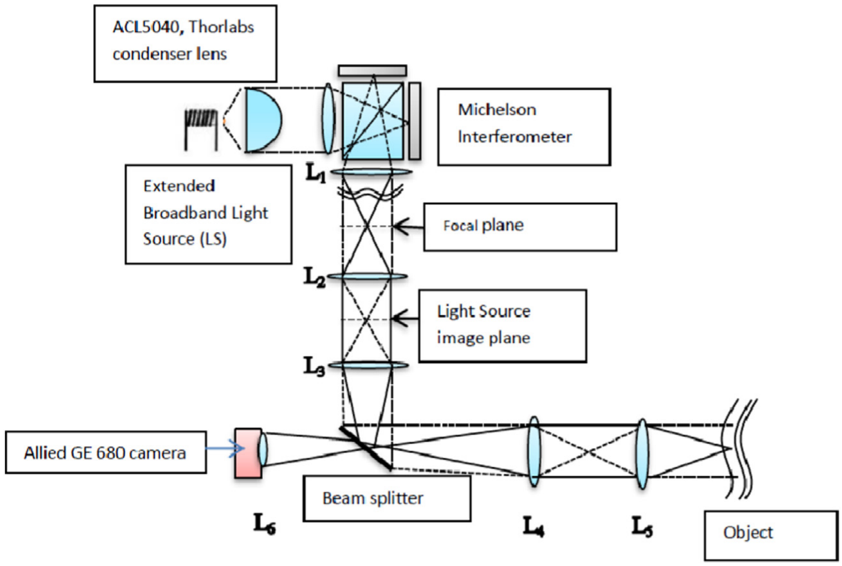

Fig. 1. The optical system for the suggested full field OCT method.

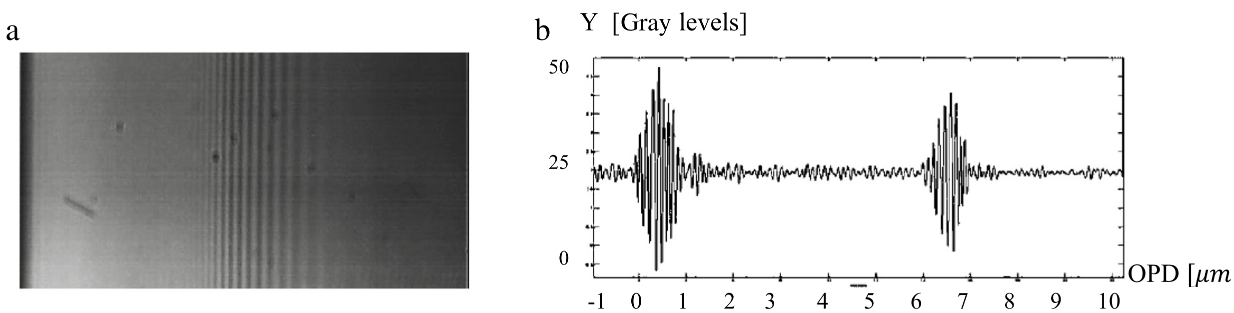

Fig. 2. (a) A typical fringe pattern obtained on object's surface. (b) A typical interferogram at a certain point on object's surface.

and a Michelson interferometer. The light of the source was filtered by a filter with $\bar{\lambda}$ = 500 nm and $\Delta\lambda$ = 250 nm. Accordingly, the coherence length of the illumination light which also determines the axial measurement resolution, was $l_c \sim \frac{\bar{\lambda}^2}{\Delta\lambda} = 1000$ nm. The optical power on the object was 0.1 mW. By moving one of the interferometer's mirrors continuously by a stepper-motor, a continuous cosine spectrally-modulated illumination light of the light source is attained. The fringe pattern of the non spatially-coherent light source is formed at the effective focal plane of the lens L_1 with the focal length f_1 = 40 mm and is imaged and cast on a layered object (located in a conjugate plane of the fringe pattern plane) by a relay system, i.e. lenses L_2–L_5 with the following focal lengths; f_2 = 75 mm, f_3 = 40 mm, f_4 = 45 mm, f_5 = 25 mm, and a beam splitter. The imaging path gathered the reflected light from the object and images it on a camera. The imaging system consists of two lenses L_4 and L_5 that are also part of the illumination system and an additional imaging lens L_6 with focal length f_6 = 30 mm behind the beam splitter close to the detector's plane where a 1280 × 1024 GE 680 CCD camera with a pixel size of 5.4 μm is located. The magnification of the imaging system is ×5.

