The effect of backward injecting wavelength on the mode-locking dynamics of a semiconductor amplifier based fiber laser

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ABSTRACT

The wavelength dependent mode-locking performances of a SOAFL under the backward optical injection via a sinusoidal-modulated distributed feedback laser diode (DFBLD) at 1 GHz repetition rate are characterized. The backward optical injection has to be sufficiently high to saturate a SOA and then depletes most of the excited state electrons in the SOA. In order to obtain shorter mode-locking pulsewidth, the DFBLD injecting wavelength should be slightly longer than the peak wavelength of SOA gain to benefit from shorter gain-recovery time and larger modulation depth. As the wavelength of a DFBLD approach the central wavelength of SOA, the shortest pulse was measured via a digital sampling oscilloscope (DSO). The pulses can also be obtained by DFBLD backward injection at 1535 nm in feedback of SOAFL, leading to the optimized pulsewidths of 22.7 ps.

Keywords: Semiconductor optical amplifier, fiber laser, harmonic mode-locking, backward optical injection, cross-gain modulation.

1. INTRODUCTION

Semiconductor optical amplifiers (SOAs) have been demonstrated for numerous applications including optical switching [1], optical amplification [2], and all-optical wavelength conversion [3], due to their features of fast switching time [4], high optical gain, wide optical bandwidth, small dimensions, and potential for integration. However, the inherent fast gain dynamic or short carrier lifetime (< 1 ns) of SOA can lead to signal distortion if the device is operated at nearly gain-saturation condition of the SOA. The distortion can appear in several forms depending on the type of input signals. For digital signals, the distortion causes pulse distortion or intersymbol interference [5]. For analog signals, the distortion results in intermodulation distortion (IMD) or high nonlinear distortion [6]. For wavelength-division-multiplexed (WDM) signals, the distortion leads to four wave mixing or crosstalk [7]. Recently, a SOA-based fiber ring laser has been extensively investigated due to its broad wavelength-tuning range, high stability, narrow linewidth, single-mode output capability, etc. [8-11] Various new mode-locking techniques such as active nonlinear polarization rotation, [12] cross-phase modulation, [13] cross-gain modulation [14] have emerged for the SOAFL system. The optical pulse injection locking scheme using an intra-cavity semiconductor active filter [15] or laser diode [16] gas also been previously demonstrated. Subsequently, the mode-locking of a semiconductor optical amplifier fiber ring laser (SOAFL) has been theoretically [17] and experimentally [18] studied. The backward optical injection has recently emerged as a new mode-locking technology for SOA-based fiber lasers (SOAFLs), which is achieved by seeding a high-level sinusoidal-modulated signal to deplete the gain medium in the SOAFL. This is also known as the optical cross-gain modulation (XGM) technique. In principle, the XGM is implemented backward feeding a modulated optical signal (or data) at a relatively high level into the SOA, which leads to a crosstalk on another (lower level) unmodulated signal at a different wavelength (called the probe). On exit from the SOA the probe signal will carry the modulations from the original modulated signal. However, the cross-gain modulated waveform is the inverse of the modulated input signal. The wavelength conversion is achieved by filtering out the original signal, such effect is enhanced when operated the SOA close to gain-saturation under the seeding of a relatively high level data signal. This requires a preamplication of the data signal before entering the SOA and post-amplification of the converted signal at the output.

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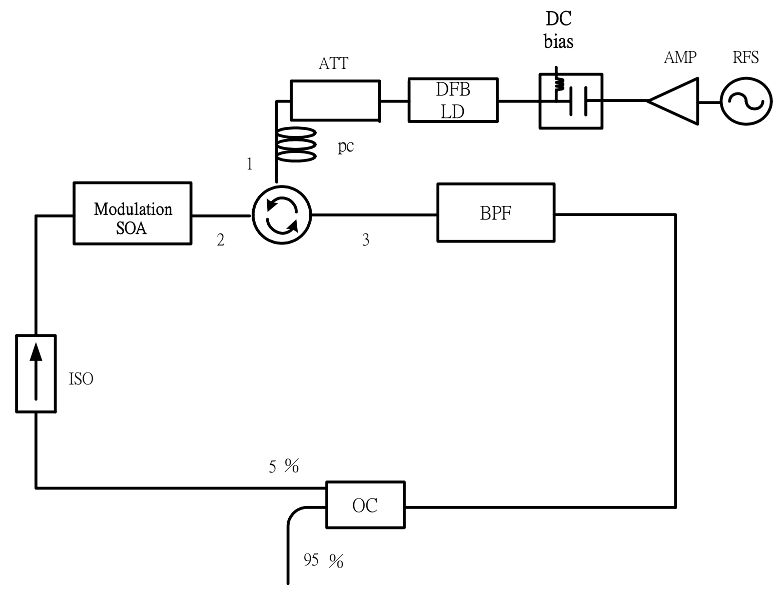

