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Ultrafast Optical Tomography Systems using Coherence Agility

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ABSTRACT

Described are three types of optical imaging systems based on source coherence agility. On axis ultrafast microsecond sub-surface imaging is achieved by use of a broadband low coherence optical source to implement fast Doppler time domain optical coherence tomography (OCT). This system is formed as a combination of a fast scan acousto-optically implemented variable optical delay line with a single acousto-optic (AO) Bragg cell optical heterodyne interferometer. A second imaging system is introduced with a no-moving parts probe design and fast microsecond speed optical spatial scanning along one dimension implemented using a fixed wavelength high coherence source with a single Bragg cell AO interferometer. The third design involves realization of a spectral domain OCT system implemented via the use of a tunable laser in the proposed single AO cell heterodyne interferometer.

KEYWORDS: Fiber-optics, Biomedical Instruments, High Speed, time domain OCT, spectral domain OCT

1. INTRODUCTION

In recent years, optical technology has shown great promise for in-vivo tomography and systems using both low coherence and high coherence light have been built and tested. Optical coherence tomography (OCT) systems of the time domain type rely on using small temporal coherence relatively broadband (e.g., > 10 % instantaneous bandwidth) light to accomplish high resolution (10-100 microns) depth direction image slices from a test sample such as a tissue [1-3]. The time domain coherence gating effect is used to separate the coherent back scattered photons from the in-coherent photons. Hence, intensity information of the coherent returned light is used after interference with a reference wave to generate the desired image. So far, low spatial crosstalk image formation has been implemented on a point-by-point basis by moving either the point probe head or sample [3-5].

Instruments have also been built as phase contrast optical microscopes [6-7] using high temporal coherence to form high depth resolution imaging interferometers, again using mechanical means to generate the true image. In both the broadband light and narrowband light cases, image acquisition is a slow process (due to mechanical inertia) leading to limitations when the sample contains fast temporal effects such as flow patterns and neuronal or cellular activity. Ideally, a no-moving parts spatial sampling system is required that can produce fast Mega Hertz (MHz) point scan rates. So far, no such mechanism has been introduced to implement this goal in an ultrafast fashion.

In the case of moderately fast Doppler OCT systems of the time domain processing type, the majority implementations have used moving parts delay lines, such as with 2 KHz [8] and 4 KHz scanning mirrors [9] and 2.4 KHz spinning mirror array [10]. Another more ambitious approach using optical comb frequency generation has been

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proposed with a 500 KHz capability, although, this technique is hindered by the use of complex and costly Giga-Hertz bandwidth electro-optical modulators and electronics [11]. Based on these discussions, the field of temporally sensitive or evolving biomedical optics can undergo a paradigm shift if it is possible to provide biologically vital subsurface information on a microsecond per scan spot (along depth direction imaging) basis in combination with Doppler information. In effect, both a temporal and spatial map of the probed biological sample (that maybe undergoing temporally stimulated effects) can be made via a low crosstalk temporal/spatial sampling technique leading to unprecedently low noise electrical spectrum capture and optical tomography, all implemented in real-time using one simple cost effective instrument.

Optical interferometric microscopes are powerful biological characterization tools for various applications. For instance, neuron membranes move up/down and deform on a nanometer scale when stimulated with neurotransmitters [12]. Similarly, DNA sequencing can be implemented by detection of sub-nanometer level optical phase perturbations, as first studied by a Los Alamos Lab. group [13] and also suggested by N.A. Riza [14-15]. Scanning interferometric microscopes are in particular useful instruments to create real-time images. Today, these scanning interferometric microscopes use moving parts designs to sample the probing region, leading to limited operational speeds (in KHz rates) and sensing resolution (e.g., $\lambda/500$). In addition, these instruments require precision mechanics to reduce air current and vibrational effects, making an expensive instrument. Furthermore, these instrument have limited Doppler acquisition capabilities, partly due to their slow sample scanning mechanisms and partly because they involve KHz level intermediate frequency (IF) generation. Hence, it would also be highly useful to the biomedical community if one can realize a Doppler Scanning Interferometric Optical Microscope with Angstrom level phase sensing capability. The second part of this paper achieves this goal by elegantly switching the instrument operational ports of the Doppler OCT system and using a coherent source.

