

A 3.5-ps Mode-Locked Semiconductor Optical Amplifier Fiber Laser generated by 60-ps Backward Optical Dark Pulse-Train Injection

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ABSTRACT

The relationship between the backward optical injection waveform and the mode-locked pulse shape of semiconductor optical amplifier fiber laser (SOAFL) is studied. The SOA plays both the roles of a gain medium and an optically controlled modulator in this work. The injected optical comb-like bright and dark pulse-train with 60-ps pulsewidth was generated using a Mach-Zehnder intensity modulator (MZM) which DC-biased voltage of 1.7 V and 7.2 V, respectively. The backward injection of optical dark pulse-train results in a wide gain-depletion width (and a narrow gain window) within one modulation period, which is necessary for perfect mode-locking the SOAFL. In opposite, the backward injection of short optical pulse of bright optical pulse-train only causes a less pronounced gain-depletion effect. Such a broadened gain window can hardly initiate the mode-locking process. The backward comb-like dark pulse-train modulation is much easier to initiate harmonic mode-locking in the SOAFL than the bright pulse-train or sinusoidal-wave injection, which generates pulsewidth as short as 15 ps at 1 GHz. After propagating through 195m-long dispersion-compensating fiber, the pulsewidth of the mode-locked SOAFL can be linearly compressed to 13.5 ps. The linewidth and time-bandwidth product of the compressed SOAFL pulses are 1.78 nm and 0.8, respectively. The pulsewidth can further be nonlinearly compressed by using a 4695m-long single-mode fiber. The shortest mode-locked SOAFL pulsewidth of 3.5 ps at repetition frequency of 1 GHz by using cross-gain modulation technique is reported for the first time.

Keywords: semiconductor optical amplifier (SOA), Mach-Zehnder intensity modulator, comb-like dark pulse-train, modulation, optical cross-gain modulation, harmonic mode-locking, nonlinear compression.

1. INTRODUCTION

Backward injection is a novel technology to achieve mode-locked semiconductor optical amplifier fiber laser (SOAFLs). Gain and loss modulation are well-known techniques for achieving mode-locking in versatile lasers. Many experiments on cross-gain-modulation (XGM) based mode-locked lasers have been studied in detail [1-16]. Patrick primarily demonstrated an actively rational-harmonic mode-locked EDFL with 8.4 ps pulses at a repetition rate of 20 GHz using an all-optically-modulated SOA as a mode-locker [7]. In this approach, the SOA was operated at the high-gain condition and gain-depleted by a high-power mode-locked laser pulse-train, resulting in a complicated phase and amplitude modulation of the circulated light in EDFL. Later on, the backward optical injection has emerged as a new mode-locking technology for semiconductor optical amplifier (SOA) based fiber lasers (SOAFLs), which is achieved by seeding a high-level pulse-train to result in the XGM of the SOA in the SOAFL. A mode-locked pulsewidth of 4.3 ps under such an XGM technique was demonstrated by gain-depleting the SOA via a compressed pulse-train generated by a gain-switched distributed-feedback laser diode (DFBLD) [8]. The SOA plays both the roles of a gain medium and an optically controlled modulator in aforementioned works, while the mode-locking is initiated after fast periodical gain-depletion and relatively slow gain-recovery in the SOA under strong pulse injection. Recently, higher repetition rate (up to 40 GHz), shorter pulsewidth (2.5 ps), and wider wavelength tuning range (~ 20 nm) have also been obtained from the SOAFL [10]. Notably, multi-wavelength channeled output has also been reported [11]. More recently, Lin et al. [16] obtained the shortest mode-locked pulsewidth of 12 ps at repetition frequency of 5 GHz in their SOAFL for the first time. In this case, the SOA can be employed as a loss-modulator by using XGM technique with a separated constant-gain medium in the SOAFL. The optical sinusoidal-wave signal from DFBLD was backward injected into one SOA (driven at 72 mA) for loss-modulation and the other constant-gained SOA (needed as the gain-medium in the SOAFL) was driven by 142 mA. The sufficiently high injection therefore saturates the SOA and depletes its excited state

