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Instantaneous Spectroscopic SS-OCT Imaging Using a Simultaneous Dual-Band Swept Laser and Common-Path Fiber Probe

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ABSTRACT

A simultaneous 1310/1550 swept-source optical coherence tomography system is implemented by combining a novel dual-band swept laser source and an integrated common-path GRIN lensed fiber interferometer/probe. High-speed synchronized dual-wavelength tuning is performed by using two laser cavities with a single dual-window polygonal. Simultaneous *in vivo* OCT imaging at 1310 and 1550 nm is demonstrated. This dual-band technique brings together common-path fiber probe potentially allows instantaneous *in situ* functional OCT imaging with high quality spectroscopic contrast and stable phase measurements.

Keywords: optical coherence tomography, swept source optical coherence tomography, dual-band swept source, spectroscopic contrast, dual-window polygonal, fiber common-path interferometer, GRIN fiber lens, fiber probe,

1. INTRODUCTION

Optical coherence tomography (OCT) is an emerging noninvasive imaging modality for visualizing tissue details *in vivo* at spatial resolutions approaching histology. 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 contrast¹. The conventional methods of extracting spectroscopic information are computationally expensive and rely on wavelength dependency of the scattering and absorption coefficients within one wavelength band only. Simultaneously imaging at two distinct spectral regions has been demonstrated by time-domain², full-field³, and spectral-domain⁴ OCT. However, several limitations, such as slow imaging speed or free-space optical probing configuration restrict them in many real-time, *in vivo*, and endoscope applications. Swept-source OCT (SS-OCT) has received much attention in recent years not only because of its higher signal-to-noise ratio at high imaging speeds but also for its imaging possibilities to collect a signal from deeper structures using a longer wavelength. Two designs of wavelength swept laser sources have been demonstrated based on the polygonal mirror filter^{5,6} and piezotunable Fabry-Perot (FP) filter at 1300⁷ and 1550nm⁸. 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 and without⁹ 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. Both swept sources published so far produce sweeping in only a single wavelength band, to the best of our knowledge.

In this presentation, we report a simultaneous 1310/1550 two-wavelength-band swept laser source and a dual-band common-path SS-OCT system using a GRIN lensed fiber probe. Simultaneous imaging at the 1310 and 1550nm wavelength bands is achieved. Using an ultra-small fiber probe allows *in vivo* endoscope and interstitial noninvasive diagnostics with instantaneous high-quality spectroscopic contrast. On the other hand, the common-path configuration is able to reject common mode noise and implement high-stability quantitative phase measurement¹⁰.

2. DUAL-BAND FIBER RING SWEPT LASER SOURCE

The schematic of the 1310/1550 dual-band swept laser is presented in Figure 1 (a). 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. For increasing the free spectral range (FSR) of the polygonal narrowband filter, Littrow configurations were utilized for both bands. The reflected light from the polygon scanner facets illuminate the diffraction gratings at Littrow's angle.

Figure 1. (a) Schematic diagram of the dual-band fiber ring swept laser source: PC, polarization controllers; FBG, fiber Bragg grating; Ci, circulator. (b) Measured normalized dual-band spectrum of our dual-band swept laser.

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 Figure 1 (b). 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 clipping⁹:

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

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 μ m OCT axial resolutions in air for 1310 and 1550 bands.

From an oscilloscope measured output power of our dual-band swept laser over two wavelength scans (not shown here), the scan duration of 15.34 μ s is observed which 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. 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.

Figure 2 (a). Schematic diagram of our simultaneous dual-band common-path SS-OCT system. D: detector. WDM: wavelength division multiplex. Solid and dotted line: optical and electronic paths, respectively. (b) Scanning electron micrograph of a GRIN fiber lens tip used in the system. Inlet: images of intensity profile at three locations: focus point (center), Rayleigh range to and from focus point.

3. DUSL-BAND SS-OCT SYSTEM AND COMMEND-PATH GRIN FIBER PROBE

Figure 2 (a) shows setup of the dual-band common-path SS-OCT system. The simultaneous swept laser outputs of 1310 and 1550 nm bands are connected to two matched optical circulators. The appropriate output is then connected to a broadband 1310/1550 WDM outputting into a single-mode optical fiber (SMF). The SMF is fusion-spliced with a GRIN fiber lens¹¹. The light reflected from the glass-air surface of the GRIN lens is used as reference reflection, which is combined with light reflected from inside the sample to form a common-path configuration. This common-path interferometer can pass both bands of light and overcomes the difficulty of bandwidth limitation in fiber circulators used in conventional fiber-based OCT systems. In addition, the common path interferometric topology has the advantage of running high stable phase measurement¹⁰ and the drawback of limited adjustment of the optical power in reference arm for SNR optimization. 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 as shown in Fig. 2 (b). 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. 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 sampling is implemented by using pre-calibrated tables for each wavelength. Color encoded images are then processed after inverse Fourier transformation⁴. From point spread functions of the two wavelength bands at different depths measured using a partial reflector and the GRIN-lensed probe, SNR of 50.5 dB for 1310 nm and 50.9 dB for 1550 nm are obtained in the focusing depth range of 0.5-0.8 mm when optical power illuminating on the sample with approximately 13 and 8 mW for 1310 and 1550 nm, respectively. The two bands have a similar sensitivity of 95 dB, and 1550 nm penetrates the air deeper than 1310 nm. Measured axial resolutions are 9 and 19 μm for 1310 and 1550 nm, respectively, which are agreed well with the swept wavelength ranges for the two bands.

Figure 3. *In vivo* color encoded OCT images (3mm $\times$ 1.2mm) of human finger acquired from our fiber-based simultaneous dual-band SS-OCT system processed by the depth ratio correction method¹² at 1310 (green) and 1550 nm (red) center wavelengths. SG: sweat gland.

Application of our technique to biological imaging is demonstrated in Fig. 3, which shows the color encoded OCT image of the human finger processed using the depth ratio correction method¹² at 1310 (green) and 1550 nm (red) central wavelengths. The two sweat glands in epidermis layer as shown in SG in Figure 3 have a dispersion property. The dispersion property between the 1310nm and 1550 nm bands of sweat gland ducts could be caused by the local water amount, collagen and muscles.

4. CONCLUSION

A novel method of simultaneous dual-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 OCT image 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 OCT 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.

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