NRC Publications Archive Archives des publications du CNRC

Simultaneous Multi-Wavelength-Band Optical Frequency Domain Imaging for Spectroscopic Investigations

Mao, Youxin; Chang, Shoude; Murdock, Erroll; Flueraru, Costel

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien
DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1117/12.901161>

Infrared Sensors, Devices, and Applications; and Single Photon Imaging II, pp.
81551A-1-81551A-7, 2011-09-16

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=9f62c9fa-c610-4e13-be11-0677b2173964>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=9f62c9fa-c610-4e13-be11-0677b2173964>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the
first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la
première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez
pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Simultaneous Multi-Wavelength-Band Optical Frequency Domain Imaging for Spectroscopic Investigations

Youxin Mao, Shoude Chang, Erroll Murdock, and Costel Flueraru
Institute for Microstructural Sciences, National Research Council Canada,
1200 Montreal Rd, Ottawa, K1A 0R6, ON, Canada

ABSTRACT

A novel method of simultaneous multi-wavelength-band common-path optical frequency domain imaging is proposed for spectroscopic applications. Simultaneous multi-band wavelength tuning can be performed by using multiple fiber-ring cavities with corresponding optical semiconductor amplifier as their gain mediums and narrowband optical filters with a single polygonal scanner for synchronization. A simultaneous 1310/1550 dual-band swept laser source is constructed as a proof concept prototype. Broadband 1310/1550 wavelength-division multiplexing is used for coupling two wavelengths into a common-path single-mode GRIN-lensed fiber probe to form a dual-band common-path optical frequency domain imaging. Simultaneous imaging at 1310 and 1550 nm is achieved by using a depth ratio correction method. This technique allows potential for *in vivo* endoscopic high-speed functional optical frequency domain imaging with high quality spectroscopic contrast with low computational costs. On the other hand, the common path configuration is able to suppress common mode noise and potentially implement high stability quantitative phase measurements.

Keywords: wavelength swept source, optical frequency domain imaging, optical coherence tomography, common-path, biomedical imaging.

1. INTRODUCTION

Optical Coherence Tomography (OCT) [1] is an emerging non-invasive cross-sectional imaging modality for visualizing tissue details *in vivo* at resolutions approaching histology. Because OCT uses light, it is different from other existing imaging techniques such as ultrasound, a variety of functional and spectroscopic techniques are available to expand its capabilities, including polarization, absorption, elastography, Doppler, and dispersion analysis [2]. In terms of improving the classification of different tissue types and pathology, the analysis of spectroscopic properties has shown to be a simple and powerful tool for achieving additional imaging contrast [3]. The conventional methods of extraction spectroscopic information are computational expensive and rely on the wavelength dependency of the scattering and absorption coefficients within one wavelength band only [4-7]. Simultaneously imaging at two distinct spectral regions has been demonstrated by time-domain [8], full-field [9], and spectral-domain [10] OCT. However, limitations of their slow imaging speed and/or free-space optical probing configuration restrict them in many real-time, *in vivo*, and endoscopic applications.

Optical frequency domain imaging (OFDI), or named swept-source OCT (SS-OCT) [11] has received much attention in recent years not only because of its higher SNR at high imaging speeds but also for its imaging possibilities in the longer wavelength range, where the reduced light scattering by tissue enables OCT to collect signal from deeper structure compared to OCT imaging based on shorter source wavelengths. With the advantage of the balanced detection and high-speed swept source, OFDI can offer higher imaging speeds and SNR by comparing to spectrometer based SD-OCT system. Two appropriate wavelength swept laser sources have been demonstrated based on the polygonal mirror filter [11] and piezo-tunable Fabry-Perot (FP) filter [12]. In the polygonal mirror scheme, the angular wavelength dispersion resulting from a diffraction grating was directed to match the facet size and angular sweep of the high-speed polygon scanner with [13] and without [14] a telescope. In the piezo-tunable FP filter scheme, resonant operation of the filter results in high-speed turning with a sinusoidal and bidirectional scan. In comparison, the high-power unidirectional linear wavelength sweeps generated by the polygonal mirror scheme are more favorable for OFDI imaging applications

* Linda.mao@nrc-cnrc.gc.ca; phone 1 613 993-7331; fax 1 613 954 3338; <http://ims-ism.nrc-cnrc.gc.ca/>

than that generated by the piezo-tunable FP filter. Both swept sources published so far, based on our knowledge, produce sweeping in only a single wavelength band.

