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Advances in Optical Coherence Tomography

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ABSTRACT

Traditionally applied to imaging the eye, optical coherence tomography (OCT) is now being extended to fields outside ophthalmology and optometry. The tremendous increase in acquisition speed of the spectral domain OCT technology in the last decade has enabled the OCT community to contemplate real time volume display, has opened the field of no-dye angiography and that of fast interrogation of deformation patterns in elastography. The presentation will review the OCT applications in ophthalmology and endoscopy as well as the dynamic field of broadband and fast tunable optical sources for OCT. Current research in Kent combined spectral domain and time domain OCT principles into a new method, Master/Slave OCT, that delivers fast display of any number of *en-face* OCT images. The Master/Slave method simplifies the OCT technology, the signal processing as well as gives parallel, direct access to information from multiple depths in the tissue. A review is presented on the advances of OCT that make the technology useful for numerous directions in medical imaging and for non-destructive testing.

Keywords: optical coherence tomography, non-invasive imaging, high resolution, tissue, medical imaging.

1. INTRODUCTION

Optical coherence tomography (OCT) was invented by combining low coherence reflectometry with lateral scanning of an investigating optical beam [1]. The number of reports on optical coherence tomography (OCT) continues to double every three years. Although the subject was initially confined to a dedicated conference at the Biomedical Optics Photonics West, it has spread to other related conferences. There is practically no conference on biomedical optics without OCT. Optical waves do not penetrate much into tissue and OCT is the method that makes the most out of the little depth interval, which in retina and skin is below 2 mm. However, the number of resolved points along the axial coordinate continued to grow given the attention given to enlargement in the optical spectrum of OCT sources. With the recent advances in ultra-wide bandwidth sources, axial resolution was improved to below the level of 1 micron, within a resolution interval achievable so far by confocal microscopy only. The last decade has also witnessed increase in the rate of delivery of depth resolved information, which has exceeded several MHz for sufficient signal to noise ratio [2]. Acquisition speed increase has enabled recent reports of high resolution delivery of several volumes a second useful in real time display of surgery intervention and ablation. Another relevant progress was that in multimodality, with OCT integrated with other optical techniques, such as fluorescence and optoacoustics and the tendency of OCT groups to identify OCT applications outside the traditional field of eye imaging.

2. PRINCIPLES OF OPERATION

There are mainly two types of operation [3] in the practice of low coherence reflectometry (interferometry): (i) time domain (TD), where interference takes place for optical path difference in the interferometer (OPD) less than the coherence length (defining the axial resolution) of the optical source and (ii) spectral (Fourier) domain, where modulation of the spectral content of signal at the interferometer output is employed, for OPD values reaching the instantaneous coherence length of the interfering waves (that define the axial range). Spectral domain OCT uses a spectrometer (Sp), as shown in Fig. 1, to read the optical spectrum at the interferometer output and Fourier domain OCT uses a narrow tuneable laser, a swept source (SS) to "scan" the spectrum in conjunction with a photodetector, as shown in Fig. 2.

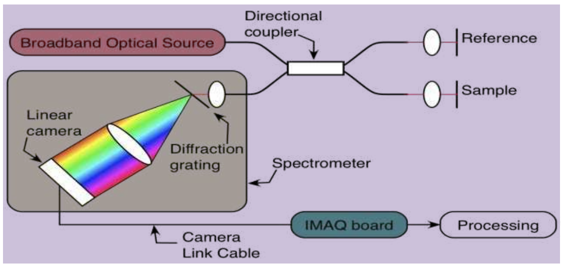

Figure 1. Sp-OCT configuration.

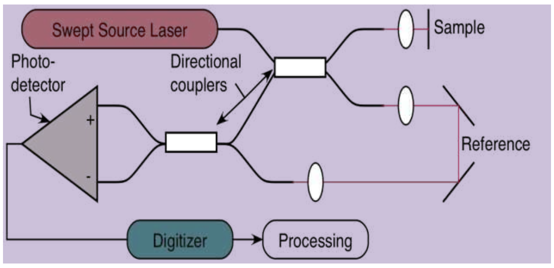

Figure 2. SS-OCT configuration.

