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Control of period-one oscillation for all-optical clock division and clock recovery by optical pulse injection driven semiconductor laser*

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The period-one oscillation produced by an external optical pulse injection driven semiconductor laser is applied to clock recovery and frequency division. By adjusting the repetition rate or injection power of the external injection optical pulses to lock the different harmonic frequencies of the period-one state, the clock recovery and the frequency division (the second and third frequency divisions) are achieved experimentally. In addition, in frequency locking ranges of 2 GHz and 1.9 GHz, the second and third frequency divisions are obtained with the phase noise lower than –100 dBc/Hz, respectively. Our experimental results are consistent well with the numerical simulations.

Keywords: clock division, clock recovery, optical pulses injection, nonlinear dynamics

PACC: 4265, 4260, 4230Q

1. Introduction

Nonlinear dynamics of semiconductor lasers has been extensively studied in recently years due to its important role in current optical communications.[1−3] Subject to external perturbations such as current modulation,[4] optical injection,[5] optical feedback,[6,7] and optoelectronic feedback,[8] varieties of nonlinear phenomena have been observed and investigated. Among them, optical injection is the most direct way to drive semiconductor lasers into instability and it can also control the output states of semiconductor lasers to the greatest content.

With optical injection, the semiconductor lasers invoke different periodic states[5] that are useful in various fields. One of them, for example, is an optical time division multiplexing (OTDM) system, where the clock at the line rate must be divided in order to demultiplex an individual channel, and therefore the subharmonic frequency is required. When the optical injection is strong enough to lead the semiconductor laser into a period-two oscillation state, the subharmonic frequency can be obtained to be half the modulation frequency. Frequency divisions at 12.4 GHz,[9] 18.56 GHz,[10] and 19.6 GHz[11] have been achieved. In the previous studies, we achieved the frequency division of optical pulses at 6.32 GHz.[12,13] In all the above studies, the researchers utilized the period-two oscillation state of the semiconductor laser for achieving the second frequency division, and the frequency division range was limited to no more than 1 GHz.

In this paper, utilizing an optically injected semiconductor laser, we obtain not only the fundamental frequency, but also the high order subharmonic frequency of the period-one (P1) state, which is useful for all-optical clock division. Furthermore, in 2 GHz and 1.9 GHz frequency locking ranges, the phase noises of the subharmonic frequencies obtained in our experiments are lower than –100 dBc/Hz.

2. Numerical simulation

The schematic setup for optical pulse injection is shown in Fig.1. Both the master laser and the slave laser are from single longitudinal mode laser diodes. The slave laser is optical pulse injected by the current modulation master laser. By adjusting the injection strength, the frequency detuning between the two lasers, and the repetition rate of the injected optical pulses, the slave laser can oscillate in different states.

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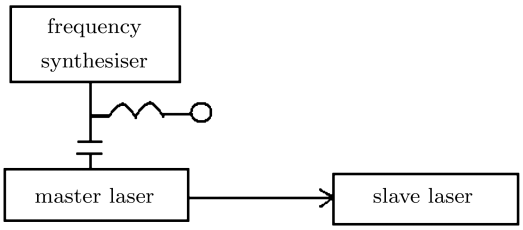


Fig.1. Schematic setup for optical pulses injection.

The dynamics of slave laser subjected to optical pulses can be described by the following single-longitudinal-mode rate equations:

$$\frac{\mathrm{d}N_{1,2}(t)}{\mathrm{d}t} = J - \frac{N_{1,2}(t)}{\tau_\mathrm{n}} - g(N_{1,2}(t) - N_0)\frac{S_{1,2}(t)}{1+\varepsilon S_{1,2}(t)}, \quad (1)$$

$$\frac{\mathrm{d}S_{1,2(t)}}{\mathrm{d}t} = \Gamma g(N_{1,2(t)-N_0})\frac{S_{1,2(t)}}{1+\varepsilon S_{1,2(t)}} + 2\frac{k_\mathrm{inj}}{\tau_\mathrm{in}}\sqrt{S_2(t-\tau_\mathrm{c})S_1(t)}\cos\xi(t) - \frac{S_{1,2(t)}}{\tau_\mathrm{p}} + \frac{\Gamma\beta N_{1,2(t)}}{\tau_\mathrm{n}} \quad (2)$$