In this paper, we propose a novel method of fiber-based simultaneous multi-wavelength-band swept laser source and common-path multi-wavelength-band optical frequency domain imaging for spectroscopic applications. Simultaneous multi-band tuning is proposed by using multi fiber-ring cavities with corresponding optical semiconductor amplifiers as their gain mediums and multi narrowband optical filters with a single polygonal scanner. We report a simultaneous two wavelength bands swept laser source and fiber-based dual-band common-path optical frequency domain imaging. Simultaneous 1310/1550 dual-wavelength tuning is performed by using two fiber-ring cavities with corresponding optical semiconductor amplifier as their gain mediums and two narrowband optical filters using a single dual-window polygonal scanner. The measured average output power of 60 mW and 25 mW have been achieved in 1310 and 1550 nm bands, respectively, while the two wavelengths were swept simultaneously from 1235 nm to 1395 nm for 1310nm band and from 1520 nm to 1580 nm for 1550 nm band. A broadband wavelength-division multiplexing is used for coupling 1310/1550 two bands to a common-path interferometer with a single fiber probe. Simultaneous OFDI at 1310 and 1550 nm at an A-scan rate up to 65 kHz is demonstrated. This technique allows potentially for *in vivo* high-speed functional OFDI with high quality spectroscopic contrast. On the other hand, the common path configuration is able to suppress common mode noise and potentially implement high stability quantitative phase measurement [15].

2. PROPOSED METHOD

2.1. Fiber-based high-speed and high-power simultaneous multi-band swept laser source

Fig. 1. Schematic diagram of the simultaneous multi-wavelength-band swept laser source. Cir: circulator, SOA: semiconductor optical amplifier, PC: polarization controllers, GT: grating, FBG: fiber Bragg grating.

The schematic of proposed simultaneous multi-wavelength-band swept laser is presented in Fig. 1. The multi-wavelength-band swept source comprises of multiple extended ring cavity semiconductor lasers and high-speed optical narrow-band intra-cavity wavelength-scanning filters with a single high-speed polygonal scanner. Tuning of the laser with multiple bands can be accomplished by spinning the polygon with multiple opened windows, enabling synchronized sweeping of the wavelength bands. Broadband optical semiconductor amplifiers (SOA) can be used as the cavity gain medium. For increasing free spectral range (*FSR*) of the polygonal narrowband filter and simplifying the setup, Littrow configurations can be utilized for the all wavelengths.

2.2. Simultaneous fiber-based common-path multi-wavelength-band optical frequency domain imaging

Fig. 2. Schematic diagram of proposed fiber-based multi-wavelength-band common-path OFDI system. D: detector. WDM: wavelength division multiplex. Solid and dotted line: optical and electronic paths, respectively

Fig. 2 shows the setup of the proposed fiber-based simultaneous multi-band common-path swept-source optical frequency domain imaging system. The simultaneous swept laser outputs of multi bands are connected to match optical circulators. The appropriate output is then connected to broadband WDM array outputting into a single-mode optical fiber (SMF) array. Each SMF is fusion-spliced with a fiber-lens [16]. The lights reflected from the glass-air surfaces of each lens are used as reference reflections, which is combined with light reflected from inside the sample for corresponding channel to form multi common-path configurations. Each common-path interferometer can pass two adjoined of lights, this not only overcomes the difficulty of bandwidth limitation in fiber circulators used in conventional fiber-based OCT systems, but also gives highly stable quantitative phase measurements [15]. Detector outputs of each wavelength band are digitized using multi-channel data acquisition card (DAQ), which will depend on the number of band. The start trigger signal is used to initiate the function generator for the galvo scanner and initiate the data acquisition process for each A-scan. K-linear samplings are implemented by using pre-calibrated tables for each wavelength. Encoded color images with the multi-band wavelength are processed using a method of depth ratio correction after inverse Fourier transformation (IFT). The method of depth ratio correction will be described in the following section.

3. CONSTRUCTION of DUAL-BAND OFDI

As a proof concept prototype, a dual-band OFDI system is constructed [17]. The dual-band swept source comprises two extended ring cavity semiconductor lasers and two narrowband intracavity wavelength filters with a single high-speed polygonal scanner. Tuning of the laser with two wavelength bands is accomplished by spinning the polygon with two opened windows, enabling synchronized sweeping of two wavelength bands. Two broadband semiconductor optical amplifiers (SOAs) at 1310 (Covega, BOA1132) and 1550nm (Covega, BOA1004SXL) central wavelengths were used as the cavity gain medium. A customized two-window 72-facet polygon scanner with four adjustable repetition rates (SA34, Lincoln Laser) was employed. The reflected light from the polygon scanner facets illuminate the diffraction gratings at Littrow's angle and retrace the path back to the collimators. Two complete wavelength sweeps are produced simultaneously for each partial rotation of the polygon through an angle of $2\pi/N$ in the two windows, where N ($=72$) is the number of mirror facets. The sweeping angles of the reflected light for the two bands double the polygon's rotation angle. Two Newport gratings (33009BK02-540R and 53015BK01-530R) with the same groove frequency (T) of 1200 lines/mm were used in the filter for the 1310 and 1550nm bands, respectively. The calculated Littrow's angles (θ_{lit}) are 52° and 68° at the center wavelength of 1310 and 1550 nm, respectively. The two diffraction gratings are placed close to