The second type, (ii) listed above is therefore implemented either as a Sp-OCT or SS-OCT system. In both Figs. 1 and 2, a lateral scanner should be added before the sample to implement repetition of spectrum reading

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across several lateral pixels. In Fig. 1, a single splitter, a directional coupler in single mode fibre is sufficient to implement a Michelson interferometer. In Fig. 2, two splitters are used, in order to implement balanced detection, where the photodetector unit contains two photodetectors and the output signal sent to the digitiser is produced as the difference of the two photodetector signals. In Sp-OCT the axial range is determined by the coherence length of waves dispersed or diffracted in the spectrometer while in SS-OCT the instantaneous coherence length is that of the SS emission during sweeping. While TD-OCT has no limit in terms of the axial range, modern practice of OCT prefers Sp-OCT or SS-OCT due to the capability of encoding a long axial interval into the spectral modulation. Via a fast Fourier Transform (FT), the modulation of the spectrum (channelled spectrum) is translated into a reflectivity profile in depth (A-scan), while the TD-OCT delivers a single point at a time, that mechanically selected where OPD = 0. Sp-OCT and SS-OCT replaced the mechanical scanning of OPD in TD-OCT with “scanning” the optical spectrum that obviously can be performed by the two methods described above, non-mechanically.

3. SIGNAL PROCESSING

Signal processing applied to OCT progressed continuously, keeping pace with the demands for high axial resolution and speed of acquisition. Both demands put different constraints on the methods adopted. The most effort was concentrated on Sp-OCT and SS-OCT methods, due to their superiority in terms of signal to noise ratio [4].

3.1. Decoding Channelled Spectrum Modulation

Nonlinearity of spectrum reading in converting optical frequency (wavenumber) into time (given by the spectrometer geometry in SP-OCT and by tuning the SS in SS-OCT) coupled with dispersion in the interferometer requires data processing before the FFT step. This slows the signal processing and has been addressed by engaging field programmable gated array (FPGA) and graphic processing unit (GPU) devices. For a 1 MHz reading of the spectrum with 1000 cycles, 1 GHz signal is generated that shows the demand for methods applied to high speed digitisers. In Kent, we addressed this issue with a new method, Complex Master Slave (CMS) [5,6], that eliminates the FFT entirely and replaces the conventional signal processing with multiple correlation processors, a processor for each depth targeted. An immediate advantage is not only tolerance to nonlinearities in the method to decode signal and tolerance to interferometer dispersion, but the CMS method allows a direct production of *en-face* views direct, at any depth of interest, without the need to assemble the volume of data as the FFT method needs. CMS also opens new perspectives in signal processing by eliminating calculations for axial intervals that are not needed. This is useful in dynamic focus, where repetition of acquisition is necessary for several focus adjustments along the depth of the scanning beam, to implement Gabor filtering [7]. Another method we reported refers to nonlinear reading of the spectrometer, using a chirped clock, applicable to Sp-OCT only [8]. The clock is chirped in opposition to the nonlinear function describing the spectrometer operation.

3.2. Mirror Terms

Another problem of the Sp-OCT and SS-OCT is the mirror terms [9]. While TD-OCT obviously can distinguish between positive and negative OPD values equal in modulus, the Sp-OCT and SS-OCT are blind to the OPD sign. This leads to generation of symmetric images in respect to OPD = 0. Several solutions have been proposed using phase modulation and frequency shifting. A passive solution was devised based on Talbot bands [10]. This represents another application of handling the coherence length of interfering waves. By combining the delay in the interferometer with the delay created by diffraction between the left and right side of the incident beams on the grating, distinction become possible between signals due to positive or negative OPD values of the same modulus.

3.3. OCT Angiography

A significant evolution stemming from signal processing is the no dye angiography or OCT angiography (OCTA) [11]. This is based on sensing tiny variations in amplitude and phase between successive A-scans from the same lateral pixel or B-scans from close lateral positions. Decorrelation mapping can separate static tissue from moving fluids and in this way vessels flown by blood are made to stand out in the image. This is considered as a new revolution in ophthalmology as OCTA has eliminated the need to inject a dye, that is the conventional method to see the vasculature in the eye. However, OCTA is still not able to see leakage and therefore more research is needed to complement the current technology with other non-invasive modalities. However, the signal processing developed for OCTA has transcended ophthalmology towards other applications, such as monitoring the state of liveliness of embryos [12].

