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(54) **INTEGRATED OPTICAL COHERENCE ANALYSIS SYSTEM**

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(58) **Field of Classification Search**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,686,990 A 11/1997 Laznicka, Jr.  
5,716,324 A 2/1998 Toida  
5,810,719 A 9/1998 Toida  
5,823,942 A 10/1998 Toida  
6,549,548 B2 \* 4/2003 Kuznetsov et al. .... 372/32  
7,126,693 B2 \* 10/2006 Everett et al. .... 356/479  
7,415,049 B2 8/2008 Flanders et al.  
7,486,405 B2 2/2009 Hogan

(Continued)

FOREIGN PATENT DOCUMENTS

EP 1 842 483 A1 10/2007  
JP 06-063048 A 3/1994

(Continued)

OTHER PUBLICATIONS

Meissner, S., et al., "Investigation of Murine Vasodynamics by Fourier Domain Optical Coherence Tomography," Proc. of SPIE-OSA Biomedical Optics, SPIE, vol. 6627, 2007, pp. 66270D-1 to 66270D-10.

(Continued)

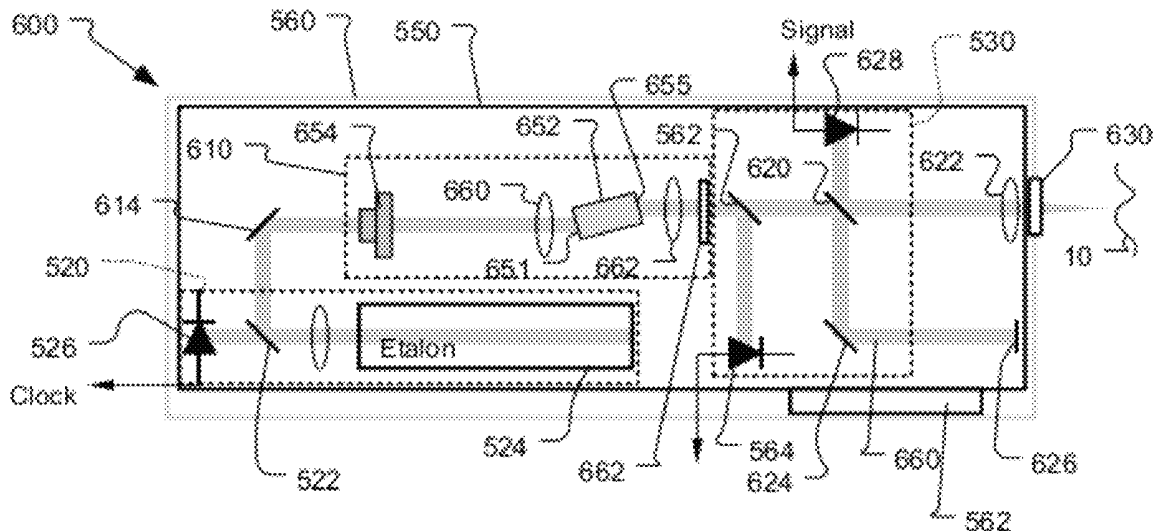
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(57) **ABSTRACT**

Optical coherence tomography (OCT) probe and system designs are disclosed that minimize the effects of mechanical movement and strain to the probe to the OCT analysis. It also concerns optical designs that are robust against noise from the OCT laser source. Also integrated OCT system-probes are included that yield compact and robust electro-opto-mechanical systems along with polarization sensitive OCT systems.

**25 Claims, 9 Drawing Sheets**



(56)

## References Cited

## U.S. PATENT DOCUMENTS

7,720,526	B1	5/2010	Modell	
7,916,387	B2*	3/2011	Schmitt .....	359/344
8,259,303	B2	9/2012	Johnson et al.	
2002/0093655	A1	7/2002	Everett et al.	
2003/0048840	A1	3/2003	Ling et al.	
2004/0052480	A1*	3/2004	Benzoni et al. ....	385/94
2004/0218189	A1	11/2004	Izatt et al.	
2005/0024646	A1	2/2005	Quadling et al.	
2005/0094949	A1	5/2005	Mink	
2005/0254061	A1	11/2005	Alphonse	
2006/0055936	A1	3/2006	Yun et al.	
2006/0079762	A1	4/2006	Norris et al.	
2006/0109478	A1	5/2006	Tearney et al.	
2006/0195019	A1	8/2006	Premachandran et al.	
2006/0241493	A1	10/2006	Feldman et al.	
2007/0024868	A1	2/2007	Izatt et al.	
2007/0055117	A1*	3/2007	Alphonse .....	600/310
2007/0081166	A1*	4/2007	Brown et al. ....	356/479
2007/0088219	A1	4/2007	Xie et al.	
2007/0134615	A1	6/2007	Lovely	
2007/0146726	A1	6/2007	Quadling et al.	
2007/0238955	A1*	10/2007	Tearney et al. ....	600/407
2008/0007734	A1	1/2008	Park et al.	
2008/0024788	A1	1/2008	Shimizu et al.	
2008/0043244	A1	2/2008	Hatori et al.	
2008/0049232	A1	2/2008	Vakoc et al.	
2008/0062429	A1	3/2008	Liang et al.	
2008/0090199	A1	4/2008	Noguchi et al.	
2008/0118886	A1	5/2008	Liang et al.	
2008/0175465	A1*	7/2008	Jiang et al. ....	382/131
2008/0186501	A1	8/2008	Xie	
2008/0194947	A1	8/2008	Kokkelink et al.	
2008/0228033	A1	9/2008	Tumlinson et al.	
2008/0252901	A1	10/2008	Shimizu et al.	
2009/0018436	A1	1/2009	Gey Van Pittius et al.	
2009/0021745	A1	1/2009	Tamura	
2009/0046295	A1*	2/2009	Kemp et al. ....	356/479
2009/0069794	A1	3/2009	Kurtz	
2009/0122383	A1*	5/2009	Reyes et al. ....	359/238
2009/0290167	A1	11/2009	Flanders et al.	
2011/0216325	A1*	9/2011	Schmitt .....	356/479

## FOREIGN PATENT DOCUMENTS

JP	2003-050199	A	2/2003
JP	2003-172690	A	6/2003
JP	2004-344262	A	12/2004
JP	2007-209536	A	8/2007
JP	2007-298461	A	11/2007
JP	2008-070350	A	3/2008
WO	2006/133030	A2	12/2006
WO	2007/041125	A1	4/2007
WO	2010111795	A1	10/2010

## OTHER PUBLICATIONS

Moon, S., et al., "Normalization detection scheme for high-speed optical frequency-domain imaging and reflectometry," *Optics Express*, vol. 15, No. 23, Nov. 12, 2007, pp. 15129-15146.

Popp, A., et al., "Imaging of the three-dimensional alveolar structure and the alveolar mechanics of a ventilated and perfused isolated rabbit lung with Fourier domain optical coherence tomography," *Journal of Biomedical Optics*, vol. 11, No. 1, Jan./Feb. 2006, pp. 014015-1 to 014015-9.

Tumlinson, A., et al., "Endoscope-tip interferometer for ultrahigh resolution frequency domain optical coherence tomography in mouse colon," *Optics Express*, vol. 14, No. 5, Mar. 6, 2006, pp. 1878-1887.

International Search Report mailed Jan. 12, 2010, from International Application No. PCT/US2009/044179, filed on May 15, 2009.

International Preliminary Report on Patentability mailed Nov. 25, 2010, from International Application No. PCT/US2009/044179, filed on May 15, 2009.

Schmitt R. et al. "A Two Dimensional Scanning Setup for Precise Addressing of Fibers in a Fiber Bundle," *Cirp Annals Elsevier BV*, vol. 56, No. 1, Jan. 1, 2007, pp. 505-508.

Extended European Search Report and Annex to the European Search Report, mailed Nov. 25, 2013, from European Application No. 13185133.9, filed Sep. 19, 2013.