Fig. 1 Schematic diagram of the backward injection mode-locked SOAFL; ATT: electrical attenuator; Amp: power amplifier; BPF: bandpass filter; Circulator: optical circulator; DFBLD: distributed feedback laser diode; ISO: optical isolator; OC: Optical coupler; PC: polarization controller; SOA: semiconductor optical amplifier; RFS: RF synthesizer.

With this technique optically harmonic mode-locking of a SOAFL is demonstrated by periodically gain-depletion modulating the SOA with a backward injection from purely sinusoidal-wave modulated optical signal. Such a modulation scheme is completely different from previous demonstrations using internal-gain modulation or external cavity-loss modulation, which exhibits several advantages such as all-optical operation and ultrafast response. Many experiments on XGM based mode-locked SOAFLs have been studied in detail [19,20]. Patrick and co-workers primarily demonstrated an actively rational-harmonic mode-locked EDFL with 8.4 ps pulses at a repetition rate of 20 GHz by using an all-optically-modulated SOA as a mode-locker [19]. 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 DFBLD [20]. More Recently, Lin *et al.* [21] 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. In our work, the wavelength dependent mode-locking performance of a SOAFL under the backward optical injection via a sinusoidal-wave-modulated DFBLD at repetition rate of 1 GHz are characterized. We demonstrate an actively mode-locked SOAFL that uses a single intracavity SOA to provide both gain and gain modulation. The gain modulation of the SOA is provided by cross-gain saturation from an external sinusoidal-wave-modulated DFBLD. The optical gain-depletion induced mode-locking dynamics of a semiconductor optical amplifier based fiber ring laser backward injected by purely sinusoidal-modulated distributed feedback laser diode is experimentally demonstrated. The effect of backward injection wavelengths from the DFBLD on the mode-locking pulse shapes of SOAFL is analyzed. Three DFBLDs with different central wavelengths of 1530 nm, 1535 nm and 1550 nm are used to backward-injection mode-lock the SOAFL operated at high-gain condition.

2. EXPERIMENT SETUP

Figure 1 illustrates the backward-optical-injection mode-locked SOAFL system, which consists of one travelling-wave typed SOA, a butterfly-packaged DFBLD with central wavelength of 1530 nm,1535 nm and 1550 nm at specified temperature of 25 ^{o}C, an optical circulator, a faraday optical isolator, an optical tunable bandpass filter (OBPF), and an optical coupler with power-splitting ratio of 5:95. In the experiments, the polarization controller is carefully adjusted to control the polarization of the light injection into the SOA. 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. The SOA which is DC-biased at highly above threshold is backward injected by the sinusoidal wave generated by the DFBLD. The SOA is operated at 15 ^{o}C. The SOA is realized to play both the roles of gain medium and modulator in this experiment, while the mode-locking is initiated after fast periodical gain-depletion and relatively slow gain-recovery in the SOA under strong pulse-injection. The injected optical pulse results in a temporally short gain-window, which must be adjusted at wavelengths different from the mode-locking pulses. The optical injection is subsequently filtered out to avoid the regenerative amplification process of the injection occurring in the SOAFL. Figure 2 illustrates the sinusoidal waveform injected into the SOA. In order to get the mode-locking performance of the backward optical-modulated SOAFL, the DFBLD is sinusoidal wave modulated at 1 GHz using a RF synthesizer (ROHDE＆SCHWARZ SML01) with a power amplifier of 40-dB gain. The average power of the sinusoidal wave modulated DFBLD which is injected into the SOAFL is 11.43 mW. The modulation depth is adjusted to nearly 100% by controlling the DC bias current of the SOA. The DFBLD optical sinusoidal wave is backward injected into the SOAFL via an optical circulator. The use of the isolator in the SOAFL ensures the unidirectional propagation of light, and prevents the lasing and circulation of the seeded DFBLD signal in SOAFL. The cavity length is 14 m, corresponding to the fundamental frequency of 14 MHz. The central wavelength and output power of the DFBLD backward-injection mode-locked SOAFL are 1533.5 nm and 80.4 μW, 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).

