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Comparisons of typical nonlinear states in single- and dual-beam optically injected semiconductor lasers

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ABSTRACT

The characteristics of the typical nonlinear states in an optically injected laser system with single- and dual-beam injection are analyzed and compared numerically. Both single- and dual-beam optical injection systems can generate periodic oscillations and chaos states but with different characteristics. By observing the evolution process of periodic oscillations, it is found that dual-beam injection induced periodic oscillations have multiple time series patterns including continuous periodic signals with single peak (CPS) and continuous periodic signals with subharmonic (CPSSH), while for single-beam injection with either of the dual-beam injection parameters generated periodic oscillations, the extremum numbers of the time series equal to the frequency period numbers of the optical spectrum. In addition, the great advantages of bandwidth enhancement effect for chaos oscillations are obtained by using dual-beam injection. Furthermore, extensive numerical simulations reveal that dual-beam injection system undergoes period-doubling routes to chaos, which is identical to that in single-beam injection system. Finally, the characteristics of newly clustered NDFWM dynamics in dual-beam injection system are analyzed.

1. Introduction

The semiconductor laser systems with various perturbations, such as optical injection [1,2], optical feedback [3,4], and optoelectronic feedback [5,6] have been extensively studied in recent years. Rich nonlinear dynamics have been observed and demonstrated. The primary dynamical states include stable locking, periodic oscillations and chaos. With the development of different applications of the various dynamics [7–9], understanding and investigation of new nonlinear dynamics subject to more than one perturbation have attracted much attention recently [10–24]. A period-doubling bifurcation routes to chaotic coherence-collapse regime were observed in a laser diode subject to both optical and optoelectronic feedbacks [10], where the optoelectronic feedback can suppress or invert the bifurcation sequence. The bandwidth enhancement effect was obtained in an optical injection locking system with varying levels of optical feedback from an external reflector [11]. It was found that an optically injected laser subject to optoelectronic feedback generated the dynamics of stable locking, periodic oscillation, chaotic oscillation, regular pulsing, quasiperiodic pulsing, and chaotic pulsing [12], either period-doubling or quasiperiodic route to chaos were observed in the system. Meanwhile, the bandwidth broadening effect for chaotic states was observed. A directly modulated fiber-optical CATV system based on light injection and optoelectronic feedback was proposed to improve systems′ overall performances, including the carrier-to-noise ratio, composite second order, and composite triple beat [13]. However, only a few attentions were attracted on the nonlinear dynamics in a dual-beam optically injected laser system. Troger et al. reported a theoretical and experimental study of a slave laser subject to external light injection from several lasers [14]. A secondary locking region in a semiconductor laser with optical injection from two master lasers was observed by Al-Hosiny et al. [15]. It was demonstrated that the stability map would be modified to expand the chaos region with injection of two optical signals into a distributed feedback (DFB) laser [16]. The bandwidth of chaotic Fabry–Perot (FP) laser was enhanced due to dual-beam injection [17]. A pushed locking phenomenon was observed in an optically injected semiconductor laser system and was analyzed by using the medium-gain model [18]. We have fully investigated various nonlinear dynamic scenarios [19] and shown the complete mapping of different scenarios in dual-beam optically injected semiconductor laser system for varying injection strengths and detuning frequencies of the two injection beams [20]. The dynamics of dual-beam optical injection have been applied to photonic microwave generations [21–24]. Compared with single-beam injection, dual-beam injection system could generate tunable microwave signals with better performances, such as broader tuning range, narrower bandwidth and higher amplitude of the total power [21,22]. Based on slave multi-transverse mode VCSELs subject to two-frequency optical injection,

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the microwave beyond THz region were demonstrated with broad tuning ranges and narrow linewidths [23]. A broadcasting downlink Radio-over-fiber (RoF) system based on dual-beam optical injection with amplitude modulation and tunable microwave frequency was studied [24]. Frequency multiplication microwave generation based on sideband injection locking of dual-wavelength DFB laser was reported in [25], where microwave modulated master laser was equivalent to multiple optical injections. However, no attempt has been made to investigate the time series patterns for periodic oscillations in dual-beam optically injected semiconductor lasers. Besides, the different characteristics of the typical nonlinear states in single- and dual-beam optical injection system are not compared and analyzed.

In this paper, the nonlinear dynamics between single- and dual-beam optically injected semiconductor laser systems are compared numerically. The dynamics of an optically injected laser subject to more than one injection beam are much more interesting and complex than those of a single-beam injected laser. It is investigated that periodic oscillations due to dual-beam injection have multiple time series patterns including continuous periodic signals with single peak (CPS) and continuous periodic signals with subharmonic (CPSSH), while for single-beam injection with either of the dual-beam injection parameters generated periodic oscillations, the extremum numbers of the time series equal to the frequency period numbers in the optical spectrum. This would help system designers to choose the operation conditions giving CPS and/or CPSSH, or to avoid operation with irregular dynamics. Furthermore, compared with frequency modulation (FM) characteristics of periodic oscillations in single-beam injection system, those in dual-beam injection system have amplitude modulation (AM) characteristics. In addition, it is found that the bandwidth of chaotic oscillations can be further increased by dual-beam injection and the chaos region is broadened simultaneously. As the key parameter, the bandwidth of chaotic signals restrict the bit rate of random sequence, the range resolution of chaotic lidar, and the transmission rate of optical chaos communications. The bandwidth enhancement via dual-beam injection provides higher bit rate for chaos communications. Besides, the dual-beam optically injected laser is found to follow a period-doubling route to chaos. Considering the various time series patterns of periodic oscillations in dual-beam injection system, the evolution process of period-doubling route is demonstrated by the power spectra. In addition, two types (Type Iand II) of clustered nearly degenerate four-wave mixing (NDFWM) created by dual-beam optical injection are described. We focus on illustration of the property of Type II with NDFWM taking place on the optical spectra of periodic oscillations dominated by both the injection beams, considering Type I with NDFWM taking place on the optical spectra of periodic oscillations dominated by the stronger injection beam has been observed in our previous publication [19]. The potential applications of clustered NDFWM in WDM-(Radio-over-fiber) RoF signal are introduced as well.

