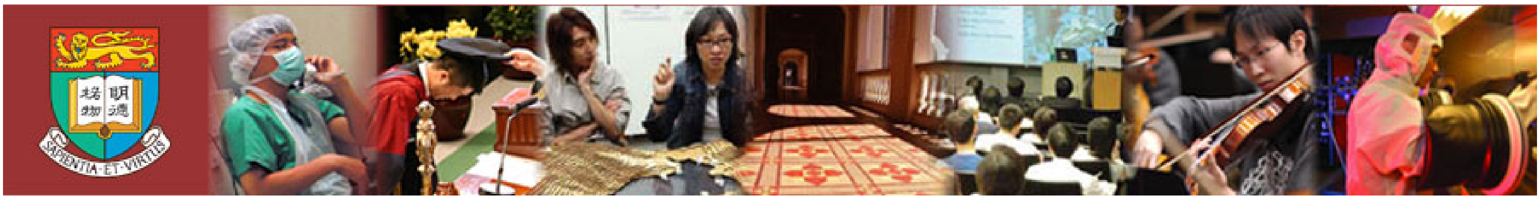

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Fourier Domain Mode Locking Laser Sweeping Based On Optical Parametric Amplification

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Abstract: We present a Fourier domain mode locked (FDML) laser scanning from 1516 to 1550 nm and 1567 to 1597 nm using optical parametric amplifier (OPA) as the gain medium. The output power of -4.85 dBm with sweep rate of 39.6 kHz is achieved.
OCIS codes: (190.4970) Parametric oscillators and amplifiers; (140.3600) Lasers, Tunable

1. Introduction

The Fourier Domain Mode Locking (FDML) technique becomes one of the most common swept-sources used for a series of biomedical imaging, spectroscopy and sensing applications [1-3]. In FDML, a laser cavity is constructed by a gain medium and a tunable optical bandpass filter which is driven by a sawtooth signal in order to match the optical roundtrip time of light in a several kilometer long laser cavity [4]. As the sweeping wavelength range of FDML is determined by the amplification regime of the gain medium used, different gain media 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 and some sweeping wavelengths cannot be demonstrated. For RA, [ref. 6] shown that the sweeping range was only 30nm. For fiber OPA, thanks for its femtosecond response time [8], high gain [9] and wide gain bandwidth [10], it enables us to vary the sweeping wavelength range by changing the position of pump wavelength with potential gain bandwidth of 200 nm. 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. In this paper, we propose and demonstrate a FDML using OPA as the only gain medium without extra EDFA inside the cavity and using fiber Fabry-Perot filter (FFP-TF) as tunable filter. The lasing wavelength is swept from 1516 to 1550 nm and from 1567 to 1597 nm with total sweep range of 64 nm. An output power of -4.85 dBm is achieved at sweep rate of 39.6 kHz with lasing line width is about 0.08 nm. The output spectrum of the wavelength-swept laser and the output pulse shape are shown.

2. Experimental setup

The schematic diagram for the FDML wavelength swept laser bases on OPA is shown in Fig. 1. The gain medium is 400-m highly-nonlinear dispersion-shifted fiber (HNL-DSF) with zero-dispersion wavelength (ZDW) at 1554 nm and dispersion slope of 0.035 ps/nm^2/km.