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electrons to cause the wavelength of mode-locking ‘see’ periodical loss in the ring cavity. A theoretical model for explaining the effect of the waveform shape of the modulating signal on the mode-locking performance of the SOAFL is proposed [16]. In their work, different mode-locking results of the SOAFL with the sinusoidal-wave and pulse modulated SOA, and their correlation with the gain depletion dynamics is discussed and compared. In this paper, the relation between the injection waveform and the mode-locked pulse shapes is demonstrated for the first time. A bright comb-like and a dark comb-like pulse-train are injected into the SOAFL, respectively, to observe the shapes of the mode-locked pulses. To obtain the shortest pulsewidth at 1 GHz, a dark comb-like pulse-train is capable of generating the shortest pulse of 15 ps. The characteristics such as pulsewidth and pulse shape between these two opposite modulation schemes are also compared and explained.

2. EXPERIMENTAL SETUP

Figure 1 illustrates the backward-optical-injection mode-locked SOAFL system, which consists of one travelling-wave typed SOA, a 1.55- μm butterfly-packaged DFBLD with central wavelength of 1535 nm at specified temperature of 25 $^{\circ}\text{C}$, a comb generator, an erbium-doped fiber amplifier, a Mach-Zehnder interferometer intensity modulator (MZM), an optical circulator, a faraday optical isolator, an optical tunable bandpass filter (OBPF), and an optical coupler with power-splitting ratio of 50:50. The SOA which is DC-biased at highly above threshold (225 mA) is backward injected by the comb-like dark pulse-train generated by the DFBLD. In principle, the SOA plays both the roles of gain medium and modulator.

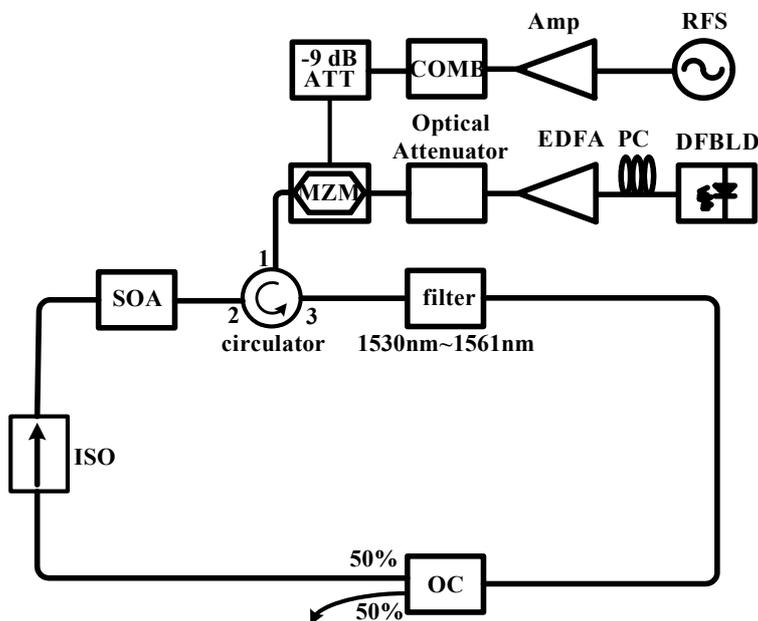


Fig. 1 Schematic diagram of the backward injection mode-locked SOAFL. ATT: electrical attenuator; Amp: power amplifier; COMB: comb generator; circulator: optical circulator; DFBLD: distributed feedback laser diode. EDFA: erbium-doped fiber amplifier; ISO: optical isolator; OC: optical coupler; SOA: semiconductor optical amplifier; RFS: RF synthesizer.

