

Experimental investigation on the nonlinear dynamic characteristics of mutually delay-coupled semiconductor lasers system

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For a system of mutually coupled semiconductor lasers (SLs) with nanosecond (ns) order delay time, the nonlinear dynamic characteristics of this system have been investigated experimentally. Under different relative coupling level k and frequency detuning $\Delta\nu$ ($=\nu_1-\nu_2$, where ν_1, ν_2 are the free-running frequencies of SL1 and SL2, respectively), diverse nonlinear dynamic behaviors such as stable locking (S), four-wave mixing (FWM), period-one (P1), period-two (P2), period-three (P3), period-four (P4), multi-period (Pm), quasi-period (QP) and chaos (CO), have been observed. Furthermore, a map of dynamical states in the parameter space consisting of the relative coupling level k and the frequency detuning $\Delta\nu$ have also been given.

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1. Introduction

As an excellent and easily experimentally realizable example of coupled nonlinear oscillators, mutually delay-coupled semiconductor lasers (SLs) have attracted much attention in recent years because of their wide applications in various aspects such as achieving high output power in lasers array [1], optical memories [2], optical flip-flops [3], quantum-noise reduction [4] and chaos secret communication [5-9]. Moreover, researches on the dynamical characteristics of mutually delay-coupled SLs will be helpful for comprehending nonlinear dynamics of other coupling oscillators such as cellular neural networks or biological oscillators [10-11]. For a mutually delay-coupled system composed of two SLs, the output of one laser is coupled into the other laser, and vice versa. The existence of spatial separation between these two lasers inevitably results in a time delay. Such a time delay sometimes is one of important factors to specify the dynamic state of this system due to large bandwidth and fast time scales. For the case of the delay time on the order of the relaxation oscillation (so-called short coupling time regime), the dynamics of such a system have been extensively investigated in the past [12-15]. Various phenomena were reported such as stable compound laser modes, multi-stabilities and mode jumps in the locking regions [13], localized synchronization (power spectrum synchronization) for non-identical SLs under the periodic state [15]. For the case of the very large delay time (the corresponding distances between the lasers is longer than

10cm), two coupled non-identical SLs with different relaxation oscillation frequencies can still exhibit localized synchronized oscillation [16]. Spontaneous symmetry breaking followed by leader-laggard dynamics and asymmetric role of the two lasers has been observed in Ref. [17]. Generalized chaos synchronization in low frequency fluctuation regimes and high frequency fluctuation regimes are experimentally demonstrated [18]. Meantime, based on the Maxwell-Block equation, a dynamical model suitable for describing two mutually delay-coupled SLs have been developed and the relevant theoretical investigations have been performed [19-20].

However, to the best of our knowledge, previous relevant studies on mutually delay-coupled SLs mostly focus on particular nonlinear dynamics states for the system parameters varying only within a small range, but the integrated dynamic characteristics for varying the frequency detuning or coupling strength within a large range has not been reported. In this paper, the nonlinear dynamic characteristics of mutually delay-coupled SLs system are experimentally investigated by varying the relative coupling level and the frequency detuning within a relatively wide range. Diverse dynamic states have been observed, and the nonlinear dynamic characteristics are mapped as a function of the relative coupling level and the frequency detuning between the two SLs.

2. Experimental setup

Fig. 1 is the schematic of experimental setup of mutually delay-coupled semiconductor lasers system. Two InGaAsP/InP distributed feedback semiconductor lasers (DFB-SLs) with side-mode suppression ratio (SMSR) >50 dB are used in this experiment, and they are driven by the ultra-low-noise current sources (ILX-Lightwave, LDX-3620). Using the temperature controller (ILX-Lightwave, LDT-5412 with 0.01 K accuracy), the free-running frequencies of DFB-SLs can be adjusted. The output of SL1 is collimated by an aspheric lens (AL1), after that, the beam is split into two parts through a beam splitter (BS1). One part is injected into SL2 via a neutral density filter (NDF) and BS2, and the other part is sent to the signal detection system via an optical isolator (OI1) and a fiber coupler (FC1). A 12 GHz bandwidth photo-detector (PD, New Focus 1544-B) is used to convert the optical signal to an electrical signal. A 26.5 GHz bandwidth radiofrequency (RF) spectrum analyzer (Agilent E4407B) is used to detect the frequency spectra. An optical spectrum analyzer (Ando AQ6317C) with a wavelength resolution of around 0.01 nm is used to detect the optical spectra. Meanwhile, the output of SL2 experiences the similar process. During the experiment, the coupled delay time is fixed at 3.45 ns. The coupling optical power P_0 is monitored at point "T" by an optical power meter and the relative coupled level k is defined as the ratio of P_0 to P_{0max} , where P_{0max} is the maximum of P_0 . The different relative coupled level k can be obtained by adjusting the NDF.