The purpose of this paper is to introduce three imaging systems for Biomedical applications that for the first time, to the best of our knowledge, can provide the mentioned paradigm shift in biological sample data acquisition via its unique near simultaneous temporal and spatial sampling method. The proposed three optical instruments with an ultracompact design can operate as a generic in-vivo probe for any disease and organ with both internal and external operating conditions. With current state-of-the-art optics, one can expect in real-time, a thousand spatial point slices (in z by OCT and x/y by microscope), and Mega-Hertz band temporal/Doppler information from the biological sample. Applications possible with these instruments include stimulated neuron imaging, blood flow measurements, intracavity imaging, cancer tumor detection, retinal imaging, skin mapping, and diabetes diagnostics.

The concept of using in-line acousto-optics (or Bragg cells) to form switched high speed freespace/bulk-optic/fiber-optic variable optical delay lines was proposed, to the best of our knowledge, by N. A. Riza [16]. Similarly, the concept of using in-line acousto-optics (or Bragg cells) to form a high speed scanning interferometric microscope was proposed, to the best of our knowledge, by N. A. Riza [17]. Using these two mentioned innovations, we showed how Bragg cells could be used to form a high speed Doppler time domain processing OCT system where the Bragg cell is used to select the delays required for OCT depth scan image formation [18]. Initial experimental results using available off-the-shelf components have indeed given positive feedback for improved designs. Specifically, these early results with limited 50 nm bandwidth sources and narrow band Bragg cells have demonstrated 20.7 micron axial resolution scans with eleven image slices [19]. The transmissive version of the proposed scanning microscope [17] has also shown the promise for the reflective interferometric microscope design that is part of this paper. The reflective design, similar in architecture to the proposed Doppler OCT system, is the preferred design for biomedical probe applications as it is compact and can operate by using specular/reflections from biological samples. In addition, when this single AO cell interferometer is used with a tunable laser (instead of the fixed wavelength laser), a Fourier domain processing OCT system can be realized.

Hence, for the first time, agile bulk-mode acousto-optic Bragg cells combined with either broadband sources for Doppler time domain OCT (and tunable laser for spectral domain OCT) and highly coherent fixed wavelength source for interferometric optical microscopy, are proposed for biomedical applications where speed of probe operations is critical to observe fast effects and remove motion artifacts. The proposed probe smart optics will operate at speeds of a microsecond per probe beam, and these probes will be studied, designed, and realized specifically for the biomedical arena. The next section deals with the proposed three instruments.