and

$$\frac{\mathrm{d}\phi_{1,2}(t)}{\mathrm{d}t} = \frac{1}{2}\alpha\left[\frac{\Gamma g(N_{1,2}(t)-N_0)}{1+\varepsilon S_{1,2}(t)} - \frac{1}{\tau_\mathrm{p}}\right] - \frac{k_\mathrm{inj}}{\tau_\mathrm{in}}\sqrt{\frac{S_1(t-\tau_\mathrm{c})}{S_2(t)}}\sin\xi(t), \quad (3)$$

where $N(t)$ is the carrier density, $S(t)$ is the photon density and ϕ is the phase. The injection can be applied to the second terms on the right-hand side of Eqs.(2) and (3). J is the pump current normalized by electron charge. $\Delta\nu = (\omega_2 - \omega_1)/2\pi$ denotes the frequency detuning of the two lasers. k_inj is the injection parameter that describes the injection strength received by the slave laser and can be written as

$$k_\mathrm{inj} = (1-r)\sqrt{\frac{r_\mathrm{inj}}{r}}, \quad (4)$$

where r is the amplitude reflectivity of the laser front facet, r_inj represents the percentage of the master laser output amplitude injected into the slave laser.

The parameters of the two lasers in our simulations are listed in Table 1. Numerical calculations are performed by the Rung-Kutta integration.

Table 1. Parameter values of master and slave lasers.

Parameter	Symbol	Master laser	Slave laser
Electron charge	q/C	1.6×10^{-19}	1.6×10^{-19}
Active region volume	V/m^3	1.2×10^{-16}	1.5×10^{-16}
Carrier lifetime	τ_N/ns	2	2
Photo lifetime	τ_P/ps	2	2
Optical confinement factor	Γ	0.5	0.4
Carrier density at threshold	$N_\mathrm{th}/\mathrm{m}^{-3}$	1.5×10^{24}	4×10^{23}
Carrier density at transparency	N_0/m^{-3}	1×10^{24}	3×10^{23}
Gain saturation parameter	ε/m^3	3×10^{-23}	3×10^{-23}
Linewidth enhancement factor	α	4.5	4.5
Gain coefficient	β	1×10^{-5}	1×10^{-5}

Figure 2 shows the time series and the spectra of the fundamental frequency, the second frequency division, the third frequency division, and the fourth frequency division, obtained numerically with the repetition rates of optical pulses being 6.53, 13.06, 19.59, and 25.93 GHz, respectively. The injection parameter and the frequency detuning are fixed at 0.15 and 3 GHz, respectively. The fundamental frequency is shown in Figs.2(a–i) and 2(a–ii). When the optical pulse repetition rate is close to the oscillation frequency of the P1 state, the frequency of the output signal equals the repetition rate of the optical pulses. Thus the fundamental frequency comes to being. By modulating the optical pulse repetition rate from 6.53 to 13.06 GHz, where the repetition rate is close to the second harmonic frequency of the P1 state, the second frequency division is observed (see Figs.2(b–i) and 2(b–ii)). It means that the output clock frequency is half the repetition rate of the injected optical pulses. Similarly, when the repetition rates are close to the third and fourth harmonic frequencies of the P1 state, the third and fourth frequency divisions are observed (see Figs.2(c-i), 2(c-ii), 2(d-i) and 2(d-ii)), respectively.

