DEVELOPMENT OF FULL-FIELD SWEPT-SOURCE OPTICAL COHERENCE TOMOGRAPHIC SYSTEM FOR SCIENTIFIC AND ENGINEERING APPLICATIONS

By

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submitted in fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2008

DEDICATED

TO MY

PARENTS

CERTIFICATE

This is to certify that the thesis entitled **"DEVELOPMENT OF FULL-FIELD SWEPT-SOURCE OPTICAL COHERENCE TOMOGRAPHIC SYSTEM FOR SCIENTIFIC AND ENGINEERING APPLICATIONS"** being submitted by **Satish Kumar Dubey** to the Indian Institute of Technology, Delhi for the award of the degree of "**DOCTOR OF PHILOSOPHY**", is a record of the authentic research work carried out by him under my supervision and guidance. He has fulfilled all the requirements for submission of this thesis, which to the best of our knowledge has reached the required standard.

The material contained in this thesis has not been submitted in part or full to any other University or Institute for the award of any other degree.

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ACKNOWLEDGEMENT

I express my profound indebtedness to my Supervisor **Dr. Dalip Singh Mehta,** for his constant encouragement, guidance and never-ending patience. Credit of introducing me to the area of optical coherence tomography goes to him.

I am highly grateful to **Prof. Chandra Shakher,** for his constant encouragement and inspiration along with valuable suggestions throughout my research work. He has devoted considerable time to provide inputs at various stages of the work.

I am thankful to **Mr. Mohd. Mosarraf Hussain, Mr. Gyanendra Sheoran, Mr. Ranjeet Kumar, Ms. Tulsi Anna** and **Mr. Jai Prakash Rana** who have been with me during my research work in the Laser Applications and Holography Laboratory, Indian Institute of Technology Delhi. They have been extending valuable support and co-operation at various junctures of my research work.

Scientific discussions and valuable suggestions from **Dr. Arun Anand** is highly appreciated. I am also thankful to **Mr. Pradeep Kushwaha, Mr. K L Mishra, Dr. Gufran S Khan, Mr. Rakesh Singh, Neeraj Lakhotia** and **Vinod Siddhu** who have always been the source of inspiration to me during the present work.

Thanks are also due to the technical staff of the workshop in Instrument Design Development Centre for the help rendered by them. Particularly, **Mr. Rajaram** has been always more than eager to render helps. The technical help provided by **Mr. N. Devadasa** is gratefully acknowledged. I am also thankful to **Mr. Surinder Singh and Mr. S. C. Bansal** for extending their valuable help at times.

At last, I express deep sense of gratitude to my parents, family members and friends whose support and inspiration in various stages of my research work in the laboratory have greatly helped me to realize this work.

Date: **Satish Kumar Dubey**

ABSTRACT

Optical coherence tomography (OCT) has become one of the most essential techniques for biomedical imaging and diagnostics due to its ultrahigh resolution characteristics. Although, having been applied in biomedical imaging for more than a decade, the technique has still not been able to catch much attention of the researchers and scientists working in other disciplines. Present work is an attempt to bring the attention of researchers in exploring the potential of OCT and profilometry in other disciplines apart from its parent area, i.e. bio-photonics. In the present study, a swept-source system incorporating a broad band superluminiscent diode (SLD) and an acousto-optic tunable filter (AOTF) has been developed. The swept-source system has been applied in various disciplines of science and engineering for two and three-dimensional imaging applications.

Chapter I gives an introduction of optical coherence tomography technique. This chapter presents the physics of OCT, its classification and various aspects of OCT system design along with a brief review of the present status of the field. Development of the technique from its nascent stage to the current status has been covered in this chapter. Various issues such as choice of a source, axial and lateral-resolution, OCT image quality and detection mechanism has also been presented. The chapter also provides a glimpse of its applications in several fields including biology, medicine and other areas. Further possibilities of the improving the OCT technique have also been discussed.

Chapter II discusses the development of a swept-source system. The swept-source incorporates a broadband SLD and an AOTF. Light emitted by SLD was coupled to the input of AOTF through a polarization maintaining single-mode optical fiber connected through an FC/PC connector. AOTFs are solid-state electronically tunable optical filters that select precise wavelengths by applying appropriate RF-frequency and hence no mechanically moving parts are required. By sweeping the input RF to AOTF in a constant step, output wavelength of the source can be tuned in a desired manner. Thus a frequency-tunable quasi-monochromatic source has been realized by scanning the wavelength of broad-band SLD using AOTF. The chapter also deals with design of a compact interferometer and its application in different disciplines of science and engineering. The system exhibits linear wave number-RF signal characteristics. With the modified interferometric system, interference fringe signals are obtained easily by placing the object on the other side of beam splitter.