\* cited by examiner





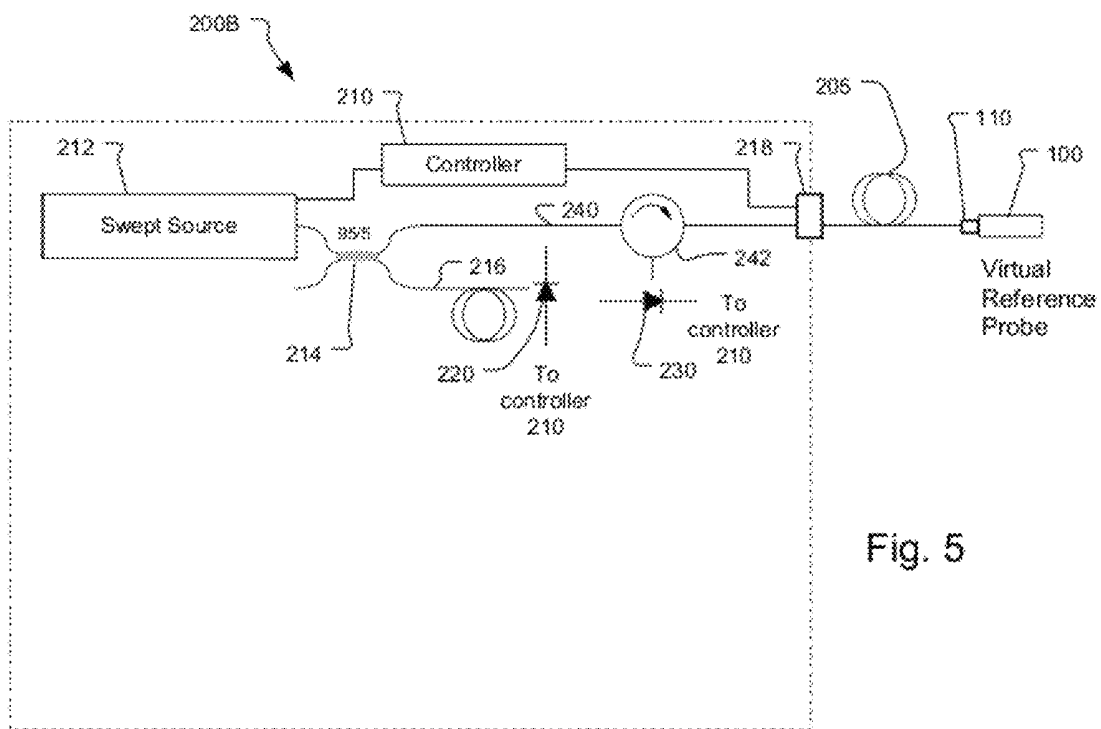


Fig. 5

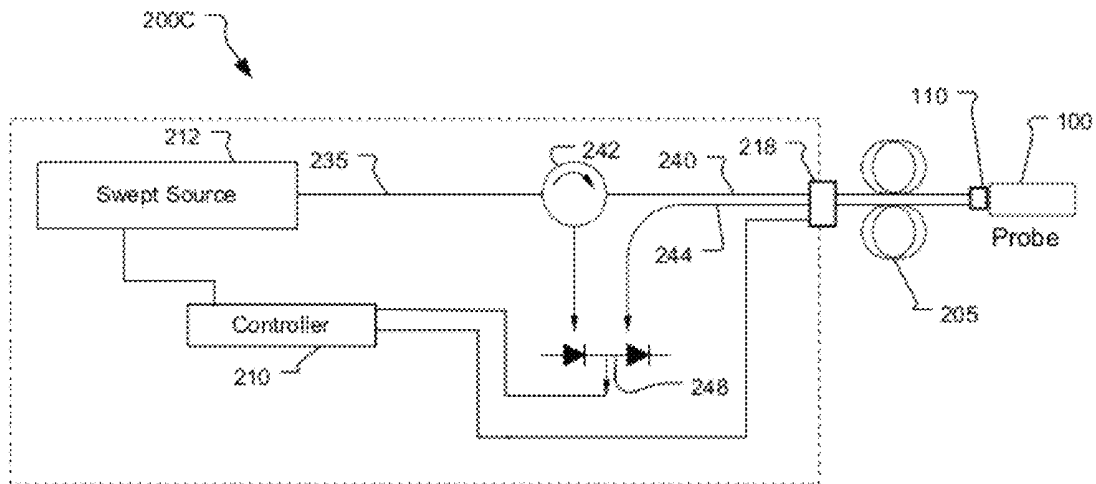


Fig. 6

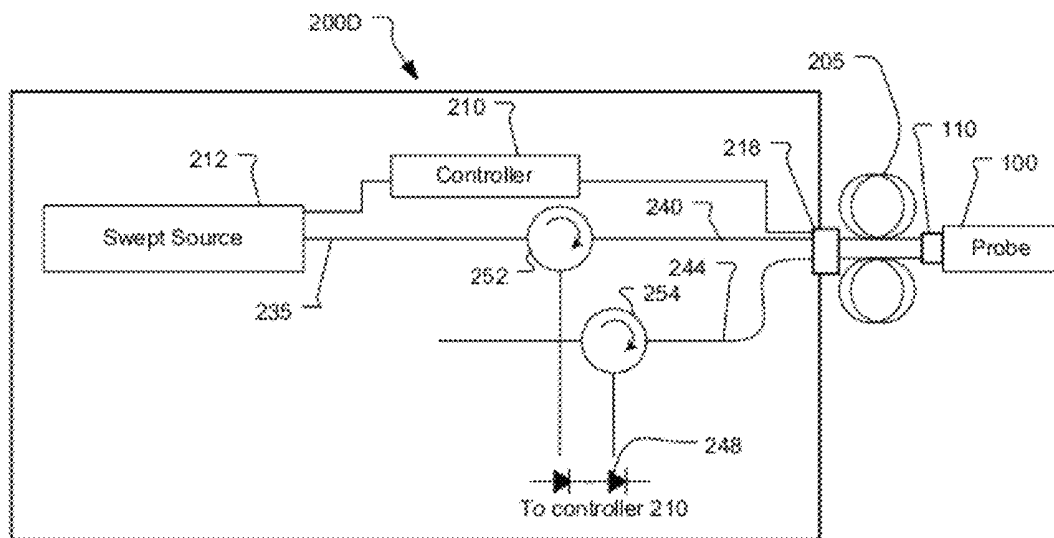


Fig. 7

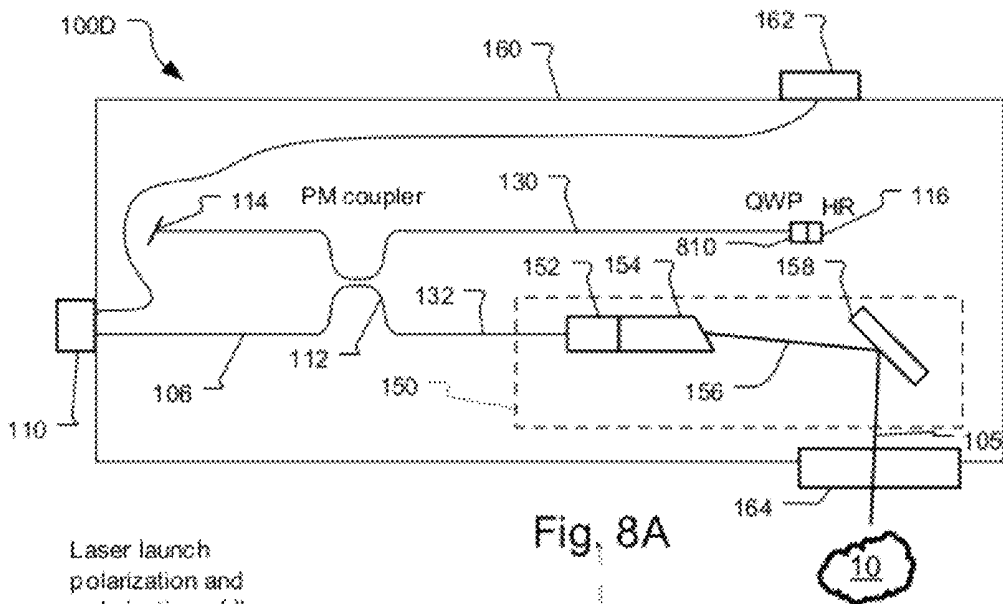


Fig. 8A