2. FAST SCAN HETERODYNE TIME DOMAIN OCT USING ACOUSTO-OPTICS

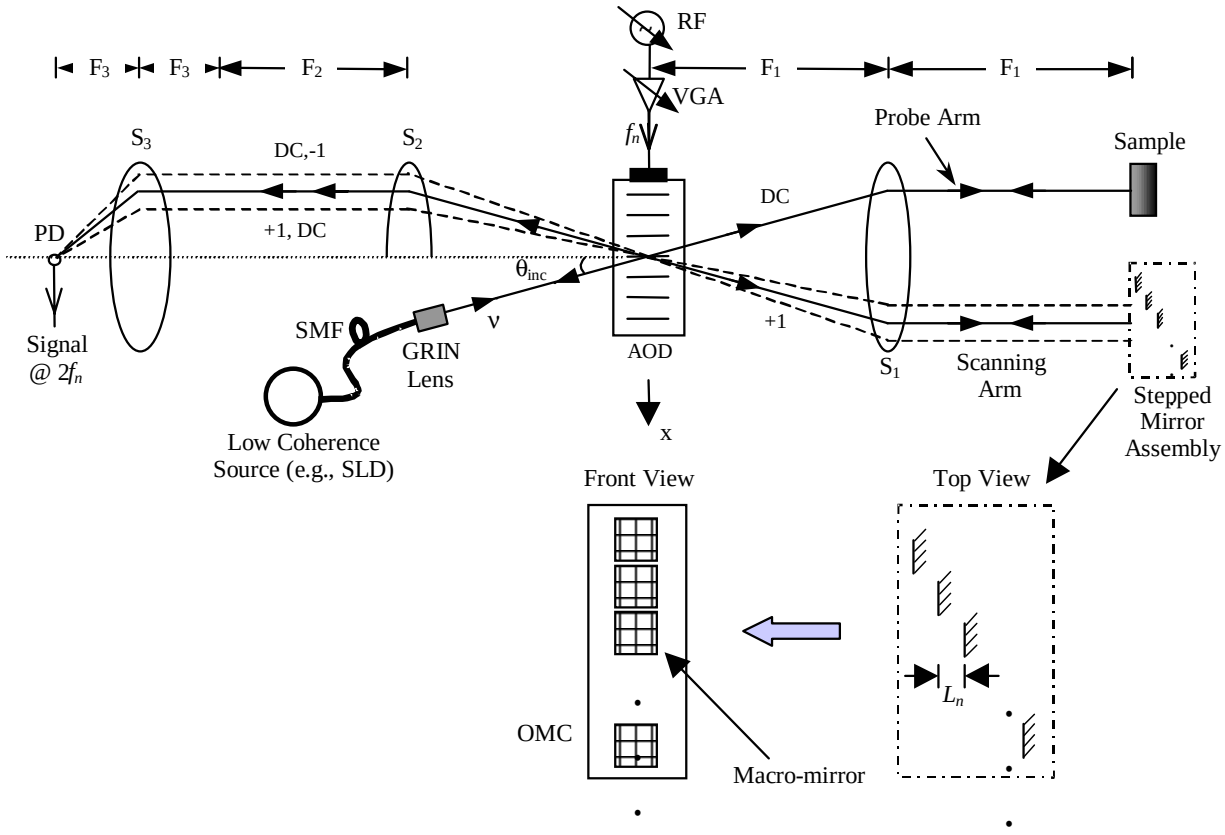


Fig.1a. The high speed time domain processing Doppler OCT system that produces both spatial and temporal maps of the in-vivo biological sample. S_i: Spherical Lenses; ν: Optical Frequency; PD: Photodetector; AOD: Acousto-Optic Device; F_i: Focal Length of i^{th} Lens; GRIN Lens: Gradient Index Lens; SLD: Superluminescent Diode; OMC: Optical MEMS Chip.

Figure 1 show the proposed high speed no moving parts scanning probe system for high speed Doppler OCT. The acousto-optic (AO) device or Bragg cell is fed with a RF drive signal of frequency f_n, where the index n = 1,2,..., N. Here, N are the total number of independent delays provided by the acousto-optic delay line. N is then equivalent to the number of image slices the OCT system can acquire along the optical axis. The AO Bragg cell simultaneously does the job of both delay-path selection and output beam realignment. The light from the low coherence light source is Bragg matched to the AO cell for center wavelength λ_c, with the spherical lens S_1 used for beam alignment. With AOD driven, the incident broadband light splits into a DC beam that strikes the test sample, and a deflected +1 order, positive Doppler shifted diffracted beam. Depending on the frequency f_n, this deflected beam enters one of the delays in the N-element delay array. Hence, the deflected light beam travels through an electrically chosen optical path of length L_n and acquires a time delay of $\tau_n = (2L_n n_f)/c$, where n_f is the refractive index for the delay medium and c is the speed of light in free-space. Note that τ_n should be more than the coherence time of the laser source.

Optical media such as a stepped mirror can be fabricated using current micro-fabrication methods to act as the distributed delay path array in our OCT system (see Fig.1). Microelectromechanical systems (MEMS) technology is another attractive approach to fabricate the distributed delay path array. With current MEMS technology, several micromirrors can be used to make one macro-mirror for reflecting the selected portion of the Gaussian optical beam. This will avoid reflection from the neighboring macro-pixels of the stepped mirror to get a clean heterodyne optical

