Chapter 3

Backward Bright- and Dark- Optical-Comb Injection Mode-locked semiconductor optical amplifier fiber laser at repetition rates of 1 GHz and 10 GHz

3.1 Introduction

Backward optical injection is a novel technology to achieve mode-locking in semiconductor optical amplifier based fiber-ring lasers (SOAFLs) [1-8]. The backward optical injection induced periodical gain-depletion as well as cross-gain modulation (XGM) in a SOAFL has been experimentally demonstrated and theoretically discussed [4-6]. Previously, a 4.3-ps pulse was obtained by gain-depleting the SOAFL with a compressed laser diode pulse-train at repetition of 20 GHz [2]. Similar experiments demonstrated at a higher repetition rate up to 40 GHz, a shorter pulsewidth of 1.9 ps and a wider wavelength tuning range of about 20 nm [3-5]. Particularly, the comparison between sinusoidal-wave and pulsed injection induced XGM and mode-locking were done to explain the effect of the injecting waveform on the gain-depletion dynamics and the mode-locking performance of SOAFL. The established theoretical model suggests an optimized mode-locking under sufficiently large-duty-cycle and high-level injection. In this paper, we demonstrate for the first time the comparison on optical harmonic mode-locking of a SOAFL via backward injection of optical comb-like bright and dark pulse-trains (referred hereafter as bright- and dark-optical combs) with a pulsewidth of 60 ps at repetition frequency of 1 GHz. The differences in mode-locked pulsewidth and pulse shape between two opposite modulation schemes are also interpreted, and the correlation between the gain-depletion time and mode-locking pulsewidth is discussed. To further shorten the SOAFL pulsewidth, the fiber-based linear dispersion compensation and nonlinear soliton compression techniques are also reported.

3.2 Experimental setup and principle of operation

Figure 3.2.1 illustrates the backward-optical-injection mode-locked SOAFL system with cavity length of 14 m, which consists of one traveling-wave typed SOA at 1530 nm, an optical circulator, a faraday isolator, an optical tunable bandpass filter (OBPF), and an output coupler (OC) with a power-splitting ratio of 50%.

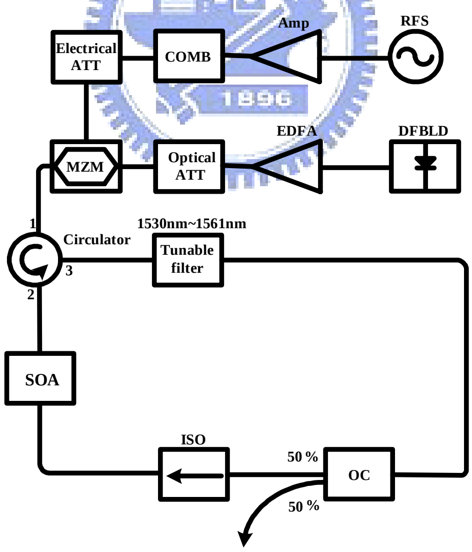

Fig. 3.2.1 The schematic diagram of the backward-optical- injection mode-locked SOAFL. ATT: attenuator; Amp: power amplifier; COMB: comb generator; DFBLD: distributed feedback laser diode. EDFA: erbium-doped fiber amplifier; ISO: optical isolator; OC: optical coupler; SOA: semiconductor optical amplifier; RFS: RF synthesizer.

The SOA was DC-biased at 225 mA (well above threshold current of 50 mA). To backward optical-inject the SOA for harmonic mode-locking, a butterfly-packaged distributed feedback laser diode (DFBLD, biased at 70 mA) operated at 1535 nm and 25^{o}C was amplified by a 20dB-gain erbium-doped fiber amplifier (EDFA), and externally modulated by a Mach-Zehnder intensity modulator (MZM) driven with an electrical comb generator (COMB). The COMB is operated at input power of 29 dBm by using an RF synthesizer (Rohde&Schwarz SML01) in connection with a power amplifier of 40-dB gain. By changing the DC-bias level of the MZM at 1.2V- and 0.3V , the bright- and dark-optical combs with pulsewidth of ≤60 ps can be obtained at the MZM output, as illustrated in Fig. 3.2.3.

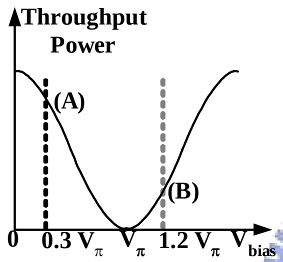

Fig. 3.2.2 The driving points of Mach-Zehnder modulator for (A) dark- and (B) bright-optical combs.