their polygon scanner facets to decrease beam displacement on the diffraction gratings and reduce the cavity lengths. Three inline miniature polarization controllers (PCs) were used in both cavities for individually aligning the related polarization states. About 1.5 m of cavity lengths were obtained for both bands. An output coupler with a 60/40 ratio was used (60% of the power is coupled out) for both cavities. The 10% output power of the 1310nm band was connected to a fiber Bragg grating (FBG) for a swept laser start trigger. The simultaneous swept laser outputs of 1310 and 1550 nm bands are connected to two related optical circulators. The appropriate output is then connected to a broadband 1310/1550 WDM outputting into a SMF fusion-spliced with a GRIN fiber lens to form a common-path configuration. The GRIN lens used in this work has a diameter of 0.14 mm and a beam profile: working distance of 0.7 mm, depth of field of 0.4 mm, and lateral OCT image resolution of 19 μm . Detector (PDB120C, Thorlabs) outputs of each wavelength band are digitized using a two channels data acquisition card (ATS 9440, Alazartech, Montreal) with 14-bit resolution and sampling speed of 100 MS/s.

4. RESULTS and DISCUSSIONS

Normalized spectrum emitted from our dual-band swept laser, measured using an optical spectrum analyzer (OSA) in peak-hold mode with a resolution of 1 nm, is shown in Fig. 3 (a). Full sweeping wavelength ranges of 160 and 62 nm centered at 1307 and 1550 nm for the two bands were obtained, respectively. The FSR of the Littrow configuration used in our filter setup are given in the following equations by assuming there is no beam clipping [14]:

$$FSR = 2 \cdot \frac{1}{T} \cdot \frac{4\pi}{N} \cdot \cos(\theta_{lit}) \quad (1)$$

FSR of 179 and 109 nm are calculated at the center wavelength of 1310 and 1550nm in our setup, which respectively correspond to the maximum wavelength sweeping ranges for the two bands. Measured full sweeping wavelengths of 160 and 62 nm are 91 % and 51 % of the theoretical FSR values for the two respective central wavelengths. The FWHM bandwidth of 121 and 47 nm would respectively correspond to 6.2 and 22.5 μm OCT axial resolutions in air for 1310 and 1550 bands.

Fig.3 Measured normalized dual-band spectrum (a), oscilloscope traces (1550 band: solid-line and 1310 band: dotted-line) with start trigger (dashed-line) at a repetition rate of 65.19 kHz (b), and output powers versus injection current of the SOA (c) of our dual-band swept laser.

Fig. 3 (b) shows the measured related output power of our dual-band swept laser over two wavelength scans using an oscilloscope. The observed scan duration of 15.34 μs corresponds to a repetition rate of 65.19 kHz. The duty cycles of 91% and 51% for the 1310 and 1550 bands, respectively, match their percentages of the theoretical FSR values. The lower duty cycles at the 1550 band could be caused by the beam clipping on the polygon facet and/or the lower efficiency of the grating at the longer wavelength near 1600nm. Better managing of the beam size of the collimator

and/or using of a high efficient Holographic grating (Newport, 33009FL02-544H) may overcome this issue. Fig. 3 (c) shows output power versus the injection current of the SOA. Measured average output powers of 60.2 and 26.9 mW were obtained in the 1310 and 1550 nm bands, respectively, at an injective current of 0.6 A on both SOA. The laser threshold currents were 80 and 130 mA for the 1310 and 1550 bands, respectively.

In an optical frequency domain imaging system, bandwidth (Δf) of the interference signal frequency corresponding to optical source properties (i.e. central wavelength λ_0 and bandwidth $\Delta\lambda$) at a certain image depth (z) is given by [2]:

$$\Delta f = \frac{2\Delta\lambda}{\lambda_0^2} \cdot z \cdot f_A \quad (2)$$

where, f_A is A-scan frequency. From Eq. (2), the interference signal frequency will be different at the different central wavelengths. It will induce the different image pixel scales when the optical source used in the different central wavelengths which caused by the inverse Fourier transformation. Therefore, the ratio of the image pixel scales at the two central wavelengths will equal to the ratio of the signal frequency bandwidth.