signal at the output. The optical signal will, therefore, correspond only to the selected slice of the test sample, defined by the path length difference of the interfering beams and the coherence length of the broadband source.

After retroreflection, the signal beam and the reference beam pass through the AOD for second Bragg diffraction. The second Bragg diffraction with the light propagation in reversed direction generates the realigned DC,-1 and +1,DC output beams for the interference and heterodyne signal generation at $2f_n$. Note that the delays are terminated in a mirror assembly. Spherical lenses S_2 and S_3 make an imaging system with $-F_3/F_2$ magnification to get stationary interfering beams on the photodetector (PD).

The proposed OCT design allows precise control of the optical split ratio by controlling the AOD RF drive power. This feature, as opposed to existing OCT systems, increases the imaging performance of the OCT system in highly scattering tissues and thus allows to probe deeper into the sample.

Fundamentally, OCT systems use a broadband light source for high axial resolution inside the sample or living tissue under examination. Inherently, AO devices are Bragg-mode wavelength sensitive elements. Hence, Bragg cells have been ignored for use with OCT systems. In the design shown in Fig.1, we exploit a newly identified aspect of the Bragg cell that now makes them attractive for OCT applications. Namely, that the Bragg cell generated two beams (e.g., diffracted +1 order and undiffracted DC beam) are naturally possessing an unbalanced and orthogonal spectrum with respect to each other. This mismatch in spectrums in-turn violates the ideal auto-spectrum condition for a high signal-to-noise ratio broadband interferometric sensor such as OCT.

