Fourier Domain Mode Locking Laser Based On Two-Pump Optical Parametric Amplification

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Abstract- **We present a Fourier domain mode locked (FDML) laser scanning from 1540 to 1570 using two-pump optical parametric amplifier (OPA) as the gain medium. The sweep rate of 39.683 kHz is achieved.**

I. INTRODUCTION

Swept sources have been playing an important role in a series of biomedical imaging, spectroscopy and sensing applications [1-3]. Fourier domain mode locking technique is widely used to generate the swept sources due to the ease of implementation. In FDML, a laser cavity is constructed by a gain medium and a tunable optical bandpass filter which is driven by a periodical sinusoidal signal. It matches the fiber laser ring cavity with the round trip time of the photons circulating in the cavity such that when one wavelength arrives at the filter, it combines with the same particular wavelength that is being generated [4]. Various gain medium such as semiconductor optical amplifier (SOA) [1, 5]. Raman amplifier (RA) [6] and erbium doped fiber amplifier (EDFA) [7] have been demonstrated in FDML. However for SOA and EDFA, their amplification windows are limited by the material properties, the sweeping wavelength of FDML is fixed. While for RA, it was shown that the sweeping range was about 30nm [6]. Thanks for the femtosecond response time [8], high gain [9] and wide gain bandwidth [10] provide by OPA, its gain regime can be varied by changing the position of the pump. Hybrid FDML using OPA has been demonstrated by Cheng et al. [11] using polygon filter as the tunable filter and with an extra EDFA adding inside the cavity to complement the dip due to gain spectrum of one-pump OPA. However the central dip could not be completely be compensated by the EDFA hence a disjoint in the sweeping spectrum was inevitable. A central spike between the up/down scanned pulses was observed which was due to the residue of the pump. In this paper, we propose and demonstrate a two-pump OPA FDML which can sweep continuously without a disjoint in frequency spectrum and without a central spike between up/down scan pulses as the pumps can be completely removed.

II. EXPERIMENTAL SETUP

The schematic diagram for the FDML wavelength swept laser based on two-pump OPA is shown in Fig. 1. Two pumps were generated by a continuous-wave (CW) tunable laser source (TLS1 and TLS2) with wavelengths at 1535 nm and 1585 nm respectively. They were then phased modulated by phase modulators (PM) with 1 Gbps 2^{23}-1 pseudo-random

bit sequence (PRBS) in order to suppress the stimulated Brillouin scattering (SBS) effect [12].
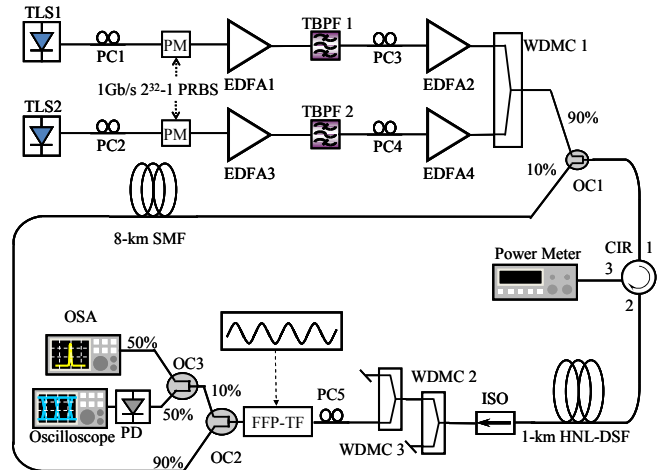

Fig.1. Experimental setup of FDML based on two-pump OPA.

