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A novel generation scheme of ultra-short pulse trains with multiple wavelengths

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ABSTRACT

We demonstrate a novel scheme based on active mode locking combined with four-wave mixing (FWM) to generate ultra-short pulse trains at high repetition rate with multiple wavelengths for applications in various fields. The obtained six wavelengths display high uniformity both in temporal and frequency domain. Pulses at each wavelength are mode locked with pulse duration of ~44.37 ps, signal-to-noise ratio (SNR) of ~47.89 dB, root-mean-square (RMS) timing jitter of ~552.7 fs, and the time-bandwidth product of ~0.68 at repetition rate of 1 GHz. The experimental results show this scheme has promising usage in optical communications, optical networks, and fiber sensing.

1. Introduction

Ultra-short pulse sequences at high repetition rate with multiple wavelengths have important applications for dense-wavelength-division multiplexing (DWDM) networks [1], optical-time-division multiplexing (OTDM) networks, and optical fiber sensors [2]. Previously, various methods to generate pulse trains with multiple wavelengths have been proposed. Most of them utilize passively mode-locked fiber laser systems with fiber Bragg gratings [3–6], however, the obtained pulse trains have the disadvantages of low repetition rate and undesirable profile. Another of them make use of injection locking of gain switched fabry-perot (FP) laser diodes [7,8], nevertheless, the output pulse train is often highly chirped with low power. Also, many other methods are reported, such as temporal-spectral multiplexing of the optical pulses [9,10], inserting frequency shifter in the laser cavity or employing specially designed dispersion fibers in cavity [11–15], but both of them show defects of low signal-to-noise ratio (SNR) and unstable operation.

Therefore, in this paper, we proposed a promising scheme to achieve ultra-short pulse trains with multiple wavelengths by combining active mode-locking technique with non-degenerate four-wave mixing (FWM) effect. Active mode-locking is a key method to get ultra-short optical pulses [16–19], which has many advantages including high repetition rate, low root-mean-square (RMS) timing jitter [20] and long-term stability. And, non-degenerate FWM is a third order nonlinear effect [21–24], which performs high benefits such as ultra-fast response time, high wavelength conversion efficiency and flexible wavelength selection. Furthermore, by adjusting parameters as pump wavelength, power, and polarization state to meet phase-matching [25–27] for FWM, a variety of wavelengths are obtained stably and effectively. Experimental results show that ultra-short pulse sequences at 1 GHz with six standard ITU-100G wavelengths are generated simultaneously. Benefiting from active mode locking in SOA-based ring-cavity fiber laser with forward injecting, the achieved pulses at each wavelength are mode locked with pulse duration of ~44.37 ps, signal-to-noise ratio (SNR) of ~47.89 dB, root-mean-square (RMS) timing jitter of ~552.7 fs, and the time-bandwidth product of ~0.68 at repetition rate of 1 GHz. Due to non-degenerate FWM in HNLF [28–31], the six wavelengths we obtained shows perfect uniformity, which can be directly applied in optical communications, optical networks, and sensing.

2. Experiment setup

Fig. 1 shows the experimental configuration, which consists of three

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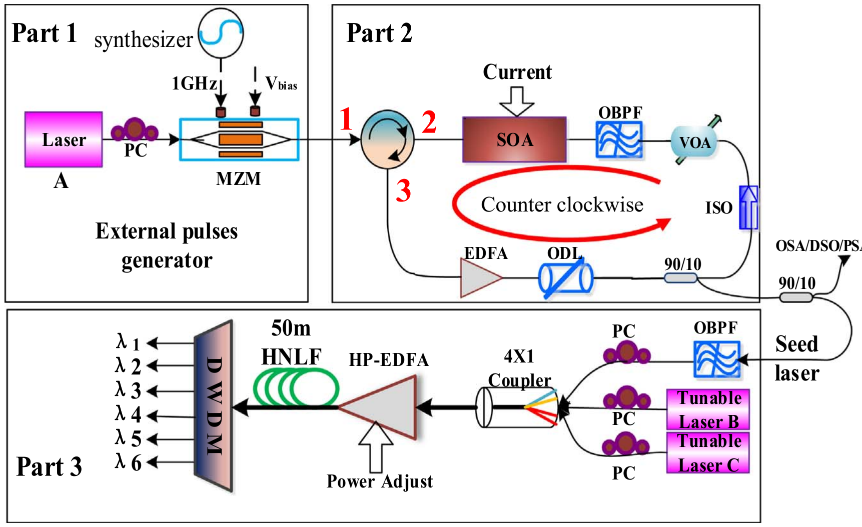

Fig. 1. Schematic diagram of experimental configuration.