We has solved this fundamental limitation of Bragg cell use for OCT by deploying the new interferometric architecture of Fig.1 where the two interfering beams have the same power spectral profile over the bandwidth of the broadband source. This is made possible by (a) Using a single Bragg cell and forcing the initially split beams to undergo another Bragg cell diffraction after retroreflection from the sample and reference mirror (moreover, retroreflection naturally occurs in OCT), and (b) By picking the right two beams to eventually interfere and heterodyne mix at the photo-detector. Specifically, the DC,-1 and the +1,DC diffracted beams are picked for final detection as the power spectrum of both these beam undergo the same spectral spoiling and hence have spectral match, a condition required for high signal-to-noise ratio autocorrelated detection. In short, assuming that the power spectrum of the incident broadband light is given by $s(\lambda)$, and the power spectral profile of a diffracted beam is given by $\eta(\lambda)$ when illuminated by unity or flat spectrum light, the net power spectrum of a DC,-1 and +1,DC double diffracted beam is to a first approximation given by the same expression; $s(\lambda)\eta(\lambda)\,[1-\eta(\lambda)]$. Hence, this OCT probe design satisfies the optimal coherent detection condition, and thus allows the Bragg cell to be used as a vital high speed z-scan device required for sub-surface biological sample imaging.

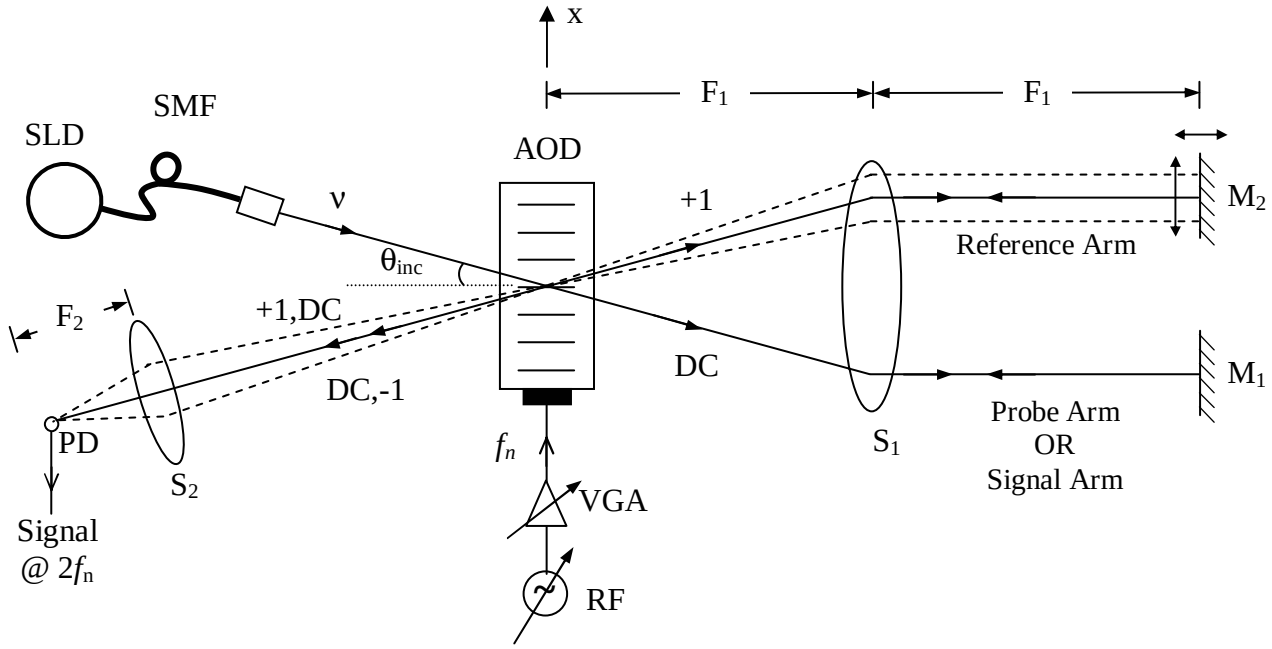
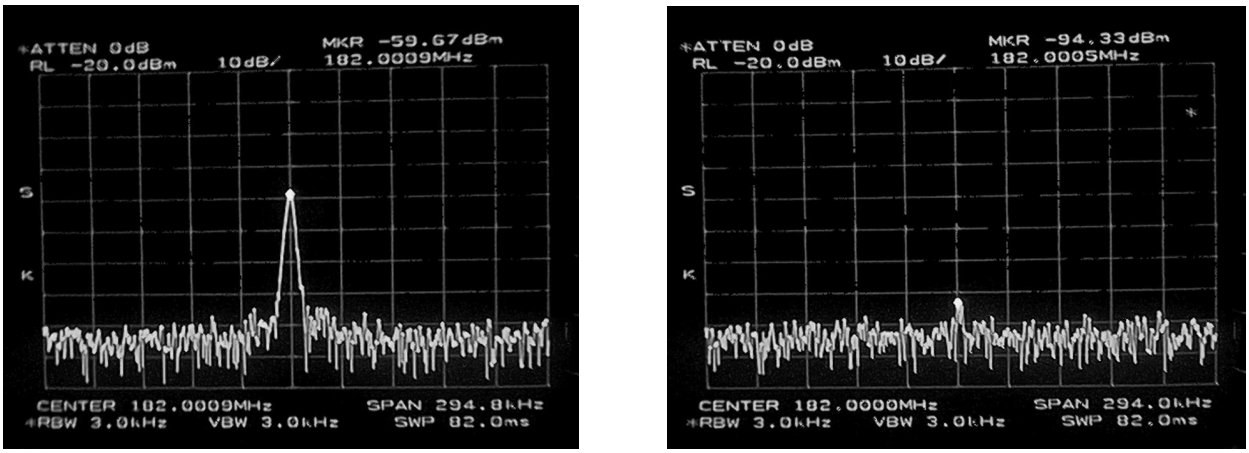


