Impact of Monolithic Saturable Absorber on the Performance of Subharmonically Mode-Locked Lasers at Millimeter-Wave Frequencies

H. C. Bao, Y. J. Wen, and H. F. Liu

Abstract—A detailed comparison of the characteristics of 40-GHz pulses from a subharmonic mode-locked monolithic laser diode with and without saturable absorber (SA) is demonstrated, in terms of timing jitter, frequency detuning, amplitude modulation, and extinction ratio. The experimental results show that saturable absorption in laser cavity improves the extinction ratio and suppresses amplitude modulation and timing jitter, while no SA section in laser cavity is cost-effective and offers subharmonically mode-locked pulses a larger frequency detuning range.

Index Terms—Amplitude modulation, monolithic semiconductor laser, saturable absorber, subharmonic mode-locking, timing jitter.

I. INTRODUCTION

THE GENERATION of high-repetition rate optical pulses from monolithic semiconductor lasers is very important for future high-speed optical communications and signal processing systems [1], [2]. Among the methods of optical pulse generation, the subharmonic mode-locking technique, which forces a laser to oscillate at its resonance frequency by the injection of electrical or optical signals with repetition rate at a subharmonic of the laser’s resonance frequency, has been shown to have an additional advantage of alleviating the constraints of high-frequency driving electronics while maintaining the high quality of mode-locked pulses [3]–[5]. Recently, the generation of 256-GHz pulses from a subharmonically mode-locked (SML) monolithic semiconductor laser with saturable absorption (SA) section was reported [5]. On the other hand, a 140-GHz pulse train has been generated by subharmonic mode-locking of a laser diode without an SA section [6]. But a comprehensive comparison of the characteristics of the pulses generated by these two methods, which is useful for wisely selecting techniques of generating high-repetition rate pulses in system design, has not been carried out. In this paper, a monolithic semiconductor laser was utilized to generate SML pulses by using these two techniques. The timing jitter, frequency detuning, amplitude modulation, and extinction ratio of the pulses affected by saturable absorption in the laser cavity are investigated. The detailed knowledge about characteristics of pulses this paper offers is useful for selecting proper components and techniques in system applications since different applications have different requirements for pulse characteristics.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup for investigating the effects of SA on the performance of SML laser output, which includes a master laser and a slave laser. The master laser is a gain switched (GS) distributed feedback laser diode (DFB-LD, 1550 nm), operating at 9.675 GHz which corresponds to the fourth subharmonic of the slave laser’s resonance frequency. Gain switched pulses with pulsewidth of 19 ps were linearly compressed to 7 ps by using a 1-km-long dispersion compensation fiber ($D = -26$ ps/nm/km). An erbium-doped fiber
amplifier (EDFA) was used to boost the power of the compressed pulses, and an optical bandpass filter (BPF) was utilized to eliminate the excess amplified spontaneous emission noise from the EDFA. The slave laser is a multisection laser diode (LD) which has a gain section, an SA section, a distributed Bragg reflector (DBR) section, and a phase control (PC) section, with a center wavelength of 1546 nm and a cavity frequency around 38.7 GHz. The material of the SA section is the same as that of the gain section. As the SA section is driven by positive current, it provides gain in laser cavity rather than absorption. While the SA section is open-circuited, grounded, and reverse-biased, it offers from weak to strong absorption in the slave laser cavity. In all those cases, the slave laser could generate short pulses with a repetition rate at its resonance frequency by the injection of the compressed pulses from the master laser. At the output of the slave laser, another optical bandpass filter was used to remove the residual master laser output from the slave laser output. The output of the SML pulses was measured by using an optical spectrum analyzer, an autocorrelator, and an RF spectrum analyzer in conjunction with a high-speed photo diode (PD) detector.

III. EXPERIMENTAL RESULTS

We investigated the characteristics of SML pulses in terms of extinction ratio, amplitude modulation, and timing jitter by varying the biasing conditions at the absorber section of the monolithic semiconductor. In this investigation, the driving current of the gain section was 60.5, 60.5, 107.4, and 139.4 mA, respectively, when SA section is positively driven at 10.3 mA, open-circuited, grounded, and reverse-biased at $-0.2 \text{ V}$, respectively. Under positively driven condition, SA section and gain section were uniformly pumped, which is equivalent to a single long gain section.