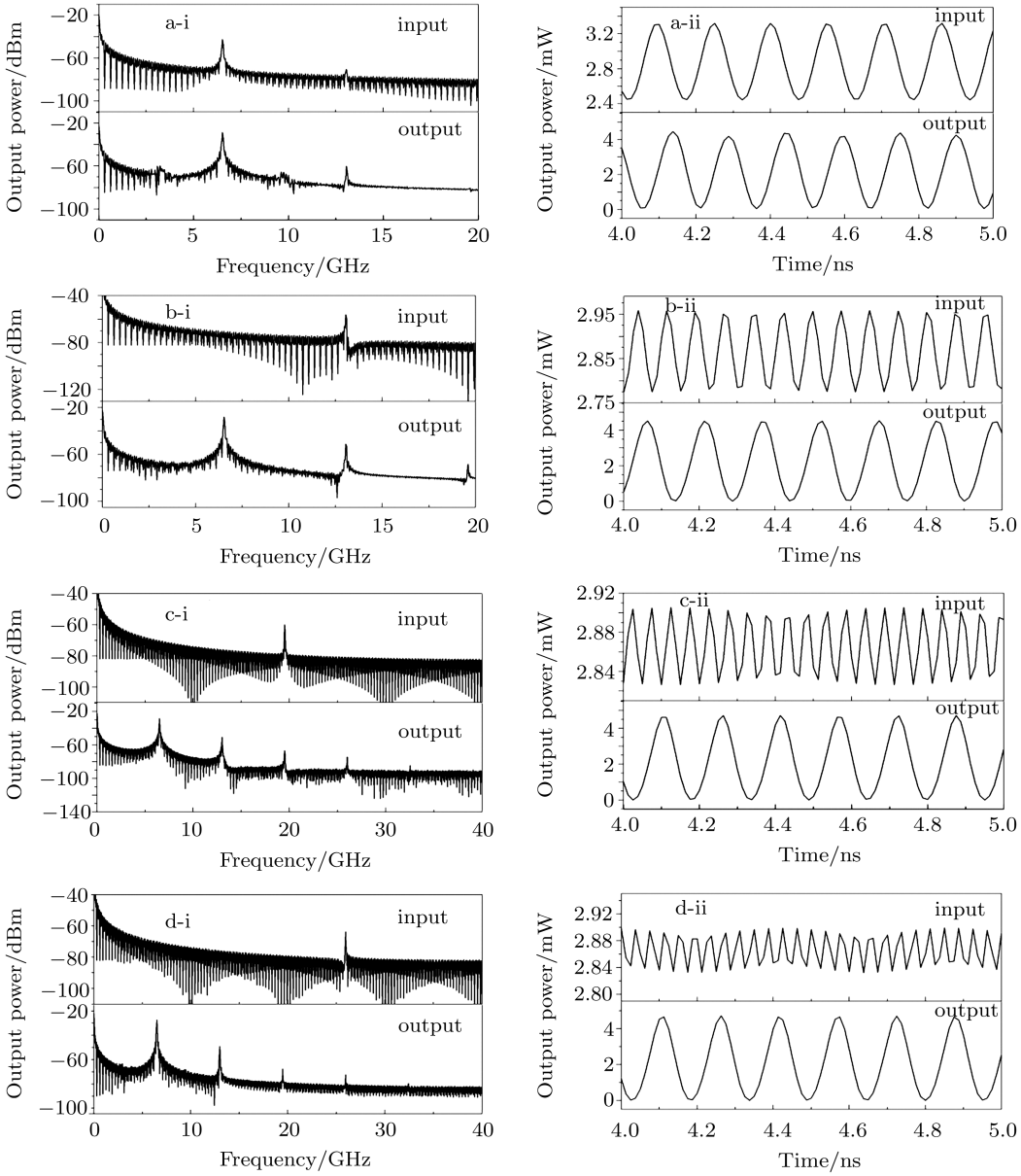


Fig.2. Different frequency divisions of semiconductor laser with different repetition rates: 6.53 GHz ((a–i) and (a–ii)), 13.06 GHz ((b–i) and (b–ii)), 19.59 GHz ((c–i) and (c–ii)) , and 25.93 GHz ((d–i) and (d–ii)).