The linearly modulated DFB is backward seeded into the SOAFL for XGM operation, which then induces harmonic mode-locking via the fine adjustment of the modulation frequency to match the one harmonic mode of the SOAFL. To obtain the comb-like dark pulse-train, an electrical pulse generator (comb generator) in connection with a MZM is used to modulate the backward injection continuous light. The comb generator is driven by a RF synthesizer (ROHDE&SCHWARZ SML01) with a power amplifier of 40-dB gain at repetition frequency of 1 GHz. The short electrical pulse generated by the comb generator is used to modulate the Mach-Zehnder intensity modulator, which is biased at 1.7 V to obtain the comb-like pulse-train. The generated comb-like dark pulse-train is observed by a digital

sampling oscilloscope. The biased current of the DFBLD and RF modulation power of the RF synthesizer are optimized at 70 mA and 12 dBm, respectively. Note that the electrical pulse-train is attenuated by a RF attenuator and the MZM is biased at positive operating region to avoid distortion of the pulse shape. Figure 5 also shows the characteristic curve of MZM. When the MZM is biased at 1.7 V in the positive operating region (see Fig. 5) and modulated by the electrical comb-like dark pulse-train, the output optical pulse-train is obtained, as shown in Fig. 6 (A). When the MZM is biased at 7.2 V in the negative operating region (see Fig. 5) and is modulated by the electrical comb-like dark pulse-train, the output optical pulse-train is obtained, as shown in Fig. 6 (B). The average power of the comb-like dark pulse-train modulated DFBLD which is injected into the SOAFL is 4.46 mW. The pulsewidth of the injected dark/bright comb-like pulse-train from DFBLD is 60 ps. When the dark comb-like pulse is injected into the semiconductor optical amplifier, the output pulsewidth of the mode-locked pulse-train is 15 ps. In contrast, when the bright comb-like pulse-train is injected into the semiconductor optical amplifier, the mode-locked pulse-train will carry a large pedestal. The modulation depth is adjusted to nearly 100% by controlling the DC bias current of the SOA. In experiment, the optical dark pulse-train generated from DFBLD is backward injected into the SOAFL via an optical circulator. The use of the isolator in the ring cavity of the SOAFL ensures the unidirectional propagation of light, and prevents the lasing circulation of the seeded DFBLD signal in the ring cavity of the SOAFL. The cavity length is 14.14 m, corresponding to the fundamental frequency of 14.14 MHz. Consequently, the harmonic mode-locking of the SOAFL is achieved when the modulation frequency of the injected dark pulse-train of DFBLD coincides with any one harmonic longitudinal-mode frequency of the SOAFL. The central wavelength and output power of the DFBLD backward-injection mode-locked SOAFL are 1530.24 nm and 26.78 μ W, respectively. The SOAFL output power is monitored using an optical power meter (ILX Lightwave, OMM-6810B). The peak amplitude and pulsewidth of mode-locked SOAFL pulses are measured via a digital sampling oscilloscope (HP 86100A+86116A, $f_{3dB} > 53$ GHz and $t_{FWHM} = 9$ ps).

3. RESULTS AND DISCUSSION

3.1 Backward injection of the comb-like dark pulse-train into SOA

The comb-like dark pulse-train generated from DFBLD is backward injected into the semiconductor optical amplifier (driven at 225 mA) for loss-modulation. As the DFBLD power was increased from 1.31 to 4.46 mW, the mode-locked SOAFL pulsewidth shrink significantly.