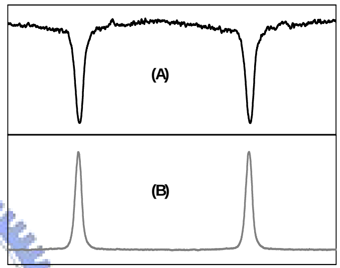

Fig. 3.2.3 The (A) dark- and (B) bright-optical combs.

The average powers of the bright- and dark-optical combs (see Fig. 3) injected into the SOAFL are 0.61 mW and 4.46 mW, respectively. The dark-optical comb is backward injected into the SOAFL via the optical circulator, which then induces a gain-depletion modulation depth of nearly 100% under fine adjustment of the SOA driving current. In contrast, the bright-optical-comb injected SOAFL leaves much residual gain in the SOA. The use of the isolator and OBPF ensure unidirectional propagation and avoid the lasing of the injected optical-comb in the SOAFL. The harmonic mode-locking is achieved when the repetition frequency of the injected dark-optical comb exactly coincides with one harmonic longitudinal-mode frequency of the SOAFL.

3.3 Results and Discussion

3.3.1 Comparison of SOAFL pulses mode-locked by comb-like dark and bright-pulse-train modulated SOA

With the backward injection of the dark-optical comb, the central wavelength and output power of the harmonic mode-locked SOAFL are 1530.24 nm and 26.78 μW, respectively. The mode-locked SOAFL pulsewidth significantly shrinks from 68 ps to 15 ps at a repetition frequency of 1 GHz (measured by an auto-correlator after de-convolution) as the average power of the dark-optical comb increases from 1.3 to 4.5 mW, which is already the shortest pulsewidth ever reported in similar systems at repetition rate of 1 GHz. The dark-optical comb injection-mode-locked SOAFL pulse shape is shown in Fig. 4(b). In principle, the mode-locking pulsewidth 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 gain bandwidth of SOA, g_0 is single-pass integrated gain of SOA, and δ denotes the modulation depth. The mode-locking pulsewidth reaches its minimum when the modulation depth is sufficiently high. However, the excess injecting power (up to 6.46 mW) oppositely leads to a pulse broadening due to the decrease in gain and modulation depth of the SOA. In contrast, the SOAFL mode-locked by backward injecting a bright-optical comb only shows a tiny pulse-train with an extremely large level of continuous-wave background. Such a worse mode-locking feature under backward injection of a bright-optical comb has previously been interpreted, as attributable to the insufficient gain-depletion of the SOA within one modulation period. When the SOA is gain-depleted by backward injection of a bright-optical comb, the gain of the SOA cannot be fully depleted and the SOA almost remains in the gain regime. This is due to the insufficient backward injected photon density by the bright-optical comb in one modulating period, which is far smaller than that by the dark-optical comb. This eventually contributes to a huge continuous-wave component in the SOAFL output.

The optimized mode-locking scheme is to operate the SOA at a high-gain condition and then gain-deplete the SOA via a high-power dark-optical comb shown in Fig. 3.3.1.1 (a). This eventually results in a perfect mode-locking pulse-train with peak power of 3.46 mW, as shown in Fig. 3.3.1.1 (b). In comparison, the backward injection of a low-power bright-optical comb (see Fig. 3.3.1.1 (c)) with short pulsewidth only depletes the gain of the SOA in a relatively narrow duration, which leaves a large amount of residual gain in the SOA. Consequently, the backward bright-optical comb injection fails to induce sufficient modulation depth δ in the SOA for perfect mode-locking as shown in Fig. 3.3.1.1 (d). The mode-locked pulse is generated from the SOAFL, but associated with a long pedestal in the falling part. Such a continuous-wave pedestal behind the mode-locked pulses cannot be eliminated even by optimizing all of the other system parameters (except the decreasing in gain of SOA). The determination of the minimum gain-depletion width required for mode-locking the SOAFL was previously demonstrated, which clearly interpreted that a backward pulsed injection with duty cycle of <30 % contributes less to the initiation of harmonic mode-locking in the SOAFL [6]. Both the larger gain-depletion (modulation) depth and the narrower gain width of the SOA are mandatory to the build-up of the mode-locking in SOAFL.

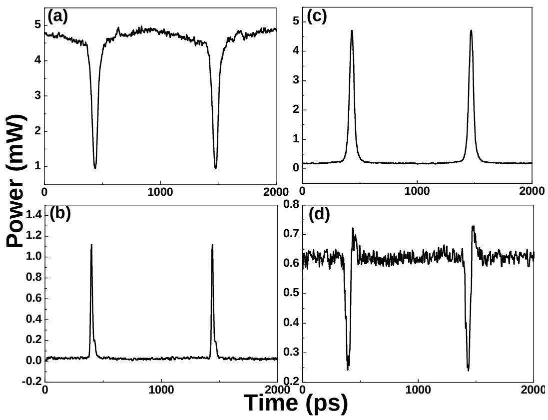

Fig. 3.3.1.1 The backward optical injected (a) dark and (b) bright-optical combs, and their corresponding mode-locked SOAFL pulse-trains are shown in (c) and (d), respectively.