We also numerically study the fundamental frequency extraction and the subharmonic frequency extraction from a pseudorandom bit stream (PRBS). In addition, by adjusting the injection parameter and the frequency detuning to 0.2 and 20 GHz, respectively, we achieve high repetition rate clock extraction. Figures 3(a-i), 3(a-ii), 3(b-i) and 3(b-ii) show the time series and the spectra of the recovered clock and the second division clock, respectively. Figure 3(a1) shows the scenario of 20 Gb/s pseudorandom return-to-zero (RZ). When the repetition rate of the PRBS is close to the oscillation frequency of the P1 state, clock recovery is achieved. Figures 3(a2) and 3(a3) are the time series and the spectra of the extracted clock of 20 GHz, respectively. Similarly, by adjusting the repetition rate of the injected data to 2×20 Gb/s (see Fig.3(b1)), where the repetition rate is close to the second harmonic frequency of the P1 state, the second frequency division is achieved. Figures 3(b2) and 3(b3) are the corresponding time series and spectra of the second division clock at 20 GHz, respectively. The fundamental frequency is useful for optical clock extraction from the damaged signal in an all-optical regenerator system, and the subharmonic frequency is useful for all-optical time demultiplexing. The above results are qualitatively verified with the measurements in the following section.

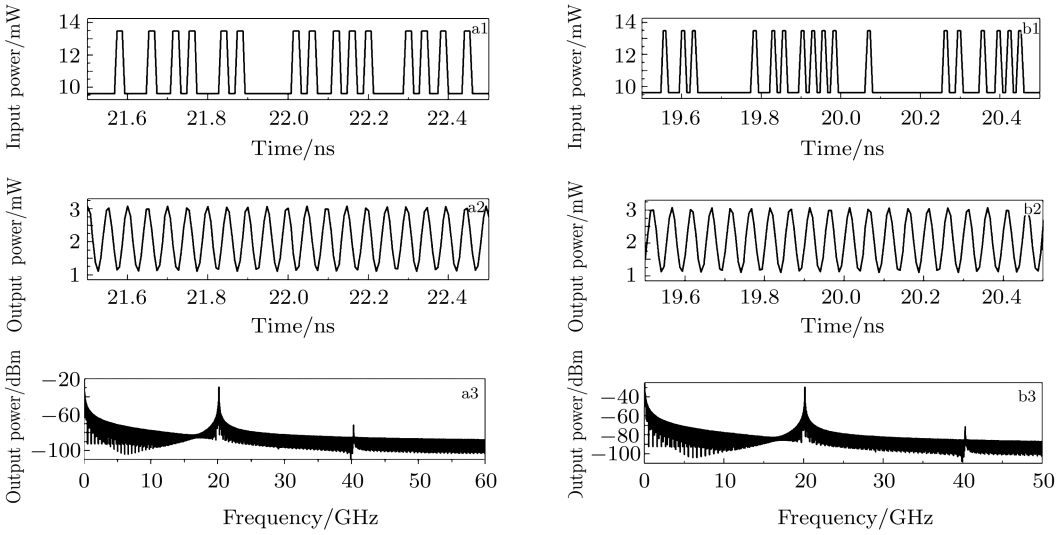


Fig.3. The time series and radio frequency (RF) spectrum clock recovery (a) and second frequency division (b).

3. Experimental results

Our experimental setup is shown in Fig.4. The master laser is a 1550 nm distributed feedback laser diode (DFB-LD). The optical pulses are generated from the DFB-LD which combines an electro-absorption modulation (EAM). A frequency synthesizer (Agilent E8257D) is employed to adjust the repetition rate of the optical pulses. After being amplified by an erbium-doped fibre amplifier (EDFA), the optical pulses are injected into the slave laser through an optical circulator. A polarization controller (PC) is used to control the coupling efficiency of the light injected into the slave laser. The output pulses from the slave laser are measured by a sampling oscilloscope (Agilent 86100B), an optical spectrum analyser (Agilent 86140B) and an RF spectrum analyser (Agilent N9010A).

