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Editors
K. Wörhoff, L. Agazzi,
N. Ismail, X. Leijtens

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Towards Integrated Optical Coherence Tomography System on Silicon on Insulator

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Optical Coherence Tomography (OCT) is an emerging optical imaging technology with ever growing number of applications. OCT enables micron scale cross-sectional imaging of subsurface microstructures by measuring the backscattered intensity of light from subsurface layers of the materials. Current OCT imaging systems are fiber or free space optics based and they can be miniaturized through integrated photonics. We discuss the design parameters for photonic components for OCT such as broadband light source, splitters and output couplers on silicon on insulator platform, which can be fabricated using CMOS compatible wafer scale process.

Introduction

Optical Coherence Tomography (OCT) is an optical imaging technique capable of providing cross-sectional subsurface images of inhomogeneous materials, such as biological tissue, with micron scale resolution in real time. OCT imaging is analogue to ultrasound imaging but instead of using sound waves it uses broadband light source. Using broadband light rather that ultrasound provides 10 times higher resolution, however penetration depth is lower. In a typical state of the art spectral OCT system, as shown in Figure 1a, light from a broadband light source is split into two arms by a splitter. The beam in the sample arm is focused on the tissue and the light in the reference arm is send to a fixed mirror. The back reflected light from multiple layers within the tissue is collected with the same focusing optics and is interfered with the light reflecting from the fixed mirror in the reference arm. The interference signal is detected with a spectrometer and Fourier Transform of the interferogram provides the depth profile of the sample. By scanning the beam laterally over the sample, 2D cross-sectional and 3D volumetric images are obtained.

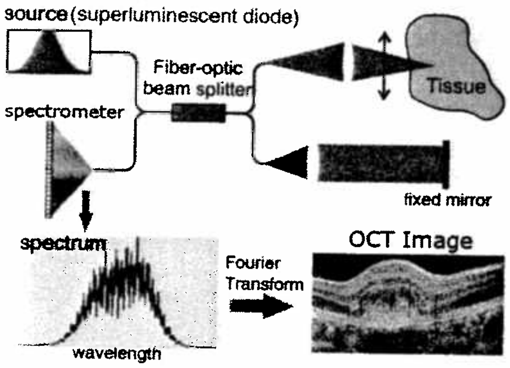

Figure 1a. Schematic of spectral domain OCT

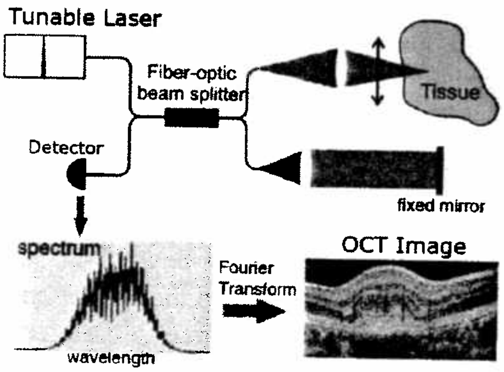

Figure 1b. Schematic of swept source OCT

A variation of such an OCT system (Figure 1b) is also commonly realized by replacing the broadband source by a tunable laser source, and the spectrometer with a photodetector. By rapidly sweeping the source wavelength over a broad wavelength range, and detecting the signals with the photodetector, the same spectral interference can be obtained, thus making them theoretically identical systems. OCT can image tissue cross-sections with < 10 μm resolution at depths exceeding 2 cm in transparent tissues (e.g. human eye and animal embryos) and 2-3 mm in highly scattering (non-transparent) tissues such as the skin and materials like plastics and ceramics.

Current commercial and research OCT systems are fiber/free space optics based and bulky. Miniaturization of OCT through integrated photonics will provide more stable interferometric detection and will bring significant cost reduction, which will increase the deployment of this technology. However, there has been little research on implementation of OCT on a chip. In these studies [1,2] only the splitter and the reference arms have been implemented using integrated optics, external source and detectors were coupled with optical fibers.

Nanophotonic silicon on insulator (SOI) is a versatile platform for a variety of integrated photonic components [3]. An SOI wafer consist of a thin top Si (refractive index $n = 3.45$) layer sitting on silica (SiO_2, n= 1.45) layer, which is carried on a thick Si substrate. Photonic components are realized by etching the top Si layer, resulting in high refractive index contrast in all directions. Using wafer scale CMOS processes, low loss (2dB/cm) waveguides with core sizes of 0.1 μm^2 and bend radii of 5 μm can be realized. Using such wafer scale processes for silicon, low-cost, high density, integrated photonic components that can be mass-fabricated and integrated with CMOS electronics on the same substrate. Although silicon is not an efficient light emitter and detector in the near infrared wavelengths, active elements can be heterogeneously integrated on top of the silicon wafer. Using the SOI platform together with heterogeneous integration of sources and detectors a complete optical coherence tomography system can be realized.

In this paper, we focus on the design issues of OCT system on SOI platform.

Design considerations of miniaturized OCT Systems on SOI

An OCT system consists of components such as light source, detector(s), splitter/combiner, waveguides, delay line, and focusing element(s). In this discussion we will omit the time domain OCT which is inherently less sensitive than spectral domain OCT systems and requires a scanning delay line, as opposed to fixed delay line in spectral domain OCT.