Laser launch polarization and polarization of  $\parallel$  return

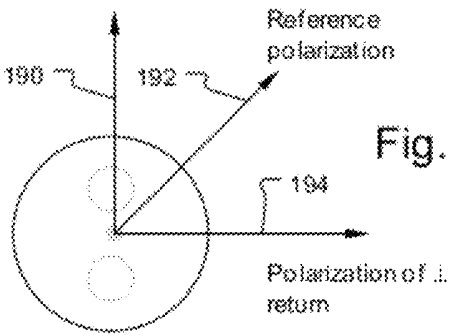


Fig. 8B

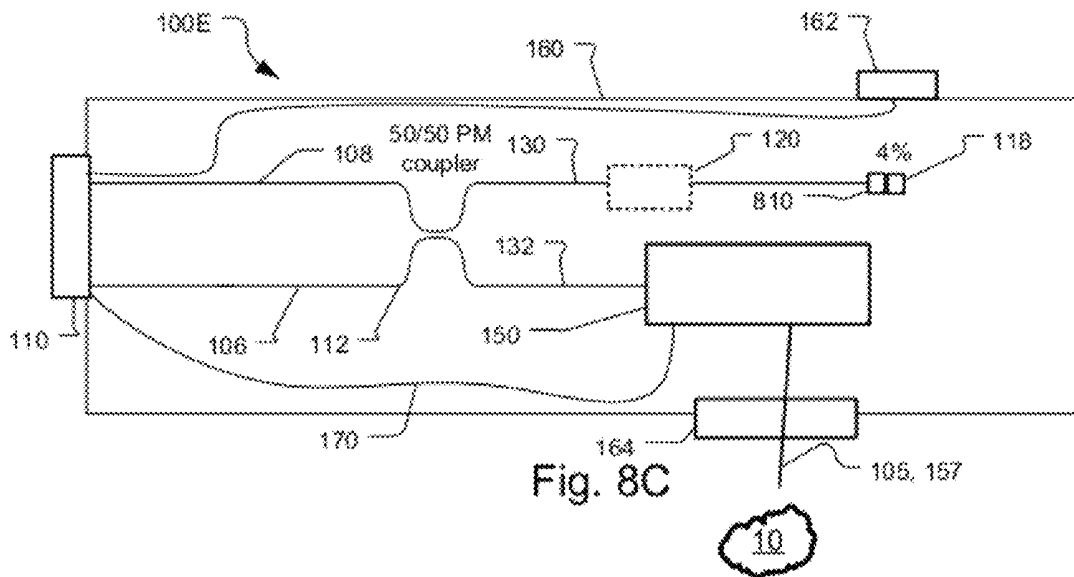


Fig. 8C

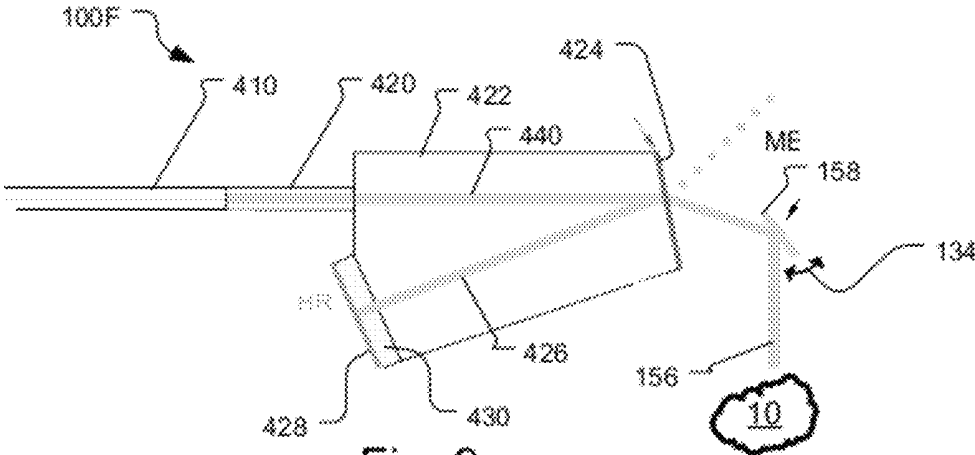
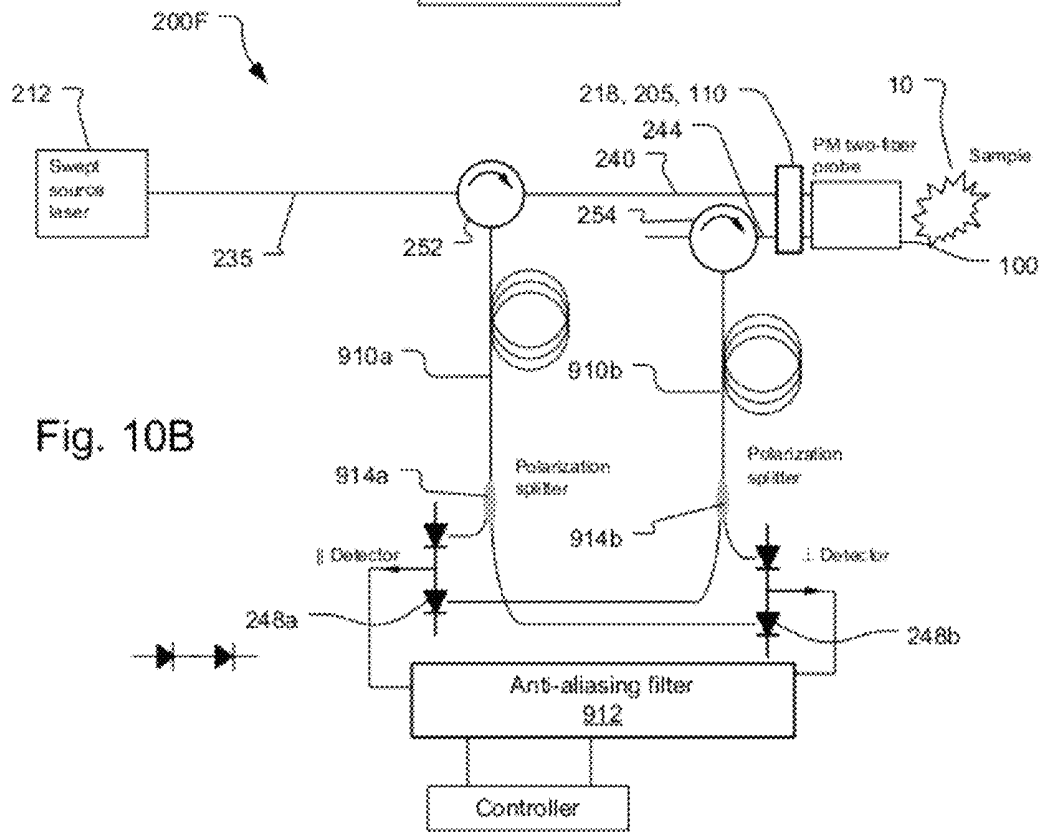
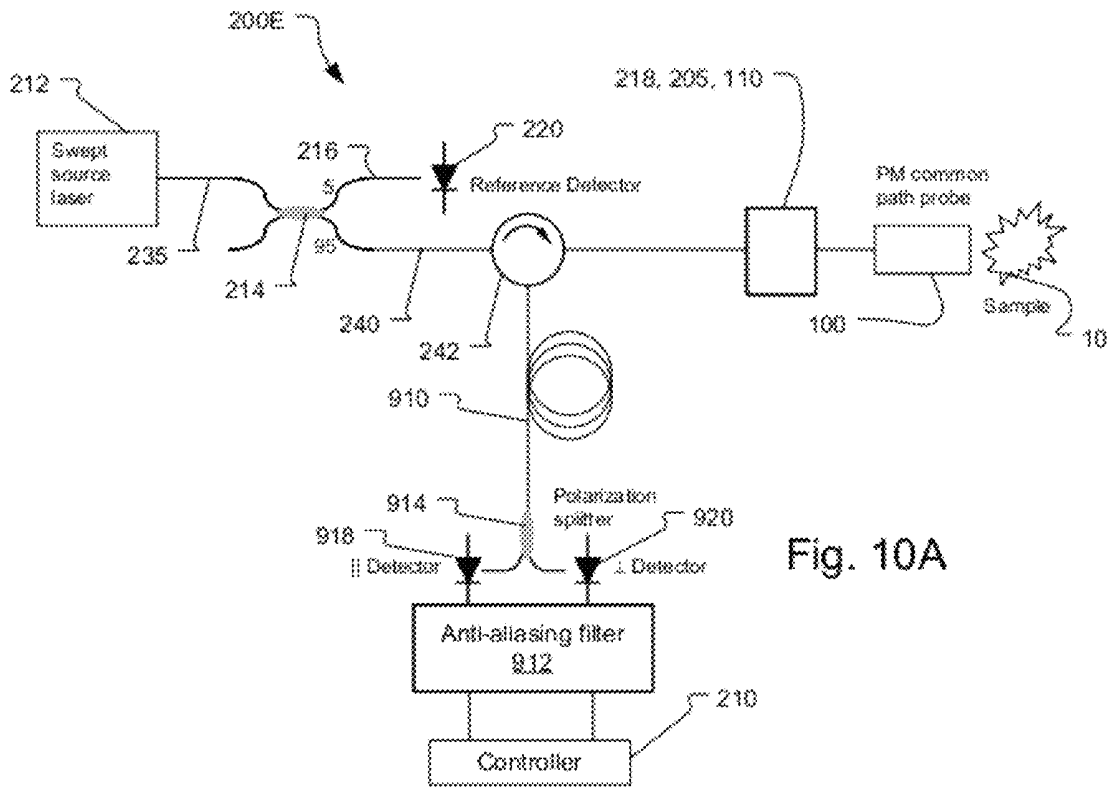