The first object that was measured is a 2D silicon substrate covered by seven nominally uniform transparent polyester sheets. The physical thicknesses and the refractive indices of the transparent sheets are given in Table 1:

The OPD between the two mirrors of the interferometer was scanned from zero OPD to maximal OPD of 400 microns in 50 nm steps. As the OPD between the two mirrors of the interferometer varied, the fringes on the object also varied and the spectrum of the light at each point was modulated by a variable cosine function. Whenever the OPD between the two mirrors of the interferometer matched a certain OPD between any two sheets' interfaces at any point of the object, a constructive interference was obtained at that point. The intensity of the reflected light from each sheet's surface and thus the interference intensity depended on the refractive index difference between any two adjacent sheets according to Fresnel reflection formula. The images of the 2D object were acquired by the camera every OPD step movement, 8000 images in all. The frame rate of the camera is 16 fps thus the whole process took about 8 min. A typical fringe pattern obtained on the object's surface acquired by the camera is shown in Fig. 2a. The interferogram at each object's point was obtained by plotting the gray levels of the detected signal at the camera at a certain point as a function of the OPD between the interferometer's mirrors, where the gray level is interpreted as the intensity of light. A typical interferogram is shown in Fig. 2b.

Table 1
The physical nominal thicknesses and the refractive indices of the stack of transparent layers.

Sheet number	Physical nominal thickness [μm]	Refractive index
1	50	1.3
2	23	1.64
3	50	1.7
4	50	1.64
5	15	1.3
6	25	1.7
7	25	1.7

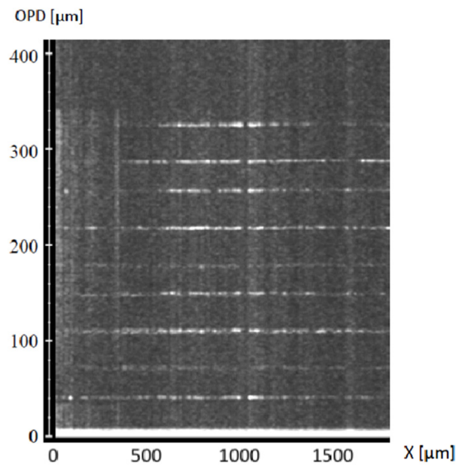

Fig. 3. An image of the interferograms intensities of a cross section of the object as a function of the OPD between the two interferometer's mirrors.

An image of the interferograms intensities of a cross section of the object as a function of the OPD between the two interferometer's mirrors is shown in Fig. 3.

As can be seen by Fig. 3, there are more than ten constructive interferences at each point of the cross section due to a constructive interference between light reflected from any two sheets' surfaces at the object. The thick line at the bottom of the image represents the intensity of the constructive interference when the OPD of the interferometer's mirrors is zero.