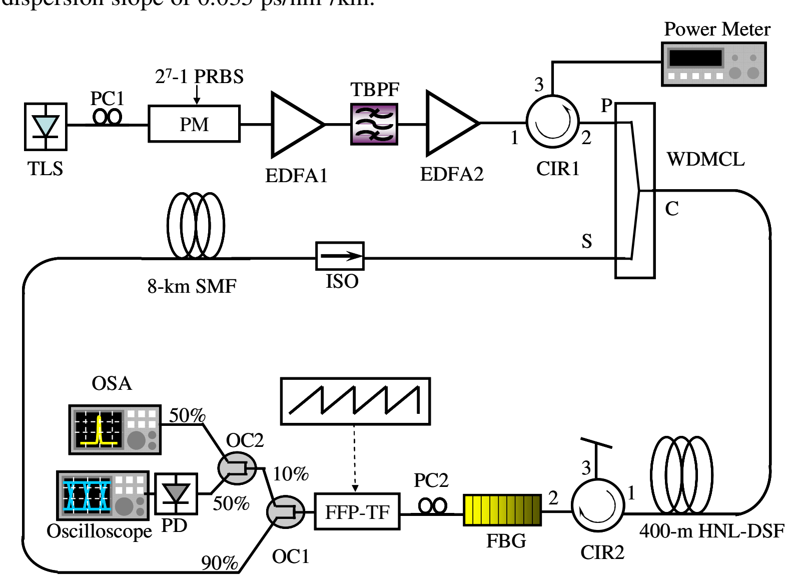

Fig. 1. Experimental setup of FDML based on OPA.

The pump is generated by a continuous-wave (CW) tunable laser source (TLS) with wavelength at 1555 nm. It is then phased modulated by a phase modulator (PM) with 10 Gbps 2^7-1 pseudo-random bit sequence (PRBS) in order to suppress the stimulated Brillouin scattering (SBS) effect [12]. The polarization controller (PC), PC1, is used to align the state of polarization (SOP) of the pump to the PM. The pump is then amplified by two-stage EDFAs, EDFA1 and EDFA2, with a tunable bandpass filter (TBPF) inserted between the two EDFAs to remove amplified spontaneous emission (ASE) noise. A circulator (CIR1) is inserted between the EDFA2 and wavelength-division multiplexing coupler (WDMCL) to prevent the reflected pump power from HNL-DSF that will damage the equipment. Power meter is used to monitor the reflected pump power. After CIR1, the pump is launched to HNL-DSF for parametric amplification through port P (λ_{pump} = 1553.23 - 1555.44 nm) of WDMCL. As the pump power is about 1.3 W, in order to prevent the pump oscillating inside the cavity and cause damage, a fiber Bragg grating (FBG) with center wavelength 1555 nm is used to remove the pump. CIR2 is used to couple away the reflected pump. To enable FDML operation, the FFP-TF is driven by a triangular 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 needed to synchronize the cavity round trip time, 8-km single-mode fiber (SMF) is added inside the cavity. Isolator (ISO) in the cavity is to enable uni-directional operation. The signal is coupled back into HNL-DSF through port S (λ_{signal} = 1527.51 - 1552.47 nm, 1556.46 - 1565.60 nm) of WDMCL. A 10/90 optical coupler (OC1) in the cavity provided 90% feedback and 10% output. The output signals are monitored by an optical spectrum analyzer (OSA) and oscilloscope through photodetector (PD) with 26-GHz bandwidth through OC2.

3. Experimental results and discussions

Fig. 2(a) shows the spectra of the wavelength-swept laser from 10% port of OC1. The sweeping ranges are from 1516 to 1550 nm and 1567 to 1597 nm with total 64 nm usable FDML spectra. The disjoint sweeping range is due to the characteristic gain spectrum for one pump OPA. The non-uniform shape of the FDML spectrum is due to its corresponding gain spectrum of one pump OPA. These two problems can be solved by using two-pump OPA [13]. For two-pump OPA, the two pumps are located at two sides of gain spectrum so that when we filter away the pumps, it will not cause the disjoint of spectrum. Moreover OPA with two orthogonal pumps is able to provide a polarization independent flat gain spectrum which may give a uniform and flatter FDML spectrum. The central spike located at wavelength 1555 nm is the residual pump from OPA; we believe that it can be further suppressed by using another FBG with higher reflectivity. Fig. 2(b) shows the pulse waveform of the corresponding spectra. From the waveform, it can be observed that there are four pulses for each scan, two for up-scan and two for down-scan. In the up-scan range, the filter is tuning from short to long wavelength while the opposite occurs in down-scan. In normal case, there are one up-scan pulse and one down-scan pulse for the whole scanning period. In our case, there are two up-scan pulses and two down-scan pulses; the reason is due to the disjoint sweeping ranges. The asymmetry of the up-scan pulses and down scan-scan pulses is due to the uneven gain at different wavelength. Again, these two problems can be solved by two-pump OPA.