By backward bright- and dark- optical-comb injection mode-locked semiconductor optical amplifier fiber laser at repetition rates of 10 GHz. A traveling-wave typed SOA with gain peak at 1556 nm and linewidth of 35 nm was DC-biased at 345 mA (well above threshold current of 50 mA). A tunable laser at 1550 nm was externally modulated by a Mach-Zehnder intensity modulator (MZM) driven with an electrical comb generator (COMB) and amplified by a 20dB-gain erbium-doped fiber amplifier (EDFA), which is then used to backward inject and cross-gain modulate the SOA for harmonic mode-locking. The COMB is operated at an input power of 41.6 dBm using an RF synthesizer (Rohde&Schwarz SML01) in connection with a power amplifier of 30 dB gain. By operating the DC-bias level of the MZM at 0 V, the dark optical-combs with pulsewidth of $\leq$ 25 ps can be obtained at the MZM output, as illustrated in Fig. 3.3.1.2 (b). The intra-cavity isolator and optical band-pass filter (OBPF) ensure unidirectional propagation and avoid the lasing of the injected optical optical-comb in the SOAFL. The backward dark-optical-comb injected SOAFL are harmonic mode-locked at central wavelength and output power of the 1556 nm and 132.2 μW, respectively.

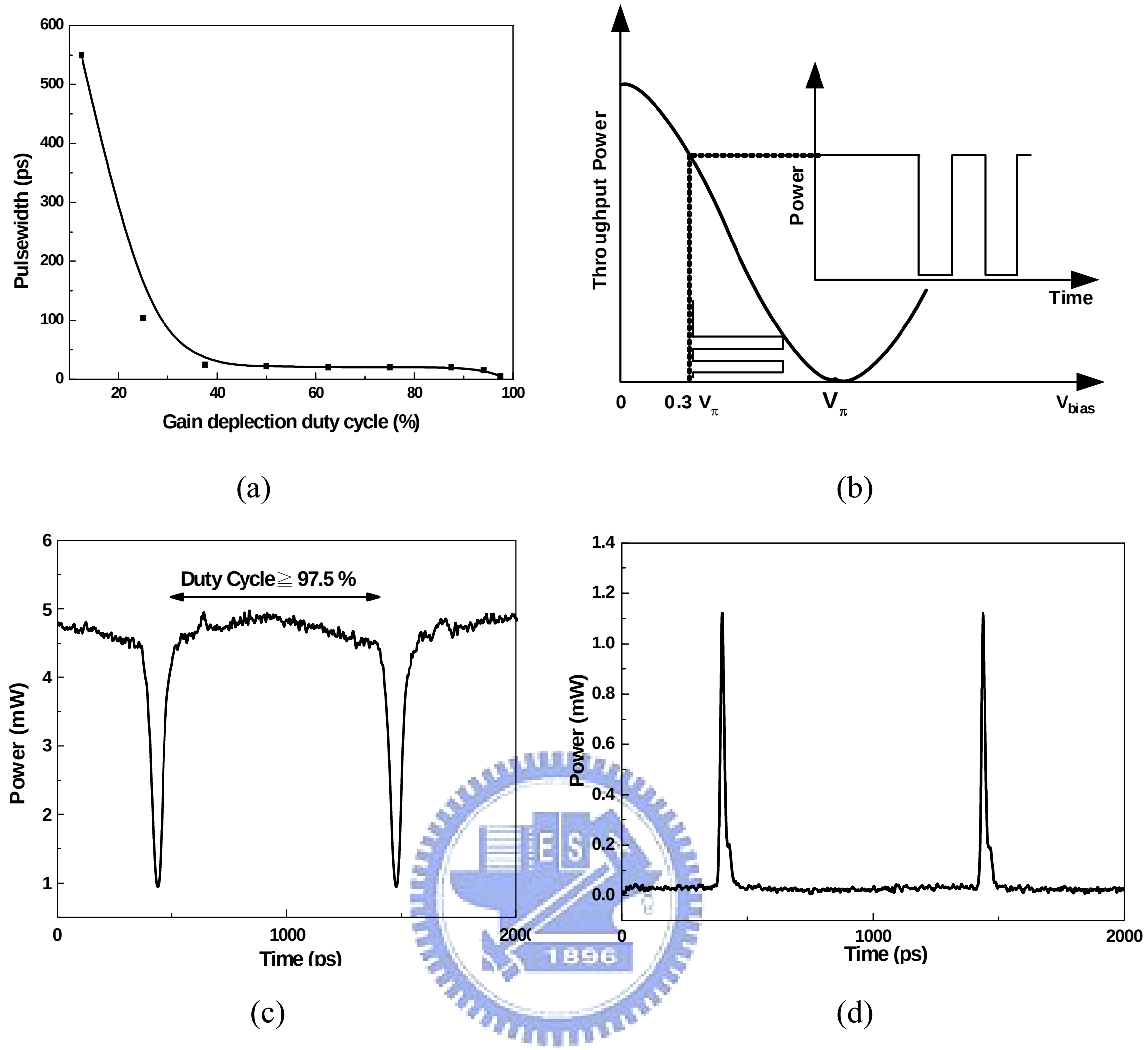

Fig. 3.3.1.2 (a)The effect of gain-deplection duty-cycle on mode-locked SOAFL pulsewidth; (b)The optimized driving condition of Mach-Zehnder modulator for dark-optical comb generation; The pulse-trains of (c) dark-optical-comb and (d) mode-locked SOAFL.

Short mode-locking pulsewidth can be obtained as the gain depletion duty cycle of the SOA is greater than 40% within one period, as shown in Fig. 3.3.1.2 (a). The experiments elucidate an optimized mode-locking condition for the SOAFL is to dissipate most of the gain in the SOA within one modulation period. This is implemented by backward injecting the SOA with a dark optical-comb shown in Fig. 3.3.1.2 (c), which induces a gain depletion duty cycle of up to 97.5% and a nearly 100% gain-depletion modulation depth in the SOAFL. Such an operation results in a perfect mode-locking pulse-train with peak power of 2.45 mW and pulsewidth of 5.4

ps (de-convolution from an auto-correlator trace) under an injecting power of 0.5 mW, as shown in Fig. 3.3.1.2 (d).