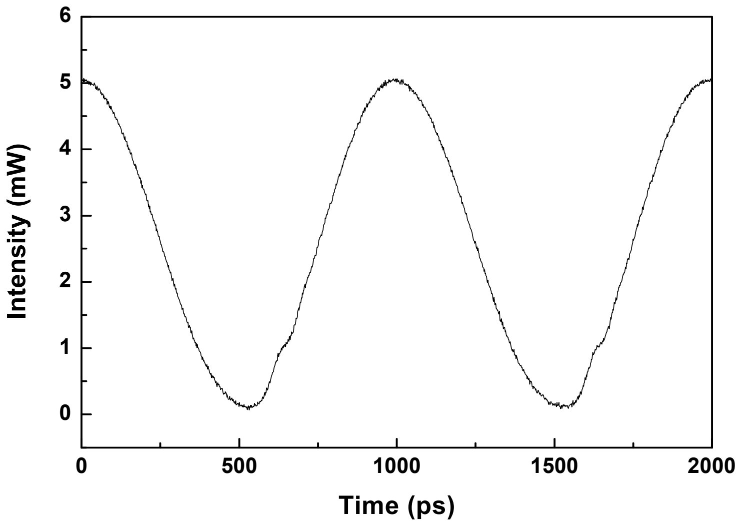

Fig. 2 The sinusoidal waveform injected into the SOA from an optical circulator.

3. RESULTS AND DISCUSSION

Three DFBLDs with different central wavelengths of 1530 nm, 1535 nm and 1550 nm are used to backward-injection mode-lock the SOAFL at biased current of 91.8 mA (I_{th}, SOA=20 mA). The backward injected is performed by using a circulator, which is used to ensure the unidirectional propagation of light. In first experiment, an optical tunable bandpass filter (BPF) with central wavelength of 1533.5 nm is employed to filter out the residual DFBLD component in the SOAFL. To obtain the best modulation depth at the specified gain of SOA, the optimized coupling ratio of the SOAFL is determined as 99 %. This leaves a relatively low power circulating inside the SOAFL for perfect mode-locking. Such a low feedback power further increases the sensitivity of the SOA to the high-repetition-rate backward

injected signal and prevents the excessive gain depletion from starting the mode-locking. As a result, the perfect mode-locking is achieved by driving the DFBLD with RF power of 3.6 dBm and biased current of 70 mA, which results in an average power of 80.4 μW, peak power of 0.227 mW. The shortest pulsewidth of the DFBLD backward injected SOAFL is 22.7 ps. The pulses can also be obtained by DFBLD backward injection at 1530 nm or 1550 nm in feedback of SOAFL, leading to the optimized pulsewidths of 35.2 ps and 24.6 ps, respectively.
Nonetheless, neither the illumination at the other (shorter than 1530 nm or longer than 1550 nm) wavelengths can induce shorter pulsewidth even by optimizing the other parameters. In previous work, it is observed that the gain recovery time of SOA backward injected at near bandedge is shorter than that backward injected at higher energy. The carriers at lower energy states recovers faster than at higher energy states. Such an short-wavelength injection thus favors the mode-locking process. In experiment, it is also found that the optimized feedback power required for the SOAFL backward injected at 1535 nm is less than that at 1530 nm. Consequently, there is narrower gain-window of SOAFL at 1535 nm, providing better pulse-train of SOAFL. On the other hand, the recovery time of gain at 1550 nm is shorter than 1535 nm, it is far from the gain-peak power of our SOA (1533.5 nm). Therefore, the injection at 1550 nm can not induce a sufficient depletion depth in SOA for perfect mode-locking. The sinusoidal-wave modulated DFBLD was backward injected into the SOA for loss-modulation. Figure 3 illustrated the gain profile of SOA in our system. The central wavelength of the SOA was 1533.5 nm. Figure 4 illustrated the temporal traces of measured pulsewidth by detuning injection power. As the DFBLD power was increased from 0.8 mW to 11.4 mW, the mode-locked SOAFL pulsewidth shrink significantly. The mode-locking of the SOAFL can be initiated at the modulation minimum of the DFB, where the gain of SOA is least depleted and recovers back to overcome the cavity loss. Perfect mode-locking of the SOAFL is achieved when the DFBLD injecting power increases to 11.4 mW. In principle, the mode-locking pulsewdith (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 (on-to-off transmission ratio of the modulated DFB). 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.