Fig. 4. (a) Measured interference signals at 1310 nm and 1550 nm when put a mirror at 100 μm distance from the end surface of the GRIN fiber probe. (b) Normalized point-spread functions at 1310 nm and at 1550 nm obtained after inverse Fourier transformations of interference signals without any depth ratio correction. (c) Normalized point-spread functions at 1310 nm and at 1550 nm after depth ratio correction. (d) Normalized point-spread functions shown the FWHM bandwidth at 1310 nm and at 1550 nm.

Fig. 4 (a) shows the waveforms of the interference signals at 1310 nm and at 1550 nm measured when put a mirror at 100 μm distance away from the end surface of the GRIN fiber probe in our dual-band common-path OFDI system. The ratio of the signal frequency bandwidth at 1310 and 1550 nm of 2.46 is obtained measured from Fig. 4 (a). Fig.4 (b) shows normalized point-spread functions (PSF) at 1310 nm and at 1550 nm obtained by inverse Fourier transformations of interference signals without any depth corrections. The ratio of the peak pixels of the two wavelengths is equal to 2.46 as well, which agreed with above theory. After the depth ratio correction, e.g. dividing the pixel of 1310 nm by 2.46 and

converting the pixel to distance for both wavelength, the normalized point-spread functions at 1310 nm and at 1550 nm are shown in Fig. 4 (c). By using the same method to the all acquired A-scan data, encoded color images in the same scale with the different wavelengths can be obtained. The tissue structures with high quality spectroscopic contrast with different wavelength can be visualized directly without high computational costs. Fig. 4 (d) shows the normalized point-spread functions indicating the full width half maximum (FWHM) bandwidth at 1310 nm and at 1550 nm. Measured FWHM of 9 and 19 μm at 1310 and 1550 nm central wavelength, respectively, are obtained, which correspond to the axial resolutions of the OFDI system for the two wavelengths. The higher FWHM bandwidths of PSF measured at 1310 nm wavelength band in comparison with that calculated from the FWHM swept source bandwidth (6.2 μm) could be caused by the limitation of the bandwidth of the low-cost fiber fused WDM used in the system. A well designed high quality high cost WDM made by thin-film filter could improve the resolutions at the wavelength band.

5. DUAL-BAND IMAGINGS

Application of our technique to biological imaging is demonstrated in Fig. 5. Fig. 5 (a) and (b) show *in vivo* OFDI images ($3\text{mm} \times 1.2\text{ mm}$) of human finger acquired from our fiber-based simultaneous dual-band OFDI system processing at individual center wavelength of 1310 nm and 1550 nm, respectively. Higher axial resolution in the image at 1310 nm is visualized in comparison with that at 1550 nm wavelength band. The penetration depth of image at 1550nm is slight larger than that at 1310 nm although the water absorption at 1550nm wavelength is higher than that at 1310 nm wavelength. Fig. 5 (c) shows the color encoded OFDI image of the human finger processed using the depth ratio correction method described above in this paper at 1310 (green) and 1550 nm (red) center wavelengths. The three sweat glands in epidermis layer as shown in SG1, SG2 and SG3 in Fig. 5 (c) have different dispersion properties. SG1 is in the same location at both wavelengths, SG2 is shifted at the two wavelengths, and SG2 is only discovered in the 1550 nm band. The different dispersion property between the 1310nm and 1550 nm bands of sweat gland ducts could be caused by the local water amount, collagen and muscles.

Fig 5. *In vivo* OFDI images ($3\text{mm} \times 1.2\text{mm}$) of human finger acquired from our fiber-based simultaneous dual-band SS-OCT system processed at individual center wavelength of 1310 nm (a) and 1550 nm (b). Color encoded OCT image of the human finger processed by the depth ratio correction method at 1310 (green) and 1550 nm (red) center wavelengths. SG: sweat gland.