The polarization controllers (PC1 and PC2) were used to align the state of polarization (SOP) of the pumps to the PMs. The dithering pumps were then amplified by two-stage EDFAs, C-band EDFA (EDFA1 and EDFA2) and L-band EDFA (EDFA 3 and EDFA4), with tunable bandpass filters (TBPF) inserted between the two EDFAs to suppress amplified spontaneous emission (ASE) noise. They were combined together by wavelength division multiplexing coupler (WDMC1) before launching into a 1-km highly nonlinear dispersion-shifted fiber (HNL-DSF) with zero-dispersion wavelength (ZDW) at 1560 nm, dispersion slope of 0.024 ps/nm^2/km and nonlinear coefficient $\gamma = 14$ W^{-1}km^{-1}. A circulator (CIR) was used to prevent the reflected pump power. The input C-band pump was 26 dBm while the input L-band pump was 24 dBm. To prevent pumps oscillating inside the cavity and cause damage, WDMC 2 and WDMC 3 were used to remove the residue pumps. In order to enable FDML operation, the Fabry-Perot filter (FFP-TF) was driven by a sinusoidal wave periodically with a period matched to the optical round-trip time of the laser cavity, or a harmonic thereof. The FFP-TF used has a free spectral range (FSR) of ~160 nm at 1550 nm and a finesse of ~750. To reduce the driving frequency required to synchronize the cavity round trip time, an 8-km single-mode fiber (SMF) was added inside the cavity. Isolator (ISO) in the cavity is to enable uni-

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directional operation. A 10/90 optical coupler (OC2) in the cavity provided 90% feedback signal and 10 % output. 90% feedback signal was then combined with the pump by OC1 while 10% output signal was monitored by an optical spectrum analyzer (OSA) and oscilloscope.
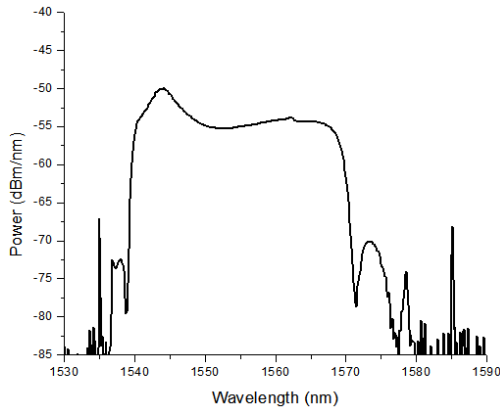
III. Experimental results and discussions

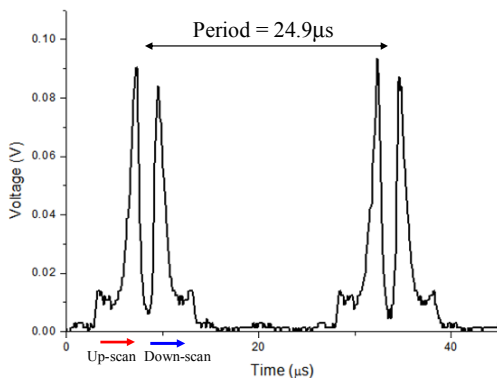Fig.2. FDML spectrum based on two-pump OPA.

Fig.3. Pulse waveform of two-pump OPA FDML.

As shown in Fig. 2, two-pump OPA FDML generates a continuous spectrum as expected. The two spikes locate at 1535 nm and 1585 nm are the residual pumps. The sweeping range is from 1540 nm to 1570 nm. The sweeping range of FDML depends on the two-pump OPA gain spectrum and broader the spectrum is desired. Broader OPA gain spectrum can be obtained by increasing the pump power and changing the wavelengths of two pumps. In our case, the sweeping range is restricted by the transmission port of the WDMC 2 and WDMC 3 which were used to filter the pump away. It is believed that the problem can be solved by using two FBGs to filter the two pumps instead of using WDMC.

Fig. 3 shows the pulse waveform of the two-pump OPA FDML. We defined up-scan as the case where filter is tuning from short to long wavelength while the opposite occurs in down-scan. It can be observed clearly pulse waveform of the two-pump OPA FDML shows a more coherent pulse and there is no notch on either up-scan or down-scan pulse when comparing with [11]. The period between the pulses is 24.9 μs which matches well with the driving frequency of the FFP-TF. The output power is -13.5 dBm. The low output power is due to OC1 where only 10% of 90% of feedback are combined with the pump. The output power could be increased by replacing OC1 with a proper WDMC.

IV. Conclusion

In this paper, we proposed and demonstrated an FDML wavelength-swept fiber laser using two-pump OPA as the gain medium. The sweeping range was from 1540 nm to 1570 nm with output power -13.5dBm at sweep rate of 39.7 KHz. The output spectrum and pulse waveforms are observed. The pulses obtained can resemble a Gaussian shape which is suitable for Optical coherence tomography.

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