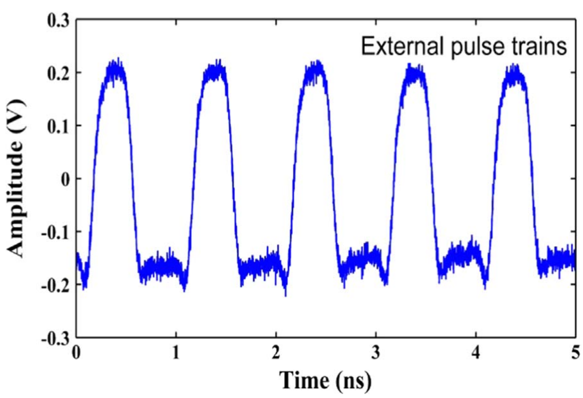

Fig. 2. External pulse trains with 1 GHz repetition rate.

parts. This mode-locked fiber laser based on actively mode-locking is composed by two part, one is the external injection signal which decides the output repetition rate of the pulse laser; the other is the mode-locked fiber cavity which aims to generate a base frequency which is 1/N (N is the integer) of the frequency of the injection to realize harmonic mode-locking. Light in the ring cavity propagates with counter clockwise direction. Part 1 is the external pulses generator providing the injection to part 2, which contains a tunable CW laser (labeled as A in Fig. 1), a LiNbO3 modulator (Eospace Company) and a radio frequency (RF) synthesizer (Analog signal Generator, Agilent E8257D). The CW laser is modulated by a 1 GHz sinusoidal signal generated from the RF synthesizer to output external pulses. To maintain the polarization state for enough output power and extinction-ratio for modulation, a polarization controller (PC, General Photonics, PLC-M02) is employed in front of the modulator.

Part 2 is a SOA-based ring cavity to produce mode-locked pulses with external injection from part 1. The external pulses are injected into the SOA-based ring-cavity via a three ports circulator. The SOA (IPSAD1503, InPhenix Company) can provide 30-dB small-signal gain with 200-mA dc drive current. A wavelength-tunable optical band-pass filter (OBPF) with a 3-dB bandwidth of 1.8 nm is inserted after SOA for wavelength selection of output pulses. An EDFA and a variable optical attenuator (VOA) are used to balance the gain and loss of the cavity, an isolator (ISO) is used to ensure unidirectional oscillation in the ring-cavity. The total length of the ring-cavity is about 32 m corresponding to the fundamental frequency of f_r =6.4 MHz. Furthermore, to realize the harmonic mode-locking of the ring-cavity, a tunable optical delay line (ODL, General Photonics, VDL-001) with maximum range of 600 ps is used to adjust the length of ring-cavity.

Light in the cavity experiences process as follows: Firstly, the external pulses are injected into the port 1 (marked “1” in part 2 of Fig. 1) of circulator and passed to the SOA through port 2 (marked “2” in part 2 of Fig. 1), the injected light is amplified nonlinearly while the gain of the SOA's active area is modulated by the periodic pulses based on XGM and XPM. Then the amplified light forwardly reaches the ISO through an OBPF and VOA, and ejected. At the same time, the emitting light of SOA backwardly reaches the port 2 of the circulator and then is passed to EDFA through port 3 (marked “3” in part 2 of Fig. 1). Then

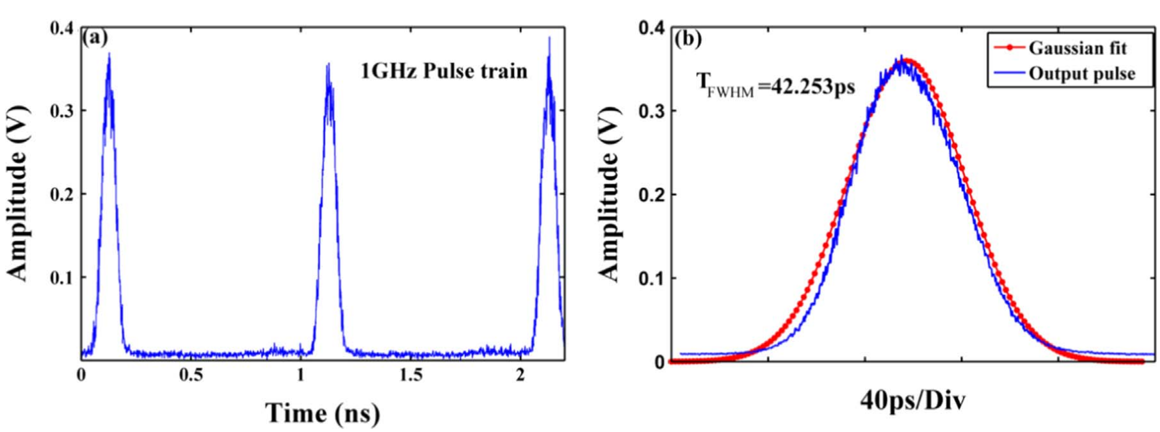

Fig. 3. (a) The mode-locked pulse trains of seed laser. (b) Comparison of pulse trace and Gaussian profile.