The extinction ratio is an important characteristic in evaluating the quality of the generated pulses. We simply define extinction ratio as the ratio of the maximum level to the minimum level in the autocorrelation trace of pulses. Fig. 2 shows the dependence of extinction ratio of SML pulses on the injected optical power. The maximum extinction ratio is 11.61, 11.73, 14.43, and 20 dB, respectively, with the SA section positively driven at 10.3 mA, open-circuited, grounded, and reverse-biased at $-0.2 \text{ V}$, respectively. Fig. 2 shows that saturable absorption in laser cavity helps to increase the pulse extinction ratio. In addition, lower injection power is required to generate these high extinction ratio pulses. However, as the SA section was grounded and reverse-biased, the required powers for maximum extinction ratio are slightly higher than that when SA section was open-circuited, which can be attributed to their higher driving current in the gain section. We also measured the pulsewidth and pulse energy of generated pulses for different bias conditions as shown in Table I. The measurement was carried out under the condition where extinction ratios are maximal. With the increase of saturable absorption effect in cavity, the pulsewidth was reduced and the pulse energy was increased as shown in the Table I. The increase of pulse energy is a result of higher driving current in gain section for SA bias conditions with stronger absorption effect.

The undesired amplitude modulation of SML pulses is another measure in evaluating the quality of the generated optical pulses. The amplitude modulation was defined from the measured RF spectrum of the slave laser output after optical injection, which is the ratio of the RF power at the injection frequency (9.675 GHz) to that at the slave laser resonance frequency [8]. The dependence of amplitude modulation of SML pulses as a function of injected optical power is shown in Fig. 3. From no to increased saturable absorption in laser cavity by putting the SA section positively driven at 10.3 mA, open-circuited, grounded, and reverse-biased at $-0.2 \text{ V}$, the amplitude modulation of SML pulses was reduced. Therefore, saturable absorption in cavity helps to suppress the amplitude modulation of the SML pulses.

Frequency detuning is another measure of pulse quality. Fig. 4 shows the measured timing jitter of the fourth SML pulses as a function of frequency detuning. Here the timing jitter was calculated by integrating the measured single-side-band noise (from 100 Hz to 10 MHz) at the detected signal component corresponding to the repetition rate of the pulse train. As the SA was positively driven, open-circuited, grounded, and reverse-biased, the injected powers were 1.06, $-3.27$, $-2.82$, and $-2.42 \text{ dBm}$, and the corresponding timing jitters at zero detuning were 0.18, 0.17, 0.14, and 0.12 ps, respectively. We define the frequency detuning range as the frequency range over which the generated pulses can be obtained.
optical signal can be tuned from the cavity resonance frequency of the slave laser with timing jitter remaining within ±0.1 ps of that at zero detuning. The detuning ranges of SML pulses when SA section is positively driven by 10.3 mA, open-circuited, grounded, and reverse-biased at −0.2 V are 600, 430, 220, and 130 MHz, respectively. Saturable absorption in the cavity reduces timing jitter at zero detuning; however, it also greatly reduces the frequency detuning range.

Fig. 5 shows the extinction ratio of SML pulses as a function of frequency detuning, where the injection powers for different driving conditions were the same as what used in Fig. 4. At zero detuning, the extinction ratio are 11.61, 11.73, 14.43, and 20 dB, respectively, as the SA section is positively driven at 10.3 mA, open-circuited, grounded, and reverse-biased at −0.2 V. If we define the frequency detuning range as the frequency range of slave laser output where the extinction ratio degradation is within 3 dB from its value at zero detuning, the detuning ranges are 820, 670, 280, and 110 MHz, respectively, as the SA section is uniformly pumped, open-circuited, grounded, and reverse-biased. Although saturable absorption in cavity helps to increase the extinction ratio, it reduces the frequency detuning range as shown in Fig. 5.

IV. Conclusion

A comprehensive comparison of the characteristics of the optical pulses generated from a monolithic semiconductor laser by subharmonic optical injection with the SA section operated under different bias conditions is presented. The extinction ratio, timing jitter, amplitude modulation, and locking range were evaluated in terms of injected optical power and frequency detuning. The experiments show that saturable absorber section in laser cavity helps to improve extinction ratio, suppress amplitude modulation and timing jitter, while no SA section in laser cavity scheme is cost effective, and offers SML pulses with larger locking range and detuning range. For system applications such as long-haul DWDM system using return-to-zero modulation format, where the requirement for extinction ratio of optical signal source is very high, the pulses generated from a semiconductor laser with a saturable absorber section is more suitable. But for some systems such as fiber radio system, where the requirement for extinction ratio of optical signal source is not so high, selecting signal generation from a semiconductor laser without a SA section could achieve more benefit of large detuning range and low cost.

ACKNOWLEDGMENT

The authors would like to thank Dr. Y. Ogawa for providing the monolithic semiconductor laser.

REFERENCES