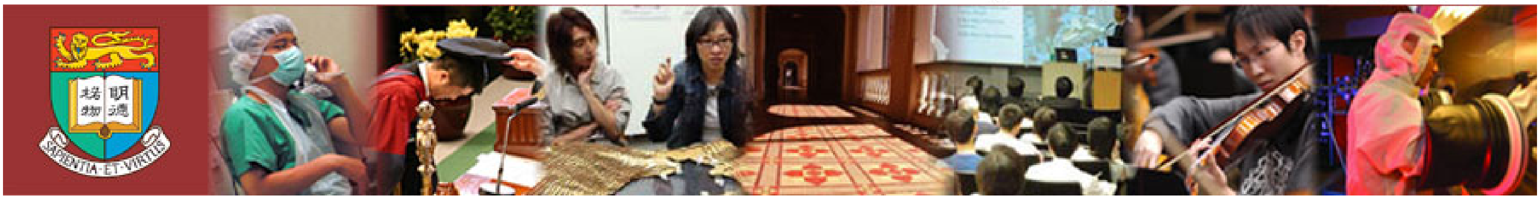

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In Vivo OCT Imaging Based on La-Codoped Bismuth-Based Erbium-Doped Fiber

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***Abstract*— We demonstrate a Fourier domain mode-locked laser based on lanthanum-codoped bismuth-based erbium-doped fiber (Bi-EDF) for swept source optical coherence tomography (SS-OCT) imaging. Raman amplification is incorporated to suppress the gain competition and homogenous linewidth broadening effects of Bi-EDF. A wavelength sweeping bandwidth of 81 nm is generated under stable operation. Therefore, *in vivo* OCT imaging of human finger print and orange slices is enabled and the results are also presented. This scheme paves the way for doped fiber amplifiers to be employed to generate ultra-wideband SSs for OCT applications.**

***Index Terms*— Erbium, bismuth, mode locked laser, optical imaging.**

I. INTRODUCTION

OPTICAL coherence tomography (OCT) [1], [2] is an emerging non-invasive, non-contact imaging modality for visualizing cross-sectional information of tissues with micrometer resolution. Recently, the swept source OCT (SS-OCT) system, which employs Fourier domain mode-locked (FDML) swept laser [3], [4], has been extensively investigated due to the higher acquisition speed and improved sensitivity compared with the conventional OCT systems, e.g. time-domain OCT (TD-OCT) [5], [6].

To date, most of the implementation of FDML swept lasers utilize semiconductor optical amplifier (SOA) as the gain medium. Due to its compact size and comparably wide gain bandwidth (∼100 nm), SOA is well suited for the purpose of FDML swept lasers for OCT applications. Nevertheless, it can still be justified to investigate other gain media for the FDML swept laser. First, the gain bandwidth of SOA depends inversely on the optical confinement and the cavity length, which makes it difficult and not cost-effective to further enlarge its gain bandwidth for ultrahigh-resolution OCT. Second, there are several disadvantages of SOAs when compared with other kinds of optical amplifiers. For instance, the SOA has a relatively higher noise figure and lower gain compared with erbium-doped fiber amplifier (EDFA) [7]. Compared with fiber optical parametric amplifier (FOPA), which can achieve up to 400 nm of gain bandwidth [8], the available gain bandwidth of SOA is much narrower. SOA has limited gain "windows" while fiber Raman amplification (FRA) could arbitrate the amplification "window", which is merely determined by the pumping wavelength [9].