2. Theoretical model analysis

The resonant coupling characteristics between the circulating optical filed and the carrier electrical field is changed in an optically injected semiconductor laser system. Compared with the single-beam optically injected laser system, double master light beams optically injecting a slave laser introduces additional degree of injection parameters and therefore exhibit more complex dynamics. These systems can be described by the nonlinear ordinary differential rate equations as below:

$$\frac{dA}{dt} = \left[-\frac{\gamma_c}{2} + i(\omega_0 - \omega_c)\right]A + \frac{\Gamma}{2}(1 - ib)gA + \eta\sum_m A_m e^{-i\Omega_m t} \qquad (1)$$

$$\frac{dN}{dt} = \frac{J}{ed} - \gamma_s N - gS \qquad (2)$$

where A is the complex intracavity field amplitude at the free-running angular frequency ω_0 of the slave laser, γ_c is the cavity decay rate, ω_c is the resonance frequency of the cold slave laser cavity, Γ is the confinement factor of the optical mode inside the gain medium, b is the linewidth enhancement factor, g is the optical gain, η is the injection coupling rate, $A_m = |A_m|e^{i\varphi_m(t)}$ are the complex amplitudes of the external injection fields with $\varphi_m(t)$ being the phases of the injection fields. $m=1$ and 2 stand for the system with single- and dual-beam optically injected laser system, respectively. The detuning frequencies of the injection fields, measured with respect to the free-running slave laser frequency $\omega_0/2\pi$ are $f_m = f_{MLm} - \omega_0/2\pi = \Omega_m/2\pi\xi_m = \eta|A_m|/\gamma_c|A_0|$ is the dimensionless injection strengths, and A_0 is the free running A. N is the charge carrier density; J is the injection current density; e is the electronic charge; d is the active layer thickness; γ_s is the spontaneous carrier relaxation rate; and S is the active region photon density [27]. The gain is defined as $g = (\gamma_c/\Gamma) + \gamma_n\big((N - N_0)/S_0\big) - \gamma_p\big((S - S_0)/\Gamma S_0\big)$ [28]. Eqs. (1) and (2) are solved by second-order Runge–Kutta integration for a duration longer than 1 μs for each time series. The dynamical parameters can be experimentally extracted from the slave laser using a well established four-wave mixing technique [29]. We use a set of parameters for a high-speed InGaAsP/InP DFB semiconductor laser at 1.3 μm wavelength [30]: $\gamma_c = 5.36 \times 10^{11}\ \mathrm{s}^{-1}$, $\gamma_s = 5.96 \times 10^9\ \mathrm{s}^{-1}$, $\gamma_n = 7.53 \times 10^9\ \mathrm{s}^{-1}$, $\gamma_\mathrm{p} = 1.91 \times 10^{10}\ \mathrm{s}^{-1}$, $b = 3.2$, and $\tilde{J} = ((J/ed) - \gamma_s N_0)/\gamma_s N_0 = 1.222$. The optical spectrum and power spectrum are obtained from the Fourier transform of $A = a_r + ia_i$ and $|A|^2$.

3. Results and discussions

3.1. Periodic oscillations

Periodic oscillations can be triggered by both single-beam and dual-beam optically injected laser systems. The P1 state is the simplest nonlinear state among periodic oscillations that contain periodic spectrum components with the fundamental frequency f_0 as the period. Meanwhile, P1 oscillation is the initial state from which periodic oscillations starts to go to chaos during the period-doubling routes. The P1 state created by single-beam injection has the property of FM, the fundamental frequency f_0 starts from the detuning frequency f_1 and increases with the injection strength ξ_1. However, for a given positive detuning frequency, the fundamental frequency has a maximum value corresponding to the Hopf bifurcation point where the injected laser leaves the P1 state to become stably locked [30]. The evolution states of periodic oscillations from P1 to P2 and eventually to chaos in dual-beam injection systems have been observed in our earlier research [19]. It is found that the P1 states from dual-beam injection system exist at a large region and with AM characteristic, the fundamental frequency is the difference frequency between the injection two beams. Therefore, f_{0max} in single-beam optically injected laser system could be further increased by dual-beam injection technique.

Further investigation reveals the relationship between the P1 region and the injection parameters in dual-beam injection system. Fig. 1 mapped the P1 region as functions of injections strengths ξ_1 and ξ_2 for fixed detuning frequency of $f_1 = 25$ GHz and different detuning frequencies of $f_2 = 50$ GHz, 70 GHz, 90 GHz. The stable locking thresholds ξ_{2t} for 50 GHz, 70 GHz and 90 GHz are 0.63, 0.84 and 1.06, respectively, and that of 25 GHz is 0.38, which is indicated by ξ_{1t} in the figure. The P1 states exist above the boundary lines shown in Fig. 1. The blue triangle line, black square line, and red circle line indicate the boundary lines for $f_2 = 50$ GHz,