Fig.1b: Time domain OCT system setup for the experiment.



OCT Signal for
In-Coherence Case

OCT Signal for
Out of Coherence Case

Fig.2 Time domain OCT data from a Lung sample provided by Prof. Geoff McLennan, Univ. of Iowa Medical School.

The Fig.1b system is used as a time domain freespace OCT system to measure data from a lung sample. As an example, the data shows a 34 dB signal dynamic range for two different axial scan locations of the lung sample accessed by scanning the reference mirror (instead of accessing a stepped mirror) in the AO OCT system. The difference in signal strength can be due to a cavity effect in the lung sample that is filled with air pockets acting as optical boundaries. The AOD is driven at 91 MHz and the IF is 182 Mhz.

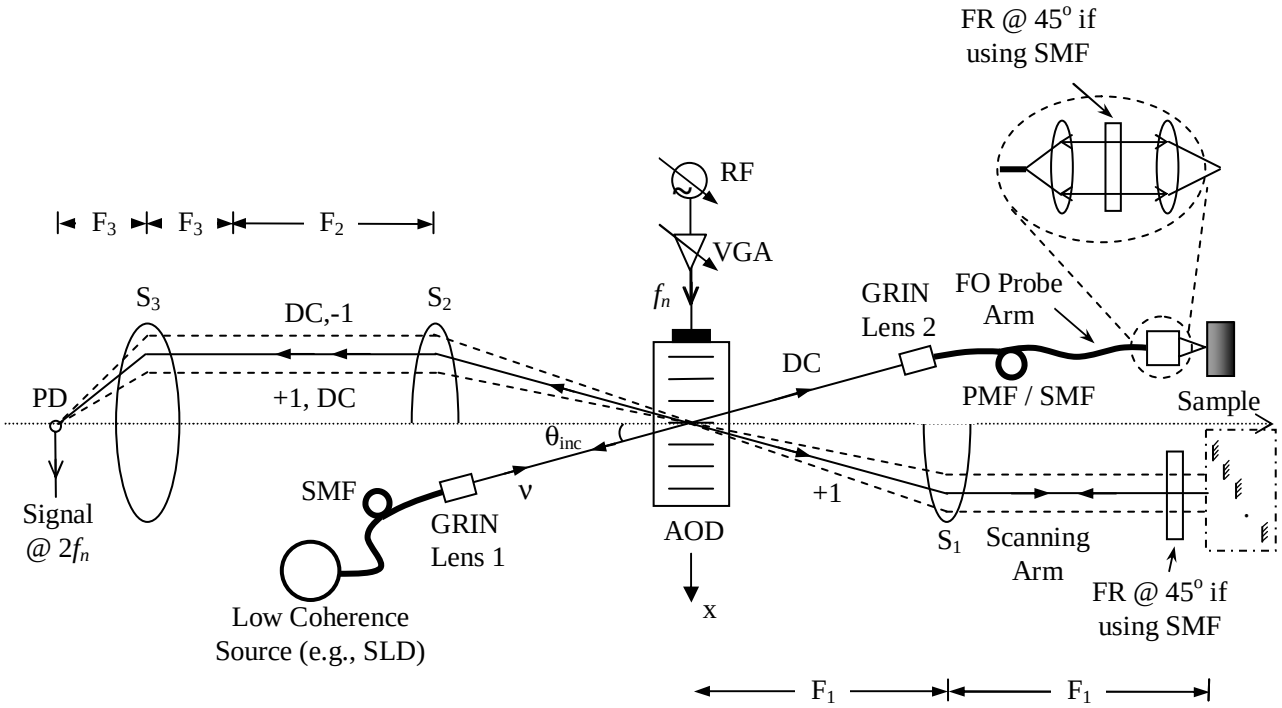
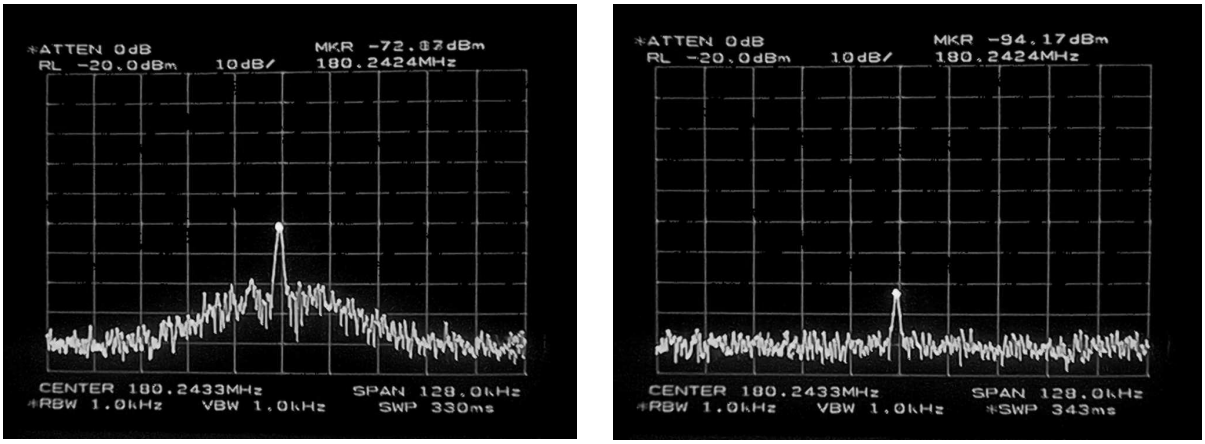


Fig.3. The Fig.1 system can be reconfigured as a confocal OCT system using a fiber-optic sample frontend.



OCT Signal for
In-Coherence Case

OCT Signal for Slightly
Out of Coherence Case

Fig.4 The Fig.3 confocal OCT system data for the lung sample.

Fig.4 shows time domain OCT data for the lung sample taken using the fiber-optic confocal OCT system in Fig.3.