4. CONCLUSION

A novel method of simultaneous multi-wavelength-band common-path optical frequency domain imaging is proposed for spectroscopic applications. A high-speed and high-power simultaneous 1310/1550 dual-wavelength-band swept laser source based on a single two-window polygon filter was demonstrated. A dual-band common-path optical frequency domain system was implemented as a proof concept prototype. Simultaneous dual-band tuning is performed by using two fiber-ring cavities with corresponding optical semiconductor amplifier as their gain mediums and two narrowband optical filters using a single dual-window polygonal scanner. The measured average output power up to 60 mW and 25 mW have been achieved in 1310 and 1550 nm bands, respectively, while the two full swept wavelength ranges are 160 nm and 62 nm for 1310nm band and 1550 nm band, respectively. A broadband wavelength-division multiplexing is used for coupling 1310/1550 two bands to a common-path interferometer with a single fiber probe. Simultaneous OFDI of human finger at 1310 and 1550 nm at an A-scan rate up to 65 kHz is demonstrated. Our novel method allows potentially for instantaneous high-quality OFDI spectroscopic analysis and stable phase measurements in simultaneous two wavelength bands. By using an ultra-small fiber probe, this technique allows for *in vivo* endoscope and interstitial noninvasive diagnostics with potential application in functional (spectroscopic) investigations.

REFERENCE

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography", Science **254**, 1178-1181 (1991).
2. W. Drexler and J. Fujimoto, Optical Coherence Tomography: Technology and application (Springer, 2008).
3. U. Morgner, W. Drexler, F. X. Kärtner, X. D. Li, C. Pitris, E. P. Ippen, and J. G. Fujimoto, "Spectroscopic optical coherence tomography", Opt. Lett., **25**, 111 (2000). D. Adler, T. Ko, P. Herz, and J. Fujimoto, Opt. Express **12**, 5487 -5501 (2004).
4. D. Adler, T. Ko, P. Herz, and J. Fujimoto, "Optical coherence tomography contrast enhancement using spectroscopic analysis with spectral autocorrelation" Opt. Express **12**, 5487 -5501 (2004).
5. C. Xu, P. Carney, and S. Boppart, "Wavelength-dependent scattering in spectroscopic optical coherence tomography", Opt. Express **13**, 5450-5462 (2005).
6. A. Dubois, J. Moreau, and C. Boccara, "Spectroscopic ultrahigh-resolution full-field optical coherence microscopy", Opt. Express **16**, 17082-17091 (2008).
7. R. Leitgeb, M. Wojtkowski, A. Kowalczyk, C. K. Hitzenberger, M. Sticker, and A. F. Fercher, "Spectral measurement of absorption by spectroscopic frequency-domain optical coherence tomography", Opt. Lett. **25**, 820-822 (2000).
8. F. Spöler, S. Kray, P. Grychtol, B. Hermes, J. Bornemann, M. Först, and H. Kurz, "Simultaneous dual-band ultra-high resolution optical coherence tomography", Opt. Express **15**, 10832-10841 (2007).
9. D. Sacchet, J. Moreau, P. Georges, and A. Dubois, "Simultaneous dual-band ultra-high resolution full-field optical coherence tomography" Opt Express **16**, 19434 (2008).
10. S. Kray, F. Spöler, M. Först, and H. Kurz, "High-resolution simultaneous dual-band spectral domain optical coherence tomography", Opt. Lett. **34**, 1970 (2009).
11. S.H. Yun, G.J. Tearney, J.F. de Boer, N. Iftimia, and B.E. Bouma, "High-speed optical frequency-domain imaging", Opt. Exp. **11**, 2953-2963 (2003).
12. R. Huber, M. Wojtkowski, J.G. Fujimoto, J.Y. Jiang, and A.E. Cable, "Three-dimensional and C-mode OCT imaging with a compact, frequency swept laser source at 1300nm", Opt. Exp. **13**, 10523-10537 (2005).
13. Y. Mao, C. Flueraru, S. Sherif, and S. Chang, "High Performance Wavelength-Swept Laser with Mode-Locking Technique for Optical Coherence Tomography", Opt. Comm., **282**, 88-92 (2009).
14. S. M. R. M. Nezam, "High-speed polygon-scanner-based wavelength-swept laser source in the telescope-less configurations with application in optical coherence tomography", Opt. Lett., **33**, pp.1741-1743 (2008).
15. J. Zhang, B. Rao, L. Yu, and Z. Chen, "High-dynamic-range quantitative phase imaging with spectral domain phase microscopy", Opt. Lett. **34**, pp. 3442-3444 (2009).
16. Y. Mao, S. Chang, S. Sherif, and C. Flueraru, "Graded-index fiber lens proposed for ultrasmall probes used in biomedical imaging", Appl. Opt. **46**, 5887-5894 (2007).
17. Y. Mao, S. Chang, E. Murdock, C. Flueraru, "Simultaneous dual-wavelength-band common-path swept-source optical coherence tomography with single polygon mirror scanner", Optics Letters, **36**, 2011-2013 (2011).