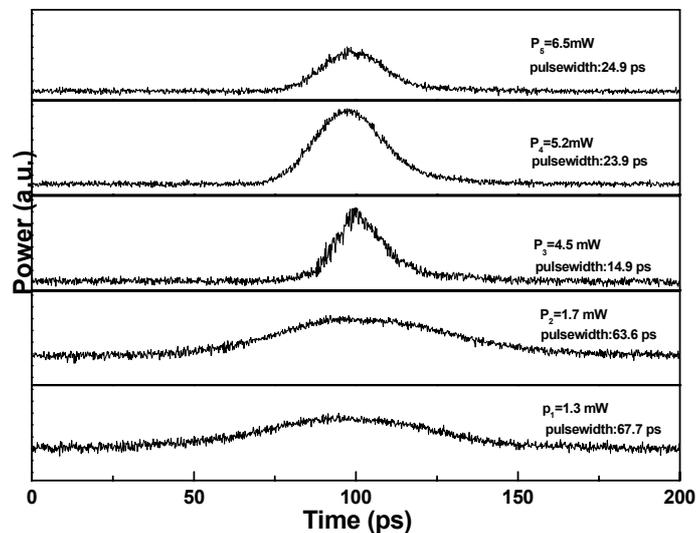


Fig. 2 Temporal traces of measured pulsewidth by detuning injection power.

In principle, the mode-locking pulsewidth (t_{FWHM}) is directly proportional with $(g_0)^{1/4}/(\delta^2 \cdot f_m^2 \cdot \Delta\nu^2)^{1/4}$, where f_m denotes the modulation frequency, $\Delta\nu$ represents homogeneous linewidth, g_0 is single-pass integrated gain, and δ denotes the on-to-off modulation depth. The insufficient backward-injecting power from DFBLD thus could not effectively deplete the gain of SOA, which fails to induce sufficient modulation depth δ in SOA for perfect mode-locking. Perfect mode-locking of the SOAFL is achieved when the DFBLD injecting power increases to 4.46 mW. The corresponding pulsewidth and peak power are 15 ps and 1.41 mW, respectively.

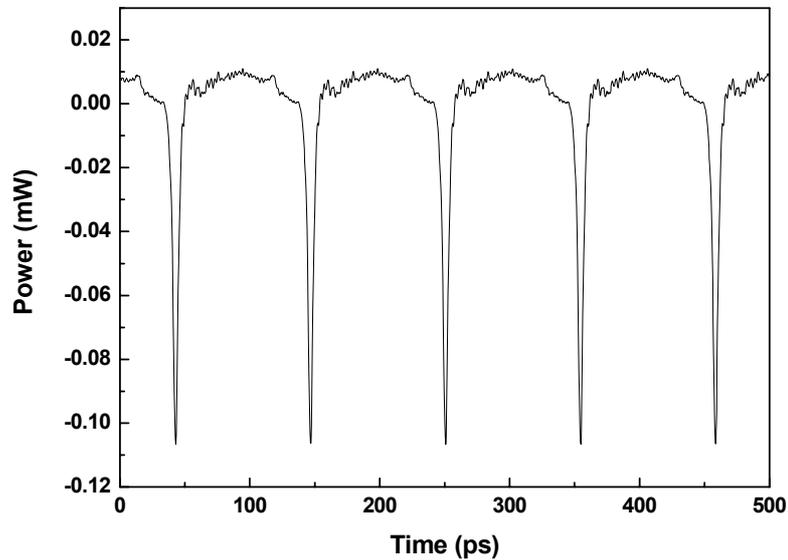


Fig. 3 The electrical comb-like pulse-train.

3.2 Compare the results of the SOAFL with the comb-like pulse-train and dark pulse train modulated SOA

Figure 3 shows the electrical comb-like dark pulse-train. Figure 5 shows the characteristic curve of the MZM. When the MZM is biased at 1.7 V in the positive operating region (see Fig. 5) and modulated by the electrical comb-like dark pulse-train, the output optical pulse-train is obtained, as shown in Fig. 6(A). In this approach, the SOA was operated at the high-gain condition and gain-depleted by a high-power output optical pulse-train, resulting in a short pulse-train, as shown in Fig. 6(C). In contrast, when the MZM was biased at negative operating region (7.2 V), the modulated signal was inverted in shape as compared with the former. When the MZM is biased at 7.2 V in the negative operating region (see Fig. 5) and modulated by the electrical comb-like dark pulse-train, the output optical pulse-train is obtained, as shown in Fig. 6(B). In contrast, the SOA was operated at the high-gain condition and gain-depleted by a short-pulsewidth and high-power optical pulse-train. Thus, the short gain-depletion period and the large residual gain in the semiconductor optical amplifier result in a pulse-train with an obvious pedestal, as shown in Fig. 6(D).