Fig. 9



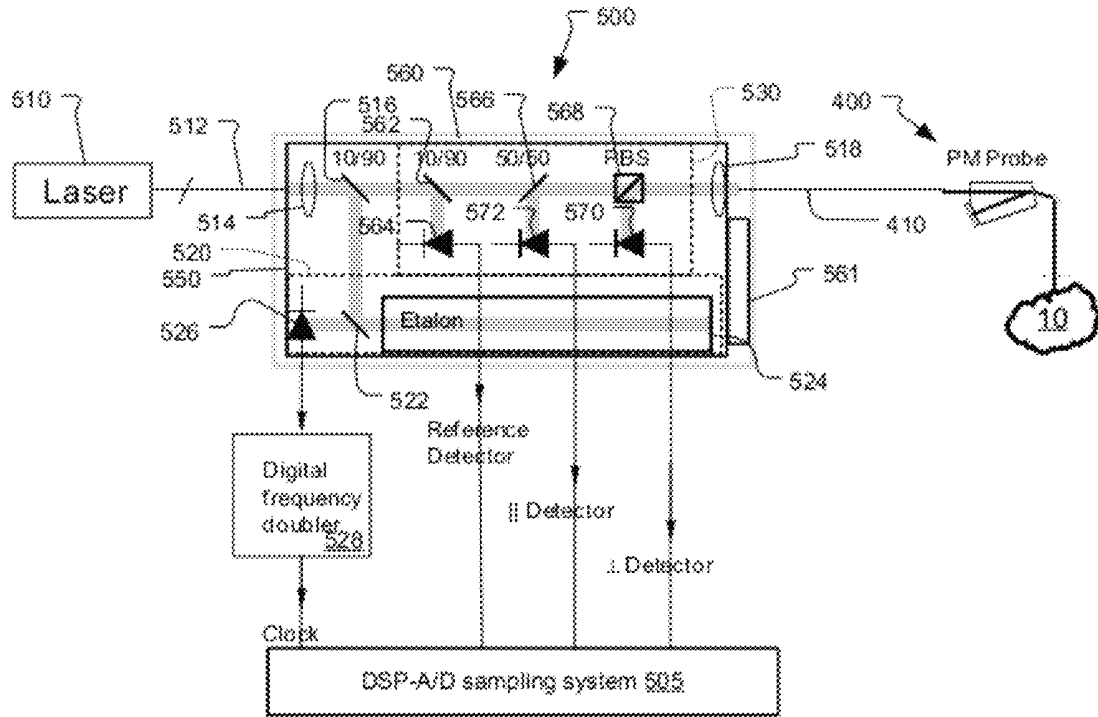


Fig. 11A

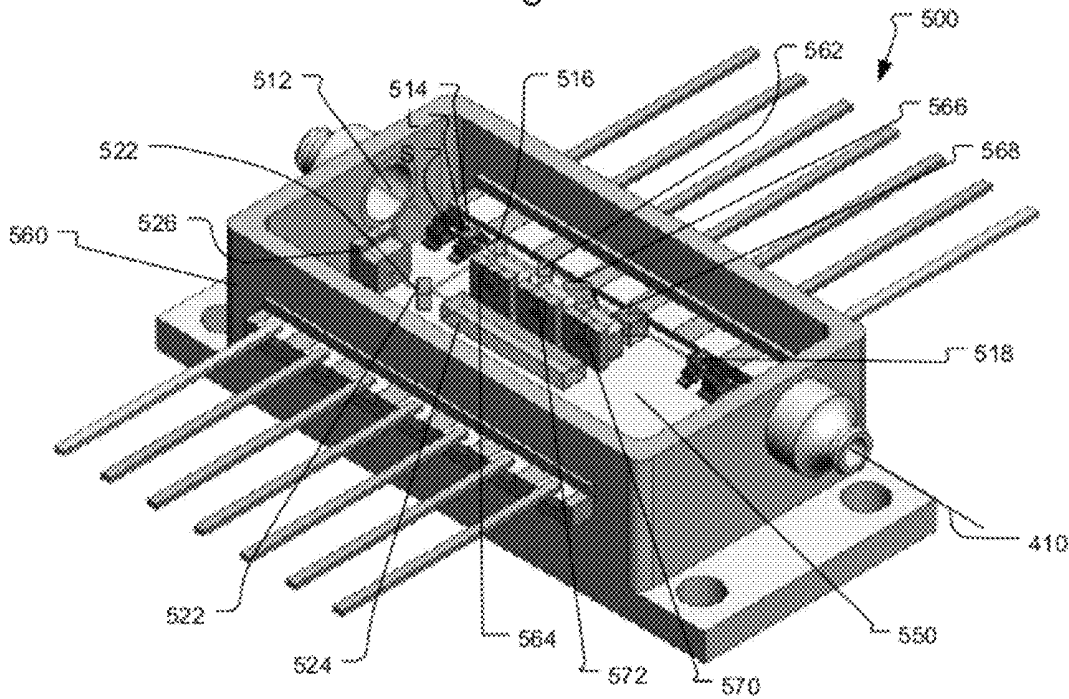


Fig. 11B

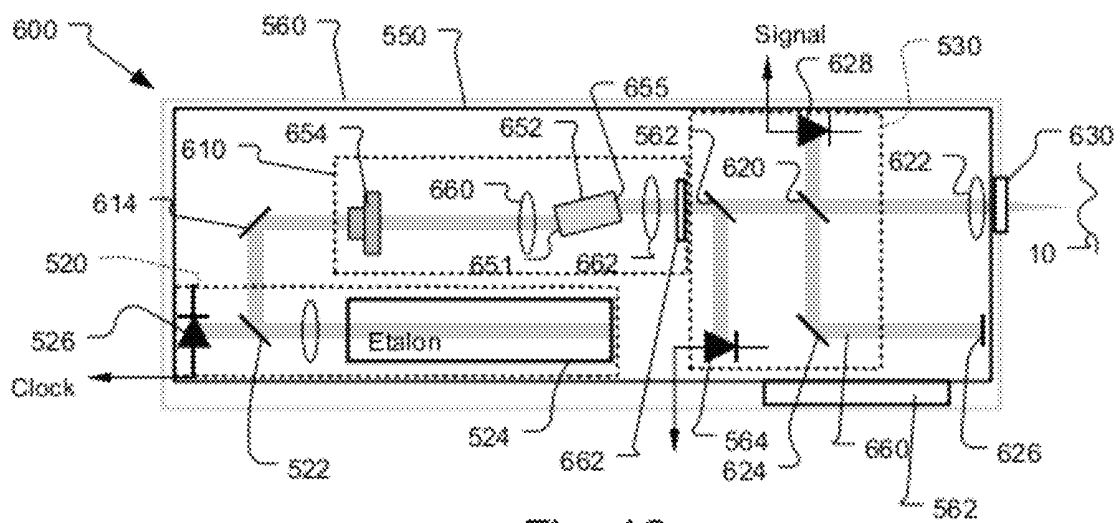


Fig. 12

# INTEGRATED OPTICAL COHERENCE ANALYSIS SYSTEM

## RELATED APPLICATIONS

This application is a Divisional of U.S. application Ser. No. 12/466,993, filed on May 15, 2009, which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application No. 61/053,241, filed on May 15, 2008, both of which are incorporated herein by reference in their entirety.

This application is related to U.S. Continuation application Ser. No. 13/568,507, filed on Aug. 7, 2012, by Bartley C. Johnson et al., entitled "OCT Combining Probes and Integrated Systems," now U.S. Patent Publication No. US 2012/0300215 A1, which is incorporated herein by reference in its entirety.

## BACKGROUND OF THE INVENTION

Optical coherence analysis relies on the use of the interference phenomena between a reference wave and an experimental wave or between two parts of an experimental wave to measure distances and thicknesses, and calculate indices of refraction of an object of interest. Optical Coherence Tomography (OCT) is one example technology that is used to perform usually high-resolution cross sectional imaging that can provide images of objects such as biological tissue structures, for example, on the microscopic scales in real time. Optical waves are sent through an object and a computer produces images of cross sections of the object by using information on how the waves are changed.

The original OCT imaging technique is the time-domain OCT (TD-OCT), which uses a movable reference mirror in a Michelson interferometer arrangement. Another type of optical coherence analysis is termed Fourier domain OCT (FD-OCT). Other terms are time encoded Frequency Domain OCT and swept source OCT. These techniques use either a wavelength swept source and a single detector, sometimes referred to as time-encoded FD-OCT or TEFD-OCT, or a broadband source and spectrally resolving detector system, sometimes referred to spectrum-encoded FD-OCT or SEFD-OCT. FD-OCT has advantages over time domain OCT (TD-OCT) in speed and signal-to-noise ratio (SNR).

TEFD-OCT has advantages over SEFD-OCT in some respects. The spectral components are not encoded by spatial separation, but they are encoded in time. The spectrum is either filtered or generated in successive frequency steps and reconstructed before Fourier-transformation.

Probe design is an important aspect of OCT system design, especially on systems that are intended to analyze the human body, such as medical diagnostic systems. On one hand, the probes must be mechanically robust to withstand use and possibly repeated use by medical care delivery personnel such as doctors, nurses and technicians in clinical settings. The probes should also be robust against noise generated from the use in their intended application. For example, OCT probe systems for intravascular analysis applications are typically long, extending from at least the point of access, such as the femoral artery to the coronary or carotid artery that is to be scanned. Moreover, the probes are often spun at high speed within a sheath while being pulled-back through the artery section of interest to generate a cylindrical scan. Any concomitant mechanical stress on the fiber can induce length changes and birefringence due to twisting. Probes for dental applications typically include a long umbilical that connects the handpiece/optical interface

to the OCT analysis system or console; noise introduced in the OCT analysis due to mechanical shock to both the umbilical and handpiece/optical interface should be minimized.

## SUMMARY OF THE INVENTION

The present invention concerns probe and OCT system designs that minimize noise and interference due to the effects of mechanical movement and strain on the OCT system. It also concerns optical designs that are robust against amplitude noise from the OCT laser source. In embodiments, this is achieved by combining the OCT signals from the reference arms and signals arms of the OCT interferometer in the handpiece itself. This combining is performed by fiber couplers that are easily integrated into compact handpieces and connected to scanning units and fiber reference arms. Thus, noise due to movement and stress to the system, such as to the umbilical that connects the analysis system to the probe, does not corrupt the OCT analysis and/or image since the noise is common and does not appear on only the reference or signal arms of the interferometer. In examples, amplitude referencing is performed and delay matched to the interference signals to compensate for the optical delay associated with the umbilical and other components. Also integrated OCT system-probes are included that yield compact and robust electro-opto-mechanical systems along with polarization sensitive OCT systems.

In general, according to one aspect, the invention features, an optical coherence tomography probe, comprising: a handpiece housing; an optical window in the handpiece housing; a reference arm reflector in the handpiece housing; an interference signal fiber coupler in the handpiece housing that receives an optical coherence tomography (OCT) signal from an OCT analysis system and divides the OCT signal between a reference optical fiber arm and a signal optical fiber arm; and an optical window in the handpiece housing through which the OCT signal from the signal optical fiber arm is transmitted to an object of interest and through which an object OCT signal is received from the object of interest and coupled into the signal optical fiber arm. The object OCT signal is mixed or combined with the OCT signal from the reference optical fiber arm that is reflected by the reference arm reflector to generate an interference signal that is transmitted from the handpiece housing to the OCT analysis system.

In general according to another aspect, the invention features an optical coherence tomography method. This method comprises receiving an OCT signal from an OCT analysis system in an interference signal fiber coupler located within a handpiece housing and dividing the OCT signal between a reference optical fiber arm and a signal optical fiber arm, transmitting the OCT signal on the signal optical fiber arm from the handpiece housing to an object of interest and receiving an object OCT signal from the object of interest into the handpiece housing and coupling the object OCT signal onto the signal optical fiber arm, combining the object OCT signal with the OCT signal from the reference optical fiber arm to generate an interference signal, and transmitting the interference signal from the handpiece housing to the OCT analysis system.

In general, according to still another aspect, the invention features an optical coherence tomography system. This system comprises a swept source laser for generating the OCT signal that is transmitted to a handpiece, a detector system that detects the interference signal received from the

handpiece and a controller that uses the response of the detector system to generate an image of an object of interest.

In general, according to another aspect, the invention features, an integrated optical system for detecting an interference signal generated by an OCT probe. The integrated optical system comprises an hermetic package, an optical bench in the hermetic package, a detector system attached to the bench for detecting the interference signal, and a beam splitter system attached to the bench that couples an OCT signal from a swept laser source to the OCT probe and couples the interference signal from the OCT probe to the detector system.

In general, according to another aspect, the invention features, an integrated OCT system. The system comprises a hermetic package having an optical window, an optical bench in the hermetic package, a swept source laser system attached to the optical bench for generating an OCT signal, a detector system attached to the bench for detecting an interference signal. A beam splitter system is attached to the bench that couples the OCT signal from the swept laser source through the optical window to an object of interest, couples a portion of the OCT signal to a reference arm, couples light returning from the reference arm to the detector system, and directs light returning from the object of interest to the detector system.

The above and other features of the invention including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale; emphasis has instead been placed upon illustrating the principles of the invention. Of the drawings:

FIG. 1 is a schematic view of an optical coherence tomography (OCT) probe according to a first probe embodiment of the present invention;

FIG. 2 is a schematic view of an OCT probe according to a second probe embodiment of the present invention;

FIG. 3 is a schematic view of an OCT probe according to a third probe embodiment of the present invention;

FIG. 4 is a schematic view of an OCT system according to a first system embodiment of the present invention;

FIG. 5 is a schematic view of an OCT system according to a second system embodiment of the present invention;

FIG. 6 is a schematic view of an OCT system according to a third system embodiment of the present invention;

FIG. 7 is a schematic view of an OCT system according to a fourth system embodiment of the present invention;

FIG. 8A is a schematic view of an OCT probe that provides for polarization sensitivity according to a first polarization probe embodiment of the present invention;

FIG. 8B illustrates the polarization of input signal, reference signal and return signals;

FIG. 8C is a schematic view of an OCT probe that provides for polarization sensitivity according to a second polarization probe embodiment of the present invention;

FIG. 9 is a plan view of the optical components of an OCT probe including an integrated reference path;

FIG. 10A is a schematic view of a polarization sensitive OCT system according to a first polarization system embodiment of the present invention;

FIG. 10B is a schematic view of a polarization sensitive OCT system according to a second polarization system embodiment of the present invention;

FIG. 11A is a schematic plan view of an integrated OCT engine according to the present invention;

FIG. 11B is a perspective view of the integrated OCT engine according to the present invention; and

FIG. 12 is a schematic plan view of an integrated OCT engine/probe according to the present invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows an optical coherence tomography (OCT) probe **100A** that has been constructed according to the principles of the present invention (first probe embodiment).

Generally, the probe **100** comprises a handpiece housing **160**. This handpiece housing is typically grasped by an operator of the OCT system. It is characterized by a rigid portion that connects to an OCT analysis unit by an intervening flexible or articulated umbilical.