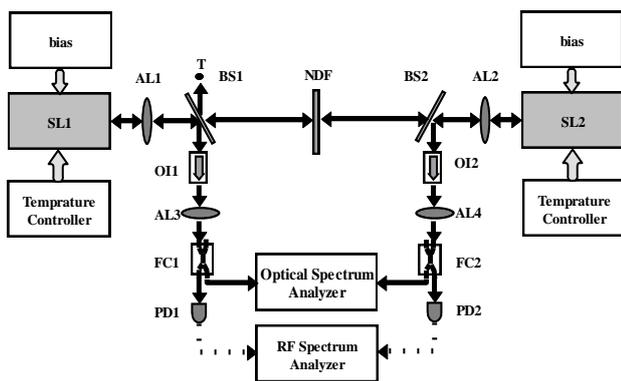


Fig.1. Experimental setup of mutually delay-coupled semiconductor lasers system. SL: semiconductor laser; AL: aspheric lens; BS: beam splitter; OI: optical isolator; PD: photo-detector; NDF: neutral density filter; FC: fiber coupler. The solid lines indicate the optical paths, while the dashed lines indicate the electronic paths.

3. Experimental results and discussion

In the experiment, SL1 and SL2 are biased at 21.22 mA and 21.30 mA respectively. The temperature of SL1 is fixed at 22.05 °C and the corresponding free-running wavelength is 1549.904 nm. The frequency detuning $\Delta\nu$ ($=\nu_1-\nu_2$, where ν_1, ν_2 are the free frequencies of SL1 and SL2 respectively) can be controlled by adjusting the temperature of SL2.

3.1 Several dynamic states of mutually delay-coupled SLs system

The dynamical behaviors of mutually delay-coupled SLs system closely depend on $\Delta\nu$ and k . Under different values of $\Delta\nu$, different dynamic state can be observed by varying k .

3.1.1 Without frequency detuning

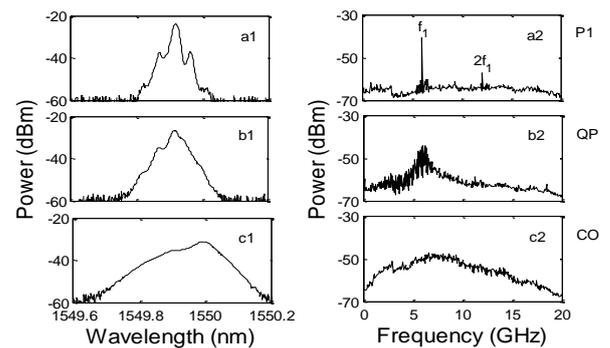


Fig. 2. Optical spectra (left column) and frequency spectra (right column) of SL1 under $\Delta\nu=0$ GHz for $k=0.0168$ (a), 0.0279 (b), and 0.9517 (c). P1: period-one; QP: quasi-period; CO: chaos oscillation.

Fig. 2 shows optical spectra and frequency spectra of SL1 under zero frequency detuning for $k=0.0168$ (a), 0.0279 (b), and 0.9517 (c), where only the output of SL1 is given for the dynamic state of SL2 is similar as that of SL1. For $k=0.0168$ as shown in (a), the optical spectrum has five peaks and the corresponding frequency spectrum has an obvious peak which locates at f_1 (about 6.05GHz) close to the relaxation oscillation frequency f_r , and the second peak in frequency spectrum emerges at about 12.09 GHz which is the harmonic of f_1 . Thus, under this circumstance, SL1 operates at period-one (P1) oscillation. For $k=0.0279$ (see (b)), the optical spectrum is broadened obviously and more frequency component appears in the frequency spectrum, and it can be concluded that SL1 operates at quasi-period (QP) state. For $k=0.9517$ (see (c)), the optical spectrum is broadened seriously and the frequency spectrum becomes continuous and smooth,

which indicates that the laser operates at chaos oscillation (CO) state.

3.1.2 With frequency detuning

When there exists frequency detuning between two SLs, the output of SL1 becomes more complex. Fig. 3 shows the optical spectra and frequency spectra of SL1 at $\Delta\nu=3\text{GHz}$, where (a)-(d) are for $k=0.0036, 0.0089, 0.0092,$ and 0.0094 , respectively. For $k=0.0036$ (see (a)), there are two obvious peaks at f_1 and f_2 in the frequency spectrum, where f_1 is close to f_r and f_2 is about half of f_1 . Under this case, SL1 operates at period-two (P2) state. For $k=0.0089$ (see (b)), besides the frequency f_1 close to f_r , the sub-harmonics f_2 (about $2/3 f_1$) and f_3 (about $f_1/3$) are also observed in the frequency spectrum, so the output state of SL1 is period-three (P3). For $k=0.0092$ (see (c)), more peaks such as f_1 close to f_r, f_2 (about $f_1/2), f_3$ (about $3/4 f_1$), and f_4 (about $f_1/4$) appear in the frequency spectrum, and this indicates the laser operates at period-four (P4) state. For $k=0.0094$ (see (d)), a lot of frequency components can be observed in the frequency spectrum, so the system enters into a multi-period (Pm) state. It should be pointed out that other states such as P1, QP, and CO states have also observed for $\Delta\nu=3\text{GHz}$ though they have not been given in Fig. 3. Therefore, compared with that for $\Delta\nu=0\text{GHz}$, the dynamic characteristics are more complex and much more states can be observed in mutually delay-coupled SLs system with frequency detuning.