Previously, Patrick *et al.* have ever obtained a pulsewidth of 8.4 ps at 10 GHz from a similar system using the externally injected pulses are derived from a 10 GHz, 1543 nm harmonically mode-locked external cavity semiconductor laser. These pulses are optically amplified in a dual-stage 1480 nm-pumped erbium-doped fibre amplifier (EDFA), which launches a mean optical power of 10dBm into the TWSLA via a wavelength division multiplexing element, assuming a net loss of 7 dB across the TWSLA. He *et al.* also reported a pulsewidth of 21 ps at 5 GHz in a wavelength tunable cross-gain modulated SOAFL. T. Papakyriakopoulos *et al.* demonstrated a nearly transform-limited 4.3-ps pulse-train at 20 GHz over a 16-nm tuning range with the externally introduced pulses were generated from a 10-GHz gain-switched DFB laser diode operating at 1548.5 nm. These pulses were compressed to 15 ps with dispersion-compensation fiber (DCF) before being amplified in an EDFA and injected into the ring cavity. With a fine adjustment on the waveform of backward injected optical signal, we have previously obtained the shortest mode-locked pulsewidth of 12 ps from the SOAFL at repetition frequency of 5 GHz by using either sinusoidal-wave or digital TTL pattern

externally modulated DFBLD. In comparison, our scheme show a great potential in generating shorter pulses at higher repetition rates since the mode-locked laser pulsewidth is inverse proportional to the square root of repetition frequency. On the other hand, Kim et al. externally modulated SOAFL have ever observed the compression of an 18.4 ps pulse from an externally sinusoidal-wave modulated SOAFL system. After passing through a 2-km standard SMF with an anomalous group velocity dispersion of 18 ps/km-nm at 1550 nm, the output laser pulse was compressed to a transform-limited one, which exhibits pulsewidth, linewidth and time-bandwidth product of 6.8 ps, 0.5 nm and 0.44, respectively.

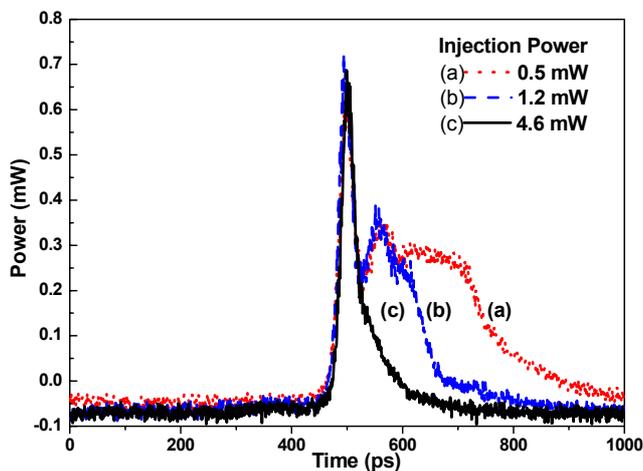


Fig. 4 The Effect of injection power on mode-locking pulsewidth

By varying the backward injection power of the dark pulse-train, the insufficient injection power (see traces (a) and (b) of Fig. 4) induces a pedestal following the pulse. Smaller injection power causes a larger pedestal. As the injecting power increases to 4.6 mW, a pulse without the pedestal is obtained. Therefore, the sufficient gain-depletion time (by enlarging the backward injecting power) and short gain-recovery time are essential for mode-locking the SOAFL.