The housing **160** comprises an optical window element **164**, which is typically tilted and anti-reflection coated to prevent spurious reflection back into the OCT system. This optical window element **164** is transmissive to the optical frequencies at which the OCT system operates. In one example, the OCT system operates in the near infrared. In some embodiments, the optical window **164** is also transmissive to visible optical frequencies to enable a visible targeting beam to pass through the window to indicate where the non-visible infrared OCT signal is impinging on the object of interest **10**.

The handpiece **160** in one implementation includes an electro-optical connector **110**. This electro-optical probe connector **110** enables operator connection to and disconnection from an OCT analysis system. In one example, the electro-optical probe connector **110** provides the OCT and interference signals between the probe system **100** and the analysis system along with electrical control signals.

In other embodiments, the umbilical is integral with the probe such that the connector **110** is not used.

In more detail, the OCT signal, such as light from a swept source laser, is received from the OCT analysis system via the connector **110** and coupled onto an OCT/interference signal optical fiber **106**. The OCT/interference signal fiber **106** couples the OCT signal received from the OCT analysis system to an interference/OCT signal coupler **112**. In one example, the interference/OCT signal coupler **112** is a 90/10 percent fiber coupler, and thus does not divide the light evenly between the two output ports. Specifically, the interference/OCT signal coupler **112** provides the OCT signal received on the OCT/interference signal fiber **106** to a reference arm optical fiber **130** and a signal arm optical fiber **132**, with most of the light, i.e., 90% or greater, in this current example, on the signal arm optical fiber **132**.

The reference arm optical fiber **130** forms the reference arm of an interferometer that is implemented, preferably entirely, within the handpiece housing **160**. Specifically, the reference arm optical fiber **130** terminates in a reflector **116**. In one example, the reflector **116** is simply a highly reflective coating at the end of the reference arm optical fiber **130**. Exemplary highly reflective coatings include dielectric stack

coatings and metalized endfacet coatings that are deposited on the endfacet of the reference arm optical fiber 130. In other examples, the reflector 116 is implemented as a discrete mirror element, and possibly including a discrete lens to collimate and couple light between the endfacet of the reference arm optical fiber 130 and the mirror reflector.

The signal arm optical fiber 132 transmits the received OCT signal to a scanning unit 150. The scanning unit 150 couples the OCT signal between the object of interest 10 and the signal arm optical fiber 132.

In the illustrated embodiment, the scanning unit 150 comprises an optional glass or transmissive spacer 152 that is secured to the endfacet of the signal arm optical fiber 132. This spaces the endfacet of the signal arm optical fiber 132 from a GRIN (graded refractive index) lens element 154, which has an angled output facet to prevent parasitic reflections. The GRIN lens 154 focuses the OCT signal from the signal arm optical fiber 132 onto the sample 10. The free-space light beam 156 is directed to a fold mirror 158 that directs the OCT signal beam 156 through the optical window 164 to the object of interest 10. Then light returning from the object of interest 10 is coupled back through the optical window 164 to reflect off of the fold mirror 158 and be coupled back into the signal arm optical fiber 132 via the GRIN lens 154 and the spacer element 152.

In a preferred embodiment, the fold mirror 158 is a scanning mirror. Specifically, it is driven to both tip and tilt in the x and y axes as indicated by arrow 134. In one implementation, this is a micro electro mechanical system (MEMS) mirror that scans the OCT signal beam 156, such as raster scans, over the object of interest 10 in order to generate a three-dimensional image of the object of interest 10.

In the typical embodiment, the handpiece housing 160 also supports one or more electrical control switches 162. These control switches 162 are coupled to the OCT analysis system via the opto-electrical connector 110 via control line 170. The switches are used by the operator to begin and end OCT scanning and activate a visible targeting laser during the OCT analysis of the object of interest 10. Preferably, the switches 162 are also used to electronically drive and control the scanning mirror 158.

The light returning from the object of interest 10 on the signal arm optical fiber 132 is combined with the light returning from the reflector 116 on the reference arm optical fiber 130 in the interference/OCT signal coupler 112. This combination generates the interference signal that is transmitted to the OCT analysis system on the OCT/interference signal optical fiber 106 via the electro-optical connector 110.

Since the typical fiber coupler is a four port system, some interference signal light is also coupled onto the fourth arm that terminates in the termination 114. This light is lost in this exemplary embodiment. Otherwise, a three-port coupler is used in other implementations. The length of the reference arm optical fiber 130 is important to control the scanning depth in the object. Specifically, the length of the reference arm optical fiber 130 is sized so that plane 175 is the zero distance virtual reference plan of the OCT system. Thus, the optical path length of the reference arm optical fiber 130 is made equal to the sum of the optical path lengths of the signal arm optical fiber 132, transmissive spacer 152, GRIN lens element 154, and the free space path to the reference plane 175, including window 164.

The probe 100 in some sense a "common path" probe, with one fiber connection back to the OCT system. It would typically be used with some sort of relative intensity noise (RIN) reduction system. One option is to use a balanced

receiver to accept input from the probe in one detector and a laser amplitude signal in the other (US2009/0046295 A1, Kemp, et al., Feb. 19, 2009, FIG. 13). Another option is to ratio the probe signal with that of a laser power monitor (Normalization detection scheme for high-speed optical frequency-domain imaging and reflectometry, Suchei Moon and Dug Young Kim, 12 Nov. 2007/Vol. 15, No. 23/OPTICS EXPRESS 15129).

FIG. 2 shows a second embodiment of the OCT probe 100B. This embodiment is generally similar to the first probe embodiment but uses two OCT/interference signal fibers 106, 108 to optically connect the OCT probe 100 to the OCT analysis system. This probe is compatible with standard balanced receiver/relative intensity noise (RIN) reduction scheme, and would also suppress autocorrelation artifacts from the sample signal interfering with itself.

In more detail, the OCT signal from the OCT analysis system is received via the electro-optical connector 110 typically through a flexible umbilical on a first OCT/interference signal fiber 106 and a second OCT/interference signal fiber 108, or only one of these fibers.

The light is then coupled to via a 50/50 interference/OCT signal coupler 112 between the reference arm optical fiber 130 and the signal arm optical fiber 132.

The OCT signal on the reference arm optical fiber is transmitted to a partial reflector 118. In one example, this partial reflector reflects back less than 10%, such as 4% or less, of the OCT signal light that carried on the reference arm optical fiber 130. In one example, this partial reflector 118 is implemented as a dielectric stack or metal coating on the endfacet of the optical fiber 130.

Light on the signal arm optical fiber 132 is transmitted to the scanning unit 150. This directs the light as described previously through the optical window 164 to the object of interest 10. Returning light in turn passes through the optical window 164 and is coupled by the scanning unit 150 to the signal arm optical fiber 132.

The OCT signal returning on the reference arm optical fiber 130 and the light from the object of interest returning on the signal arm optical fiber 132 is combined in the 50/50 interference/OCT signal coupler 112. This combination generates the interference signal that is transmitted back to the OCT analysis system on the first and second OCT/interference signal fibers 106, 108 via the electro-optical connector 110.

FIG. 3 shows a third embodiment of the OCT probe system 100C. This embodiment is similar to the second embodiment OCT probe system of FIG. 2. The difference lies in the configuration of the reference arm. In this example, the reference arm optical fiber 130 includes an attenuator 120 that attenuates the OCT signal carried on the reference arm optical fiber 130. The light passing through the attenuator 120 is then reflected by a highly reflecting endfacet 116. This highly reflecting end facet is typically implemented as described in connection with the first probe embodiment of FIG. 1. The OCT light returning from the reflector 116 passes through the attenuator 120 and then on the reference arm optical fiber 130 to the interference/OCT signal coupler 112.

The potential problem associated with the embodiment of FIG. 2 is dissipating the light that is transmitted through the partial reflector 118. This transmitted light is then potentially within the handpiece housing 116 and can potentially serve as an interference source: either being coupled back into the reference arm optical fiber 130 creating multipath interference or possibly interfering with the OCT signal that is transmitted to and from the object of interest 10. This

potential problem is addressed in the embodiment of FIG. 3 by using the attenuator 120 to absorb the excess OCT signal light in the reference arm to ensure that it does not create interference. In examples, the attenuator 120 is a lossy element that is implemented by fiber microbending, through a lossy fiber splice, or other means.

FIG. 4 illustrates an OCT analysis system 200A that is compatible with the OCT probe of FIG. 1. Specifically, the OCT analysis system 200A provides electrical and optical connection to the probe 100 via a typically flexible or articulated umbilical 205. Specifically, this umbilical extends between an OCT analysis system electro-optical connector 218 and the probe connector 110. This flexible umbilical 205 allows the reference probe 100 to be moved around the object of interest, such as the patient, to enable analysis of regions of interest of the patient, such as the patient's teeth or skin in some examples.

The OCT signal receive by the probe 100 is generated in the preferred embodiment by a swept laser source 212. An exemplary source is that described in U.S. patent application Ser. No. 12/396,099, filed on 2 Mar. 2009, entitled Optical Coherence Tomography Laser with Integrated Clock, by Flanders, et al., which is incorporated herein by this reference.

The OCT signal generated by the swept source laser is transmitted to a 50/50 OCT/amplitude reference fiber coupler 214 on a swept source optical fiber 235. The 50/50 coupler 214 divides the OCT signal from the swept source 212 between an amplitude reference fiber 216 and the OCT probe optical fiber 240. This OCT probe optical fiber 240 transmits the OCT signal from the 50/50 coupler 214 to the unit connector 218. Similarly, the returning interference signal from the reference probe 100 is received via the unit connector 218 on the probe optical fiber 240 and is then divided by the 50/50 OCT/amplitude reference fiber coupler 214.

The path match optical fiber 216 has a length that corresponds to twice the optical delay between the OCT/amplitude reference fiber coupler 214 and the reference probe 110 plus the delay from coupler 214 to interference signal photodiode detector 230. In this way, the delay induced by the path match optical fiber is consistent with the combined delay associated with OCT signal to the probe 100 and the interference signal returning on optical fiber 240 from the probe. The OCT signal light transmitted through the path match optical fiber 216 is then detected by an amplitude reference photodiode detector 220 which is then sampled by the controller 210 and used to remove amplitude noise in the system from the swept source 212.

