High-Level Dynamics in Semiconductor Lasers: Regimes and Applications

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Abstract

While solitary single-mode semiconductor lasers normally emit continuous-wave radiation, their rich nonlinear dynamics, such as periodic oscillations and chaos, can be excited through various perturbation schemes. These highly complex dynamical behaviors can be well controlled by properly adjusting the experimentally accessible parameters of perturbations. The ability to control the dynamical behavior of semiconductor lasers, together with the profound dynamical characteristics, not only provides valuable opportunities for the study of nonlinear laser dynamics but also opens up great possibilities for a wide range of novel applications.

I. INTRODUCTION

Semiconductor lasers fall within the class B category of lasers, where the polarization of the gain medium adiabatically follows changes in the oscillating field and the population inversion. The equation describing the polarization can therefore be adiabatically eliminated. This leaves two first-order nonlinear differential equations, one for the complex oscillating field and one for the population inversion, to describe the dynamics of a single-mode semiconductor laser. Because the phase of the oscillating field is a free parameter of no particular physical significance on the laser dynamics, the complex field equation can be replaced by a real equation in terms of the photon density. A free-running single-mode semiconductor laser therefore does not show any exciting dynamical behavior, except relaxation oscillation resonance.

Semiconductor lasers differ from many other lasers in that the free carriers, which control the optical gain, have a strong effect on the refractive index. This establishes a strong coupling between the amplitude and phase of the oscillating field in the laser cavity. When a single-mode semiconductor laser is subject to an external perturbation, such as optical injection, the phase of the oscillating field is no longer a free parameter but plays a key role in the development of high-level laser dynamics through the amplitude-phase coupling. The simple equation for the photon density must be replaced by an equation for the complex oscillating field. The enhancement in the degree of freedom can induce a variety of different dynamical behaviors of the laser, which include chaos, periodic oscillations, quasi-periodicity, and self-mixing [1].

The highly complex dynamical behaviors can be well controlled by properly adjusting the experimentally accessible parameters of a perturbation. The ability to control the dynamical behavior of a semiconductor laser, combined with the profound dynamical characteristics, not only provides valuable opportunities for the study of nonlinear laser dynamics but also opens up great possibilities for a wide range of novel applications. For example, while self-mixing has been studied for metrology, sensing, physical quantity measurement, and laser parameter measurement, chaos has been proposed for cryptography, high-speed random number generation, and high-resolution ranging and imaging.

In this talk, we will particularly focus on the study of period-one (P1) nonlinear dynamics in semiconductor lasers subject to external optical injection. By undamping the relaxation resonance of a semiconductor laser through continuous-wave (CW) optical injection at a Hopf bifurcation point, the P1 dynamics can be invoked. While the optical injection regenerates, oscillation sidebands that are equally separated from the regeneration by an oscillation frequency sharply emerge, leading to a self-sustained oscillation of the optical intensity. Since the optical injection reduces the necessary gain for the injected laser, the laser cavity resonance red-shifts through the antiguidance effect. The lower oscillation sideband is therefore resonantly enhanced as opposed to the upper one. As a result, the lower oscillation sideband has a power that is not only one to two orders of magnitude higher than the upper oscillation sideband but is also close to the regeneration. These unique characteristics of the P1 dynamics have attracted much research interest for various applications in optical signal processing and microwave photonics.

There has been a strong demand in distributing microwave subcarriers over long distances through fibers for antenna remoting applications, such as wireless access networks, leading to the study of microwave photonics. Such radio-over-fiber links adopt an architecture where microwave subcarriers are generated in the optical domain at central offices and next transmitted to remote base stations through fibers. Microwave subcarriers are converted to the electrical domain at the base stations using photodetectors, which are next radiated by antennas over small areas. Certain features of such generated microwave subcarriers are necessary to simultaneously satisfy the requirements in both the optical domain and the electrical domain. These include high microwave frequency, low phase noise, broadband frequency tunability, optical single-sideband (SSB) modulation, and high optical modulation depth. By taking advantage of the P1 dynamics of semiconductor lasers, microwave subcarriers can be generated or improved to possess such features, as demonstrated in the following presentation.