4. ACQUISITION SPEED

Using Sp-OCT and 4 cameras with a 1×4 switch, 1 MHz A-scan rate was achieved [13]. However, SS-OCT presents superior potential in achieving ultra-fast A–scan rates given the maturity of several solutions for ultra-fast sweeping. Frequency domain mode-locked laser (FDML) [2] and akinetic solutions, such as based on dispersive cavity mode locked lasers [14] reported recently achieved MHz tuning rates. This configuration is based on dual resonance, a resonance for mode locking (at hundreds of MHz) and a resonance on the repetition of the ramp driving the VCO (MHz) determining the instantaneous optical frequency, as shown in Fig. 3. However, the technology that looks poised to revolutionize the field of SS-OCT is time stretch. This uses fs or ps broadband pulses. There are commercial broadband sources based on supercontinuum, that use over tens of MHz repetition rate pumping. By employing a passive dispersing element, such as a dispersion compensating fibre (DCF) or arrays of chirped fibre Brag gratings (cFBGs), waves of different wavelengths reach the dispersing element output at different times. This is equivalent with sweeping. The ultra-wide bandwidth of the supercontinuum laser can lead to unprecedented axial resolution achievable with SS-OCT, delivered by a tuning laser with tuning rates exceeding tens of MHz. Good quality OCT images of mudfish eyes and skin were demonstrated at a 11.5 MHz sweeping rate [15]. The narrower linewidth exhibited by time stretch lasers compared to commercial swept lasers results in a longer axial range (exceeding a few cm).

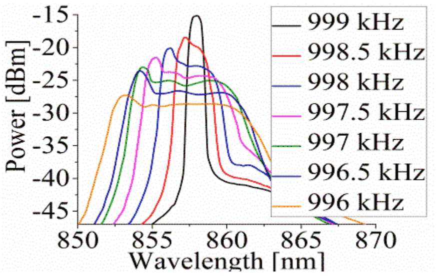

Figure 3. Optical spectra at the SS output measured for seven values of detuning of the sweeping frequency starting from resonance [15].

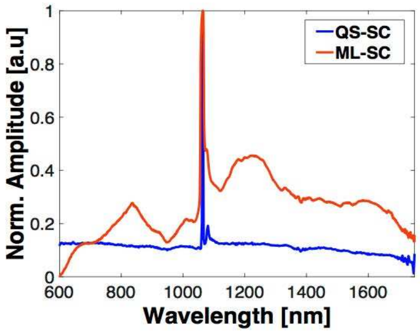

Figure 4. Spectrum of two NKT ultrabroadband supercontinuum sources. QS-SC: Q-switch pump at 22.2 kHz; ML-SC: mode-locked pump at 320 MHz [17].

5. AXIAL RESOLUTION

From superposing spectra of several superluminescent diodes, OCT technology progressed to that of optical sources based on supercontinuum whose spectrum extends over the concatenated spectra of Silicon and In GaAs photodetectors, as shown in Fig. 4. Such sources drive Sp-OCT set-ups. Two spectra are shown, for two different pump sources driving the photonics crystal fibre, a mode locked pump at 320 MHz and a Q-switch pump at 22.2 kHz. Both spectra extend from visible to infrared, with the Q-switch source at a fraction of the cost of the mode locked source [16], but with slower OCT. An immediate challenge for the technology of cameras is that the spectral definition determines the axial range. If the same number of pixels is maintained on the camera and the bandwidth of the optical source is increased, then the axial range suffers. To secure a long axial range and the improved axial resolution due to the increase in the bandwidth, linear cameras with many more pixels are necessary.

6. MULTIMODALITY

The availability of a scanner allows extension of OCT set-ups to imaging fluorescence. From early implementations of combining OCT and fluorescence for imaging the eye and endoscopy, the technology has evolved to that of combining photoacoustics (PA) with OCT [17]. While OCT signal is depended on backscattering, the PA signal is produced by absorption. Therefore, a dual system OCT/PA can provide morphology in the OCT channel and molecular contrast in the PA channel. Having pulses of wide bandwidth, with sufficient energy, allows spectroscopic PA. Spectroscopy may add the extra dimension of function, by detecting differences between the haemoglobin and deoxyhemoglobin in tissue.

7. TOWARDS AKINETIC OCT

Recent reports of ultra-fast OCT on the human eye have suggested that more important than signal to noise ratio is phase stability of the signal to allow sensitive phase measurements. This has been recently strengthened using a Photron camera at 75 k frames/s, to acquire images of 640×368 pixels achieving an equivalent acquisition of A-scans at 46.5 MHz, and a maximum volume rate of 167 Hz [18]. Use of a fast camera has helped with the phase stability when compared with eye movements, but the use of a camera deprived the system of confocality. In Kent, we also applied the Master Slave technology to a full field configuration OCT [19].

8. CONCLUSIONS

Given the technical differences between the Sp-OCT and SS-OCT, Sp-OCT is recommendable for high resolution OCT, while SS-OCT is recommendable for high speed A-scanning. Using supercontinuum sources in visible, Sp-OCT allows submicron resolution. Sweeping at over hundred MHz rates become possible using the time stretch technology for SS-OCT. The advances in OCT technology made it useful for better diagnosis of the eye as well as spread of OCT technology to other medical imaging directions and non-medical, such as in non-destructive testing of materials, with exquisite applications in art conservation [20].

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