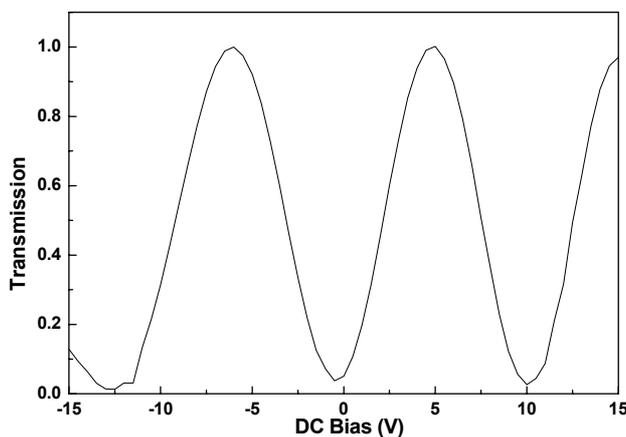


Fig. 5 The characteristic curve of Mach-Zehnder intensity modulator.

On the other hand, the backward injection of the bright pulse only depletes the gain of the SOA at a relatively narrow duration, which leaves a large amount of residual gain in the SOA. As a result, the mode-locked pulse is generated, but contains a long pedestal in the falling part. Such a nearly steady state pedestal behind the mode-locked pulses can not be eliminated even by optimizing all of the other system parameters.

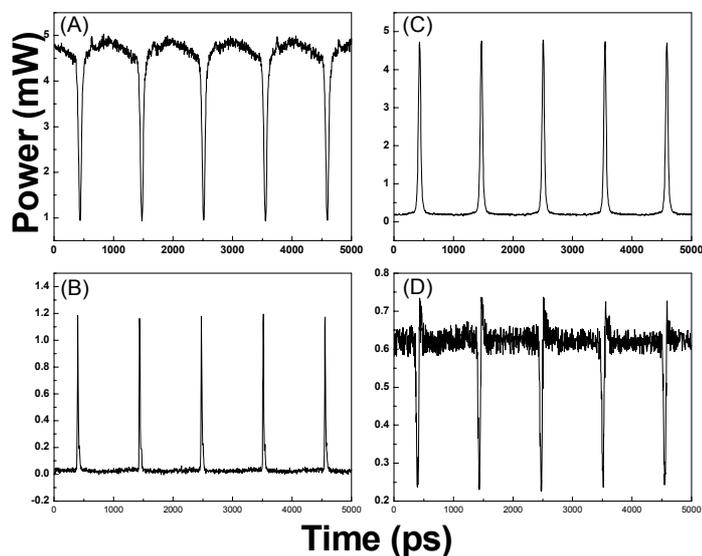


Fig. 6
 A. The optical comb-like dark pulse-train.
 B. Experimental pulse shapes of the SOAFL mode-locked by optical comb-like dark pulse-train.
 C. The optical comb-like bright pulse-train.
 D. Experimental pulse shapes of the SOAFL mode-locked by optical comb-like bright pulse-train.

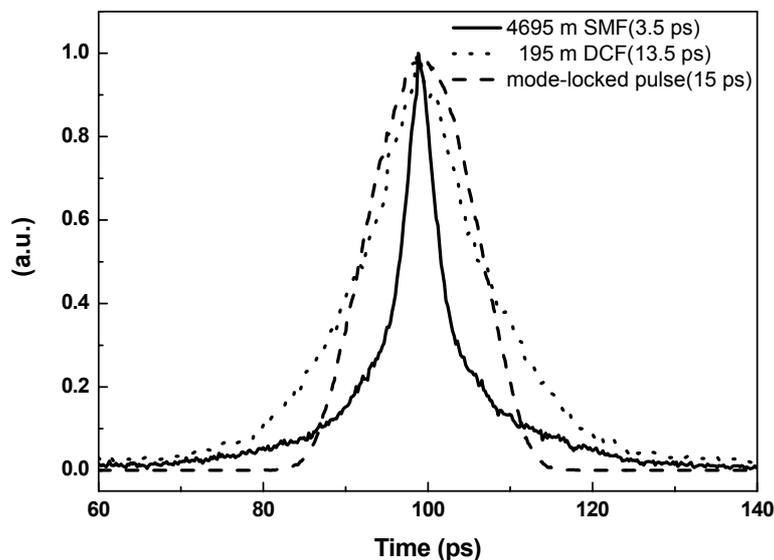


Fig 7. Comparison of three kinds of pulsewidth from mode-locked, linear compression and nonlinear compression.