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II. PHOTONIC MICROWAVE GENERATION

By taking advantage of the self-sustained oscillation of the optical intensity, the P1 dynamics is a nature oscillator that generates microwaves upon optical waves. Simply adjusting the power and frequency of the optical injection can continuously tune such generated microwaves from a few to tens or even hundreds of gigahertz, an all-optical scheme without suffering from limited electronic bandwidths. The two-tone feature of the P1 dynamics also manifests a feature of optical SSB modulation, which is preferred for fiber distribution to mitigate the microwave power fading effect.

The spontaneous emission noise of the injected laser, however, deteriorates the spectral purity of the generated microwaves, leading to a considerably broad 3-dB linewidth, typically on the order of 1 to 10 MHz. In addition, fluctuations in the power and frequency of the optical injection relative to those of the injected laser lead to significant microwave frequency jitters, typically on the order of 100 MHz. To improve the spectral purity and stability, the optical feedback scheme [2] and the optical modulation sideband injection locking scheme [3] were proposed, where the microwave linewidth was reduced by 2 and 6 orders of magnitude, respectively.

III. PHOTONIC MICROWAVE AMPLIFICATION

Direct or external modulation of semiconductor lasers is the simplest scheme to superimpose microwaves of high spectral purity onto optical waves. However, owing to the inherent nature of either scheme, the resulting optical modulation depth is low, typically less than 20%. This results in low microwave power after photodetection, leading to low detection sensitivity, short transmission distance, and low link gain.

Attributed to the red-shift of cavity resonance induced by CW optical injection, the lower oscillation sideband of the P1 dynamics is resonantly enhanced and thus can have a power close to the regeneration of the optical injection. Under the same injection condition, sending a microwave-modulated optical signal generated by the direct or external modulation scheme into the laser can also invoke the same P1 dynamics. By take advantage of the resonance enhancement, the optical modulation depth of the microwave-modulated optical signal can thus be improved up to 100% through considerable enhancement of the lower modulation sideband, achieving microwave amplification optically [4]. Microwave amplification of more than 30 dB was demonstrated for microwave frequency up to 60 GHz. The highest achievable frequency was restricted by the bandwidth of the devices used in the study. Amplification at a higher frequency, such as 100 GHz or more, is feasible.

IV. OPTICAL DSB-TO-SSB CONVERSION

Because of the inherent nature, direct or external modulation of semiconductor lasers typically generates an optical carrier carrying two modulation sidebands of equal intensity, commonly referred to as optical double-sideband (DSB) modulation. When such an optical DSB signal propagates along a fiber, each spectral component experiences a phase shift of different level due to chromatic dispersion. At remote base stations, the photodetected beat signals between the modulation sidebands and the optical carrier may add up constructively or destructively depending on their phase relationship. This gives rise to a fluctuation of the generated microwave power at base stations of different distances. To minimize this microwave power fading effect, an optical carrier carrying two modulation sidebands of significantly unequal intensity, commonly referred to as optical SSB modulation, is preferred.

Resulting from the red-shift of cavity resonance induced by CW optical injection, the lower oscillation sideband of the P1 dynamics typically has a power that is one to two orders of magnitude higher than the upper one. Under the same injection condition, sending an optical DSB signal into the laser can also invoke the same P1 dynamics. By take advantage of the intensity asymmetry between the P1 oscillation sidebands, the optical DSB signal can therefore be converted into an optical SSB signal though creating an intensity asymmetry of more than 20 dB between the modulation sidebands [5]. Such DSB-to-SSB conversion was achieved for microwave frequency up to 40 GHz. The highest demonstrable frequency was restricted by the bandwidth of the devices used in the study. Conversion for a higher frequency, such as 100 GHz or more, is possible. The conversion system can be self-adapted to certain changes in the operating microwave frequency and can operate stably under certain fluctuations of the injection power and frequency.

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