

**FULL-FIELD FREQUENCY DOMAIN OPTICAL COHERENCE
MICROSCOPY FOR SIMULTANEOUS TOPOGRAPHY AND
TOMOGRAPHY OF ENGINEERING AND BIOLOGICAL
MATERIALS**

TULSI ANNA



**INSTRUMENT DESIGN DEVELOPMENT CENTRE
INDIAN INSTITUTE OF TECHNOLOGY DELHI, INDIA
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TOMOGRAPHY OF ENGINEERING AND BIOLOGICAL
MATERIALS**

by

TULSI ANNA

INSTRUMENT DESIGN DEVELOPMENT CENTRE

Submitted

in fulfillment of the requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI, INDIA

FEBURARY, 2012

Dedicated to,

My mother

and

In the memory of my father

CERTIFICATE

This is to certify that the thesis entitled “**FULL-FIELD FREQUENCY DOMAIN OPTICAL COHERENCE MICROSCOPY FOR SIMULTANEOUS TOPOGRAPHY AND TOMOGRAPHY OF ENGINEERING AND BIOLOGICAL MATERIALS**” being submitted by **TULSI ANNA** to the **Instrument Design Development Centre, Indian Institute of Technology, Delhi** for the award of the degree of **DOCTOR OF PHILOSOPHY**. This thesis is a record of bona-fide work carried out by her under our guidance and supervision. In our opinion the thesis has reached the standards fulfilling the requirements for submission relating to the degree.

The results contained in this thesis have not been submitted to any other University/Institute for the award of any degree or diploma.

Dr. D. S. Mehta

INSTRUMENT DESIGN DEVELOPMENT CENTRE
INDIAN INSTITUTE OF TECHNOLOGY DELHI

Prof. Chandra Shakher

INSTRUMENT DESIGN DEVELOPMENT CENTRE
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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ABSTRACT

Coherence of light plays an important role in imaging, diagnostics, optical metrology, and optical instrumentation. Optical coherence tomography (OCT) is a prominent imaging technology based on low coherence interferometry (LCI) which offers various advantages, such as, high-resolution, cross-sectional imaging of biological tissues and engineering materials. This unique capability of OCT has opened the door to explore various applications in the field of biology, medicine and material science. Earliest versions of OCT were developed in time-domain detection mode. Recently, frequency-domain OCT (spectral-domain and swept-source versions) has been developed which are higher acquisition speed, improved sensitivity and better signal to noise ratio than traditional OCT with time-domain detection. But, still the lateral scans are needed in all conventional OCT systems. More recently, the OCT system has been extended to full-field detection to get faster data acquisition. In full-field OCT (FF-OCT) detector arrays are used, that record 2D - interference fringes and thus make the need of lateral scan redundant. The FF-OCT technique has recently become more popular, in which the depth scan (A-scan) and lateral scan (B-scan) can simultaneously be obtained. FF-OCT systems are using all implementation of OCT i.e., time-domain (TD), spectral -domain (SD) and swept-source (SS) versions. In the present study, FF-OCT based on SS implementation which is completely non-mechanical scanning i.e. full-field swept-source OCT (FF-SS-OCT) has been developed. Due to non-mechanical scanning capability of FF-SS-OCT system, its various applications such as new biological and engineering applications are presented in the thesis.

Chapter I presents the literature survey about the development of FF-SS-OCT. The chapter provides the basic physical principle used in OCT systems, its classification along with a brief review of the past and recent developments in the field. Various parameters which govern the systems performance, such as, axial and transverse-resolution, sensitivity and detection mechanism have also been studied and presented. A brief description about the swept-source-OCT (SS-OCT) and FF-SS-OCT system has also been presented. The details about the swept-source using a broadband superluminescent diode (SLD) and an acousto-optic tunable filter (AOTF) are described. The chapter also provides the applications of OCT in several fields including biology and engineering.