3. FAST SCAN HETERODYNE OPTICAL MICROSCOPE USING ACOUSTO-OPTICS

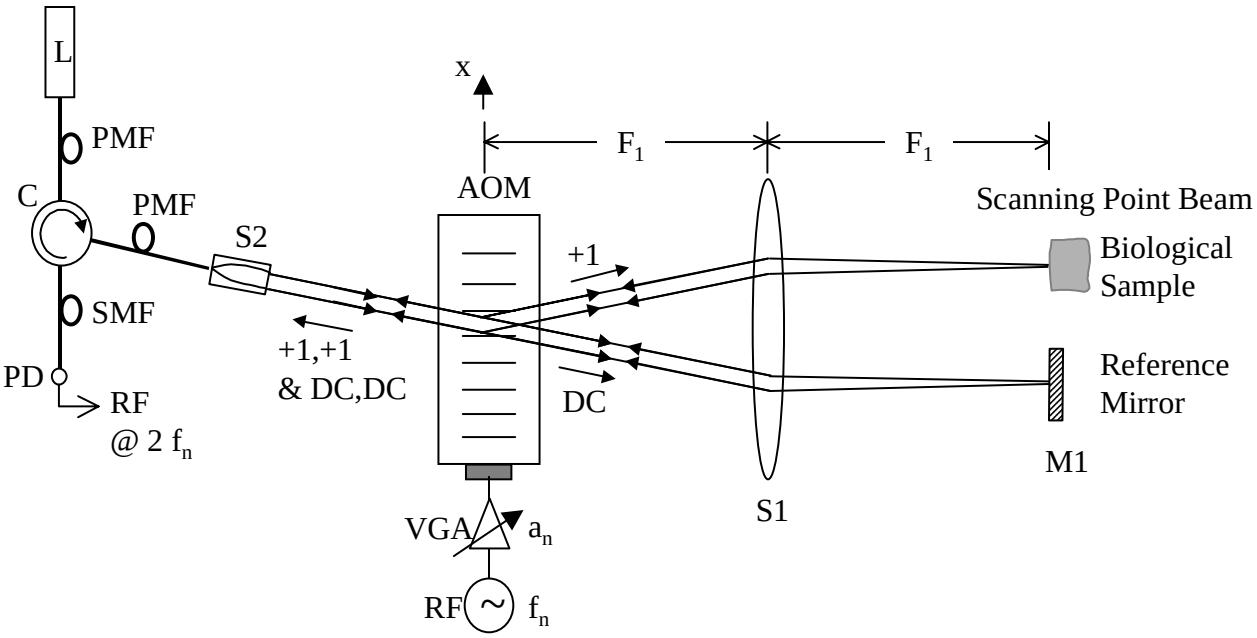


Fig.5 The basic high speed scanning Doppler Optical Microscopy system that produces both spatial and temporal maps of the in-vivo biological sample. S1: Spherical Lens; S2: Fiber GRIN Lens ν: Optical Frequency; PD: Photodetector; AOD: Acousto-Optic Device; F1: Focal Length of S1 Lens; GRIN Lens: Gradient Index Lens; L: High Coherence Laser Diode; M1: Reference mirror; VGA: Variable Gain Amplifier; C: Fiber-optic Circulator; PMF: Polarization Maintaining Fiber; SMF: Regular Single Mode Fiber.

Fig.5 shows the proposed coherent scanning microscope that can lead to Angstrom level sensitivity [20-21]. Note the similarity in the OCT and microscope architectures. Here in Fig.5, a retroreflective optical path is used via the optical circulator device (C) to form the detection signal port that generates an RF at frequency $2f_n$, where f_n corresponds to the RF drive for the Bragg cell for the nth scan position on the biological sample. The two beams that are used for interference are the DC,DC beam that tracks the original input beam path and the +1,+1 double diffracted beam that on first diffraction acts as a linear point scanning beam on the sample and on reflection from the sample undergoes another +1 diffraction to create a double diffracted beam that is inline with the original input beam. Hence, these two returning beams are able to enter the fiber coupled GRIN lens S2 for transmission via circulator to photodetector for heterodyne detection. The laser L used is a high coherence narrowband source and can be a visible band laser diode. Because a typical Bragg cell can have a 1000 point storage capacity, the Bragg cell can also generate a 1000 scan points in space. As the detected signal from the photodetector is at a typical 100 MHz IF, the 1/f noise in this microscope is low as $2f_n$ is high (e.g., 100 MHz). This is another major benefit of the proposed scanning optical microscope where a potential 1000 point spatial map can be realized with a point high speed detector (and not with a 1000 point detectors), thus saving cost and power consumption. The Fig.5 system also forms a scanning confocal microscope.

