Power enhanced and fast swept source for phase conjugate optical coherence tomography

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Abstract: We have developed a wavelength-swept source based on fiber parametric amplification and Fourier domain mode locking with increased power and speed to take full advantage of 2x resolution enhancement and dispersion cancellation of phase-conjugate OCT.

OCIS code: 180.1655, 110.4500, 190.4410, 190.5040, 270.0270.

1. Introduction

As a novel optical coherence tomography (OCT) technology, phase conjugate OCT (PC-OCT) uses phase conjugated beams to realize phase-sensitive detection in Michelson interferometer, resulting in a two-fold resolution enhancement and even-order dispersion cancellation [1]. In comparison to quantum OCT (Q-OCT) [2], which shares the same measurement improvement, PC-OCT employs standard photodetection rather than single-photon coincidence counting thus enabling faster data acquisition and high speed imaging.

The PC-OCT was demonstrated by Le Gouët *et al.* [3] using a light source based on spontaneous parametric down-conversion (SPDC), which generated two beams possessing phase-sensitive cross correlation. However, the power and bandwidth of the SPDC source were limited. In addition, the imaging speed was slow and the apparatus was hampered by temperature fluctuation.

In this paper, we report a strongly amplified high speed wavelength-swept light source for PC-OCT. By introducing a bidirectional fiber OPA (BD-FOPA) and a Fourier domain mode locking (FDML) laser, the source achieves an output power on the order of mW, which is several orders of magnitude higher than the SPDC source. Improvement in source power and speed should further strengthen the potential of PC-OCT as a practical imaging method.

2. Source experimental setup

PC-OCT requires two key components: a source, which generates two phase conjugate beams, and a phase conjugator. In principle, both processes can be completed in a fiber OPA setup instead of SPDC with fiber OPA [4]. The former, which is based on various nonlinear interactions such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) occurring in the high nonlinear fiber (HNLF), exports an amplified signal and idler, which are also conjugate in phase.

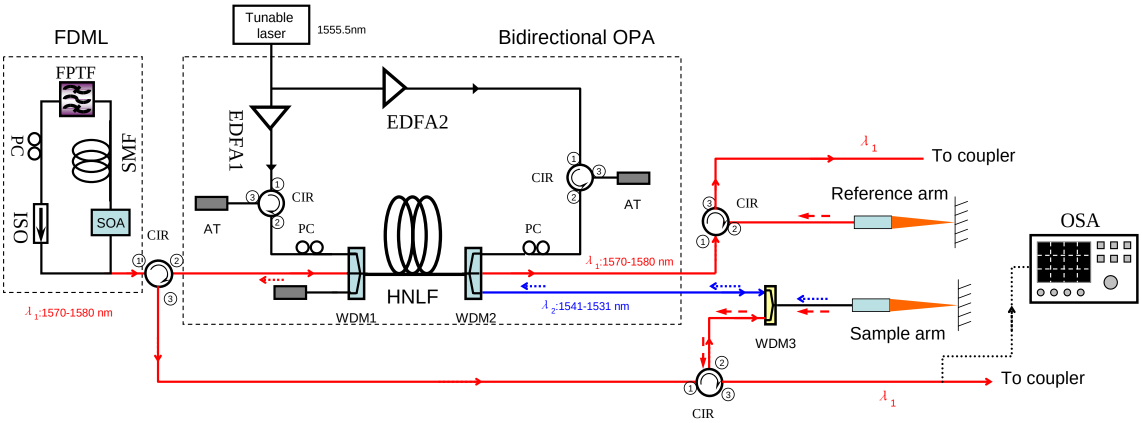

Fig. 1 Source setup for PC-OCT. FPTF: Fabry Perot tunable filter; ISO: isolator; SOA: semiconductor optical amplifier; AT: attenuator; CIR: circulator; PC: polarization control; WDM: wavelength-division multiplexer; HNLF: high nonlinear fibers; OSA: optical spectrum analyzer.

To the best of our knowledge, we are the first group to develop a bidirectional fiber OPA to produce and convert conjugate beams in one single HNLF. With WDM couplers and high power circulators, the 400 m HNLF can be effectively used twice. As shown in Fig. 1, the first OPA, which is pumped by a high power

1555.5 nm laser, amplifies the signal light from the FDML. The generated signal and idler beams to the right of the HNLF possess phase-sensitive cross correlation, as required as a source for PC-OCT [1, 3]. The idler is focused onto the target (a high reflector) in the sample arm. The backscattered photons return to WDM2 and are processed by the fiber OPA again for phase conjugation. The phase-conjugate idler at the left output is then sent to interrogate the sample a second time. This process leads to 2x resolution enhancement and converts the phase-sensitive cross correlation to phase-insensitive cross correlation, while also achieving dispersion cancellation.