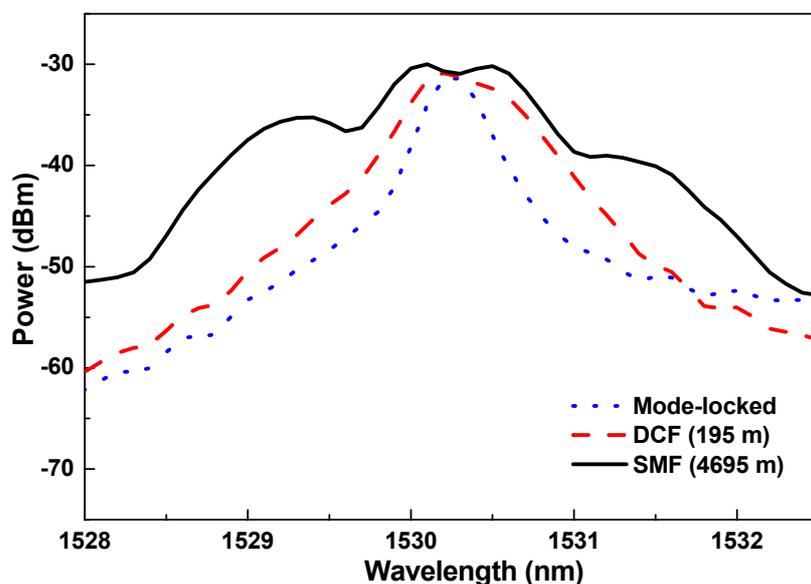


Fig 8. Lasing spectra of dark optical comb mode-locked SOAFL before (dotted) and after propagating through 195 m DCF (dashed) or 4695 m SMF (solid).

After propagating through 195m-long dispersion-compensating fiber, the pulsewidth of the mode-locked SOAFL can be linearly compressed to 13.5 ps, as shown in Fig. 7. Because the mode-locked pulse output power is too low to generate a high-order soliton, an additional optical power amplifier is added between the MZM and DFBLD. Thus, the amplified peak power of the pulse can induce a high-order soliton effects and the pulse can be further compressed to 3.5 ps. The linear and nonlinear pulse compression experimental results are shown as Figure 7. Figure 8 shows the optical spectra of mode-locked pulses under original, linearly compressed, and nonlinearly compressed condition, respectively. In original mode-locked pulse, the linewidth and time bandwidth product are 15 GHz and 0.81, respectively. After propagating through 195m-long DCF, the linewidth and time bandwidth product of the mode-locked pulse are 38 GHz and 0.52, respectively. The nonlinear compression via 5km SMF further increases the linewidth of SOAFL pulse to 260 GHz, while the time bandwidth product is 0.91.

4. CONCLUSION

The harmonic mode-locking dynamics of an optical backward injection modulated SOAFL has been investigated. The backward comb-like pulse-train modulation is much easier to initiate harmonic mode-locking in the SOAFL than the sinusoidal-wave pulse-train modulation and can generate mode-locked pulse with pulsewidth of as short as 15 ps at 1 GHz. The effects of gain-depletion time and gain-recovery time on the build-up of the mode-locked SOAFL pulse-train are elucidated in our previous work, and the comb-like pulse-train are found to be extremely suitable for XGM induced mode-locking. The difficulty in mode-locking the SOAFL by an optical short pulse injection is also demonstrated and explained, which is attributed to the insufficient gain-depletion time and the large residual gain in the SOAFL. The results indicate that the SOAFL mode-locked by backward optical comb-like dark pulse-train exhibits better mode-locking performance than that modulated by a comb-like bright pulse-train. The mode-locked pulse can be further compressed after propagating through 195m-long DCF (13.5 ps) and 4695m-long SMF (3.5 ps).

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