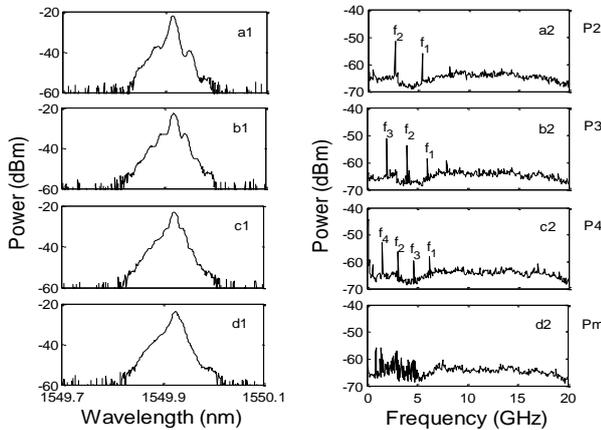


Fig. 3. Optical spectra (left column) and frequency spectra (right column) of SL1 under $\Delta\nu=3\text{GHz}$, where (a)-(d) are for k is $0.0036, 0.0089, 0.0092,$ and 0.0094 , respectively. P2: period-two; P3: period-three; P4: period-four; Pm: multi-period.

In addition, during the experiment, for the two SLs with free-running wavelengths of $\lambda_1=1549.904$ nm and $\lambda_2=1549.892$ nm, respectively, stable locking state at wavelength of 1549.897 nm has been observed for $k=0.01$. The wavelength of locking state is not equal to either λ_1 or λ_2 , which is different from that for unidirectional optical

injected locking. Under the case of unidirectional optical injected locking, the wavelength of slave SL is locked at the wavelength of master SL. The reason is that mutually coupling between two SLs affects their dynamics simultaneously.

3.2 Mapping of the nonlinear dynamic characteristics of mutually delay-coupled SLs

By continuously changing k and $\Delta\nu$, the various dynamic characteristics can be obtained, which have been mapped in Fig. 4. This map clearly shows that the states of mutually coupled SLs are very complex and very sensitive to k and $\Delta\nu$. For the region of low k and $\Delta\nu \approx f_r/2$, diverse dynamical states such as P2, P3, and P4 have been exhibited. Especially, it should be pointed out that the P3 region, which does not appear in unidirectional optical injection SL system, has been found.

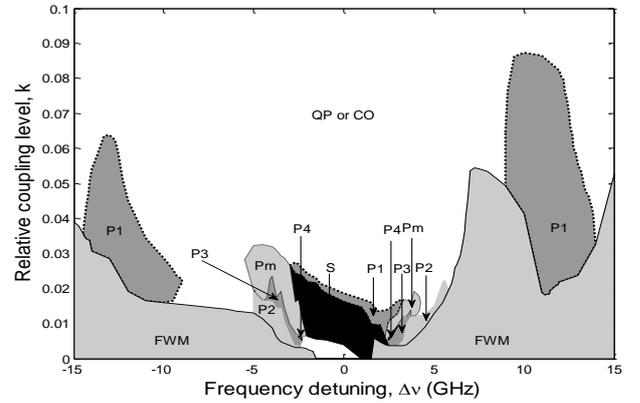


Fig. 4. Mapping of the nonlinear dynamic characteristics of mutually delay-coupled SLs. S: stable locking state; P1: period-one; P2: period-two; P3: period-three; P4: period-four; Pm: multi-period; FWM: four-wave mixing; QP: quasi-period; CO: chaos oscillation.

4. Conclusions

In this paper, the nonlinear dynamical characteristics of two mutually coupled SLs with large delay time of 3.45 ns, are investigated experimentally. It is demonstrated that the frequency detuning $\Delta\nu$ and the relative coupled level k play an important role on the nonlinear dynamics of system. By changing $\Delta\nu$ and k , rich nonlinear dynamic phenomena such as P1, P2, P3, P4, Pm, S, QP and CO states have been observed. The nonlinear dynamic distribution of the mutually coupled SLs system has been mapped based on experimental data. The results show that the output states of mutually coupled SLs are very complex and many different states can be observed through changing k and $\Delta\nu$.

Acknowledgments

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