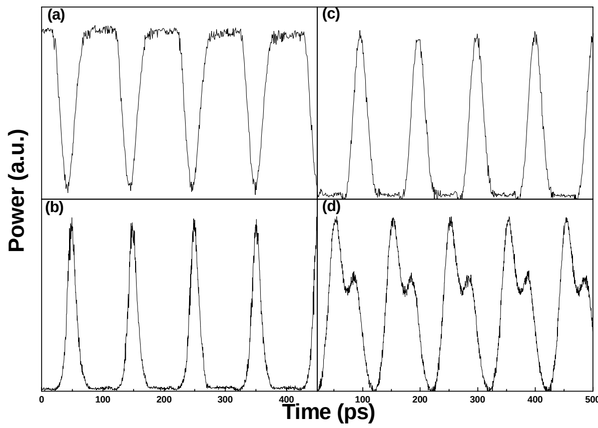

Fig. 3.3.1.3 The backward optical injected (a) dark and (b) bright-optical combs, and their corresponding mode-locked SOAFL pulse-trains are shown in (c) and (d), respectively.

Alternatively, a tunable laser operated at 1530-1550 nm was amplified by a 20dB-gain erbium-doped fiber amplifier (EDFA), and was then externally modulated by a Mach-Zehnder intensity modulator (MZM) driven with an electrical comb generator (COMB). The COMB is operated at input power of 41.6 dBm by using an RF synthesizer (Rohde & Schwarz SML01) in connection with a power amplifier of 30-dB gain. By changing the DC-bias level of the MZM at 5.2V and 0V, the bright- and dark-optical combs with pulsewidth of ≤ 25 ps can be obtained at the MZM output, as illustrated in Fig. 3.3.1.2. The average powers of the bright- and dark-optical combs (see Fig. 3.3.1.2) injected into the SOAFL are 0.44 mW and 0.5 mW, respectively. The dark-optical comb is backward injected into the SOAFL via the optical circulator, which then induces a gain-depletion modulation depth of nearly 100% under fine adjustment of the SOA driving current. In contrast, the bright-optical-comb injected SOAFL leaves much residual gain in the SOA. The use of the isolator and OBPF ensure unidirectional propagation and avoid the lasing of the injected optical-comb in the SOAFL. The harmonic mode-locking is achieved when the repetition frequency of the injected dark-optical comb exactly coincides with one harmonic longitudinal-mode frequency of the SOAFL. The Faraday isolator was used to ensure unidirectional oscillation in the ring and to prevent the externally introduced signal from circulating in the cavity. Since the SOA exhibits polarization dependent gain, a polarization controller was inserted prior to the SOA for obtaining a maximum backward injection power initially. A tunable optical bandpass filter (OBPF) with a 1.2-nm bandwidth was used for output wavelength selection, and a circulator is added behind the SOA to receive the dark-optical-comb injection and to ensure the mode-locking output in another direction.

3.4 Reference

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