The thicknesses of the object's sheets were calculated by an iterative algorithm presented briefly below. At each point of the image, the algorithm starts by obtaining the minimal and maximal OPDs according to the constructive interferences at the interferogram. The minimal OPD represents an existing minimal sheet OPD and the maximal OPD represents the sum of all layers OPDs. The maximal number of possible existing layers is assumed by the number of existing combinations of constructive interferences. The algorithm assumes that the exiting OPDs are the smaller OPDs and it calculates the combinations that should appear and compare them to the interferogram. Any assumed OPD that its combinations do not match the interferogram is omitted and replaced. The algorithm converged when all assumed OPDs and their order matched the interferogram. Fig. 4 shows the calculated thicknesses at a certain point versus the nominal ones. Due to the small refractive index difference between the sheets 2, 3 and 4 and sheets 6 and 7, the intensity of the interferences that correspond to those sheets were low and the signals were below the sensitivity of our camera. Thus, in our experiment, the three sheets 2, 3 and 4 and the two sheets 6 and 7 were detected as only one sheet each. The whole 2D object tomography was calculated using the algorithm for each object's point.

The deviation between the measured values and the nominal ones which are larger than 10% may be explained by the flexibility of the object. Thus, a calibrated rigid object also was measured.

The object consisted of a bare silicon wafer substrate covered by two different acrylic polymer layers. The bottom layer thickness is about 7.5 μm and on top of part of it a second layer with total thickness of about 18 μm. Each layer was UV cured after smearing. Part of the image of the object and its measured colored height map are shown in Fig. 5. The image consists of 500×800 pixels, $5 \times 5\ \mu m^2$ each. From the figure it can be seen that at the sharp edges there are some artifacts due to lack of specular reflected light. The tomography of the object was obtained by acquiring multiple images of the fringe patterns while moving one of the interferometer's mirrors continuously and increasing the OPD between the two mirrors and thus modulating the spectrum of the light source. The 2D tomography of the object was reconstructed by the algorithm mentioned above.

It should be noted that since the tomography is obtained by an imaging system and not by a scanning system, the spatial resolution of the measured object is determined by the camera and the optical spatial resolution of the imaging system, which in our case was about 5 μm.

To assess the accuracy of this measurement technique, a cross section of the object was calibrated using wide band polarized reflectometer Nova T500. The Nova T500 is a well-known commercial polarized reflectometer with sub nanometer accuracy that is being used for traceable and high accuracy measurements in the semiconductor industry.

A plot of the thicknesses D of the layers of the cross section of the object as a function of the location X, is shown in Fig. 6. The dashed and the dotted lines represent the layer thicknesses as measured by the suggested method and the crosses represent the layer thicknesses at several points as measured by Nova T500. As can be seen in the figure there is a good matching between both measurements techniques. According to our results, assuming that the reflectometer's measurements are accurate, our suggested FFOCT yielded a highly accurate measurement, up to 2000 nm, of the object.

4. Discussion

The replacement of the spatially coherent broadband light source for full field measurements by a fully non spatially coherent broadband source produces additional challenges to resolve the interference signal.

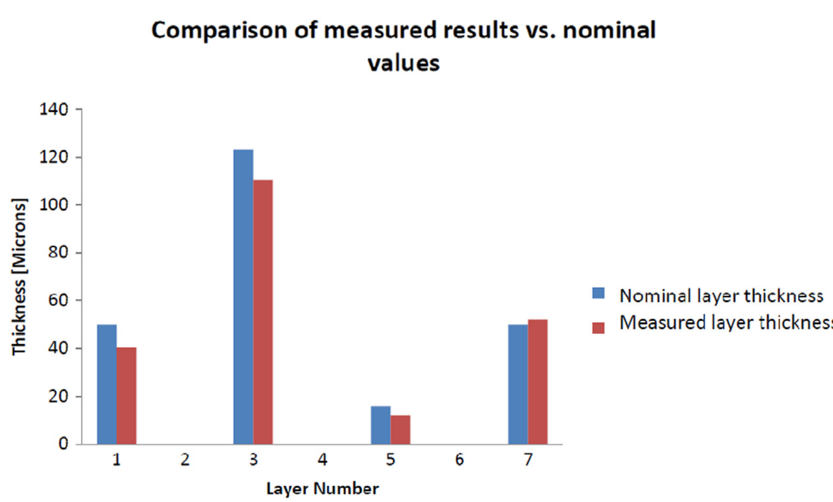

Fig. 4. The calculated thicknesses vs. the nominal ones at a certain object's point.

