Amplitude Noise of Subharmonically Hybrid Mode-Locked Pulses Generated From a Monolithic Semiconductor Laser

H. C. Bao and H. F. Liu

Abstract—**Broad-band amplitude noise (100 MHz to 20 GHz) of 40-GHz pulses generated by a subharmonically hybrid mode-locked (SHML) monolithic semiconductor laser is investigated. Experiments show that the amplitude noise can only be suppressed at some certain subharmonic members, while the phase noise can be suppressed by subharmonic hybrid mode-locking under many subharmonic members.**

***Index Terms*—Amplitude noise, mode-locked lasers, monolithic semiconductor laser, phase noise, relative intensity noise.**

I. INTRODUCTION

OPTICAL PULSES generated by the mode locking of semiconductor lasers have attracted considerable attention because of their short pulsewidth, high repetition rate, small frequency chirping and high stability, and the promising applications in high-speed optical communications, microwave photonics systems, and ultrafast data processing. Passive mode locking is one of best candidates for obtaining short highly repetitive optical pulses, because it needs no external driving signal. However, the pulses cannot be synchronized with external signal and exist large timing jitter [1]. The drawbacks can be overcome by implementing recently developed subharmonic hybrid mode-locking and synchronous mode-locking techniques, where the passive mode-locked pulses are synchronized by injection of electrical signal or optical pulses at a subharmonic of the cavity resonance frequency [2], [3]. These techniques offer a distinct advantage of alleviating the requirement for high frequency driving signal over hybrid mode locking and synchronous mode locking. Although timing jitter, amplitude modulation, and locking ranges of pulses generated by using these techniques have been extensively investigated [2]–[5], the characterization of amplitude noise has not been carried out yet. For applications of mode-locked pulses to optical communications and photonic analog to digital conversion, broad-band amplitude noise must be characterized and reduced as much as possible. In this letter, we investigate the broad-band amplitude noise of 40-GHz pulses generated from a monolithic semiconductor laser by the subharmonic hybrid mode locking.

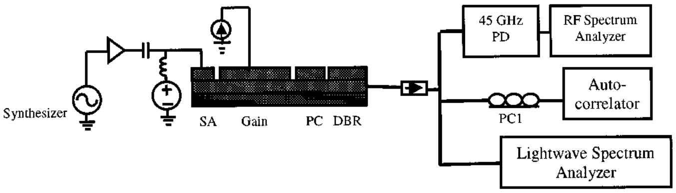

Fig. 1. Experimental setup for measurement amplitude noise from subharmonically mode-locked laser.

II. EXPERIMENT

A monolithic laser with gain, saturable absorber (SA), phase control (PC), and a distributed Bragg reflector (DBR) section was used in this study, as shown in Fig. 1. When the SA section of the laser was reverse biased and the gain section was biased at a current higher than 80 mA, the laser would be passively mode-locked and generated a pulse train with a cavity round trip frequency of $\mathrm{f_o} = 39.2$ GHz. The pulsewidth measured by an autocorrelator was 5 ps, and the width of the spectrum envelope was 0.7 nm, giving a time bandwidth product of 0.44, which shows that the generated pulse train is nearly transform limited. Subharmonic hybrid mode locking of the monolithic laser was realized by injecting a radio frequency (RF) signal into the SA section with a frequency at a subharmonic of the laser resonant frequency [2], [3]. A HP 8564E RF spectrum analyzer in conjunction with a 45-GHz photodetector was used to measure the RF spectrum and phase noise of the output from the mode-locked laser. The relative intensity noise (RIN) of mode-locked pulses was evaluated by using an HP 7400A 22-GHz lightwave spectrum analyzer with a built-in photodiode and low-noise RF preamplifier.