The interference signal returning from the OCT probe 100 and received on OCT probe optical fiber 240 is transmitted through the 50/50 OCT/amplitude reference fiber coupler 214 to the interference signal detector 230. This detector detects that light which is then sampled by the controller 210.

In one example, the amplitude reference detector 220 and the interference detector 230 are combined into a balanced detector system for rejection of the amplitude noise from the swept source 212 in the interference signal. In this case, the optical power levels at the two detectors need to be balanced (For example, see a similar RIN reduction scheme in US2009/0046295 A1, Kemp, et al., Feb. 19, 2009, FIG. 13). Alternately, the signal from the amplitude reference detector 220 can be digitally divided in the controller 212, for example, by the interference signal from detector 230 for RIN reduction (Normalization detection scheme for high-speed optical frequency-domain imaging and reflectometry,

Sucbei Moon and Dug Young Kim, 12 Nov. 2007/Vol. 15, No. 23/OPTICS EXPRESS 15129).

FIG. 5 illustrates a second system embodiment 200B of the OCT analysis system that is also compatible with the probe of FIG. 1. This system makes more efficient use of the available optical power, but has more expensive components.

The second embodiment 200B uses an unbalanced OCT/amplitude reference fiber coupler 214 to divide the OCT signal from the swept source 212 between the amplitude reference path match fiber 216 and OCT probe optical fiber 240. The OCT signal light on the OCT probe optical fiber 240 passes through interference signal circulator 242 to be transmitted to the reference probe 100 via the unit electro-optical connector 218. In turn, the interference signal returning from the reference probe 100 is directed by the circulator 242 to interference signal detector 230.

The use of the circulator 242 leads to a more optically efficient system relative to FIG. 4 since the 95/5% OCT/amplitude reference fiber coupler 214 of this embodiment allows most of the OCT signal, greater than 90% and preferably 95% or more, generated by the swept source 212 to be directed to the object of interest with only a small amount being used to generate the amplitude reference.

FIG. 6 illustrates a third embodiment 200C of the OCT analysis system that is compatible with the probes of FIGS. 2 and 3. In this example, the OCT signal generated by the swept source 212 is transmitted on swept source optical fiber 235 to interference signal circulator 242 and then on OCT probe optical fiber 240 to the optical probe 100 via the unit connector 218. The interference signal from the OCT probe is then received on interference signal optical fiber 244 and the OCT probe optical fiber 240. The returning interference signal light on OCT probe optical fiber 240 is directed by the interference signal circulator 242 to the balanced detector 248. The interference signal received on the interference signal optical fiber 244 is directly coupled to the balanced detector 248.

The balanced receiver reduces the effect of RIN on the system's signal-to-noise ratio. The common-path probe systems in FIGS. 4 and 5 also have methods to reduce the effects of RIN. A major advantage of the two-fiber probe (FIGS. 2 and 3) and the corresponding system (FIG. 6) is that the autocorrelation image (sample light interfering with itself) is strongly attenuated.

In implementations, the balanced receiver 248 is an auto-balanced receiver (one example is manufactured by New Focus. Part number 2017), which automatically balances the electrical signals from the two detectors even in the presence of mismatched lightwave signals impinging on the two detectors.

FIG. 7 illustrates a variant, fourth embodiment 200B of the OCT system that uses two circulators 252, 254 for the two fiber probe embodiments. This configuration is similar to that in FIG. 6, except that it incorporates a "dummy" circulator 254 (one port not used) to help balance the lightwave signals present at the two detectors of the balanced receiver 248. If closely matched, the interference signal circulators 252, 254 will have similar optical losses vs. wavelength and balance the lightwave signals to the two detectors. A better match provides improved signal-to-noise performance and attenuation of the autocorrelation image. Better matching by the additional circulation may be preferred to the use of an autobalanced detector for cost and performance reasons.

FIG. 8A illustrates a first polarization sensitive embodiment 100D of the OCT probe 100. Generally, this OCT

probe is similar to the first probe embodiment of FIG. 1, thus, the descriptions associated with FIG. 1 are relevant here. This probe 100D, however, allows for polarization dependent or sensitive OCT analysis. Specifically, it enables the analysis of the OCT signal and the polarization characteristics of the object of interest 10.

In more detail, the OCT signal received on the OCT/Interference signal fiber 106 is a highly polarized signal such as a signal from a semiconductor external cavity laser system. To preserve polarization, the OCT/Interference signal fiber 106 is polarization maintaining optical fiber.

Specifically, as illustrated in FIG. 8B, the polarization of the swept source OCT signal is polarized according to one, slow, axis of the polarization maintaining (PM) fiber 106 that is used for the OCT/Interference signal fiber 106. See polarization 190.

The polarized OCT signal is divided by the interference/OCT signal coupler 112, which is a 50/50 polarization-maintaining coupler. The polarized OCT light is transmitted over the reference arm optical fiber 130, which is PM fiber, to the reflector 116. In this embodiment, there is an intervening quarter wave plate 810. This rotates the polarization of the light by  $22\frac{1}{2}$  degrees. As a result, the returning OCT signal light has both a portion that is polarized parallel to the input OCT signal but also perpendicular to the input OCT signal, see polarization 192 in FIG. 8B.

The OCT light that is transmitted through the PM interference/OCT signal coupler 112 onto the signal arm optical fiber 132, which is PM optical fiber, is directed to the object of interest 10 as described previously via the scanning system 150.

Light returning from the object of interest 110, however, now is potentially polarized according to the birefringence properties of the object of interest 10 and thus will have polarizations aligned along axis 190 and also fast axis 194, see FIG. 8B. Thus, the signal light returning from the object of interest 10 is then combined with the two polarizations returning from the reference arm optical fiber 130 by the PM coupler 112. Thus, this light then returns on the OCT signal/interference signal optical fiber 106 to the OCT analysis system. Interference signal now has two polarizations allowing for the polarization dependent OCT analysis of the object of interest.

FIG. 8C shows a second embodiment polarization sensitive probe 100E that is analogous to the two fiber probes of FIGS. 2 and 3 and is compatible with standard balanced receiver/relative intensity noise (RIN) reduction scheme, and would also suppress autocorrelation artifacts from the sample signal interfering with itself.

In more detail, the OCT signal from the OCT analysis system on a first OCT/interference signal fiber 106 and a second OCT/interference signal fiber 108, or only one of these fibers. These fibers are PM fiber.

The light is then coupled to via a 50/50 interference/OCT signal PM fiber coupler 112 between the reference arm optical fiber 130 and the signal arm optical fiber 132, which are both constructed of PM fiber.

The OCT signal on the reference arm optical fiber 130 is transmitted to a partial reflector 118. In one example, this partial reflector reflects back less than 10%, such as 4% or less, of the OCT signal light that carried on the reference arm optical fiber 130. Alternatively, attenuator 120 is used in combination with a highly reflecting reflector. In either case, the intervening quarterwave plate 810 shifts the polarization so that the returning OCT signal now has component polarizations along each axis of the PM fiber.

Light on the signal arm PM optical fiber 132 is transmitted to the scanning unit 150. This directs the light as described previously through the optical window 164 to the object of interest 10. Returning light in turn passes through the optical window 164 and is coupled by the scanning unit 150 to the signal arm PM optical fiber 132.

The OCT signal returning on the reference arm optical fiber 130 and the light from the object of interest returning on the signal arm optical fiber 132 is combined in the 50/50 interference/OCT PM fiber coupler 112. This combination generates the interference signal for each polarization that is transmitted back to the OCT analysis system on the first and second OCT/interference PM fibers 106, 108 via the electro-optical connector 110.

FIG. 9 illustrates an OCT probe 100F that includes an integrated reference arm. In this example, the OCT signal from the swept source laser is transmitted on an OCT/Interference signal optical fiber 410. The OCT signal is coupled to the probe body 422. In a preferred implementation, an intervening graded index fiber 420 connects the OCT/Interference signal optical fiber 410 to the probe body 422. The graded index fiber 420 collimates the OCT signal so that the beam 440 that is transmitted through the optical probe body 422 is collimated. The light passes through interface 424 to be directed to a scanning fold mirror 158, which scans see arrow 134. This allows the OCT signal beam 156 to be scanned over the object of interest 10.

Light returning from the object of interest is directed by the scanning fold mirror 158 through interface 424 to be directed back into the OCT/interference signal fiber 410 via the graded index fiber 420.

The probe body 422 includes an integrated reference arm. Specifically, the interface 424 is a partial reflector so that a portion, typically less than 10%, of the OCT signal beam 440 is directed to a reference arm that is within the transmissive probe body 422 to be directed to an interface 428 that has a high reflecting coating on it. This reflects light back to the interface 422 to mix or combine with the light returning from the object of interest to generate the interference signal that is then coupled via the graded index fiber 420 to the OCT/Interference signal fiber 410.

In one embodiment, this integrated OCT probe performs polarization dependent OCT analysis. In this example, a quarterwave plate 430 is attached to the probe body 422 to the interface 428 to rotate the light so that the light is now polarized along both axes. The OCT/interference signal fiber 410 is then polarization maintaining fiber.

FIG. 10A shows a first embodiment of a swept source polarization sensitive OCT system 200E that is compatible with the polarization sensitive, common path probes of FIGS. 8A and 9. In this embodiment, all of the optical fibers in the system are polarization maintaining.

In more detail, the swept source laser 212, provides a linearly polarized output aligned to the slow axis of the PM fiber of the system and specifically the PM fiber used for the swept source optical fiber 235. The OCT/amplitude reference fiber coupler 214 is similarly a PM fiber coupler that divides light between the amplitude path match fiber 216 and the OCT probe PM fiber 240. Preferably the OCT/amplitude reference fiber coupler 214 is an unbalanced coupler so that most of the OCT signal is transmitted to the sample, i.e., greater than 90% and preferably 95% or more. The OCT signal light on the OCT probe optical fiber 240 passes through interference signal circulator 242 to be transmitted to the reference probe 100 via the OCT probe optical fiber 240 and potentially a unit optical connector 218, umbilical 205, and probe connector 110.

In turn, the interference signal returning from the reference probe **100** is directed by the circulator **242** through a length of detector PM optical fiber **910**. This fiber has a long length so that mixing of the parallel polarized light and the perpendicular light occurs at a frequency that is cut by an anti-aliasing filter **912** between the optical detectors **918**, **920** and the analog-to-digital converters of the controller **210** that are used to sample the detector signals. For example, if the anti-alias filter removes any OCT image information at displacements greater than 5 mm, the fiber must be long enough that returns for the slow and fast axis light are separated >5 mm over the propagation distance. A typical fiber length is tens of meters for a few m of displacement.