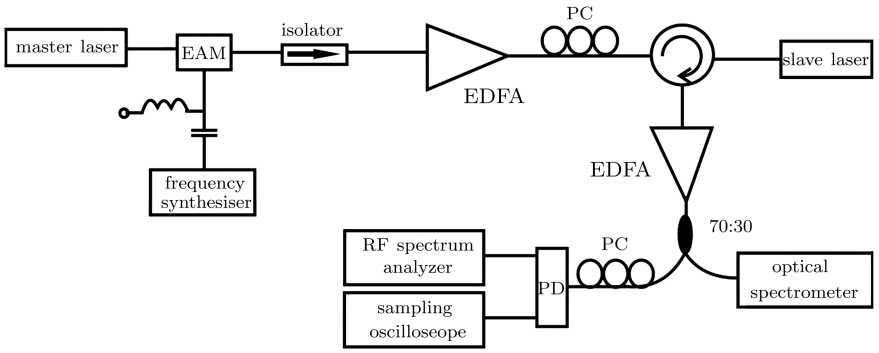


Fig.4. Experimental setup of optical pulses injection.

The master laser and the slave laser are biased at $1.61I_{\mathrm{th}}$ and $1.24I_{\mathrm{th}}$, respectively. The frequency detuning between the two lasers is 2.5 GHz. The slave laser is injected by optical pulse with an average optical power of –0.64 dBm. Figure 5 shows the time series and the spectra of the fundamental frequency, the second frequency division and the third frequency division obtained experimentally, which are similar to simulation results. In Figs.5(a–i) and 5(a–ii), by injecting the optical pulses with a repetition rate of 6.1 GHz, we observe a fundamental frequency of 6.1 GHz, where the frequency is close to the oscillation frequency of the P1 state. The second and third frequency divisions generated in experiment are shown in Figs.5(b-i), 5(b-ii), 5(c-i) and 5(c-ii), when the repetition rates are 12.4 and 18 GHz, which are close to the second and third harmonic frequencies of the P1 state, respectively.

