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High Quality Factor Q and Low Timing Jitter from MLLD Using Optical Injection

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Abstract We have compressed timing jitter of mode-locked laser diode (MLLD) using 10 GHz base standard clock optical injection and 10 Gbit/s PRBS data pulse signal optical injection when the wavelength of the base standard injection clock light is equal to the wavelength of MLLD. Small timing jitter of 0.25 ps was obtained at − 5 dBm injection optical power. The quality factor was 3000 with hybrid MLLD when the electrical power was + 27 dBm.

Key words clock optical pulse, OTDM, MLLD, timing jitter.

1 Introduction

In long-distance and ultrahigh speed optical communication systems based on all-optical signal processing of optical time division multiplexion (OTDM) and soliton transmission, short pulse sources with low jitter and high quality factor are needed. An optical pulse shorter than 5 ps was generated from a monolithic MLLD and its mode locking frequency had high repetition-rate of 10~100 GHz. However, a timing jitter of such a passive MLLD was higher than 20 ps. Several papers have reported about the timing jitter compression based on injection locking using a master oscillator[1]. The 2.5 ps timing jitter was achieved. Considering an application to an optical clock extraction, a novel evaluation parameter for MLLD, such as a quality factor Q in a jitter reduction filter function, is required. The use of a Fabry-Perot resonator, in order to extract an optical timing clock, has a quality factor of 100[2]. A laser of longer medium waveguide has high quality factor Q [3], but the process of producing a waveguide laser is very difficult. In this paper, we describe a 0.25 ps low timing jitter and high quality factor from MLLD using base standard clock optical injection or 10 Gbit/s data pulse injection. We have discussed a filtering characteristics of MLLD through analysis, and made a comparison of timing jitter between Q factor and other kinds of parameters.

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(i.e. injection power).

2 Experimental

Fig. 1 shows a diagram of the experimental configuration. The CW light from a laser diode (LD) passes through an electrical absorption (EA) modulator to produce the base light pulses, and these pulses pass through the erbium-doped fiber amplifier (EDFA) and finally go through the $LiNbO_3$ modulator which employs the Mach-Zehnder (M-Z) interferometer mechanism. Another pulse train after the EA modulator is directly injected into the MLLD.

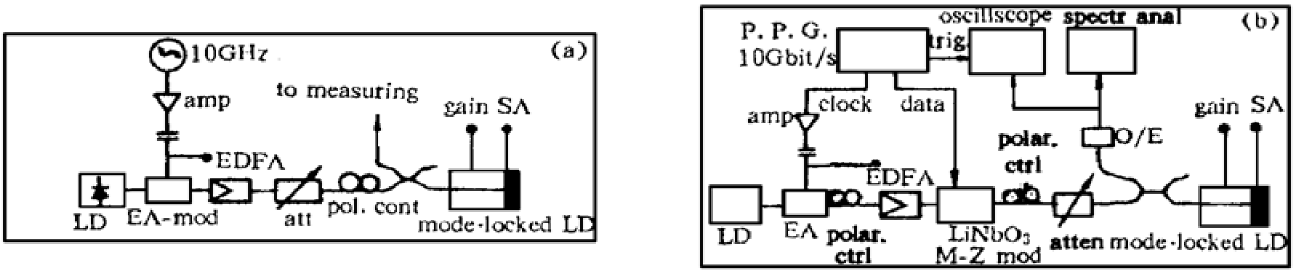

Fig. 1 Experimental setup for optical clock extraction: (a) 10 GHz base standard clock optical pulse injection, (b) 10 Gbit/s(PRBS 2^n-1) data pulse injection

We used two different kinds of signal injection, one is a base standard pulse generated by EA signal. In Fig. 1(a), an EA modulator drive signal is generated from microwave synthesizer and amplified by microwave amplifier. The base standard clock optical pulse injected to MLLD has very low jitter value that is limited by jitter measurement unit. The monolithic MLLD used is a two-section strained InGaAs/InGaAsP Multiple-Quantum-Well(MQW) LDs. The length of the MLLD was designed to be 4.33 mm with a 130 μm-long saturable absorber (SA) section and 4.2 mm long gain section. The MLLD was operated at 1.547 μm wavelength. There was a separator between the injection light and the MLLD output. Compared with Fig. 1(a), a $LiNbO_3$ modulator is used in Fig. 1(b), so that the LD pulse is modulated by a $LiNbO_3$ modulator with a 10 Gbit/s (PRBS 2^n-1) data pulse signal.

3 Results and discussion

We checked the operating condition by measuring the timing jitter and quality factor of regenerated clock pulse from MLLD.

Fig. 2 shows the curves of the timing jitter by changing the injection power of passive MLLD. The 0.25 ps minimum timing jitter was achieved at −5 dBm average injection optical power. But when the electrical power was set to +27 dBm, the minimum timing jitter is 0.95 ps from the hybrid MLLD. From this, we can see that the timing jiter at the injection mode locking condition, compared with the hybrid timing jitter, is becoming very small.