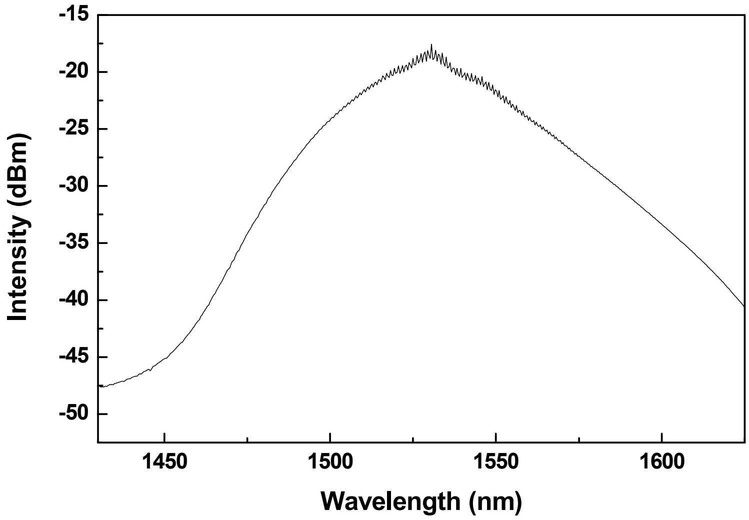

Fig. 3 The gain profile of the modulated semiconductor amplifier.

The mode-locking of the SOAFL can be initiated at the modulation minimum of the DFB, where the gain of SOA is least depleted and recovers back to overcome the cavity loss. It is relatively easy to observe that an insufficient pulse injection could result in a narrower gain-depletion window, which eventually makes the mode-locked SOAFL pulses noisy and broad, producing to the corresponding pulsewidth and peak power are 22.7 ps and 227 μW, respectively.

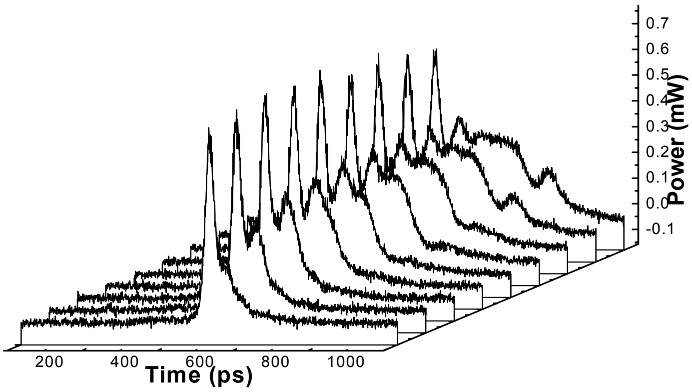

Fig. 4 The temporal traces of measured pulsewidth by detuning injection power.

Figure 5 compares the results of mode-locking pulse shapes generated by three DFBLDs of different central wavelengths. This corroborayes again the carriers at lower energy states recovers faster than at higher energy states, which requires less injecting power for mode-locking the SOAFL with shorter pulsewidth.

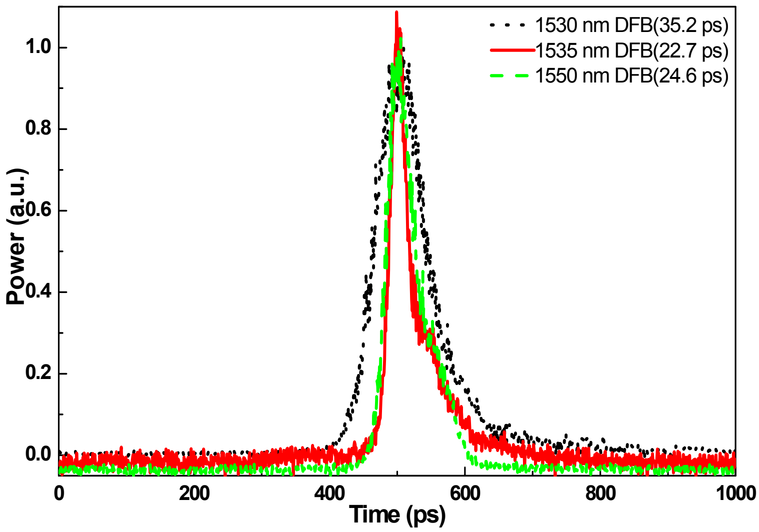

Fig. 5 Comparison of pulsewidths from mode-locked, three different kinds of central wavelength DFB.