3. Power enhancement and high sweeping speed

The first OPA process, which is pumped by EDFA1, exports two phase conjugate beams centered at 1534 and 1577 nm respectively, as shown in Fig. 2. With 0.8 W pump power and 317 µW FDML input, we produce an output power of 663 µW between 1525 and 1545 nm. The intensity level of 30 µW/nm is much higher than1nW/nm, which is reported in a previous study [3]. Here, FDML is an independent part acting as a high speed wavelength-swept signal to the first OPA. It employs a standard mode locking structure where the amplified wavelength is selected by the FPTF and uses SOA as the gain medium. The FDML component achieves a 48 kHz sweeping rate.

The 1534nm beam from the BD-FOPA is focused on the sample and then backscattered (a mirror system with a reflectivity of 42%). The backscattered light returns to HNLF to be amplified by the BD-FOPA again with a pump power of 0.8 W. The idler output whose spectrum centers at about 1577 nm is refocused on the mirror. An optical spectrum analyzer (OSA) measured 9.5 nm bandwidth for the phase-conjugate idler, whose time-domain trace is shown in Fig. 3, which has the same sweep rate as that of the FDML laser.

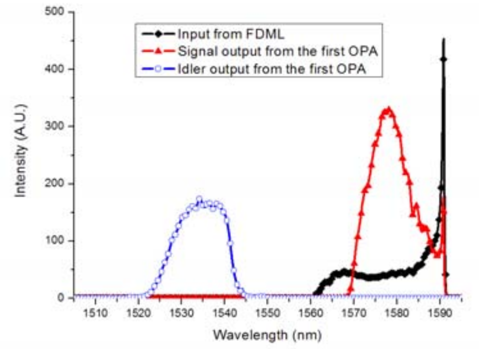

Fig. 2 Spectra of FDML and two output beams in the first OPA process.

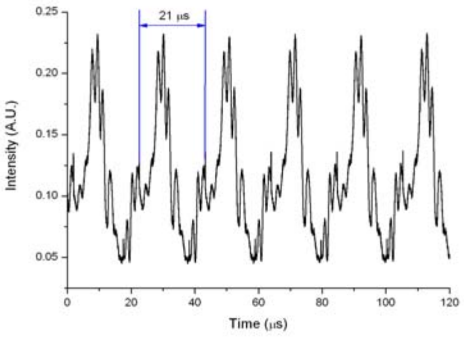

Fig. 3 Time domain intensity trace of the output at the OSA end.

4. Summary

We have demonstrated a strongly amplified and high speed wavelength-swept source specifically designed to increase the source power and stability for PC-OCT. The BD-FOPA and FDML based structure offer two advantages compared to the previous setup based on SPDC: first, generation of phase conjugated beams with high output power, and second, high sweeping speed with the 1580 nm FDML laser. The source bandwidth is currently limited to 9.5 nm because of the 10 nm gain spectrum of the fiber OPA. By choosing a more appropriate HNLF and a higher pump power, the gain range can be dramatically improved. A Fourier domain (FD) PC-OCT can be implemented by matching the optical path length between the two arms. Improvement on power and speed can potentially enable FD PC-OCT to be realized and applied to biomedical imaging.

5. Acknowledgment

This work was supported in part by the Research Grants Council of the Hong Kong Special Administrative Region, China under Projects HKU 7139/06E, HKU 7172/07E and HKU 7179/08E. The authors would like to thank Professor Jeffrey H. Shapiro for the beneficial discussion and also Sumitomo Electric Industries for providing the HNLF.

6. References

[1] Erkmen, B.I. and J.H. Shapiro, *Phase-conjugate optical coherence tomography.* Physical Review A, 2006. **74**: p. 041601.
[2] Nasr, M.B., et al., *Demonstration of dispersion-canceled quantum-optical coherence tomography.* Physical Review Letters, 2003. **91**(8): p. 083601.
[3] Le Gouet, J., et al., *Experimental realization of phase-conjugate optical coherence tomography.* Optics Letters, 2010. **35**(7): p. 1001-3.
[4] Cheng, K.H.Y., et al., *Wavelength-swept spectral and pulse shaping utilizing hybrid Fourier domain modelocking by fiber optical parametric and erbium-doped fiber amplifiers.* Optics Express, 2010. **18**(3): p. 1909-1915.