4. HETERODYNE SPECTRAL DOMAIN OCT USING ACOUSTO-OPTICS

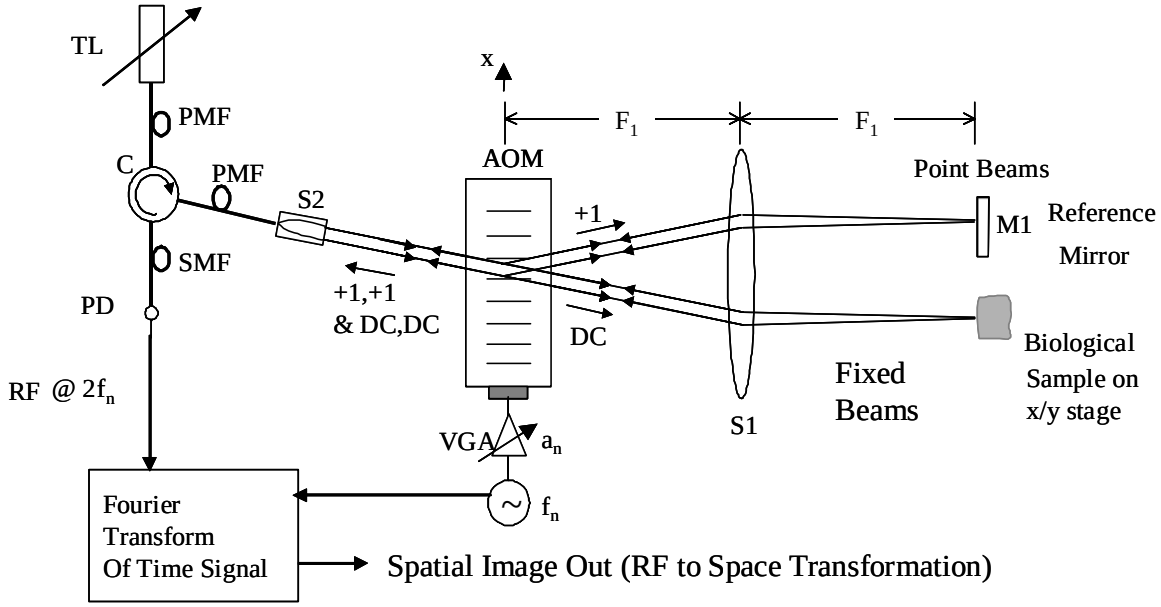


Fig.6 The Fourier-domain Doppler OCT system that produces both spatial and temporal maps of the in-vivo biological sample. S1: Spherical Lens; S2: Fiber GRIN Lens ν: Optical Frequency; PD: Photodetector; AOD: Acousto-Optic Device; F1: Focal Length of S1 Lens; GRIN Lens: Gradient Index Lens; L: High Coherence Laser Diode; M1: Reference mirror; VGA: Variable Gain Amplifier; C: Fiber-optic Circulator; PMF: Polarization Maintaining Fiber; SMF: Regular Single Mode Fiber.

Fig.6 shows how the Fig.5 system can be modified to realize a Fourier-domain Doppler OCT system. Here, a tunable laser is used as the light source and detected IF signal is Fourier transformed to deliver the axial scan image OCT data. The signal beam is the fixed DC beam while the reference beam is the diffracted AO beam. Both beams are fixed as the AOM drive RF tracks the laser wavelength to maintain Bragg match, as shown recently in a previous application module [22]. Note that the IF is RF frequency coded to different laser wavelengths that correspond to different z-scan locations along the biological sample. An RF spectrum analyzer can be used to generate the desired z-scan image. X-Y scan can be implemented via traditional means on the signal beam such as via an x-y scan micromirror. Note that IF phase information is preserved via phase-locking with the external reference source. Also, this is a point-to-point confocal mapping system where the output IF is generated as a swept frequency that has a 1:1 match with the laser wavelength sweep and the z-scan starring mode sample axial sweep. The entire process is smooth and analog in nature versus requiring a discrete detector optical array with an optical spectrum analyzer (such as of the grating type). Hence, the true analog processing nature of the proposed Fig.6 instrument can result in performance advantages over a spatially discretized parallel processor. Both state-of-the-art tunable lasers and RF sources and related AOD can operate with MHz sweep rates, leading to fast image generation for this spectral domain OCT system.

5. CONCLUSION

Using source coherence agility, features of the proposed two OCT systems (time domain and spectral domain [23]) and the coherent scanning interferometric microscope are:

- High Speed
  The ability to switch a delay (for time domain OCT) or spatial probe (for microscope) in a microsecond allows the near continuous generation in real-time or faster of low RF and spatial crosstalk optical tomographic and

spectral data even with rapidly varying in time electrically/chemically triggered biological effects. In addition, Doppler effects can be sampled to examine sample temporal behavior.

- Spectral and Spatial Power Control
  The ability to control the power levels of each generated reference and probe beam via the RF drive power control of the Bragg cell allows smart probing of the biological sample for optimum optical image formation. As analog RF frequency and amplitude tuning is used, fine tweeking of the optical power and beam position is possible to optimize sample general probe system operation and calibration.

- No Moving Parts Spatial/Delay Access
  As the complete probe for 1-D spatial mapping uses no moving parts, a high reliability probe can be realized.

- In-Line Optical Design
  Since a single Bragg cell is used in an in-line retroreflective design, the instruments are robust to mechanical vibrations, air currents, and thermal effects, leading to ultra-high phase resolution interferometric detection.

- High IF Designs
  As the photo-generated current is produced on a high (e.g., 100 MHz), IF band, the 1/frequency noise in detection electronics is greatly reduced. Furthermore, the Doppler sensing bandwidth of the instrument is also greatly enhanced. This gives added flexibility to the biomedical user.

- Fiber-based Designs
  Use of the single mode fiber (SMF) leads to a confocal microscopy design.

Future work relates to the design and demonstration of these acousto-optic device-based optical imaging systems for biomedicine.

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