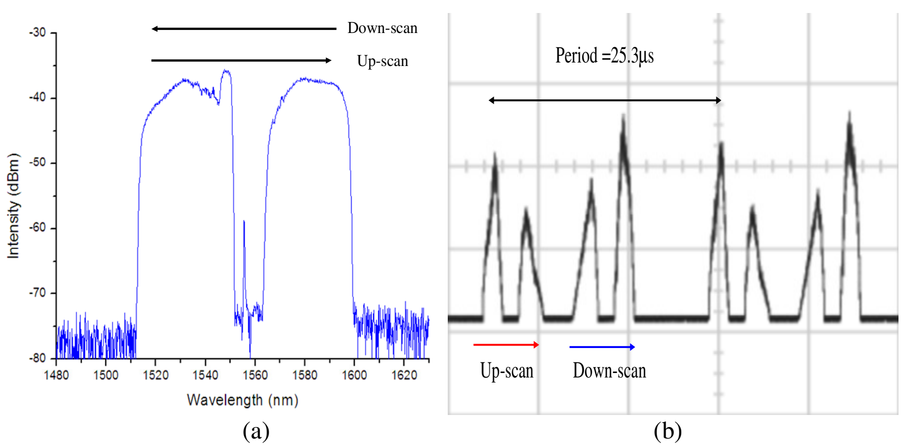

Fig. 2. (a) Output spectrum of the wavelength-swept laser, (b) corresponding pulse waveform with time scale is 10 µs/div.

Fig. 3 shows the discrete spectra of the wavelength-swept of the laser by adjusting the bias voltage of FFP-TF manually instead of applying a sawtooth voltage. The little spikes are due to the four wave mixing (FWM) effect. When the signal is filtered by FFP-TF and looped back to the cavity, an idler will be generated. After several roundtrips, the power of idler will be high and cannot be completely removed by FFP-TF which causes those spikes. From the spectra, it can be observed that for the region around 1550 nm, the power of lasing wavelengths are smaller, the reason is due to smaller OPA gain at that region. The lasing wavelength is stable with linewidth of about 0.08 nm.

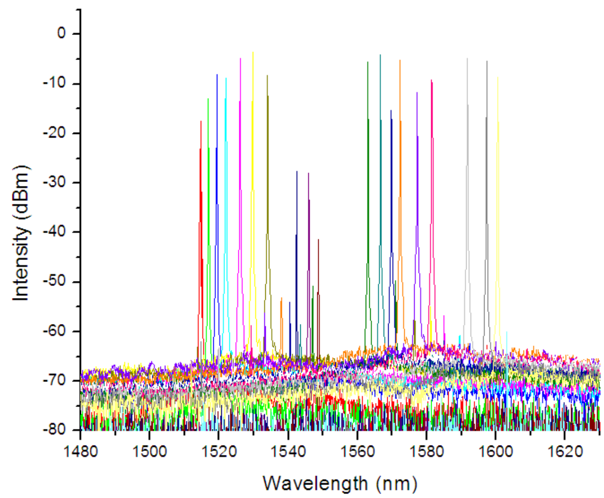

Fig. 3. Output spectra of the wavelength-swept laser with DC voltage applied to FFP-TF.

4. Conclusions

We have proposed and demonstrated an FDML wavelength-swept fiber laser using OPA as the gain medium. The sweeping range was from 1516 to 1550 nm and 1567 to 1597nm with output power -4.8dBm at sweep rate of 36.9 kHz. The output spectra and pulse waveform were observed. The experiment can be further improved by using two-pump OPA in which it will produce continuous and flat gain spectrum.

5. Acknowledgment

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