Through the curves, we can see that in a definite range when the injection power becomes larger, the timing jitter becomes smaller. Because when the injection power is high, the special function of pulse timing jitter is being controlled by the injection light, and the timing jitter of the outputhas the same property as that of the injection light. So that the timing jitter of the output

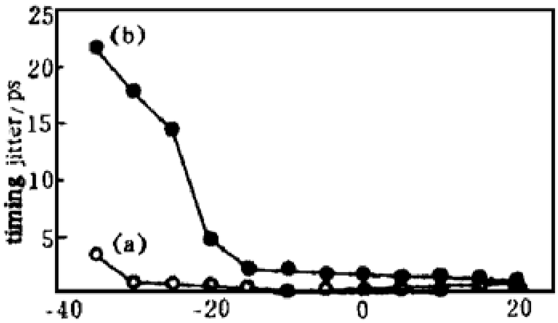

Fig. 2 The timing jitter of optical injection MLLD and hybrid MLLD. (a) The minimum timing jitter is 0.25 ps, (b) The minimum timing jitter is 0.95 ps
(a) injection power for injection MLLD/dBm
(b) input electrical power for hybrid MLLD/dBm

light becomes small, as this injection light has only 0.4 ps timing jitter. This is just like stimulated emission transition and henceforth the output from the MLLD has even less timing jitter. When the injection light is weak, it does not have any influence on passive MLLD, so this is actually the MLLD itself. The timing jitter of the output light of higher than 20 ps was generated.

In the experiment of the optical clock extraction, when the regenerative clock pulse was extracted from the MLLD by data pulse train input, the MLLD can be called a filter. Therefore, the quality factor Q is an important parameter for the optical transmission.

We have firstly used 10 GHz base standard clock optical injection. In Fig. 3, the different quality factors are illustrated by changing the injection power, we can see that the higher the injection power, the smaller the quality factor. In Fig. 4, a sharp bandpass filtering characteristics centered around ~ 10 GHz (the full width at half maximum was 5 MHz) was obtained. The quality factor ($Q = \omega/\delta\omega$) of hybrid MLLD was 3000 at 5 dBm input electrical power and 2000 at − 30 dBm injection optical power of MLLD.

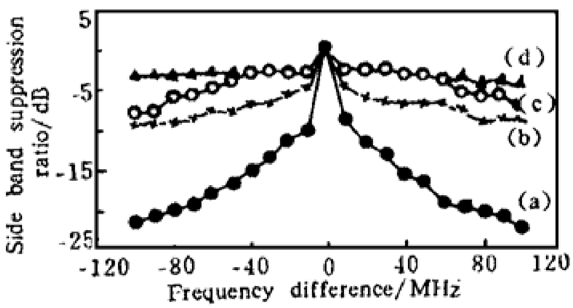

Fig. 3 Side band suppression ratio vs. frequency difference between center carrier and sidband; parameter is injection optical power. (a) − 30 dBm (b) − 20 dBm (c) − 10 dBm (d) 0 dBm

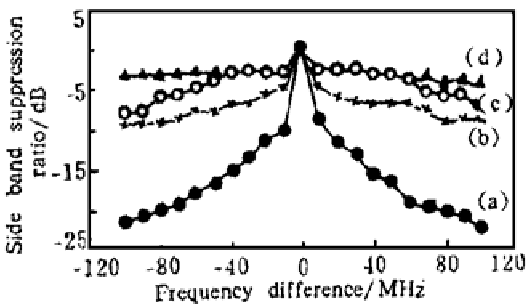

Fig. 4 In the same timing jitter of injection MLLD and hybrid MLLD, the suppression ratio vs. frequency different. (a) Injection MLLD, (b) Hybrid MLLD

We have also tried to use 10 Gbit/s PRBS $2^n - 1$ data pulse signal injection to MLLD and measured the filtering effect of MLLD. The condition is the same as in the sequence of data pulse, the injection power is different, so as with the filtering effect produced. The lower the injection power, the larger the quality factor, this is the same as stated above (See Fig. 5).

Fig. 6 gives the timing jitter and quality factor by changing the injection power of 10 Gbit/s PRBS ($2^9 - 1$) data pulse signal. When the injection power is − 10 dBm, − 20 dBm, − 30 dBm, the timing jitter and quality factors are 6.0 ps, 6.4 ps, 21 ps and 170, 2000 and 3000, respectively. The trade-off between the timing jitter and the quality factor was observed. This reason is not clear. In Fig. 7, we can see, from the curves obtained in the experiment at the condition when the injected power is the same, the larger the sequence of data pulse, the smaller the filter effect. The larger the difference in intensity between the MLLD pulse and the injected data pulse, the more obvious the filtering effect. So that the MLLD is locked strongly. The regenerated pulse from MLLD has a low timing jitter because the unlocked portions have been filtered out, thus the performance of the filter becomes better.