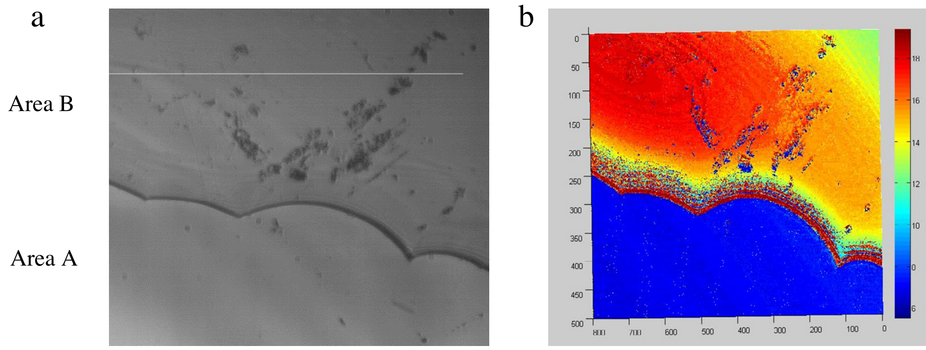

Fig. 5. (a) A 2D image of a layered object: *Area A*, single layer (7.5 μm). *Area B*, two layers (~18 total). (b) The measured colored height map of the object.

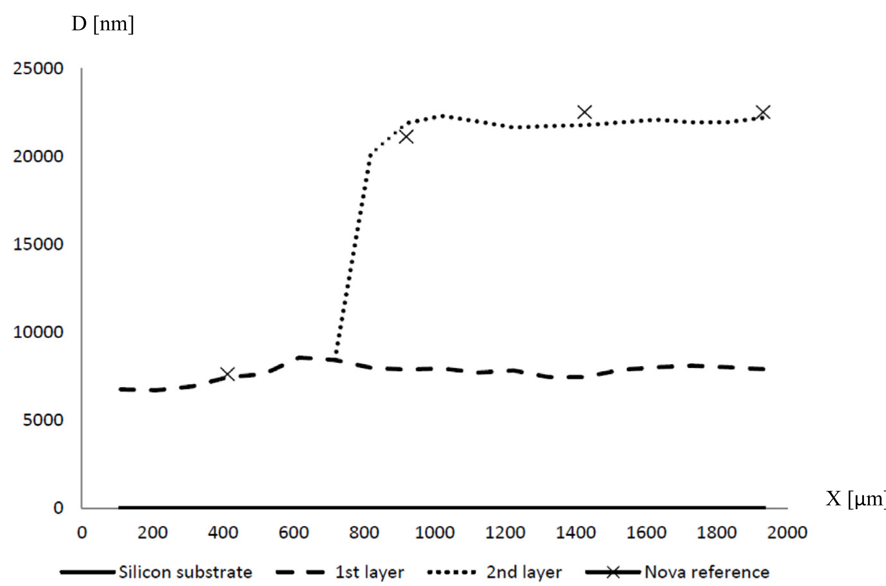

Fig. 6. A plot of the thicknesses *D* of the two layers at one cross-section of the layered object. *Solid line,* silicone substrate. *Dashed line,* bottom layer. *Dotted line,* top layer. *Cros*, Nova reference.

This is the main reason that naturally current OCT systems prefer to use high spatially coherence light source where the information is collected by scanning the object point by point. Another characteristic of common dual beam OCT systems is that the object is being used as one of the interferometer's arms. Such approach imposes some design restrictions and enforces the reference plane to be close and in contact with the object.

The current presented common path approach is breaking the frame of these limits and enables using a much broader band and fully non-spatially coherence light source for full field measurements without the need for a reference arm. In this approach, the illumination system relays spectrally modulated light towards the object, using a simple external, very broad band and low spatially coherence light source and gets a release from the need of reference arm. Accordingly, the complexity of the system is transferred into the illumination module far from the object where the measured object may even be located inside an additional optical system, such as the retina inside the eye. In this approach there is no need for an identical reference arm that may be very complex.