Various efforts to utilize other gain media have been demonstrated in the FDML swept laser cavity, such as EDFA [10], FRA [11], and FOPA [12]. However, to date, none of those implementations can fully utilize the whole gain bandwidth of those gain media, and therefore could not be practically used for OCT applications due to the very limited achieved sweeping bandwidth (less than 30 nm). Doped fiber amplifiers, on the other hand, can provide large gain bandwidth and have been stated elsewhere [13]. One promising candidate is lanthanum (La)-codoped bismuth-based erbium-doped fiber (abbreviated as Bi-EDF in the literature) amplifier. Recent developments of Bi-EDF have demonstrated its potential applications for ultra-broadband amplifiers, covering O-, E-, S-, C-, and L-bands [14]. Therefore, it has the potential to be utilized in the ultra-broadband FDML swept laser for ultrahigh-resolution OCT applications. However, it has never been applied to the swept source laser cavity as the gain medium, especially in the FDML regime, due to its gain competition and homogeneous linewidth broadening effects, which make it difficult to obtain wide sweeping bandwidth under stable operation.

In this Letter, we propose and experimentally demonstrate for the first time, to the best of our knowledge, an FDML swept laser with Bi-EDF amplifier (Bi-EDFA) as the gain medium for OCT applications. FRA is also incorporated to suppress the gain competition and homogeneous linewidth broadening effects of the Bi-EDF. Therefore, the gain bandwidth of the Bi-EDF could be fully utilized. A wavelength sweeping bandwidth of 81 nm is achieved under stable operation. *In vivo* OCT imaging results of human finger print and orange slices are also presented.

II. EXPERIMENTAL SETUP

The schematic diagram of the proposed setup for the FDML swept laser based on Bi-EDF is presented in Fig. 1. The ring cavity comprised a section of 56-cm Bi-EDF as the gain

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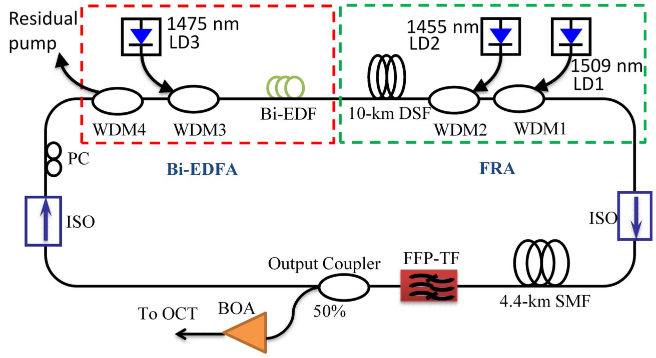

Fig. 1. Schematic diagram of the FDML swept laser based on Bi-EDFA. FFP-TF: fiber Fabry-Perot tunable filter; SMF: single-mode fiber; ISO: isolator; PC: polarization controller; DSF: dispersion–shifted fiber; WDM: wavelength division multiplex; LD: laser diode; BOA: booster optical amplifier.

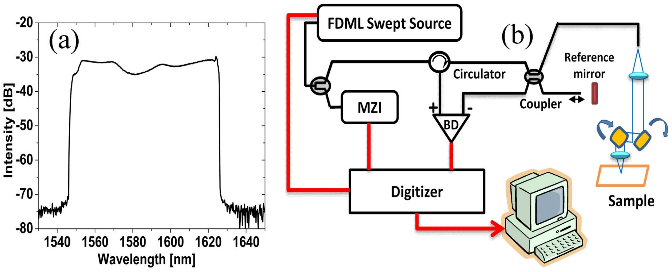

Fig. 2. (a) Output spectrum of the wavelength swept laser; (b) OCT imaging system. MZI: Mach–Zehnder interferometer; BD: balanced detector. The black line is fiber, while the red line is electrical cable.

medium. A fiber Fabry–Perot tunable filter (FFP-TF by *Micron Optics*) served as a narrow-band filter for active wavelength selection, and it has a free spectral range (FSR) of 200 nm at 1550 nm, a finesse of 1000, and was tuned periodically at the cavity round-trip time. Two isolators were inserted to ensure unidirectional lasing. The output coupler provided 50% output. As stated in [7], it is an intrinsic property that an EDF has strong homogeneous line broadening effects and gain competition, which make the lasing wavelengths within the large homogenous linewidth broadening region unstable at room temperature. Since FRA mechanism can effectively suppress the gain competition of EDF [7], it is incorporated with Bi-EDFA to achieve stable FDML operation at the room temperature.