III. RESULTS AND DISCUSSION

The root-mean-square amplitude noise N_{AM} of mode-locked pulses is the integration of measured RIN [6], [7]

$$N_{AM} = \sqrt{\int_{f_1}^{f_2} RIN\,\mathrm{d}f} \qquad (1)$$

where $f_1 = 100$ MHz and $f_2 = 20$ GHz are the low and high integration frequency, respectively. In our experiment, f_1 was the lowest frequency that the HP71400 lightwave spectrum analyzer could respond, and f_2 was half of laser repetition frequency.

The relative intensity noise of mode-locked pulses is large when the pulsewidth of the mode-locked pulses is small. Fig. 2

Manuscript received June 18, 2001; revised August 6, 2001.

The authors are with the Australian Photonics Cooperative Research Center, Photonics Research Laboratory, Department of Electric and Electronic Engineering, The University of Melbourne, Parkville, VIC 3010, Australia (e-mail: hongchun@ee.mu.oz.au).

Publisher Item Identifier S 1041-1135(02)00070-8.

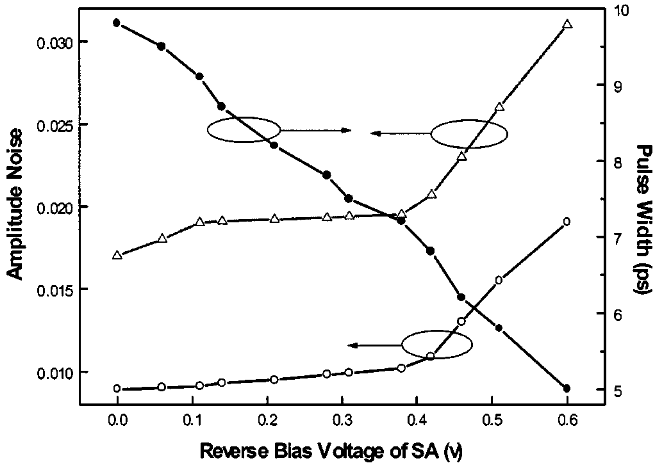

Fig. 2. The measured amplitude noise and pulsewidth of mode-locked pulses as a function of the bias voltage on the SA section of laser. Solid triangles: Pulsewidth of passively mode-locked pulses. Open triangles: Amplitude noise of passively mode-locked laser. Open circles: Amplitude noise of the 3rd SHML laser.

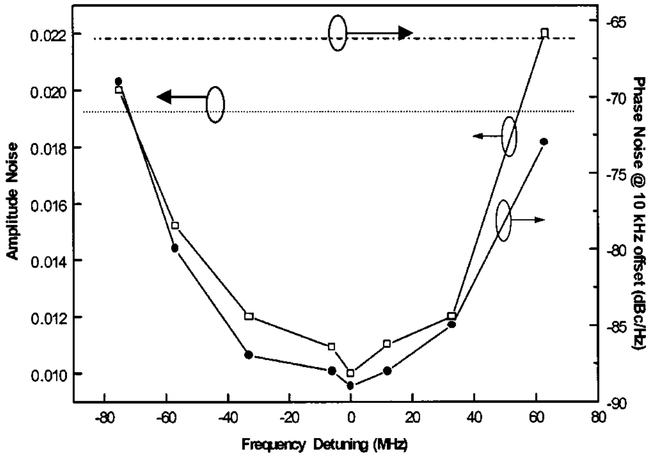

Fig. 3. The measured amplitude noise (open circles), the phase noise (solid circles) of SHML pulses as a function of frequency detuning, and the amplitude noise (dotted line) and phase noise (dashed–doted line) of the passively mode-locked laser.

