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

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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,

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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

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