The Bi-EDF was pumped by a 120 mW laser diode (LD3) operating at 1475 nm via a wavelength-division multiplexer (WDM3). The $Er^{3+}$and La^{3+}concentration in the Bi-EDF are 6470 wt-ppm and 4.4% wt, respectively. The peak absorption of the Bi-EDF at the wavelength of 1480 and 1530 nm are 167 and 267 dB/m, respectively. Both ends of the Bi-EDF were angle spliced to high numerical aperture fiber (Corning HI980) before splicing to single-mode fiber (SMF-28), so as to provide better mode-field diameter matching.

The Raman pump source was a 320 mW laser diode (LD2) operating at 1455 nm and a 120 mW laser diode (LD1) operating at 1509 nm. They were coupled by WDM1 and WDM2, respectively. FRA, as shown in green dashed box in Fig. 1, was composed of a spool of 10-km dispersion-shifted fiber (DSF) as the Raman gain medium, to suppress the gain competition and homogeneous linewidth broadening effects of the Bi-EDF. Two Raman pumps were employed to provide a broad Raman gain spectrum such that it could cover the whole gain bandwidth of the Bi-EDFA, and therefore, stabilize the gain mechanism in the FDML laser cavity across the whole gain bandwidth. The residual pump was filtered out by the WDM4. The fiber delay line was a spool of 4.4-km SMF; therefore, the total cavity length gave rise to a sweeping frequency of 14.5 kHz. Owing to the requirement of necessary cavity length to generate a wideband Raman gain to suppress the gain competition effects, the sweeping frequency is limited in this sense. However, the swept rate can be expected to be increased further if the external buffering technique is adopted [15]. A semiconductor booster optical amplifier (BOA, COVEGA 5937) is used to boost the output power for optical imaging.

The integrated output spectrum of the FDML swept laser based on Bi-EDFA before the BOA was measured by an optical spectrum analyzer (OSA) in the peak-hold mode, as shown in Fig. 2(a). The spectra spanned a range from 1547 nm to 1628 nm, approximately 81 nm. The full width at half maximum (FWHM) was measured to be ∼70 nm. It should be noted that the bandwidth of the swept laser was limited by the gain spectrum of the utilized Bi-EDF, which has been described in detail elsewhere [13]. In brief, the gain spectrum of Bi-EDF is determined by the spectroscopic properties of the Er^{3+}, La^{3+}, and Bi^{3+} ions, the glass structure of the optical fiber, and the wavelength and power of the pump laser. It can be expected that different doped ions in the Bi-EDF may be yet to be investigated to provide even larger gain bandwidth. Note that because of the extra gain introduced by FRA, the output spectrum was slightly nonuniform. The average output power was measured to be 2.4 mW, and the power after BOA was measured to be 15.3 mW. The 3-dB bandwidth of the BOA is ∼102 nm, which will not affect the spectral range of the FDML swept laser, and is only intended to boost the power of the FDML output for optical imaging.

Fig. 2(b) shows the experimental setup used for OCT imaging based on the proposed FDML swept laser. 5% output of the FDML swept laser was coupled into a Mach–Zehnder interferometer (MZI) (INT-MZI-1550, *Thorlabs*) with a FSR of 103 GHz for recalibration of time to optical frequency. The interference fringe signal was acquired on one channel of a two-channel, high-speed digital acquisition card (ATS460, *Alazartech*, Montreal) with 14-bit resolution and sampling speed up to 125 MS/s. Balanced detector (BD) with a bandwidth of 100 MHz and a trans-impedance gain of 50,000 V/A was employed to suppress the background noise and enhance the amplitude. The resampling and fast Fourier transform (FFT) procedures were performed by a graphical processing unit card (GTX460, *NVIDIA*) inserted into a standard personal computer (Dual core, *Dell*). The spline interpolation and FFT algorithms were programmed in the CUDA 2.3 environment and packaged into a dynamic link library (DLL) for calling by LabVIEW codes. The processing speed under the LabVIEW environment is sufficient to perform real-time *in vivo* imaging in our setup.