Chapter III demonstrates the application of full-field swept-source OCT in biometrics. Fingerprinting is one of the most widely used methods by forensic scientists for identifying and authenticating individuals. A fingerprint pattern is an oriented texture pattern of ridges and furrows at global level and minutiae at local level. Invariant texture representation of the fingerprint can be extracted by combining both global and local discriminatory information, i.e., the spatial frequency and orientations in the texture pattern. Usually, it is latent fingerprints that are left at crime scenes. Such fingerprints are of very poor quality and require great effort to render visible because of the varying physical and chemical compositions of the surfaces bearing them. When a finger comes into contact with a surface, the dielectric residue corresponding to ridge patterns leaves an impression onto the surface. Being at depth, furrow leaves no impression as such and corresponding region represents the substrate surface itself. This property is made use to detect the fingerprint impressions. In most of the detection techniques, these surfaces undergo physical or chemical processing to enhance contrast of the fingerprint. However, applying chemicals or powders onto the surface may change the composition of impression itself and may lead to incorrect results. In this chapter, application of full-field SS-OCT has been demonstrated to retrieve the brightness distribution of latent fingerprints along with local variations of the fingerprint textures even with very low power at the interferometer output. The OCT images were reconstructed without any physical and chemical processing of the sample.

Importance of composite materials has increased tremendously in recent years due to their multidisciplinary applications ranging from sporting goods, textiles, biomedical engineering and automobile industries to space applications. Chapter IV deals with the sub-micrometer imaging of composite materials using high resolution swept-source OCT system. The resolution of the OCT image obtained is further improved using Gaussian spectral shaping. Composites employ the fundamental principle of a fibrous reinforcement improving the properties of the matrix in which that reinforcement is contained. The greatest advantage of composite materials is their strength and stiffness combined with lightness and durability. As most of the physical and chemical interactions are governed by surface properties of material, dramatic changes in its properties are observed depending upon the nature of constituents used i.e., their size, shape and orientation; and the method of its preparation. Vast application of composite materials requires extensive attention in the structural diagnosis and characterization of these materials. This chapter presents a method for the structure characterization of such materials using high resolution full-field swept source OCT. The SS-OCT system presented in chapter 2 was further modified to improve the image quality. The SS-OCT system in this chapter makes uses of a Linik type interference microscope instead of Michelson interferometer used in conventional OCT systems. In this configuration, identical microscope objectives are placed in both the reference and sample arms of the interferometer that not only improves the intensity of the signal at the sample but also yields better resolution. This technique can be used at every step from fabrication of the material in assessing the filler content till the final characterization to study the orientation of different constituents. The proposed technique is very cost-effective as compared to other characterization techniques. Slice images of the internal structures of the composite materials are constructed using proposed technique that can be very helpful in the quality check ups of the material. Unlike the conventional OCT systems, axial resolution of the tomographic images obtained using this configuration depend upon both the coherence length and the NA of objectives and not the coherence length alone. First, we have tested this system for some test samples such as onion slice and then applied for characterization of ultra high molecular weight polyethylene composite and other fabrics.

Chapter V presents the engineering applications of the developed swept-source system. In this chapter, Talbot effect has been applied for the profilometry of three-dimensional objects by changing the wavelength instead of mechanically moving the grating or detector planes. Phenomenon of self-imaging of periodic objects, also known as the Talbot effect finds great application in optical metrology and spectrometry. In all of these applications, a periodic grating is illuminated by a monochromatic spatially coherent light and the grating self-image planes are projected onto the objects. To obtain information about the range, depth or displacement, either the grating or the object and detector planes are moved mechanically. However, in high precision optical metrology, mechanical movement of any of the components during the measurement may pose serious drawbacks. According to the Talbot effect, the self image plane distances from the periodic object are directly proportional to the square of the pitch of the grating and inversely proportional to the wavelength of light. The self-image plane distances can easily be shifted by means of changing either the pitch of the grating or the wavelength of the laser light. A change in the pitch of the grating is comparatively difficult; however, the change of the wavelength of laser light is easier and cost-effective. Further, lasers produce spatially and temporally coherent light with high brightness and are most suitable for the Talbot effect and its applications. First, we have used two-wavelength Talbot effect that uses laser sources at two different wavelengths; 632.8 nm and 532 nm, to measure the fixed step-height of a three-dimensional object. The principle was further extended to measure the 3-D step height using wavelength scanning Talbot effect. Multiple wavelength scanning system is the same as the one used for swept-source OCT applications. The wavelength scanning system incorporates a unique combination of broadband SLD and an AOTF.

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