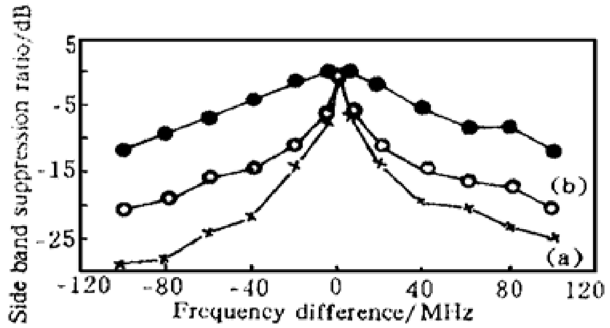

Fig. 5 In the same sequence of data pulse (2^9-1) light, there is a trade-off between timing jitter and quality factor

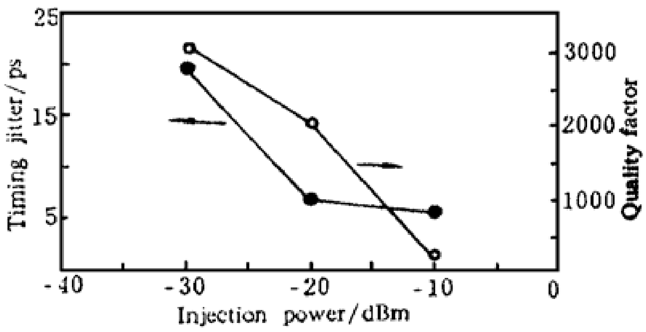

Fig. 6 Timing jitter and quality factor by changing power of 10 Gbit/s PRBS(2^9-1) data pulse light, there is a trade-off between timing jitter and quality factor

To confirmit, we have used the simulated data pulse signal from a microwave signal synthesizer with 10 GHz and mixed with 0~ 500 MHz signal injection, the results are the same too. At the condition of the same injection power of − 20 dBm, changing the difference in intensity between the stimulated data pulse and the MLLD for 10 dB, 20 dB, 30 dB and 40 dB, the quality factor is different as shown in Fig. 8.

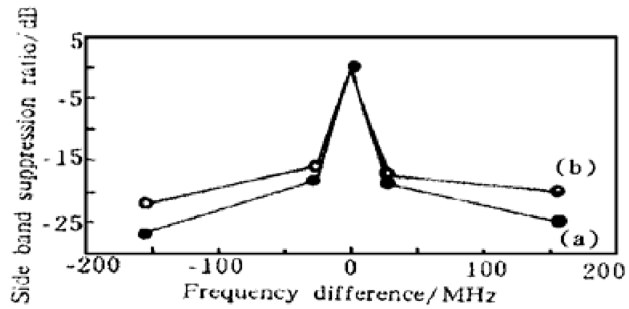

Fig. 7 Sideband suppression ratio vs. frequency difference: in the same injection optical power (− 20 dBm), sequence of the data pulse is different (a: PBRS $2^{11}-1$, b: PBRS 2^7-1)

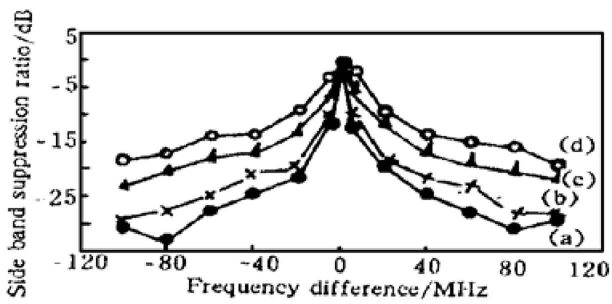

Fig. 8 Condition in the same injection power(− 20 dBm) of the simulated data signal, sideband suppression ratio vs. frequency difference; parameters is different (a: 10 dB, b: 20 dB, c: 30 dB, d: 40 dB)

4 Conclusion

In summary, we have demonstrated injection optical MLLD at 10 GHz which can generate low jitter and high quality factor, this is due to the combination of the short pulse of the MLLD and EA-modulated low jitter injection light. The main advantages of this technology are its insensitivity to injection clock light wavelength and its simple configuration. Therefore, it is applicable to transmission system operating above 100 Gbit/s.

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用光脉冲注入从锁模激光二极管再生低抖动高 *Q* 值光时钟

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摘 要 采用 10 GHz 基准时钟光和 10 Gbit/s 的数据脉冲信号光注入到锁模激光二极管, 降低了周期抖动, 当注入功率为 −5 dBm, 在基准时钟光波长等于锁模激光二极管的光波长时, 获得的最小抖动为 0.25 ps, 采用混合锁模激光二极管, 在注入功率为 +27 dBm 时, 其 *Q* 值达 3000.

关键词 时钟光脉冲, 光时分复用, 锁模激光二极管, 周期抖动。