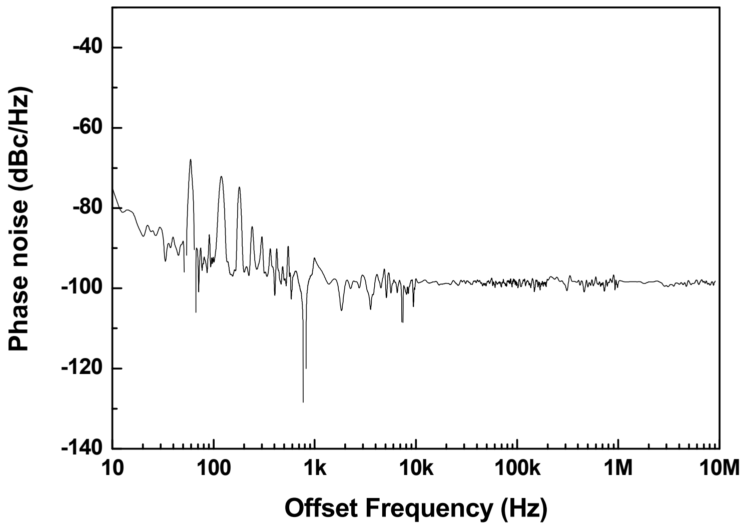

Fig. 6 SSB phase noise of the mode-locked optical pulse.

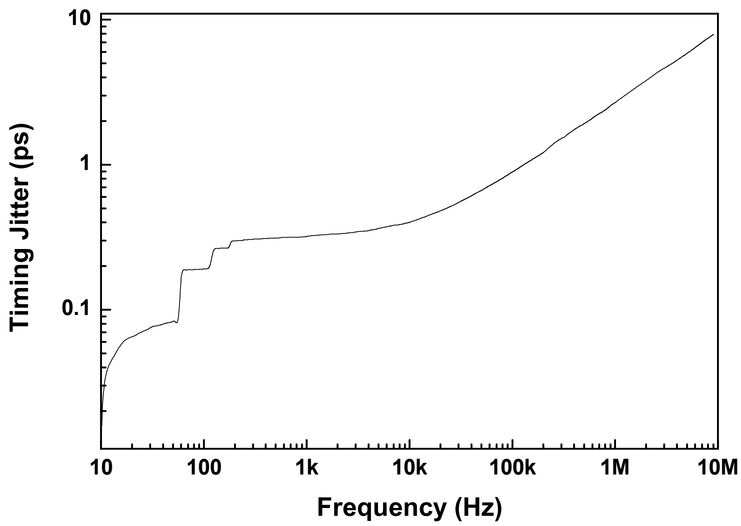

Fig. 7 Timing jitter of the mode-locked optical pulse.

At last the timing jitter is calculated from the subtracted SSB phase noise density spectrum to exclude the contribution of amplitude noise. At zero detuning condition, it is found that the timing jitter remains relatively low (< 0.3 ps) at offset frequency below 100 kHz. The measured timing jitter is relatively stable pulse-train with almost unchanged timing jitter observed within locking range. However, the variation of the timing jitter is not symmetrical under the positive and negative detuning process. When modulation frequency of DFBLD coincides with the frequency harmonic mode in SOAFL, the gain modulation is able to resynchronize the circulating pulse to the modulation frequency, which eventually results in a stable pulse-train with low timing jitter. The mode-locking is destroyed if the modulation frequency detunes beyond the locking range, which inevitably causes a phase slip between the circulating pulses and the pulsed gain modulation window on each round trip.

4. CONCLUSION

In conclusion, we demonstrate a clearly interprets that a backward pulse injection at longer wavelengths (corresponding to smaller gain of SOA) is less contributed to the initiation of harmonic mode-locking in the SOAFL. Both the larger gain-depletion depth and the narrower gain-modulation width are important to the build up the mode-locking in SOAFL. When the modulation power of the sinusoidal wave modulated 1535 nm DFB is sufficiently high, the DFB backward injected SOAFL is easily to harmonic mode-lock since both the gain-depletion depth and gain-modulation width is large enough. On the other hand, the gain-depletion width of the SOAFL induced by backward injection of 1530 nm DFB sinusoidal wave only provides a much broadened gain-modulation window, which is unavailable to strictly confine and to synchronize the contributed longitudinal modes of the SOAFL in a short time manner. Consequently, the laser is not perfectly mode-locking but continuous-wave lasing with periodically spatial holes due to the gain reduction by backward DFB sinusoidal waveform seeding. In this work, the shortest pulsewidth of the DFBLD backward injected SOAFL is 22.7 ps. The pulses can also be obtained by DFBLD backward injection at 1530 nm or 1550 nm in feedback of SOAFL, leading to the optimized pulsewidths of 35.2 ps and 24.6 ps, respectively.

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