An interference signal polarization splitter **914**, which can be implemented with fiber-optic components or bulk optic components, separates the two signals of different polarizations and routes them to separate detectors, a parallel polarization detector **918** and a perpendicular polarization detector **920**.

The system controller **210** generates and displays two images by separately processing the interference signals of the two polarizations: One where the light scattered from the sample **10** has the same polarization as the illumination light generated by the swept source laser **212**, the parallel light; and a second image where the scattered light is polarized perpendicular to the illumination light.

FIG. **10B** shows a polarization sensitive OCT analysis system **200F** that is compatible with the polarization dependent, two-fiber probe of FIG. **8C**.

In this example, the OCT signal generated by the swept source **212** is transmitted on swept source optical fiber **235** to interference signal circulator **252** and then on OCT probe optical fiber **240** to the optical probe **100**, via potentially a unit optical connector **218**, umbilical **205**, and probe connector **110**. The interference signal from the OCT probe is then received on interference signal optical fiber **244** and the OCT probe optical fiber **240**. Returning interference signal light on OCT probe optical fiber **240** is directed by the circulator **252** to the detectors. The interference signal received on the interference signal optical fiber **244** directed to the detectors by circulator **254**.

Similar to the embodiment of FIG. **10A**, long lengths of PM fiber **910a**, **910b** are used on the optical paths to the detectors to prevent cross mixing of the parallel and perpendicular waves. On the other hand, the PM detector fibers **910a**, **910b** should have matched lengths.

A first interference signal polarization splitter **914a** separates the polarizations of the interference signal received from interference signal circulator **252**. A second interference signal polarization splitter **914b** separates the polarizations of the interference signal received from interference signal circulator **254**.

The perpendicular polarization interference signals from each splitter **914a**, **914b** are detected by a perpendicular balanced detector **248b** and the parallel polarization interference signals are detected by parallel polarization balanced detector **248a**.

This system has the RIN reduction and auto correlation image suppression properties of the polarization insensitive systems of FIGS. **2** and **3**, because of the use of balanced detection. The PM fibers **910a** and **910b** would have to be long to prevent polarization mixing as described above. They need to be roughly matched in length, so that the propagation delay difference is much less than the reciprocal of the highest electrical frequency generated in the detector systems.

FIG. **11A** shows an integrated polarization dependent OCT system **500** that has been constructed according to the principals of the present invention and is compatible with the OCT probes of FIGS. **8A** and **9**.

Generally the integrated polarization dependent OCT system **500** comprises a tunable swept source laser subsystem **510**, which generates a wavelength or frequency tunable optical signal, a clock subsystem **520**, which generates k-clock signals at spaced frequency increments as the OCT signals or emissions of the laser **510** are spectrally tuned over a spectral scan band, and a detector subsystem **530**, which includes an amplitude references and interference signal detectors. The k-clock signals are used to trigger sampling, typically in an OCT sampling analog to digital converter (A/D) system **505**.

The detector subsystem **530** and clock subsystem **520** of the integrated polarization dependent OCT system **500** are integrated together on a common optical bench **550**. This bench is termed a micro-optical bench and is typically less than 20 millimeters (mm) by 30 mm in size, and preferably less than 10 millimeters (mm) by 20 mm in size so that it fits within a standard butterfly or DIP (dual inline pin) hermetic package **560**. In one implementation, the bench is fabricated from aluminum nitride. A thermoelectric cooler **561** is preferably disposed between the bench **550** and the package **560** (attached/solder bonded both to the backside of the bench **550** and inner bottom panel of the package **560**) to control the temperature of the bench **550**.

To collect and collimate the OCT signal light exiting from polarization maintaining fiber **512** from the tunable laser **510**, an input lens structure **514** is used. Preferably, the input lens structure **514** comprises a LIGA mounting structure, which is deformable to enable post installation alignment, and a transmissive substrate in which the lens is formed. The transmissive substrate is typically solder or thermocompression bonded to the mounting structure, which in turn is solder bonded to the optical bench **550**.

The input lens structure **514** couples the light from the laser **510** to a partially reflecting 10/90 substrate that functions as input beam splitter **516**. A majority of the beam enters the detector subsystem **530** and the remaining beam is directed to the clock subsystem **520**. In one example, greater than 90% of the input beam from the laser **510** is directed to the detector subsystem **530**.

The OCT signal light is divided in the clock subsystem by a clock beam splitter **522**, which is preferably a 50/50 splitter. The clock beam splitter **522** divides the light between to a clock etalon **524** and a k-clock detector **526**. Any light not reflected by the splitter **522** is directed to a beam dump component that absorbs the light and prevents parasitic reflections in the hermetic package **560**.

The clock etalon **524** functions as a spectral filter. Its spectral features are periodic in frequency and spaced spectrally by a frequency increment, termed free spectral range (FSR), that is related to the refractive index of the constituent material of the clock etalon **524**, which is fused silica in one example, and the physical length of the clock etalon **524**. The etalon can alternatively be made of other high-index and transmissive materials such as silicon for compactness, but the optical dispersion of the material may need to be compensated for with additional processing inside the controller/DSP **505**. Also, air-gap etalons, which are nearly dispersionless, are another alternative.

The contrast of the spectral features of the etalon is determined by the reflectivity of its opposed endfaces. In one example, reflectivity at the etalon endfaces is provided by the index of refraction discontinuity between the constituent

material of the etalon and the surrounding gas or vacuum. In other examples, the opposed endfaces are coated with metal or preferably dielectric stack mirrors to provide higher reflectivity and thus contrast to the periodic spectral features.

In the illustrated example, the clock etalon **524** is operated in reflection. The FSR of the clock etalon is chosen based on the required scanning depth in an OCT system. The Nyquist criterion dictates that the periodic frequency spacing of the clock etalon that defines the sample rate be twice the largest frequency period component of the sample, thus setting the optical thickness of the clock etalon to twice the required imaging depth. However, as is typically done with clock oscillators, the periodic waveform can be electrically frequency doubled, tripled, etc, see doubler **528**, or can be halved to obtain the desired sample rate while choosing an etalon of a length that is convenient for handling and that easily fits within the package **560** and on the bench **550**. A thicker etalon compensates better for nonlinear frequency scanning than a thinner one due to its finer sample rate, but it is larger and more difficult to fabricate, so a tradeoff is made depending upon the laser tuning linearity, system depth requirements, and manufacturing tolerances. Moreover, a thicker etalon requires a laser of comparable coherence length to generate stable clock pulses, so the laser coherence length can also help dictate the design of the etalon thickness.

The light returning from the clock etalon **524** and not reflected by beamsplitter **522** is detected by detector **526**. The light detected by detector **526** is characterized by drops and rises in power as the frequency of the tunable signal scans through the reflective troughs/reflective peaks provided by the clock etalon **524**.

The detector photocurrent is amplified and conditioned. The clock signal is multiplied or divided in frequency by multiplier/divider **528**, depending on the needs of the OCT system's application and the requirement for a convenient etalon (or other clock interferometer) size within the butterfly package **560**. A digital delay line is also added to the doubler circuitry **528** in some embodiments to compensate for any round-trip optical delay to the probe **400**.

The OCT signal that is transmitted through the input beam splitter **516** enters the detector subsystem **530**. The detector subsystem **530** comprises an amplitude reference splitter **562** that directs a portion of the OCT signal, typically less than 10%, to an amplitude reference detector **564**. This detector **564** is used to detect amplitude noise in the OCT signal.

Light transmitted through the amplitude reference splitter **562** passes through a parallel detector splitter **566**, a polarization beam splitter **568** and is coupled onto OCT/Interference signal optical fiber **410** to the polarization dependent OCT probe **400** by output lens structure **518**.

The returning interference signal from the OCT probe **400** is separated into its two polarizations by the polarization beam splitter **568**. The portion of the interference signal that is perpendicular to the polarization of the OCT signal from the laser **510** is directed to and detected by a perpendicular interference signal detector **570**. The portion of the interference signal that has a polarization that is parallel to the polarization of the polarization of the OCT signal from the laser **510** and that passed through the polarization beam splitter **568** is directed by the parallel detector splitter **566** and detected by the parallel interference signal detector **572**.

The k-clock signal is used by the digital signal processing and analog-detector sampling system **505** as a sampling clock to trigger the sampling of the amplitude reference signal, the parallel detector signal, and the perpendicular

detector signal. This information is used to perform the Fourier transform to reconstruct the image of the object including a polarization dependent OCT image at the two polarizations.

FIG. **11B** shows one physical implementation of the integrated polarization dependent OCT system **500** in a butterfly package **560**. In this example, the lid of the package **560** is removed to expose the components of the bench **560**. This view also shows the LIGA structures **S** that attach the lens substrates **L** to the bench **560**.

FIG. **12** shows another integrated OCT system **600** that has been constructed according to the principals of the present invention. This system integrates the swept source **610**, k-clock system **520**, detector system **530**, and reference arm **660** on a bench **550**, and within a hermetic package **560**.

Generally the integrated laser clock system **600** comprises a tunable laser swept source subsystem **610**, which generates a wavelength or frequency tunable OCT signal, a clock subsystem **520**, which generates k-clock signals at spaced frequency increments as the tunable signals or emissions of the laser **610** are spectrally tuned over a spectral scan band, and a detector subsystem **530**. The clock signals are generally used to trigger sampling of detector system.

The tunable laser subsystem **610**, clock subsystem **520**, and the detector subsystem **530** are integrated together on a common optical bench **550**. This bench is termed a micro-optical bench and is usually less than 20 mm by 30 mm and preferably less than 10 mm by 20 mm in size so that it fits within a standard butterfly or DIP (dual inline pin) hermetic package **560**. In one implementation, the bench is fabricated from aluminum nitride. A thermoelectric cooler **562** is disposed between the bench **550** and the package **560** (attached/solder bonded both to the backside of the bench and inner bottom panel of the package **560**) to control the temperature of the bench **550**.

In more detail, the tunable laser **610** in the preferred embodiment is based on the tunable laser designs disclosed in U.S. Pat. No. 7,415,049 B2, which is incorporated herein in its entirety by this reference.