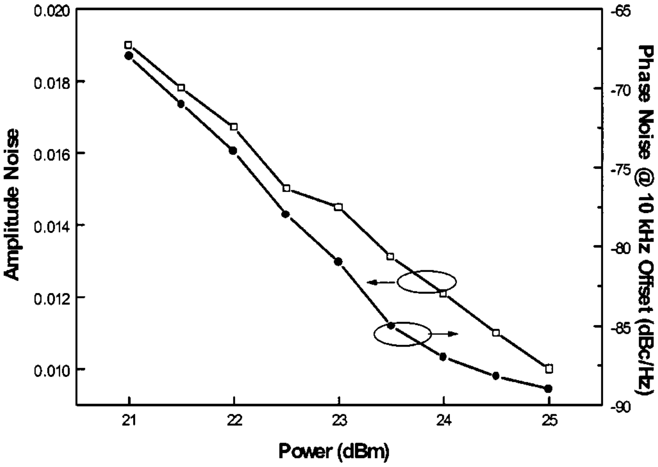

Fig. 4. The measured amplitude noise and the phase noise of SHML pulses as a function of the power of injected RF signal.

shows that as the reverse biased voltage applied to the SA section is increased, the pulsewidth of mode-locked pulses reduces, which is the normal method to obtain short mode-locked pulses. But amplitude noise from passively mode-locked laser and 3rd SHML laser were increased as well. A tradeoff between obtaining short optical pulses and reducing amplitude noise exists in both passively mode-locked laser and SHML laser. As shown in Fig. 2, the amplitude noise of passively mode-locked pulses was suppressed about 3 dB to 0.9% by the third subharmonic mode-locking technique, where the injected RF power was kept at 25 dBm.

The timing jitter of mode-locked laser leads to an increase in amplitude noise. The pulses in the laser cavity arrive at the gain section or SA section at different time each round trip because of the timing jitter of the mode-locked laser, while the loss of laser cavity is a periodic function of time, since the SA section of the laser is modulated by the RF signal. Therefore, the pulses would obtain different gain each round trip, and the intensity of the pulses would fluctuate. As a result, the amplitude noise is directly related to the timing jitter of mode-locked laser. Fig. 3 shows that both the phase noise and amplitude noise increased as the frequency of the RF signal was detuned from $f_o/3$. The increase of phase noise is because the driving signal could not fully stabilize the mode-locked pulses, while it is detuned from $f_o/3$ [2], [3]. As the phase noise increases, the amplitude noise increases as well. When the frequency of RF signal was further tuned away, the amplitude noise of SHML pulses exceeded that of passive mode-locked pulses (1.92%), while the phase noise did not exceed that of passive mode-locked laser (-66 dBc/Hz). In this case, a weak component at laser resonance frequency of f_o appeared beside the stabilized component, with a frequency four times of RF driving signal frequency, and the beating of the two components causes the increases in amplitude noise.

The power of the injected RF signal affects both the phase noise and the amplitude noise of SHML pulses, as shown in Fig. 4, where the injected RF signal is tuned exactly at one third of the laser resonance frequency f_o. With the increase of RF injected power, both the phase noise and the amplitude noise of SHML laser were reduced [2], [3]. This result proves again that the phase noise of the laser is one of factors that affect the amplitude noise.

Fig. 5 shows the amplitude noise (open squares) and phase noise (solid circles) as a function of subharmonic number, where the RF power of injected signal was 25 dBm for the third–sixth subharmonic mode locking, and 20 dBm for the second subharmonic mode locking, because of 20-GHz amplifier gain limitations. The dotted line in Fig. 5 indicates the amplitude noise and phase noise of passively mode-locked pulses. At the second subharmonic, the injected RF signal was not strong enough to stabilize the pulses, where the phase noise was as large as -70 dBc/Hz at 10 kHz offset frequency, and the amplitude noise was close to that of passively mode-locked laser. The amplitude noise was suppressed at the third subharmonic hybrid mode locking, since the pulses were well stabilized, in which the phase noise approached a minimum of -89 dBc/Hz. Accompanying with the reduction of phase noise, the amplitude noise of mode-locked pulses was reduced as well.

