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

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**Abstract**—We report a FDML swept laser based on Bi-EDF fiber for the first time. A sweeping bandwidth of 81 nm is achieved. In vivo OCT imaging is presented to justify the feasibility of this work.

**Keywords**— Fiber, erbium, optical coherence tomography.

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 has been extensively investigated [3]. To date, most of the implementation of FDML swept lasers utilize semiconductor optical amplifiers (SOA) as gain media. Various other gain medium such as erbium-doped fiber amplifier (EDFA) [4], fiber Raman amplifier (FRA) [5] and fiber optical parametric amplifier (FOPA) [6] have been reported. However, none of those implementations can be practically used for OCT applications due to the very limited achieved sweeping bandwidth (less than 30 nm). Doped fiber amplifier, on the other hand, can provide large gain bandwidth and has been stated elsewhere [7]. One promising candidate is lanthanum (La)-codoped bismuth-based erbium-doped fiber (abbreviated as Bi-EDF in the context) amplifier [7]. However, it has never been applied to the swept source laser cavity as gain media, especially in the FDML regime, due to its gain competition and homogeneous linewidth broadening effects, which makes it difficult to obtain wide sweeping bandwidth under stable operation.

Here, we propose and experimentally demonstrate for the first time, to the best of our knowledge, a FDML swept laser with Bi-EDF amplifier (Bi-EDFA) as gain media 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 the human skin are also presented.

II. EXPERIMENTAL SETUP

The schematic diagram of the proposed setup for 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 medium. A fiber Fabry-Perot tunable filter 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 [8], it is an intrinsic property that an EDF has a strong homogeneous line broadening effects and gain competition, which makes 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 [8], it is incorporated with Bi-EDF 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. It was then coupled into the cavity by a wavelength-division multiplexer (WDM3). The erbium concentration and the La 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 nm 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. Both of them 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. Note that in order to utilize the whole gain bandwidth of the Bi-EDFA, 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 stabilized 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 cavity across the whole gain bandwidth. The residual pump therefore stabilized the gain mechanism in the FDML laser cavity.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The integrated output spectrum of the FDML swept laser based on Bi-EDFA before the BOA was measured by an optical spectrum analyzer (OSA), 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. Note that because of the extra gain introduced by FRA, the output spectrum was slightly nonuniform. The average output power was measured to be 3.4 mW, and the power after BOA was measured to be 15.3 mW. 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 details in [7]. 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 EDF may be yet to be investigated to provide even larger gain bandwidth.

The experimental setup used for in vivo OCT imaging, the finger print of a healthy human volunteer was imaged, as depicted in Fig. 2(d). 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 ~1.4. We can observe that the image identifies clear morphology structures such as dermis, epidermis and sweat gland, which was indicated in the picture. 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 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 a FDML swept laser based on Bi-EDFA for OCT application. 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 wide band swept source for OCT application.

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