Chapter II deals with the principle, experimental design and application of FF-SS-OCT system. The optical set-up consists of a swept-source system, a compact Michelson interferometer and an area detector. A brief characterization of SLD and AOTF and how a frequency-tunable quasi-monochromatic source (swept-source) has been realized by scanning the wavelength of broadband SLD using AOTF has been presented. In the present chapter the application of FF-SS-OCT system in the micro-electro-mechanical systems (MEMS) based on silicon integrated circuits (ICs) and metal oxide semiconductor (MOS) has been demonstrated. The precise measurement of film-thickness, defect detection and sub-surface imaging of ICs nondestructively is important for industrial applications, which has a great importance in the development of ongoing miniaturization of semiconductor devices. With the help of present system by means of sweeping the frequency (wavelength) of the light source, multiple interferograms were recorded. By selective Fourier filtering both amplitude (optically sectioned images) and the phase map (topography) of the object was reconstructed. This system has the potential for the sub-surface

imaging of silicon ICs and thin-film multilayer structures and further it can detect subsurface defects and provide structural information, such as, morphology and film uniformity. The main advantages of the proposed system are completely non-mechanical scanning, ease of alignment, high stability because of its nearly common-path geometry and compactness. By increasing the magnification of the imaging lens the lateral resolution can further be increased, however, in this one has to sacrifice with the scanning area of the object.

In chapter III a 3D shape measurement of the micro-lens arrays using FF-SS-OCT system has been demonstrated. Micro-lenses, micro-prism and other diffractive optical elements are of great interest for numerous and diverse applications. Various manufacturing and fabrication technologies have been developed to realize these micro-lens arrays. Due to their diverse applications the precise control of the shape, surface quality as well as the uniformity of these parameters across the lens arrays and their optical performance is major requirement for particular application. Number of optical methods has been proposed for testing and characterization of micro-lenses. Among these methods, the interferometric testing methods are more promising to inspect the micro-lens arrays. Recently, LCI has also been introduced for a quantitative phase reconstruction of micro-lens arrays. In the present chapter experimental arrangement of FF-SS-OCT for the 3D shape measurement of micro-lens arrays is explained. In this case the refracting samples (spherical and cylindrical micro-lens arrays) were kept before the beam splitter (BS) of the Michelson interferometer. The signal processing is done by the Fourier transform technique. Optically sectioned images, i.e., amplitude images give the information of surface uniformity and sub-surface defects during the fabrication, whereas the phase map

provides the quantitative information of height variation which can further give the refractive index distribution of the micro-lens arrays.

Most of the biological and other multi-layer objects are transparent in nature, therefore transmission mode OCT system would be advantageous for such objects, as light passes through the sample arm only once and the amount of light transmitted through the sample is more than the reflection mode. Until now digital holography, tomographic phase microscopy and other optical techniques have been reported in transmission geometry for the quantitative phase measurement of transparent objects. In **Chapter IV** the amplitude and quantitative phase imaging of transparent objects in transmission mode using FF-SS-OCT system (using a fiber-optic version of Mach-Zehnder interferometer) has been presented. The system is applied for multilayer transparent cello tape as a test sample and a biological cell (onion skin) imaging. The measurement in transmission mode has an advantage of high light intensity throughput, therefore, it provides high signal to noise ratio. Thus FF-SS-OCT in transmission mode has the significant advantage over reflection mode OCT and this may lead to volumetric and quantitative imaging of the transparent samples.

In chapter V a high-resolution full-field optical coherence microscopy (FF-OCM) using swept source for the quantitative imaging of biological cells has been reported. The conventional OCT uses low NA objective lenses to generate cross-sectional images resulting low transverse resolution and to improve it, the OCM was developed. High NA objectives have been used in OCM leading to better transverse resolution. OCM uses both the time-domain and frequency-domain techniques but again it has major disadvantage as the light beam is scanned point by

point mechanically over the sample (i.e., X-Y- Z scanning). Recently, various FF-OCM systems have been developed in which the sample is entirely illuminated in the image field and 2D-interference fringes were recorded using CCD camera /detector. The present high resolution FF-OCM is using a Mirau-type interferometric objective lens. 2D - inference fringe signal is produced by Mirau-interferometric objective lens. Optically sectioned amplitude, quantitative phase imaging and variation in the refractive index profiles of the RBCs at different times have been demonstrated. The present system provides high axial and transverse resolution for 50X Mirau objectives, uses parallel detection, and measures *en-face* images without X, Y, Z mechanical scanning. As the system is having common path geometry it is more stable and less sensitive to external perturbation. Further, the system is compact and uses single objective lens as compare to OCMs based on Michelson and Linnik-type interferometric objective lenses therefore the phase stability of the present system is high.

In chapter VI the main conclusion of the thesis and scope for the future is presented.

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