In the current implementation, the tunable laser **610** comprises a semiconductor gain chip **652** that is paired with a micro-electro-mechanical (MEMS) angled reflective Fabry-Perot tunable filter **654** to create external cavity laser (ECL) with the tunable filter **654** being an intracavity tuning element and forming one end, or back reflector, of a laser cavity of the tunable ECL.

The semiconductor optical amplifier (SOA) chip **652** is located within the laser cavity. In the current embodiment, both facets of the SOA chip **652** are angled relative to a ridge waveguide **58** running longitudinally along the chip **652** with the back facet **651** and the front facet **655** being anti-reflection (AR) coated. A partially reflecting substrate **662** provides reflectivity to define the front reflector of the laser cavity.

To collect and collimate the light exiting from each end facet of the SOA **652**, two lens structures **660**, **662** are used. Each lens structure **660**, **662** comprises a LIGA mounting structure, which is deformable to enable post installation alignment, and a transmissive substrate in which the lens is formed. The transmissive substrate is typically solder or thermocompression bonded to the mounting structure, which in turn is solder bonded to the optical bench **550**.

The first lens component **660** couples the light between the back facet of the SOA **652** and the tunable filter **654**. Light exiting out the front facet of the SOA **652** is coupled by a second lens component **662** to the detector subsystem **530**.

The angled reflective Fabry-Perot filter **654** is a multi-spatial-mode tunable filter having a curved-flat optical resonant cavity that provides angular-dependent, reflective spectral response back into the laser cavity. This effect is discussed in more detail in incorporated U.S. Pat. No. 7,415,049 B2. In the referred embodiment, the curved mirror is on the MEMS membrane and is on the side of the filter **654** that adjoins the laser cavity. The flat mirror is on the opposite side and faces the laser cavity. The flat mirror preferably has a higher reflectivity than the curved mirror. Currently the reflectivities for the flat and curved mirrors are typically 99.98% and 99.91%, respectively, in order to achieve the desired reflectivity and requisite linewidth of the filter **654** in reflection.

The light transmitted by the tunable filter **654** is coupled out of the laser cavity and into the clock subsystem **520** by fold mirror **614**, which are reflective coated substrates that are solder bonded to the bench **550**, fold the beam of the light from the tunable laser subsystem **610**, allowing for a dimensionally compact system.

The light then passes to a beam splitter **522**, which is preferably a 50/50 splitter to a clock etalon **524**. Any light transmitted by the splitter **522** is preferably directed to a beam dump component that absorbs the light and prevents parasitic reflections in the hermetic package **560** and into the laser cavity and detectors.

The light returning from the clock etalon **524** is detected by detector **526** to form the k-clock signal.

The detector subsystem **530** receives the OCT signal from the tunable laser subsystem **610**. The OCT signal passes through an amplitude reference splitter **562**, and interference/reference splitter **620**. The OCT signal is focused by an output lens **622** on the object of interest **10**. The OCT signal exits the hermetic package **560** via a transmissive window **630** that is provided in the side of the package **560**.

The OCT signal that is reflected by the interference/reference splitter **620** is directed to a reference arm **660** including reference arm fold mirror **624** to a reference arm mirror **626**.

Light returning from the reference arm mirror **624** is mixed or combined with light from the sample **10**, which is received by received by window **630** and focused by lens **622**, at interference/reference splitter **620** to form the interference signal that is detected by interference signal detector **628**.

Signal to noise ratio (SNR) improvement by reducing the effects of RIN is performed by digitally dividing the interference signal from detector **628** by the amplitude reference signal from detector **564** before FFT processing. This is a compact system for performing A-scans, but movement of the package **560** or the sample **10** would allow B-scans to be made. Additionally, a MEMS mirror scanner could be incorporated before the package's output lens to perform this function without movement of the sample or the package in some implementation.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. An integrated optical system for detecting an interference signal generated by an optical coherence tomography (OCT) probe, the integrated optical system comprising:

- a package;
- an optical bench in the package;

a detector system attached to the bench for detecting the interference signal, the detector system comprising at least one detector system beam splitter, a first interference detector for detecting a first polarization of an interference signal and a second interference detector for detecting a second polarization of the interference signal;

a polarization beam splitter system attached to the bench that receives an OCT signal from a swept source and couples the OCT signal to the OCT probe, which is external to the package, and couples the interference signal from the OCT probe to the first interference detector and the second interference detector of the detector system;

an input lens installed on the optical bench that forms a beam of the OCT signal that is transmitted through the at least one detector system beam splitter and the polarization beam splitter system; and

an output lens installed on the optical bench that receives the beam of the OCT signal from the input lens after passing through the at least one detector system beam splitter and the polarization beam splitter system.

2. A system as claimed in claim 1, further comprising an amplitude reference beam splitter attached to the bench that receives the beam of the OCT signal from the input lens prior to the OCT signal being received by a polarization beam splitter of the polarization beam splitter system, the amplitude reference beam splitter reflecting a portion of the OCT signal and an amplitude detector for detecting the portion of the OCT signal.

3. A system as claimed in claim 1, further comprising an input beam splitter attached to the bench that receives the beam of the OCT signal from the input lens prior to the OCT signal being received by a polarization beam splitter of the polarization beam splitter system, the input beam splitter reflecting a portion of the OCT signal and a k-clock optical reference attached to the bench for spectrally filtering the portion of the OCT signal and a k-clock detector, attached to the bench, for detecting the OCT signal filtered by the k-clock optical reference to generate a k-clock signal.

4. A system as claimed in claim 1, further comprising a thermoelectric cooler for controlling the temperature of the optical bench.

5. An integrated OCT system, comprising:

- a package having an optical window;
- an optical bench in the package;
- a swept source system implemented on the optical bench for generating an OCT signal, wherein the swept source system comprises a gain chip and a micro-electro-mechanical filter, which are secured to the optical bench;

a detector system attached to the bench for detecting an interference signal and comprising at least one detector system beam splitter;

an interferometer attached to the bench, the interferometer comprising a beam splitter system, a reference arm, and a signal arm, the beam splitter system receives the OCT signal from the swept source, couples a portion of the OCT signal to the signal arm and through the optical window to an object of interest, couples a portion of the OCT signal to the reference arm, and couples light returning from the reference arm and light returning from the object of interest to the detector system as the interference signal;

a first lens installed on the optical bench that forms a beam of the OCT signal that is transmitted through the

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detector system, the at least one detector system beam splitter, and the beam splitter system of the interferometer; and

an output lens installed on the optical bench that receives the beam of the OCT signal after transmission through the detector system, the at least one detector system beam splitter, and the beam splitter system of the interferometer and directs the beam onto the object of interest.

6. A system as claimed in claim 5, further comprising an amplitude detector attached to the bench for detecting a portion of the OCT signal from the swept source system.

7. A system as claimed in claim 5, further comprising a k-clock optical reference attached to the bench for spectrally filtering the OCT signal and a k-clock detector for detecting the OCT signal filtered by the k-clock optical reference to generate a k-clock signal.

8. A system as claimed in claim 5, further comprising a thermoelectric cooler for controlling the temperature of the optical bench.

9. A system as claimed in claim 5, wherein the beam splitter system comprises only a single beam splitter which is attached to the optical bench.

10. A system as claimed in claim 5, wherein the reference arm is entirely contained within the package.

11. A system as claimed in claim 5, wherein the swept source comprises a swept laser source.

12. A system as claimed in claim 5, wherein the package is a butterfly or dual inline package.

13. A system as claimed in claim 1, wherein the swept source comprises a swept laser source.

14. A system as claimed in claim 1, wherein the output lens couples the OCT signal into an optical fiber that transmits the OCT signal to the OCT probe.

15. A system as claimed in claim 1, wherein the package is a hermetic package.

16. A system as claimed in claim 1, wherein OCT signal generated by the swept source is coupled via optical fiber to the input lens installed on the optical bench.

17. A system as claimed in claim 7, wherein the k-clock signal is received by an analog to digital sampling system to trigger the sampling of the detector system.

18. A system as claimed in claim 15, wherein the hermetic package is a butterfly or dual inline package.

19. A system as claimed in claim 5, wherein the package is a hermetic package.

20. A system as claimed in claim 1, wherein the optical bench is less than 20 millimeters (mm) by 30 mm in size.

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21. A system as claimed in claim 5, wherein the optical bench is less than 20 millimeters (mm) by 30 mm in size.

22. A system as claimed in claim 1, further comprising a thermoelectric cooler disposed between the optical bench and a bottom panel of the package.

23. A system as claimed in claim 5, further comprising a thermoelectric cooler disposed between the optical bench and a bottom panel of the package.

24. A system as claimed in claim 5, wherein the window is provided on a side of the package.

25. An integrated OCT system, comprising:

a hermetic package having an optical window;

an optical bench in the package;

a swept source system implemented on the optical bench for generating an OCT signal, wherein the swept source system comprises a gain chip and a micro-electro-mechanical filter, which are secured to the optical bench;

a detector system attached to the bench for detecting an interference signal and comprising at least one detector system beam splitter;

an interferometer attached to the bench, the interferometer comprising a beam splitter system, a reference arm, and a signal arm, the beam splitter system receives the OCT signal from the swept source, couples a portion of the OCT signal to the signal arm and through the optical window to an object of interest, couples a portion of the OCT signal to the reference arm, and couples light returning from the reference arm and light returning from the object of interest to the detector system as the interference signal;

a k-clock optical reference attached to the bench for spectrally filtering the OCT signal;

a k-clock detector for detecting the OCT signal filtered by the k-clock optical reference to generate a k-clock signal;

a first lens installed on the optical bench that forms a beam of the OCT signal that is transmitted through the detector system, the at least one detector system beam splitter, and the beam splitter system of the interferometer; and

an output lens installed on the optical bench that receives the beam of the OCT signal after transmission through the detector system, the at least one detector system beam splitter, and the beam splitter system of the interferometer and directs the beam onto the object of interest.

\* \* \* \* \*

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摘要(译)

公开了光学相干断层扫描 (OCT) 探针和系统设计, 其最小化了探针对 OCT 分析的机械运动和应变的影响。它还涉及对 OCT 激光源噪声具有鲁棒性的光学设计。此外, 还集成了 OCT 系统探头, 可产生紧凑而坚固的电光机械系统以及偏振敏感的 OCT 系统。