Bandwidth of the OCT system is a fundamental design parameter and determines the axial resolution of the images (Figure 2a). Therefore, for axial resolution around 10 μm, the bandwidth of each component of the system should be in the order of 50 nm. A superluminescent diode with such a bandwidth can be heterogeneously integrated on SOI [4]. Splitter/combiner structures can be designed as multimode mode interference (MMI), directional, or y-branch couplers. Among those y-branch couplers have bandwidth exceeding far beyond 50 nm. Another component that might limit the bandwidth of the system is the output coupler which sends the light out of the chip. For vertical output coupling grating couplers [5] can be used. These out of plane couplers have bandwidth of 40 nm. The standard in plane butt coupling, which has more than 100 nm bandwidth is a better choice for broad bandwidth devices. A conventional butt coupling can be efficiently realized by using inverted tapers to increase the spot size at the output.

Another design consideration for OCT is the spectral resolution of system, which limits the penetration depth (Figure 2b). Penetration depth of 2 mm will be useful for many applications. From Figure 2b, we see that the resolution of the spectrometer in spectral domain OCT should be approximately 0.2nm. For an OCT system with FWHM bandwidth of 50 nm, a spectrometer with 100 nm range would be appropriate, thus requiring 500 spectrometer channels. State of the art micro-spectrometer on SOI with 0.2 nm resolution has been realized with an arrayed waveguide grating (AWG) of 50 channels [6]. In principle, by increasing the size of the structure the number of channels can be increased, however imperfections in the fabrication process and substrate thickness causes phase errors. Combination of several wavelength selective structures, such as microring resonators with AWGs or planar concave gratings may help to increase the number of channels to several hundreds. A planar light-wave circuit of arrayed waveguide grating on silica with 400 channels and 0.2 nm resolution has been demonstrated by NTT (personal communication), however further research and development is necessary to obtain these parameters using SOI. A conceptual design of spectral OCT system on SOI is given in Figure 3a.

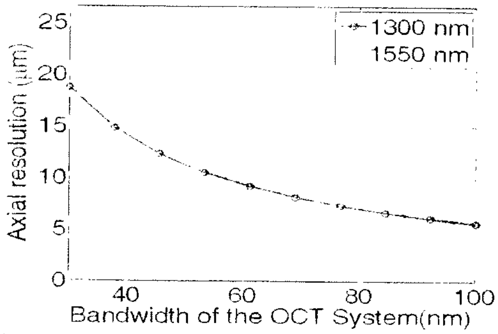

Figure 2a. The relation between bandwidth of the OCT system and axial resolution

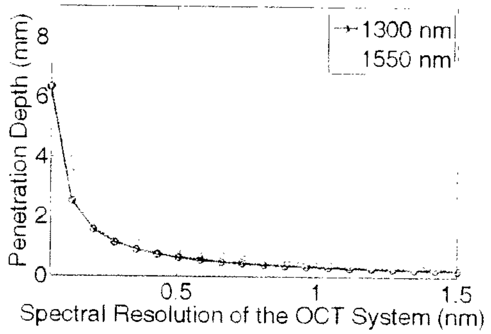

Figure 2b. The effect of spectral resolution of the OCT system on penetration depth

A swept source OCT system eliminates the complexity of a spectrometer, detection side in swept source OCT consists of a single photodetector. However, the complexity comes in the tunable laser source, which should have a tuning range comparable to a superluminescent diode. For real time imaging, a KHz scan rate is sufficient and can be realized by several wavelength selective mechanisms such as thermo-optic effect, liquid crystals, and electro-mechanical means. In swept source OCT, the linewidth of the tunable laser determines the spectral resolution of the system. The tunable laser can contain several longitudinal modes, which is a flexibility in the design, as long as the linewidth satisfies the spectral resolution requirements. A schematic of swept source OCT system on SOI is shown in Figure 3b.

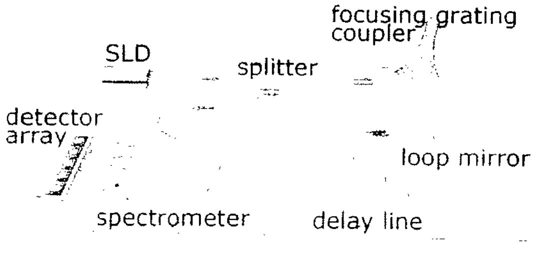

Figure 3a. Schematic of spectral domain OCT on SOI

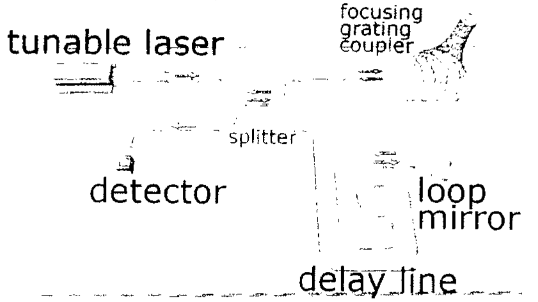

Figure 3b. Schematic of swept source OCT on SOI

In interferometric systems, polarization should also be considered for efficient interference. On planar photonic circuits, single mode waveguides are routinely used and the requirement of a polarization controller is eliminated, while fiber optic interferometric systems have to be calibrated with polarization controllers.

Future Work

Most of the fundamental components for an optical coherence tomography system are available on SOI platform for mass fabrication. In order to compete with the current state of the art OCT systems further research is necessary in miniaturized high resolution dense spectrometers, and rapidly tunable sources.

Acknowledgements

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