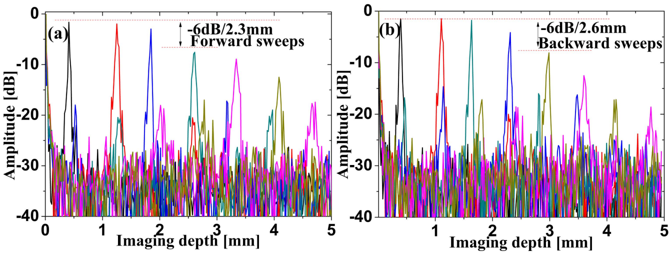

Fig. 3. Roll-off curves for forward sweeps (a) and backward sweeps (b).

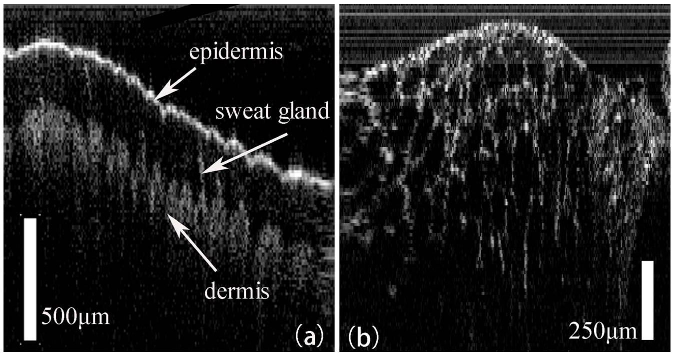

Fig. 4. *In vivo* OCT imaging of human fingerprint (a) and a slice of orange (b).

III. Results and Discussions

The sensitivity roll-off characteristic, which was determined by the back-reflected signal amplitude from a single mirror reflection, of the FDML swept laser based on Bi-EDFA, for the forward sweep (left) and backward sweep (right) are depicted in Fig. 3(a) and 3(b), respectively. The roll-off curve depicts the 6-dB drop of 2.3 mm (forward) and 2.6 mm (backward), respectively. The backward sweep, therefore, was used for OCT imaging as it shows slightly better performance than the forward sweep. Further improvement of the roll-off performance can be achieved by controlling the dispersion inside the cavity.

To further demonstrate the applicability of this swept laser for OCT imaging, the finger print of a healthy human volunteer was imaged, as depicted in Fig. 4(a). The image has a size of 542 × 280 pixels, corresponding to a physical width of 2.9 mm and a height of 1.5 mm. The depth was rescaled by the estimated tissue refractive index $\sim$1.4. We can observe that the image identifies clear morphological structures such as dermis, epidermis, and sweat gland, noted by the arrows in Fig. 4(a). Fig. 4(b) shows the image for a slice of orange sample. As suggested in [2], the 70-nm FWHM bandwidth corresponded to a theoretical resolution of 20 μm, while the measured resolution was around 25 μm. This is in reasonably good agreement with the theoretical calculations. The slight degradation of the measured value is due to the distorted output spectrum from the Gaussian shape and the inaccuracy occurred in the recalibration process from time to optical frequency. The sensitivity was measured with an attenuated, calibrated reflection from a mirror, and the effective sensitivity was about 89 dB.

The quality of the OCT image significantly depends on the swept laser source performance. The tuning bandwidth of 81 nm is the largest hitherto demonstrated for the FDML swept laser based on the doped fiber amplifier. It can be predicted that different doped ions in the EDF remains to be investigated and optimized to provide even larger gain bandwidth in the near future.

IV. Conclusion

In conclusion, for the first time we demonstrated an FDML swept laser based on Bi-EDFA for OCT applications. FRA was also incorporated into the cavity to suppress gain competition and homogenous linewidth broadening of Bi-EDF. A wavelength sweeping bandwidth of 81 nm was generated under stable operation. This scheme paves the way for doped fiber amplifiers to be employed as a useful source for generating ultra-wideband swept sources for OCT applications.

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