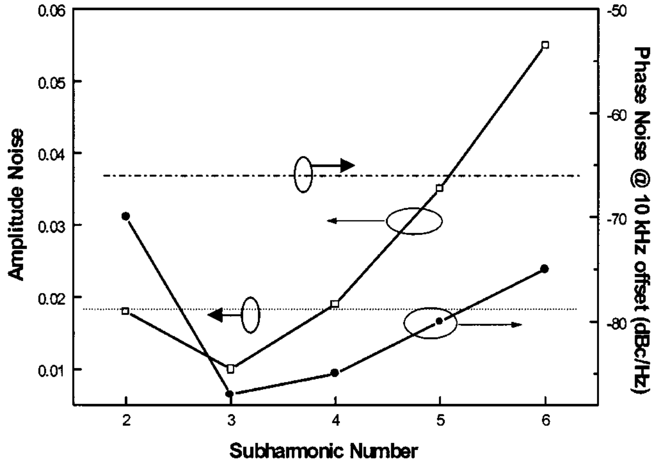

Fig. 5. The measured amplitude noise (open squares), phase noise (solid circles) of SHML laser as a function of subharmonic number, and the amplitude noise (dotted line) and phase noise (dashed–doted line) of the passively mode-locked pulses.

However, from the fourth to the sixth subharmonic hybrid mode-locking, the amplitude noise increased with the raising of subharmonic number, since the phase noise increased and the laser has large modulation response at a frequency close to the relaxation oscillation frequency. The noise of the injected signal would also be added to SHML laser with larger ratios at larger subharmonic numbers, because the frequency of the injected signal is closer to the relaxation oscillation frequency. Therefore, the amplitude noise increased with the increase of subharmonic number. There is a tradeoff between choosing large subharmonic number and reducing the amplitude noise for pulse generation using subharmonic hybrid mode locking.

IV. CONCLUSION

The amplitude noise of passively mode-locked pulses could be suppressed and enhanced by a subharmonic mode-locking technique depending on the working parameters chosen. For typical subharmonic numbers, as the mode-locked laser is well stabilized, the amplitude noise from passively mode-locked laser is suppressed by a subharmonic hybrid mode-locking technique.

REFERENCES

[1] D. J. Derickson, R. J. Helkey, A. Mar, J. R. Karin, J. G. Wasserbauer, and J. E. Bowers, “Short pulse generation using multisegment mode-locked semiconductor lasers,” *IEEE J. Quantum Electron.*, vol. 28, pp. 2186–2202, Oct. 1992.

[2] T. Hoshida, H. F. Liu, M. R. H. Daza, M. Tsuchiya, T. Kamiya, and Y. Ogawa, “Generation of 33 GHz stable pulse trains by subharmonic passively mode-locked semiconductor laser,” *Electron. Lett.*, vol. 32, pp. 572–573, Mar. 1996.

[3] A. Nirmalathas, H. F. Liu, Z. Ahmed, D. Novak, and Y. Ogawa, “Subharmonic synchronous and hybrid mode-locking of a monolithic DBR laser operating at millimeter-wave frequencies,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 434–436, Apr. 1997.

[4] T. Hoshida, H. F. Liu, M. Tsuchiya, Y. Ogawa, and T. Kamiya, “Extremely low-amplitude modulation in a subharmonically hybrid mode-locked monolithic semiconductor laser,” *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1160–1162, Sept. 1996.

[5] H. C. Bao, H. F. Liu, Y. J. Wen, and A. Nirmalathas, “Suppression of amplitude modulation of pulses generated from a subharmonically mode-locked semiconductor laser,” *IEEE Photon. Technol. Lett.*, vol. 13, pp. 629–631, June 2001.

[6] K. Sato, I. Kotaka, Y. Kondo, and M. Yamamoro, “Actively mode locked strained—InGaAsP multiquantum-well lasers integrated with electroabsorption modulators and distributed Bragg reflectors,” *IEEE J. Select. Topics Quantum Electron.*, vol. 2, pp. 557–565, Sept. 1996.

[7] K. Sato, A. Hirano, and H. Ishii, “Chirp-compensated 40 GHz mode-locked lasers integrated with electroabsorption modulators and chirped gratings,” *IEEE J. Select. Topics Quantum Electron.*, vol. 5, pp. 590–595, May/June 1999.