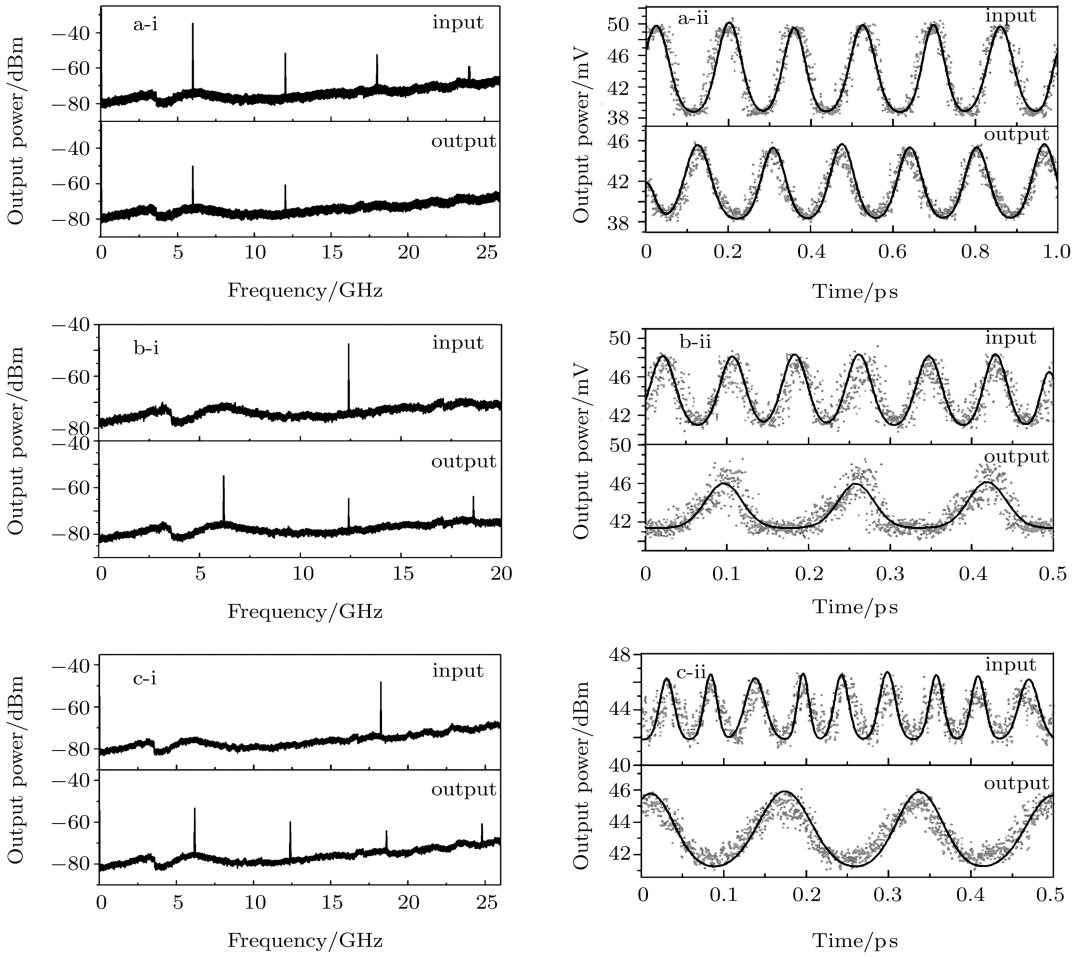


Fig.5. Different frequency divisions of semiconductor laser with different repetition rates: 6.1 GHz ((a–i) and (a–ii)), 12.4 GHz; ((b–i) and (b–ii)), and 18 GHz ((c–i) and (c–ii)).

In addition, we study the phase noise of the frequency division. As shown in Figs.6(a) and 6(b), by adjusting the repetition rate of the optical pulse, we obtain the second and third frequency divisions in the frequency locking ranges of 2 GHz and 1.9 GHz, respectively. Both of the phase noises of the frequency divisions are of low than –100 dBc/Hz. The results indicate that a low phase noise division signal can be obtained when the repetition rate is deviated from the harmonic frequency of the P1 state. It means that when the injected optical pulse with a fixed repetition rate is in the frequency locking range, the second and third frequency divisions can be achieved.

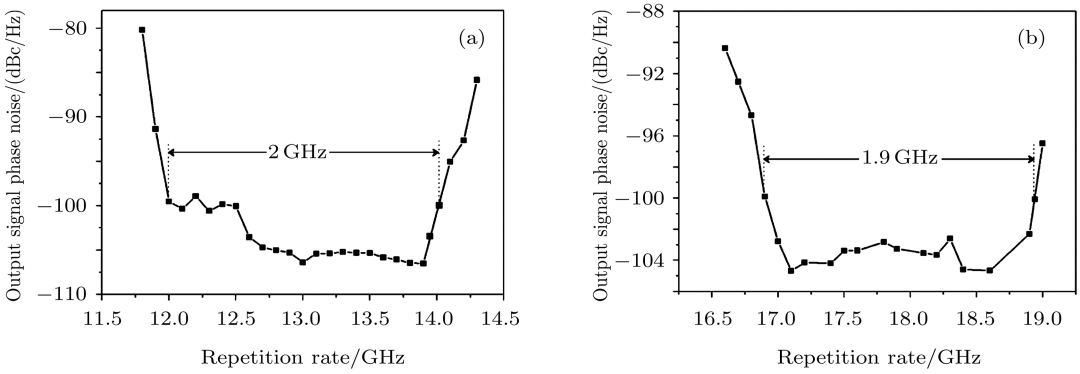


Fig.6. Output signal phase noise versus the repetition rate, where panel (a) shows the second frequency division, and panel (b) exhibits the third frequency division.