Nevertheless there are some limitations or delicate points relating to the suggested approach. First, in the case of multilayers, it will have easier understanding of the results once the reflectivity of one of the interfaces is significantly higher than the rest of the interfaces. However, the level of confidence on the stack measurement will increase, once the interpretation was done and the complexity in the analysis was resolved. This is due to the understanding of the interpretation of the many reflectivity combinations of all OPD's between the interfaces. Another potential obstacle can come from the fact that the interference SNR depends on the reference that exists in the object. Typical example for such limitation case is once the interfaces in the object that are now being used as internal reference may have low contrast or non-specular reflection.

The cons and pros that were discussed here may lead to the applications that may suit the method and system that is suggested here. In this case applications with ultra-thin layers can be considered, while samples that do not have abrupt internal interfaces should be avoided. (e.g. interface that can reflect the light with minimal scattering and good contrast). Applications such as retina investigation, that are being done today by OCT should to be tested, because a relative abrupt interface in the ERP layer may be still questionable due to its non specular reflectivity. A better candidate is measurement of the tear film in the cornea front. This application needs sub micron axial resolution and have good abrupt specular reference as the lipid–air.

5. Conclusion

A method for a full field, "en-face" tomography using a fully non spatially-coherent extended broadband light source is introduced. In this approach, the spectrum of the light source was modulated by an interferometer and the interference fringes were created at the focal plane of the illuminating optical system even with the lack of the spatial coherence. By controlling the illumination focal length, the plane in the 3D space to be measured can be chosen. Due to exploiting one of the object's layers as a reference layer for the interference, Full Field "en-face" measurements are obtained without the need for a reference beam and thus simplifying the optical measurement system. The accuracy of this method was assessed by measuring a layered object and calibrating it by a well-known commercial polarized reflectometer with sub nanometer accuracy.

References

[1] A. Dubois, L. Vabre, A.C. Boccara, E. Beaurepaire, High-resolution full-field optical coherence tomography with a Linnik microscope, Appl. Opt. 41 (4) (2002) 805–812.

[2] A. Dubois, K. Grieve, G. Moneron, R. Lecaque, L. Vabre, C. Boccara, Ultrahigh-resolution full-field optical coherence tomography, Appl. Opt. 43 (14) (2004) 2874–2883.

[3] J. Yi, J. Gong, X. Li, Analyzing absorption and scattering spectra of micro-scale structures with spectroscopic optical coherence tomography, Opt. Express 17 (15) (2009) 13157–13167.

[4] A. Grebenyuk, A. Federici, V. Ryabukho, A. Dubois, Numerically focused full-field swept-source optical coherence microscopy with low spatial coherence illumination, Appl. Opt. 53 (8) (2014) 1697–1708.

[5] A.H. Bachmann, R. Michaely, T. Lasser, R.A. Leitgeb, Dual beam heterodyne Fourier domain optical coherence tomography, Opt. Express 15 (15) (2007) 9254–9266.

[6] S. Epshtein, A. Harris, G. Locketz, I. Yakubov, Y. Yitzhaky, Y. Arieli, Spatial-phase-shift imaging interferometry using spectrally modulated white light source, Opt. Lett. 39 (24) (2014) 6966–6968.

[7] S. Zwick, S. Heist, R. Steinkopf, S. Huber, S. Krause, C.n. Bräuer-Burchardt, P. Kühmstedt, G. Notni, 3D phase-shifting fringe projection system on the basis of a tailored free-form mirror, Appl. Opt. 52 (14) (2013) 3134–3146.

[8] S. Huang, Z. Zhangn, Y. Zhao, J. Dai, C. Chen, Y. Xu, E. Zhang, L. Xie, 3D fingerprint imaging system based on full-field fringe projection profilometry, Opt. Lasers Eng. 52 (2014) 123–130.