4. Discussion

Under optical pulses injection, due to the beating of the injection signal's light frequency and the injected laser's free-running frequency,[14] the P1 state comes to being. The frequency of the P1 state is of high phase noise, and it is not used for clock extraction. However, when the frequency of P1 state is locked, the linewidth spectrum of the frequency of P1 is narrowed, and the optical clock with low phase noise can be extracted. As shown in Fig.7, the narrow linewidth spectrum is the frequency of injected optical pulse signal, and the broad linewidth spectra are contributed by the P1 state oscillation frequency, the second harmonic frequency and third harmonic frequency, separately. When the oscillation frequency or the harmonic frequency of the P1 state approaches the frequency of the injected optical pulses, the oscillation frequency and the harmonic frequencies can be locked and narrowed, and then the optical clock with the phase noise lower than –100 dBc/Hz is obtained (see Fig.5). The oscillation and the harmonic frequencies of the P1 state are dependent on the injected optical power.[14] As shown in Fig.8, the oscillation frequency of the P1 increases with the optical pulse power increasing. Thus in the optical communication, by adjusting the injected optical power, we can shift the oscillation frequency and the harmonic frequency of the P1 state. When the oscillation frequency of the P1 state approaches to the repetition rate of the injected optical signal pulses, the oscillation frequency and the harmonic frequencies are locked and narrowed as shown in Fig.5(a–i). Consequently, the optical clock that approaches to the repetition rate of the optical pulses can be extracted. Similarly, by adjusting the injected optical power, when the second or the third harmonic frequency of the P1 state approaches to the repetition rate of the pulses, the oscillation and the harmonic frequencies of the P1 will be locked, the second or third clock division occurs, respectively. In our experiment, restricted by the maximal frequency ranges of the synthesizer and the RF spectrum analyser, we cannot obtain the fourth frequency division.

The optical clock that equals the fundamental frequency, or the second subharmonic frequency, or the third subharmonic frequency, is useful for applications in optical communication. In an OTDM system, clock division converts the clock frequency into a submultiple of the input data rate for all-optical demultiplexing. Thus the subharmonic frequency is essential. In the all-optical regenerator system, in order to obtain the optical clock for recovering the damaged signal, the clock frequency that equals the input signal rate is needed. Our results reveal that the all-optical clock recovery and the clock division are viable by using semiconductor laser subjected to optical pulses injection.

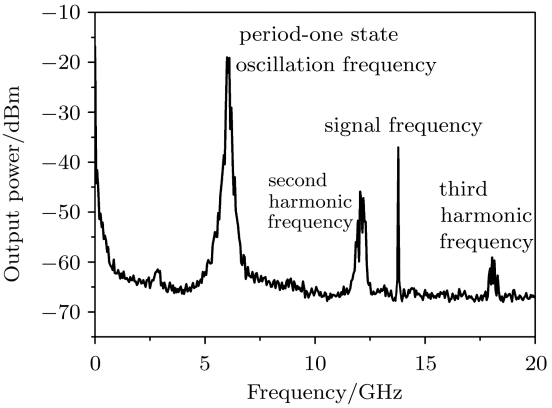


Fig.7. The period-one state spectra of the slave laser with optical pulse injection.

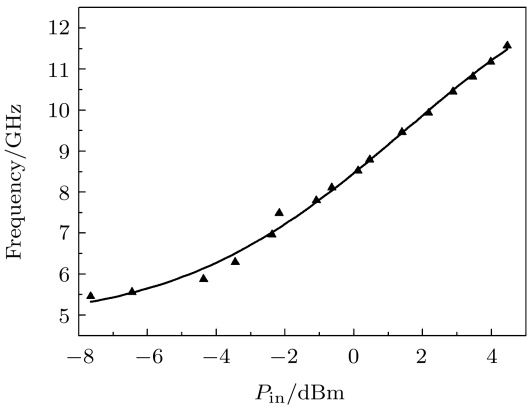


Fig.8. The dependence of oscillation frequency of the period-one state on injected optical power.

5. Conclusions

By adjusting the repetition rates or the optical power of the optical pulses, we extract the fundamental frequency and its high order subharmonic frequency based on the period-one oscillation state of the semiconductor laser. In addition, in a large frequency locking range, the subharmonic frequency is obtained with the phase noise below –100 dBc/Hz. The experimental results are consistent well with numerical results. Our findings indicate the period-one oscillation of semiconductor laser offers potential applications in all-optical clock recovery or clock division.

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